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Assessment of exposure approaches in air pollution and health research in Australia and New Zealand

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ABSTRACT

It is increasingly acknowledged that the quality of, and/or lack of, exposure data are often a weakness in studies examining links between air quality and health. In this paper we review studies of air pollution and health in Australia and New Zealand and assess the quality of exposure data used. There have been over eighty peer reviewed published studies looking at air quality in Australia and New Zealand. Of these, over thirty have looked overtly at health endpoints, and more than twenty more have referred to health and/or exposure in some way. We conclude that the measures of exposure used in most of these studies are not great indicators of exposure. However, studies in this part of the world are no different to studies around the world where exposure estimates are also often weak. We suggest that as scientists we must acknowledge and accept this weakness while also agreeing that we can and must strive to develop better exposure estimates that account for intra-urban variability in pollution levels, personal mobility, and the importance of micro-environments in personal pollution exposure.

INTRODUCTION

Internationally there have been a number of epidemiological studies that have shown associations between ambient air pollution levels and a range of adverse health effects, including mortality, hospital admissions, GP visits and restricted activity days. A criticism often levelled at these relates to the quality of the air pollution exposure data (Nuckols et al. 2010). The argument is that the measures for air quality used in these studies are rarely good indicators of the quality of the air people are actually exposed to, and that this limitation weakens the research, to the extent that "*the quality of the study is never better than the quality of the exposure data*" and "*exposure is the Achilles heel of most studies*" (quotes from Nuckols et al. 2010). This paper will assess the quality of exposure data used in studies of air pollution and health in Australia and New Zealand. It will start by examining the role of air quality standards in air quality management, and suggest how they might unwittingly be affecting the nature of exposure assessment carried out. It will then briefly describe some of the main methods used to assess air pollution exposure, before reviewing published air pollution and health studies in Australia and New Zealand and assess the quality of air pollution exposure estimates used in them.

Air quality standards, regulations and guidelines

A key approach to improving air quality has been the adoption of air quality guidelines and, more recently, standards. These are meant to represent air pollution levels below which there is believed to be no or little impact on human health and are widely accepted by national and international practitioners based on recent assessments of air pollution and health effects (Ministry for the Environment 2005; WHO, 2006). A guideline is usually a suggested value that is not enforceable while a standard is enforceable. In many instances a government will set a guideline and then develop it later into a standard. The World Health Organisation (WHO) has set air quality guidelines[1] for key pollutants (Table 1) that aim to provide a uniform scientific basis for understanding the effects of air pollution on human health and provide a guideline for local and national air quality standards and management

1 The WHO do not have the powers to set and enforce standards.

(WHO, 2006). Australian and New Zealand governmental authorities use these figures (and others) as a guideline to set national ambient air quality standards (Table 1) which are monitored by fixed site monitoring stations. Australia and New Zealand have similar air quality monitoring protocols, whereby the governing authorities stipulate which monitoring methods are appropriate for the different pollutants (Ministry for the Environment 2005). There are also regulations governing where monitoring must take place, with sites needing to be representative of the environment under investigation and take into account the temporal variations in pollutant concentrations. Monitoring sites should ideally be able to measure peak concentrations, which are likely to be near emission sources such as traffic, as well as peak background concentrations, which will be away from obvious sources, in order to gain a "fair" representation of air pollution exposure. It should also be noted that levels of some pollutants can vary significantly over very short distance for example across busy road intersections. While the standards refer to exposure, the monitoring undertaken to meet them is still required to be carried out at fixed ambient sites, thus ignoring many of the components of an individual's personal exposure such as work, home and in-vehicle exposures. In terms of the research carried out examining health and pollution, this results in a wealth of data that has been collected for the purpose of monitoring compliance with standards. Consequently much of the research carried out uses this available monitoring data. This ultimately has implications for the quality of the exposure assessment used in the research, which will be discussed later.

<Table 1>

HOW DO WE ASSESS EXPOSURE?

When conducting monitoring programmes or research on air quality and its effects, it is important to distinguish between concentration and exposure. Concentration is generally referred to as the quantitative expression of the amount of pollutant within a given environment at a particular time and place (Janssen and Metha, 2006), whereas exposure is determined by the amount of time people spend in that environments and is a more accurate indication of what individuals actually breath in. Concentrations tell us about the quality of air at a particular point at a particular time, whereas exposure is an indication of what individuals might actually breathe in. It is this latter information that is really needed if we wish to accurately relate air quality to health endpoints, but it is the former that is the basis for Australian and New Zealand air quality standards. The following sections will briefly explain some of the main approaches to air quality measurement and pollution exposure assessment.

