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Melbourne Mortality Study

EFFECTS OF AMBIENT AIR POLLUTION ON DAILY MORTALITY IN MELBOURNE 1991-1996

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FOREWORD

Air quality is consistently ranked as the main environmental concern within urban communities. The quality of the air that we breathe can affect our health and well-being. Much of what we do on a daily basis impacts significantly on our air environment. Motor vehicles, industry and home heating all impact on the air pollution levels experienced in Melbourne and can adversely affect our health.

This report presents the results of an epidemiological study conducted by EPA and its partners into the effects of air pollution on daily mortality in Melbourne. The statistical analysis, conducted by the researchers at the School of Public Health, Griffith University, utilises state of the art statistical methods to identify the impacts of ambient air pollution on daily mortality. The results of the study show that current levels of air pollution in Melbourne are associated with increases in daily mortality and are consistent with studies conducted elsewhere in Australia and overseas.

The main pollutants of concern arise predominantly from motor vehicles and industrial sources. The associations shown in this study indicate that strategies to reduce levels of these pollutants are important to reduce the risk of adverse health effects. Such strategies have been developed as part of the Air Quality Improvement Plan (AQIP) for the Port Phillip Region. The success of these strategies will ensure that air quality in Melbourne will continue to improve and as a result the associated health risks will diminish. The results of the Melbourne Mortality Study provide important information to assist in the development of air quality measures at both a State and National level that will provide protection of the health of Victorians.

This study raises many issues and I encourage all those with an interest in air quality and public health to participate in the debate we, as a community, need to have if we are to develop sustainable solutions to the problem of providing healthy air in our major urban areas.

I would like to thank the authors of this report Dr Lyn Denison from the EPA, Associate Professor Rod Simpson, Anna Petroeschevsky, Dr Lukman Thalib, Shannon Rutherford from Griffith University, Associate Professor Gail Williams from the University of Queensland Geoff Morgan from the NSW Health Department and Dr Jonathan Streeton for their careful and robust analysis which forms the basis of this report.

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CHAIRMAN
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EXECUTIVE SUMMARY

In recent years there has been considerable interest in the adverse health effects associated with exposure to air pollution. The results of many epidemiological studies have shown increases in daily mortality, hospital admissions and emergency room visits for respiratory and cardiovascular disease and exacerbation of existing diseases such as asthma associated with ambient levels of air pollution. Most of these associations have been observed in epidemiological studies conducted in the US, UK and Europe. To date very few studies have been conducted in Australia. Recent studies conducted in Sydney and Brisbane have shown that the effects observed overseas do occur in Australia.

The Melbourne mortality study has been conducted to investigate the effects of air pollution on daily mortality. The study period covers 1991 to 1996 and the pollutants considered are ozone, nitrogen dioxide, fine particles and carbon monoxide. Mortality from respiratory and cardiovascular disease as well as all non traumatic causes were examined in the 'all ages', greater than 65 years and less than 65 years age groups. In addition to examination of the entire Melbourne Statistical Division, both regional and seasonal analyses were conducted. Two statistical methods were used to test the robustness of the observed associations.

The results of the study show that after controlling for the effects of weather and other confounding factors, air pollution in Melbourne is associated with increases in daily mortality. The strongest and most robust relationships were observed for ozone and nitrogen dioxide. Associations were also observed for fine particles and carbon monoxide but these relationships were not as strong as those observed for the other pollutants. The results of multi-pollutant analyses showed that although effects were observed for individual pollutants, these effects were not independent of the other pollutants. The observed associations were stronger during the warm season for all pollutants.

The main sources of ozone and nitrogen dioxide in Melbourne are motor vehicles and industrial processes involving hydrocarbons or combustion. The results suggest that strategies to reduce these pollutants are important to reduce the risk of adverse health effects arising from exposure. The results of this study are consistent with other studies conducted within Australia and overseas.

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INTRODUCTION

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In recent years there has been considerable interest in the adverse health effects associated with exposure to air pollution. The results of many epidemiological studies have shown increases in daily mortality associated with ambient levels of air pollutants. Relationships have also been observed between ozone and daily mortality, but until recently, NO2 and CO at current ambient levels were not thought to be of concern with respect to public health. With increasing sensitivity in the statistical methods used in epidemiological studies, associations are now being observed between these pollutants and adverse health effects which has led to increased interest in these pollutants.

In Australia there have been very few studies investigating the effects of air pollution on health. Studies conducted in Brisbane and Sydney have shown that the associations between ambient air pollution and daily mortality observed in overseas studies also occur in Australia.

1.1. Aim

The aim of this study was to examine the relationship between ambient air pollution and daily mortality in Melbourne. The study period covered the years 1991 through 1996. The pollutants considered were fine particles, ozone, nitrogen dioxide and carbon monoxide. Sulfur dioxide was not included in the analysis as levels in Melbourne are very low and often below detectable levels.

The analysis involved an epidemiological time-series study of the relationship between ambient levels of air pollution in Melbourne and daily mortality due to all causes, respiratory and cardiovascular disease. The methodology used followed that developed by researchers in Europe and the United States, which enables direct comparisons of results between studies. Two statistical approaches were used to demonstrate the robustness of the association between air pollution and daily mortality.

1.2. Background

On the 26 June, 1998, the National Environmental Protection Council (NEPC) made a National Environment Protection Measure (NEPM) for ambient air quality which sets national air quality standards for the six major pollutants nitrogen dioxide (NO_2), particles (as PM_{10}), carbon monoxide (CO), ozone (O_3), sulfur dioxide (SO_2), and lead (Pb). This is the first time that a consistent set of air quality standards has been in place across Australia and will allow comparisons of air quality across different regions to be made.

The NEPM (Ambient Air Quality) standards have been set to be protective of human health. These standards are based primarily on the results of studies that have been conducted overseas. Whether these findings can be extrapolated to the Australian situation has been the subject of much debate. In general, air quality in Australian cities is much better than that observed in many American and European cities. Recent work in Sydney (Morgan et al. 1998a and b) and Brisbane (Simpson et al. 1997) has indicated that current levels of ambient air pollution in these cities are making significant contributions to variations in daily mortality and hospital admissions for cardio-respiratory disease and that the effects observed overseas do occur

here as well. There is a commitment in the NEPM to undertake a review of the particle standard by the year 2001 and a full review by 2005. An important part of this review will be the expansion of the local database relating to air quality and health issues.

Despite being the second largest city in Australia, few studies have investigated the association between air pollution and health in Melbourne. Particle pollution is a concern during the autumn and winter given the widespread use of wood fires for heating during this time. Generally, the highest particle levels are observed during this period although high levels can also be observed during the summer. However, levels of SO_2, which in North American and European cities is often highly correlated with particles, are very low in Melbourne due the absence of significant point sources in the area and the low sulfur content of Australian fossil fuels. Melbourne thus provides a good opportunity to examine the health effects of particles and other pollutants without the potential confounding effects of SO_2.

1.3. Study area

The city of Melbourne is located on the southeast coast of Australia, on the northern edge of Port Phillip Bay. The study area is contained within a 30 km radius of the CBD and is the major part of the Melbourne Statistical Division identified by the Australian Bureau of Statistics. This area contains several air monitoring stations which are thought to be representative of air quality within the region. The Melbourne Statistical Division recorded a population of 2,994,280 persons in the 1996 Census. The city of Geelong, located to the south west of Melbourne, is not included in the study area.

Melbourne's climate, best described as Mediterranean, is dominated by the proximity of Port Phillip Bay. Melbourne is located on the northern edge of the bay. The weather is variable but generally cool in spring, warm in summer, mild in autumn and cold in winter. The topography and climate combine to make the region an area of high pollution potential during still weather. The study area to the east of Melbourne is bounded by the Dandenong Ranges that rise to about 700 metres. The Great Dividing Range which runs east-west is located approximately 100 kilometres to the north and rises to about 2000 metres. In summer elevated ozone concentrations are associated with warm temperatures and stable atmospheric conditions. In autumn and winter the major concern is fine particles.

REVIEW OF THE HEALTH EFFECTS OF AIR POLLUTION

Studies of the health effects of air pollution have shown associations between ambient air pollution levels and adverse health effects, including increases in daily mortality, increases in hospital admissions and emergency room attendances, as well as exacerbation of asthma. Most the observed effects have been associated with respiratory (including asthma) and cardiovascular disease. These studies have been conducted in various parts of the world with differing climates, socioeconomic status and pollutant levels and mixes. Most of the recent information has arisen from epidemiological studies.

Epidemiological studies evaluate the incidence of diseases or effects and risk factors and associate these with air pollution data; they do not demonstrate causality or provide clear evidence of the mechanisms of such diseases or effects. Specifically, epidemiological studies concentrate on showing whether associations exist, rather than how they might be explained at a pathogenic or mechanistic level. Animal studies and experimental exposure, or chamber, studies with humans help to generate data from which hypotheses concerning the mechanisms for the effects of air pollution can be formulated. This in turn can aid in the design of epidemiological studies. A large amount of work is currently under way worldwide in an attempt to elucidate biological mechanisms for the effects observed in epidemiological studies.

The biological mechanisms by which air pollution may cause increased morbidity and mortality have been the focus of a large amount of research. For ozone and nitrogen dioxide it is clear the free radicals play a role in leading to an inflammatory response in the airways. For carbon monoxide the mechanism involves the binding of CO to haemoglobin in the blood which interferes with oxygen transport in the body. For particles the biological mechanism is still unclear but there is increasing evidence that inflammation of the airways may be important in the biological response. The role of the macrophage in the observed responses is emerging as a key issue. The alveolar macrophage is the central lung cell in the regulation of the immune response to inhaled pathogens and the development of inflammation. It is also apparent from the epidemiological studies that there are groups within the population that are particularly susceptible to the effects of air pollution. These include the elderly, people with existing respiratory and cardiovascular disease, asthmatics, and children.

In recent years the health effects associated with exposure to particles have been the focus of extensive research worldwide. Results of epidemiological studies have provided no evidence for the existence of a threshold value below which no adverse health effects are observed. Extensive epidemiological studies have been conducted in various parts of the USA with differing levels of particles and differing pollution mixes. These studies have been the subject of many reviews (Streeton, 1997; US EPA, 1996; Bascom et al., 1996; Dockery and Pope, 1994). The US studies have been used to make some compelling arguments in support of a causal link between short-term increases in particle pollution and adverse health effects. These studies have been conducted in settings with substantial variability in type and concentrations of copollutants and meteorology, with the only consistent factor being the particle concentration. Studies from the eastern US and Canada have had to deal with a mix of summer pollutants which include particles, SO_2 and O_3, as well as

acid aerosol. Concentrations of these pollutants are correlated to a greater or lesser extent depending on the setting.

Attempts to attribute effects to only one pollutant have prompted questions as to whether it is possible to do so. However, the US studies include those performed in settings where there is only minimal concern about the effects of these copollutants. For example, the Utah Valley experiences high levels of particles during the winter months that arise mainly from a local steel mill, and very low SO_2 levels. Ozone is only of concern during the summer and therefore does not confound the effects of particles during winter. As the population is predominantly a Mormon community they have a very small proportion, approximately 6%, of the population who smoke.

The studies conducted in this area have looked at increases in daily mortality, hospital admissions, decreases in lung function, increases in respiratory symptoms and increased school absenteeism using a variety of statistical methods and have found consistent associations between exposure to particles and adverse health effects.

The results of the US studies show a consistent 1% increase in daily mortality associated with a $10ug/m^3$ increase in daily average PM_{10} levels. In general the effect estimates observed in the UK and Europe are lower than those observed in the USA. The reason for this is unclear but may be due to high levels of acid aerosols in the USA, or possibly the use of black smoke in the UK and European studies (UK Department of Health, 1998). The differences observed in the results from the studies in different parts of the world suggest that the dose response relationships determined within a particular country or region may not be readily transferable to other areas. However, results obtained from studies conducted in Sydney and Brisbane are consistent with the findings of the US studies.

Epidemiological evidence indicates that a wide variety of health outcomes are possible from exposure to ozone: increases in short-term effects on mortality, hospital admissions and emergency room attendances, increases in symptoms and decreases in lung function. At an experimental level, evidence relates short-term physiological and pathological changes in the respiratory system in humans. Although potentially more important, there is not a lot of evidence regarding long-term effects.

Epidemiological studies have shown that ambient O_3 levels are associated with hospital admissions and emergency room visits for respiratory disease (including asthma) and with increases in respiratory symptoms, airway responsiveness and decreases in lung function. These effects are correlated with both daily 1-hour maximum and 8-hour maximum O_3 levels with the strongest effects observed with a 1-day lag. There is also evidence that O_3 may be associated with an increase in daily mortality, mainly in the elderly and in people with existing cardiovascular or respiratory disease. The results of the epidemiological studies have not shown any clear evidence of a threshold below which adverse effects associated with exposure to O_3 are not observed.

During the 1996 review of the National Ambient Air Quality standards in the US, the US EPA concluded that although an association between ambient O_3 exposure in areas with very high O_3 levels and daily mortality has been suggested, the strength of any such association remained unclear (US EPA, 1996b). Since that time a number of studies have been published which relate ambient ozone levels to increases in daily mortality (Touloumi et al., 1997; Sartor et al., 1997; Borja-Arburto et al., 1997; Loomis et al., 1996; Simpson et al., 1997). The most consistent associations have been observed for mortality from cardiovascular causes in the elderly.

Epidemiological studies have also shown adverse health effects associated with exposure to NO_2. The mortality studies have indicated that exposure to ambient levels NO_2 levels are associated with increases in daily mortality from respiratory and cardiovascular causes. Effects are seen in all age groups. Many of these studies have been reviewed by UK Department of Health, (1998), Streeton, (1997), WHO, (1997), Bascom et al., (1996).

The results of recent studies have added strength to the possible association between ambient NO_2 exposures and increases in daily mortality. Studies from Canada, Europe (APHEA) and Australia have all found increases in daily mortality associated with exposure to NO_2 at relatively low levels. These associations appear to be independent of the effects of other pollutants.

In recent years there has been renewed interest in the health effects of CO. There have been several studies that have shown associations between increases in daily mortality and ambient CO levels. The earlier studies have been reviewed by UK Department of Health (1998) and Bascom et al (1996). These early studies showed associations between daily mortality and ambient CO levels but at levels much higher that those currently observed in urban areas. More recent studies have also shown such an association even at the lower levels currently experienced. Until recently it was thought that current exposure levels were unlikely to produce serious health outcomes, however the results of these recent

studies brings this into question. Several studies (Sheppard et al, 1999; Schwartz, 1999; Morris and Naumova, 1998; Yang et al, 1998; Polniecki et al, 1997; Schwartz, 1997) have shown that ambient levels of CO are associated with hospital admissions for cardiovascular disease at concentrations as low as 3ppm (1-hour maximum). These effects have been observed in all age groups.

Although there has been a large number of studies conducted overseas investigating the relationships between air pollution and adverse health effects, very few studies have been conducted in Australia. The main studies to date have been conducted in Sydney and Brisbane. The results of the Melbourne study will contribute to an Australian database that shows that the effects observed in overseas studies are also observed in Australia.

METHODOLOGY

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3.1 DATA

3.1.1 HEALTH DATA

Mortality data: Mortality data for the period January 1, 1991 to December 31, 1996 were obtained from the Australian Bureau of Statistics. To ensure a complete data set, the months September to December, 1996, were excluded from the analysis; many deaths occurring toward the end of 1996 were not registered until 1997 and were thus not included in the raw mortality data set for 1996. Cause of death groups were aggregated into broad categories of respiratory mortality (ICD-9 460-519), cardiovascular mortality (ICD-9 390-459) and total (all cause) mortality (all ICD-9 <800), with three age groups (all ages, <65 and 65+) considered in the analysis. An 'other cause' category was also considered in preliminary analyses. Deaths resulting from digestive disorders were used as a control diagnosis. Deaths of residents occurring outside the study area (eg interstate or elsewhere in Victoria) were excluded from the analysis, as were deaths of non-residents in the study area.

Influenza data: Influenza data were obtained from the Victorian Infectious Disease Registry and Laboratory for both influenza A and B. These data are based on laboratory notifications and are considered unreliable for the purposes of this study as the lag period between the onset of symptoms and notification is unknown. The data obtained showed that no significant epidemics of influenza occurred during the period under consideration. ABS mortality data show that, for the study period, only 0.03% of total deaths were due to influenza. Therefore, due to the low contribution to total deaths and the unreliability of the data, control for influenza was considered unnecessary.

3.1.2 AIR POLLUTION DATA

Pollutant data were obtained from the Environment Protection Authority (Victoria) (EPA) which has been collecting air quality data since 1979. PM_{10} has been monitored since 1988 using hi-volume samplers and TEOMs have been operating since 1995.

The pollutants considered in the analysis were particles (24-hour / 1-hour maximum bsp), O_3 (1-hour / 4-hour / 8-hour), NO_2 (1-hour / 24-hour), and CO (1-hour / 8-hour). Lags up to 3 days were investigated as well as 3- and 5-day cumulative averages. Hi-volume sampling data for PM_{10} was available every sixth day for the study period.

Relationships between filter-based measures and bsp, which is available on a daily basis throughout the study period, were investigated. Using relationships derived from the seasonal correlations between bsp and TEOM $PM_{2.5}$, a daily $PM_{2.5}$ data set was constructed for the study period. A recent EPA study has shown that the relationship between $PM_{2.5}$ and PM_{10} is both site and season specific. Using the relationships determined in that study a PM_{10} data set was constructed for the study period.

Measurements at six monitoring sites were used to estimate ambient concentrations of O_3, five sites were used for particles and NO_2 while regional estimates for CO were based on data collected at three sites in the study area. All stations were in operation throughout the study period, were positioned in residential areas away from major point sources and were considered representative of levels experienced throughout the Port Phillip Airshed. In instances where pollutant data were missing at a particular site on a given day, the missing data were estimated using the mean of the non-missing sites on that day adjusted for the 3-month seasonal mean of missing site over the 3-month seasonal mean of the network. Figure 1 shows the location of monitoring sites within the study area.

Meteorological data: Meteorological data (minimum, maximum and average temperature, dew point temperature, relative humidity and rainfall) were supplied by EPA on an hourly basis at all sites within the study area. Lags up to 2 days were investigated as well as 2-, 3- and 4-day cumulative averages. Data were also obtained from the Bureau of Meteorology.

