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Review article

Air pollution and the demand for hospital services: a review

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Abstract

Time-series studies published since 1993 on the association between short-term changes in air quality and use of hospital services, including both inpatient and emergency room use, are reviewed. The use of nonparametric analysis, often incorporating generalized additive models (GAMs), has increased greatly since the early 1990s. There have also been three major multi-city studies, which together analyzed data from well over 100 cities in Europe and North America. Various air pollutants, especially ozone (O_3), particulate matter (PM), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), were generally found to be significantly associated with increased use of hospital services. Ozone tends to have stronger effects in the summer during periods of higher concentrations. Several studies revealed synergistic effects between pollutants such as PM and SO_2. Overall, short-term exposure to air pollutants is found to be an important predictor of increased hospital and emergency room use around the world.

Keywords: Air pollution; Hospital services; Particulate matter

1. Introduction

Air pollution has been associated with acute reductions in lung function, aggravation of asthma, increased risk of pneumonia in the elderly, low birth weight in newborns and death (Anderson, 1999; Bates, 1999; Lee et al., 2003). In addition, long-term exposure to particulate matter (PM) has been associated with an increase in lung cancer and cardiopulmonary mortality (Pope et al., 2002). In clinical studies, ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and particulate matter have been shown to exacerbate asthma, primarily by augmenting airway inflammation (Peden, 1999). Overall, there is overwhelming evidence that anthropogenic air pollution is detrimental to human health (CEOH, 1996; Samet, 1999).

Despite the presence of overwhelming evidence that air pollution affects human health, some significant challenges remain. One of the biggest challenges in resolving the human health/air quality relationship is the collection of reliable health data from a broad sample of the population. It is difficult to monitor individual asthma attacks or reduced lung function in large populations, as most people treat themselves without medical assistance. Studies that focus on individual responses to pollution are useful, but resource intensive and limited in the number of monitored individuals. Extrapolation from small samples of individuals to entire populations (such as a city) is challenging. Another approach is to use institutional records that are often gathered for other reasons. This type of study is termed an ‘ecological study,’ because it focuses on changes in populations rather than individuals. There are many potential sources of population-based data that have been used in ecological studies relating air pollution to health effects. For example, the daily absenteeism rate in Nevada elementary schools was shown to increase 3.79% (95% CI 1.04–6.55%) and 13.01% (95% CI 3.41–22.61%), for every 1.0 ppm CO and 50 ppb O_3 increase, respectively (Chen et al., 2000). Another common source of respiratory data is records of hospital inpatient and emergency room (ER) visits. With detailed information on the number of people visiting the hospital everyday and their diagnosis, it is possible to glean some information about the relative number of respiratory emergencies in a population. Many studies have used this

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technique, and virtually all found that the number of people that go to the emergency room for respiratory reasons increases after pollution events (Mannino et al., 2002).

Well over 100 studies of the association between air chemistry and hospital services have been published since the 1960s. In 1993, Frederick Lipfert reviewed this literature and concluded that almost all of the studies found a significant relationship characterized by elasticities of about 20% (i.e., a 100% change in air pollution is associated with a 20% change in health outcome) (Lipfert, 1993). Here, a selection of studies of hospital services and methodological developments published since 1993 are reviewed. As Lipfert (1993) explained, "much of the extant review literature on the health effects of air pollution is organized by pollutant rather than by type of health response or end point.... Reviewing the epidemiological literature by type of health effect allows a more direct comparison of study methodologies and of the relative effects of different pollutants." While toxicological studies are free to focus in on a single pollutant, epidemiological studies investigate actual exposures as individuals go about their lives, which of course includes exposure to various mixtures of pollutants. Epidemiological studies are not well suited to separate the effects of individual pollutants, but have the strength of measuring the impact of real-life exposures in a large population. This review concentrates on time-series studies of hospital utilization and is organized by geographical region in order to illustrate the diversity of locations in which this type of study has been performed and the overall agreement of findings. The strength of this organization is that each study is considered in its entirety and not divided by pollutant. This serves to prevent each pollutant from each study being considered as a separate example of exposure, when in reality, study populations are often exposed to a mixture of pollutants simultaneously.