Surrogates

One relatively simple approach for estimating exposure is to use spatial surrogates. Spatial surrogates are used to allocate geographically distributed data to higher resolution geographic areas based on some form of activity or socio-economic/demographic data (Boulton et al. 2002). Surrogates often relate to the nature of the source. For instance in studies looking at the health effects of exposure to traffic pollution, proximity to road or some additional indicator of traffic such as composition or volume of traffic, can be used. The advantage of surrogate data are that they require no actual data about pollution, emissions or meteorology and can therefore be very cheap to collect. The disadvantage is that they often contain no information about the levels of pollution or the emissions or meteorology that result in pollution and, unless well validated, can be inaccurate. In addition, the data generally applies for a place, not a person, and is usually for a long term average.

Modelling

Models utilise a series of variables to estimate air pollution exposure at a local or national spatial scale. There are a number of types of models; dispersion models, receptor models, stochastic models, compartment or box models (Colls 2002) along with regression based models, most commonly land use regression models. Many of the models need some understanding of meteorology coupled with some measure of emissions. Modelled data are usually then compared to monitoring data to validate the model. Many studies looking at air pollution and health have employed atmospheric dispersion models, rather than a statistical model, to establish a relationship. Dispersion models mathematically simulate how air pollution disperses in the ambient environment by taking into account local wind patterns and air pollutants emitted from sources. The quality of the output of such models often rests on the quality and availability of the input data, which can often be lacking or of poor quality. In addition, mathematical dispersion models are also severely limited by our understanding of wind flows in complex environments, even with very sophisticated maths. As a result even if the data were extremely good, the models still might not work very well. A more recent tool in exposure assessment has been Land Use Regression (LUR) modelling. First used in the late 1990s (Briggs et al. 1997), LUR models use monitored levels of pollutants of interest as the dependent variable and variables, such as traffic, topography and other geographic variables as the independent variables in a multivariate regression model (Hoek et al. 2008; Ryan and LeMasters 2007). The advantage of LUR models is that they use data that can be more readily collected or collated, often using GIS. They are now widely used and have been to shown in urban area to perform "*typically better or equivalent to geo-statistical methods such as kriging*[2] *and conventional dispersion models*" (Hoek et al. 2008). The advantage of modelling is that models require no actual data about pollution and can potentially be cheap to run. They can also provide data at a very fine spatial resolution. The disadvantage is that they are not information about actual levels of pollution and, unless well validated, can be inaccurate. They rely on the quality of the input data, for example emissions and meteorology, and the ability of the model. If any of these is of poor quality, then the adage '*garbage in, garbage out*' applies. In addition, to improve accuracy, models are becoming more sophisticated. This can result in them becoming more expensive and more reliant on high quality data inputs. Finally, the data generally applies for a place, not a person, and the emissions data are often long term averages.

Fixed site monitoring

Monitoring ambient air quality is essential to understanding how the quality of air is changing over time and, in some cases over space and is an essential tool in managing

2 Kriging is a geostatistical technique that estimates values between sampling sites by means of spatial interpolation

the environmental risk from air pollution to health and ecosystems. Local and regional authorities follow monitoring regulations set by the governing authority. These methods usually use single or multiple fixed site monitoring stations to monitor ambient (outdoor) air quality. The data from monitoring stations can also be applied to various models to estimate air quality in areas with no monitoring stations, as well as providing an understanding of how air pollutant concentrations are influenced or behave under temporal, geographic and meteorological variations. The main problem with using monitoring data for a single or few points is that they cannot account for the fact that intra-urban variations in air quality are often greater than inter-urban variations (Wilson et al. 2005), and it has been argued that "a*s a result, measurements from central monitoring sites are not sufficient for use in exposure assessment or for epidemiologic studies*" (Health Effects Institute 2010, 3-27). The advantage of monitoring is that it provides actual pollution values for the time and place where the sampling took place. The disadvantage is that it can only provide data for the time and place of sampling, and thus the temporal and spatial resolution of the data is generally poor. In addition, the data applies for a place, not a person. Finally, monitoring can be very expensive.

Personal sampling

Personal sampling is a more reliable and accurate way of estimating the air an individual is actually exposed to. Personal sampling studies involve attaching small portable samplers to individuals which accompany these people as they go about their normal daily activities. Personal sampling has the benefit of sampling personal exposure to air pollution while the person is mobile. This can include measuring exposure in potentially highly polluted microenvironments. However, there are many disadvantages that have limited their use in air quality and health studies. Carrying out personal sampling is expensive and logistically complex and consequently most personal sampling studies are small. Applying the results to large populations is rarely possible in any meaningful way. The advantage of personal sampling is that it provides an actual pollution exposure value for the time the sampling took place. The disadvantage is that it can only provide data for the individual at the time of sampling, and thus the temporal resolution of the data is limited. The challenge is applying this data to other individuals. In addition, personal sampling can be very expensive, especially if carried out simultaneously on a large group of individuals.