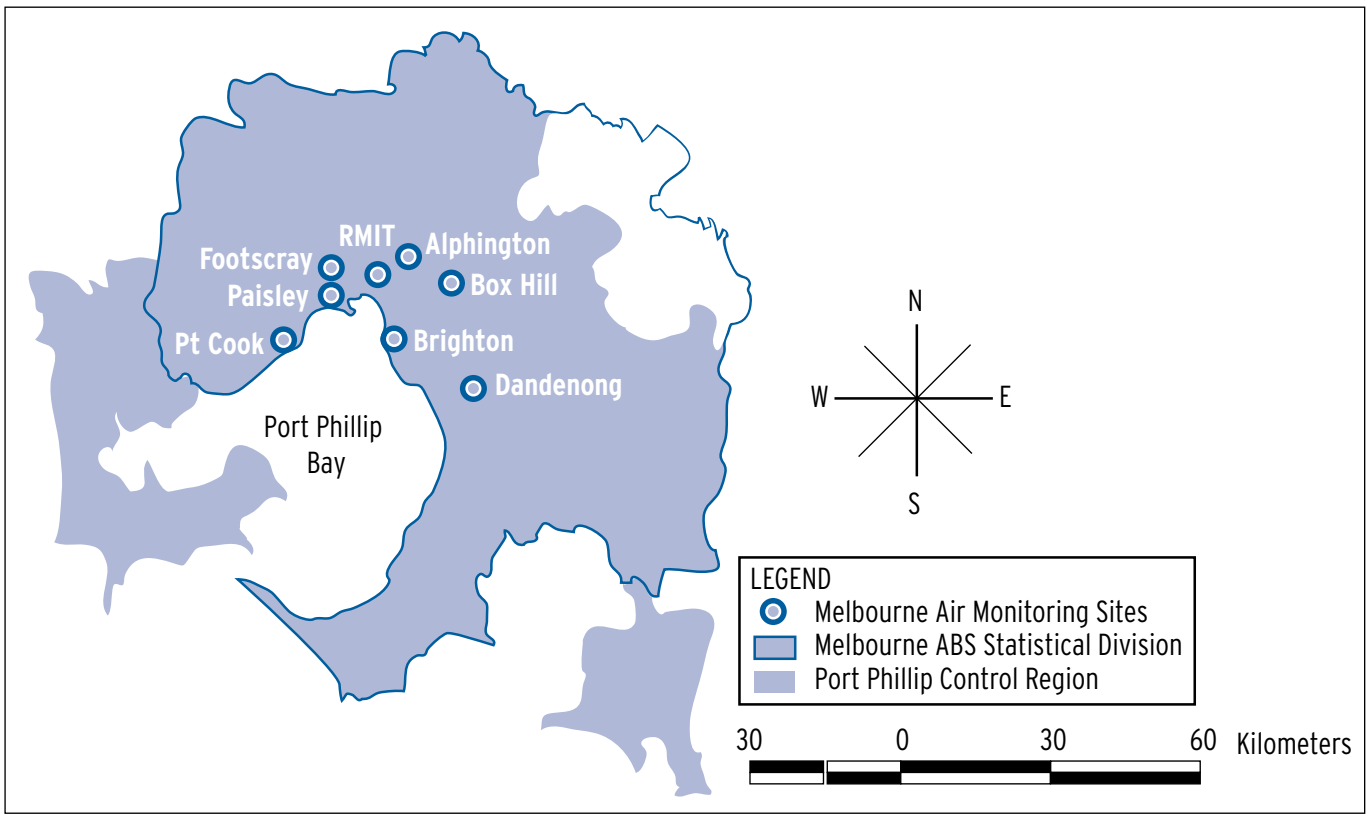
3.2 STATISTICAL ANALYSIS

As both pollutant levels and daily mortality may be sensitive to climate / weather and other temporal factors such as season and long term trend in levels of pollution and mortality over time, it is important to control for these effects in the analysis. A number of statistical approaches to controlling for such influences have been used in previous investigations into the health effects of air pollution. Two such methods of analysis, trigonometric filtering (based on the APHEA I protocol) and the more recent approach to this type of analysis - nonparametric smoothing using Generalised Additive Models (GAM), were used to investigate the relationships between air pollution and daily mortality in Melbourne.

Trigonometric filtering involves fitting a series of sine and cosine terms to the data to control for the long-term cycles. Generalised Additive Modelling is a more flexible approach that allows the fitting of a 'smooth' curve to the data, allowing the actual cycles occurring in the data to be controlled without 'forcing' cycles (as in the trigonometric approach) that may not be present in the data. Both of these methods have been used extensively overseas in this field of research (Schwartz et al., 1996; Katsouyanni et al., 1995, 1996; Hoek et al., 1997). The use of the two methods in this analysis has enabled a comparison of findings to test whether results are sensitive to the statistical approach used. Of the two methods, the GAM approach is considered to be a better method of modelling the pollution-health association, and therefore more weight will be given to the results of the GAM in this report.

Sections 3.2.1 and 3.2.2 discuss in detail the major steps in the analysis for each approach.

Figure 1 - Location of EPA Air Monitoring Stations



3.2.1 THE APHEA(I) PROTOCOL

The APHEA I protocol is a parametric approach to analysing epidemiological time-series data to detect the short-term health effects of air pollution (Schwartz et al., 1996). The protocol uses Poisson regression, controlling for a range of temporal cycles (season, long-term trend, holidays) and meteorological variables.

Most of the steps in the APHEA protocol were followed - the main steps taken in this analysis are summarised below.

Step 1 Preliminary analysis: The preliminary analysis involved examination of univariate statistics including diagnostic plots to determine the presence of seasonality, long term trends and discrepancies in the data. The degree of autocorrelation in each of the dependent variables was also examined.

Step 2 Harmonic analysis: Strong seasonal variation is a characteristic of daily mortality. In addition to cycles related to weather patterns, other long-term cycles such as those related to epidemics may be present. To control for such cycles the APHEA approach includes a series of sine and cosine terms in the model. The selection of sinusoidal terms involves an iterative process of identifying the cyclical patterns and building the model with the aim of removing as much of the seasonal/long term trends and autocorrelation in each outcome variable as possible. The APHEA approach uses periodograms generated by the SPECTRA procedure in SAS (SAS Institute Inc.) to identify cycles in each health outcome variable.

Only cycles greater than 60 days are considered, as the aim of this procedure is to remove long-wave cycles without removing any short-term cycles that may be relevant to the pollution-health relationship. In this analysis, rather than basing the selection of terms on the results of the Spectral analyses, each of the following cycles were included in each model: 60 days, 75 days, 90 days, 120 days, 6 months, 1 year and 2 years. The inclusion of all cycles was considered necessary to adequately filter out any cycles in the mortality data not related to air pollution. Model building was performed using linear regression with a log-transformed dependent variable, so that the coefficient of determination (R^2, the amount of variation explained by the model) can be used as a 'goodness of fit' measure.

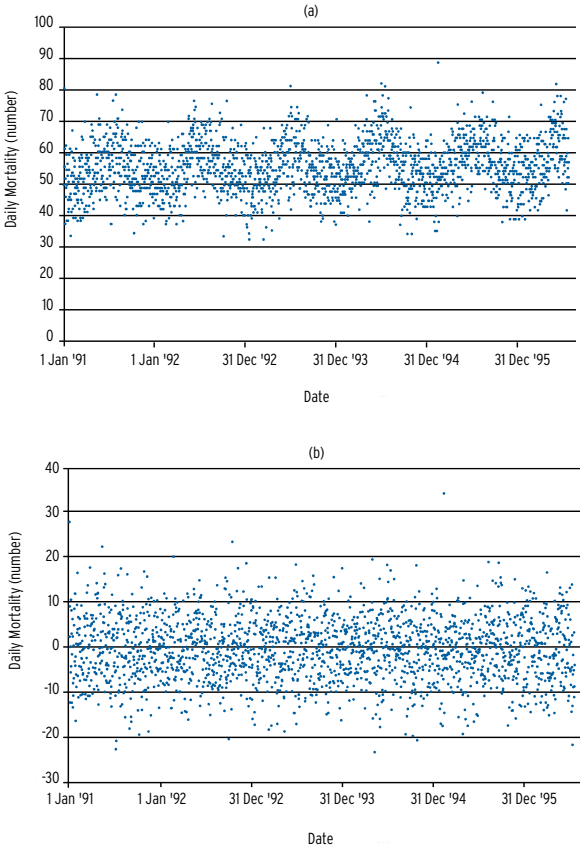
Step 3 Addition of temporal variables: Temporal variables used in each model included variables that account for the effects that day of week, public holidays (Christmas/New Year) and year may have on daily mortality. Time variables for long-term trend (time, time^2) were also included to account for increases in daily mortality associated with changes in population over the study period.

Step 4 Addition of meteorological variables: Relationships between meteorological variables (and their respective lags) and the residuals (i.e. the observed values minus the predicted values) from the models in Step 3 were examined using Spearman's Correlation analysis. As the relationship between meteorological variables and daily mortality may not be linear, and may in fact be curvilinear (with increased rates at very low and very high temperatures), various transformations (eg $|x-\bar{x}|$, $|x-x|^{-2}$ for t_{max} and $t_{min} <\bar{x}$) of the meteorological variables were included amongst the variables examined in this step. The APHEA protocol specifies that the same lag be used for each of the meteorological variables in the model. The most significant lag of a 'set' of meteorological variables was therefore selected for each of the outcome variables considered in this analysis. After investigation of various transformations of the meteorological variables, the 'set' comprised the following: $|x-\bar{x}|$ for maximum and minimum temperature (to control for the effects of extreme temperatures), maximum dewpoint temperature and rainfall.

Figure 2 illustrates the effect of Steps 1 through to 4 on the data for all cause mortality. Figure 2(a) shows the raw time series for this outcome. Figure 2(b) shows the residuals for all cause mortality after adjusting for all temporal and meteorological factors. Note the absence of the seasonal patterns in Figure 2(b).

Step 5 Addition of pollutant variables using Poisson regression: After building models for each of the dependent variables using linear regression, the models were run for the observed dependent variables using Poisson regression in the GENMOD procedure. Overdispersion was controlled for using the PSCALE option (SAS Institute Inc.). Overdispersion is a common phenomenon in count processes and occurs where the variance, rather than being equal to the mean (as assumed in a Poisson distribution), is instead proportional to the mean (Schwartz et al., 1996).

Figure 2 - Effect of filtering process on time series for all cause mortality: a) Time series, daily all cause mortality, all ages; b) Model residuals after controlling for all cycles, day of week, meteorological factors and long-term trend



Step 6 Multi-pollutant models: As pollutants are often highly correlated, it is important to determine whether relationships observed in the single pollutant models in Step 5 remain after controlling for other pollutants. It is inappropriate to include highly correlated potential confounding pollutants as continuous variables in the same model. The problem of co-linearity between pollutants in this analysis was overcome by first fitting the potential confounding pollutant to the base model, and then fitting the pollutant in question to the residuals of that model.

Step 7 Seasonal Models: To determine whether the observed relationships between the pollutants and mortality varied between seasons, all models were re-run for the cool (April-October) and warm (November-March) seasons separately. The cool season corresponds to the winter smog season that is characterized by high particle levels. The warm season corresponds to the summer smog period characterized by high O_3 levels. In the seasonal models, 'sets' of meteorological variables were selected separately for each season.

3.2.2 GENERALIZED ADDITIVE MODELS

The second stage of the analysis utilized Generalized Additive Models (GAM) (Hastie and Tibshirani, 1990). GAM is a non-parametric regression approach that models the dependent variable as a sum of smooth functions of predictor variables. GAM was used to confirm and test the robustness of the relationships found using the first method of analysis. The steps in the analysis using GAM were similar to those of the APHEA Protocol using trigonometric filtering. The basic aim was to model temporal variations in the data in the initial step, and then address meteorological and other confounding variables in subsequent steps. The steps below outline the approach used and are based on the approach taken in a study of the effects of particles and ozone on daily mortality in Rotterdam (Hoek et al. 1997).

Step 1 Determine the smoothed function of time over the study period: A range of smoothing algorithms is available for use in GAM – cubic smoothing splines were used in this analysis. The degree of smoothing required was determined using Akaike's Information Criterion (AIC), which was calculated as the sum of the residual deviance and two times the degrees of freedom (df). The AIC optimises the smoothing function by showing whether the decrease in deviance in the model resulting from the addition of another parameter is worth the use of additional df (Hoek et al., 1997).

Step 2 Temporal variables: Day of week was added to the model regardless of its significance in the model due to the variation in mortality that occurs across the week. The holiday dummy variable was added only if it resulted in an improvement in the AIC.

Step 3 Addition of meteorological variables: All lags were considered, and unlike the first stage of the analysis using trigonometric filtering, the combination of meteorological variables giving the lowest AIC value (as opposed to the same set of lags) was retained in the model.

Step 4 Addition of pollutants: All pollutant lags were considered as linear terms in single pollutant models (all reported parameter estimates refer to linear terms).

Step 5 Multi-pollutant models: The same technique employed in the trigonometric filtering was used to determine whether the relationships identified in the previous step were retained after controlling for other pollutants.

Step 6 Seasonal investigations: Due to the nature of the GAM process the seasonal investigations involved a slightly different approach to that used in the trigonometric models. Seasonal dummy variables and season-pollutant interaction terms were added to the single pollutant models to test for seasonal effects.

Influenza Data

After consultation with researchers from Europe an alternative method of controlling for respiratory epidemics was trialed. A dummy variable representing the 90th percentile of a 7-day moving average for total respiratory mortality was created to control for such epidemics in the total and cardiovascular mortality all-ages categories.

RESULTS

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Between January 1, 1991 and August 31, 1996 there were a total of 114 539 non-accidental deaths in the Melbourne study region, including 50 341 (44%) deaths due to cardiovascular disease and 9260 (8%) due to respiratory disease. The majority of deaths (80%) occurred in those persons aged greater than 65 years. Table 1 gives the descriptive statistics for each of the outcome variables considered for the entire study period and by season.

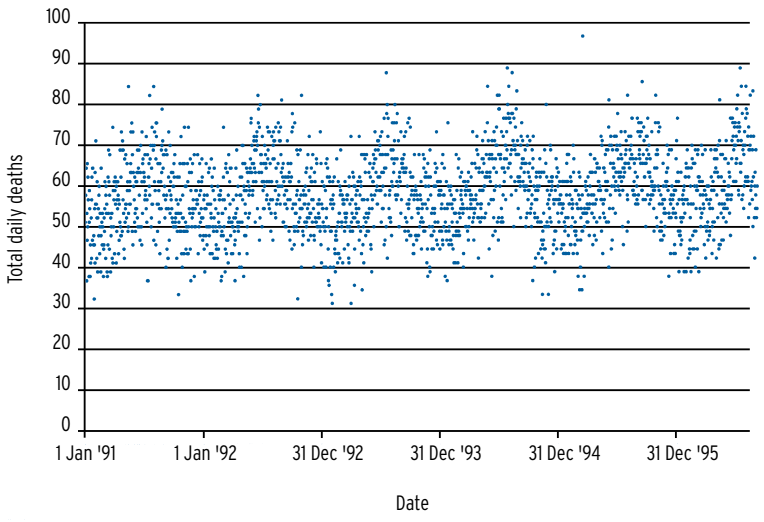
Table 1 - Mean daily deaths by cause, Melbourne, January 1991- August 1996 (n=2070)

Outcome	Whole study period				Cool season[a]				Warm season[b]			
	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Cardiovascular												
0-65	2.7	1.7	0	11	2.8	1.7	0	11	2.5	1.5	0	9
65+	21.6	5.1	7	41	22.9	4.9	8	39	19.7	4.7	7	41
Total	24.3	5.4	8	43	25.7	5.3	9	43	22.3	4.8	8	43
Respiratory												
0-65	0.5	0.7	0	4	0.6	0.7	0	4	0.4	0.6	0	3
65+	4.0	2.2	0	15	4.4	2.3	0	15	3.4	1.9	0	10
Total	4.5	2.3	0	16	4.9	2.4	0	16	3.8	2.0	0	11
All deaths												
0-65	10.9	3.4	1	25	11.1	3.3	1	25	10.6	3.4	1	23
65+	44.5	7.9	20	73	46.7	7.6	22	73	41.2	7.0	20	71
Total	55.3	8.6	31	90	57.8	8.4	32	83	51.8	7.6	31	90
Digestive	1.8	1.4	0	7	1.9	1.4	0	7	1.7	1.3	0	7

a Cool season: April-October (n=1223)
b Warm season: November-March (n=847)

The Melbourne study region experienced an average of 55 deaths per day attributable to non-traumatic causes over the study period. Daily mortality was on average slightly higher in the cool season, although the highest number of deaths on any one day (90 deaths) occurred in the warm season (18 March 1995). Figure 3 illustrates the seasonal variations present in the daily mortality data for total deaths in Melbourne over the study period. Appendix E contains time series plots for the major outcome variables considered in this analysis.

Figure 3 - Total Daily Deaths in Melbourne, January 1, 1991- August 31, 1996



Correlations between pollutant levels recorded at the different monitoring sites were generally high. Ozone was monitored at six stations; Alphington, Dandenong, Footscray, Pt Cook, Paisley and Brighton (see Figure 1). Inter-site correlations ranged between 0.76 and 0.91 for the 8-hour concentration, 0.78 and 0.92 for the 4-hour concentration, and 0.79 and 0.91 for the 1-hour maximum concentration. Ozone levels were, on average, highest at Pt Cook, although the maximum level of 144 ppb (1-hour maximum) was recorded at Footscray. Lowest concentrations (on average) were recorded at Alphington.

Fine particles (measured as bsp) and NO_2 were measured at five monitoring stations in the study area; Alphington, Dandenong, Footscray, Pt Cook, and Paisley. Inter-site correlations for particles ranged between 0.79 and 0.96 for the 24-hour concentration, and 0.65 and 0.82 for the 1-hour maximum concentration. Highest mean daily particle concentrations were recorded at Alphington, with peak concentrations recorded at Footscray (24-hour) and Paisley (1-hour maximum). Lowest average concentrations were recorded at Pt Cook. For NO_2, inter-site correlations ranged between 0.39 and 0.88 for the 24-hour concentration and 0.54 to 0.82 for the 1-hour maximum measure. Levels of NO_2 were on average highest at Alphington, with peak levels recorded at Footscray. Lowest mean concentrations occurred at Pt Cook.

CO was recorded at three monitoring sites within the study area; Alphington, Parliament Place and Footscray. Inter-site correlation coefficients ranged between 0.77 and 0.84 for the 8-hour concentration and 0.76 and 0.78 for the 1-hour maximum concentration. Recorded CO levels were, on average, highest at Alphington, with lowest levels measured at the Footscray monitoring site. Appendix A contains inter-site correlation coefficients and site-specific pollutant concentrations and pollutant correlation coefficients.