Papers were considered for review using the National Library of Medicine's PUBMED database (http://www.ncbi.nlm.nih.gov) and include a selection of longitudinal studies of daily air quality and hospital services published in English. Papers were selected using two criteria: type of analysis and geographic location. The type of analysis was limited to time-series studies that compared daily air quality with daily variation in demand for hospital services (either inpatient or emergency room). Articles were also selected to provide a sample of studies from diverse geographic areas and cultures. While most reviews of this literature to date have been primarily focused on studies conducted in North America and Western Europe, this review includes articles from four continents. Secondary articles from the same research effort (i.e., same city or data set) were excluded. The specific type of analysis performed, confounding effects accounted for, predictor variables included, and presence or absence of a significant relationship are noted.

2. Review of methodology

2.1. Standardized protocols

At least three major initiatives have been undertaken in the past 10 years to create a standardized procedure for time-series analysis of air quality and health outcome data to facilitate multi-city comparisons. The Air Pollution and Health: a European Approach (APHEA) protocol, published in 1996, describes a methodology for a comparative multi-city study in Europe (Katsouyanni et al., 1996). That protocol has been used to investigate the effects of air pollution in about 30 cities to date. Another major project to standardize analytical protocol was the National Morbidity, Mortality, and Air Pollution Study (NMMAPS) (Samet et al., 2000). The NMMAPS project has analyzed morbidity and mortality data for the 90 largest cities in the United States and made a detailed description of their methodology available. Another large study is the Meta-Analysis of the Italian Studies on Short-term Effects of Air Pollution (MISA), which focuses on eight of the largest cities in Italy (Biggeri et al., 2001). The majority of other studies published in the past 10 years has not specifically followed any of these protocols, but instead has used some combination of the techniques they describe.

2.2. Generalized additive models

All models are wrong; some are useful (Box, 1979).

Many of the most recent studies use generalized additive models (GAMs), a powerful new technique developed by Hastie and Tibshirani (1999). Essentially, an extension of generalized linear models, GAMs have the flexibility to include nonparametric relationships between variables. This ability is especially useful in modeling health events because the relationships are often not well described by linear or quadratic terms. GAMs are commonly employed to model seasonal variation in hospital services that would otherwise be difficult to account for (Burnett et al., 2001; Samet et al., 2000, Tenias et al., 2002).

In late 2001, GAM techniques received attention because the default parameters in at least one major statistical package were found to be too lax and led to overestimation of pollution effects along with an underestimation of standard errors in even major studies such as the NMMAPS (Dominici et al., 2002; Samet et al., 2000; Stieb et al., 2003). However, this discovery shifted relative risk estimates only slightly (and only in the studies that used the software) and did not change any key findings of studies to date (Colburn and Johnson, 2003). While application of GAMs warrants caution, they can be used successfully if suitable convergence parameters are used.

2.3. Control for low-frequency variability and other temporal confounders

The seasonal variability of hospital service utilization exceeds the variability from air pollution over the course of days. To understand how the short-term (i.e., daily to weekly) variability in air chemistry affects health, long-term (i.e., seasonal to annual) variations must be removed. There are several methods available to accomplish this, including both parametric and nonparametric techniques. In addition, the long-term variation may be filtered out prior to modeling, or accounted for within the model. The APHEA project, for example, used parametric quadratic and sinusoidal terms within the model to account for season (Katsouyanni et al., 1996; Lewis et al., 2000). However, most recent studies, such as the NMMAPS project and APHEA-II, use semi-parametric or nonparametric techniques such as smoothing splines or LOESS, a locally weighted scatter plot smoother to model seasonality (Burnett et al., 2001; Samet et al., 2000). Cakmak et al. examined the differences between these methods and found that all can adequately account for seasonality if used properly. In that study, the authors looked at the relationship between ozone and respiratory hospital admissions for Toronto, Canada, from 1981 to 1991. They found that the O_3 relative risk for an interquartile (75th minus the 25th percentile values) change was 0.874 if no temporal trends were removed and around 1.020 for models that removed variability greater than 1 month. They found no significant difference between the different methods. Burnett et al. (2001) later argued that both health and air chemistry/weather data should be filtered for long-term temporal variation before bringing all the data together in a model. They argue that accounting for season within the model can lead to residual confounding in the cycles between admissions and air pollution. However, when prefiltering data, researchers must be mindful of changes

