DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

Air Quality Study for the NSW Greater Metropolitan Region

A Sydney Air Quality Study Program Report

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Environment, Energy and Science
Department of Planning, Industry and Environment
4 Parramatta Square, 12 Darcy Street, Parramatta NSW 2150
PO Box A290, Sydney South NSW 1232
Phone: +61 2 9995 5000 (switchboard)
Phone: 1300 361 967 (Environment, Energy and Science enquiries)
TTY users: phone 133 677, then ask for 1300 361 967
Speak and listen users: phone 1300 555 727, then ask for 1300 361 967
Email: info@environment.nsw.gov.au
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Executive summary

The Sydney Air Quality Study is a multi-year research program led by the NSW Department of Planning, Industry and Environment (DPIE), in collaboration with the NSW Environment Protection Authority (EPA), and the NSW Ministry of Health. The study is designed to provide robust information to government, business and the community on the state of air quality in the NSW Greater Metropolitan Region (GMR) and to support the development of actions to improve current and future air quality. The study investigates:

- how air pollution varies in time and space across the NSW GMR
- the major sources of emissions contributing to air pollution
- how air pollution affects human health and the environment.

The study integrates data and information from the NSW DPIE Air Quality Monitoring Network, the NSW EPA's Air Emissions Inventory for the NSW GMR, and research outcomes from particle characterisation studies to elaborate on the current state of air quality in the NSW GMR. The capabilities of regional airshed modelling and air pollution exposure modelling are also developed to support the emissions scenario modelling and the health impact assessment of air pollution.

Results from the first phase of the study (2017–2019) are presented in this report. Major outcomes, including an evaluation of the performance of the regional airshed modelling system – the coupled Conformal Cubic Atmospheric Model (CCAM) and Chemical Transport Model (CTM) for the NSW GMR – and new insights into major sources of particulate matter less than 2.5 microns in diameter ($PM_{2.5}$; fine particles) and ozone have been published in peered-reviewed papers in a special issue, Air Quality in New South Wales, Australia, of the journal *Atmosphere* .

Major findings from these studies are:

- Air quality in Sydney is comparable with other cities in Australia and good by world standards. However, particle pollution and ozone concentrations occasionally exceed national air quality standards.
- Air quality has been good in the NSW GMR between 2012 and 2018, except for south-west and north-west Sydney. Air quality was classified as very good or good for 69–88% of days in the Sydney and Hunter regions, 83–91% of days in the Illawarra, and 88-97% of days on the Central Coast. South-west and north-west Sydney experienced more days with poor or worse air quality due to ozone and particle pollution.
- The performance of the regional airshed modelling system (the CCAM–CTM) established for the NSW GMR is comparable to similar models documented in the literature.
- New insights into major source contributions to fine particles and ozone are,

  for fine particles:
  - Human activities account for 40% of population-weighted annual average $PM_{2.5}$ concentrations across the NSW GMR.
  - Major sources of human source contribution are from wood heaters (31%), industry (26%), on-road motor vehicles (19%), power stations (17%) and non-road diesel and marine emissions (6%).

  and for ozone:
  - Motor vehicles and commercial-domestic sources are the most significant contributors to maximum ozone levels in south-west Sydney, followed by vegetation and power stations.

- Emissions from vegetation, commercial-domestic sources and power generation play an important role in ozone formation in north-west Sydney.

This study contributes to the evidence base the NSW Government relies on to support the development of actions and policies to improve air quality across the NSW GMR. Further analysis of the health impact assessment of air pollution based on the airshed modelling results is underway and will be included in the next phase of the study. Future air quality projections and potential impacts on human health and the economy will also be addressed in the next phase of the study.

1. Introduction

Clean air is essential for health, wellbeing and the environment. Although air quality in New South Wales (NSW) is good by international standards, air pollution continues to have a significant impact on human health and the economy. It is an environmental issue of interest for NSW residents (NSW OEH 2017a) and the NSW Government (NSW Government 2016).

Previous studies have estimated the health cost of particle air pollution in the Greater Sydney Metropolitan Region to be around $6.4 billion (AUD 2016) each year or over $1000 per person (NSW DEC 2005; Jalaludin et al. 2011). A significant portion of health effects are due to premature deaths resulting from long-term exposure to fine particles. In Sydney, about 430 premature deaths (about 2% of total deaths) and 630 hospital admissions for respiratory and cardiovascular conditions were attributable to airborne particles less than 2.5 micrometres in diameter ($PM_{2.5}$) concentrations in 2007 (Broome et al. 2015).

Air pollution also affects natural ecosystems, urban environments, agricultural crops and climate. In future, population growth and ageing, urbanisation and densification of urban areas, increased transport and energy demands, and climate change could lead to poorer air quality and associated health and environmental outcomes.

1.1 Study objective

This study was designed to provide robust information to government, business and the community on the state of air quality in NSW and support the development of actions to improve current and future quality of the air across the State.

The study will:

1. Improve our understanding of the past, current and future air quality and the impacts of air pollution on human health in the NSW Greater Metropolitan Region (GMR).
2. Quantify the contribution of major emissions sources to air pollution and its consequent impact on human health and the economy.
3. Support the development of evidence-based air policies and programs by identifying persistent and emerging issues
4. Highlight opportunities to improve air quality and realise public health and economic benefits.

1.2 Study overview

This study integrates and expands the evidence base to address gaps in our understanding of air quality and its impacts in the NSW Greater Metropolitan Region (NSW GMR), which includes the Sydney, Illawarra, Central Coast, Newcastle and Hunter Valley regions (Figure 1).

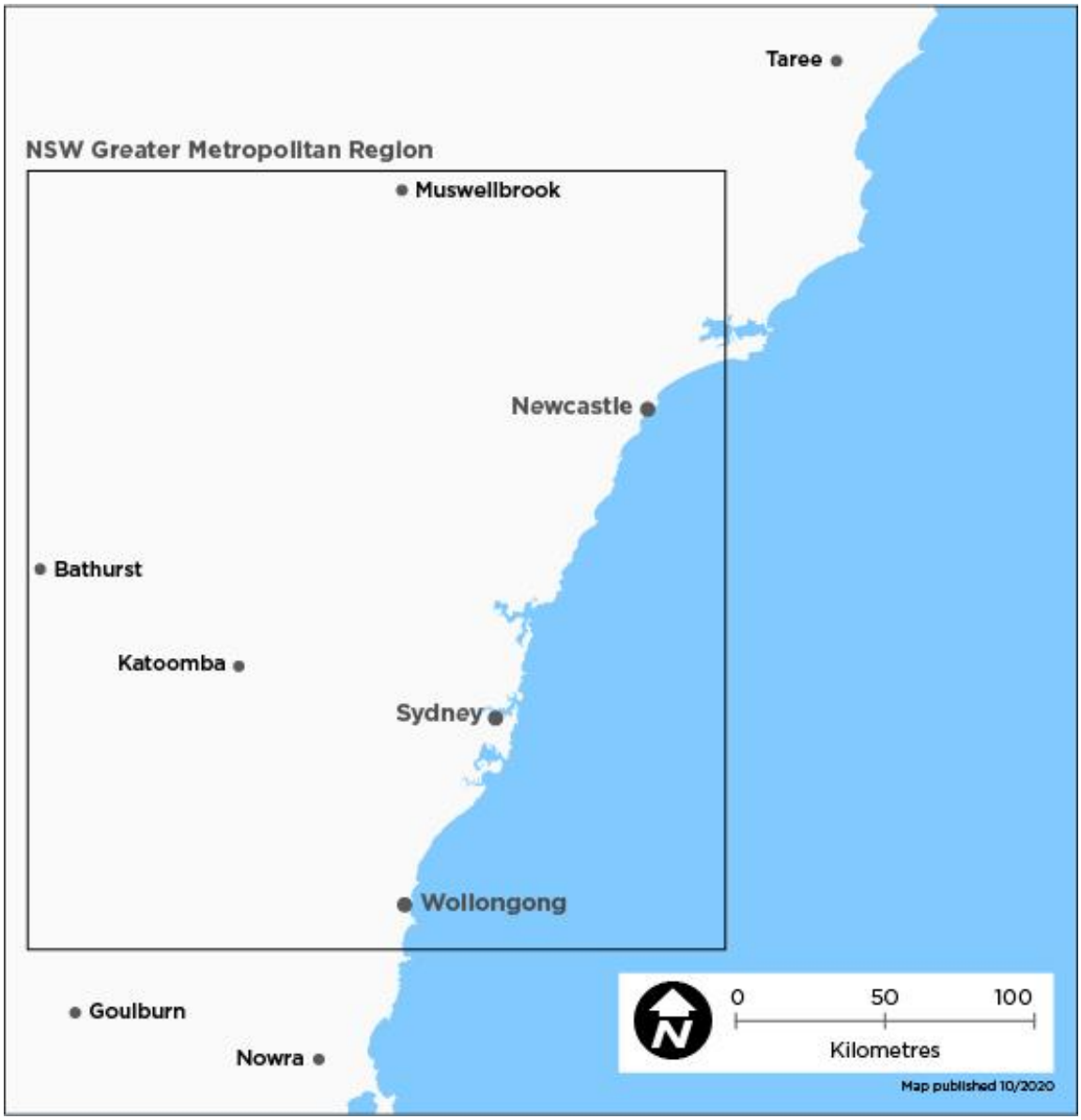


Figure 1 The NSW Greater Metropolitan Region, defined by the NSW Environment Protection Authority

The study draws on data and information from:

- community research undertaken as part of the NSW Government's Who Cares about the Environment program
- stakeholder submissions made in response to the NSW Clean Air Consultation Paper released in October 2016 and the NSW Clean Air Summit held in June 2017
- the NSW Air Quality Monitoring Network and the NSW Environment Protection Authority Air Emissions Inventory for the GMR in NSW
- research studies such as the Sydney Particle Study (NSW OEH 2014c) and the Sydney Particle Characterisation Study (Cohen et al. 2016).

Regional air quality modelling, pollution exposure modelling, and health-impact assessments were undertaken to develop and extract the required knowledge to carry out this study.

2. Sources of information

We use a range of data and methods (Figure 2) to:

- determine how air pollution varies in time and space across regions
- identify the main sources of air pollution
- assess how air pollution affects human health and the environment.

Community research, ambient air-quality monitoring, air emission inventories, particle characterisation studies, air quality modelling, exposure analysis, and health and economic analysis are used to help characterise air pollution and its impacts in the region.

Related research also supports our understanding of how pollutants are emitted and transported in the air, how they react with other pollutants and form new (secondary) air pollutants, and how air pollution affects health, the environment and the economy.

2.1 Communities and air quality

Every three years since 1994, the Department of Planning, Industry and Environment (DPIE; previously the Office of Environment and Heritage (OEH)) has conducted a survey of the New South Wales (NSW) community to track trends in the public's environmental views, priorities, knowledge and actions. Findings from the most recent Who Cares about the Environment? survey (OEH 2017), conducted in 2015, showed that:

- Most respondents (81%) were satisfied with their local air quality – people living in the South East, Southern Highlands and Central West regions were more likely to be satisfied whereas those living in the Hunter and Sydney regions were less likely to be satisfied.
- Thirteen per cent of respondents raised air pollution as environmental issue (down from 17% in the 2012 survey). Sydney residents were significantly more likely to mention air pollution/quality compared to residents living in the rest of NSW (17% vs 8%), and air pollution/quality were more likely to be cited as issues in Southern Sydney (21%), South West Sydney (19%) and Western Sydney (18%).
- Most survey respondents were concerned to some degree about the effects of extreme weather and air pollution, with some significant differences associated with the age, location and household income of respondents. Sydney residents were more likely to be concerned 'a great deal' about the effects of air pollution (31% vs 22%).

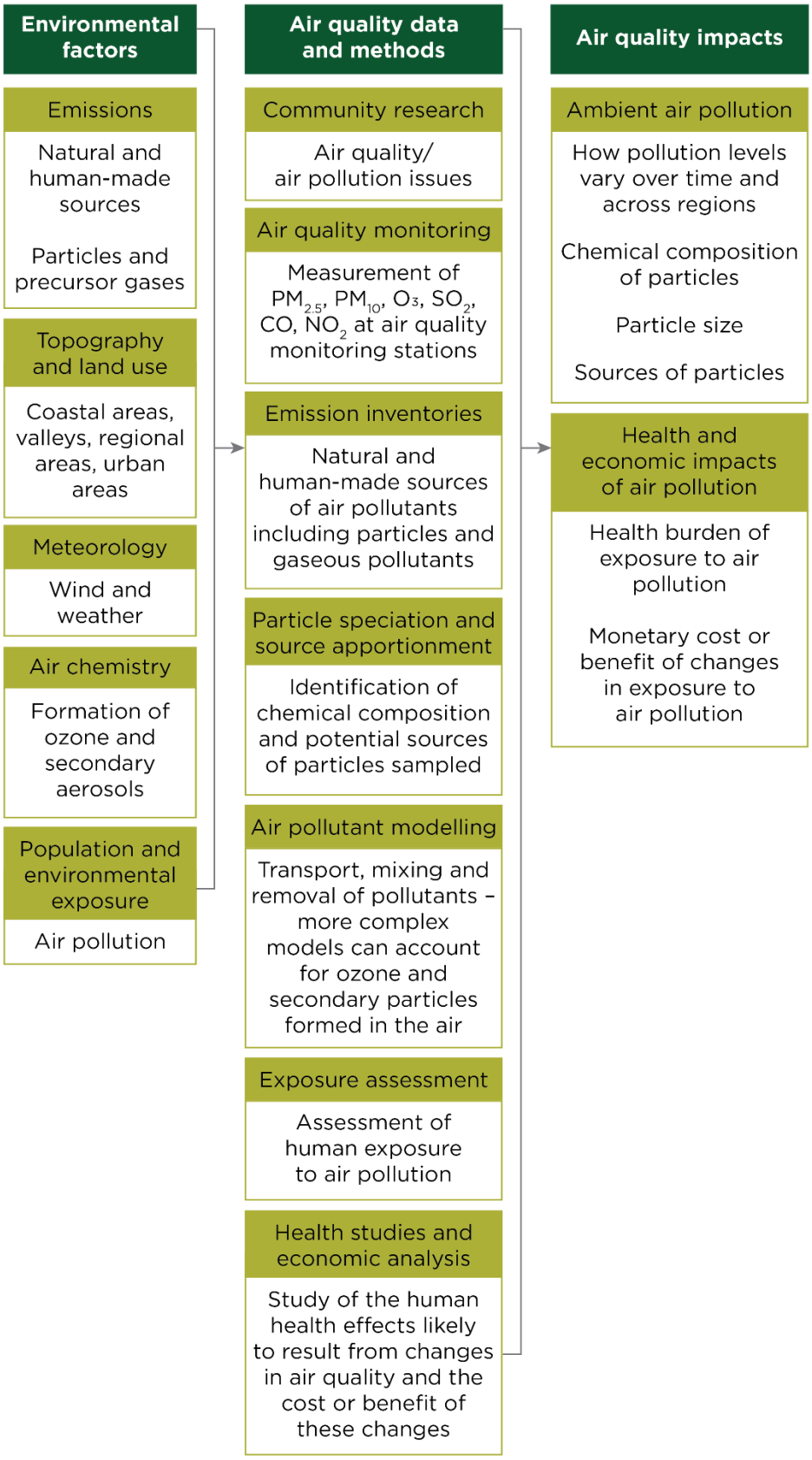


Figure 2 Data and methods used in this study to understand air pollution and its impacts. CO = carbon monoxide; NO_2 = nitrogen dioxide; O_3 = ozone; $PM_{2.5}$ = particulate matter 2.5 micrometres or less in diameter; PM_{10}, = particulate matter 10 micrometres or less in diameter; SO_2 = sulfur dioxide.

2.2 Air quality monitoring in the NSW Greater Metropolitan Region

The NSW air quality monitoring network has been designed to cover the complex topography and variable meteorological conditions across New South Wales, as well as diverse emission sources. This extensive monitoring network produces data needed to determine the spatial and temporal variation in air pollutants, population exposure to air pollutants, and to evaluate the performance of air quality models. Observational data can also be used to assess the efficiency of the implemented strategies, programs and regulations.

The NSW Air Quality Monitoring Network provides continuous, high-quality measurements of air pollutant concentrations and this information is publicly available in near real-time (i.e. within an hour of the measurement being made). This network monitors regional air quality for assessing general population exposures and compliance with national air quality standards.

DPIE currently operates air quality monitoring stations in the Sydney, Central Coast, Illawarra, Lower Hunter and Upper Hunter regions (Figure 3). The stations continuously monitor ozone (O_3), nitrogen oxides (NO_x, NO, NO_2), particulate matter (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_2), carbon monoxide (CO), visibility and meteorology (wind speed, wind direction, air temperature and relative humidity) as shown in Table 1. Each air quality monitoring station conforms to the National Environment Protection (Ambient Air Quality) Measure AAQ and provides a measure of regional air quality across the NSW Greater Metropolitan Region (GMR). The monitoring sites are also designed to conform, as far as practical, to the Australian Standard AS/NZS 3580.1.1:2007 Methods for sampling and analysis of ambient air – Part 1.1: Guide to siting air monitoring equipment.

The former NSW Community DustWatch Network, which became part of the Rural NSW Air Quality Monitoring Network in January 2018, includes over 30 stations run by DPIE monitor to monitor particulate concentrations (Figure 4). It gathers data about particulate concentrations and dust storms, and provides valuable information on wind erosion that helps care for land and soils.

Table 1 Air quality monitoring stations in the NSW Greater Metropolitan Region operated by DPIE in 2019

Region		Station	Year established	Ozone (O_3)	Nitrogen oxides (NO_x)	Particles (PM_{10})	Particles ($PM_{2.5}$)	Sulfur dioxide (SO_2)	Carbon monoxide (CO)	Visibility (nephelometry)	Meteorology
Sydney	East	Chullora	2002	✓	✓	✓	✓	✓	✓	✓	✓
		Sydney CBD	2019	✓	✓	✓	✓	✓	✓	✓	✓
		Earlwood	1978	✓	✓	✓		✓		✓	✓
		Linfield	1994	✓	✓	✓	✓			✓	✓
		Macquarie Park	2017	✓	✓	✓	✓	✓	✓	✓	✓
		Randwick	1995	✓	✓	✓	✓			✓	✓
		Rozelle	1970	✓	✓	✓	✓	✓	✓	✓	✓
	North-west	Parramatta North	2017	✓	✓	✓	✓		✓	✓	
		Prospect	2007	✓	✓	✓	✓	✓	✓	✓	✓
		Richmond	1992	✓	✓	✓	✓	✓		✓	✓
		Rouse Hill	2019	✓	✓	✓	✓	✓	✓	✓	✓
		St Marys	1992	✓	✓	✓		✓		✓	✓
	South -west	Bargo	1996	✓	✓	✓	✓	✓		✓	✓
		Bringelly	1992	✓	✓	✓	✓	✓		✓	✓
		Campbell-town West	2012	✓	✓	✓	✓	✓	✓	✓	✓
		Camden	2012	✓	✓	✓		✓	✓	✓	✓
		Liverpool	1988	✓	✓	✓		✓	✓	✓	✓
		Oakdale	1996	✓	✓	✓		✓		✓	✓
Roadside		Bradfield Highway	2019	✓	✓	✓	✓	✓	✓	✓	✓
Central Coast		Wyong	2012	✓	✓	✓	✓	✓	✓	✓	✓
Illawarra		Wollongong	1992	✓	✓	✓	✓	✓	✓	✓	✓
		Albion Park South	2005	✓	✓	✓	✓	✓		✓	✓
		Kembla Grange	1994	✓	✓	✓	✓			✓	✓
Lower Hunter		Beresfield	1993	✓	✓	✓	✓	✓		✓	✓
		Newcastle	1992	✓	✓	✓	✓	✓	✓	✓	✓
		Wallsend	1992	✓	✓	✓	✓	✓		✓	✓
Upper Hunter		Bulga	2011			✓					✓

Region	Station	Year established	Ozone (O_3)	Nitrogen oxides (NO_x)	Particles (PM_{10})	Particles ($PM_{2.5}$)	Sulfur dioxide (SO_2)	Carbon monoxide (CO)	Visibility (nephelometry)	Meteorology
	Camberwell	2011			✓	✓				✓
	Maison Dieu	2011			✓					✓
	Mt Thorley	2011			✓					✓
	Aberdeen	2011			✓					✓
	Jerrys Plains	2011			✓					✓
	Merriwa	2012			✓					✓
	Muswell-brook	2010		✓	✓	✓	✓			✓
	Muswell-brook North-west	2011			✓					✓
	Singleton	2010		✓	✓	✓	✓			✓

Note: CBD = Central business district; DPIE = Department of Industry, Planning and Environment

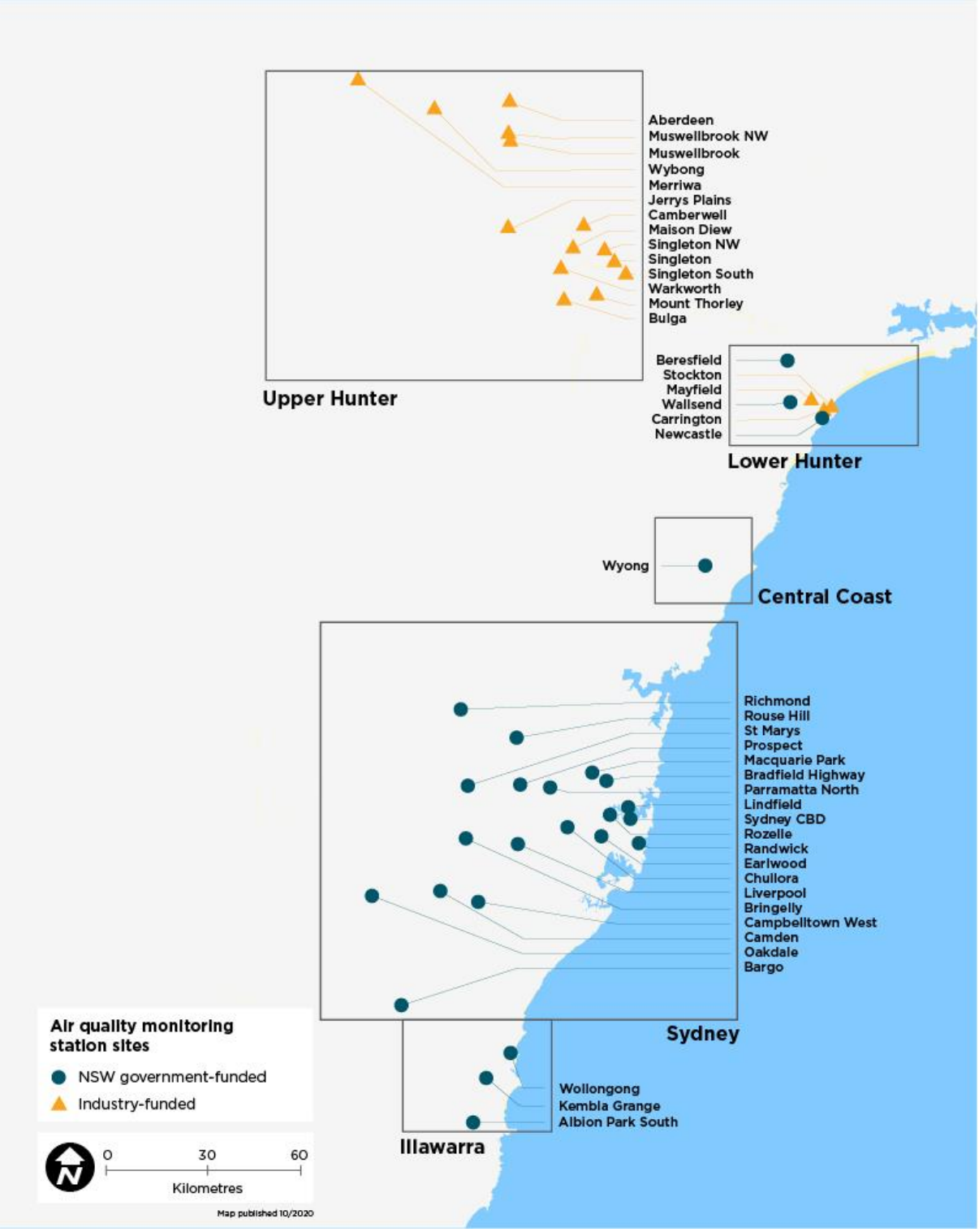


Figure 3 NSW government-funded and industry-funded air quality monitoring stations in the NSW Greater Metropolitan Region in 2019.