Table 2 presents the descriptive statistics for the meteorological variables and each of the pollutant concentrations (averaged across the monitoring network) considered in the analysis.

Ozone levels were highest in the warm season, while levels of NO_2 and CO were highest in the cool season. Particle levels were, on average, highest in the cool season, although peak levels (maximum 1 hour) were recorded in the warm season in late March 1994. This peak was due to an extended episode of calm, stable meteorological conditions giving rise to a period of high particle levels and poor visibility. Ozone levels were also elevated during this time. This period was unusual both in its intensity and duration. The State Environment Protection Policy (SEPP) (Ambient Air Quality) sets air quality objectives for visibility reducing particles. During this period very high pollution levels were observed with policy levels for particles breached on 8 consecutive days. Heavy pollution levels were recorded on 4 days. PM_{10} levels monitored on an every six day cycle were only available for one day during this period. Levels ranged from 49.2 ug / m^3 at Paisley to 70.4 ug / m^3 at Collingwood. At most stations PM_{10} levels exceeded the NEPM standard of 50 ug / m^3. High levels of particles were not necessarily associated with high levels of other pollutants. Days experiencing very high particles levels only

Table 2 - Mean daily levels of pollutant (network average) and meteorological variables, Melbourne, January 1991- August 1996 (n=2070)

Outcome	Whole study period				Cool season[a]				Warm season[b]			
	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
O_3 (ppb)												
8 hour	22.19	9.04	1.67	86.17	20.06	5.89	1.67	58.00	25.27	11.56	5.67	86.17
4 hour	25.25	10.64	3.33	110.67	22.81	6.12	3.33	65.67	28.77	14.20	8.50	110.67
1 hour	27.22	12.09	4.17	126.83	24.27	6.31	4.17	71.07	31.47	16.41	11.00	126.83
bsp ($10^{-4}m^{-1}$)												
24 hour	0.26	0.25	0.04	2.52	0.29	0.27	0.04	2.52	0.22	0.20	0.04	2.07
1 hour	0.60	0.53	0.08	4.98	0.70	0.56	0.10	4.36	0.46	0.44	0.08	4.98
NO_2 (ppb)												
24 hour	11.50	5.23	1.12	33.79	13.26	4.87	1.58	33.79	8.95	4.64	1.12	29.46
1 hour	23.58	9.87	4.52	80.48	25.88	8.51	5.07	80.48	20.27	10.72	4.52	70.68
CO (ppm)												
8 hour	0.95	0.73	0	5.70	1.16	0.83	0.15	5.70	0.64	0.38	0	2.63
1 hour	1.56	1.21	0.10	9.40	1.94	1.37	0.13	9.40	1.02	0.64	0.10	4.20
Min temp °C	10.15	3.96	0.08	27.03	8.00	2.95	0.08	18.60	13.26	3.08	4.63	27.03
Max temp °C	19.28	5.74	7.1	42.36	16.33	3.85	7.10	32.80	23.53	5.33	11.62	42.36
Max DP °C	11.25	3.57	3.0	22.7	9.4	2.51	3.0	18.0	13.92	3.15	4.0	22.7
Rain mm	2.09	2.09	0	91.8	1.9	4.23	0	36.6	2.36	7.55	0	91.8

a Cool season: April-October (n=1223)
b Warm season: November-March (n=847)

recorded low to moderate levels of NO_2 and CO. During this period high levels of ozone were associated with high particle levels, especially at Pt Cook, indicating the presence of secondary particles. Ozone levels also breached SEPP objectives on 8 days with the maximum at Pt Cook on 30 March 1994.

Figures 4 to 7 illustrate the temporal variations present in the pollutant data over the study period.

Figure 3a - Times series, daily average 8-hour O_3 (ppb), Melbourne Statistical Division, January 1, 1991-August 31, 1996

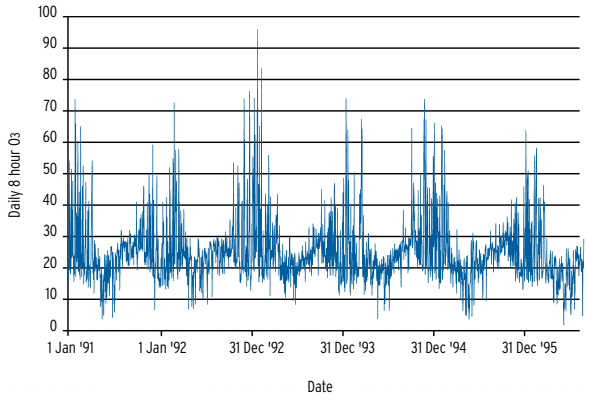


Figure 3c - Times series, daily maximum 1-hour O3 (ppb), Melbourne Statistical Division, January 1, 1991-August 31, 1996

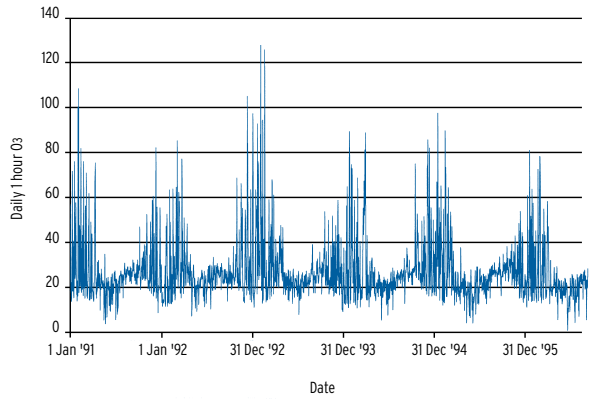


Figure 3b - Times series, daily average 4-hour O_3 (ppb), Melbourne Statistical Division, January 1, 1991-August 31, 1996

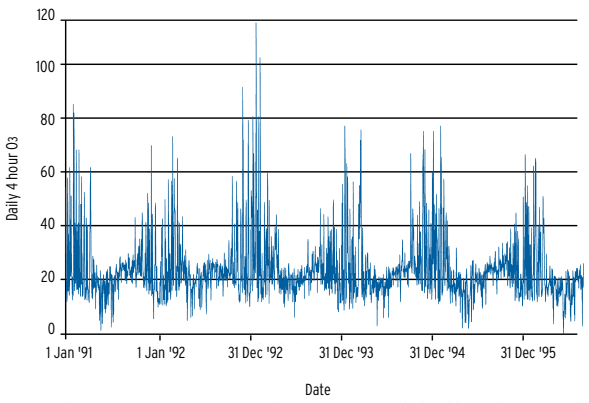


Figure 4a - Times series, daily average 24-hour NO_2 (ppb), Melbourne Statistical Division, January 1, 1991-August 31, 1996

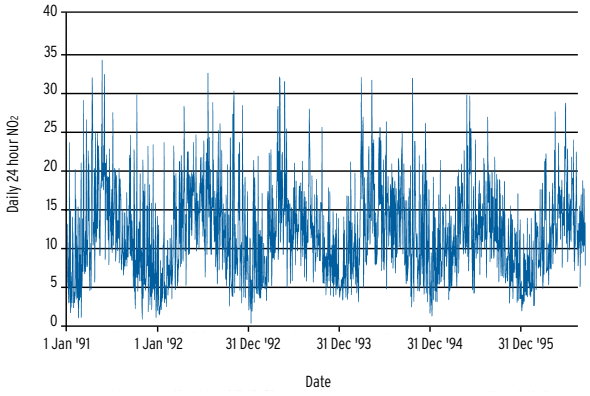


Figure 4b - Times series, daily maximum 1-hour NO_2 (ppb), Melbourne Statistical Division, January 1, 1991-August 31, 1996

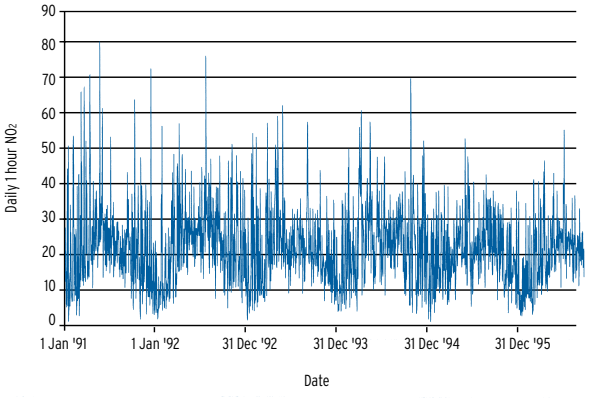


Figure 5a - Times series, daily average 24-hour bsp ($10^{-4}m^{-1}$), Melbourne Statistical Division, January 1, 1991-August 31, 1996

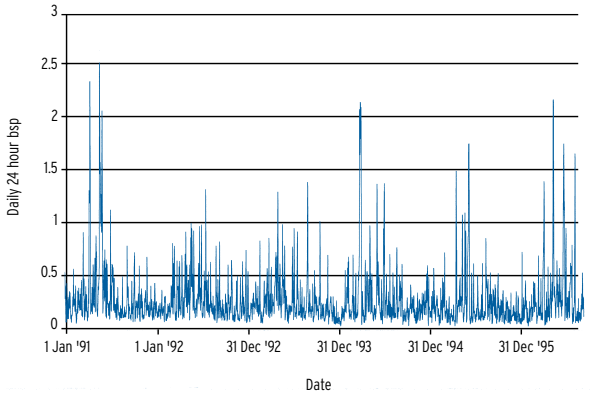


Figure 5b - Times series, daily maximum 1-hour bsp ($10^{-4}m^{-1}$), Melbourne Statistical Division, January 1, 1991-August 31, 1996

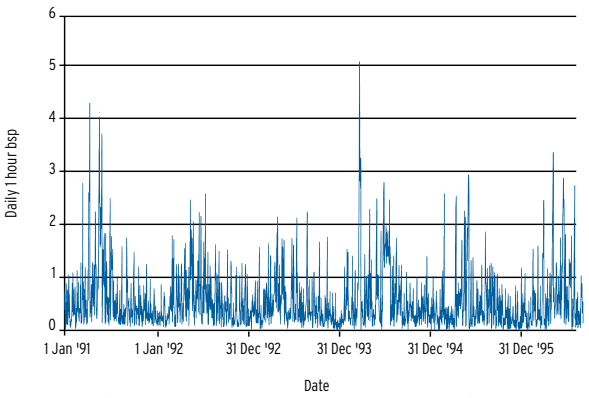


Figure 6a - Times series, daily average 8-hour CO (ppm), Melbourne Statistical Division, January 1, 1991-August 31, 1996

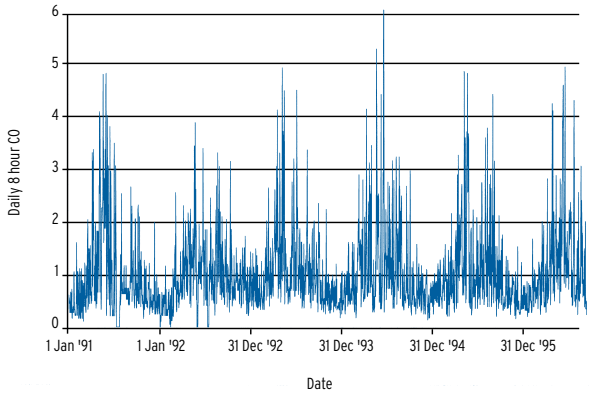
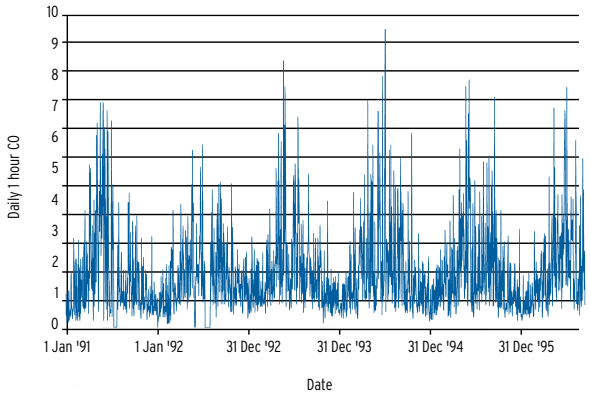


Figure 6b - Times series, daily maximum 1-hour CO (ppm), Melbourne Statistical Division, January 1, 1991-August 31, 1996



4.1. OZONE

The ozone analysis was conducted using data from the Alphington, Brighton, Dandenong, Footscray, Paisley and Pt. Cook air monitoring stations. These stations provided good spatial coverage of the Melbourne Statistical Sub-Division. Data from Mt. Cottrell could not be included as O_3 data are only collected during the summer at this site. The data from the CBD site were not included due to discontinuity in the station operation leading to large amounts of missing data during the study period. This situation arose due to relocation of the air monitoring station.

Analysis was conducted using 1-hour, 4-hour and 8-hour data from each of the air monitoring stations. For the analysis for the whole Melbourne region, the data were averaged across the sites to obtain a network average. For the regional analysis, the west region was represented by data from Foostcray, Paisley and Pt. Cook, while Alphington, Brighton and Dandenong represented the east region.

4.1.1 Results

Trigonometric Approach

The first stage of the modelling strategy involved examining the relationship between each of the pollutants included in the analysis and daily mortality using trigonometric filtering to control for seasonal cycles, and 'sets' of meteorological variables to control for the effects of weather. The base models used for each of the outcomes are presented in Appendix D. The base model is the model for each mortality group under investigation that contains all the meteorological and temporal variables of concern except the air pollution data. The variables included are described in section 3. All models contained the same set of trigonometric terms and temporal variables. The set of meteorological variables most significant to the health outcome under examination was added to the model in the last stage. Separate sets of meteorological variables were selected for each season. Generally meteorological variables at lag 2 or the 3-day cumulative average accounted for most of the variation in the model residuals. The amount of variation in the outcome variables explained by the base models ranged from just 2% (digestive deaths) to 25% (all cause mortality in the 65+ age group). Tests for autocorrelation in the residuals indicated control for this in the base models was unnecessary. Overdispersion was not found to be a major issue.

The main results for O_3 from this first stage of the analysis are presented in Tables 3. This table reports the relative risk (RR) of death (with 95% confidence limits) associated with a 1ppb increase in O_3 concentration. Only the most significant results for each pollutant are presented due to the large number of pollutant averaging periods and lags considered for each health outcome in the analysis. More complete tables of results for each outcome (including parameter estimates, standard errors, probability statistics and dispersion parameters) are presented in Appendix B.

The results of the analysis using the trigonometric approach showed consistently strong positive associations between ozone and all cause mortality and mortality due to respiratory conditions in the single pollutant models. Ozone was found to be significantly associated with all cause mortality at all averaging times and lags in the all ages group. The observed relationships were strongest at the 3-day average concentrations, where a 1ppb increase in the 8-hour concentration was associated with a 0.23% increase in the risk of death, a 1ppb increase in the 4-hour concentration was associated with a 0.20% increase in risk and a 1ppb increase in the 1-hour concentration was associated with a 0.18% increase in the risk of death.

For all cause mortality in the 65+ age group, significant associations were observed at the same day and 3-day average concentrations. The strongest of these occurred with the same day maximum 1-hour O_3 concentration, where a 1ppb increase was associated with a 0.09% increase in risk of death. In the <65 age group, marginally significant ($p < 0.10$) positive effects were found at lag 1 for the 8-hour, 4-hour and maximum 1-hour concentrations. These results are summarized in Table 3.

For respiratory deaths, same day O_3 was significantly positively associated with deaths the all ages group, while in the 65+ age group both same day O_3 and the 3-day average were significant. The most significant associations for both outcomes were found with the same day 4-hour and maximum 1-hour concentrations. Same day 4-hour O_3 was associated with a 0.4% increase in the risk of death in the all ages group and a 0.45% increase in risk of death in the 65+ group per 1ppb increase in O_3 concentration. The same day 1-hour concentration was associated with a 0.35% increase in the all ages group, and a 0.4% increase in the 65+ age group, per 1ppb increase. Marginally significant associations were also observed between O_3 and respiratory deaths in the all ages at the 3-day average 1-hour maximum and in the 65+ age group at the 5-day average 1-hour maximum concentration. No significant relationships were found between O_3 and deaths due to cardiovascular disease, or the control diagnosis of deaths due to digestive diseases.

A seasonal analysis was conducted for all cause, respiratory and cardiovascular mortality for the all ages groups. The results of this analysis revealed that while there were a number of statistically significant positive effects found O_3 in the warm period, no significant associations were found in the cool season for any of the outcomes considered. For all cause mortality, same day O_3 in the warm season was significant for the 4-hour and 1-hour

Table 3 summarises the most significant associations for each outcome obtained using the trigonometric modelling approach for the whole year models.

Table 3 Relative risk of death per unit (ppb) increase in O_3, with 95% confidence intervals, generated using trigonometric filtering

Outcome	Pollutant	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	O_3 3-day average 8-hour maximum	1.0023	1.0013-1.0033
	O_3 3-day average 4-hour maximum	1.0020	1.0010-1.0030
	O_3 1-hour maximum (lag 1)	1.0011	1.0005-1.0017
	O_3 3-day average 1-hour maximum	1.0018	1.0010-1.0026
All Cause Mortality (65+ years)	O_3 maximum 8-hour average	1.0011	1.0001-1.0021
	O_3 maximum 4-hour average	1.0010	1.0002-1.0018
	O_3 1-hour maximum	1.0009	1.0003-1.0015
All Cause Mortality (<65 years)	O_3 1-hour maximum (lag 1)	1.0012	1.0000-1.0024
Respiratory Deaths (all ages)	O_3 maximum 8-hour average	1.0045	1.0017-1.0073
	O_3 maximum 4-hour average	1.0040	1.0016-1.0064
	O_3 1-hour maximum	1.0035	1.0015-1.0055
Respiratory Deaths (65+ Years)	O_3 maximum 8-hour average	1.0051	1.0021-1.0081
	O_3 maximum 4-hour average	1.0045	1.0021-1.0069
	O_3 1-hour maximum	1.0040	1.0018-1.0062
Cardiovascular Deaths (all ages)	O_3 1-hour maximum (lag 1)	1.0007**	0.9997-1.0017
Cardiovascular Deaths (65+ years)	O_3 1-hour maximum (lag 1)	1.0005**	0.9995-1.0015

** not significant

maximum concentrations only. For respiratory deaths, significant positive associations were found for same day O_3 for the 8-hour, 4-hour and 1-hour maximum concentrations. Effect estimate sizes did not differ dramatically from those observed in the cool season, which were not found to be statistically significant. In the case of cardiovascular deaths, no significant positive relationships were observed in either season. The results of the seasonal analysis are shown in Table 4.