Table 1
Summary of reviewed articles, grouped by continent and year

Authors	Year of publication	City, nation	Model type	Years of study
Europe				
Diaz et al.	2001	Madrid, Spain	Box–Jenkins	1994–1996
Fauroux et al.	2000	Paris, France	Poisson autoregressive	1998
Lewis et al.	1999	Derbyshire, UK	log-linear autoregression	1993–1996
Tenias et al.	1998	Valencia, Spain	Poisson regression	1993–1995
Castellsague et al.	1995	Barcelona, Spain	Poisson regression	1985–1989
Asia				
Bibi et al.	2002	Ashkelon, Israel	artificial neural network	1992–1995
Hwang and Chan	2002	Taiwan	hierarchical modeling/ linear regression	1998
Lee et al.	2002	Seoul, South Korea	generalized additive	1998–1999
Nutman et al.	1998	Tel Aviv, Israel	artificial neural network	September 1993–November 1993
Australia				
Petroeschevsky et al.	2001	Brisbane, Australia	Poisson regression	1987–1994
Morgan et al.	1998	Sydney, Australia	Poisson regression	1990–1994
Johnston et al.	2002	Darwin, Australia	binomial regression	2000
North America				
Lierl et al.	2003	Cincinnati, USA	Poisson regression	Summers 1996–1997
Jaffe et al.	2003	Cincinnati, Cleveland, Columbus, USA	Poisson regression	Summers 1991–1996
Lin et al.	2002	Toronto, Canada	generalized additive	1981–1993
Burnett et al.	2001	Toronto, Canada	generalized additive	1980–1994
Tolbert et al.	2000	Atlanta, USA	generalized estimating equations, logistic regression, Bayesian	Summers 1993–1995
Steib et al.	2000	Saint John, Canada	semi-parametric Poisson GAM	1992–1996
Norris et al.	1999	Seattle, USA	semi-parametric Poisson GAM	1995–1996
Lipsett et al.	1997	Santa Clara, USA	Poisson regression	Winters 1988–1992
Delfino et al.	1997	Montreal, Canada	multiple linear regression	Summers 1992–1993
Jamason et al.	1997	New York City, USA	characterization by air mass	1982–1992
Steib et al.	1996	Saint John, Canada	generalized additive	Summers 1984–1992
Weisel et al.	1995	Central New Jersey, USA	multiple linear regression	1986–1990
Multi-region				
Wong et al.	2002	Hong Kong, London, UK	Poisson regression	1992–1997

Table 2
Summary of selected time-series studies of hospital use and air pollution published since 1993

Authors	Outcome	Age	Type of visit	Average visits per day	O_3	$PM_{10-2.5}$	PM_{10}	$PM_{2.5}$	Black smoke	TSP	NO_2/NO_x	SO_4	SO_2	CO	H^+	H_2S	Mold	Pollen	Rain
Europe																			
Diaz et al.	organic disease	all	ER	59.9 ± 12.7	+(a, s)					0	0								
	circulatory			9.8 ± 3.5	+(a, s)					0	0								
	respiratory			7.6 ± 3.7	+(s)					0	0								
Fauroux et al.	asthma	child	ER	3	+		0		0		0		0						
Lewis et al.	asthma	14+	admission	0.81	0						0						+	+	+
			or ER	1.24	0						0						+	+	+
Tenias et al.	asthma	>14	ER	1	+				0		+		0						
Castellsague et al.	Asthma	Adult	ER	2.7 (s)	0				+		+		0						
				3.9 (w)	0				0		+		0						
Asia																			
Bibi et al.	all respiratory	all	ER	5.6	0					0	+		+	0					
Hwang and Chan	lower respiratory illness	all	clinic visit	1.35 ± 0.5	0		+				+		+	+					
Lee et al.	asthma	<15	admission	7.8 ± 4.8	+		+				+		+	+					
Nutman et al.	asthma	15–75	ER	?	+						+		+						
Australia																			
Petroeschevsky et al.	asthma	all	admissions	11.3	+				0		–		0						
	respiratory			4.5	+				+		0		+						
	cardiovascular			14.1	0				0		–		0						
Morgan et al.	asthma	0–14	ER	15.5	0			0			+								
	asthma	15–64		9.0	0			0			0								
	COPD	65+		9.7	0			0			0								
	heart disease	all ages		47.2	0			+			+								
	heart disease	65+		31.8	0			+			+								
	heart disease	0–64		15.4	0			0			+								
Johnston et al.	asthma	all	ER	?			+												