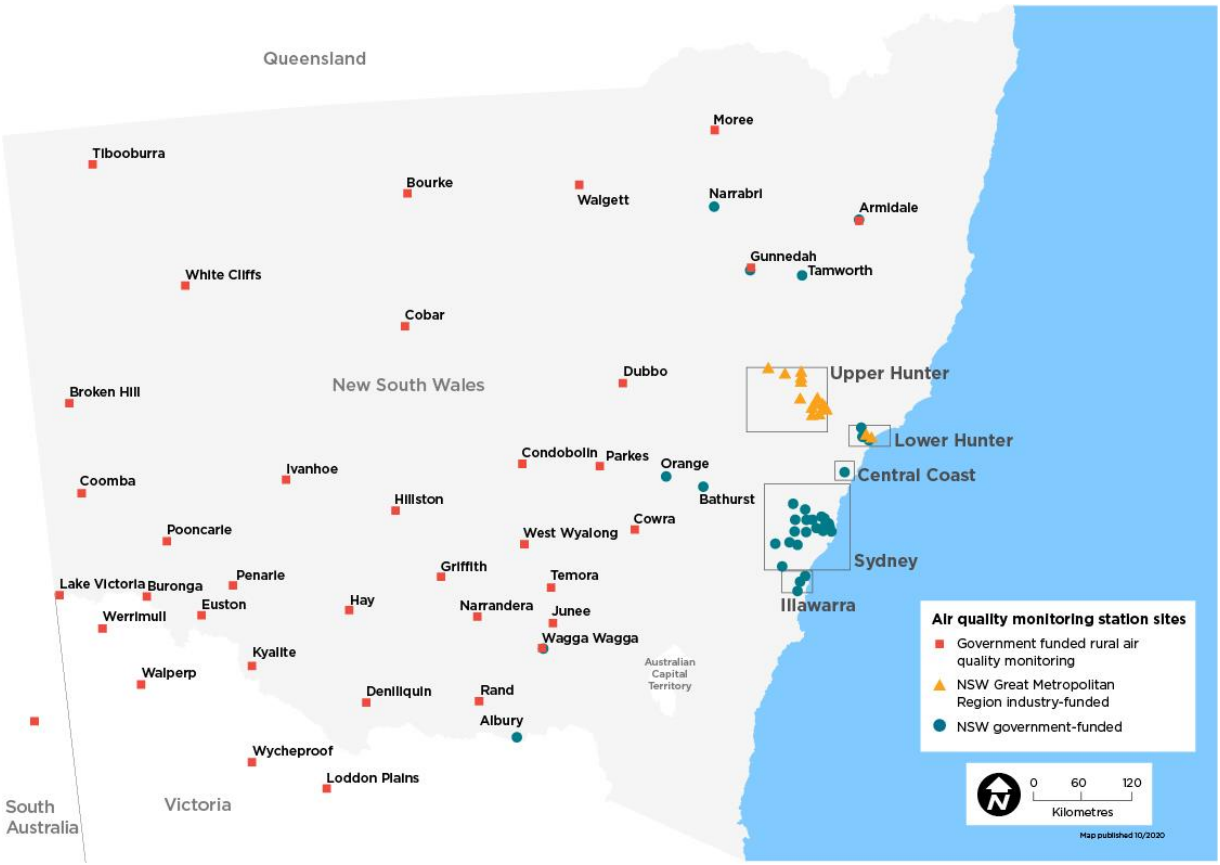


Figure 4 Government funded rural air quality monitoring sites in NSW in 2019. NSW government-funded sites and industry-funded sites in the NSW Great Metropolitan Region have also been included.

2.3 Air emissions inventory

The NSW Environment Protection Authority (EPA) Air Emissions Inventory for the GMR in NSW provides information on natural and human-made sources of air emissions. This includes primary particle emissions and precursor gas releases, which lead to secondary pollutants such as ground-level ozone and secondary aerosols formation. The air emissions inventory is used to:

- evaluate the effectiveness of existing air quality management programs, such as the Protection of the Environment Operations (Clean Air Regulation) 2010 for EPA-licensed industry, service stations and residential wood heaters
- identify new cost-effective approaches for improving air quality, like the Dust Stop program for EPA-licensed coal mines
- fulfil NSW State of the Environment reporting obligations
- model air pollutant concentrations, with information from the emissions inventory used together with meteorological and topographic data within air quality models.

The EPA updates the emissions inventory every 5 years, with data gathered from various household, commercial business and EPA-licensed industry surveys, as well as government and non-government service providers. The inventory for the 2008 calendar year (NSW EPA 2012), published in 2012, was used in this study as it was the most recent inventory available at the time the study was conducted. The inventory for the 2013 calendar year was subsequently published in October 2019 (NSW EPA 2019).

The inventory covers Sydney, Newcastle and Wollongong and surrounding regions. It presents emissions and sources for over 1000 pollutants in the GMR, where about 75% of the NSW population resides.

The inventory covers emissions from biogenic (natural and living), geogenic (natural non-living) and anthropogenic (human-made) sources. These include:

- natural sources, such as bushfires, marine aerosols and vegetation
- commercial businesses, such as non-EPA-licensed printers, quarries and service stations
- domestic activities, such as lawn mowing, portable fuel containers and wood heaters
- industrial premises, such as EPA-licensed coal mines, oil refineries and power stations
- non-road vehicles and equipment, such as dump trucks, bulldozers and marine vessels
- on-road transport, such as registered buses, cars and trucks.

The pollutants detailed in the inventory include:

- primary emissions of total suspended particles
- PM_{10} and $PM_{2.5}$
- emissions of precursors of ground-level ozone
- secondary particles
- other common pollutants, organic compounds, metals and greenhouse gases.

The web-based tool Air Emissions in My Community (NSW EPA 2014) provides an easy way for the community to learn about air emissions. It presents air emissions inventory data in a variety of interactive chart views. Data can also be displayed for different geographical areas, ranging from the entire NSW GMR down to the postcode level.

2.3.1 National Pollutant Inventory

In addition to the Air Emissions Inventory for the GMR in NSW, emissions data for industrial facilities are available from the National Pollutant Inventory (NPI). The NPI is a publicly available database that contains information on emissions reported annually by industrial facilities. Industries that exceed NPI thresholds are required to calculate and submit their emissions, which are validated by state or territory environmental regulators.

Due to the scope and scientific rigour of the Air Emissions Inventory for the GMR in NSW, it is considered the primary source for information on sources of atmospheric emissions for the GMR, including the Illawarra. However, given that the inventory is updated every 5 years, with data for 2008 the most current available at the time this study was conducted, the NPI provides a useful indication of trends in emissions from industrial facilities for more recent years.

2.3.2 National shipping air emissions inventory

The Australian Maritime College at the University of Tasmania has compiled a 2010–11 national emissions inventory, which includes ship-engine exhaust emissions and fuel consumption in Australian waters and ports (Goldsworthy & Goldsworthy 2014 and 2015). Emissions are estimated by vessel type for regions within 300 kilometres of major capital cities, including bulk carriers, containers, crude oil tankers, general cargo carriers and passenger ships etc. The emissions inventory includes PM_{10}, $PM_{2.5}$, volatile organic compounds (VOCs), CO, SO_2 and NO_x emission estimates, in addition to estimates for various air toxics and greenhouse gases.

2.4 Particle speciation and source apportionment

Particles can be made up of a range of chemical species depending on the source of the particles or precursor gases. In some cases, the chemical composition of particles in the air can indicate the source of the particles. Particle speciation studies sample airborne particles and determine the chemical composition. Mathematical models, known as 'receptor models', are then used to estimate the source/s of the particles.

The Upper Hunter Fine Particle Characterisation Study (NSW OEH and NSW Health 2013) investigated the composition and sources of fine particles in Singleton and Muswellbrook. Sampling was conducted by the former OEH in 2012. Researchers from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Nuclear Science and Technology Organisation analysed the samples and reported the findings. Woodsmoke was found to be the main component of fine particles in winter, whereas in summer fine particles were largely from industry, vehicles and sea salt in the form of secondary sulfate and industry-aged sea salt.

The Sydney Particle Study – Stage II (2010–13; NSW OEH 2014c) improved understanding of sources and exposure to particles in the Sydney region. The study comprised an observation program and the development and implementation of a modelling framework. Summer observations identified the major components of fine particles ($PM_{2.5}$) as sea salt (34%), organic matter (34%), secondary inorganic particles (15%), soil (11%) and elemental carbon (6%), and autumn observations identified organic matter (57%) as the major component of fine particles, followed by elemental carbon (16%), secondary inorganic particles (15%), soil (7%) and sea salt (5%). Chemical transport modelling, which is used to simulate atmospheric chemistry, indicated that the release of VOCs from vegetation was a major source of secondary organic particles during summer, whereas wood heaters were a dominant source of these particles in autumn.

The Lower Hunter Particle Characterisation Study (NSW EPA 2016) investigated the composition and major sources of particle pollution in the Lower Hunter in 2014–15. Nine source factors were found to contribute to $PM_{2.5}$ particles. These were: fresh sea salt (particles blown from breaking ocean waves), pollutant-aged sea salt (sea salt that has reacted chemically in the air with pollution from other sources), secondary ammonium sulfate, soil (dust particles blown from soil), wood smoke, vehicles (from on-road and non-road sources including locomotives), mixed shipping and industry, mixed industry and vehicles, and nitrate. Six source factors were identified as contributing to $PM_{2.5–10}$ particles (particles have diameters of 2.5-10 µm), namely fresh sea salt, light-absorbing carbon (coal particles may contribute to this source), soil, industry and bioaerosols (fungal spores and pollens combined with industrial emissions and sea salt).

The Sydney Particle Characterisation Study (Cohen et al. 2016) categorised datasets for mass and composition of $PM_{2.5}$ at four sites (Lucas Heights, Richmond, Mascot and Liverpool) in the Greater Sydney region from 1 January 2000 to 31 December 2014. The datasets, collected over 15 years, were converted into identifiable fingerprints for each source. The absolute and percentage contribution of each of these fingerprints to the total fine $PM_{2.5}$ mass for the Greater Sydney region were quantified.

2.5 Air quality modelling studies

Air quality models are used to predict concentrations of pollutants over a selected region to provide information about the extent of pollution. Air quality models are used to:

- estimate air quality under various emission scenarios and assess how emissions affect pollutant concentrations
- predict future changes in air pollutant levels

- evaluate the benefits of potential emission reduction measures.

A modelling framework developed for the Sydney Particle Study consisted of prognostic meteorological modelling (Conformal Cubic Atmospheric Model (CCAM) and The Air Pollution Model (TAPM)), a natural and anthropogenic emissions inventory, and chemical transport modelling (CTM). This CCAM–CTM and TAPM–CTM framework was used to model two observation periods, summer and autumn (NSW OEH 2014), and investigate how secondary particles form. Secondary particles formed in the air accounted for over 40% of $PM_{2.5}$ concentrations measured. Chemical transport modelling indicated that the release of VOCs from vegetation was a major source of secondary organic particles during summer, whereas wood heaters were a dominant source of these particles in autumn.

The CCAM–CTM modelling framework was used in the Lower Hunter Particle Characterisation Study (NSW EPA 2016a) to support sampling and analysis work and help understand the distribution of particles over the broader region (NSW EPA 2016b). CCAM–CTM was also used to model a case study of SO_2 exceedance at Muswellbrook in the Upper Hunter region (Trieu et al. 2017).

CCAM–CTM has been configured by DPIE to conduct air quality forecast modelling for the NSW GMR. The modelling system is in operation and has supported daily air quality forecasting since 2018.

2.6 Health exposure assessment

Even though air quality in NSW is good by international standards, air pollution continues to affect human health and the NSW economy. The health cost of particle air pollution in the Greater Sydney region is estimated to be around $6.4 billion (AUD 2016) each year, or over $1000 per person (NSW DEC 2005; Jalaludin et al. 2011). A considerable proportion of the health effects are due to premature deaths resulting from long-term exposure to fine particles. Research based on the population, health and $PM_{2.5}$ data for Sydney in 2007 suggests that 430 premature deaths (about 2% of total deaths) and about 630 hospital admissions for respiratory and cardiovascular conditions were attributable to 2007 $PM_{2.5}$ concentrations. Research also suggests that even small reductions in $PM_{2.5}$ air pollution may result in significant health benefits in Sydney (Broome et al. 2015).

Ship exhaust is an important source of $PM_{2.5}$ in the Greater Sydney region. A detailed inventory of ship exhaust emissions in the Greater Sydney region was used in a health impact study to investigate human exposure and the mortality effect of primary and secondary $PM_{2.5}$ related to ship exhaust. Results suggest that in 2010–11, about 1.9% of the annual average population-weighted mean concentration of all natural and human-made $PM_{2.5}$ was attributable to ship exhaust, and this rose to 9.4% in suburbs located close to ports. This study also suggests for ships within 300 kilometres of Sydney to use low-sulfur fuel (0.1%), as they do at berth, would provide more than twice the mortality benefit for the population (Broome et al. 2016).

A study by DPIE, in collaboration with NSW Health, the NSW EPA and the Centre for Air Pollution, Energy and Health Research, used modelled $PM_{2.5}$ levels to quantify the health costs of coal-fired power station emissions, and the health benefits of reducing air pollution from coal-fired power stations through energy efficiency and renewable energy actions (NSW DPIE 2020).

3. Air quality trends

3.1 Air quality standards and changes

To help protect the health of the Australian population, the National Environment Protection (Ambient Air Quality) Measure sets national ambient air quality standards for six pollutants: carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), particulate matter (PM_{10} and $PM_{2.5}$) and lead (Pb) (Table 2).

Table 2 National Environment Protection (Ambient Air Quality) Measure standards for pollutants

Pollutant	Averaging period	Standard	Maximum allowable exceedances
Carbon monoxide (CO)	8 hours	9 ppm	1 day a year
Nitrogen dioxide (NO_2)	1 hour	0.12 ppm	1 day a year
	1 year	0.03 ppm	None
Photochemical oxidants (as ozone O_3)	1 hour	0.10 ppm	1 day a year
	4 hours	0.08 ppm	1 day a year
Sulfur dioxide (SO_2)	1 hour	0.20 ppm	1 day a year
	1 day	0.08 ppm	1 day a year
	1 year	0.02 ppm	None
Particles as PM_{10}	1 day	50 µg/m³	None
	1 year	25 µg/m³	None
Particles as $PM_{2.5}$	1 day	25 µg/m³	None
	1 year	8 µg/m³	None
Lead (Pb)	1 year	0.5 µg/m³	None

Notes: µg = microgram; PM_{10} = particulate matter less than 10 micrometres in diameter; $PM_{2.5}$ = particulate matter less than 2.5 micrometres in diameter; ppm = parts per million.

DPIE uses the Air Quality Index (AQI) to provide a comparison of pollutants affecting air quality. The AQI standardises measurements of ozone, carbon monoxide, sulfur dioxide, nitrogen dioxide, air particles and visibility into an index that is used to classify air quality on a scale from ‘very good’ to ‘hazardous’.

Based on information from the New South Wales (NSW) Air Quality Monitoring Network, AQI levels for regions across the NSW Greater Metropolitan Region (GMR) from 2012 to 2018 are shown in Figure 5. Between 2012 and 2018, air quality has been good for much of the time. Air quality was ‘very good’ or ‘good’ for 69–88% of days in Sydney and the Hunter, 83–91% of days in the Illawarra, and 88% or more days on the Central Coast. South-west and north-west Sydney experienced more ‘poor or worse’ air quality days due to higher levels of ozone and particle pollution.

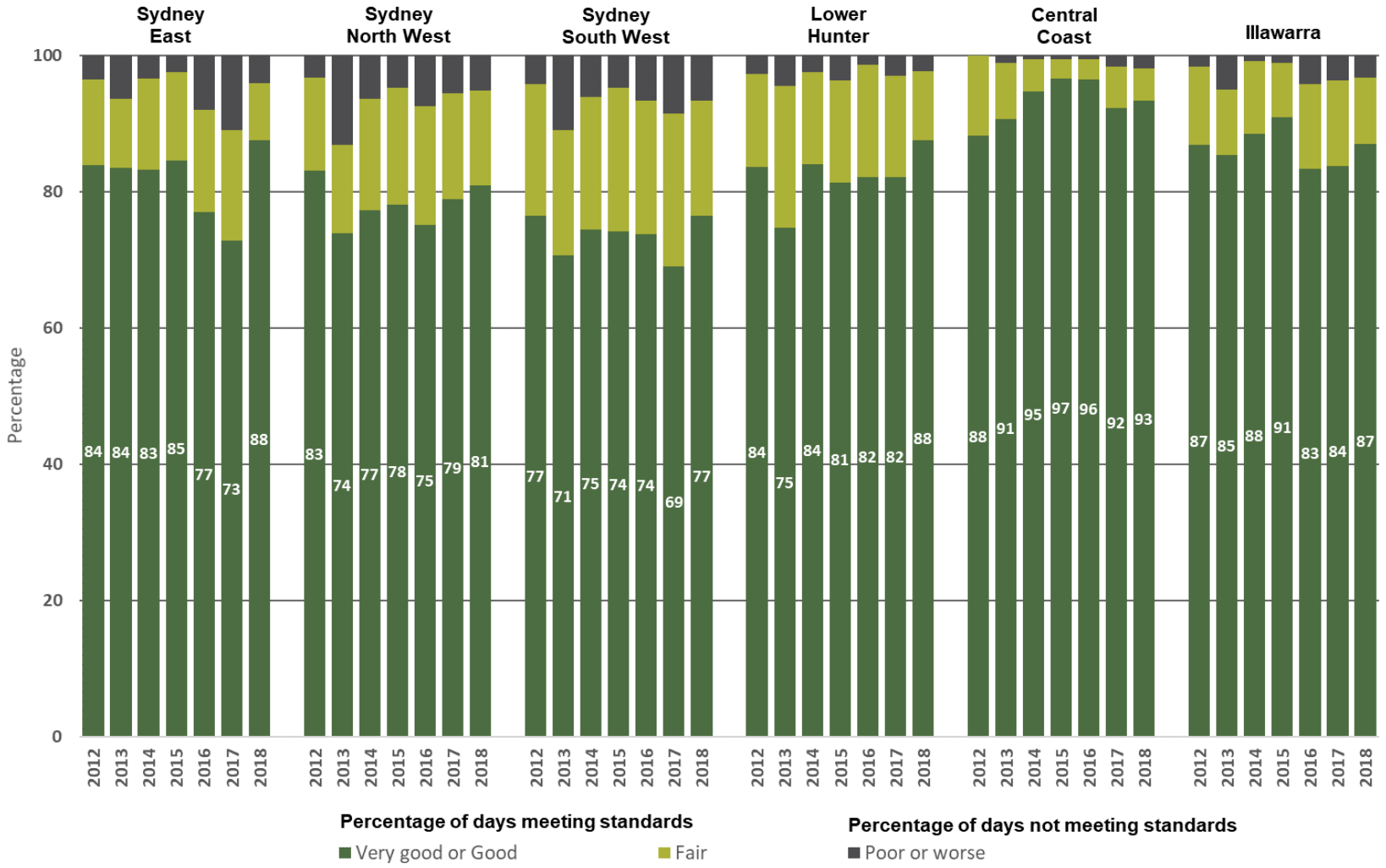


Figure 5 Air quality across the NSW Greater Metropolitan Region between 2012 and 2018 based on the Air Quality Index scale (at sites monitored against National Environment Protection Measure standards).

Increased particle pollution causes poor air quality across NSW, with exceedances of national air quality standards usually associated with regional dust storms and vegetation fires (NSW Office of Environment and Heritage (OEH) 2017; Virgilio et al. 2018). Particle pollution includes particles released directly from sources, and particles formed from chemical reactions of precursor gases in the air. Human-related sources that contribute to particle pollution in NSW include motor vehicles, residential wood heaters, mining, industry and power generation, non-road vehicles and equipment.

In Sydney and the Illawarra, poor air quality can also result from high ozone levels (NSW OEH 2014a, 2015a, 2016, 2017a, 2018 and 2019). Ground-level ozone is a secondary photochemical pollutant that forms in the air when precursor pollutants, the nitrogen oxides (NO_x) and volatile organic chemicals (VOCs), react in sunlight. High ozone levels in the Sydney basin and Illawarra result from local emissions, smog or precursors transported from other regions. Ozone levels that exceed standard levels usually occur in the warmer months, with peaks coinciding with high temperatures and bushfires (Hart et al. 2006; NSW DECCW 2010; Jiang et al. 2016).

3.1.1 Particle levels

Particle levels that exceed national standards vary significantly from year to year in the Sydney region (Figure 6). High PM_{10} and $PM_{2.5}$ levels are typically recorded during years affected by large bushfires, hazard reduction burns and/or regional dust storms. For example, the 2001–2003 and 2013 bushfires and the state-wide dust storms in September 2009. Local sources such as emissions from industrial and construction activities, small planned burns and residential wood heaters can also cause higher levels of particle pollution.