Table 4 - Seasonal Analysis: relative risk of death per 1ppb increase in O_3, with 95% confidence intervals, generated using trigonometric filtering

Outcome	Pollutant concentration	Cool Season		Warm Season	
		Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	O_3 4-hour maximum	1.0005**	0.9989-1.0021	1.0009	1.0001-1.0017
	O_3 1-hour maximum	1.0004**	0.9990-1.0018	1.0007*	0.9999-1.0015
Respiratory Mortality (all ages)	O_3 8-hour maximum	1.0043**	0.9983-1.0104	1.0045	1.0011-1.0079
	O_3 1-hour maximum	1.0039**	0.9983-1.0065	1.0039	1.0013-1.0065
	O_3 1-hour maximum	1.0033**	0.9981-1.0085	1.0035	1.0013-1.0057
Cardiovascular Mortality (all ages)	O_3 8-hour maximum (lag 1)	0.9992**	0.9968-1.0016	1.0009**	0.9993-1.0025

*marginally significant; **not significant

Air pollution monitoring for the Melbourne region has shown that peak ozone concentrations occur in the west and north west areas of the airshed indicating that pollutants arising from photochemical processes are more important in these areas. To explore the impact of these elevated levels of photochemical pollutants on daily mortality a regional analysis was conducted. This part of the analysis involved splitting the study area into two regions (see Figure 1) and analyzing these separately. Table 5 gives the regional summary statistics for the pollutants and outcomes considered.

Table 5 - Regional daily pollutant and mortality (non-accidental) summary statistics, Melbourne, January 1991-August 1996

		EAST				WEST			
		Mean	SD	Min	Max	Mean	SD	Min	Max
O_3	8 hour	21.03	9.00	1.00	80.00	23.62	9.22	2.00	92.33
	4 hour	24.15	10.29	1.67	100.67	26.49	11.09	3.67	120.67
	1 hour	26.10	11.51	2.33	117.33	28.41	12.76	4.67	136.33
NO_2	24 hour	13.39	5.37	0.00	35.50	10.05	5.54	0.00	38.25
	1 hour	25.51	9.28	1.21	77.50	21.95	10.96	1.32	96.53
bsp	24 hour	0.30	0.28	0.00	2.67	0.22	0.23	0.02	2.42
	1 hour	0.70	0.61	0.06	5.07	0.51	0.50	0.05	4.92
Total deaths:									
All causes		42.91	7.45	22.00	71.00	12.42	3.68	3.00	27.00
Cardiovascular		19.10	4.08	6.00	38.00	5.22	2.34	0.00	14.00
Respiratory		3.46	2.01	0.00	13.00	1.01	1.06	0.00	7.00

Table 6 - Relative risk of death per unit (ppb) increase in O_3, with 95% confidence intervals, generated using trigonometric filtering – All Cause Mortality (all ages).

Pollutant	East region		West region	
	Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
O_3 maximum 8-hour average	1.0009*	0.9999-1.0019	1.0022	1.0006-1.0038
O_3 3-day average 8-hour maximum	1.0012**	0.9996-1.0028	1.0033	1.0011-1.0055
O_3 maximum 4-hour average	1.0008	1.0000-1.0016	1.0018	1.0006-1.0030
O_3 3-day average 4-hour maximum	1.0013	1.0000-1.0027	1.0027	1.0009-1.0045
O_3 maximum 1-hour average	1.0008	1.0000-1.0016	1.0017	1.0007-1.0027
O_3 3-day average 1-hour maximum	1.0013	1.0001-1.0025	1.0023	1.0007-1.0039

Results from the regional whole-year models for all-cause mortality are presented in Table 6. The strongest associations for each pollutant averaging time are presented. For all cause mortality the effects for O_3 were larger and more statistically significant in the west, compared with the east where fewer significant associations were found.

Respiratory deaths were not examined in the west region due to low daily counts. In the east however, significant relationships were found with same day O_3 at the 8-hour, 4-hour and maximum 1-hour concentrations. These results are summarised in Table 7.

Table 7 - Relative risk of death per unit (ppb) increase in O_3, with 95% confidence intervals, generated using trigonometric filtering – Respiratory Mortality (all ages).

Pollutant	East region	
	Relative Risk	95% Confidence Limits
O_3 maximum 8-hour average	1.0033	1.0001-1.0065
O_3 maximum 4-hour average	1.0031	1.0005-1.0057
O_3 maximum 1-hour average	1.0028	1.0004-1.0052

No significant associations were found for cardiovascular deaths in either region (see Appendix B, Table B5) however, pollutant effects were somewhat higher in the west compared with those found in the east.

Multi-pollutant models were run to determine whether the relationships identified for O_3 in the single pollutant models (Table 3) remained after controlling for other pollutants. Only 8-hour and 1-hour O_3 and the major outcome variables (all cause, respiratory and cardiovascular mortality, all ages) were considered in this part of the analysis. In most cases significant relationships were retained in models after controlling for NO_2, CO and fine particles (measured as bsp). For all cause mortality (all ages), for which all lags and averaging times were found to be significantly associated in the single pollutant models, the significant relationships observed at lag 2 were lost after controlling for particles and CO.

Controlling for NO_2 resulted in the associations observed at lag 2 and the 5-day average losing significance. Control for NO_2 also resulted in the lag 1 O_3 effect becoming marginal at both the 8-hour and 1-hour averaging times. For respiratory deaths (all ages), which showed consistent relationships with O_3 at the same day concentrations in the single-pollutant models, significance was retained after controlling for each of the other pollutants. As no significant relationships were found between O_3 and cardiovascular deaths in the single-pollutant models, multi-pollutant models were not required for this outcome. The results of the multi-pollutant models are summarised in Appendix B, Table B3.

Summary of the Trigonometric Analysis

The results of the preliminary analysis using the trigonometric approach indicate that there is an association between ambient ozone levels and daily mortality in Melbourne. The analysis has revealed strong statistically significant associations between O_3 concentrations at most averaging times and lags considered, although the strongest associations were found at the same day or 3-day cumulative average concentrations. Significant effects were found for all cause and respiratory mortality. For respiratory mortality the strongest effects were seen in the 65+ age group. The associations observed in the single pollutant models were generally maintained in the multi-pollutant analysis. Seasonal analysis indicates that the effects are stronger during the warm season. The results of the regional analysis show that the observed effects are stronger in the west region of Melbourne where ambient O_3 levels are highest.

Sensitivity Analysis

The extent to which the results obtained in the trigonometric analysis are sensitive to the statistical method used was tested by repeating the analysis, using the same base model as used in the trigonometric approach, using Generalised Additive Models (GAM). To allow for comparison of the results between the two approaches the best function of time was fitted to the GAM model first, followed by the same temporal (with the exception of the sinusoidal terms, which were replaced by the smooth function of time) and meteorological variables as were used in the trigonometric analysis. The results of the two approaches were then directly comparable. Only the all cause mortality (all ages) outcome variable was used for the comparison of techniques. The results of this sensitivity analysis for O_3 are shown in Table 8.

The parameter estimates listed in Table 8 indicate that there is little difference in the results produced by the two different statistical approaches used to investigate the air pollution-mortality relationship in this study. The size of the pollutant effects differ only slightly, with the parameter estimates from the GAM analysis in most cases only slightly less than those produced by the trigonometric approach. There is also little difference in the statistical significance of the parameter estimates. The results shown in Table 8 illustrate the robustness of the pollutant-mortality relationships across different statistical approaches based on the same base model to control for confounding temporal and meteorological effects.

GAM Analysis – Optimal Model

The next stage in the GAM analysis involved building the optimal model using the Akaike's Information Criterion (AIC, described in section 3.2) then fitting the pollutant as a linear term to obtain a parameter estimate.

The results from the analysis using the optimal model are presented in Table 9. Base models generated using this approach differed to those used to produce the results listed in Table 8. Rather than using a 'set' of meteorological variables with the same lag to control for weather, the optimal combination of individual meteorological variables (at varying lags) which resulted in the lowest AIC was used instead. This approach to controlling for weather had a significant effect on the pollutant-mortality relationships, particularly those observed for total deaths. Base models for the outcome variables considered are listed in Appendix D.

Unlike the results using the same base model as used in the trigonometric analysis, where all lags and averaging times were significantly associated with daily all cause mortality, this approach to controlling for weather resulted in no significant associations between O_3 and all cause mortality in the all ages group. Marginal associations were found for the same day average 4-hour and maximum 1-hour concentrations. The magnitudes of the O_3 effects were also significantly reduced. Given the comparison between the two statistical techniques presented in Table 8 showed little difference in the results, the loss of size and significance of the O_3 relationships can be almost entirely attributed to the method used to control for weather (see Appendix D for base models).

Table 8 - Comparison of results generated using trigonometric filtering with results generated using Generalised Additive Models, using the same base model: All Cause Mortality

Pollutant	Trigonometric filtering			Generalised Additive Models		
	Parameter estimate	Standard error	p	Parameter estimate	Standard error	p
O_3 maximum 8-hour average	0.0013	0.0004	0.0005	0.001	0.0003	0.0010
O_3 maximum 8-hour average (lag 1)	0.0013	0.0004	0.0004	0.0012	0.0004	0.0007
O_3 maximum 8-hour average (lag 2)	0.0009	0.0004	0.0347	0.0001	0.0004	0.0221
O_3 3-day average 8-hour maximum	0.0023	0.0005	0.0001	0.0021	0.0005	0.0001
O_3 5-day average 8-hour maximum	0.0023	0.0007	0.0010	0.0022	0.0006	0.0002
O_3 maximum 4-hour average	0.0011	0.0003	0.0004	0.0009	0.0003	0.0012
O_3 maximum 4-hour average (lag 1)	0.0011	0.0003	0.0003	0.0010	0.0003	0.0006
O_3 maximum 4-hour average (lag 2)	0.0008	0.0004	0.0303	0.0008	0.0003	0.0239
O_3 3-day average 4-hour maximum	0.0020	0.0005	0.0001	0.0018	0.0004	0.0001
O_3 5-day average 4-hour maximum	0.0020	0.0006	0.0009	0.0018	0.0005	0.0005
O_3 maximum 1-hour average	0.0010	0.0003	0.0004	0.0009	0.0003	0.0007
O_3 maximum 1-hour average (lag 1)	0.0011	0.0003	0.0001	0.0010	0.0003	0.0003
O_3 maximum 1-hour average (lag 2)	0.0007	0.0003	0.0360	0.0007	0.0003	0.0301
O_3 3-day average 1-hour maximum	0.0018	0.0004	0.0001	0.0017	0.0004	0.0001
O_3 5-day average 1-hour maximum	0.0018	0.0005	0.0007	0.0016	0.0005	0.0005

For other mortality outcomes, this alternative approach to controlling for weather had a lesser effect. In the 65+ age group, O_3 was significantly associated with all cause mortality at most lags and averaging times (Table 9). The most statistically significant relationship for this outcome was observed with the 3-day maximum 1-hour O_3 concentration, which was associated with a 0.15% increase in risk of death per 1ppb increase. Same day O_3 was also found to be significantly associated with respiratory deaths in the all ages and 65+ age groups – for both of these outcomes, the 4-hour average O_3 concentration was associated with a 0.27% increase in risk of death per 1ppb increase (Table 9). No significant associations were found for cardiovascular deaths, all cause mortality in the <65 age group, or deaths due to digestive disorders (Appendix C, Table C1).

The results of the seasonal analysis conducted using GAM indicated that effects for O_3 were stronger in the warm season compared with the cool season. Table 10 lists the most significant associations observed in the warm season along with the corresponding cool season results. Significant positive associations ($p<0.05$) were found in the warm season for all cause and respiratory mortality

Table 9 - Relative risk of death per unit (ppb) increase in O_3, with 95% confidence intervals, generated using GAM

Outcome	Pollutant	Relative Risk	95% Confidence Limit
All Cause Mortality (all ages)	O_3 maximum 8-hour average	1.0006**	0.9998-1.0014
	O_3 maximum 4-hour average	1.0006*	1.0000-1.0012
	O_3 maximum 1-hour average	1.0005*	0.9999-1.0011
All Cause Mortality (65+ years)	O_3 3-day average 8-hour maximum	1.0018	1.0004-1.0032
	O_3 3-day average 4-hour maximum	1.0017	1.0005-1.0029
	O_3 3-day average 1-hour maximum	1.0015	1.0005-1.0025
All Cause Mortality (<65 years)	O_3 maximum 8-hour average (lag 1)	1.0006**	0.9990-1.0022
	O_3 maximum 4-hour average (lag 1)	1.0005**	0.9991-1.0019
	O_3 maximum 1-hour average (lag 1)	1.0005**	0.9993-1.0017
Respiratory Mortality (all ages)	O_3 maximum 8-hour average	1.0029*	0.9999-1.0059
	O_3 maximum 4-hour average	1.0027	1.0003-1.0051
	O_3 maximum 1-hour average	1.0023	1.0001-1.0045
Respiratory Mortality (65+ years)	O_3 maximum 8-hour average	1.0027*	0.9995-1.0059
	O_3 maximum 4-hour average	1.0027	1.0001-1.0053
	O_3 maximum 1-hour average	1.0024	1.0000-1.0048
Cardiovascular Mortality (all ages)	O_3 maximum 8-hour average (lag 2)	1.0005**	0.9991-1.0019
	O_3 maximum 4-hour average (lag 1)	1.0004**	0.9994-1.0014
	O_3 maximum 1-hour average (lag 1)	1.0005**	0.9995-1.0015
Cardiovascular Mortality (65+ years)	O_3 maximum 8-hour average (lag 2)	1.0006**	0.9992-1.0020
	O_3 maximum 4-hour average (lag 2)	1.0006**	0.9994-1.0018
	O_3 maximum 1-hour average (lag 1)	1.0005**	0.9995-1.0015

*marginal significance ($p<0.1$); ** not significant

Table 10 - Seasonal Analysis: relative risk of death per unit (ppb) increase in O_3, with 95% confidence intervals, generated using GAM

Outcome	Pollutant concentration	Cool Season		Warm Season	
		Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	O_3 maximum 4-hour average	0.9998**	0.9984-1.0012	1.0008	1.0000-1.0016
	O_3 1-hour maximum	0.9998**	0.9986-1.0010	1.0007	1.0001-1.0013
	O_3 3-day average 1-hour maximum	0.9996**	0.9980-1.0012	1.0010	1.0000-1.0020
All Cause Mortality (65+ years)	O_3 5-day average 8-hour maximum	1.0006**	0.9986-1.0026	1.0028	1.0008-1.0048
	O_3 5-day average 4-hour maximum	1.0004**	0.9984-1.0024	1.0024	1.0008-1.0040
	O_3 3-day average 1-hour maximum	1.0011**	0.9985-1.0029	1.0017	1.0005-1.0029
All Cause Mortality (<65 years)	O_3 4-hour maximum (lag 1)	0.9995**	0.9965-1.0025	1.0008**	0.9992-1.0024
Respiratory Mortality (all ages)	O_3 8-hour maximum	1.0016**	0.9968-1.0064	1.0033*	0.9999-1.0067
	O_3 4-hour maximum	1.0018**	0.9972-1.0064	1.0029	1.0001-1.0057
	O_3 1-hour maximum	1.0012**	0.9968-1.0056	1.0026	1.0002-1.0050
Respiratory Mortality (65+ years)	O_3 8-hour maximum	1.0004**	0.9952-1.0056	1.0035*	0.9999-1.0071
	O_3 4-hour maximum	1.0007**	0.9957-1.0057	1.0032	1.0002-1.0062
	O_3 1-hour maximum	0.9998**	0.9950-1.0046	1.0029	1.0005-1.0053
Cardiovascular Mortality (all ages)	O_3 5-day average 1-hour maximum	0.9993**	0.9967-1.0019	1.0012**	0.9994-1.0030
Cardiovascular Mortality (65+ years)	O_3 5-day average 1-hour maximum	1.0001**	0.9973-1.0029	1.0012**	0.9992-1.0032

* Marginally significant ($p<0.10$) ** Not significant

in both the all ages and 65+ age groups. No significant warm season associations were found with all cause mortality in the <65 age group or with cardiovascular mortality. No significant associations ($p<0.05$) between O_3 and any of the outcomes considered were found in the cool season.

A multi-pollutant analysis was also conducted using the GAM approach. For most outcomes the significant relationships observed for O_3 in the single pollutant models were lost after controlling for other pollutants. In the case of all cause mortality in the 65+ age group, where significant relationships were found at most lags and averaging times considered, controlling for fine particles and CO resulted in some of these relationships either becoming marginal or being lost. The associations observed for same day and 3-day average 4-hour and 1-hour maximum O_3 were retained, indicating that these effects may be independent of these other pollutants. Controlling for NO_2 however resulted in the loss of all significant relationships although marginal relationships were observed for same day and 3-day average 8-hour, 4-hour and 1-hour maximum O_3. For respiratory deaths, the significant relationships observed at same day O_3 for both the all ages and 65+ age groups were either lost or became marginal after controlling for other pollutants (Appendix C, Table C3).

Summary of GAM analysis

The results of the GAM analysis confirmed the results of the trigonometric study that showed that ambient O_3 levels in Melbourne are associated with daily mortality. However, the GAM results show that although these associations are not sensitive to the statistical methods used in the analysis, they are sensitive to the methods used for control for meteorological conditions. The approach taken for controlling for weather in the optimal GAM model resulted in a reduction in the number of significant effects observed. Nonetheless, the majority of the significant effects remained for all cause and respiratory mortality with the strongest associations observed for the same day or 3-day average concentrations. Some associations observed in the single pollutant models were retained in the multi-pollutant models, however a number were lost or became not be independent of other pollutants.

4.1.2 Discussion – O_3 Results

The results of this study indicate that there is an association between ambient O_3 levels and daily mortality in Melbourne. Strong significantly positive associations between O_3 and daily mortality were found, although effects (in terms of size and significance) were found to vary depending on the methods used to control for the highly confounding effects of weather. For both the trigonometric and GAM approaches, effects for O_3 were generally strongest at the same day or 3-day average concentrations.