North America																	
Lierl et al.	asthma	child	admission or ER	11.7	0		+									0	+
Jaffe et al.	asthma (Cincinnati)	all	ER	1.4 ± 1.4	+		0			0		+					
	asthma (Cleveland)			2.5 ± 1.6	0		+			0		0					
	asthma (Columbus)			1.1 ± 1.1	0		0			0		0					
Lin et al.	asthma	6–12	admission	1.54		+											
Burnett et al.	acute respiratory disease	< 2	admission or ER	2.9	+		+	+		+		0	+				
Tolbert et al.	asthma	< 16	ER	22 ± 9	+		+			0						0	0
Steib et al.	cardiac	all	ER	3.5	+		+	0			0	+	0	–	+	0	0
	respiratory			10.9	+		+	+			+	+	–		–	+ (s)	+ (s)
Norris et al.	asthma	< 18	ER	1.8 ± 1.6			+	+		0		0	0				
Lipsett et al.	asthma	all	ER	7.6 ± 3.3	0		+			+							
Delfino et al.	all respiratory	all	ER	87.5±22.6	+		+	+			+			+			
Jamason et al.	asthma	all	overnight admission	?	+					+		+	+				
Steib et al.	asthma	all	ER	1.5	+				0	0	0	0					
Weisel et al.	asthma	all	ER	4.5–6.0	+												
Multi-region																	
Wong et al.	asthma (Hong Kong)	15–64	admission	7.8 ± 3.4	0		0			0		0					
	respiratory	65+		91.3 ± 22.5	+		+			+		+					
	cardiac	All		98.7 ± 23.3	+		+			+		+					
	IHD	all		36 ± 10.3	+		0			+		0					
	asthma (London)	15–64		14.1 ± 5.8	0		+			+		+					
	respiratory	65+		58.3 ± 19.4	+		+			+		+					
	cardiac	All		121.7 ± 23.4	0		+			+		+					
	IHD	All		51.3 ± 10.0	0		0			+		+					

Abbreviations: +: significant relationship; 0: no significant relationship; –: negative significant relationship; a: annual; s: summer.

to the distribution of their data, as "...filtered Gaussian data is still Gaussian, [but] filtered Poisson data is not Poisson" (Schwartz et al., 1996). Many of the studies reviewed only removed the seasonal variation of the outcome variable and not the cyclical patterns of temperature, humidity and pollution. However, other variables, especially temperature, have a strong seasonal component that should be filtered prior to including it in modeling (Schwartz et al., 1996).

2.4. Review of findings

Without exception, all studies reviewed reported a significant relationship with at least one pollutant species. This may be partly influenced by publication bias—the tendency for studies that find positive results to be published, while those that find no significant effects to remain "in the file-drawer" (Scargle, 2000). Despite this, overwhelming evidence points to a significant negative impact of air pollution at levels below current air-quality standards. The three major meta-analysis projects, which are robust to publication bias, have also reported significant short-term health effects associated with air pollution. In Tables 1 and 2, the studies are summarized by region.