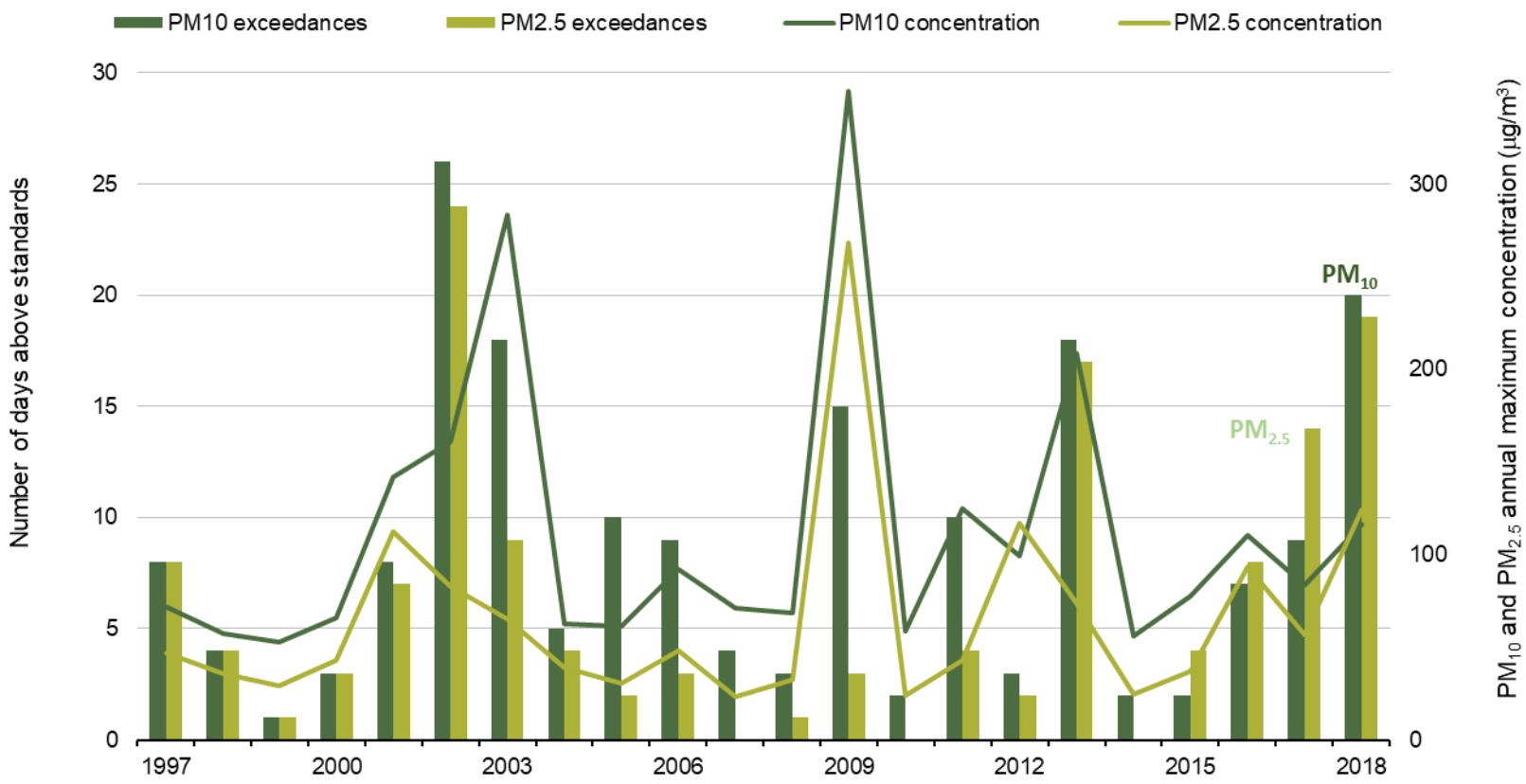


Figure 6 **PM_{10} and $PM_{2.5}$ maximum 24-hour average concentrations and number of days PM_{10} and $PM_{2.5}$ levels exceeded national 24-hour standards in Sydney between 1997 and 2018. µg/m^3 micrograms per cubic metre; PM_{10} = particulate matter less than 10 micrometres in diameter; $PM_{2.5}$ = particulate matter less than 2.5 micrometres in diameter.**

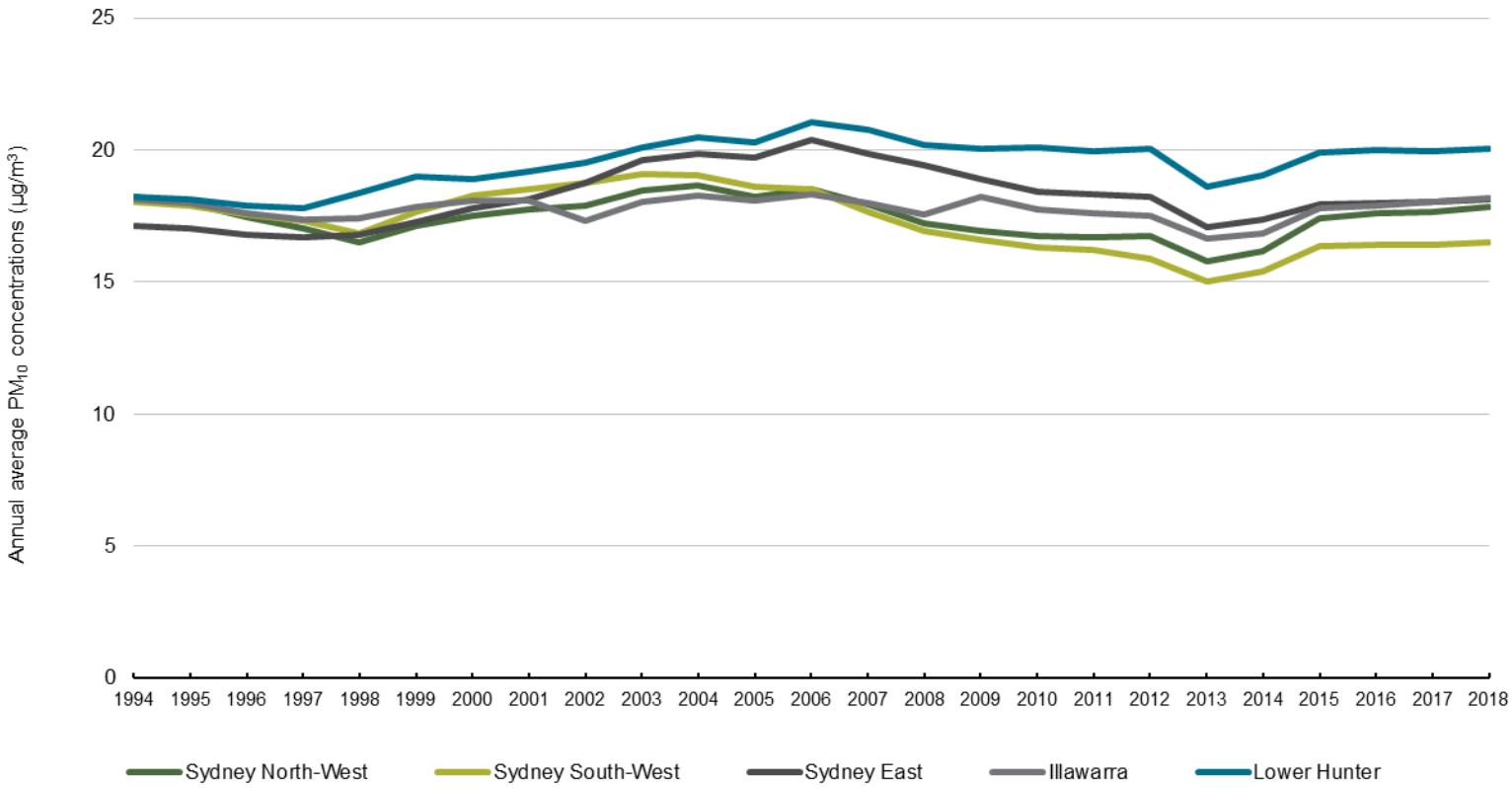


Figure 7 Annual average PM_{10} levels across the NSW Greater Metropolitan Region between 1994 and 2018. $\mu g/m^3$ = micrograms per cubic metre. $\mu g/m^3$ = micrograms per cubic metre; PM_{10} = particulate matter less than 10 micrometres in diameter.

Long-term trend analysis for PM_{10} concentrations in Sydney, the Illawarra and the Lower Hunter regions show large year-to -year variations in response to annual changes in climate, bushfires and dust storms (NSW OEH 2014b). That is, there is no discernible upward or downward trend in average levels (Figure 7). Dry El Niño years (2002–2007) are associated with a greater frequency of bushfires and dust storms and therefore higher particle pollution levels. Lower particle pollution levels tend to occur during wetter La Niña years (2010–2012). Regional dust storms, bushfires and planned burns contributed significantly to particle levels in 2009, 2013, 2016 and 2018.

Long-term trend analysis for $PM_{2.5}$ is complicated by improvements in monitoring instrumentation. Tapered elemental oscillating microbalance (TEOM) monitors were replaced with beta attenuation monitors (BAMs) across the NSW Air Quality Monitoring Network in 2012. To avoid influence from moisture to the particle measurements, TEOM monitors were fitted with heated inlets (to 50°C) to dry out particles before they landed on the filter. Therefore, the TEOM monitors generally reported lower $PM_{2.5}$ concentrations than BAMs. The long-term annual average $PM_{2.5}$ trends combine $PM_{2.5}$ measurements from the two monitor types without any adjustments (Figure 8).

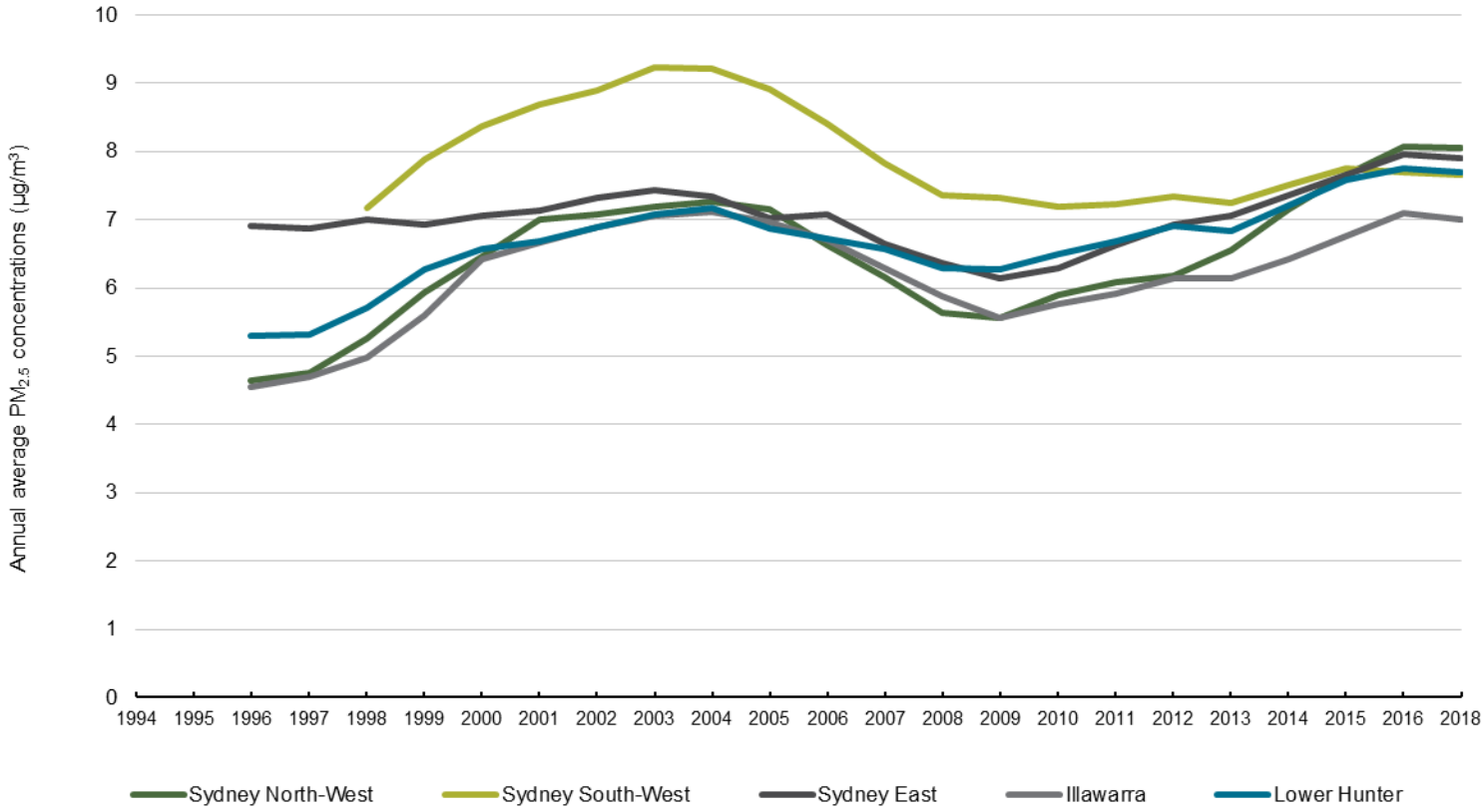


Figure 8 Trends in annual average $PM_{2.5}$ concentrations across the NSW Greater Metropolitan Region between 1999 and 2018. $\mu g/m^3$ = micrograms per cubic metre; $PM_{2.5}$ = particulate matter less than 2.5 micrometres in diameter.

3.1.2 Ozone levels

Ozone levels increased from 1994 to 2002, but from 2003 onwards have been relatively stable across the NSW GMR (Figure 9). In recent years, Sydney has had less days where ozone levels have exceeded national standards, but there is no discernible upward or downward trend in average ozone levels.

Early morning and afternoon peaks in NO_x and VOCs emissions from motor vehicles significantly influence the daily timing of peak ozone concentrations. Measures to reduce vehicle emissions, such as more stringent vehicle emission limits and the use of cleaner fuels, may be contributing to the reduction in number of days ozone levels exceeded standards in the Sydney basin.

Figure 9 Trends in annual average ozone (O_3) levels across the NSW Greater Metropolitan Region between 1994 and 2018. pphm = parts per hundred million.

3.2 Comparison of air quality between cities across the world

Annual average $PM_{2.5}$ levels in Sydney are comparable to levels in other Australian cities and low by world standards, according to a comparison of air pollution levels in cities across the world conducted by the World Health Organization (WHO) in 2016 (Figure 10). The Australian annual average $PM_{2.5}$ standard is more stringent than standards or guideline values set by the European Union, United States and the WHO.

Ozone levels measured in the Sydney, Illawarra and Lower Hunter regions in 2014 were also relatively low compared to levels reported for other major cities (Figure 11; Environment and Climate Change Canada 2016).

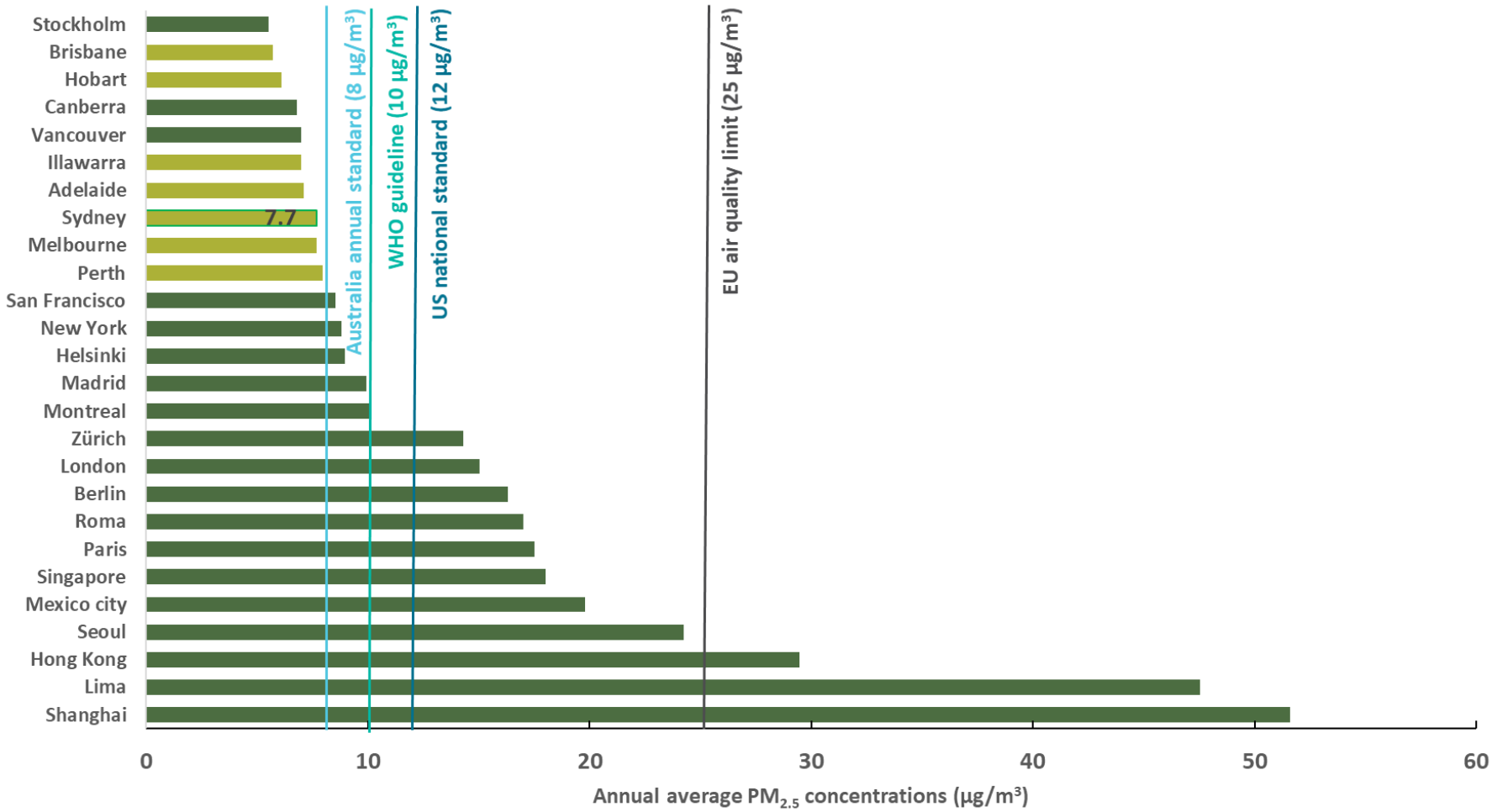


Figure 10 Annual average $PM_{2.5}$ levels measured in Sydney compared to levels in other Australian cities and cities across the world, based on 2014 measurements. µg/m³ = micrograms per cubic metre; $PM_{2.5}$ = particulate matter less than 2.5 micrometres in diameter. Source: WHO 2016

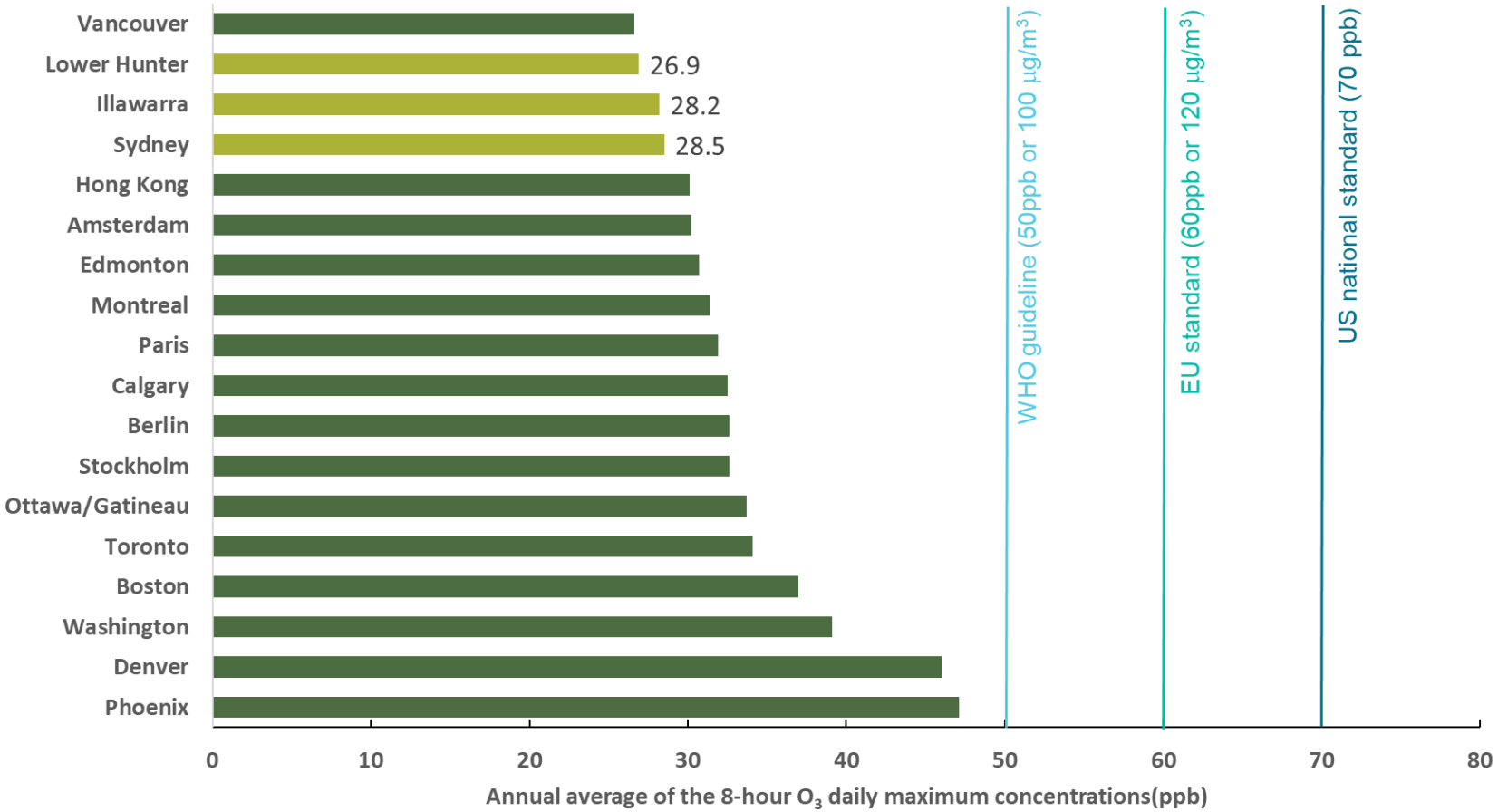


Figure 11 Annual average of the daily maximum 8-hour rolling average ozone (O_3) levels measured in NSW compared to levels in other Australian cities and cities across the world, based on 2014 measurements. µg/m³ = micrograms per cubic metre; ppb = parts per billion. Source: Environment and Climate Change Canada, 2016

3.3 Particle characterisation

Particles can be released directly into the air by sources (primary particles) or formed as 'secondary particles' in the air from the chemical transformation of precursor gases such as NO_x, VOCs, SO_2, and ammonia (NH_3). Particle characterisation provides additional information on the composition and likely sources of fine particles.

The Sydney Particle Study commissioned by the former OEH (2010−2013) improved understanding of Sydney region particle sources and exposure (Cope et al. 2014). This study combined monitoring–modelling works and showed seasonal variation in composition of fine particles (Figure 12). The summer observations were conducted in 2011 and identified the major components of measured average $PM_{2.5}$ as:

- sea salt emissions from waves breaking in the open ocean and coastal surf breaks (34%)
- organic matter, including primary particles released from sources such as car exhaust, and secondary organic particles formed in the atmosphere (34%), up to 70% of organic matter could be secondary organic particles formed from gases released by biogenic sources
- secondary inorganic particles including fine particles of sulfate, nitrate and ammonium (15%), soil (11%) and elemental carbon emitted directly to the air from sources such as vehicles, wood heaters and bushfires (6%).

The autumn observations, conducted in 2012, identified the major components of measured average $PM_{2.5}$ as:

- organic matter, including primary particles released from car exhaust, and secondary organic particles formed in the atmosphere (57%)
- elemental carbon (16%), secondary inorganic particles (15%), soil (7%) and sea salt (5%) were also observed in autumn $PM_{2.5}$ particles.

In summary, fine particles in Sydney contain a significant amount of organic matter in summer and autumn, and high levels of sea salt in summer. Major sources of secondary organic particles in the air include VOCs from vegetation in summer and wood heaters in autumn.