Summary

It is evident from the variety of air pollution and health assessment methods used, that some understanding of the quality of exposure estimates is needed. Many methods tacitly assume that people are fixed and immobile throughout their day, which is rarely the case. In addition it is known that during the average day, people spend 90 per cent of their time indoors (either at home or at work), around 4 per cent in transit or vehicles, and only 6 per cent outdoors, where most exposure estimates are based (Colls 2002). Based on this it might make sense to sample indoors but it has been demonstrated that personal exposure does not correlate well with indoor measurements (Monn, 2001). Part of the reason for this is that high exposures that can be experienced in highly polluted microenvironments. For example, it has been estimated that up to 60% of our daily particulate exposure can occur while in transit (Fruin et al. 2004). Therefore, studies examining links between air pollution and health should ideally take these variables into account when estimating exposure levels.

AIR QUALITY AND HEALTH STUDIES IN AUSTRALIA AND NEW ZEALAND

Google Scholar and Scopus were used to search the literature for all peer reviewed studies looking at air pollution in Australia and New Zealand since 1997. In addition, key researchers were contacted and asked about additional studies that might not be readily identified through a traditional literature search. From this over 80 studies conducted in Australia and New Zealand that related to a range of aspects of air pollution were identified. Of these, 32 related directly to health (Tables 2 and 3) and a further 22 referred to, or were indirectly related to, health and/or exposure (Table 4). The remainder were specifically focused on air pollution characteristics with no overt links to health (not presented in table form). This paper will focus on those studies that have directly linked air quality and health or have specifically referred to exposure, although brief mention will be made to the other papers where applicable. It should be noted that while we went to great efforts to identify all relevant studies, we will undoubtedly have missed some. However, we feel that a few missing studies should not detract from the primary aim of this review which is to assess the quality of the exposure estimates.

<Table 2>

<Table 3>

<Table 4>

Surrogate Studies

We found only one study that used surrogates to directly relate air pollution to health in some way. Franklin et al. (1999) used questionnaires to find out about smoking in the home to assess children's exposure to cigarette smoke. The nature of smoking in the home will give some indication of exposure to tobacco smoke, but arguably not a very accurate one, something the authors themselves acknowledge when they say that "*reported parental smoking is a poor indicator of environmental tobacco smoke exposure in the age group we studied*" (p73).

Modelling

While models are used widely often for regulatory reasons, we identified only a handful of studies where modelling methods were used to estimate air pollution concentrations related directly to health effects, all of which were undertaken in New Zealand.

A dispersion model, The Air Pollution Model (TAPM), was used by Sabel et al. (2007) where the original method was that of Zawar-Reza et al (2005)[3] . As in any dispersion model, TAPM relies on good quality emissions data. In Zawar-Reza's model the emissions for Christchurch were from an emissions inventory based on dividing the city into three emission bands: Inner, Suburban and Outer Christchurch, and validated against data measured at a fixed central site. While the model performs well the authors acknowledge its weaknesses including a lack of data for "natural emissions" (p257) and "the relatively complex topography of the area" (p255). In addition the resolution of the emissions data prevents identification of the spatial variation in emissions within the three bands. Scoggins et al. (2004) employed the CALGRID/CALMET urban airshed models developed by Gimson (2000) in their study. This model is a dispersion model where the emissions data come from the from the Auckland Regional Council emissions inventory (ARC 1998). A key limitation of this model lies in the quality of the emissions data as the "*accuracy of emission estimates depends on the uncertainties in activity data and emission factors*" which are potentially great (Joynt et al. 2002).

A land use regression based approach has been used in a number of studies (Fisher et al. 2007; Kingham et al. 2008a; Richardson et al. 2010; Kingham et al. 2010; Hales et al. 2010) using the method of Kingham et al. (2008b)[4]. Data sources used in the final model included census data on domestic heating, industrial emissions estimates, vehicle kilometres travelled and meteorological measurements. Results showed a good association between the model estimates and monitored data at locations where it had taken place. Regression based approaches often perform well compared to other modelling approaches by having input data available at a very fine spatial scale, and not having to rely on direct emissions data, which is often the Achilles heel of dispersion models.