2.4.1. Europe

There have been a number of studies undertaken in Europe since the early 1990s. The most notable are the APHEA and APHEA-II projects (and the related 30+ published papers), which have facilitated analysis of mortality and hospital data from 30 cities in Europe. In a brief review of that effort, particulate matter (PM_{10}) was found to be a significant predictor of all respiratory, asthma, COPD, cardiac and ischemic heart disease hospital admissions on the order of a 1% increase in admissions for a 10 $\mu g/m^3$ increase in PM_{10} (median PM_{10} values ranged from 14 $\mu g/m^3$ in Stockholm to 52 $\mu g/m^3$ in Rome). Interestingly, comparing the effect of PM_{10} in different cities revealed that cities with higher mean O_3 concentrations were more sensitive to particulate matter. Ozone itself had mixed impacts, increasing all respiratory admissions but having no measurable effect on asthma. Nitrogen dioxide was found to be significant in all respiratory and cardiac admissions, along with SO_2 (which affected children and the elderly the most). Carbon monoxide was found to be significant as a predictor of asthma (especially among children), cardiac and ischemic heart disease (Atkinson et al., 2001; Castellsague et al., 1995; Le Tertre et al., 2002; Tenias et al., 2002). The other major European initiative, MISA, used Poisson GAMs to investigate hospital admissions with respiratory and cardiac diagnosis in eight of the largest Italian cities of varying mean pollution levels (24-h mean O_3 varied from 66 to 79 $\mu g/m^3$, SO_2 from 7 to 20 $\mu g/m^3$, PM_{10} from 37 to 64 $\mu g/m^3$). They concluded that every pollutant they investigated (SO_2, NO_2, CO, PM_{10} and O_3) had a significant effect on both admission classes with the exception of ozone on cardiac admissions (Biggeri et al., 2001).

A group looked at pediatric ER visits for asthma in Paris (mean 8 h O_3 31 $\mu g/m^3$) and found that there was a 5.2% increase with every 10 $\mu g/m^3$ increase in O_3 (Fauroux et al., 2000). However, they found no significant relationships with NO_2 (mean 41 $\mu g/m^3$), SO_2 (mean 24 $\mu g/m^3$), or black smoke (BS, mean 24 $\mu g/m^3$). Another team in the UK investigated the combined effects of aerobiological (mold and pollen) and chemical pollutants on both hospital and ER visits in Derbyshire, UK (Lewis et al., 2000). They focused specifically on the question of whether or not health effects of aerobiological pollutants are enhanced by chemical pollutants (O_3, NO_2, BS) and found no significant interaction.

2.4.2. Asia

Two groups from Israel used artificial neural networks (ANNs) to study the air quality/hospital services relationship. Neural networks are gross computerized models of neural structure and behavior. They consist of 'units' (neurons) and 'links' (axons and dendrites) and are capable of recognizing and learning patterns. One compared 3 months of ER data with NO, NO_x, SO_2 and O_3 and concluded that all four pollutants were important predictors (Nutman et al., 1998). The ANN could predict ER visits and get within one visit (range 0–5) of the correct number 47% of the time. In a similar study, 3 years of ER and pollutant data from Ashkelon, Israel, were fed to an ANN, and it selected SO_2 and NO_x in each of the 10 best models. Neural networks do not require many assumptions about the data and can digest large databases. However, their 'black box' nature prohibits knowing the relative importance or even the sign of any relationships among the variables (Bibi et al., 2002).

In Seoul, Korea, researchers used a GAM to quantify that PM_{10} (mean 64 $\mu g/m^3$), SO_2 (mean 7.7 ppbv), NO_2 (32 ppbv), O_3 (average daily maximum 36 ppbv) and CO (average daily maximum 2 ppmv) are all significant predictors of pediatric asthma hospital admissions (Lee et al., 2002). In a novel study design, a team from Taiwan used hierarchical modeling to assess the impact of air pollution in 50 small townships and cities (Hwang and Chan, 2002). They found that NO_2 (mean 24 ppbv), CO (mean 1 ppmv), SO_2 (mean 5.4 ppbv) and PM_{10} (mean 58.9 $\mu g/m^3$) were all significant predictors of clinic visits for lower respiratory tract illness. Ozone (24-h mean 54 ppbv) was not found to be significant. In addition, they determined that community-specific variables, such as population density and average pollutant concentrations, altered the estimated effects of each pollutant. For example, the effect of SO_2 is enhanced in cities with higher annual mean O_3 and CO values. However, the health effects of NO_2 were not consistent and actually decreased in communities with higher mean PM_{10} values. This study design is useful for estimating health impacts in small communities across a large region.