(a) Summer

(b) Autumn

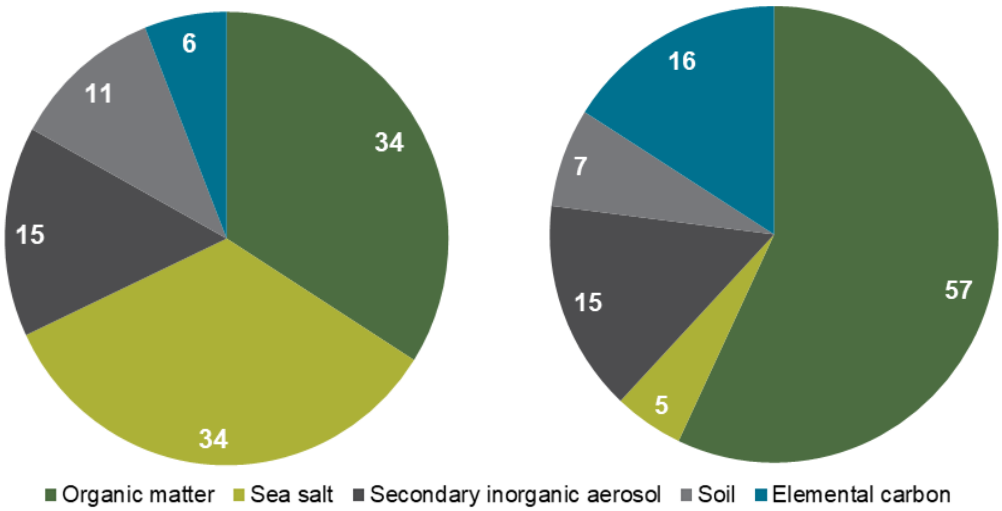


Figure 12 Chemical source groups that contribute (%) to average $PM_{2.5}$ concentrations for (a) summer 2011 and (b) autumn 2012. $PM_{2.5}$ = particulate matter less than 2.5 micrometres in diameter. Source: Cope et al, 2014

In the Sydney Particle Characterisation Study (Cohen et al. 2016), $PM_{2.5}$ data collected by the Australian Nuclear Science and Technology Organisation from four long-term sampling sites (Lucas Heights, Richmond, Mascot and Liverpool) between 1 January 2000 and 31 December 2014 was further analysed with positive matrix factorisation source apportionment techniques. The aim was to identify different source components or fingerprints that make up the measured total $PM_{2.5}$ mass at each site.

The $PM_{2.5}$ mass was split into seven major source fingerprints (Figure 13). These were: soil (windblown dust), sea (sea spray transported from the coast), mixed-secondary sulfate (secondary sulfates from power generation, industry and motor vehicles), mixed-industry-aged secondary sulfate (industrial sources with components of aged secondary sulfates and sea spray), mixed-smoke-auto (smoke from biomass burning, wood heaters and diesel vehicles), auto-1 (primary automobile source) and auto-2 (minor automobile source).

The contributions from each source varied depending on location. The seasonal variations of each source fingerprints across sites are shown in Figure 14. The contributions of source fingerprints from mixed-secondary sulfate, mixed-industry-aged secondary sulfate and sea spray were significantly higher in summer months. The contribution from mixed-smoke-auto was generally higher in winter months and the fingerprint for windblown dust was more elevated during late autumn and spring. Contributions from secondary sulfates from coal-fired power stations, industry and motor vehicles to the $PM_{2.5}$ mass peaked in the summer months (~50−70%), whereas smoke from domestic wood heaters peaked in winter months (~60−80%), and vehicle emissions contributed 15 to 30% of the annual $PM_{2.5}$ mass.

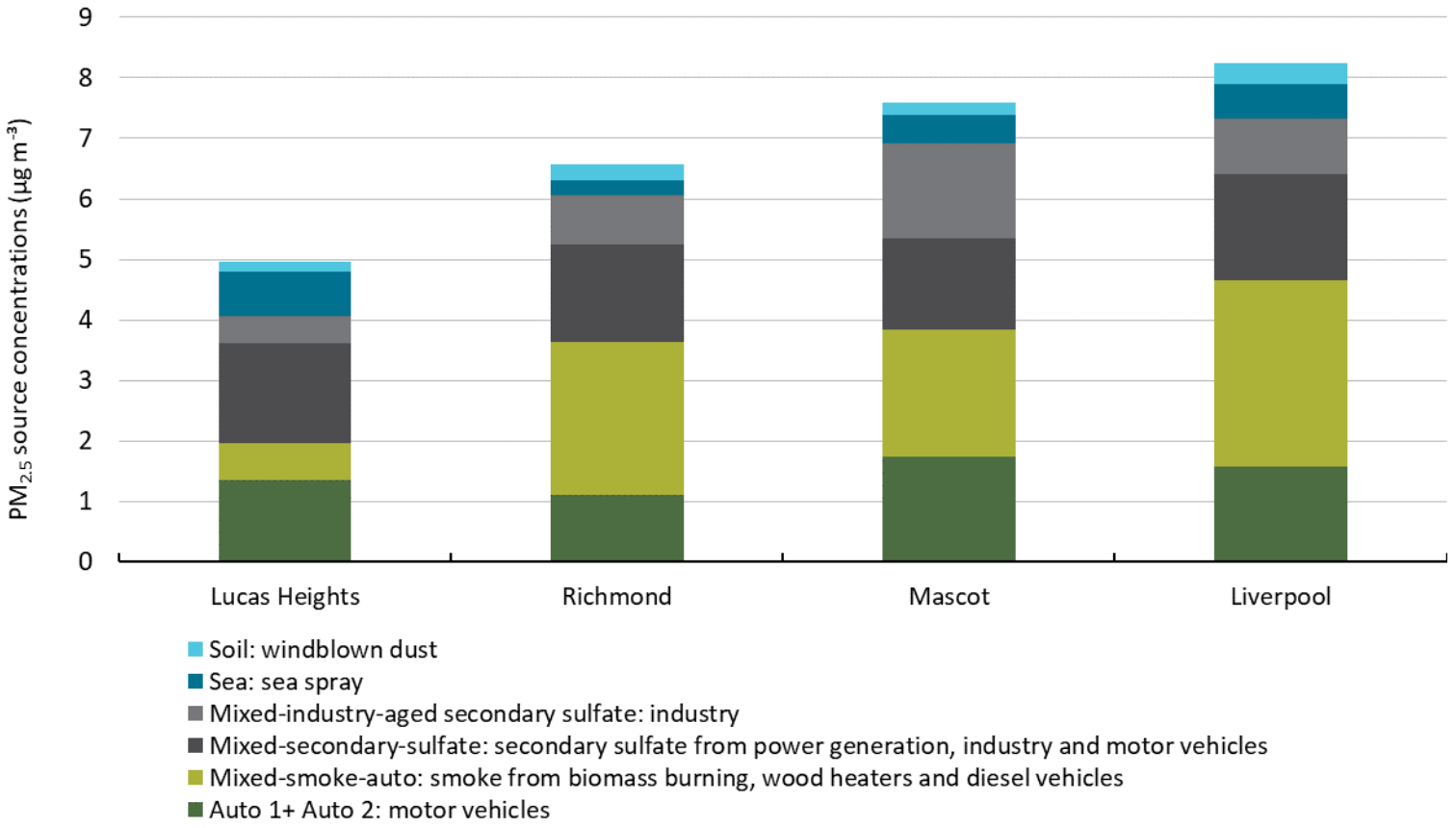
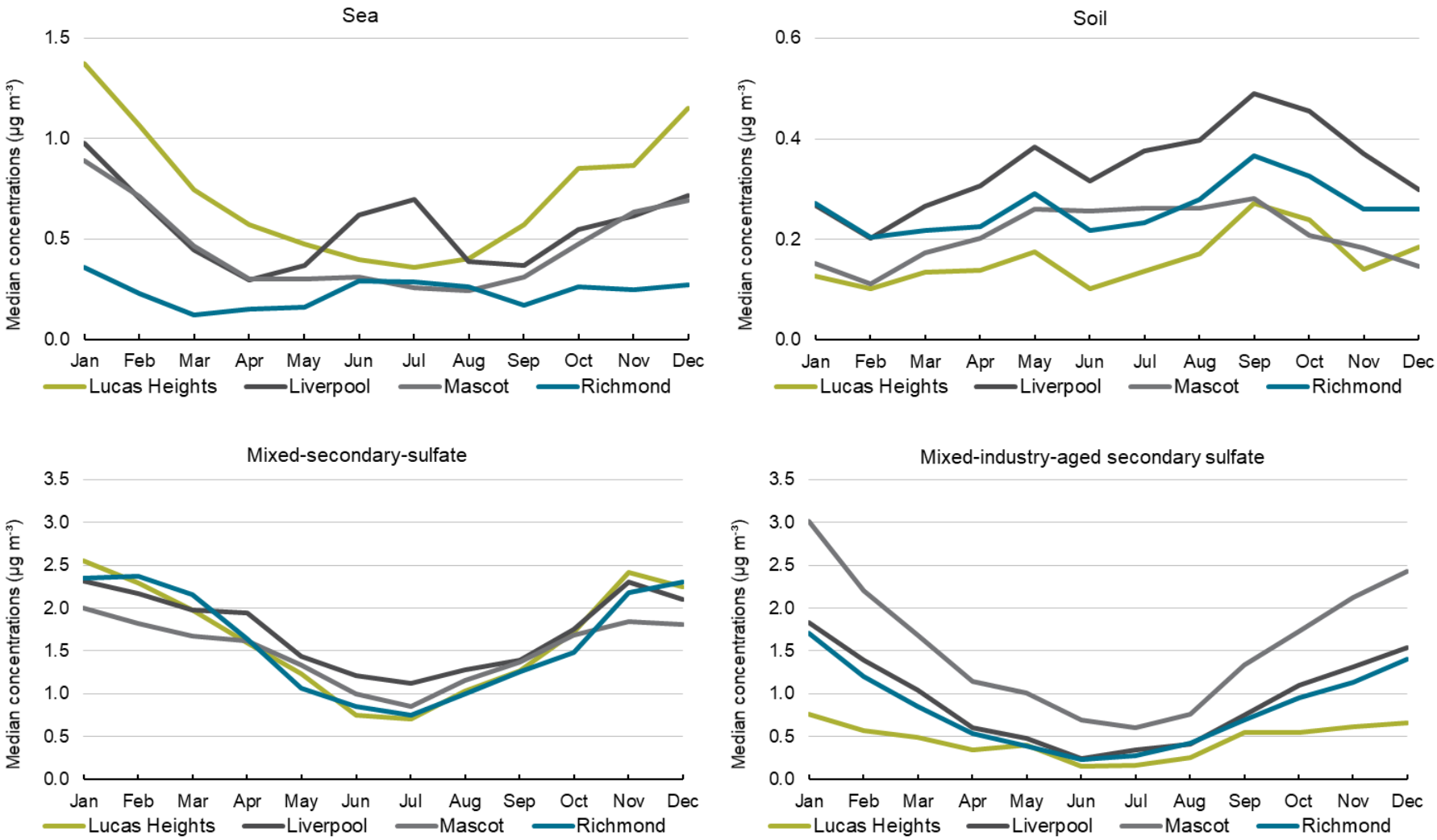


Figure 13 Average contribution from source components of fine particles ($PM_{2.5}$) at four air quality monitoring stations in Sydney over 15 years (2000–2014). $PM_{2.5}$ = particulate matter less than 2.5 micrometres in diameter. Source: Cohen et al., 2016


Sea
Soil
Mixed-secondary-sulfate
Mixed-industry-aged secondary sulfate
Median concentrations (µg m-3)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Lucas Heights
Liverpool
Mascot
Richmond

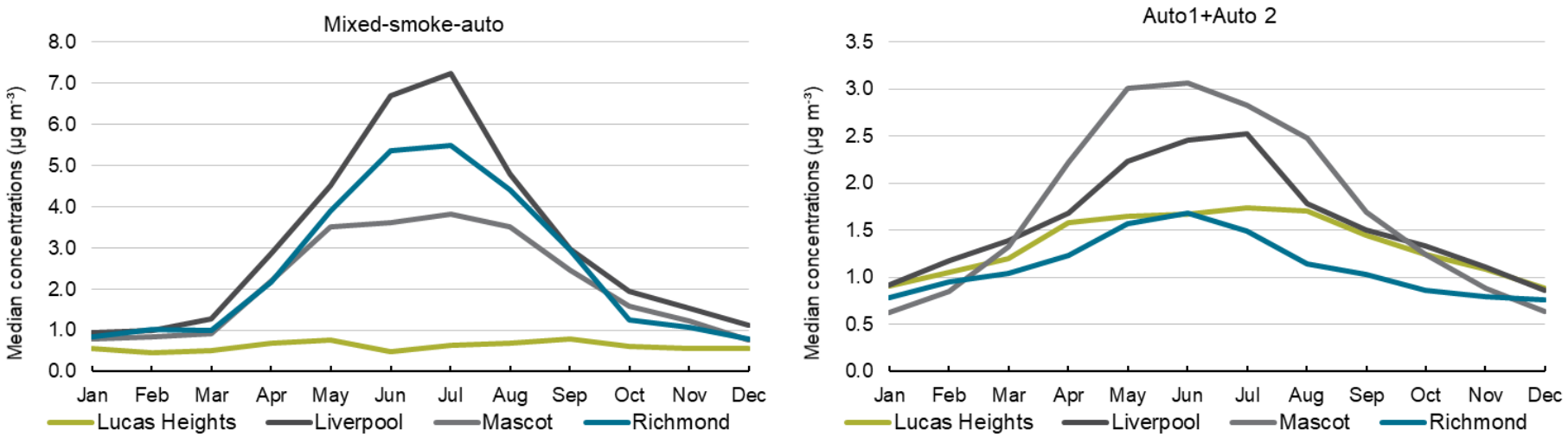
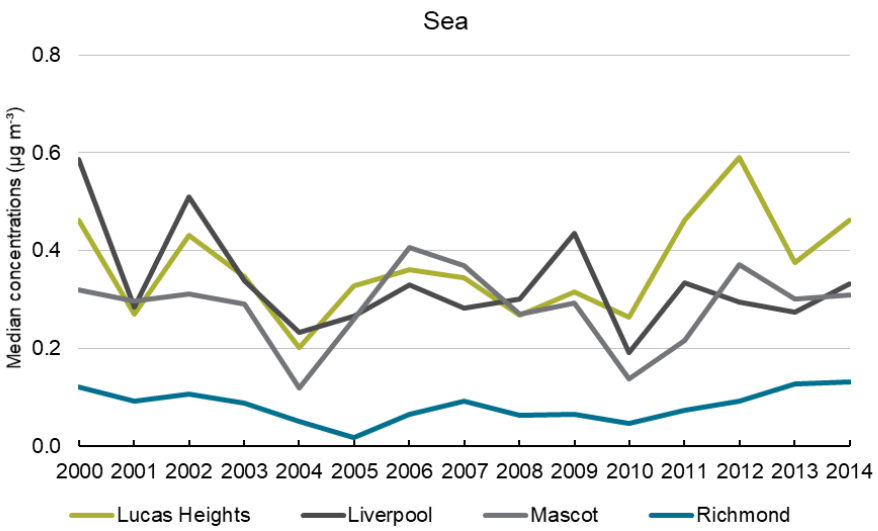
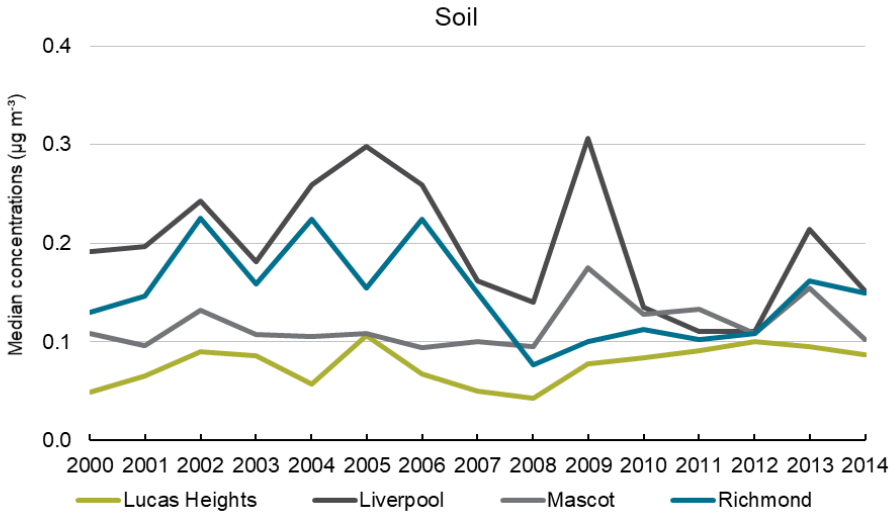


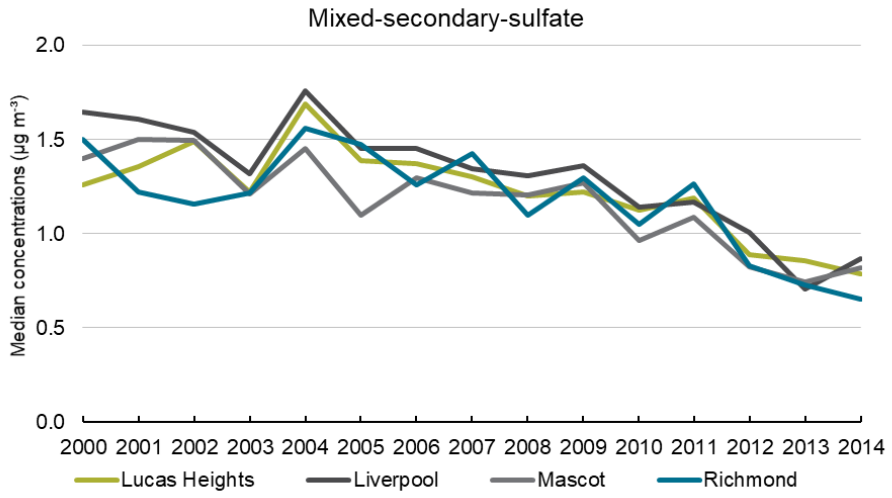
Figure 14 Variations of the monthly average source fingerprint contributions for fine particles ($PM_{2.5}$) across the Greater Sydney region between 2000 and 2014. µg/m3 = micrograms per cubic metre; $PM_{2.5}$ = particulate matter less than 2.5 micrometres in diameter. Source: Cohen et al., 2016

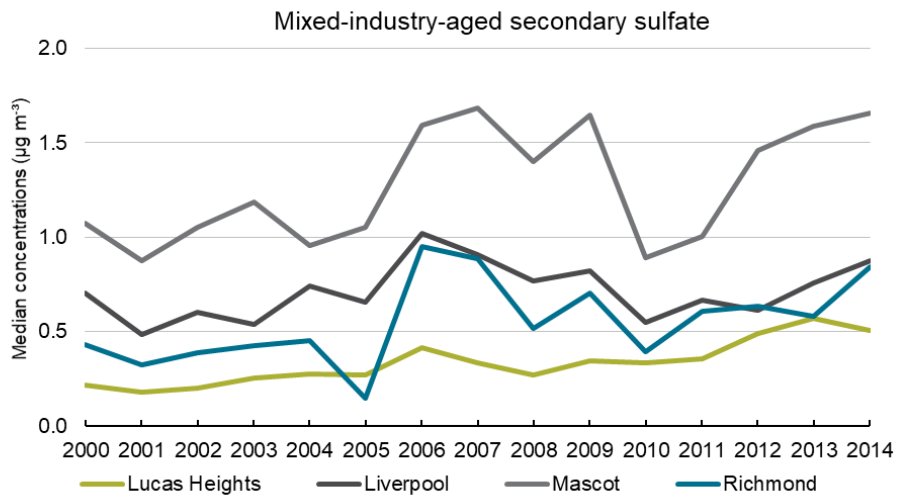
The long-term trends in source fingerprint contributions to fine particle ($PM_{2.5}$) air pollution for 2000–2014 are shown in Figure 15. Secondary particles from power generation, industry and motor vehicles (Mixed-secondary-sulfate) reduced across sites from an average of 1.5 $\mu g/m^3$ in 2000 to 0.8 $\mu g/m^3$ in 2014. Contributions from biomass burning, wood heaters and diesel vehicles (Mixed-smoke-auto) as well as motor vehicles (Auto1+2) significantly reduced by about 40% from 2000 to 2007 and have remained relatively constant since 2007. There was a more significant inter-annual variation in contributions from industry (Mixed-ind-aged secondary sulfate) and sea spray. The contributions from dust were significantly elevated during bushfire and dust-storm affected years (2003–2006; 2009; 2013).

The Upper Hunter Fine Particle Characterisation Study (NSW OEH and NSW Health 2013) investigated the composition of $PM_{2.5}$ in Singleton and Muswellbrook. Conducted in 2012, the aim of the study was to provide communities in Muswellbrook and Singleton with scientific information about the composition of fine particles in their local environment. $PM_{2.5}$ levels were higher in the cooler months from May to October. Wood smoke was a dominant contributor at both sites during the winter, but to a greater extent at Muswellbrook. In summer, secondary sulfate and industry-aged sea salt were the dominant contributing factors. This was due to the higher contribution of fossil fuel combustion-related particles and sea salt during the summer, both of which represent large-scale regional sources (Figure 16).


Sea
Median concentrations (µg m-3)
0.8
0.6
0.4
0.2
0.0
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014
Lucas Heights
Liverpool
Mascot
Richmond


Soil
Median concentrations (µg m-3)
0.4
0.3
0.2
0.1
0.0
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014
Lucas Heights
Liverpool
Mascot
Richmond


Mixed-secondary-sulfate
Median concentrations (µg m-3)
2.0
1.5
1.0
0.5
0.0
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014
Lucas Heights
Liverpool
Mascot
Richmond


Mixed-industry-aged secondary sulfate
Median concentrations (µg m-3)
2.0
1.5
1.0
0.5
0.0
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014
Lucas Heights
Liverpool
Mascot
Richmond

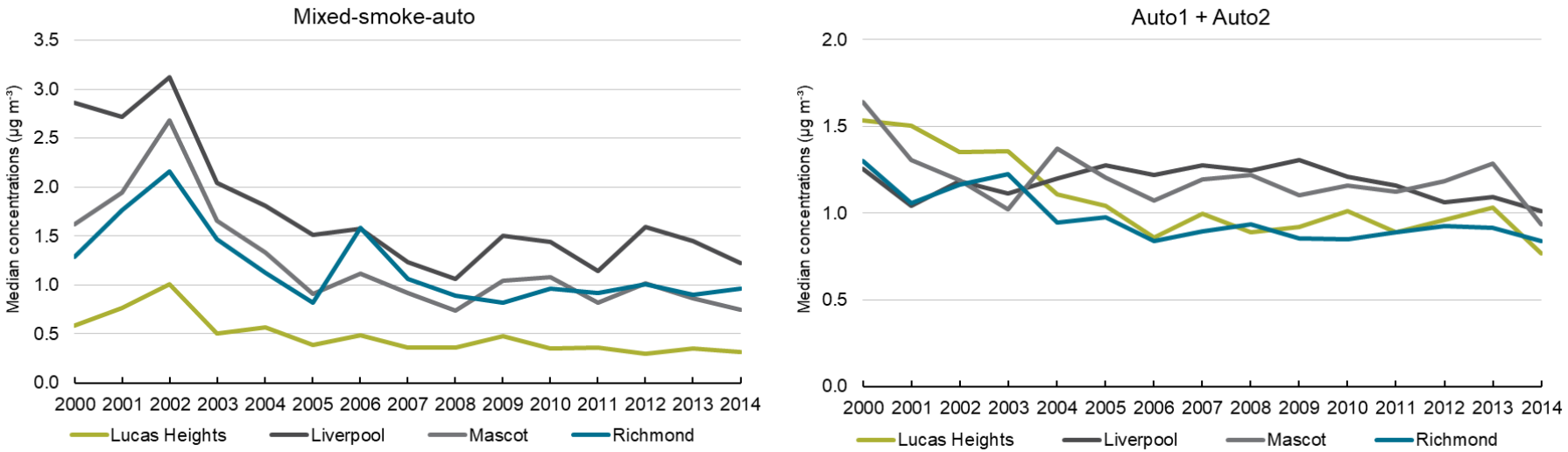


Figure 15 Trends in annual source fingerprint contributions to fine particle ($PM_{2.5}$) air pollution between 2000 and 2014. Concentrations are illustrated as annual medians to avoid outliers. µg/m^3 = micrograms per cubic metre; $PM_{2.5}$ = particulate matter less than 2.5 micrometres in diameter.