Using the trigonometric approach, significant associations were found between O_3 and all cause and respiratory deaths for the all age and 65+ age groups. Marginal associations were observed in the <65 age group. The largest pollutant effects were observed in respiratory deaths in the 65+ group, where a 1ppb increase in the same day 8-hour concentration was associated with a 0.5% increase in risk of death. Ozone effects were, in most cases, consistent across the range of pollutant averaging periods examined (8-hour, 4-hour, 1-hour), with all cause mortality in the all ages group showing consistency across all lags. Analysis by season indicated that the observed O_3 effects were more statistically significant and slightly stronger in the warm season. The O_3 effects obtained in the trigonometric analysis were in most cases retained after controlling for other pollutants, suggesting the effects for O_3 are independent of other pollutants. No significant associations were found between O_3 and cardiovascular mortality. The preliminary regional study (performed using the trigonometric approach only) indicated O_3 effects were stronger in the west, where levels of ambient O_3 are higher.

The results of the GAM analysis are considered to be more reliable as the GAM approach is more rigorous than the trigonometric method. Effect estimates generated using the GAM approach were more conservative than those based on the trigonometric approach. Statistically significant associations were found for all cause mortality in the 65+ age group, respiratory deaths in the all ages and 65+ age groups. In contrast to the trigonometric results, where all lags and averaging periods were significant, only marginal associations were found in the all cause mortality (all ages) group using GAM. The difference in results can be almost entirely attributed to the method used to control for meteorological conditions.

In whole-year models using the GAM approach, the increased risk of death associated with a 1ppb increase in O_3 ranged from a 0.08% increase for all cause mortality in the 65+ age group (same day maximum 1-hour concentration), to a 0.27% increase for respiratory mortality in the all ages group (same day 4-hour concentration). The results of the seasonal analysis conducted using GAM indicated that effects for O_3 were stronger in the warm season compared with the cool season. Significant positive associations ($p<0.05$) were found in the warm season for all cause and respiratory mortality in both the all ages and 65+ age groups. No significant warm season associations were found with all cause mortality in the <65 age group or with cardiovascular mortality. No significant associations

($p<0.05$) between O_3 and any of the outcomes considered were found in the cool season. In a number of cases the significant associations found for O_3 using the GAM approach were lost or became marginal after controlling for other pollutants in the model, particularly NO_2, suggesting that the observed effects are not independent of the other pollutants. This result is in contrast to that obtained using the trigonometric approach, where the results indicated an independent effect of O_3. As with the trigonometric approach, no significant associations were found between O_3 and cardiovascular deaths.

Comparison with other Studies

A number of studies have been published which relate ambient ozone levels to increases in daily mortality (Touloumi et al, 1997; Sartor et al, 1997; Borja-Arburto et al, 1997; Simpson et al, 1997; Loomis et al, 1996). The most consistent associations have been observed for mortality from cardiovascular causes in the elderly. The results of the current study, where no significant associations were found between O_3 and cardiovascular deaths in any age group, are in contrast to findings from research conducted overseas but are similar to other studies conducted in Australia (Simpson et al., 1997; Morgan et al, 1998).

Studies conducted as part of the APHEA project have suggested that there is an association between O_3 and daily mortality (both all cause and cardiovascular mortality) (Touloumi et al, 1997). Data on daily mortality and O_3 were obtained for the APHEA cities of Athens, Barcelona, London, Lyon and Paris. As part of a meta-analysis, data were also obtained for Amsterdam, Basel, Geneva and Zurich (which were not originally examined in the APHEA project). Effects for O_3 were found to be greatest in London, where a 25ppb increase in O_3 was associated with an 8.6% increase in risk of death (all causes). A meta-analysis conducted on the results from all cities found a 2.9% (95% CI: 1 – 4.9%) increase in daily mortality associated with a 25ppb increase in daily 1-hour maximum O_3. The results of the Melbourne study, where a 4.5% increases in all cause mortality was associated with a 25 ppb increase in 1-hour maximum O_3, are consistent with the results of the APHEA study.

In the meta-analysis of the APHEA studies the association was greater for mortality from cardiovascular causes than from respiratory disease. The O_3 association remained significant with the inclusion of other pollutants, although the effect was slightly reduced with the inclusion of black smoke. The authors concluded that the results of the meta-analysis support the hypothesis of a causal relationship between increases in O_3 concentrations and daily mortality. Mean 1-hour O_3 levels in these studies ranged from 7 to 44ppb. In the Melbourne study the association with deaths from respiratory disease were stronger than those for all cause mortality with an 8.8% increase per 25ppb increase in same day 1-hour maximum O_3 concentration. A similar result was found for all cause mortality in the elderly where an 8.6% increase in mortality was found to be associated with a 25 ppb increase in same day 1-hour maximum O_3 concentration.

A study from Belgium has also shown an association between ozone has been found increases in daily mortality in the elderly (Sartor et al., 1997). A significant positive association was observed between 24-hour average O_3 levels and daily mortality with the strongest association observed for the daily average O_3 of the previous day. A 12.5% increase in all cause mortality was associated with a 25 ppb increase in daily average ozone concentration. The associations observed in this study were dependent on temperature.

The association between daily mortality and O_3 has been extensively studied in Mexico City (Borja-Arburto et al, 1997; Loomis et al, 1996). In single pollutant models a significant positive association was observed between daily 1-hour maximum O_3 and daily mortality. The effects were greatest for cardiovascular disease in the elderly. The association with cardiovascular disease remained after controlling for TSP although the effect estimate was slightly reduced. The association with cardiovascular disease was dependent on different averaging times with the strongest association observed for 24-hour and 8-hour averages.

A study conducted in Brisbane for the period 1987 to 1993 found a significant association between daily all cause mortality and O_3 (Simpson et al, 1997). The significance of the association was not altered by the addition of other pollutants (in the form of high-pollution dummy variables) into the model. A 10ppb increase in average 8-hour O_3 was associated with a 2.4% increased risk of death (all causes). The corresponding increased risk associated with the 1-hour maximum concentration was 1.6%. These results are similar to those observed in the Melbourne study where a 10ppb increase in 8-hour average and 1-hour maximum O_3 were associated with a 2.3% and 2% increase in all cause mortality respectively. Although positive associations were also found for cardiovascular and respiratory deaths in the Brisbane study, they were not statistically significant. The results of the Brisbane study also indicated a possible threshold for the effects of O_3 occurring in the highest quintile of data (1-hour maximum O_3, range 31-102ppb, mean 42ppb). Daily maximum 1-hour O_3 concentrations ranged from 2.5 to 101.5ppb with a mean of 24.2ppb. Daily maximum 8-hour O_3 concentrations ranged from 1.7 to 63.4ppb with a mean of 18.1ppb.

A study conducted in Sydney also found an association between ambient O_3 levels and daily mortality (Morgan et al., 1998). In the Sydney study a 2.04% increase in all cause mortality was associated with an increase of 30ppb in 1-hour maximum O_3 levels. This association lost significance after controlling for other pollutants in the model. The effects observed in the Sydney study are smaller than those observed in the current study.

The UK Department of Health has recently reviewed the health effects attributed to ozone exposure (UK Department of Health, 1998). Using the data from the APHEA studies it was estimated that 12,500 premature deaths per year could be attributed to O_3 levels in the UK. This estimate was based on the assumption that no threshold exists for the effects of O_3 on daily mortality.

KEY FINDINGS

1. Ambient O_3 levels are associated with daily mortality in Melbourne.

2 The observed effects are robust to the statistical methods used but are sensitive to the methods used to control for weather.

3. The observed effects are greater in the warm season.

4. Regional analysis has shown that the effects are greaterin the west region of Melbourne compared with the east.

5 The results of this study are consistent with studies overseas and other Australian studies.

4.2 NITROGEN DIOXIDE

The NO_2 analysis was conducted using data from the Alphington, Dandenong, Footscray, Paisley and Pt. Cook air monitoring stations. The data from other sites were not included due to discontinuity station operation and large amounts of missing data during the study period.

Analysis was conducted using 1-hour and 24-hour average data from each of the air monitoring stations. As for O_3 the analysis for the whole Melbourne region was conducted using data averaged across the sites to obtain a network average. For the regional analysis, the west region was represented by data from Foostcray, Paisley and Pt. Cook, while Alphington and Dandenong represented the east region.

4.2.1 Results

Trigonometric Approach

The methodology used in the trigonometric analysis is described in Section 5.1.1. The results of this analysis have shown NO_2 to be strongly associated with daily mortality, particularly with all-cause mortality. Significant relationships were found at most lags in the all ages group, at the lag 1 and 3-day 24-hour average concentrations in the 65+ age group, and at lag 1 for the 24-hour and maximum 1-hour concentrations in the <65 age group. Relationships were generally strongest at the lag 1 24-hour concentration with a 1ppb increase in NO_2 associated with a 0.31% increase in the risk of death in the all ages group, a 0.23% increase in risk of death in the 65+ group, and a 0.34% increase in risk of death in the <65 age group. Nitrogen dioxide was also significantly associated with respiratory deaths in the 65+ age group at lag 1 for the 24-hour and maximum 1-hour concentrations, with a 0.59% and 0.26% increase in risk of death (respectively) found per 1ppb increase in the NO_2 concentration. A marginal association was also found between 3-day average 24-hour NO_2 and respiratory deaths in this age group. For cardiovascular deaths in the all ages group, significant associations were found between NO_2 at the lag 1 24-hour concentration, while a marginal association was observed at this lag for the maximum 1-hour concentration. A significant association was also found between NO_2 and the control cause of death, digestive disorders. The results of the trigonometric models are shown in Table 11.

The seasonal analysis found the effects of NO_2 were much stronger and more significant in the warm season compared with the cool season. For all cause mortality (all ages), significant positive associations were identified

Table 11 Relative risk of death per 1ppb increase in NO_2, with 95% confidence intervals, generated using trigonometric filtering

Outcome	Pollutant	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	NO_2 24-hour average (lag 1) NO_2 1-hour maximum (lag 1)	1.0031 1.0014	1.0017-1.0045 1.0008-1.0020
All Cause Mortality (65+ years)	NO_2 24-hour average (lag 1) NO_2 1-hour maximum (lag 1)	1.0023 1.0008	1.0005-1.0041 1.0000-1.0016
All Cause Mortality (<65 years)	NO_2 24-hour average (lag 1) NO_2 1-hour maximum (lag 1)	1.0034 1.0017	1.0004-1.0064 1.0003-1.0031
Respiratory Deaths (all ages)	NO_2 24-hour average	1.0035**	0.9985-1.0085
Respiratory Deaths (65+ years)	NO_2 24-hour average (lag 1) NO_2 1-hour maximum (lag 1)	1.0059 1.0017	1.0007-1.0112 1.0003-1.0031
Cardiovascular Deaths (all ages)	NO_2 24-hour average (lag 1) NO_2 1-hour maximum (lag 1)	1.0025 1.0010*	1.0003-1.0047 0.9998-1.0022
Cardiovascular Deaths (65+ years)	NO_2 24-hour average (lag 1)	1.0019**	0.9995-1.0043

* marginally significant (p<0.1); ** not significant

Table 12 - Seasonal Analysis: relative risk of death per 1ppb increase in NO_2, with 95% confidence intervals, generated using trigonometric filtering

Outcome	Pollutant concentration	Cool Season		Warm Season	
		Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	NO_2 24-hour average	0.9997**	0.9979-1.0015	1.0048	1.0020-1.0076
	NO_2 24-hour average (lag1)	1.0020	1.0002-1.0038	1.0038	1.0010-1.0066
	NO_2 1-hour maximum	0.9997**	0.9987-1.0007	1.0018	1.0006-1.0030
	NO_2 1-hour maximum	1.0009*	0.9999-1.0019	1.0012	1.0000-1.0024
Respiratory Mortality (all ages)	NO_2 24-hour average	0.9970**	0.9906-1.0034	1.0167	1.0080-1.0255
	NO_2 1-hour maximum	0.9972**	0.9938-1.0006	1.0066	1.0030-1.0103
Cardiovascular Mortality (all ages)	NO_2 24-hour average (lag 1)	1.0019**	0.9993-1.0045	1.0039*	0.9997-1.0081

* marginally significant (p<0.1); **not significant

at the same day, lag 1 and 3-day average concentrations for both 24-hour average and maximum 1-hour NO_2. Significant positive associations were also observed in the cool season for the 24-hour and 1-hour concentrations, lagged by 1 day. While no significant relationships were found between NO_2 and respiratory deaths (all ages) in the whole-year models, strong significant positive associations were found in the warm season for this outcome at the same day, 3-day and 5-day averages for 24-hour NO_2, and at the same day and 3-day average for 1-hour maximum NO_2. No significant associations were found in the cool season. For cardiovascular deaths, a marginally significant positive association was found for the lag 1, 24-hour concentration in the warm season, with no significant associations observed in the cool season. Nitrogen dioxide concentrations were higher during the cool season. The results of the seasonal analysis are shown in Table 12.

Air pollution monitoring for the Melbourne region shows that on average the highest levels of NO_2 occur in the east, although peak concentrations were observed in the west. Table 5 gives the regional summary statistics for the pollutants and outcomes considered.

Results from the regional whole-year models for all-cause mortality are shown in Table 13. The significant associations observed for the east is reported with the corresponding data for the west for all cause mortality (all ages). Nitrogen dioxide was not found to be associated with all-cause mortality in the west, but was significantly positively associated with all-cause mortality in the east at the lag 1 24-hour concentration. For cardiovascular deaths, although no significant associations were found in the regional models, pollutant effects were somewhat higher in the west compared with those found in the east (Appendix B, Table B5). Respiratory deaths were not examined in the west region due to low daily counts.

After controlling for other pollutants in the multi-pollutant models, only the strongest relationships observed for NO_2 in single pollutant models were retained. For all cause mortality (all ages), which was found to be significant at a number of lags and averaging times in the single pollutant models, only the lag 1 concentrations for 24-hour and 1-hour NO_2 remained significant after separately controlling for each of the other pollutants (Appendix B, Table B3). In the case of cardiovascular deaths (all ages), the significant relationship at lag 1 for the 24-hour concentration (along with the marginal relationship at the lag 1 1-hour concentration) was retained after controlling for CO, but lost after controlling for fine particles and O_3 (Appendix B, Table B3). As no significant relationships were found between NO_2 and respiratory mortality (all ages) in the single pollutant models, no multi-pollutant models were performed for this outcome.

Summary of Trigonometric Analysis

Strong statistically significant associations were found between NO_2 and daily mortality using the trigonometric approach. Associations were found for all cause mortality in each of the age groups considered, respiratory deaths in the 65+ age group and cardiovascular deaths (all ages). The most consistent associations were observed in the all cause mortality all ages group, with significant associations at most lags. The most significant of these was lag 1 for both the 24-hour and maximum 1-hour concentrations. Effects for NO_2 were strongest in the warm season, with significant associations found for all cause and respiratory mortality. A significant cool season effect was also found for all cause mortality (all ages). For cardiovascular deaths no seasonal effect was evident. Regional analysis found a significant association in the east region only, where levels of NO_2 are higher compared with levels experienced in the west.

Table 13 Relative risk of death per 1ppb increase in NO_2, with 95% confidence intervals, generated using trigonometric filtering, All Cause Mortality.

Pollutant	East region		West region	
	Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
NO_2 24-hour average (lag1)	1.0024	1.0006-1.0042	1.0020**	0.9994-1.0046

Sensitivity Analysis

The sensitivity analysis, that was conducted to investigate the robustness of the observed relationships to the statistical method used, shows a similar outcome to that observed for ozone. The results of this analysis are shown in Table 14.

The parameter estimates listed in Table 14 suggest, as with ozone, that there is little difference in the results produced by the two different approaches used to investigate the pollution-mortality relationship in this study. The size of the pollutant effects differ only slightly, with the parameter estimates from the GAM analysis in most cases only slightly less than those produced by the trigonometric models. There is also little difference in the significance status of the parameter estimates. A significant ($p<0.05$) relationship with 5-day average 1-hour maximum NO_2 was gained using the GAM approach and in some cases the significance of the observed relationships increased. The results in Table 13 again illustrate the robustness of the pollutant-mortality relationships across different statistical approaches based on the same base model to control for confounding temporal and meteorological effects.

GAM Analysis – Optimal Model

The results obtained using the optimal GAM model, as described in Section 5.1.1, are presented in Tables 15 and 16. As for O_3, the second approach to controlling for weather in the GAM analysis resulted in a reduction in the effect estimate size and the number of significant relationships observed between NO_2 and all cause mortality (all ages) compared with those reported in Table 10 using trigonometric filtering. Using this alternative approach to control for weather in the GAM analysis the only significant relationships were found for 24-hour average NO_2 at lag 1 and 3-day average concentrations (Table 15). For both averaging periods, a 1ppb increase in the pollutant concentration was associated with a 0.16% increase in the risk of death from all causes. Marginal associations at the same day 24-hour and lag 1 maximum 1-hour concentrations were also found.

In the 65+ age group, significant positive associations with all cause mortality were found for 24-hour average NO_2 and at the 3 and 5-day average concentrations for maximum 1-hour NO_2. The strongest of these associations occurred at the 5-day average 24-hour concentration, which was associated with a 0.31% increase in risk of death per 1ppb increase in NO_2. The 5-day average concentration of 24-hour NO_2 was also significantly positively associated with respiratory deaths in the 65+ age group, with a 1ppb increase in NO_2 concentration associated with a 0.71% increase in the risk of death. For cardiovascular deaths in the all ages and 65+ age groups, significant associations were observed for 24-hour NO_2 at the lag 1 and 5-day average concentrations, and for maximum 1-hour NO_2 at the 5-day average concentration. Again, the most significant associations were observed for the 5-day average 24-hour concentration, with a 1ppb increase in NO_2 concentration associated with a 0.15% and 0.2% increase in total cardiovascular deaths and cardiovascular deaths in the 65+ age group, respectively. No significant associations were found between NO_2 and total deaths in the <65 age group, total respiratory deaths or deaths due to digestive diseases. The results from the GAM analysis are presented in Table 15.

The results of the seasonal analysis showed strong warm season effects for NO_2 using the optimal GAM model. Table 16 lists the most significant associations found for each outcome, with the corresponding cool season results. Significant positive associations ($p<0.05$) were found in the warm season between NO_2 and most of the outcomes considered, with the exception of all cause mortality in the <65 age group, where only marginally significant positive associations were observed. The warm season effects were consistently positive and, in the case of all cause and respiratory mortality in the all ages and 65+ age groups, these associations were significant at most lags. No significantly positive associations were found between NO_2 and any of the health outcomes in the cool season.

The results of the multi-pollutant analysis showed that none of the significant relationships identified in the single-pollutant models using the optimal GAM approach were retained after controlling for other pollutants (Appendix C, Table C3). These results are similar to those obtained for ozone and indicate that the effects observed for NO_2 in the single pollutant models may not be independent of the other pollutants under consideration.