2.4.3. Australia

Parts of Australia experience regular 'bushfires' during the dry season. These fires produce high concentrations of particulate matter in some areas that have few other pollution sources, providing a somewhat unique opportunity to investigate the impact of particulates from biomass combustion. Researchers in Darwin (in the Northern Territory) compared daily asthma ER visits with daily mean PM_{10} measurements for one summer (Johnston et al., 2002). After controlling for weekday and influenza, they found that there was a significant (20%) increase in asthma visits for each 10 $\mu g/m^3$ increase in PM_{10}. They concluded that particulates from bushfires are as "injurious to human health as those from other sources."

Researchers have investigated the impact of poor air quality on hospital visits in two of the largest cities in Australia. In Sydney, investigators compared asthma, COPD and heart disease hospital admissions with O_3 (average daily maximum 25 ppbv), NO_2 (15 ppbv) and particles (mean 10 $\mu g/m^3$) (Morgan et al., 1998). They found that NO_2, particulate matter and O_3 were significant predictors of hospital visits. In Brisbane, researchers concluded that O_3, PM and SO_2 were significantly associated with respiratory and cardiovascular disease (Petroeschevsky et al., 2001). However, SO_2 was also significantly associated with digestive disorders, which were used as the control, and there was a negative relationship between cardiovascular and respiratory admissions (all ages) and NO_2, leaving the question of whether confounders were adequately controlled in the study.

2.4.4. North America

There have been at least 20 time-series studies of air quality and hospital services published in the past 10 years in North America. Here, a selection of the largest are reviewed. A group in Toronto used time-series and case-crossover analysis to understand how coarse particulate matter ($PM_{10-2.5}$) influenced asthma admissions in Toronto (Lin et al., 2002). Case-crossover analysis compares the air pollution levels at the time of each admission with the levels from specific period before and/or after the health event. They found that both methods identified a significant correlation between admissions and medium particulate matter ($PM_{10-2.5}$), which remained significant when CO, NO_2, SO_2 and O_3 were included in the model. The relative risk increased with increasing days of exposure, stabilizing at 6 days. Interestingly, the effect of either PM_{10} or $PM_{2.5}$ was not as strong, suggesting that it is the $PM_{10-2.5}$ fraction of particulate matter that is most important. Another Toronto study focused on hospitalization of children less than 2 years old for acute respiratory diseases: asthma (ICD-9 493), acute bronchitis/bronchiolitis (ICD-9 466), croup (ICD-9 464.4) and pneumonia (ICD-9 480–486) (Burnett et al., 2001). Using a generalized additive model, they reported that a 35% increase in admissions was associated with a 45-ppbv increase in the 5-day moving average of ozone (the summer average value). This effect persisted after correcting for other pollutants.

In Montreal, researchers compared O_3, PM_{10}, $PM_{2.5}$, SO_4 aerosol and aerosol acidity (H^+) with hospital admissions for respiratory reasons in 1992 and 1993 (Delfino et al., 1997). They found no relationship for ages 2–64, but did find significant effects of H^+, SO_4, O_3, PM_{10} and $PM_{2.5}$ for ages under 2 and greater than 64. Two studies have been published from Saint John, a small industrial city on the southern shore of New Brunswick, Canada. The earlier study looked at asthma ER visits in conjunction with O_3, while correcting for SO_2, NO_2, SO_4^{2-} and total suspended particulates (TSP) (Stieb et al., 1996). They found that there were 33% more visits when the daily 1-h maximum O_3 levels were above 75 ppb (the 75th percentile). The second study by the same team included 12 different aeroallergens (molds and pollens) as well as CO, H_2S, NO_2, O_3, SO_2, PM_{10}, $PM_{2.5}$, H^+, SO_4^{2-}, total reduced sulfur (TRS) and a coefficient of haze (COH) (Stieb et al., 2000). They found a significant influence of various pollutants on both cardiac and respiratory visits, especially in multi-pollutant models. Various types of aeroallergens were found to be associated with excess asthma visits.