(a) Singleton

(b) Muswellbrook

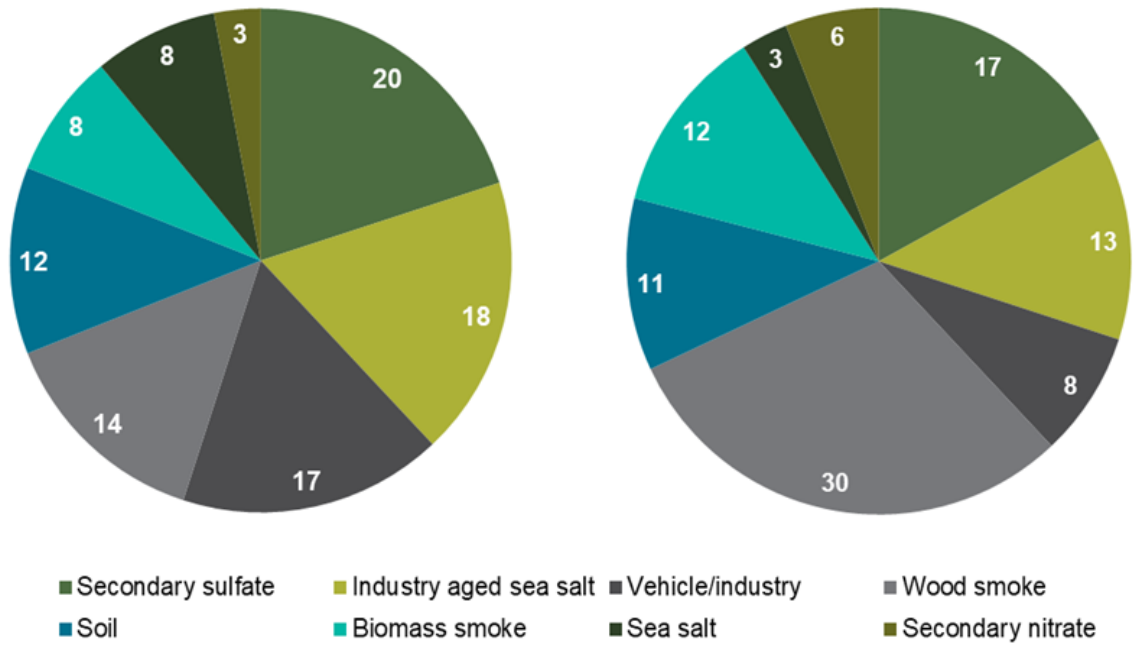


Figure 16 Proportions that factors contribute to the composition of total annual fine particle ($PM_{2.5}$) mass in the Upper Hunter Valley at (a) Singleton and (b) Muswellbrook. Source: NSW OEH and NSW Health 2013

The Lower Hunter Particle Characterisation Study, commissioned by the NSW Environment Protection Authority in 2013, investigated the composition and major sources of particle pollution in the Lower Hunter. Fine particles were monitored at four sites, including two sites representative of regional population exposure (Newcastle and Beresfield) and two sites near the Port of Newcastle (Mayfield and Stockton). Coarse particles were also monitored at Mayfield and Stockton.

Annual average fine particle concentrations were similar at Newcastle, Mayfield and Beresfield (6.4–6.7 µg/m^3) and about 40% higher at Stockton (9.1 µg/m^3). The higher levels at Stockton were mainly due to larger contributions from sea salt and primary ammonium nitrate. Ammonium nitrate, which contributed about 19% of the annual fine particle mass at Stockton and 40% in winter, was most likely due to emissions from the ammonium nitrate manufacturing facility on Kooragang Island. Other source factors and their contribution to fine particles over the year were similar across the Lower Hunter region and included:

- fresh sea salt particles: 24% at Newcastle, decreasing to 13% at Beresfield
- pollutant-aged sea salt: about 23% at all sites
- wood smoke: 15% at Beresfield, decreasing to 6% at Stockton
- secondary ammonium sulfate: about 10% at all sites
- soil dust: about 10% at all sites
- vehicle emissions: about 10% at three sites, and about 5% at Stockton
- industry factors: about 12% at three sites and 24% at Stockton
- mixed shipping and industry: about 3% at all sites
- nitrate: 19% ammonium nitrate at Stockton and secondary nitrate at other sites (6–11%).

On an annual average basis, there is about a 50:50 split between primary and secondary particles at three sites (Newcastle, Beresfield and Mayfield), and a 65:35 split at Stockton because of the significant contribution from the primary ammonium nitrate.

4. Sources of air pollution

Air pollutants are emitted from a range of human-made and natural sources. Air pollutants can be directly released into the atmosphere (primary pollutants) or can form as the result of chemical reactions from precursor substances (secondary pollutants). There are complex links between air pollutant emissions (presented in this section) and ambient air quality (presented in section 3). These include impacts from meteorology and topography, chemical reactions, location and type of emission source (Box 1). For this reason, source contributions to total emissions in a region do not compare well with source contributions at a particular location. This should be kept in mind when interpreting the emissions data presented.

Air quality within a region is affected by local sources as well as sources situated further afield, due to interregional transport (Nelson et al. 2002). Similarly, atmospheric emissions within a region can affect air quality in neighbouring areas. Although interregional transport is important, this section focuses on sources of air pollution situated within the New South Wales Greater Metropolitan Region (NSW GMR) because a comprehensive emissions data set is available. An overview of emissions within the regions of Sydney, Newcastle, Wollongong and non-urban is provided, in addition to the NSW GMR.

Box 1: Emission inventory information compared to air quality information

The relationship between emissions and ambient air quality is complex and influenced by a number of factors. It is important to understand this when interpreting emission inventory information. How emissions are dispersed, transported and transformed depends on:

- Meteorology (wind speed and direction, temperature, sunlight and rainfall) – high wind speeds tend to dilute emissions, whereas wind direction determines where they are transported. Medium- and long-range transport of emissions by wind can impact local air quality when emissions are from a large distant source. Temperature and sunlight play a key role in atmospheric reactions and the formation of secondary pollutants.
- Topography or surrounding terrain – the surface features of the land can trap emissions, influence how they disperse, or determine the direction they are transported.
- Atmospheric reactions – in addition to primary emissions released directly from sources, secondary pollutants, such as photochemical smog (ground-level ozone is an indicator) or secondary particulate matter (inorganic sulfates, nitrates and secondary organic aerosols) can form.
- Source location and type – the influence of a particular emission source on local air quality tends to decrease with distance from the source. Sources range from elevated point sources, like a boiler chimney, to ground-level sources such as motor vehicles in an urban road network or wind-blown dust from an exposed area.

4.1 Sources of air emissions

The NSW Environment Protection Authority (EPA) Air Emissions Inventory for the GMR in NSW identifies and describes sources of air emissions and provides detailed information on emissions during a given time period. The inventory discusses emissions for the entire GMR and for the smaller Sydney, Newcastle, Wollongong and non-urban regions (Figure 17). Non-urban regions are the remaining areas outside the three main urban regions. The inventory is updated every 5 years, and the 2008 calendar year emissions inventory was used in this study (NSW EPA 2012a) since the 2013 calendar year emissions inventory (NSW EPA 2019) had not been released at the time the study was undertaken.

Industry-reported emissions from the National Pollutant Inventory (NPI) show recent trends in industrial emissions and the national shipping air emissions inventory presents emissions from ships (Goldsworthy & Goldsworthy 2014).

We pay specific attention to primary particle emissions, ground-level ozone precursor pollutants (volatile organic compounds (VOCs), nitrogen oxides (NO_x), and sulfur dioxide (SO_2). These gaseous pollutants (SO_2, VOCs and NO_x) are of particular interest as they contribute to the formation of secondary particles in the air.

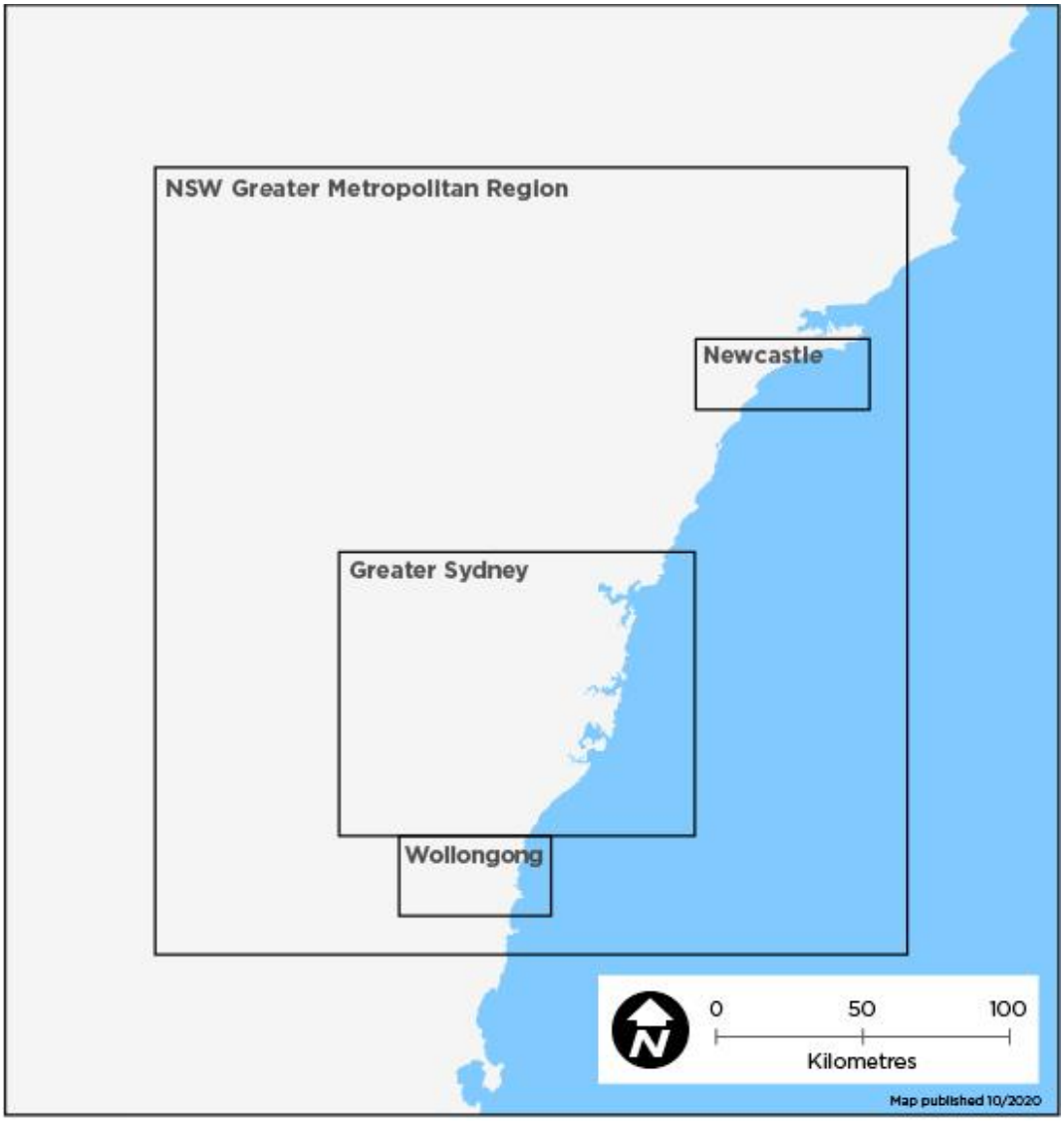


Figure 17 The NSW Greater Metropolitan Region, Greater Sydney, Newcastle and Wollongong regions represented by boxed areas.

4.1.1 Human activities and natural sources

Human activities contributed significantly to overall emissions of particles (PM_{10} and $PM_{2.5}$), SO_2, NO_x and VOCs in all NSW GMR subregions in 2008 (Figure 18). The largest contribution to emissions in the non-urban region, which dominated GMR emissions, was from human activities. The Upper Hunter region, which is located within the non-urban area, contributed emissions from coal-fired power generation and large-scale mining. The Central Coast, which is also located within the non-urban area, contributed emissions from industrial and coal-fired power generation.

Natural sources, notably biogenic emissions from forested areas, also contributed significantly to VOCs emissions across the regions.

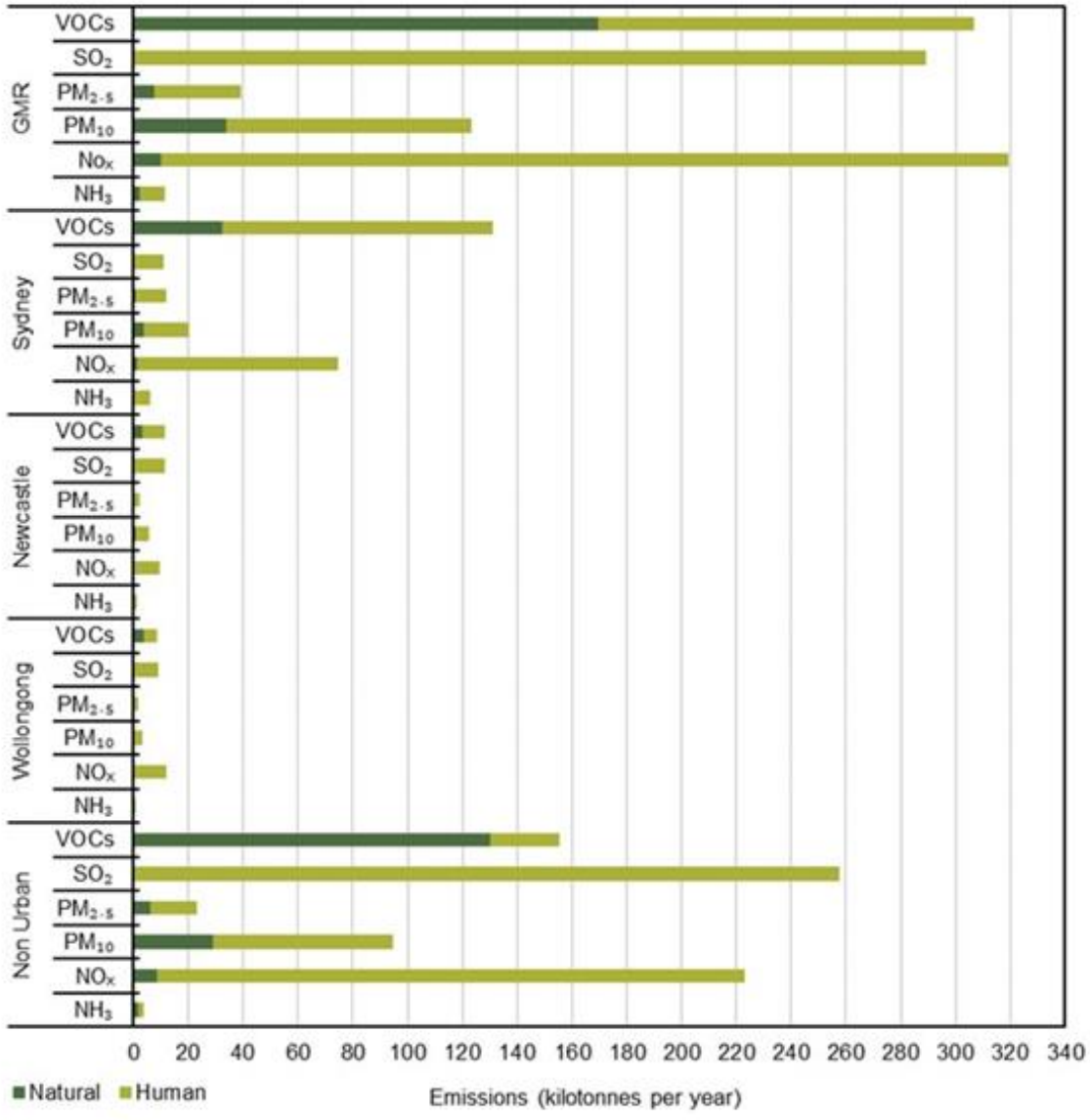
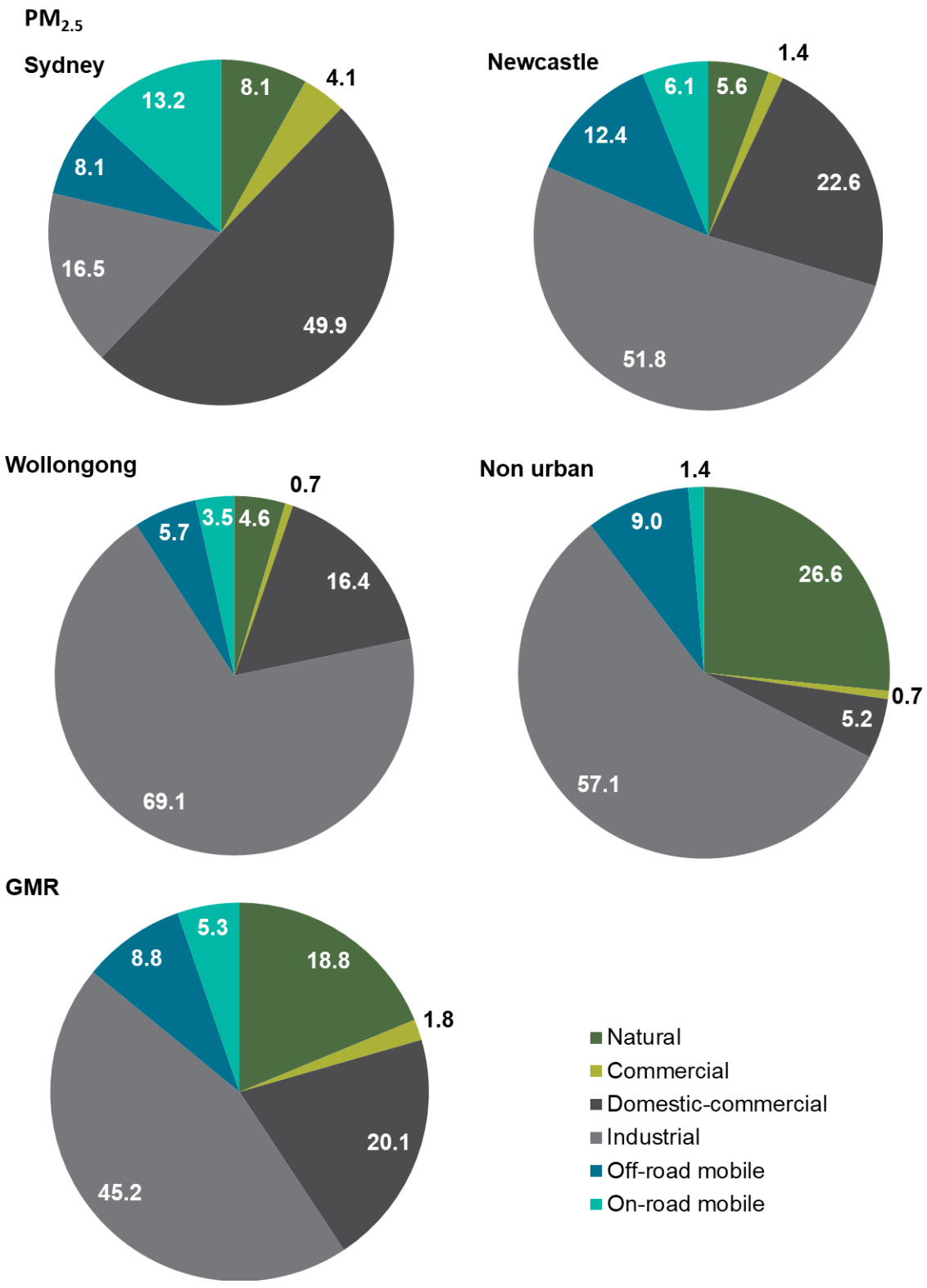


Figure 18 Contribution of human activities and natural sources to total emissions in 2008 for the Greater Metropolitan Region (GMR), Sydney, Newcastle, Wollongong and non-urban regions (kilotonnes per year). PM_{10} = particles smaller than 10 micrometres in diameter; $PM_{2.5}$ = particles smaller than 2.5 micrometres in diameter; NO_3 = nitrate; NO_x = oxides of nitrogen); SO_2 = sulfur dioxide; VOCs = volatile organic compounds.

4.1.2 Particle emissions

Major source groups contributing to PM_{10} and $PM_{2.5}$ emissions in 2008 for the Sydney, Newcastle and Wollongong and non-urban regions and the entire NSW GMR are shown in Figure 19. These include: industrial sources (i.e. EPA-licensed industries), on-road mobile sources (e.g. cars and trucks), off-road mobile sources (e.g. bulldozers, haul trucks, aircraft, ships and locomotives), domestic-commercial sources (e.g. residential wood heating), commercial activities (e.g. service stations) and natural sources (e.g. vegetation, bushfires and sea salt). Table 3 summarises the most significant contributing sources for total $PM_{2.5}$ and PM_{10} emissions for each region.


PM2.5
Sydney
8.1
4.1
13.2
8.1
16.5
49.9
Newcastle
1.4
6.1
5.6
12.4
22.6
51.8
Wollongong
0.7
3.5
4.6
5.7
16.4
69.1
Non urban
1.4
9.0
26.6
0.7
5.2
57.1
GMR
5.3
8.8
18.8
1.8
20.1
45.2
Natural
Commercial
Domestic-commercial
Industrial
Off-road mobile
On-road mobile

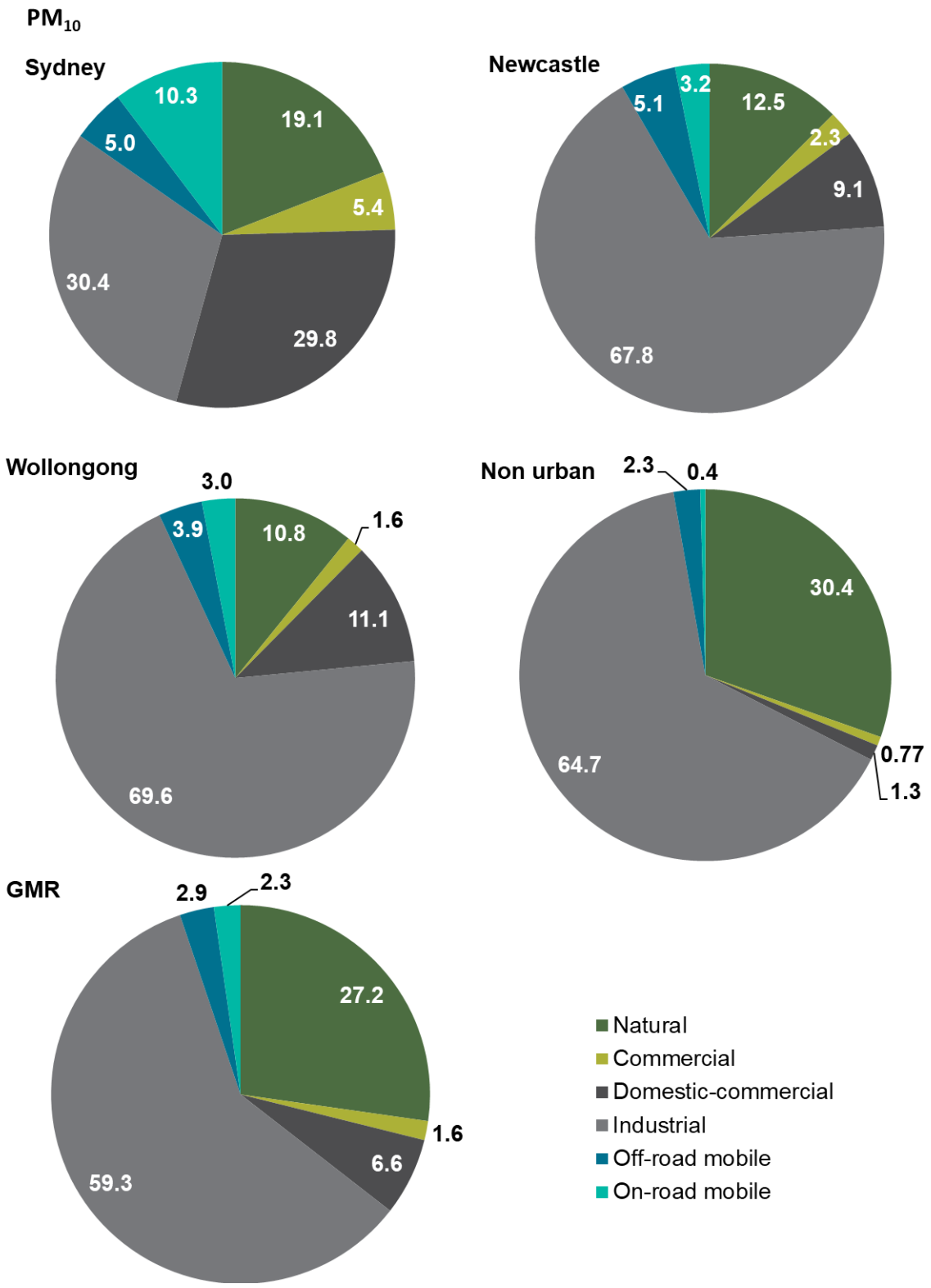


Figure 19 Percentage contribution by major source groups to emissions of particles smaller than 2.5 micrometres in diameter ($PM_{2.5}$) and particles smaller than 10 micrometres in diameter (PM_{10}) in 2008 for the Sydney, Newcastle, Wollongong, non-urban regions and Greater Metropolitan Region (GMR).