Overall models are limited by the accuracy of the model and the quality of the input data namely emissions and meterology. This can limit the quality of the exposure

3 This was also the basis for two studies related to environmental justice; Pearce et al. (2006) and Kingham et al (2007)

4 This method has also been used in some work on environmental justice (Pearce and Kingham, 2008)

estimates. For example emissions data for domestic home heating is usually seasonal averages collated at a coarse spatial resolution and thus the model output is generaly better for long term averages at coarser spatial scales. In addition they nearly always estimate the air in outdoor environments, where we know people spend relatively little time.

Fixed site monitoring

Arguably the best measure of pollution is gained by monitoring. However, monitoring stations are expensive to maintain which is the principal reason why researchers in Australia and New Zealand often rely on only single site monitoring methods to explore associations between air pollution and health.

Five studies have been identified as using single site monitoring as their measure of exposure (Baldi et al. 2009; Hales et al. 1999; Hales et al. 2000; Harre et al. 1997; and McGowan et al. 2002). As a result of single site monitoring, these studies were unable to account for any spatial variability in air quality and so adopted a temporal approach comparing health and air quality over time.

Additional studies have utilised data from additional monitoring sites but have still predominantly used a temporal approach. In some cases this has involved averaging the air quality data to provide a single exposure figure (Simpson et al. 1997; Denison et al. 2001: Morgan et al. 1998; Morgan et al. 2010; Jalaludin et al. 2006; Duc et al. 2009: Hansen et al. 2007).

A further set of studies analysed distinct sub-areas within a single urban area with monitors in those areas providing improved spatial indicators of exposure (Chen et al. 2007; Wilson et al. 2010) while other studies adopted a related approach instead allocating individuals' pollution exposure values based on the nearest monitoring station (Jalaludin et al. 2004; Hansen et al. 2009). A variant of this has involved studies that have looked at larger study areas and compared health effects in a range of cities with differing pollution exposures based on local monitoring (Simpson et al. 2005; Barnett et al. 2005; Barnett et al. 2006). The nature of these approaches added a spatial component to temporal analysis.

Other studies have also used monitoring but in differing ways. Two related studies monitored both indoor and outdoor air quality (Cavanagh et al. 2007; Epton et al. 2008) and then used short term temporal approaches to compare exposure with health. A final study (Fisher et al. 2002) used a combination of single site monitoring and multiple site monitoring, coupled with a form of modelling in cities where no monitoring took place, to estimate pollution exposure.

The problem with any studies that base their exposure assessment on fixed points is that it is now widely acknowledged that air pollution can vary hugely within urban areas, with the intra-urban variation often greater than that the inter-urban variation (Jerrett et al. 2005; Wilson et al. 2005, 2006). Unless the sampling is widespread, this variability is unlikely to be identified. While monitoring provides real values of actual pollution, it is site and time specific. Any spatial and temporal variability can only be provided for by the temporal and spatial range of the monitoring.

Personal sampling

A small number of studies have been conducted using mobile personal samplers. We identified two studies that included overt health endpoints (Dirks et al. 2009; Morawska et al. 2005).

Dirks et al. (2009) recorded personal exposure to carbon monoxide and also measured levels of carboxyhæmoglobin in blood, while Morawska et al. (2005) exposed individuals to controlled levels of known air pollutants in a chamber environment and measured the total deposition of environmental tobacco smoke (ETS), diesel and petrol smoke in the respiratory tract. In both cases, the number of subjects was small compared to epidemiological studies (8 and 14 respectively) thus making it difficult to draw broad population based conclusions. This is not a criticism of these particular studies but an inherent limitation of this type of study.

One additional study is worthy of note. While not strictly personal sampling, monitoring was carried out in the homes of individuals for which personal health data was also collected (Franklin et al. 2000). The researchers measured formaldehyde in the homes of children and compared this to levels of exhaled NO and lung function (this was part of the same study as Franklin et al. 1999).

There have been other studies involving personal sampling that have not explicitly included health outcomes (Table 4). These include studies looking at pollution exposure and travel modal choice (Chertok et al. 2004; Kingham et al. 2010); population based exposures (Horton et al. 2006; Hinwood et al. 2007; Cowie et al. 2008) and office exposures (Lee et al. 2000). There have also been a series of studies that have looked at pollution levels indoors in homes, usually compared to outdoor levels (for example Morawska et al. 2003; Kingham and Petrovic 2005; Galbally et al. 2009; Kingham et al. 2002; Jamriska et al. 1999), and in vehicles (Knibbs et al).

The strength of personal sampling is that provides real exposure values for the individuals tracked. However, the expense involved has meant few studies have been carried that have any significant health endpoint.

Other exposure related work

There have been a number of other published studies that have acknowledged, both implicitly and explicitly, the importance and value of exposure assessment (Table 4).