Summary of GAM Results

The rigorous control for meteorological conditions employed in the GAM approach reduced the magnitude and altered the significance of the pollutant effects observed in the trigonometric analysis. Significant associations were found for all cause and cardiovascular mortality in both the all ages and 65+ age groups. A significant association was also found between the 5-day 24-hour average concentrations and respiratory deaths in the 65+ age group. The most consistent associations were observed for the lag 1 24-hour and 5-day average concentrations. The increased risk associated with the lag 1 24-hour NO_2 ranged between 0.16% (all cause mortality) and 0.23% (cardiovascular mortality 65+) per 1ppb increase. For 5-day 24-hour NO_2, relative risks ranged between 0.31% (total deaths 65+) and 0.71% (respiratory 65+) per 1ppb increase. Seasonal variations were found for all cause, cardiovascular and respiratory mortality,

Table 14 - Comparison of results generated using trigonometric filtering with results generated using Generalised Additive Models, using the same base model: All Cause Mortality*

Pollutant	Trigonometric filtering			Generalised Additive Models		
	Parameter estimate	Standard error	p	Parameter estimate	Standard error	p
NO_2 24-hour average	**0.0018**	**0.0007**	**0.0096**	**0.0017**	**0.0006**	**0.0040**
NO_2 24-hour average (lag 1)	**0.0031**	**0.0007**	**0.0001**	**0.0030**	**0.0006**	**0.0001**
NO_2 3-day average 24-hour	**0.0032**	**0.0009**	**0.0008**	**0.0033**	**0.0008**	**0.0001**
NO_2 5-day average 24-hour	**0.0024**	**0.0012**	**0.0439**	**0.0031**	**0.0008**	**0.0002**
NO_2 1-hour maximum	**0.0009**	**0.0003**	**0.0067**	**0.0009**	**0.0003**	**0.0066**
NO_2 1-hour maximum (lag 1)	**0.0014**	**0.0003**	**0.0001**	**0.0013**	**0.0003**	**0.0001**
NO_2 3-day average 1-hour maximum	**0.0016**	**0.0005**	**0.0007**	**0.0016**	**0.0004**	**0.0001**
NO_2 5-day average 1-hour maximum	0.0012	0.0006	0.0645	**0.0013**	**0.0005**	**0.0072**

* Significant results highlighted in bold

Table 15 - Relative risk of death per 1ppb increase in NO_2, with 95% confidence intervals, generated using GAM – Optimal Model.

Outcome	Pollutant	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	NO_2 24-hour average (lag 1) NO_2 3-day average 24-hour NO_2 1-hour maximum (lag 1)	1.0016 1.0016 1.0006*	1.0004-1.0028 1.0000-1.0032 1.0000-1.0012
All Cause Mortality (65+ years)	NO_2 24-hour average (lag 1) NO_2 5-day average 24-hour NO_2 5-day average 1-hour maximum	1.0019 1.0031 1.0014	1.0005-1.0033 1.0013-1.0049 1.0004-1.0024
All Cause Mortality (65+ years)	NO_2 24-hour average (lag 1) NO_2 1-hour maximum (lag 1)	1.0023* 1.0012**	0.9995-1.0051 0.9998-1.0026
Respiratory Deaths (all ages)	NO_2 24-hour average	1.0027**	0.9983-1.0071
Respiratory Deaths (65+ years)	NO_2 5-day average 24-hour NO_2 5-day average 1-hour maximum	1.0071 1.0030**	1.0005-1.0138 0.9992-1.0068
Cardiovascular Deaths (all ages)	NO_2 24-hour average (lag 1) NO_2 5-day average 24-hour NO_2 5-day average 1-hour maximum	1.0021 1.0033 1.0015	1.0003-1.0039 1.0007-1.0059 1.0001-1.0029
Cardiovascular Deaths (65+ years)	NO_2 24-hour average (lag 1) NO_2 5-day average 24-hour NO_2 5-day average 1-hour maximum	1.0023 1.0043 1.0020	1.0003-1.0043 1.0015-1.0071 1.0004-1.0036

* marginally significant (p<0.1); ** not significant

Table 16 - Seasonal Analysis: relative risk of death per unit (ppb) increase in NO_2, with 95% confidence intervals, generated using GAM

Outcome	Pollutant concentration	Cool Season		Warm Season	
		Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	NO_2 24-hour average NO_2 1-hour maximum	1.0000** 0.9997**	0.9978-1.0022 0.9985-1.0009	1.0060 1.0021	1.0030-1.0090 1.0007-1.0035
All Cause Mortality (65+ years)	NO_2 3-day average 24-hour NO_2 5-day average 1-hour maximum	1.0006** 1.0001**	0.9982-1.0030 0.9985-1.0017	1.0074 1.0035	1.0040-1.0109 1.0017-1.0053
All Cause mortality (<65 years)	NO_2 24-hour average (lag 1) NO_2 1-hour maximum (lag 1)	1.0010** 1.0004**	0.9972-1.0048 0.9982-1.0026	1.0042* 1.0019*	0.9994-1.0090 0.9999-1.0039
Respiratory Mortality (all ages)	NO_2 24-hour average NO_2 1-hour maximum	0.9977** 0.9972**	0.9921-1.0033 0.9940-1.0004	1.0142 1.0054	1.0061-1.0223 1.0018-1.0090
Respiratory Mortality (65+ years)	NO_2 3-day average 24-hour NO_2 5-day average 1-hour maximum	0.9992** 0.9989**	0.9916-1.0068 0.9933-1.0045	1.0185 1.0085	1.0067-1.0304 1.0023-1.0148
Cardiovascular Mortality (all ages)	NO_2 5-day average 24-hour NO_2 5-day average 1-hour maximum	1.0017** 1.0006**	0.9981-1.0053 0.9984-1.0028	1.0053 1.0022*	1.0001-1.0106 0.9998-1.0046
Cardiovascular Mortality (65+ years)	NO_2 5-day average 24-hour NO_2 5-day average 1-hour maximum	1.0025** 1.0010**	0.9987-1.0063 0.9986-1.0034	1.0063 1.0026	1.0009-1.0118 1.0000-1.0052

* marginally significant (p<0.1); ** not significant

with effects for NO_2 significantly greater in the warm season compared with the cool season.

4.2.2 Discussion – Nitrogen Dioxide

Strong significant positive associations were found between NO_2 and daily mortality in this study. Using the trigonometric approach, associations were found for all cause mortality in each of the age groups considered, respiratory deaths in the 65+ age group and cardiovascular deaths (all ages). The most consistent associations were observed in the all cause mortality all ages group, with significant associations at most lags. The most significant of these was lag 1 for both the 24-hour and maximum 1-hour concentrations, for which a 1ppb increase in NO_2 concentration was associated with a 0.31% and 0.14% increase in risk of death (respectively). In terms of magnitude, effects were greatest for respiratory deaths in the 65+ age group, where a unit increase in lag 1 24-hour NO_2 resulted in a 0.59% increase in risk of death. Effects for NO_2 were strongest in the warm season, with significant associations found for total and respiratory deaths. Significant cool season effects were also found for total deaths. For cardiovascular deaths no seasonal effect was evident. Regional analysis found a significant association in the east only, where levels of NO_2 are higher compared with levels experienced in the west.

Again, the rigorous control for meteorological conditions employed in the GAM approach reduced the magnitude and altered the significance of the pollutant effects. Interestingly, the number of significant associations in some of the outcomes considered increased using the GAM approach, particularly for cardiovascular deaths and all cause mortality in the 65+ age group, while fewer significant associations were found for all cause mortality (all ages) compared with the trigonometric results. Significant associations were found for all cause mortality and cardiovascular deaths in both the all ages and 65+ age groups. A significant association was also found between the 5-day 24-hour average concentrations and respiratory deaths in the 65+ age group. The most consistent associations were observed for the lag 1 24-hour and 5-day average concentrations (Table 15). The increased risk associated with the lag 1 24-hour concentration ranged between 0.16% (all cause mortality) and 0.23% (cardiovascular 65+) per 1ppb increase in NO_2. For the 5-day 24-hour concentration, relative risks ranged between 0.31% (all cause mortality 65+ age group) and 0.71% (respiratory 65+) per 1 ppb increase in NO_2. Seasonal variations were found for all cause, cardiovascular and respiratory mortality, with effects for NO_2 significantly greater in the warm season compared with the cool season in these outcomes.

Comparison with other Studies

Mortality studies elsewhere have indicated that exposure to NO_2 at ambient levels increases daily mortality from respiratory and cardiovascular causes, with effects seen in all age groups. Many of these studies have been reviewed by the UK Department of Health, (1998), Streeton (1997), and Bascom et al (1996). A recent study by Burnett et al, (1998) has found an association between 24-hour average NO_2 levels and increases in daily mortality in eleven Canadian cities. Effects were also observed for other pollutants (CO, SO_2 and O_3) but were not as strong as the NO_2 effect. In single pollutant models a 1.4% increase in all cause mortality was found for an increase in 24-hour average NO_2 levels of 10 ppb. In multi-pollutant models, controlling for the effect of the other pollutants, the strength of the association with NO_2 was reduced slightly. A 1.1% increase in all cause mortality was found for an increase in 24-hour average NO_2 levels of 10 ppb. These results are similar to those observed in the Melbourne study where a 1.6% increase in all cause mortality was associated with a 10 ppb increase in daily average NO_2.

A meta-analysis from the APHEA studies has shown an association between daily mortality and daily 1-hour maximum NO_2 levels (Touloumi et al, 1997). This analysis was conducted on the results of studies conducted in six cities across Europe. The effect of NO_2 was greatest in cities that had high levels of black smoke. A 1.3% increase in daily mortality was observed for a 40 ppb increase in 1-hour maximum NO_2 levels. The effect of NO_2 was decreased but still significant after controlling for black smoke in multi-pollutant models. The associations observed for NO_2 were consistent across all cities studied. Daily average or 3-5 day average NO_2 levels were also strongly associated with daily mortality, with a 2% increase per 40 ppb increment in NO_2 concentration. The effects observed in the Melbourne study are greater than those observed in the meta-analysis of the APHEA studies.

Morgan et al (1998a) found a positive significant association between daily average 24-hour NO_2 levels and daily mortality in Sydney. An increase in 24-hour NO_2 levels (lag 1) of 20ppb resulted in an increase of 2.66% (95% CI: 0.04 – 5.35) in all cause mortality. Particles and ozone were also found to be significantly associated with all cause mortality. In the current Melbourne study, a 20ppb increase in daily average NO_2 (lag 1) was associated with a 3.2% increase in all cause mortality (all ages). A study in Brisbane (Simpson et al. 1997) found no associations between NO_2 and daily mortality.

KEY FINDINGS

1. Ambient NO_2 levels in Melbourne are associated with daily mortality.

2. The observed effects are greater in the warm season than in the cool season.

3. The strongest associations were observed for respiratory mortality in the elderly, although effects were also observed for all cause and cardiovascular mortality in other age groups.

4. The results of the regional analysis show that the observed effects are greater in the east.

5. The results of the analysis are sensitive to the method used to control for meteorological variables.

4.3 FINE PARTICLES, measured as bsp

The particle analysis was conducted using nephelometry data from the Alphington, Dandenong, Footscray, Paisley and Pt Cook. Data from the Brighton and CBD air monitoring stations could not be included in the analysis due to a large amount of missing data during the study period. Both 1-hour maximum and 24-hour average bsp concentrations were used in the analysis.

For the regional analysis data from Footscray, Paisley and Pt. Cook were used to represent the west region and Alphington and Dandenong data represented the east.

In addition to the nephelometry data, analysis was also conducted using PM_{10} collected every six days using hi-volume samplers. These data were collected at 5 sites within the Melbourne air shed including Alphington and Paisley. The other sites were Richmond, Collingwood and the CBD site.

4.3.1 Results

Trigonometric Approach

The results of the trigonometric analysis show that increases in daily mortality in Melbourne are positively associated with fine particles, however many of the observed effects were not statistically significant ($p<0.05$). A significant positive association was found between 24-hour bsp at lag 1 and all cause mortality, with a unit increase in bsp ($1x10^{-4}m^{-1}$) associated with a 2.87% increase in the risk of death. A marginal association was also found for this outcome for 1-hour maximum bsp lagged by 1 day. A marginally significant positive association was also observed between 24-hour average bsp (lag 1) and cardiovascular deaths (all ages) and all cause mortality in the less than 65 years age group. Significant negative associations were observed between bsp and deaths due to digestive disorders. The results of the trigonometric analysis are summarised in Table 17.

Analysis by season found the strongest effects for bsp on all cause and cardiovascular deaths (all ages) were in the cool season. For respiratory mortality (all ages) the effects were strongest in the warm season. A significant positive association was observed between 24-hour bsp at lag 1 and all cause mortality (all ages) in the cool season, while a marginally significant ($p<0.1$) association between same day bsp and this outcome was found in the warm season. Significant positive associations were observed between cardiovascular deaths and lag 1 24-hour bsp in the cool season, with a marginally significant positive association also found at the 5-day average concentration. While no

Table 17 Relative risk of death per unit ($10^{-4}m^{-1}$) increase in bsp, with 95% confidence intervals, generated using trigonometric filtering

Outcome	bsp concentration	Relative Risk	Lower Limit	Upper limit
All Cause Mortality (all ages)	bsp 24-hour average (lag 1) bsp 1-hour maximum (lag 1)	1.0287 1.0114*	1.0025 0.9989	1.0556 1.0240
All Cause Mortality (<65 years)	bsp 24-hour average (lag 1)	1.0480*	0.9900	1.1095
Cardiovascular Mortality (all ages)	bsp 24-hour average (lag 1)	1.0361*	0.9939	1.0802

* marginally significant ($p<0.1$)

Table 18 Relative risk of death per unit ($10^{-4}m^{-1}$) increase in bsp, with 95% confidence intervals, generated using trigonometric filtering: Seasonal Analysis.

Outcome	Pollutant concentration	Cool Season		Warm Season	
		Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	bsp 24-hour average bsp 24-hour average (lag 1)	1.0017** 1.0309	0.9723-1.0320 1.006-1.0620	1.0503* 0.9897**	0.9915-1.1126 0.9315-1.0515
Respiratory Mortality (all ages)	bsp 24-hour average bsp 1-hour maximum	0.9544** 0.9683**	0.8526-1.0683 0.9172-1.0222	1.2723 1.1383	1.0431-1.5518 1.0436-1.2415
Cardiovascular Mortality (all ages)	bsp 24-hour average (lag 1)	1.0483	1.0028-1.0959	1.0034**	0.9167-1.0983

* marginally significant ($p<0.1$); **not significant

Table 19 - Relative risk of death per unit ($1x10^{-4}m^{-1}$) increase in bsp, with 95% confidence intervals, generated using trigonometric filtering.

		East region		West region	
Outcome	Pollutant	Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	bsp 24-hour average (lag 1)	1.0055	0.9758-1.0361	1.0479*	0.9916-1.1074
	bsp 3-day average 24-hour average (lag 1)	0.9963	0.9611-1.0328	1.0582*	0.9900-1.1311
	bsp 5-day average 24-hour average (lag 1)	0.9938	0.9545-1.0348	1.0702*	0.9906-1.1560
Cardiovascular Mortality (all ages)	bsp 24-hour average (lag 1)	1.0170**	0.9721-1.0641	1.0664**	0.9805-1.1599
	bsp 3-day average 24-hour average (lag 1)	1.0110**	0.9576-1.0673	1.0759**	0.9722-1.1908
	bsp 5-day average 24-hour average (lag 1)	1.0121**	0.9524-1.0755	1.0920**	0.9708-1.2283

* marginally significant (p<0.1); ** not significant

significant associations were observed in the cool season for respiratory mortality, significant positive relationships were found for same day bsp at both the 24-hour and 1-hour maximum concentrations in the warm season. Marginal (p<0.1) associations were also found for maximum 1-hour bsp at the lag 1 and 3-day average concentrations. The results of the seasonal analysis are shown in Table 18 and (Appendix B, Table B2).

The results shown in Table 18 for the cool season suggest that cardiovascular deaths may be driving the association observed between all cause mortality and same day 24-hour average bsp.

The regional analysis showed that the associations observed between bsp and daily mortality were stronger in the west than in the east, although no statistically significant associations were found for either region. Marginally significant positive associations were found in the west between same day 24-hour average bsp as well as the 3-day and 5-day average 24-hour bsp and all cause mortality (all ages). In the east region all observed effects were non-significant. These results of the regional analysis are summarised in Table 19 and Appendix B,Table B5. As with the analysis conducted for O_3 and NO_2, respiratory deaths were not examined in the west region due to low daily numbers of deaths. In the east no significant relationships were found for this outcome.

The results of the multi-pollutant analysis showed that the significant associations identified between bsp and the major outcome variables (all ages groups) in Table 17 were lost after controlling for other pollutants. In the single pollutant models all cause mortality was significantly associated with bsp at the lag 1 24-hour concentration, and marginally associated at the lag 1, 1-hour concentration – both of these relationships were lost after controlling for other pollutants. For cardiovascular mortality, the marginal association found in the single pollutant models at the lag 1 24-hour concentration was retained after controlling for CO, but lost after controlling for O_3 and NO_2. No significant relationships were found between bsp and total respiratory deaths. These results suggest that the observed effects for bsp may not be independent of the other pollutants under consideration. The results of the multi-pollutant analysis are listed in Appendix B, Tables B3.

Exploratory Analyses

A number of analyses were conducted for exploratory purposes using limited PM_{10} and $PM_{2.5}$ data sets. These included analyses using PM_{10} data recorded every sixth day, and continuous $PM_{2.5}$ data estimated from bsp data using relationships derived between $PM_{2.5}$ and bsp data. Continuous PM_{10} data sets were constructed from the $PM_{2.5}$ data using correlations between $PM_{2.5}$ and PM_{10} derived from collocated TEOM monitors at various sites in the Melbourne airshed (Baker et al., 1999). Both the bsp and TEOM relationships are specific for the Melbourne airshed.

The purpose of this analysis was to determine whether there was any difference in the results between those obtained using a direct mass measure of particles and those using bsp. Being of an exploratory nature, these analyses were conducted using the trigonometric method only, and only the major outcome variables (all cause, respiratory and cardiovascular mortality) were considered. The descriptive statistics for the PM concentrations and complete tables of results are reported in Appendix B, Table B4.