Industrial emissions were the most significant source of $PM_{2.5}$ emissions in all regions (over 50%), except Sydney where domestic–commercial sources (notably residential wood heating) dominate (Figure 19, Table 3). Industrial sources were the second most significant source of $PM_{2.5}$ emissions in Sydney, whereas in Newcastle and Wollongong it was domestic–commercial sources, and in non-urban areas it was natural sources. The dominant contributing sources to $PM_{2.5}$ emissions across the GMR were industrial (contributing 45%), followed by domestic–commercial and natural emissions.

Industrial emissions were also the most significant source of PM_{10} across the regions, accounting for between 30–69% of total PM_{10} emissions. The next most significant sources of PM_{10} emissions were natural and domestic–commercial, accounting for up to 30% of the total PM_{10} emissions in certain regions.

Table 3 The biggest contributors to $PM_{2.5}$ and PM_{10} emissions within each region in 2008

	Sydney	Newcastle	Wollongong	Non-urban	GMR
$PM_{2.5}$	Domestic–commercial	Industrial	Industrial	Industrial	Industrial
	Solid fuel burning 93%	Ammonium nitrate production 28.5%	Iron or steel production (iron ore) 90.4%	Mining for coal 63.8%	Mining for coal 50%
PM_{10}	Industrial	Industrial	Industrial	Industrial	Industrial
	Other land-based extraction 20.9%	Mining for coal 46.7%	Iron or steel production (iron ore) 83.3%	Mining for coal 82.1%	Mining for coal 71.7%

Notes: PM_{10} = particulate matter less than 10 micrometres in diameter; $PM_{2.5}$ = particulate matter less than 2.5 micrometres in diameter

Figure 20 shows the spatial distribution of $PM_{2.5}$ and PM_{10} emissions released from anthropogenic sources across the regions.

Trends in particle emission contributions from major source groups across all regions for the 2003 and 2008 calendar years are summarised in Appendix A.

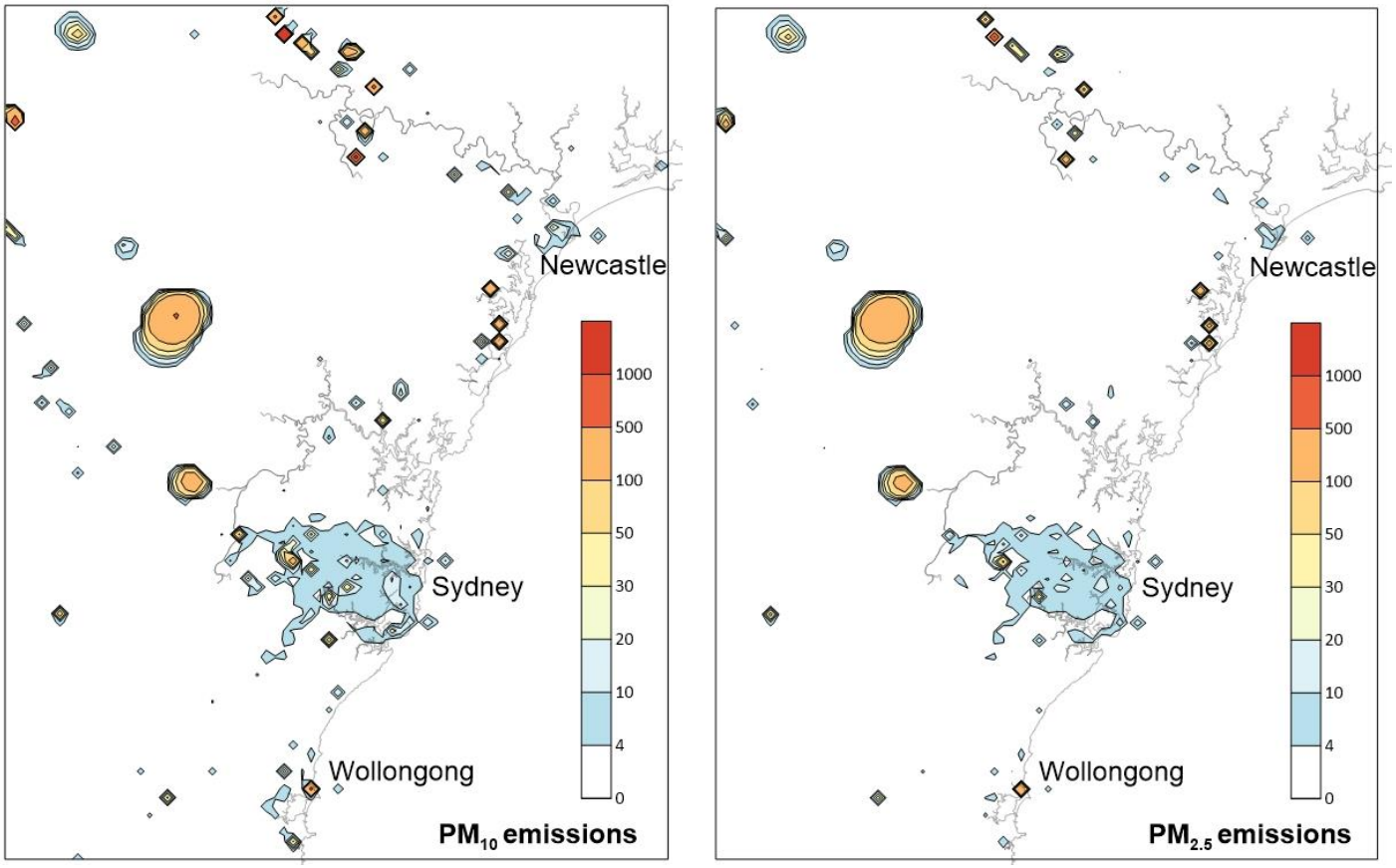


Figure 20 Total emissions (tons/year) across the Sydney, Newcastle, Wollongong and non-urban regions in 2008 for PM_{10} (left) and $PM_{2.5}$ (right). PM_{10} = particulate matter less than 10 micrometres in diameter; $PM_{2.5}$ = particulate matter less than 2.5 micrometres in diameter.

4.1.3 Gaseous emissions

Gaseous pollutants can contribute to the formation of secondary particles in the air. Figures 21–24 present major source group contributions to SO_2, NO_x, VOCs and NH_3 emissions in 2008 for the Sydney, Newcastle, Wollongong, non-urban regions and the NSW GMR. Table 4 summarises the most significant sources that contributed to total SO_2, NO_x, VOCs and NH_3 emissions within each region.

The trends in SO_2, NO_x, VOCs and NH_3 emissions from major source groups across all regions for the 2003 and 2008 calendar years are summarised in Appendix A.

Sulfur dioxide

Industrial sources contributed the greatest proportion of estimated SO_2 emissions across all regions, accounting for 52% of SO_2 emissions in the Sydney region and over 89% in all other regions (Figure 21). The next largest contributor to SO_2 emissions in the Sydney region was off-road mobile sources. Individual industrial sources that made the largest contribution to SO_2 emissions within each region are shown in Table 4.

Oxides of nitrogen

Figure 22 shows that industrial sources accounted for 66% and 78% of NO_x emissions in the Wollongong and non-urban regions. This was also seen across the GMR, with non-urban regions making the greatest contribution. On-road mobile sources accounted for 61% and 41% of NO_x emissions in the Sydney and Newcastle regions respectively, whereas in the Wollongong and non-urban regions these sources contributed 18% and 4% of NO_x emissions. Individual sources that made the largest contribution to NO_x emissions within each region are shown in Table 4.

Volatile organic compounds

Natural and domestic–commercial sources contributed around 60–65% of VOC emissions in the Sydney and Newcastle regions, whereas natural sources dominated all other regions contributing between 40 and 84% of VOC emissions (Figure 23). Vegetation was the largest source of VOC emissions in regions dominated by natural sources, whereas the use of aerosols and solvents was the main contributor to VOC emissions in the Sydney region (Table 4).

Ammonia

Industrial sources were the dominant contributor to NH_3 emissions across all regions except the non-urban regions where the largest contribution was from natural sources (Figure 24).

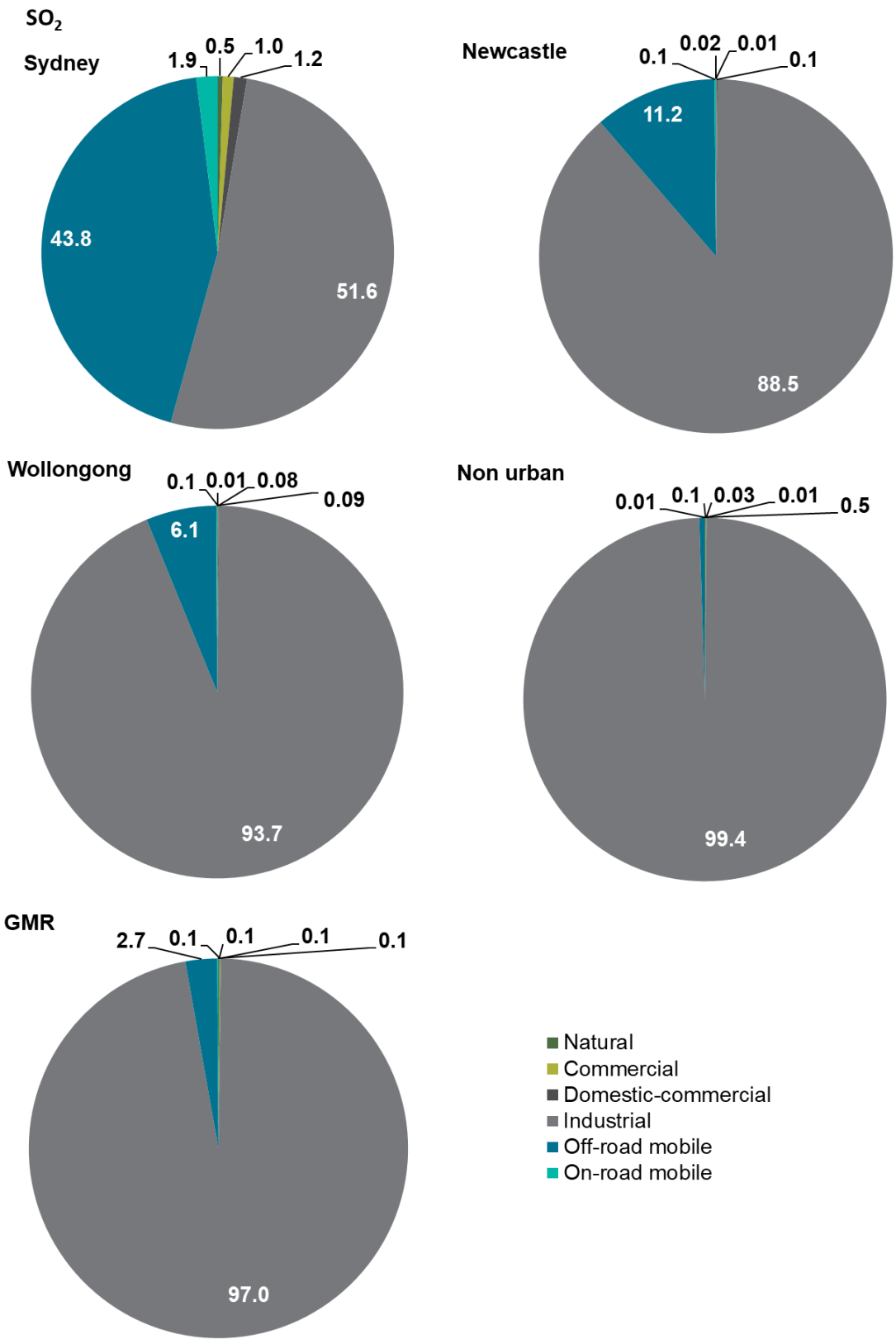


Figure 21 Percentage contribution by major source groups to sulfur dioxide (SO_2) emissions in 2008 for the Sydney, Newcastle, Wollongong, non-urban regions and Greater Metropolitan Region (GMR).

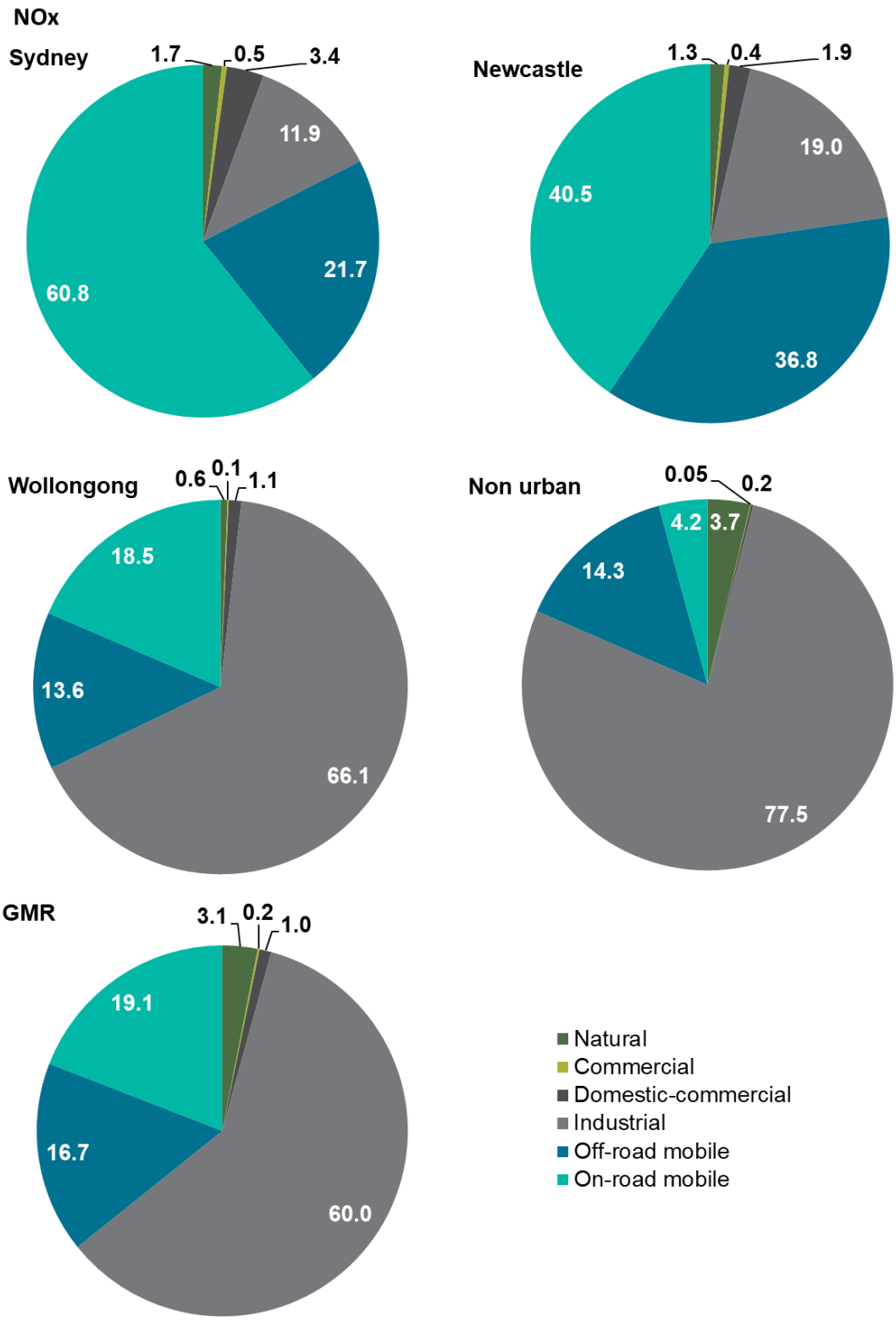


Figure 22 Percentage contribution by major source groups to nitrogen oxides (NO_x) emissions in 2008 for the Sydney, Newcastle, Wollongong, non-urban regions and Greater Metropolitan Region (GMR).

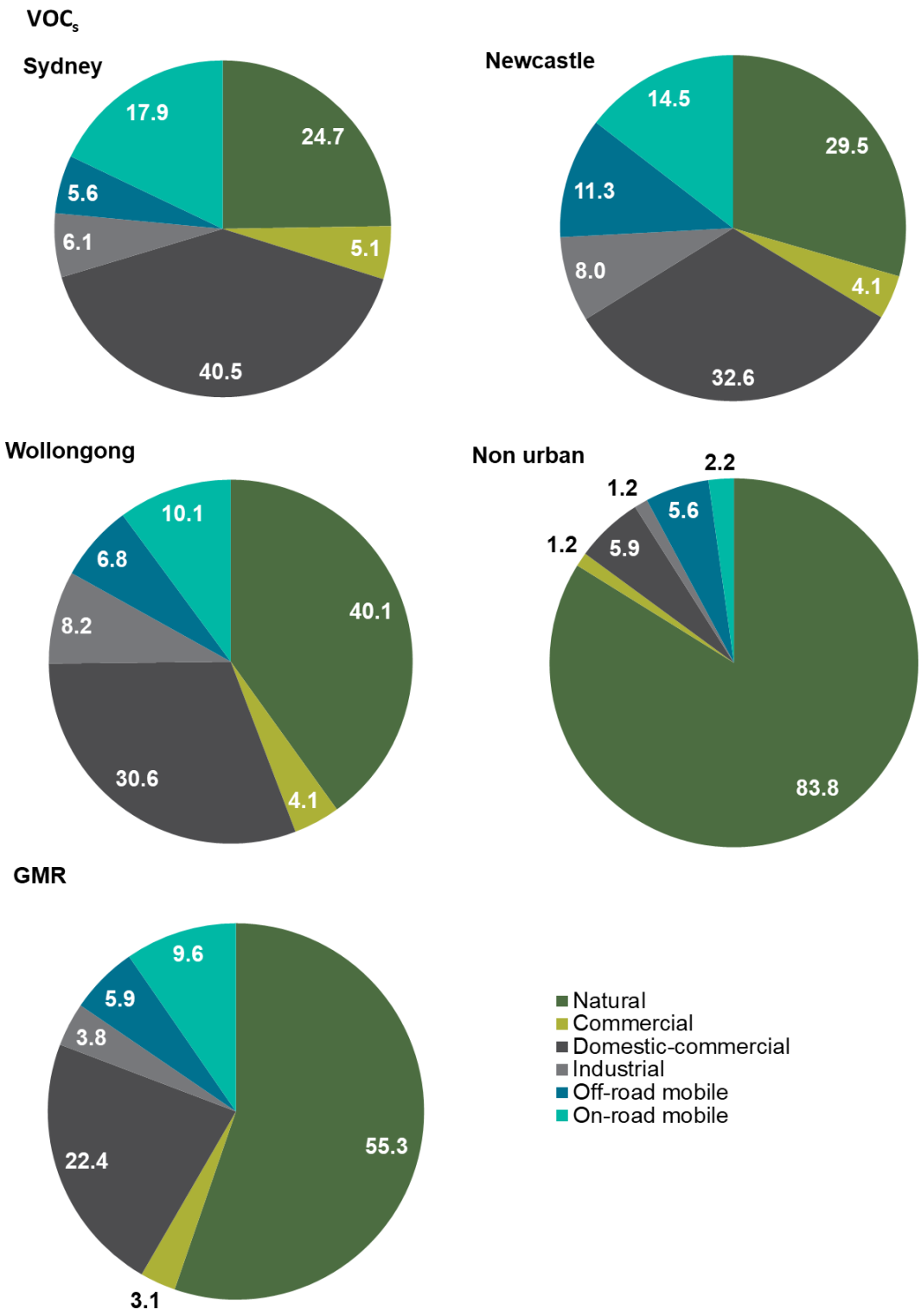


Figure 23 **Percentage contribution by major source groups to emissions of volatile organic compounds (VOCs) in 2008 for the Sydney, Newcastle, Wollongong, non-urban regions and Greater Metropolitan Region (GMR).**

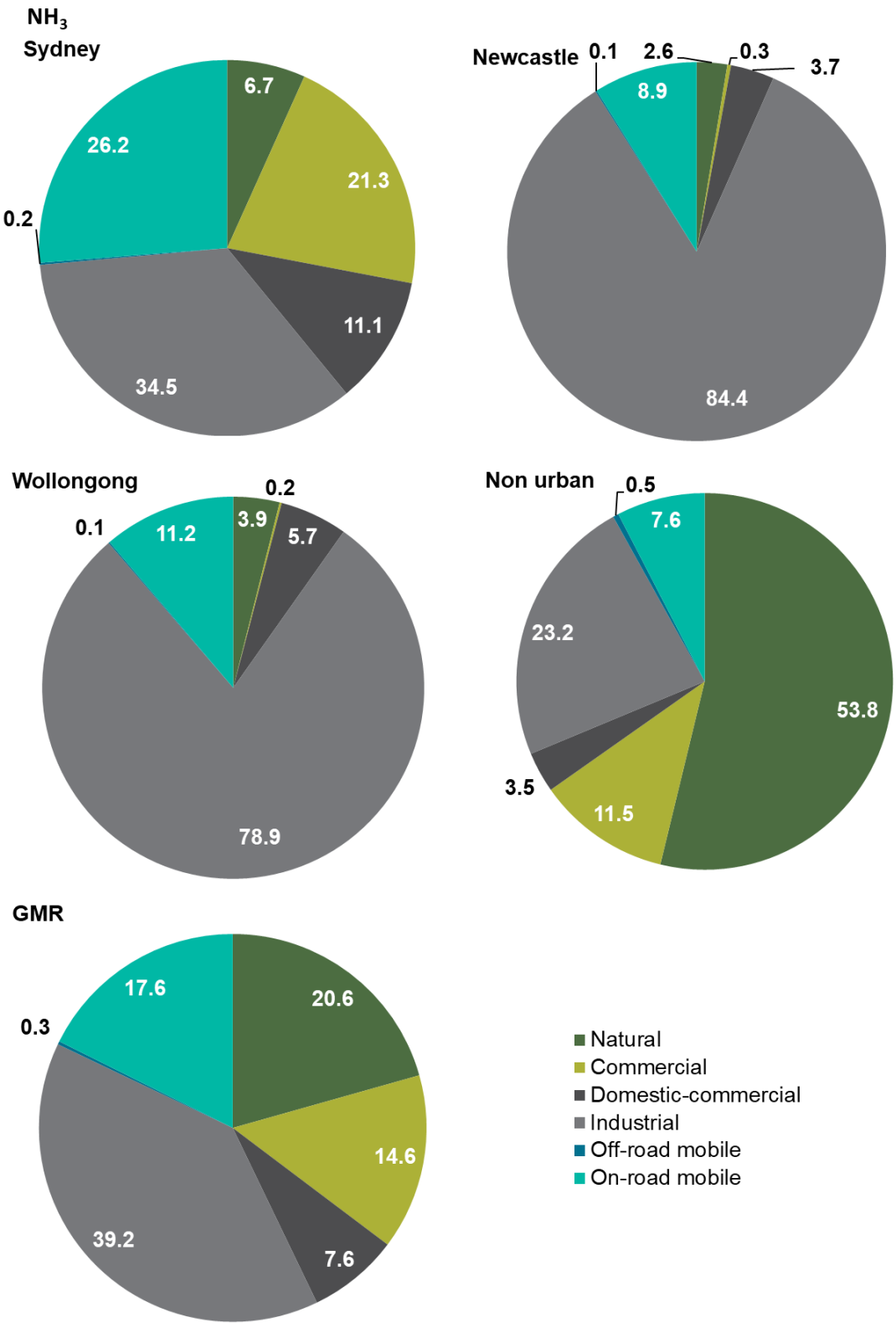


Figure 24 Percentage contribution by major source groups to nitrate (NH_3) emissions in 2008 for the Sydney, Newcastle, Wollongong, non-urban regions and Greater Metropolitan Region (GMR).