These include a number of studies of outdoor air quality that specifically refer to exposure including Lyne et al. (2008), Wilson and Zawar-Reza (2006), Morawska et al. (2002) and Wilson et al. (2006). Also worthy of mention is the work of Cowie et al. (2008) who have carried out a useful comparison of exposure methods. Finally, Rose et al. (2009), Scoggins and Fisher (2002) and Scoggins et al. (2001) have all in different ways developed or considered different approaches to assessing exposure, while not actually using examining links between air quality and health. Rose et al (2009) examined the value of using weighted road density as a predictor of air quality, Scoggins and Fisher (2002) proposed the idea of a regional pollution exposure index and Scoggins et al (2001) suggested a way of mapping airshed modelled data to census areas.

CONCLUSION

There have been over eighty peer reviewed published studies looking at air quality in Australia and New Zealand but there will no doubt be a large number of studies that have not made their way into the public forum. Of the ones reviewed, over thirty have looked overtly at health endpoints and more than twenty more have referred to health and/or exposure in some way.

The majority of papers have used monitored pollution data as their indicator of pollution exposure. Most have compared pollution and health outcomes over time. This is a well documented approach. However, increasingly we are becoming aware of the magnitude of variation that can be experienced within urban areas, and that often pollution levels can vary within cities as much as between them. A few studies have used more than one fixed site and have thus added a spatial approach to the analysis.

The second most widely used approach has been some form of modelling. This allows a spatial component to be incorporated. However, models are only as good as their input data, which can be poor, especially the emissions data. As most models use emissions generated over, and estimated for, long periods of time, so they are are best used to estimate longer term average levels of pollution. This is especially true for a land use regression models, which have been only occasionally used here, but are more widespread overseas.

Monitoring and modelling studies nearly always allocate pollution exposure to individuals based on home residence and outdoors. Yet, we know that most people spend the majority of their time indoors and a significant proportion of their daily exposure is likely to be in highly polluted micro-environments, such as while travelling. Personal pollution measurements are the most obvious way to take this into account. These have been used on only a handful of occasions in studies directly related to health, and in studies of a small number of people. This is unsurprising as these studies are costly and logistically complicated. A larger group of studies has measured pollution levels in micro-environments such as travel, in homes, and in workplaces. The results of these types of studies could potentially be incorporated into better exposure estimates in future research.

In conclusion, the measures of exposure used in most studies of air quality and health in Australia and New Zealand are probably not accurate indicators of actual exposure. However, studies in this part of the world are no different to studies around the world where, as recently acknowledged (Nuckols et al. 2010), exposure estimates are often weak. So what is the way forward? Firstly we must acknowledge and accept this weakness while also agreeing that we can and must strive to develop better exposure estimates that account for intra-urban variability in pollution levels, personal mobility, and the importance of micro-environments in personal pollution exposure.

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Tables and Figures

Table 1: Key pollutant standards and guidelines

	WHO guidelines	**New Zealand standards**	**Australian standards**
$PM_{2.5}$	10μg/m^3 annual mean 25μg/m^3 24-hour mean		25μg/m^3 24-hour mean 8μg/m^3 annual mean
PM_{10}	20μg/m^3 annual mean 50μg/m^3 24-hour mean	50μg/m^3 24-hour mean	50μg/m^3 24-hour mean
Ozone	100μg/m^3 8-hour mean	150μg/m^3 1-hour mean	0.10ppm 1-hour mean 0.08ppm 4-hour mean
Nitrogen Dioxide	40μg/m^3 annual mean 200μg/m^3 1-hour mean	200μg/m^3 1-hour mean	0.12ppm 1-hour mean 0.03ppm annual mean
Sulphur dioxide	20μg/m^3 24-hour mean 500μg/m^3 10-minute mean	570μg/m^3 1-hour mean	0.20ppm 1-hour mean 0.08ppm 24-hour mean 0.02ppm annual mean
Carbon monoxide		10mg/m^3 8-hour mean	9.0ppm 8-hour mean

Source: WHO, 2010; MfE, 2005; Department of Environment, Water, Heritage, and the Arts (Australian Government), 2010.