Continuous PM_{10} and $PM_{2.5}$, estimated from bsp data, were both significantly associated with all cause mortality (all ages) at lag 1 24-hour concentrations. A marginally significant association was also found between cardiovascular deaths (all ages) and continuous $PM_{2.5}$. Although no significant associations were found between PM_{10} measured every sixth day and all cause mortality, respiratory or cardiovascular deaths, the size of the effect estimate was greater for this measure of particles than for those obtained using data estimated from bsp data. The lack of a significant result despite the higher effect estimate may be due to the limited number of observations in this data set resulting in an increased standard error for the pollutant effect estimate. The results of these analyses are presented in Table 20.

Table 20 Relative risk of death per unit (1 ug/m³) increase in particle mass, with 95% confidence intervals, generated using trigonometric filtering

Outcome	PM concentration	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	PM_{10} 24-hour average (lag 1)	1.0009	1.0000-1.0019
	$PM_{2.5}$ 24-hour average (lag 1)	1.0019	1.0001-1.0037
	PM_{10} 24-hour average (lag 1) (every sixth day data)	1.0011**	0.9993-1.0029
Cardiovascular Mortality (all ages)	PM_{10} 24-hour average (lag 1)	1.0011**	0.9997-1.0025
	$PM_{2.5}$ 24-hour average (lag 1)	1.0025*	0.9997-1.0053
	PM_{10} 24-hour average (lag 1) (every sixth day data	1.0019**	0.9989-1.0049

*marginally significant; ** not significant

Table 21 - Relative risk of death per unit (1 ug/m³) increase in PM, with 95% confidence intervals, generated using trigonometric filtering: Seasonal Analysis.

Outcome	Pollutant	Cool Season		Warm Season	
		Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	PM_{10} 24-hour average	1.0001**	0.9991-1.0011	1.0023	1.0005-1.0041
	$PM_{2.5}$ 24-hour average	1.0001**	0.9981-1.0021	1.0050	1.0012-1.0088
	$PM_{2.5}$ 24-hour average (lag 1)	1.0020	1.0001-1.0040	1.0033**	0.9995-1.0071
Respiratory Mortality (all ages)	PM_{10} 24-hour average	0.9976**	0.9932-1.0020	1.0076	1.0012-1.0141
	$PM_{2.5}$ 24-hour average	0.9953**	0.9872-1.0035	1.0170	1.0033-1.0310
Cardiovascular Mortality (all ages)	PM_{10} 24-hour average (lag 1)	1.0016*	0.9998-1.0034	1.0001**	0.9973-1.0029

* marginally significant (p<0.1); **not significant

A seasonal analysis was performed using the estimated continuous data for PM_{10} and $PM_{2.5}$ for each of the major outcomes. PM_{10} measured every sixth day was not analysed by season due to insufficient data. For all cause mortality, significant positive associations were observed in the warm season for both PM_{10} and $PM_{2.5}$ at the same day and 3 day average concentrations. Marginally significant associations were observed at lag 1 for both PM_{10} and $PM_{2.5}$. This result is different to that found for bsp, where in the warm season only a marginally significant association was observed for the same day 24-hour concentration (Table 18). However, as was the case for bsp, a significant positive association was observed in the cool season between $PM_{2.5}$ at the lag 1 concentration and all cause mortality. For respiratory deaths the results were also similar to those found using bsp data. Effects were greater in the warm season, with significant associations at the same day concentrations for both PM_{10} and $PM_{2.5}$. In contrast, particle effects on cardiovascular deaths were greater in the cool season, although only a marginally significant cool season effect was found (PM_{10}, lagged 1 day). As shown in table 17, for bsp this concentration was significant ($p<0.05$). The results of the seasonal analysis are shown in Table 21.

Summary of Trigonometric Analysis

The results of the trigonometric analysis have shown that fine particle levels in Melbourne are associated with increases in daily mortality. A significant positive association was found between bsp and all cause mortality. Seasonal analysis revealed significant associations in the warm season for all cause and respiratory mortality, indicating stronger effects for bsp during this period. For cardiovascular deaths, a significant effect was observed in the cool season (at the lag 1 24-hour concentration).

Results from exploratory analyses using PM_{10} and $PM_{2.5}$ data reflected the results for bsp. Continuous PM_{10} and $PM_{2.5}$ were significantly associated with all cause mortality at the lag 1 24-hour average concentrations. While no significant associations were found using PM_{10} measured every sixth day (covering 332 days), pollutant effect sizes for PM_{10} measured every sixth day were generally larger than those generated using continuous data based on bsp.

Sensitivity Analysis

The sensitivity analysis, that was conducted to investigate the robustness of the observed relationships to the statistical method used, shows that the results obtained using the same base model are robust to the statistical method used. The sensitivity analysis, that was conducted to investigate the robustness of the observed relationships to the statistical method used, shows that the results for bsp, obtained using the same base model, are not quite as robust to the methods used as other pollutants. This is most likely due to the low number of significant relationships found for this pollutant and the unstable nature of the parameter estimates and the standard errors when not significant. The effect estimates for non-significant relationships for the other pollutants in this study also varied between the two methods. The results of this analysis are shown in Table 22.

Table 22 - Comparison of results generated using trigonometric filtering with results generated using Generalised Additive Models, using the same base model: All Cause Mortality*

Pollutant	Trigonometric filtering			Generalised Additive Models		
	Parameter estimate	Standard error	p	Parameter estimate	Standard error	p
bsp 24-hour average	0.0137	0.0128	0.2809	0.0072	0.0121	0.5553
bsp 24-hour average (lag1)	**0.0283**	**0.0129**	**0.0282**	0.0206	0.0122	0.0912
bsp 24-hour average (lag2)	0.0074	0.0138	0.5936	0.0037	0.0127	0.7718
bsp 3-day average 24-hour average	0.0234	0.0155	0.1302	0.0150	0.0141	0.2893
bsp 5-day average 24-hour average	0.0225	0.0179	0.2075	0.0167	0.0157	0.2893
bsp 1-hour maximum	0.0036	0.0061	0.5631	0.0001	0.0057	0.9920
bsp 1-hour maximum (lag 1)	0.0113	0.0062	0.0706	0.0080	0.0058	0.1677
bsp 1-hour maximum (lag 2)	0.0043	0.0066	0.5135	0.0030	0.0060	0.6171
bsp 3-day average 1-hour maximum	0.0094	0.0077	0.2182	0.0056	0.0068	0.4123
bsp 5-day average 1-hour maximum	0.0120	0.0089	0.1784	0.0094	0.0076	0.2188

* Significant results highlighted in bold

The parameter estimate for the statistically significant result listed in Table 22 suggests that, as with O_3 and NO_2, there is little difference in the size of the parameter estimate produced by the two different approaches used to investigate the particle-mortality relationship in this study. The significance however is reduced with only a marginal effect observed in the GAM analysis.

GAM Analysis – Optimal Model

The results obtained using the optimal GAM model are presented in Tables 23 and 24. As for the other pollutants examined in this study, this approach to controlling for weather in the GAM analysis had a significant impact on both the size and significance of the parameter estimates obtained from the trigonometric analysis. No significant positive associations were observed between bsp and any of the outcomes examined using this method for controlling for meteorological parameters in the GAM approach for the whole-year models. The direction of association varied considerably, both between outcomes and across lags and averaging times within outcomes. For all cause mortality in the <65 age group and cardiovascular mortality in both of the age groups considered, associations were consistently positive but not significant. A marginal significant association was found

Table 23 - Relative risk of death per unit ($1x10^{-4}m^{-1}$) increase in bsp, with 95% confidence intervals, generated using GAM.

Outcome	Pollutant	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	bsp 24-hour average (lag 1)	1.0043**	0.9793-1.0299
All Cause Mortality (<65 years)	bsp 24-hour average (lag 1)	1.0368**	0.9801-1.0967
Cardiovascular Mortality (all ages)	bsp 5-day average 24-hour	1.0337**	0.9870-1.0825
Cardiovascular Mortality (65+ years)	bsp 5-day average 24-hour	1.0411*	0.9911-1.0936

* marginally significant(p<0.1); **not significant

Table 24 - Seasonal Analysis: relative risk of death per unit ($1x10^{-4}m^{-1}$) increase in bsp, with 95% confidence intervals, generated using GAM

Outcome	Pollutant	Cool Season		Warm Season	
		Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	bsp 24-hour average	0.9870**	0.9582-1.0166	1.0456*	0.9974-1.0961
All Cause Mortality (65+ years)	bsp 24-hour average bsp 1-hour maximum	0.9810** 0.9867**	0.9499-1.0131 0.9714-1.0022	1.0484* 1.0208*	0.9955-1.1042 0.9964-1.0458
All Cause Mortality (<65 years)	bsp 24-hour average (lag 2)	1.0211**	0.9551-1.0917	1.0934*	0.9797-1.2203
Respiratory Mortality (all ages)	bsp 24-hour average bsp 1-hour maximum	0.9328** 0.9650**	0.8410-1.0346 0.9183-1.0141	1.1515* 1.0925	0.9744-1.3608 1.0124-1.1790
Respiratory Mortality (65+ years)	bsp 1-hour maximum	0.9670**	0.9172-1.0194	1.1016	1.0173-1.1929
Cardiovascular Mortality (all ages)	bsp 24-hour average (lag 1)	1.0293**	0.9868-1.0737	1.0138**	0.9428-1.0901
Cardiovascular Mortality (65+ years)	bsp 1-hour maximum (lag 1)	1.0355**	0.9898-1.0834	0.9986**	0.9235-1.0798

* Marginally significant (p ≤ 0.10); ** Not significant

between 5-day average 24-hour bsp and cardiovascular deaths in the greater than 65 year age group. Significant negative associations were found between bsp and the control cause of death. The results of the GAM analysis in the whole year models are presented in Table 23.

Although no significant positive associations were found in the whole-year models, the seasonal analysis yielded a number of significant positive relationships. The results of this analysis revealed effects for bsp were generally stronger in the warm season, Same day maximum 1-hour bsp was significantly associated ($p<0.05$) with respiratory mortality in the all ages and 65+ age groups in the warm season, while marginally significant associations ($p<0.10$) were observed for all cause mortality. No associations were observed between bsp and cardiovascular mortality in the warm season, or in the cool season for any of the outcomes considered. The results of the seasonal analysis are presented in Table 24.

No multi-pollutant analysis for bsp was conducted using the GAM approach due to the lack of significant positive associations found in the outcome variables considered in the single pollutant models.

Summary of the GAM analysis

The results of the GAM analysis have shown that the association observed between fine particles (bsp) and daily mortality was sensitive to the method used to control for meteorological variables. Using the GAM approach, significant associations between particles and increases in daily mortality were only observed during the warm season. Significant associations were observed between 1-hour maximum bsp and respiratory mortality in both the all ages and 65+ years age groups. Marginal associations were also observed for all cause mortality in the elderly and 1-hour maximum bsp, and between respiratory mortality in both the all ages and 65+ years age groups and 24-hour bsp. Marginally significant associations were found for all cause mortality in both the all ages and 65 + years age groups and 24-hour average bsp. A marginally significant association between the 5-day average 24-hour bsp and cardiovascular mortality in the elderly was observed in the whole year model.

4.3.1. Discussion - Particles

The results of the trigonometric analysis are consistent with the results of studies overseas and within Australia that show a positive association between daily particle levels and increases in daily mortality. The results of the GAM analysis however indicate that this relationship is dependent on the statistical methods used in the analysis and the methods used for controlling for meteorological variables. Using the GAM approach, a significant positive association between particles and increases in daily mortality was observed during the warm season. No significant associations were observed in the whole year models using the GAM approach.

The size of the effect estimates obtained in the whole year models using the trigonometric approach are similar to those obtained in studies overseas. Using the relationship derived between bsp and $PM_{2.5}$, the results of this study indicate that a 10 ug/m^3 increase in daily average $PM_{2.5}$ would be associated with a 1.4% increase in daily mortality (all cause). This result is similar to that observed in the Six Cities Study (Schwartz et al., 1996) where increases between 0.8 and 2.2% in daily mortality were associated with a 10 ug/m3 increase in daily average $PM_{2.5}$.

Comparison with other Studies

In recent years many studies have consistently shown an association between short-term exposure to particles and increases in daily mortality. In these studies investigators have observed an association between daily or the average of several days concentrations of particles (as TSP, PM_{10} or $PM_{2.5}$) and daily mortality. The results of these studies are consistent with early studies from London, but extend to lower concentrations and a large number of areas with differing climate, particle composition and varying amounts of SO_2 and other gaseous pollutants.

In general the effect estimates observed in the UK and Europe are lower than those observed in the USA. The reason for this is unclear but may be due to high levels of acid aerosols in the USA, or possibly the use of black smoke in the UK and European studies (UK Department of Health, 1998). The differences observed in the results from the studies in different parts of the world suggest that the dose response relationships determined within a particular country or region may not be readily transferable to other areas.

A study conducted in Birmingham, UK (Wordley et al, 1997) that used PM_{10} measurements found effects similar to those observed in the USA namely a 1.1% increase in daily mortality per 10 ug/m^3 increase in PM_{10}. The results from a meta-analysis of the Air Pollution and Health: European Approach (APHEA) studies, where a variety of measures of particles were used, revealed a 0.44% increase in daily mortality per 10 ug/m^3 increase in PM_{10}. It has been estimated that in Great Britain there are 8,100 premature deaths per year that can be attributed to exposure to PM_{10} (UK Department of Health, 1998).

In Australia, the association between daily mortality and air pollution has been investigated in both Sydney and

Brisbane (Morgan et al, 1998a; Simpson et al, 1997). Both Sydney and Brisbane, like most Australian cities, experience very low levels of SO_2 which means that confounding by this pollutant is unlikely. In the Sydney study (Morgan et al., 1998) nephelometry data, which is an indicator of fine particles, was found to be associated with all cause, respiratory and cardiovascular mortality. The results showed a 2.6% increase in daily mortality was associated with an increase in PM_{10} of 25 ug/m^3 , similar to that observed in studies in the USA. On the basis of this study, it was estimated that fine particle air pollution in Sydney accounts for 397 deaths per year. Daily mortality was also found to be associated with O_3 and NO_2, but when all pollutants were considered in the same model, the effect of particles dominated.

The mortality study conducted in Brisbane (for the period 1987 to 1993) found similar results (Simpson et al, 1997). Significant associations were found for daily mortality and fine particles (bsp, measured by nephelometry) and O_3. Maximum 1-hour and 8-hour bsp as well as 1-hour and 8-hour O_3 were associated with total mortality, especially in the summer. The effects of SO_2 and NO_2 on daily mortality were not significant. When all pollutants were considered in the model, O_3 and particles remained significant suggesting that the effects were independent. The associations were more significant for the elderly and for mortality from cardiovascular causes. An increase in fine particle levels corresponding to a 10 ug/m^3 increase in PM_{10} was associated with an increase in daily mortality of between 1.2 to 1.3%.

KEY FINDINGS

1. Fine particles in Melbourne are associated with small increases in daily mortality. These results are consistent with results from other studies conducted in Australia and overseas.

2. These associations are dependent on season with stronger effects observed during the warm months.

3. The effects observed for particles are stronger in the west than in the east.

4. The observed associations are dependent on the method used to control for meteorological parameters.

4.4 CARBON MONOXIDE

The analysis for CO was conducted using data from three air monitoring stations within the study area; Alphington, Parliament Place and Footscray. CO levels were, on average, highest at Alphington, with lowest levels measured at the Footscray monitoring site. Both 1-hour and 8-hour maximum CO concentrations were used in the analysis. No regional analysis was conducted for CO due to the limited number of monitoring stations for CO.

4.4.1 RESULTS

Trigonometric Approach

Carbon monoxide was consistently positively associated in single pollutant models with most of the outcomes considered, although in many cases these relationships were non-significant. A significant positive association was found with all-cause mortality at lag 1. For the maximum 1-hour concentration, a 1ppm increase in CO concentration was associated with a 0.69% increase in risk of death. In the <65 age group, marginal positive relationships were found for same day and lag 1 8-hour average CO, and for the maximum 1-hour concentration (lag 1). Significant negative associations were found for deaths due to digestive disorders for the maximum 1-hour concentration at the lag 2 and 5-day cumulative average concentrations. The results of the trigonometric analysis are shown in Table 25 and Appendix B, Table B1.

The results of the seasonal analysis show that the effects observed for CO were statistically significant only in the warm season. For all cause mortality, significant positive associations were found for maximum 1-hour CO at the same day, lag 1 and 3-day average concentrations. For respiratory mortality (for which no significant associations were observed in the whole-year models), 1-hour maximum CO was significant at the same day, 3-day and 5-day cumulative averages. Marginally positive associations were observed for cardiovascular deaths at the same day and lag 1 concentrations for 8-hour CO. For each of the outcomes considered, cool season effects were somewhat smaller than the warm season effects, and were not significant. These results are summarised in Table 26 and Appendix B, Table B2.

Table 25 - Relative risk of death per unit (1ppm) increase in CO, with 95% confidence intervals, generated using trigonometric filtering

Outcome	Pollutant concentration	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	CO 1-hour maximum (lag 1)	1.0069	1.0013-1.0126
All Cause Mortality (<65 years)	CO 8-hour maximum (lag 1) CO 1-hour maximum (lag 1)	1.0187* 1.0123*	0.9977-1.0401 0.9994-1.0253

*marginally significant

Table 26 - Relative risk of death per unit (1ppm) increase in CO, with 95% confidence intervals, generated using trigonometric filtering: Seasonal Analysis.

Outcome	Pollutant concentration	Cool Season		Warm Season	
		Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	CO 1-hour maximum	0.9954**	0.9895-1.0014	1.0245	1.0064-1.0429
	CO 1-hour maximum (lag 1)	1.0044**	0.9984-1.0105	1.0252	1.0067-1.0440
	CO 3-day average 1-hour maximum	1.0005**	0.9919-1.0091	1.0460	1.0167-1.0762
Respiratory Mortality (all ages)	CO 1-hour maximum	0.9879**	0.9666-1.0096	1.0783	1.0109-1.1503
	CO 3-day average 1-hour maximum	0.9830**	0.9521-1.0150	1.1192	1.0119-1.2379
	CO 5-day average1-hour maximum	1.0032**	0.9660-1.0419	1.1541	1.0148-1.3125
ardiovascular Mortality (all ages)	CO 8-hour maximum	0.9916**	0.9773-1.0062	1.0416*	0.9964-1.0889
	CO 8-hour maximum (lag 1)	1.0005**	0.9860-1.0152	1.0407*	0.9951-1.0884

* marginally significant (p<0.1); **not significant

In the multi pollutant analysis, the significant relationship found between CO and all cause mortality was retained after controlling for O_3, but was lost after controlling for bsp and NO_2 (in separate models). The results of the multi-pollutant analysis are shown in Appendix B, Table B3.