Table 1 **Major source groups that made the largest contribution to sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs) and nitrate (NH_3) emissions within the Sydney, Newcastle, Wollongong, non-urban regions and Greater Metropolitan Region (GMR) in 2008**

	Sydney	Newcastle	Wollongong	Non-urban	GMR
SO_2	Industrial	Industrial	Industrial	Industrial	Industrial
	Petroleum products storage 55%	Aluminium production (alumina) 98.6%	Iron or steel production (iron ore) 96.7%	Generation of electrical power from coal 98.2%	Generation of electrical power from coal 89.6%
NO_x	On-road mobile	On-road mobile	Industrial	Industrial	Industrial
	Passenger vehicle petrol exhaust 47.5%	Passenger vehicle petrol exhaust 42.7%	Iron or steel production (iron ore) 96.5%	Generation of electrical power from coal 98.2%	Generation of electrical power from coal 86.7%
VOCs	Domestic–commercial	Natural	Natural	Natural	Natural
	Domestic/commercial Solvents/aerosols 37.5%	Vegetation 99.4%	Vegetation 98.8%	Vegetation 98.5%	Vegetation 98.6%
NH_3	Industrial	Industrial	Industrial	Natural	Industrial
	Waste disposal 25%	Slaughtering or processing of animals 54.3%	Iron or steel production (iron ore) 70.3%	Vegetation 85.1%	Waste disposal 16%

4.2 Trends in industrial emissions

The NPI is the source of industry-reported emission information for Australia. Emissions information is published annually and the inventory provides useful information on yearly changes in industrial emissions for the GMR.

Annual PM_{10}, SO_2, NO_x and VOC emissions from NPI-reporting industrial facilities in the Sydney, Newcastle, Wollongong and non-urban regions, and the GMR for the 2008–09 and 2016–17 periods are shown in Figure 25. A summary and comparison for emissions among various regions are shown in Table 5.

Annual PM_{10} emissions:

- decreased from 2158 tonnes in 2008–09 to 1165 tonnes in 2016–17 in Sydney
- slightly decreased from 1879 tonnes to 1516 tonnes in the Newcastle
- significantly increased from 890 tonnes in 2008–09 to 1494 tonnes in 2016–17 in Wollongong

- increased from 57,659 tonnes in 2008–09 to 71,958 tonnes in 2016–17 in non-urban areas
- increased from 62,585 tonnes in 2008–09 to 76,134 tonnes in 2016–17 in the GMR.

Annual SO_2 emissions from NPI-reporting industrial facilities:

- decreased from 5976 tonnes in 2008–09 to 1802 tonnes in 2016–17 in Sydney
- decreased in non-urban regions from 247,686 tonnes in 2008–09 to 162,554 tonnes in 2016–17
- decreased in the GMR from 269,277 tonnes in 2008–09 to 180,877 tonnes in 2016–17
- slightly increased from 10,148 tonnes in 2008–09 to 10,867 tonnes in 2016–17 in Newcastle
- slightly increased from 5466 tonnes in 2008–09 to 5655 tonnes in 2016–17 in Wollongong.

Annual VOC emissions of 5372 tonnes were reported in 2008–09 in the Sydney region, which reduced by 40% to 3199 tonnes in 2016–17. The next largest reduction in VOC emissions was reported in Newcastle with emissions dropping by 41%. A reduction in VOC emissions between 31–41% was also reported in Wollongong, non-urban regions and the entire GMR over the same period.

Industrial facility NO_x emissions:

- decreased by 22% and 23% in Sydney, reducing from 9600 tonnes in 2008–09 to 7454 tonnes in 2016–17
- decreased in Newcastle from 2428 tonnes in 2008–09 to 1875 tonnes in 2016–17
- decreased in non-urban regions and the GMR by 27% and 25%, respectively
- increased by 28% in Wollongong, from 5280 tonnes in 2008–09 to 6758 tonnes in 2016–17.

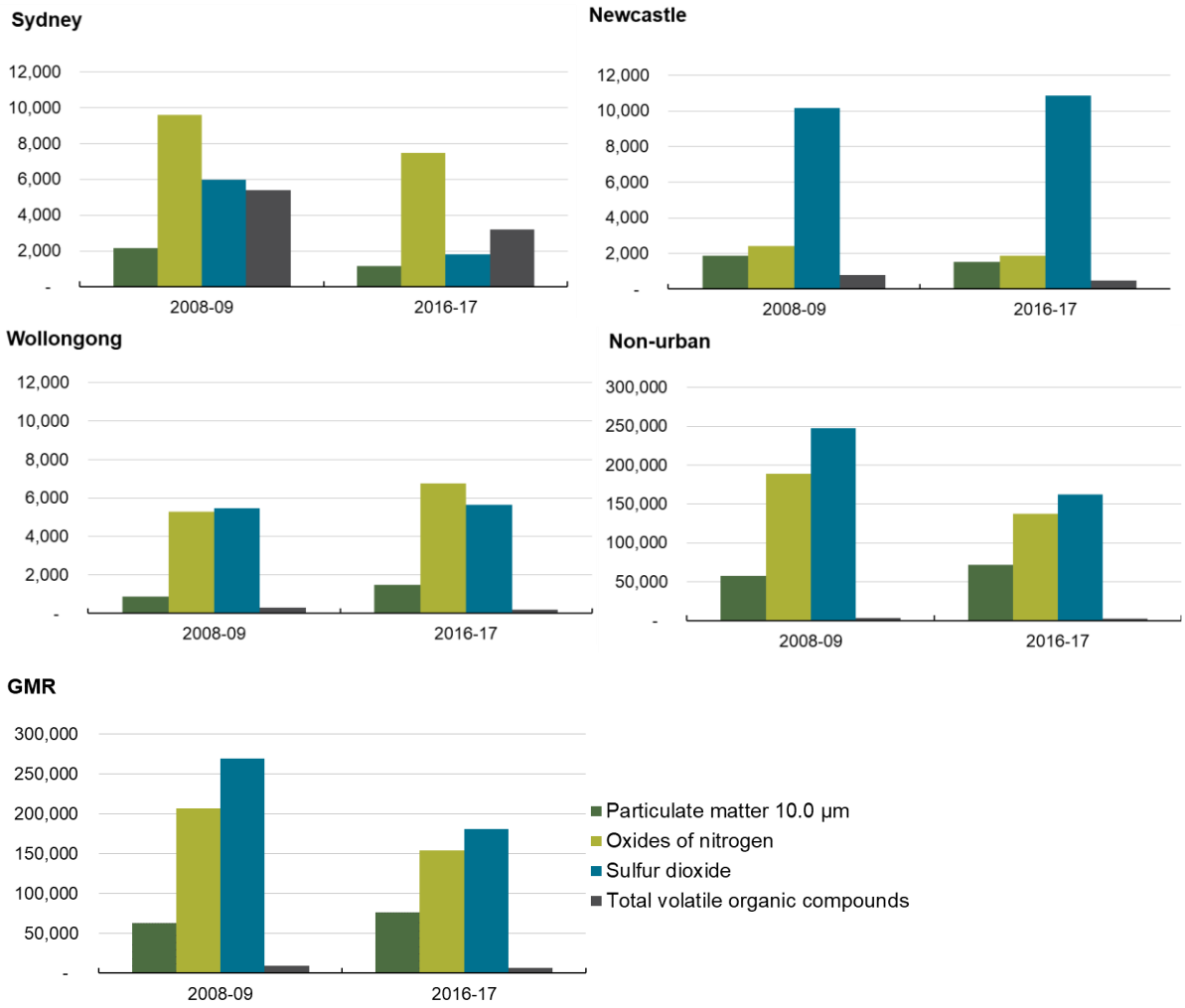


Figure 25 Total industrial facility emissions (tonnes/year) in (a) Sydney, (b) Newcastle, (c) Wollongong, (d) non-urban regions and (e) Greater Metropolitan Region (GMR). µm = micrometres.

Table 5 **Summary of industrial facility emissions for particulate matter smaller than 10 micrometres in diameter (PM_{10}), sulfur dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the Sydney, Newcastle, Wollongong, non-urban regions and Greater Metropolitan Region (GMR)**

Substance	Region	2008–09 Emissions (Tonnes/year)	2016–17 Emissions (Tonnes/year)	Difference
PM_{10}	Sydney	2,158	1,165	–46%
	Newcastle	1,879	1,516	–19%
	Wollongong	890	1,494	68%
	Non-urban	57,659	71,958	25%
	GMR	62,585	76,134	22%
SO_2	Sydney	5,976	1,802	–70%
	Newcastle	10,148	10,867	7%
	Wollongong	5,466	5,655	3%
	Non-urban	247,686	162,554	–34%
	GMR	269,277	180,877	–33%
VOCs	Sydney	5,372	3,199	–40%
	Newcastle	787	486	–38%
	Wollongong	306	181	–41%
	Non-urban	3,031	2,078	–31%
	GMR	9,496	5,943	–37%
NO_x	Sydney	9,600	7,454	–22%
	Newcastle	2,428	1,875	–23%
	Wollongong	5,280	6,758	28%
	Non-urban	188,911	137,609	–27%
	GMR	206,219	153,696	–25%

The projections of SO_2, NO_x, VOCs and NH_3 emissions from major source groups across all regions are summarised in Appendix A.

4.3 Trends in emissions from major sources

4.3.1 On-road mobile sources

Estimates of emissions from on-road mobile sources (i.e., emissions from motor vehicles travelling on-road) for Sydney have been made for base years 1991, 2003, and 2008 (Carnovale et al. 1997; DECC 2007; EPA 2012a). A reduction in on-road mobile emissions occurred in Sydney during this period. From 1992 to 2008, emissions steadily decreased, with NO_x decreasing by 27%, VOCs by 40% and PM_{10} by 20% (Figure 26). These decreases occurred despite increases in gross state product (68%), vehicle kilometres travelled (26%), energy consumption (28%) and population (18%).

Reductions in emissions from 1992 to 2008 were due to more stringent regulation of industry, residential wood heaters, fuel quality and motor vehicle emissions (EPA 2012a).

However, emission projections to 2036 (Figure 26) indicate the level of target pollutants will plateau and then rise gradually without additional actions taken to protect air quality (EPA 2016).

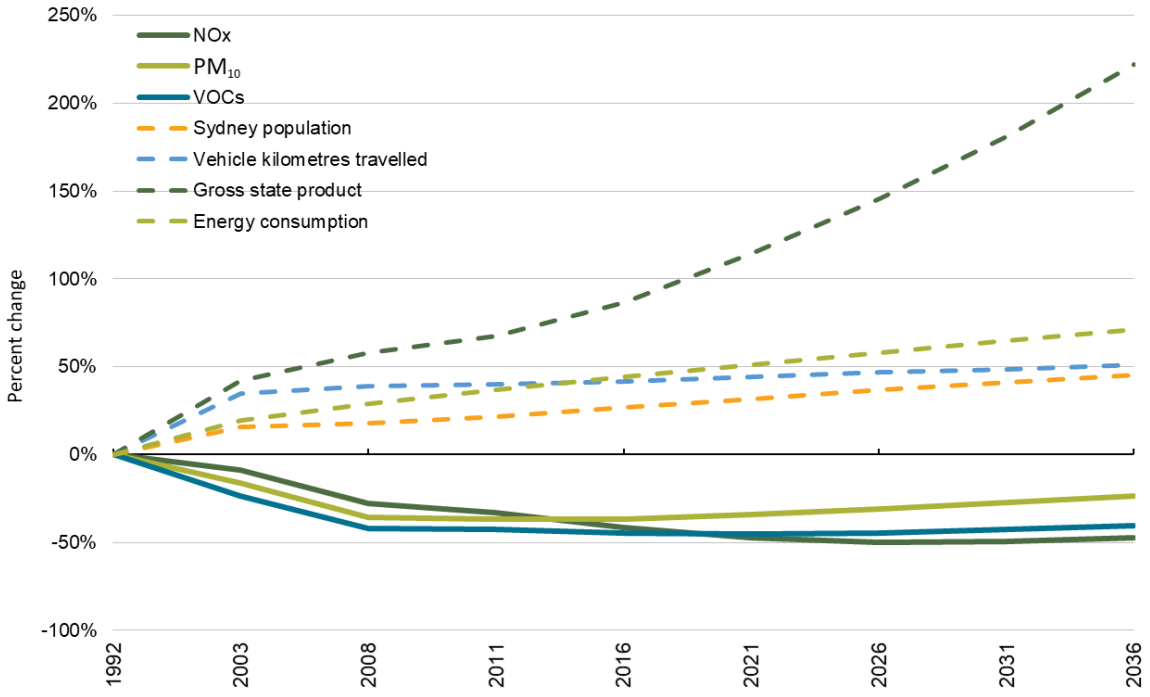


Figure 26 Trends in on-road mobile source emissions in Sydney compared with key NSW statistics. NO_x = nitrogen oxides; PM_{10} = particulate matter smaller than 10 micrometres in diameter; VOCs = volatile organic compounds. Source: adapted from EPA 2012b.

Initiatives implemented over the past decade to reduce emissions from on-road motor vehicles such as cleaner fuels and vehicles, and encouraging people to use transport options other than cars, have delivered significant reductions in emissions (EPA 2012b).

For example, emissions from on-road mobile sources in Sydney decreased significantly from 2008 to 2016, with the highest reductions in carbon monoxide (47%; Table 6). Emissions of ozone precursors NO_x (36%) and VOCs (28%) decreased, as did $PM_{2.5}$ emissions (26%).

Table 6 Emissions from on-road mobile sources in Sydney for 2008 and 2016

On-road mobile pollutant	Emissions tonnes/year		Change (%)
	2008	**2016**	
PM_{10}	2,110	1,744	–17.3
$PM_{2.5}$	1,553	1,153	–25.7
NO_x	45,392	28,940	–36.2
VOCs	23,512	16,837	–28.4
SO_2	210	171	–18.4
CO	123,712	65,227	–47.3

Notes: CO = carbon monoxide; NO_x = nitrogen dioxide; $PM_{2.5}$ = particulate matter 2.5 micrometres or less in diameter; PM_{10}, = particulate matter 10 micrometres or less in diameter; SO_2 = sulfur dioxide; VOCs = volatile organic compounds. Source: DECC 2007; EPA 2012a; EPA 2017

Passenger petrol and heavy-duty diesel vehicle exhausts are the largest on-road mobile sources of NO_x emissions (Figure 27). Non-exhaust emissions (e.g., break and tyre wear) and heavy-duty commercial diesel exhaust emissions are the most significant on-road sources of particle emissions.

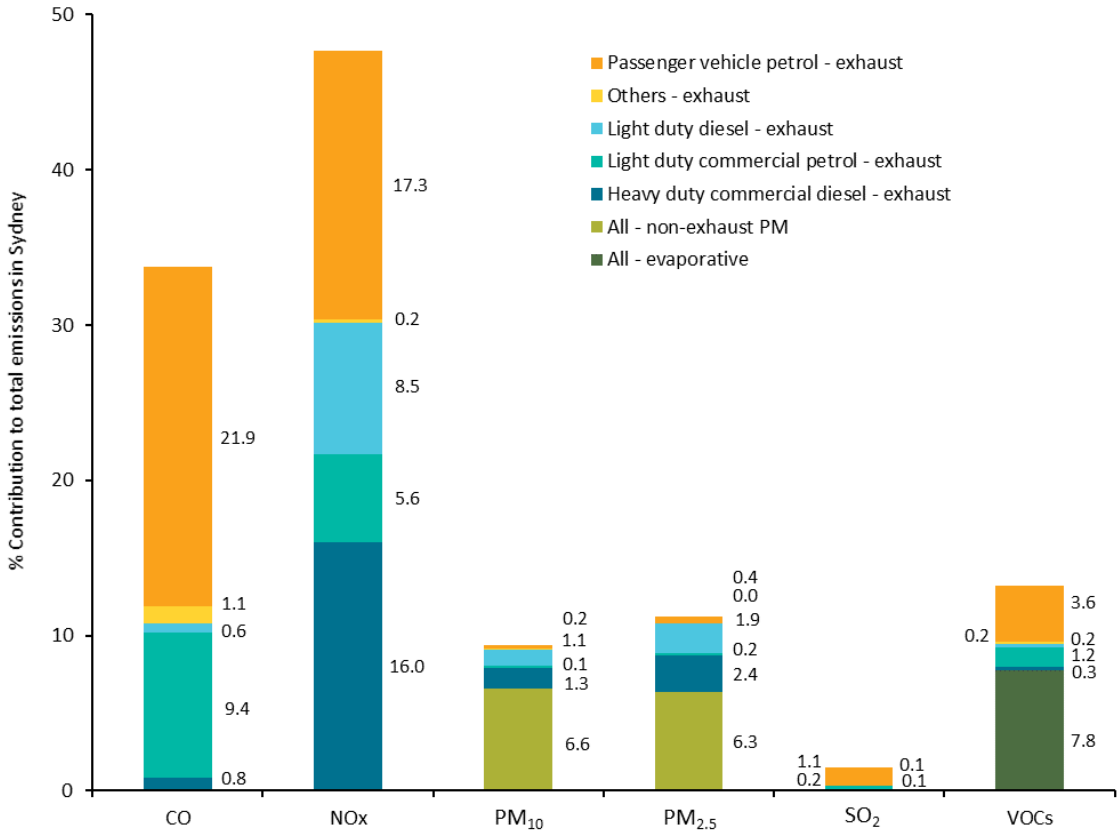


Figure 27 Contribution of on-road mobile sources, carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter smaller than 10 micrometres (PM_{10}) and 2.5 micrometres ($PM_{2.5}$) in diameter, sulfur dioxide (SO_2), volatile organic compounds (VOCs), to total Sydney emissions in 2016. Source: EPA 2012a; EPA 2017

4.3.2 Coal-fired power generation

There are currently five base-load power stations in NSW that generate electricity from coal combustion. These power stations are located at Bayswater, Liddell, Eraring, Mt Piper and Vales Point and have a combined power generating capacity of 10,240 megawatts (MW) (Australian Energy Market Operator, 2016). In recent years, coal-fired power generation accounted for about 80% of electricity generated in NSW (Figure 28). Coal-fired power generation output has reduced because the Wallerawang, Redbank and Munmorah power stations have been retired.

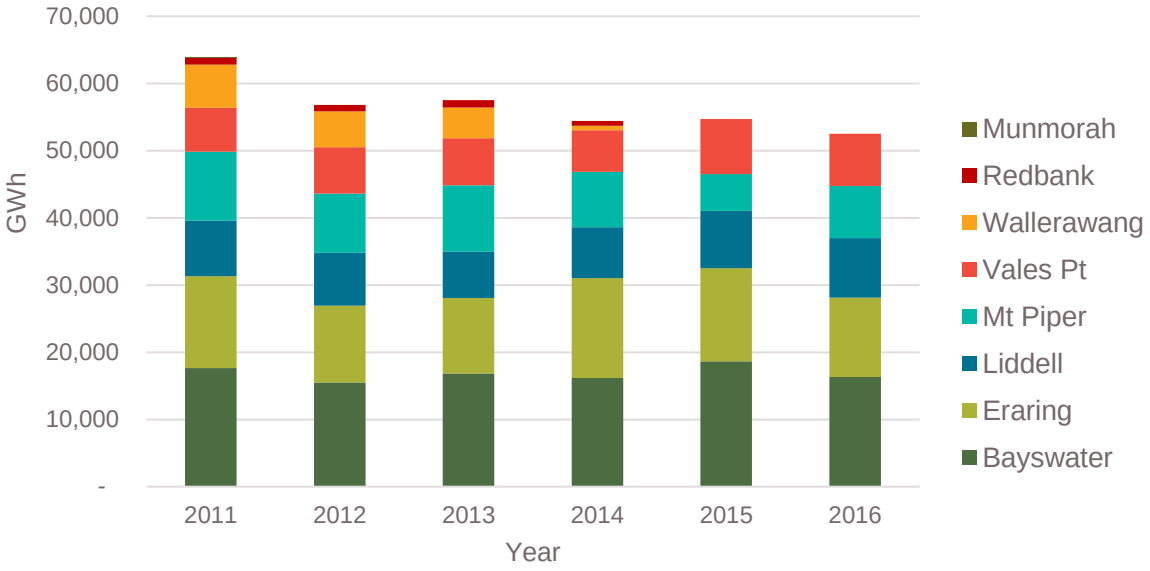


Figure 28 Historical coal-fired energy generation in NSW. GWh = gigawatt hours. Source: Australian Energy Market Operator, 2016

A study by Frontier Economics (2016) modelled the energy generation outlook for NSW using the modelling approach, scenarios and assumptions applied by the Australian Energy Market Operator (AEMO). The study forecast business as usual (baseline) energy generation rates by individual coal-fired power stations in NSW to 2044/2045, and changes to generation rates due to energy efficiency and clean energy measures. Modelling was conducted for three scenarios:

- a 'baseline' scenario, which uses the AEMO National Electricity Forecasting Report for 2016 (AEMO, 2016) medium demand forecast
- two 'demand shock' scenarios, with the impact of potential energy efficiency and clean energy measures modelled as a reduction in demand.

Trends in annual SO_2 emissions from coal-fired power generation for baseline and demand shock scenarios are illustrated in Figure 29.