Table 2: Australasian air pollution and health studies that used 'models' to assess exposure

Reference	Type	Aim/Purpose	Location	Health Measure	Air Pollution Measure
Franklin et al. 1999	Surrogate	To establish reference exhaled nitric oxide values and to investigate variables that might affect concentrations in population studies.	Perth, Aus	Respiratory health questionnaire, skin prick test, lung function	Exposure to cigarette smoke through questionnaires
Fisher et al. 2007	Modelling	Identify and quantify health risks due to people's exposure to air pollution.	All NZ	Mortality (1990-1998), and respiratory hospital admissions (1994-1998).	Regression based modelling approach validated against monitoring (Kingham et al. , 2008a)
Hales et al. 2010	Modelling	Analyse the spatial association between average PM10 exposure & mortality	All NZ	Mortality 1996-99	Regression based modelling approach validated against monitoring (Kingham et al. , 2008a)
Richardson et al. 2010a	Modelling	Investigated whether exposure to particulate pollution (PM10) varied by socioeconomic status, was associated with mortality, and was associated with greater health inequalities.	All NZ	Respiratory and breast cancer mortality (2001-2005)	Regression based modelling approach validated against monitoring (Kingham et al. , 2008a)
Kingham et al. 2010	Modelling	Investigated the contribution of domestic and traffic pollution to mortality.	All NZ	Respiratory, cardiovascular and oesophageal cancer mortality (2001-2005)	Regression based modelling approach validated against monitoring (Kingham et al. , 2008a)
Scoggins et al. 2004	Modelling	Explore and quantify the relationship between mortality and ambient NO_2 levels.	Auckland, NZ	Mortality (1996-1999) non-external, circulatory and respiratory	Modelled 1-hr average NO_2 concentrations using CALGRID/CALMET (Gimson, 2000)
Sabel et al. 2007	Modelling	Examines the spatial patterns of relative risk and clusters hospitalisations based on a small area example of Christchurch.	Christchurch, NZ	Respiratory hospital admissions (1999-2004)	TAPM dispersion model (Zawar-Reza et al. 2005)
Fisher et al. 2002	Monitoring & Modelling	Assess the health effects due to air pollution emissions from vehicles on the population of New Zealand.	All NZ	Mortality	Monitoring and derived pollution estimates using available data for all urban areas

Table 3: Australasian air pollution and health studies using fixed site or personal 'monitoring' to assess exposure

Reference	Type	Aim/Purpose	Location	Health Measure	Air Pollution Measure
Baldi et al. 2009	Fixed site	Investigate the relationship between weather, air pollution and hospital admissions in wintertime over time.	Auckland, NZ	Hospital admissions (1994-04)	Single monitoring site for NOx
Barnett et al. 2005	Fixed site	To estimate the impact of outdoor air pollution on respiratory morbidity in children.	Brisbane, Canberra, Melbourne, Perth & Sydney (Aus); Auckland & Christchurch (NZ)	Child respiratory hospital admissions (1998-2001).	Fixed site monitoring data for PM2.5, PM10, NO2, CO, O3 averaged across cities.
Barnett et al. 2006	Fixed site	To estimate the association between outdoor air pollution and cardiovascular disease.	As Barnett (2005)	Cardiovascular hospital admissions (1998-2001).	Fixed site monitoring data for PM2.5, PM10, NO2, CO, O3 averaged across cities.
Cavanagh et al. 2007	Fixed site	Explores the application of urinary 1-OHP as a biomarker of exposure to ambient air pollution in Christchurch after high and low pollution events.	Christchurch, NZ	Urinary 1-OHP in 93 male non-smoking schoolchildren after 2 high and 2 low pollution events	School indoor and outdoor monitoring for particles (Kingham et al. 2008b)
Chen et al. 2007	Fixed site	Investigate the spatial variability of particle matter air pollution and its association with respiratory emergency hospital admissions across six geographic areas in Brisbane.	Brisbane, Aus	Respiratory hospital admissions (1998-2001)	Fixed site monitoring at four sites for particles, NO2 and O3.
Denison et al. 2001.	Fixed site	To explore the relationship between air pollution and daily emergency hospital admissions	Melbourne, Aus	Respiratory and cardiovascular hospital admissions (1994-97)	Fixed site monitoring for particles, NO2, CO and O3 for 4-6 sites.
Duc et al. 2009	Fixed site	to determine associations between ambient air pollutants and ED attendances for cardiovascular disease in the elderly (>65+) using Bayesian methods	Sydney, Aus	Cardiovascular hospital admissions (1997-2001).	Data from 14 monitoring stations averaged for particles, NO_2, O3, CO & SO2 (Jalaludin et al. 2006)
Epton et al. 2008	Fixed site	Examine the health effects of ambient particulate air pollution from wood burning on school-aged students in Christchurch, New Zealand, over time.	Christchurch, NZ	Longitudinal assessment of 93 secondary school students of lung function, exhaled breath condensate (EBC) collection, urinary 1-hydroxypyrene levels and symptom diary data	School indoor and outdoor monitoring for particles (Kingham et al. 2008b)
Franklin et al. 2000	Fixed site	to investigate the possible effects of formaldehyde concentrations on exhaled Nitric oxide (as a marker of airway inflammation).	Perth, Aus	Respiratory health questionnaire, skin prick test, lung function	Formaldehyde measured with passive monitors.
Hales et al. 1999	Fixed site	To investigate the relationship between daily numbers of deaths, weather and air pollution over time.	Christchurch, NZ	Respiratory and cardiovascular mortality (1988-1993).	Monitored data for PM10, CO, SO_2 and NOx collected from CSM.
Hales et al. 2000	Fixed site	Tests a hypothesis that mortality increases with high polluted days in Christchurch over time.	Christchurch, NZ	Mortality (1988-97)	Daily particle values from central monitoring site
Hansen et al. 2007	Fixed site	Investigate the relationship between ambient air pollution during pregnancy and various proxy measures of fetal growth among full-term neonates.	Brisbane, Aus	Birth data (2000-03)	Monitored pollution (03, NO2, SO2, CO) at 18 different fixed sites for the period 1997-2004.
Hansen et al. 2009	Fixed site	To examine the associations between ambient air pollution in Brisbane and congenital anomalies (heart defects, cleft lip or palate) for comparison with previous research.	Brisbane, Aus	Birth data (1998-2004)	Monitored pollution (03, NO2, SO2, CO) at 18 different fixed sites for the period 1997-2004 (Hansen et al. 2007)