There have also been a number of studies within the United States. One study analyzed Medicaid data from Cleveland, Cincinnati and Columbus, OH, for the summers of 1991–1996 (Jaffe et al., 2003). They looked at NO_2, O_3, PM_{10} and SO_2 and ER visits for asthmatics aged 5–34 years old. They found a significant relationship between O_3 (average 8-h maximum 60 ppbv), SO_2 (mean 36 $\mu g/m^3$) and asthma visits in Cincinnati. Similarly, PM_{10} (mean 61 $\mu g/m^3$) was significantly correlated with visits in Cleveland, but nowhere else. When data from all three cities were combined, there was a borderline significance with O_3 and SO_2. Another recent study from Cincinnati considered child asthma admissions over two summers 1996–1997 (Lierl and Hornung, 2003). They found that PM_{10} and pollen grains were important predictors of asthma admissions, while O_3 and mold spores were not (interestingly, the previously mentioned study found O_3 and SO_2 to be important, but not PM_{10}, though they were considering different populations). At least two studies have been completed in Atlanta, GA. The first investigated asthma ER visits during the summers 1993–1995 (Tolbert et al., 2000). They used generalized estimating equations, logistic regression and Bayesian models and looked at O_3 (average 8-h maximum 59 ppbv), PM_{10} (mean 39), NO_x (average 1-h maximum 82 ppbv), pollen and mold. They report that both O_3 and PM_{10} were significant predictors independently, but were unable to determine which was important due to strong collinearity between them. A second study from Atlanta investigated the impact of a massive policy intervention. During the 1996 Olympic Games in Atlanta, GA, a temporary transportation policy was enacted that encouraged use of public transit. The initiative spurred citywide transportation changes resulting in an improvement in air quality (ozone decreased 27.9%) and a significant reduction in asthma events (42% in the Georgia Medicaid claims file, 44% in a health maintenance organization database, 11% in two pediatric emergency departments and 19% in the

Georgia Hospital Discharge Database) (Friedman et al., 2001).

In central New Jersey, researchers used multiple regression analysis to find that ER visits for asthma occurred 28% more frequently when mean ozone levels were greater than 60 ppbv (Weisel et al., 1995). In Santa Clara County, CA, an area with particulate pollution that is primarily (45%) from residential wood combustion (RWC), researchers compared asthma ER visits over four winters 1988–1992 (Lipsett et al., 1997). They found that asthma visits were correlated with PM_{10} and NO_2. Ozone was considered but found to be unimportant (probably due to the low winter values). This result supports the results of the Australian bushfire study previously mentioned (Johnston et al., 2002).

In a unique approach to modeling weather, synoptic air mass types were used to categorize and correct for weather (Jamason et al., 1997). They argue that use of synoptic weather types more adequately corrects for weather since it groups similar days together for comparison, rather than correcting for temperature and humidity as independent variables, as most studies have done. They found that air mass type was a significant predictor of asthma admissions in fall and winter (during which they found less of an effect of air pollution), while pollution had a greater effect in the spring and summer. This is a relatively new technique that has recently been used by a number of similar studies on mortality and pollution (Kassomenos et al., 2001, Rainham, 2000).

Another interesting area of research attempted to understand the difference between urban and rural populations. Most ecological studies have focused on urban regions, for reasons of population size and presence of air quality monitors. Rates of hospital utilization for asthma and other respiratory diagnoses are known to be higher in inner city areas, but it has been unclear whether this is due to excess utilization rather than greater need. One effort to understand this phenomenon in Rochester, NY, used recorded oxygen saturation levels (SaO_2) of the blood to quantify attack severity (severe attacks lead to low SaO_2). They found no difference in the average severity of attacks between the two populations, suggesting urban populations did have greater need (since they have higher utilization rates) and were not simply using the hospital for less severe attacks (McConnochie et al., 1999). In an attempt to answer a similar question in Seattle, asthma ER visits were regressed against $PM_{2.5}$, CO, SO_2 and NO_2, comparing the inner city with suburban areas (Norris et al., 1999). They found approximately equal effects in both regions, with both CO and $PM_{2.5}$ being significant predictors of asthma visits. This suggests that the generally higher pollution levels in inner cities may be responsible for the elevated rates of asthma exasperation, as compared with suburbs.