Summary of the Trigonometric Results

The results obtained for CO in the trigonometric analysis show few significant associations observed in the whole year models. A significant positive association was found between the maximum 1-hour concentration (lag1) and all cause mortality (all ages). Results from the seasonal analysis show that effects for CO were stronger in the warm season compared with the cool season, with significant associations found in the warm season for respiratory and all cause deaths. The positive relationship with cardiovascular deaths was marginally significant in the warm season and non-significant in the cool season. In multi-pollutant models the effect for CO was not retained after controlling for other particles or NO_2, but was retained after controlling for O3.

Sensitivity Analysis

The results of the sensitivity analysis conducted to test the robustness of the observed relationships to the statistical methods used in the analysis show that the effects observed for CO were not dependent on the statistical method used. These results are shown in Table 27. Significant results are highlighted in bold.

The parameter estimates listed in Table 27 suggest there is little difference in the results produced by the two different approaches used to investigate the CO-mortality relationship in this study. The size of the pollutant effects differ only slightly, with the parameter estimates from the GAM analysis in most cases only slightly less than those produced by the trigonometric models. There is also little difference in the significance status of the parameter estimates. A significant relationship was gained using the GAM approach 5-day average 8-hour CO. The results shown in table 27 illustrate the robustness of the observed relationships across different statistical approaches based on the same base model to control for confounding temporal and meteorological effects.

Table 27 - Comparison of results generated using trigonometric filtering with results generated using Generalised Additive Models, using the same base model: All Cause Mortality*

Pollutant	Trigonometric filtering			Generalised Additive Models		
	Parameter estimate	Standard error	p	Parameter estimate	Standard error	p
CO 8-hour maximum	0.0045	0.0046	0.3325	0.0035	0.0041	0.86
CO 8-hour maximum (lag 1)	0.0062	0.0046	0.1809	0.0053	0.0042	1.27
CO 8-hour maximum (lag 2)	0.0040	0.0046	0.3884	0.0041	0.0041	0.98
CO 3-day average 8-hour maximum	0.0091	0.0063	0.1484	0.0084	0.0052	1.60
CO 5-day average 8-hour maximum	0.0112	0.0076	0.1413	**0.0116**	**0.0059**	**1.96**
CO 1-hour maximum	-0.0009	0.0028	0.7572	-0.0010	0.0025	-0.40
CO 1-hour maximum (lag 1)	**0.0069**	**0.0028**	**0.0158**	**0.0059**	**0.0056**	**2.30**
CO 1-hour maximum (lag 2)	0.0010	0.0030	0.7453	0.0009	0.0027	0.33
CO 3-day average 1-hour maximum	0.0048	0.0041	0.2375	0.0041	0.0033	1.23
CO 5-day average 1-hour maximum	0.0066	0.0050	0.1898	0.0067	0.0038	1.78

* marginally significant (p<0.1); **not significant

Table 28 - Relative risk of death per unit (1ppm) increase in CO, with 95% confidence intervals, generated using GAM

Outcome	Pollutant concentration	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	CO 5-day average 8-hour maximum	1.0103*	0.9980-1.0227
Cardiovascular Mortality (all ages)	CO 5-day average 8-hour maximum	1.0193	1.0009-1.0380

*marginally significant

Table 29 - Relative risk of death per unit (1ppm) increase in CO, with 95% confidence intervals, generated using GAM: Seasonal Analysis

Outcome	Pollutant concentration	Cool Season		Warm Season	
		Relative Risk	95% Confidence Limits	Relative Risk	95% Confidence Limits
All Cause Mortality (all ages)	CO 5-day average 8-hour maximum CO 3-day average1-hour maximum	1.0083** 0.9971**	0.9943-1.0226 0.9890-1.0053	1.0427 1.0379	1.0014-1.0857 1.0157-1.0606
All Cause Mortality (65+ years)	CO 3-day average1-hour maximum	0.9968**	0.9885-1.0052	1.0470	1.0221-1.0724
All Cause mortality (<65 years)	CO 1-hour maximum (lag 1)	1.0058**	0.9922-1.0196	1.0289*	0.9945-1.0645
Respiratory Mortality (all ages)	CO 5-day average1-hour maximum	1.0009**	0.9700-1.0328	1.0981	1.0008-1.2049
Respiratory Mortality (65+ years)	CO 3-day average1-hour maximum	0.9893**	0.9623-1.0169	1.0986	1.0090-1.1960
Cardiovascular Mortality (all ages)	CO 5-day average 8-hour maximum	1.0163**	0.9984-1.0028	1.0261**	0.9646-1.0916
Cardiovascular Mortality (65+ years)	CO 3-day average1-hour maximum	0.9990**	0.9871-1.0111	1.0261**	0.9908-1.0627

* Marginally significant ($p < 0.10$); ** Not significant

GAM Analysis – Optimal Model

The results obtained using the optimal GAM model, as described in Section 5.1.1, are presented in Tables 28 and 29. As for the other pollutants examined in this study, the alternative approach to controlling for weather in the GAM analysis had a significant impact on both the size and significance of the parameter estimates obtained from the trigonometric analysis. The relationships observed between CO and the outcome variables considered in the whole-year models were mostly positive but not significant. A significant positive association was found between the 5-day average concentration for 8-hour CO and cardiovascular deaths (all ages), with a 1ppm increase in CO concentration associated with a 1.93% increase in the risk of death. A marginally significant association was also observed between all cause mortality in the all ages group and 5-day average 8-hour CO. A significant negative association was found between CO 1-hour maximum lagged by 2 days and deaths from digestive disorders. The results of the GAM analysis are shown in Table 28 and Appendix C, Table C1.

As has been the case with the other pollutants considered in this study, seasonal results from the GAM model for CO indicated effects for this pollutant were strongest in the warm season. These results are consistent with those observed in the trigonometric analysis. Table 29 shows the most significant of the associations observed in the warm season, along with the corresponding cool season effects. Significant warm season associations were found between maximum 1-hour CO and all cause and respiratory mortality in both the all ages and 65+ age groups. A marginally significant positive association was found for all cause mortality in the <65 age group. While no significant associations were found for cardiovascular mortality, the observed effects were greater in the warm season. No significant positive associations were found in the cool season for any outcome.

In multi-pollutant models, the significance of the relationship observed between CO and cardiovascular deaths shown in Table 28 was not retained after controlling for other pollutants (Appendix C, Table C3).

Summary of the GAM results

The results obtained for CO in this study show only a few significant associations observed in the whole year models. A significant positive association was found between 5-day average 8-hour concentration cardiovascular deaths (all ages). The effects observed for CO were stronger in the warm season compared with the cool season, with significant associations found in the warm season for respiratory and all cause mortality.

4.4.2 DISCUSSION

The results obtained for CO in this study show only one significant association in the whole year models. A significant positive association was found between the maximum 1-hour concentration (lagged 1 day) using the trigonometric approach, while the 5-day average 8-hour concentration was significantly associated with total cardiovascular deaths using the GAM approach. Results from both approaches suggested that effects for CO were stronger in the warm season compared with the cool season, with significant associations found in the warm season for respiratory and total deaths. The relationship

with cardiovascular deaths did not exhibit the same seasonal variations observed for total and respiratory deaths, although effects were slightly (but not significantly) stronger in the warm season. In multi-pollutant models the effect for CO was generally not retained after controlling for other pollutants.

Comparison with other Studies

There have been several studies that have shown associations between increases in daily mortality and ambient CO levels. Early studies showed associations between daily mortality and ambient CO levels but at levels much higher that those currently observed in urban areas (UK Department of Health 1998; Bascom et al., 1996). More recent studies have also shown such an association even at the lower levels currently experienced.

A recent study conducted in Santa Clara County, California, has shown an association between CO levels and daily mortality (Fairley, 1999). This study, which used a GAM analysis, showed highly significant associations between 24-hour average CO levels and mortality. The most significant effect was observed for a 1-day lag. The observed effects were stronger for respiratory and cardiovascular mortality than for all cause mortality. The observed associations lost significance in multi-pollutant models.

In a study by Burnett et al (1998a) an association was found between daily mortality and ambient CO levels in eleven Canadian cities with a 2.5% increase in daily mortality attributable to CO. In multi pollutant models this effect was reduced to 0.9%. The strongest association found in this study was for NO_2 with a 4.1% increase in daily mortality attributable to NO_2. Associations were also found for SO_2 and O_3. Much of the effect attributable to CO could be explained by SO_2 and NO_2.

In contrast a study conducted in Toronto, Canada (Burnett et al., 1998b) showed that CO was significantly associated with increases in daily mortality. These associations were observed between CO and mortality in all seasons, age and disease groupings analysed. TSP was also associated with increases in daily mortality. In this study it was estimated that ambient CO levels could account for 4.7% of the daily mortality in Toronto while TSP accounted for an additional 1%.

Ambient CO levels have also been associated with increases in daily mortality in Athens (Touloumi et al., 1996). The results of this study, conducted as part of the APHEA project, found a 10% increase in daily mortality for a 10mg/m^3 increase in 8-hour average CO. The strongest effects were observed for same day CO concentrations.

KEY FINDINGS

1. Ambient carbon monoxide levels in Melbourne are associated with daily mortality.

2. The observed effects are strongest in the warm season.

3. The observed associations are not sensitive to the statistical methods used for the analysis.

4. The results of the Melbourne study are consistent with recent studies from overseas.

4.5 SUMMARY OF OVERALL FINDINGS

The results of this study have shown that air pollution in Melbourne is associated with increases in daily mortality. These observations are consistent with many studies conducted overseas and elsewhere in Australia. Associations were found for all pollutants considered with the strongest effects observed for O_3 and NO_2.

DISCUSSION

5

The findings of this study suggest a strong association between air pollution and daily mortality (particularly respiratory mortality) in Melbourne. Seasonal analysis, conducted using either of the statistical approaches adopted in this study, indicate significant warm season relationships for each of the pollutants, with few associations observed in the cool season where levels of fine particles, NO_2 and CO are at their highest. This may be due in part to the fact that people spend more time outdoors during the summer and therefore have a greater exposure to air pollutants.

The regional analysis lends further support to the photochemical effect. The region to the west of Melbourne experiences high O_3 as a result of high levels of NO_2 and other precursors produced in the east being transported westward by meteorological conditions that prevail in Melbourne during the warmer months. Stronger effects for O_3 were found in the west compared with the east. In contrast, NO_2 was significant in the east, where levels are highest, with no significant associations observed in the west. While only marginally significant, effect sizes for fine particles were also larger in the west compared with the east. This may suggest that secondary particles formed by photochemical processes may be important in the observed effects. Tight control for meteorological conditions in this analysis, particularly for extremes in temperature, means that the observed warm season associations are not likely to be attributable to inadequate control for weather.

METHODOLOGICAL CONSIDERATIONS

Multi-pollutant Analysis

Moolgavkar et al (1995a and b) argue that effects of individual pollutants cannot be separated because of the high correlations between pollutants and the complexity of the mixtures involved. This is has been argued strongly in the case of SO_2 and particles. They argue that many of the studies that identify specific pollutants, such as particles, do not consider other pollutants simultaneously in the model. Of the studies that do control for other pollutants many include the other pollutants simultaneously in the model. Where pollutants are highly correlated such a practice can lead to unstable results. In this analysis control for other pollutants involved fitting the potential confounding pollutant to the model then fitting the pollutant of interest to the residuals of that model. This rigorous approach eliminated problems associated with high colinearity between pollutants, but in many cases resulted in a loss of significance of the relationship or a reduction in the size of the effect estimate. Consequently it is difficult to identify the relative contributions each of the pollutants considered are making to variations in daily mortality in Melbourne. Confounding by SO_2 is not important in this study due to the low ambient levels of SO_2 in Melbourne.

Control for weather

Tables 8, 14, 22 and 27 indicate the robustness of the pollutant-mortality relationships using different statistical techniques, providing the method of controlling for meteorological confounders are identical. A comparison of the GAM results for O_3 in Table 8 and those in Table 9 clearly demonstrates the

sensitivity of the pollutant-mortality associations to the method used to control for meteorological conditions, particularly the choice of lags. The approach used to control for weather in the trigonometric models and to generate the GAM results presented in Table 8 was based on the APHEA protocol, with the most significant 'set' of meteorological variables at the same lag used in the model. In this analysis, the set of meteorological variables contained maximum dew point temperature, rainfall and two variables representing extremes in maximum and minimum temperature. Average temperature was not used because of its high correlation with dew point temperature, the fact that it generally does not have a linear relationship with mortality, and its inability to represent the extreme minimum and maximum temperatures (which are more likely to be associated with excess daily mortality).

In the GAM approach, meteorological variables were selected on the basis of improvement in the AIC, regardless of lag. Samet et al. (1997) have shown that the effects of hot and cold temperatures on mortality take different time courses. Choosing different sets of meteorological variables for the seasonal models in the trigonometric approach confirmed these different courses. Same day or cumulative average weather terms accounted for the most variation in the warm season, while lagged weather terms (by 1 or 2 days) accounted for the most variation in the cool season. The best possible control for temperature should therefore allow for these variations in effect lag times. However, the APHEA I protocol called for the use of the 'set' of variables accounting for the most variation in the model. The use of varying lags in future work will eliminate any problems associated with varying effect times for meteorological variables. The flexibility of the GAM approach also allowed the use of average temperature as a non-linear variable in the models, with extreme variables used only where their addition resulted in a reduction in the AIC, and therefore, an improvement in model fit. This may have also contributed to the variations in results seen in Tables 8 and 9.

It could be argued that there is a degree of 'over-control' of meteorological conditions in this approach, and that some pollutant effects have been lost or reduced as a result. However, inadequate control of weather is a common criticism in this type of research, with suggestions that observed associations may be a result of incomplete statistical adjustment for the effects of weather (Samet et al., 1997). Other methods of controlling for weather have been tested, including synoptic categorisations of weather patterns that combine meteorological elements to create typical, frequently occurring "air masses" (Pope and Kalkstein, 1996). The combinations used in these studies were selected on the basis of factors in common, rather than on their ability to predict mortality, and their use did not "meaningfully change" the pollution-mortality relationship found (Samet et al, 1998). Separating the effects of pollutants from the effects of weather (particularly temperature) is a difficult task, as in many cases they are highly correlated. For example, being a photochemical pollutant, O_3 is highly correlated with maximum temperature. Thus controlling for high temperatures may also control for some of the variation in O_3 concentrations, which will impact upon (ie. reduce) the size and significance of associations between O_3 and mortality. If high temperatures are not controlled for properly, observed pollutant effects may well be a product of inadequate modelling. In this study however, statistically significant associations were found for O_3 despite the rigorous approach to controlling for meteorological conditions. The observed pollutant effects should therefore be considered conservative estimates of the impact of air pollution on daily mortality in Melbourne.

Other methodology issues

The strong and consistent relationships initially observed between total deaths and O_3 using the trigonometric approach were of interest, as cardiovascular deaths (which make up a significant proportion of total deaths) did not show the same strength and consistency in results, and respiratory deaths were too few in number to drive the strong association (Table 3). Further investigations were subsequently made looking into the effects of the pollutants on the 'other' mortality category, which also accounts for a significant proportion of total deaths. The strong associations seen for total deaths were also seen for the 'other' category (Appendix B, Table B1). A closer inspection of this category revealed the majority of deaths were due to cancer, which, when analysed separately also showed the strong relationships seen for the other and total categories.

One reason for this finding may be that the Registry of Births, Deaths and Marriages codes deaths of persons suffering cancer to the ICD-9 cancer categories even where the death is a result of cardio-respiratory failure (which has occurred as a result of the cancer but may have been exacerbated by ambient air pollution levels). Changes to the registration systems allows inclusion of a secondary cause of death in the records. This will allow further exploration of impact of secondary causes, such as heart failure, in people who are already suffering from terminal diseases. Thurston and Kinney (1995) note that generalised environmental stresses such as air pollution and severe temperatures may adversely affect any severely compromised person, regardless of the person's particular illness. Thus, even in those categories frequently used as control variables for which no biologically plausible association between air pollution

and the actual condition may exist (such as deaths due to digestive diseases), where mortality is concerned, any associations found can not necessarily be considered spurious as the death may have been the result of cardio-respiratory causes even though it wasn't coded on the death certificate in this manner.

In this study only a small number of significant relationships were found between the control cause of death category and the pollutants considered. These relationships were in most cases negative, which may well reflect the difficulties in modelling outcome variables that show very little seasonal or cyclic variations. In the trigonometric analysis cycles are forced into this data even though it may not naturally exist. This may lead to spurious associations between outcomes that would not be expected to be associated with changes in air pollution levels.

In the GAM analysis the selection of terms in the model, including the optimal degrees of freedom for the time-trend variable, was based on the minimisation of the AIC. Recent work suggests that minimising the AIC may not be the best method of selecting the optimal trend for time as it may lead to overspecification of the model, (J. Schwartz -personal communication, 1999). Specifically, using the AIC to select the number of degrees of freedom for the time-trend variable may result in a model that could remove some of the short-term relationships that may exist between pollution and mortality. To be sure this did not occur in the analyses for the results reported, some additional models were run which contained trend for time with smoothing parameter selection based on partial autocorrelation plots. In the outcomes examined, the number of degrees of freedom for the smoothing parameter selected using this approach was in each case less than that used in the approach using the AIC. While partial autocorrelation plots indicated slight overspecification in the original model, the changes in the smoothing parameters for the time trend variables had very little impact on the size and significance of pollutant effects and have not altered the conclusions of the study.

The dummy variable representing the 90th percentile and above of a 7-day moving average for respiratory mortality (all ages) was created after consultation with researchers in Europe. The purpose of this variable was to control for influenza and other respiratory epidemics that were not accounted for in the original analysis due to the inadequacy of the available influenza data. The dummy variable was trialed (after the major analysis was completed) on the all ages groups for all cause and cardiovascular mortality. The addition of the dummy variable to models for these outcomes, while highly significant, did not alter the size or significance of the pollutant-mortality relationships reported in this study.

6. CONCLUSIONS

The results of this study have shown that ambient air pollution in Melbourne is associated with increases in daily mortality. Although all the air pollutants under consideration, ozone, nitrogen dioxide, fine particles and carbon monoxide, were found to be associated with daily mortality, the strongest associations were observed for ozone and nitrogen dioxide. The main sources of these pollutants in Melbourne are motor vehicles and industry, and the results suggest that strategies to reduce these pollutants are important to reduce the risk of adverse health effects arising from exposure. The results of this study are consistent with other studies conducted within Australia and overseas.

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