Harre et al. 1997	Fixed site	To examine statistical associations between winter air pollution levels and pulmonary function, symptoms, and medication use in subjects with COPD over time.	Christchurch, NZ	Peak flow and respiratory symptom diary data for 40 people (3 months in 1994)	Central site Monitoring for PM10, CO, SO_2 and NO_2.
Jalaludin B et al. 2006	Fixed site	To determine the acute effects of pollution on the daily number of ED visits for cardiovascular disease in the elderly (>65yrs) using GLM	Sydney, Aus	Cardiovascular hospital admissions (1997-2001).	Data from 14 monitoring stations averaged for particles, NO_2, O3, CO & SO2.
Jalaludin et al. 2004	Fixed site	Examine the relationship between air pollution and lung function, respiratory systems and asthma medication use in three groups of children in western Sydney and South west Sydney.	Sydney, Aus	Child asthma diaries, airway responsiveness, skin prick tests for allergens, and symptom data	Data from 6 monitoring stations for particles, NO_2, and Nox used and exposure based on nearest site
McGowan et al. 2002	Fixed site	Explore the relationship between particulate air pollution and admissions to hospital with cardio-respiratory illness over time.	Christchurch, NZ	Respiratory and cardiovascular hospital admission (1988-98)	Monitoring at central fixed site for CO, SO_2, PM_{10}, NOx
Morgan et al. 1998	Fixed site	Examine the effects of outdoor air pollution on daily hospital admissions	Sydney, Aus	Respiratory and cardiovascular hospital admission (1990-94)	Calculated exposure from 3-14 fixed site monitors for particles, O_3 and NO_2.
Morgan et al. 2010	Fixed site	To assess the health effects of bushfire particulates compared with urban particulates in Sydney, Australia, 1994-2002.	Sydney Aus	Mortality data and influenza hospital admissions	PM10 (8 monitoring sites), ozone (10 monitoring sites), PM2.5 (3 monitoring sites)
Simpson et al. 1997	Fixed site	Examine the associations between daily mortality and air pollution, 1987-1993.	Brisbane, Aus	Respiratory mortality	Three monitoring sites: NO_2, SO_2, O_3
Simpson et al. 2005	Fixed site	To examine the short-term effects of air pollution on daily respiratory and cardiovascular mortality.	Brisbane, Melbourne, Perth and Sydney, Aus.	Respiratory and cardiovascular mortality data	Fixed monitoring sites for NO2, CO, O3, PM10, PM2.5, particles (Simpson et al. 1997)
Wilson et al. 2010	Fixed site	Present results from a study in Christchurch, New Zealand of the relationship between restricted activity days and daily concentrations of PM based on intraurban monitoring data.	Christchurch, NZ	Staff and students school absence	Central site and 8 school monitoring sites (July 2003, June 2004),
Dirks et al. 2009	Personal sampling	To examine links between CO measurements and carboxyhæmoglobin levels in blood	NZ	Carboxyhæmoglobin levels in blood in 8 subjects per week for 2 weeks (2008)	Personal sampling of CO for 8 people
Morawska et al. 2005	Personal sampling	To investigate the deposition in the human respiratory system of three common types of combustion aerosols.	Brisbane, Aus	Lung function	Personal sampling for fine particles for 14 people

Table 4: Other Australasian air pollution studies that refer specifically to health and/or exposure.