2.4.5. Multi-region

While most studies have limited their scope to a single country or surrounding countries, a team used Poisson regression to compare hospital admissions and air quality between Hong Kong and London (Wong et al., 2002). They found that respiratory admissions (≥ 65 years of age) were related to PM_{10}, NO_2, SO_2 and O_3 in both cities. In addition, associations in both cities were during the driest periods. Significant associations were also found between PM_{10}, NO_2 and SO_2 for cardiac admissions. Ozone was significant in London but not in Hong Kong. The authors concluded that air pollution has significant and remarkably similar effects in both cities, regardless of differences in social, lifestyle and environmental factors, suggesting that the relationship is causal.

3. Summary

The studies reviewed here encompass a variety of methodologies to investigate the short-term impact of air pollution on public health. Each of the studies reported a significant relationship with at least one air pollutant (Table 2). All have accounted for seasonality and weather in some way, most utilizing nonparametric techniques. The significance of these relationships is not sensitive to analytical or smoothing techniques. Despite the weight of evidence suggesting a significant impact of many pollutants, there are some curious irregularities in the findings presented here. Ozone was the most commonly studied pollutant, being included in 22 of the 25 articles. Of these 22, a significant association was found in 15 of them (68%). Particulate matter (measured as PM_{10}, $PM_{2.5}$, $PM_{10-2.5}$ or TSP) was included in 21 studies and found significant in 16 (76%) of them. Nitrogen species (NO_2 and NO_x) were included in 19 studies and found significant in 11 (58%) of them. Sulfur species (SO_4 and SO_2) were included in 16 studies and found significant in 10 (63%) of them. While the majority of studies found a significant impact for each pollutant studied, not all pollutants in all locations were found to be significant. At first glance, these findings may seem to be inconsistent, but can be explained in the context of ecological studies. Ecological studies of this type use complex analysis to identify relatively small effects. Compared to seasonality, weekday and other temporally varying factors, the increase in hospital use due to elevated pollution levels is relatively small. In addition, there are the issues of exposure measurement error due to heterogeneous outdoor air pollution and indoor air quality, as well as personal activities, all of which will tend to decrease the estimate of effects (sometimes to the extent of eliminating statistical significance). In addition, some of the inconsistency can be related to study design. For example, the study on RWC pollution in California only considered winter data (as the researchers were interested in the effects of winter RWC) and thus had low concentrations of ozone (the 1-h maximum during the study period was 70 ppbv) (Lipsett et al., 1997). Even if there are no thresholds below which there are no effects, the smaller the pollution signal, the more difficult it is to isolate the health response from other confounders. However, most studies included data from at least 1 full year and thus are not susceptible to this phenomenon.

Therefore, each estimate from a careful study of this type should be considered conservative, and an absence of evidence for a relationship should not be used as evidence for an absence of a relationship. While no single ecological study provides enough evidence to argue for a causal relationship between air pollution and health, dozens of studies from around the world have all come to virtually the same conclusion—that short-term variations in air pollution have measurable impacts on public health. It is also important to note that no study reported the presence of any short-term threshold pollutant value below which there were no health effects. This implies that pollution levels below national air quality standards are harmful to the public health. In fact, many of the studies reviewed here were completed in cities that seldom, if ever, had air pollution levels that exceeded national standards. While past improvements in some pollutants in some regions have probably led to fewer pollution-related health events, these studies make it clear that current levels of pollution are associated with significant increases in health distress. The cities included in this review have varying pollution levels, but all revealed a significant effect of air pollution.

It is also important to keep in mind that visits to the ER or hospital represent only a small percentage and most severe (i.e., the tip of the iceberg) of the total impacts of air pollution. Thurston (1997) has estimated that respiratory hospital admissions and ER visits represent only about 0.1% of all adverse impact cases. This is critical to understand because it places the results of ecological studies of hospital admissions and ER visits in the context of much larger impacts of air pollution on public health. Epidemiological studies from diverse communities with unique air quality and weather phenomenon have determined that short-term variations in air quality negatively affect human health at the population level. In conjunction with the vast literature on controlled exposures, animal models, cohort studies and cross-sectional studies, the evidence from time-series studies strongly suggests that there is a significant causal relationship between air pollution and health problems.

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