Citation	Aim/Purpose	Location	Air Pollution Measure
Chertok et al. 2004	To compare exposure to benzene, toluene, ethylbenzene, xylene (BTEX) and nitrogen dioxide for commuters in central Sydney	Sydney, Aus	Personal BTEX and NO_2 passive samplers
Cowie et al. 2008	Explore the use of a variety of methods for assigning exposure to traffic related air pollution	Sydney, Aus	Compared various modelling methods - LUR, modelling; proximity measures (e.g. distance to main road); fixed site monitor data; and, personal monitoring
Galbaly et al. 2009	Determine the contribution of wood heater emissions to indoor domestic air pollution of VOCs benzene, toluene, ethylbenzene and xylene: BTEX compounds.	Launceston, Aus	Indoor sampling using BTEX passive samplers
Hinwood et al. 2007	Establish how behaviour and lifestyle activities influence personal exposure to air toxics and BTEX.	Adelaide, Melbourne, Perth & Sydney, Aus	Personal sampling using diffusion tubes
Horton et al. 2006	To determine the concentrations of benzene to which residents are exposed during their daily activities.	Perth, Aus	Personal sampling using diffusion tubes
Jamriska et al. 1999	To investigate relationship indoor and outdoor exposure to sub-micrometer particles in the vicinity of a busy arterial road.	Brisbane, Aus	Indoor and outdoor sampling of particles.
Kingham and Petrovic, 2005	To investigate levels of indoor NO2 air pollution in Nelson.	Nelson, NZ	Monitoring indoor and outdoor using diffusion tubes
Kingham et al. 2008a	To develop a method for estimating annual average particulate pollution concentrations for small areal spatial units in New Zealand	All NZ	Regression based modelling approach validated against monitoring
Kingham et al. 2002	Examining the relationship between indoor and outdoor pollution levels in relation to home heating and nature of building.	Christchurch, NZ.	Monitoring 24hrs indoor and outdoor averages for $PM_{2.5}$ inside and outside of 3 homes over a 4 week period winter 2001.
Kingham et al. 2010	To compare exposure to PM_{10}, $PM_{2.5}$, PM_1, ultrafines and CO for commuters in Christchurch and Auckland, NZ	Christchurch and Auckland, NZ	Personal PM, CO and ultrafine measurements
Knibbs et al. 2009	To quantify on-road particle concentration in a tunnel, relate these measurements to traffic volume and fleet composition, to better understand potential exposures.	Sydney, Aus	Particles measured inside and outside vehicles
Lee et al. 2000	Measure indoor, outdoor, and personal NO2 concentrations & estimate personal exposure when commuting in the working population	Brisbane, Aus	Indoor/outdoor samplers, personal exposure model
Lyne et al. 2008	To measure levels of PM10 traffic-related pollution and assess the exposure of children in outdoor play areas to this pollution.	Auckland, NZ	PM10 measurements outdoors at 8 childhood centres for 4 weeks each.
Morawska et al. 2002	To study the city wide variability of pollutants & interpret the results in relation to population exposure assessment	Brisbane, Aus	Comparison of NOx, ozone and PM_{10} for 3 monitoring sites
Morawska et al. 2003	Monitor indoor air quality and investigate indoor/outdoor air quality relationship	Brisbane, Aus	Indoor sampling in 15 homes for particles compared to central fixed site
Morawska et al. 2008	To review and synthesize the existing knowledge on ultrafine particles in the air with a specific focus on those originating due to vehicle emissions.		Review
Rose et al. 2009	To develop and validate a new predictor, weighted road density, for NO2	Sydney, Aus	Road based surrogate index based on 38 passive diffusion samplers for NO_2 3x2-week periods
Scoggins and Fisher. 2002	Proposes a regional air pollution exposure index (RAPEI) for Auckland, Wellington, Canterbury and Otago regions.	NZ	Annual NOx emissions for census areas used to develop a surrogate based index
Scoggins et al. 2001	Explores the development of new techniques able to be applied to assessments of exposure and public health effects of ambient air pollution	Auckland, NZ	Modelling of CO and SO2 using CALMET & CALGRID
Wilson and Zawar-Reza, 2006	To evaluate the effectiveness of using TAPM to estimate small-area particulate air pollution exposures within an urban area using winter monitored data from 11 sites across Christchurch.	Christchurch, NZ	TAPM dispersion model based on 11 fixed sites sampling for PM_{10}

Wilson et al. 2006	Examine daily concentration variations in PM_{10} at a neighbourhood scale in two winter months in Christchurch	Christchurch, NZ	One central site & ten school based monitoring sites PM_{10}