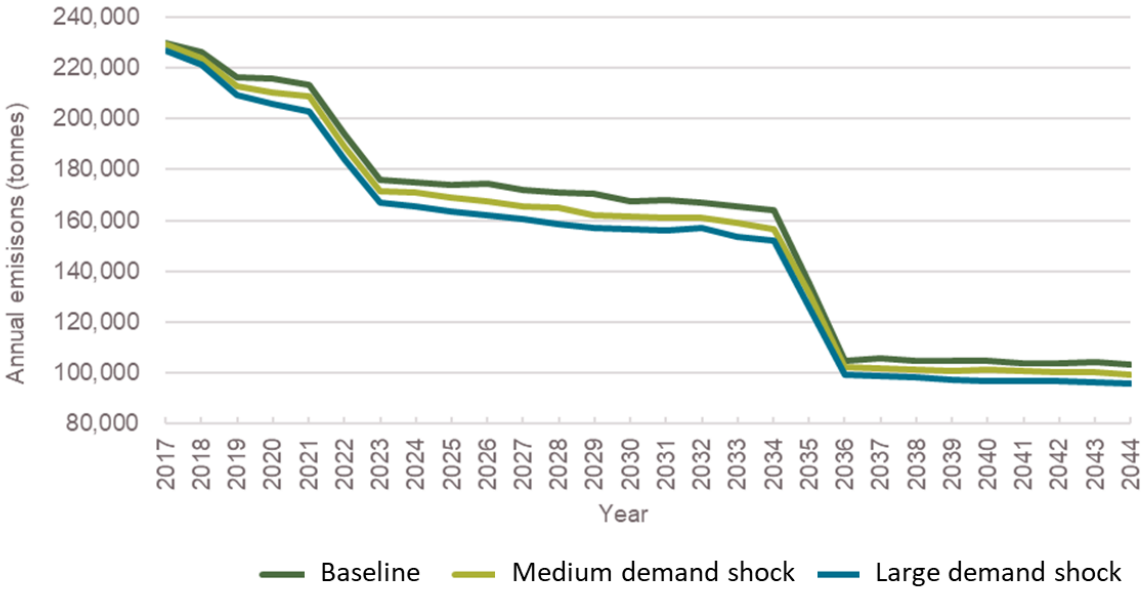


Figure 29 Projected annual sulfur dioxide emissions for NSW coal-fired power generators for baseline and demand shock scenarios. Source: Frontier Economics 2016

4.3.3 Residential wood heating

Wood combustion and associated $PM_{2.5}$ emissions from 2003 to 2013 are shown in **Error! Reference source not found.**. Wood smoke emissions peaked in the NSW GMR in 2008. Since then there has been a small reduction in emissions from wood heaters. This is mostly due to uptake of wood heaters with better emission controls and reduction in firewood burnt by about 8% from 2008 to 2013. Figure 31 shows the main sources of energy for heating in NSW households from 2005 to 2014. About 10% of household in NSW used wood heaters as their main heating source during winter months.

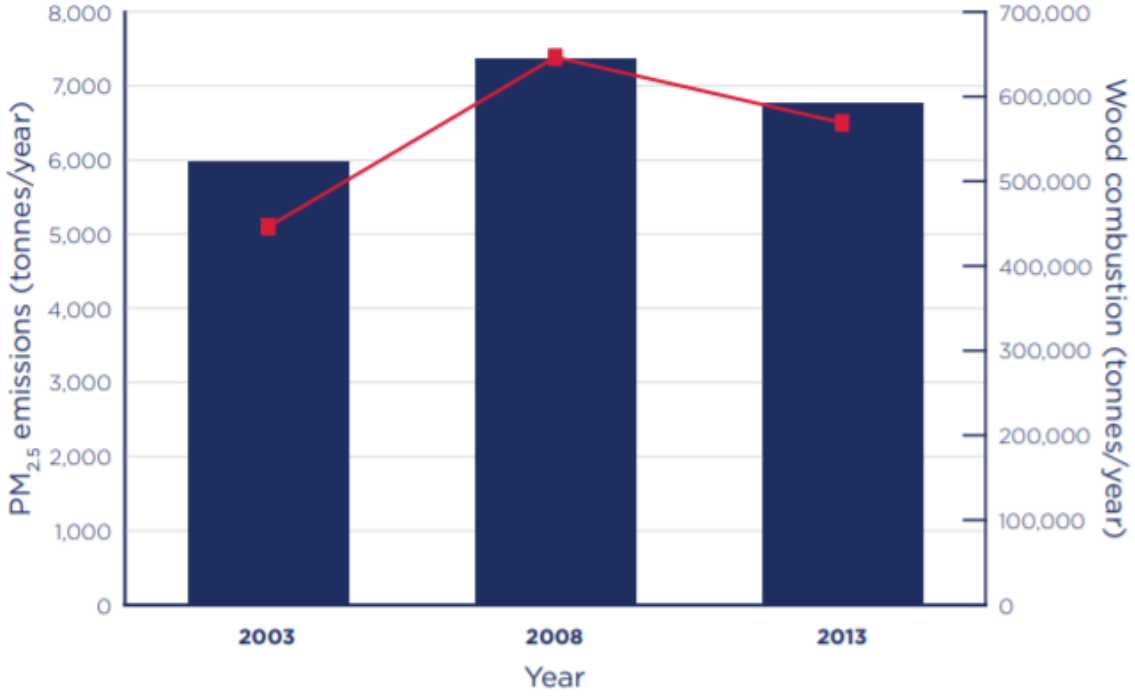


Figure 30 Emissions of particulate matter 2.5 micrometres or less in diameter ($PM_{2.5}$) from residential wood heating and wood combustion in NSW from 2003 to 2013. Source: EPA 2017

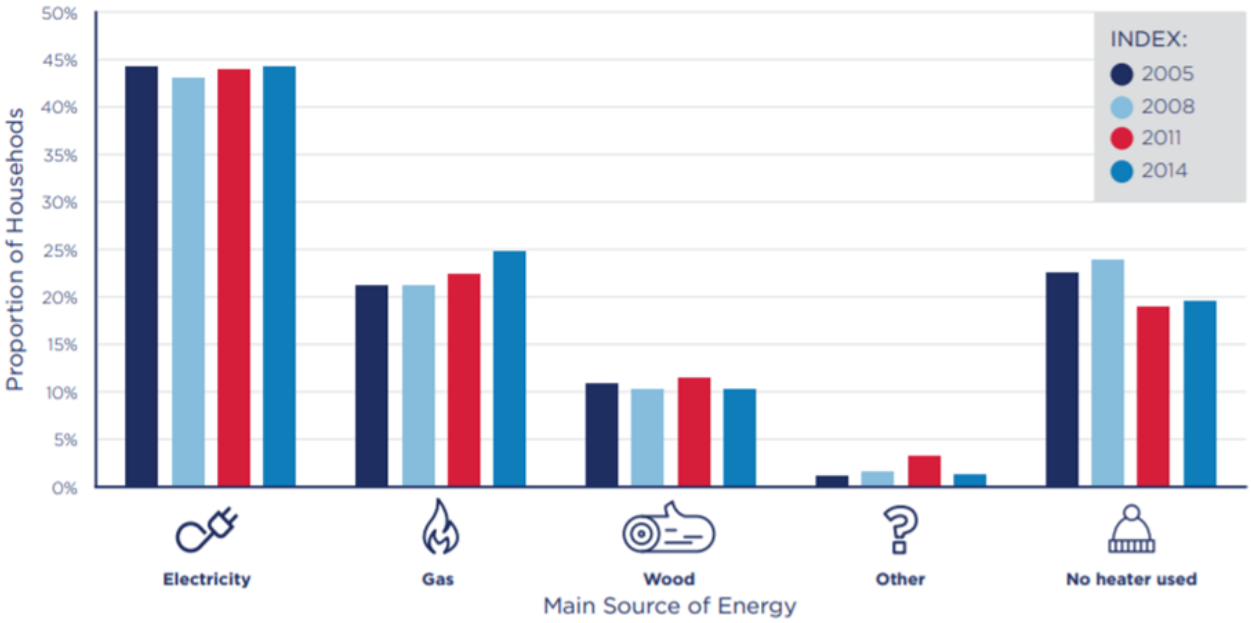


Figure 31 Main sources of energy for heating NSW households from 2005 to 2014. Source: EPA 2017

4.3.4 Non-road sector emissions

Despite the introduction of increasingly stringent national emissions standards for on-road diesel trucks and vehicles since 1996, there are no similar national standards in place controlling emissions from non-road diesel plants and equipment. This includes non-road diesel powered construction and mining equipment, rail locomotives, equipment at ports, and ships. The non-road sector is the largest source of fine particle emissions that remains largely unregulated.

$PM_{2.5}$ emissions from non-road sources (primarily emitted from diesel vehicles and equipment) were estimated to increase by 17% between 2003 and 2008, despite reductions in regulated on-road and industrial sources. In 2008, industrial vehicles and equipment accounted for 56% of $PM_{2.5}$ emissions from non-road mobile sources, with shipping and locomotive emissions contributing 20% and 16% respectively.

More information on $PM_{2.5}$ emissions from shipping drawn from the national shipping air emissions inventory (NSW EPA 2015) indicates that many ships are powered by large engines operating on high sulfur fuel and emit high levels of fine particles and sulfur dioxide. $PM_{2.5}$ emissions from shipping within the Port Kembla area in 2010–11 were estimated to be about 51 tonnes/year (Goldsworthy & Goldsworthy 2015).

At Port Kembla, most $PM_{2.5}$ shipping emissions were estimated to occur when vessels were at berth, with auxiliary engines being the most significant source of emissions (Figure 32). Although emissions associated with ships at anchor were relatively low, it is notable that most anchorage associated with Port Kembla occurs outside port boundaries (and therefore is not included in the inventory for the port).

(a) (b)

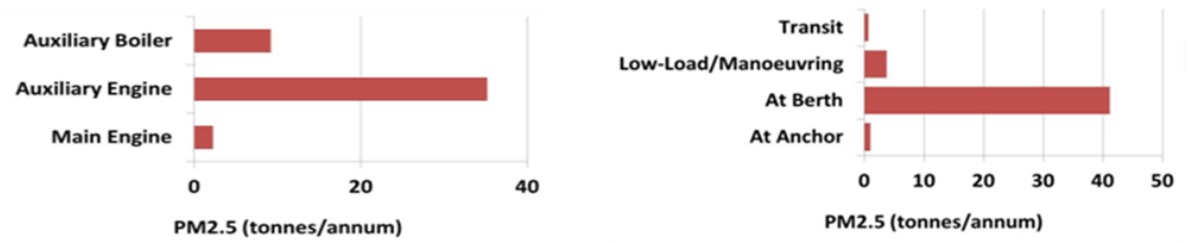


Figure 32 $PM_{2.5}$ shipping emissions for Port Kembla in 2010–11 by (a) machinery type and (b) activity. Source: Goldsworthy & Goldsworthy 2014

Most fine-particle emissions from shipping at Port Kembla in 2010–11 were estimated to come from bulk carriers (51%), general cargo (21%) and vehicle carriers (21%). Emissions for general cargo activity in 2012–13 at Port Kembla had reduced by about 25%, with little change in bulk exports (Goldsworthy & Goldsworthy 2014).

5. Regional airshed modelling

Air quality in Sydney is comparable with other cities in Australia and good by world standards. However, particle pollution and ozone concentrations occasionally exceed national air quality standards (see section 3). The New South Wales (NSW) Air Quality Monitoring Network delivers robust, continuous air pollution data from stations at various locations across NSW. Regional airshed modelling is a powerful tool which provides projected high-resolution spatial and temporal variations in air pollution for an entire region, not just at air monitoring stations. Airshed modelling is also widely used for air quality management and estimating exposure of a population to air pollution and related health impacts.

5.1 Model descriptions

The coupled Conformal Cubic Atmospheric Model (CCAM) and Chemical Transport Model (CTM; hereafter, the CCAM–CTM modelling system) allows for the modelling of continental scale emissions, thus improving estimates of background air pollution concentrations.

We used the CCAM–CTM in this study to model regional air quality in the NSW Greater Metropolitan Region (GMR) and investigate the characteristics of criteria pollutants. The estimates from the CCAM–CTM also provide the necessary information as the exposure input into health impact assessments.

The modelling system we used included the CCAM meteorology module, anthropogenic and natural emission modules, and a CTM (Figure 33).

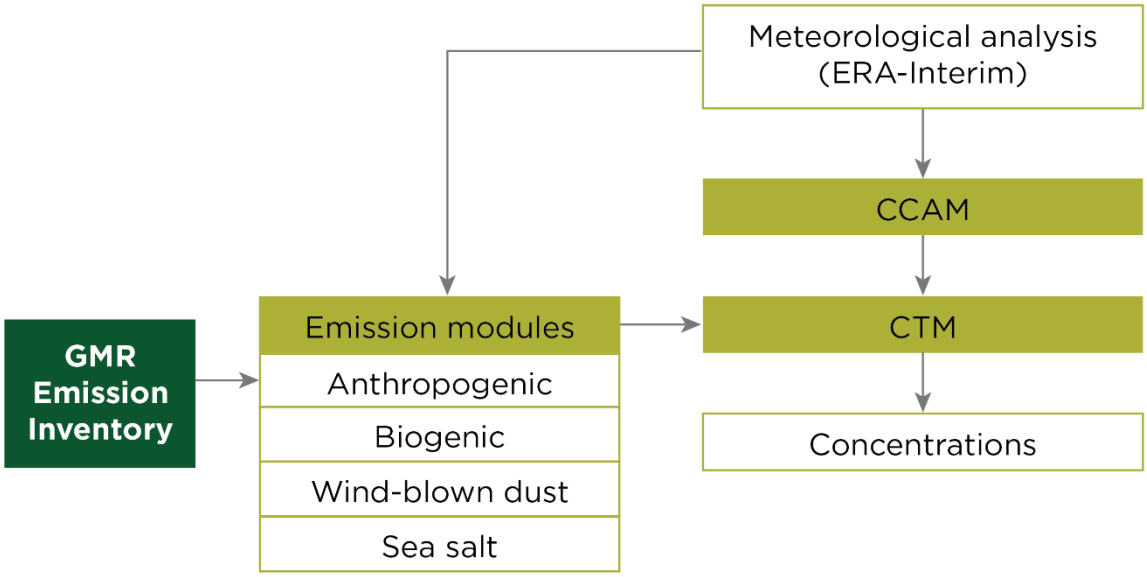


Figure 33 Schematic diagram of the Conformal Cubic Atmospheric Model (CCAM) and Chemical Transport Model (CTM; CCAM–CTM modelling system) used in this study. ERA-interim = European Reanalysis Interim; GMR = Great Metropolitan Region.

CCAM–CTM modelling uses four nested domains, which include:

1. the outermost Australian domain (CTM AUS) at 80 x 80 kilometre resolution (75 x 65 grid cells)
2. the New South Wales domain (CTM NSW) at 27 x 27 kilometre resolution (60 x 60 grid cells)

3. the Greater Metropolitan Region domain (CTM GMR) at 9 x 9 kilometre resolution (60 x 60 grid cells)
4. the innermost domain covering the Greater Sydney region (CTM GSYD) at 3 x 3 kilometre resolution (60 x 60 grid cells).

The configuration of the CTM GMR and CTM GSYD domains is shown in Figure 34. CCAM–CTM was run for the whole of 2008 to predict air pollution levels by criteria pollutant.

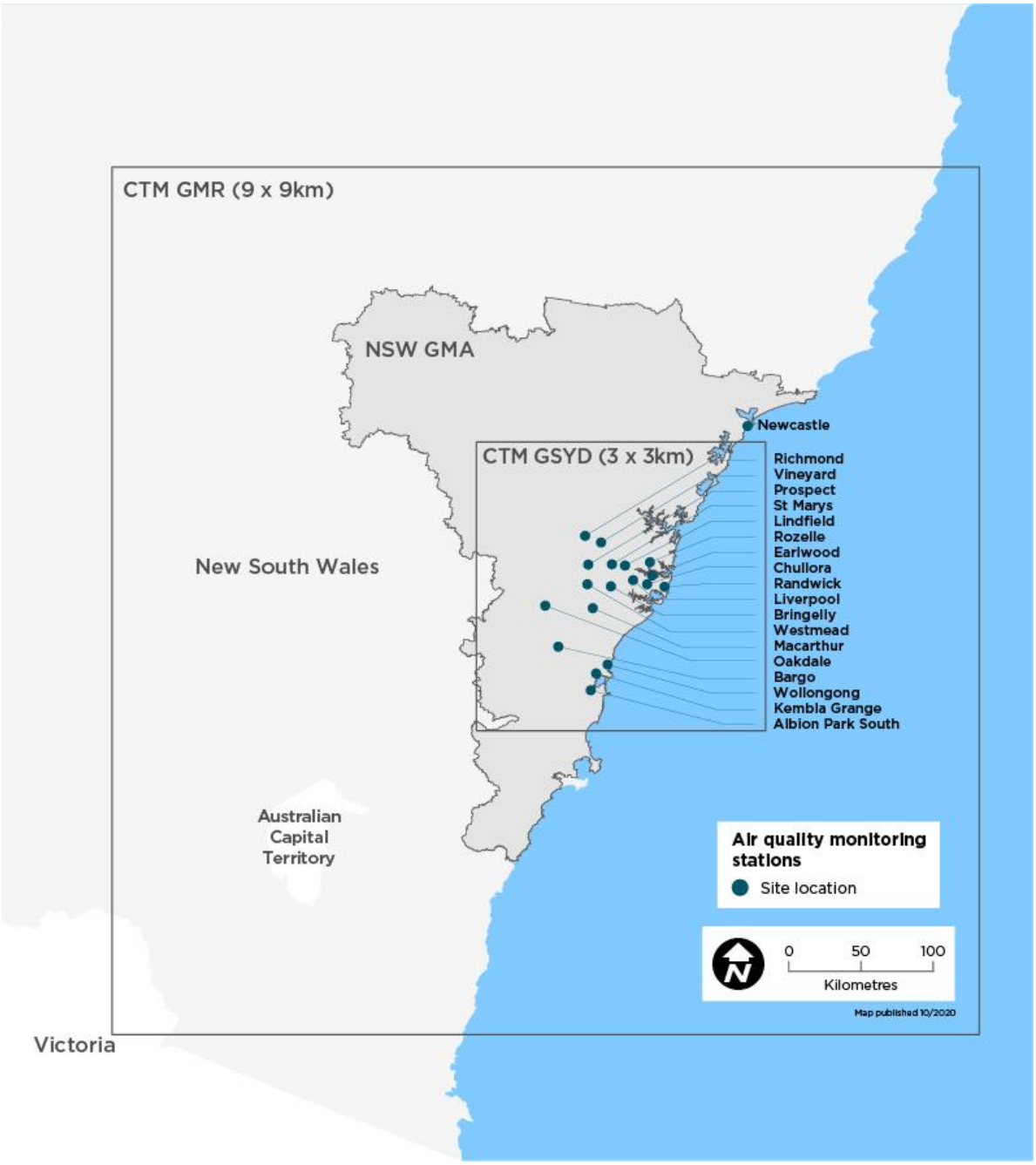


Figure 34 Modelling domains for the NSW Greater Metropolitan Region (Chemical Transport Model (CTM GMR) and Greater Sydney (CTM GSYD). The NSW Greater Metropolitan Area (NSW GMA) domain as defined in the Clean Air Regulation 2010 is also shown. Locations of NSW air quality monitoring stations referenced in the study are identified with blue dots.

5.1.1 Meteorological module

CCAM is a semi-implicit, semi-Lagrangian atmospheric climate model based on the conformal cubic grid (McGregor and Dix 2008). Further details on the design of CCAM can be found in a report by McGregor (2005).

We used data from the European Reanalysis Interim (ERA-Interim), a global atmospheric reanalysis produced by the European Centre for Medium-Range Weather forecasts, as the host general circulation model (GCM). This data was fed into CCAM and downscaled into four nested domains (see section 5.1) The 35 vertical level configurations of CCAM were also used. The model configurations of CCAM we used are summarised in Table 7.

Table 7 Conformal Cubic Atmospheric Model (CCAM r3019, released May 2016) configurations used in this study

Model Version: CCAM r3019 (released May 2016)		
Model specifications		
Domain	Number of nests	4
	Horizontal resolution (for each nest)	80 kilometres (km), 27 km, 9 km, 3 km
	Number of ‘x’ grid points (per nest)	75, 60, 60, 60
	Number of ‘y’ grid points (per nest)	65, 60, 60, 60
	Number of vertical layers	35
	Height of first layer	10 metres
Initial and boundary conditions	Meteorology input	European Reanalysis Interim (ERA)-Interim
	Analysis and initialisation	CCAM use a scale-selective filter to assimilate (or nudge) CCAM towards the ERA-Interim data
Parameterisations	Microphysics scheme	Cloud microphysics with prognostic condensate (Rotstayn 1997)
	Longwave radiation scheme	Schwarzkopf and Ramaswamy (1991)
	Shortwave radiation scheme	Freidenreich and Ramaswamy (1999)
	Land surface scheme	Community Atmosphere–Biosphere Land Exchange model (CABLE) (Kowalczyk et al 2006)
	Planetary boundary layer/turbulence scheme	McGregor et al (1993) and Holtslag and Boville (1993)
	Convection scheme	McGregor (2003)
	Aerosol scheme	Rotstayn and Lohmann (2002)
Planetary boundary layer height (PBLH) calculations	Description	Equation 3.11 documented in Holtslag and Boville (1993), use a critical bulk Richardson number of 0.25 (not 0.5 as in the paper).

5.1.2 Emissions modules

The anthropogenic emissions input into modelling was taken from the NSW Environment Protection Authority (EPA) Air Emissions Inventory for the GMR in NSW for calendar year 2008 (NSW EPA 2012). The inventory is updated every 5 years, and the 2013 calendar year emissions inventory had not been released at the time this modelling study was undertaken. This inventory comprises detailed source and emissions data for over one hundred industrial, commercial, transport, agricultural and residential activities, and over one thousand pollutants. Emissions from natural sources including wind-blown dust, marine aerosol and volatile organic compounds (VOCs) from vegetation, are calculated in-line within the CTM, as documented by Cope et al. (2009 and 2014). Emissions from vegetation fires were not accounted for in this study.

The 2008 NSW EPA Air Emissions Inventory data were segregated into four categories comprising 16 major source groups to facilitate regional airshed modelling (Table 8).

The categories cover:

- On-road motor vehicles – includes emissions from petrol exhaust, diesel exhaust, other exhaust, petrol evaporation and non-exhaust particulate matter
- Non-road diesel and marine – includes emissions from shipping and commercial boats, industrial vehicles and equipment, aircraft (flight and ground operations), locomotives and commercial non-road equipment
- Industrial point sources – comprises emissions from gas- and coal-fired power generation and all other industrial stack or vent emissions
- Other industrial, commercial and domestic–commercial sources – includes residential wood heating, industrial area source emissions as separate major source group, and with all other sources in this category combined in a third group.

Point sources were modelled at specific location with stack properties (stack height and radius, gas exit temperature and velocity) being input. Other emissions were provided as area sources with emission rates allocated over a 1 x 1-kilometre grid covering the GMR.

Weekday and weekend time-resolved emission profiles for each month were developed for each source group listed in Table 8 from the 2008 NSW GMR Air Emissions Inventory. Each emission profile consisted of 17 species: nitric oxide(NO), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), particulates (particulate matter less than 10 micrometres in diameter (PM_{10})), higher aldehydes, ethene, ethanol, formaldehyde, isoprene, methanol, alkenes (olefins), alkanes (paraffins), toluene, unreactive species, xylene, and ammonia (NH_3). Emissions for other species (e.g., particulate matter less than 2.5 micrometres in diameter ($PM_{2.5}$), elemental carbon, organic carbon, dust, levoglucosan, sulfur trioxide (SO_3), extended set of VOC species) required for the CTM were estimated and modelled by applying source-dependent fractions (see Appendix B).

Petrol exhaust, diesel exhaust, petrol evaporation and residential wood heater emissions were further scaled in-line within the CCAM–CTM modelling system based on the modelled ambient temperature at each grid point. February 2008 was used as the reference month for petrol exhaust, diesel exhaust and petrol evaporation emissions, with temperature-adjusted emissions for other months based on this reference month. Residential wood heater emissions were varied by heating degree days, which were calculated based on the modelled ambient temperature using July 2008 as the reference month and temperature-adjusted emissions calculated for other months.

Table 8 The four categories and 16 major source groups segregated from the 2008 NSW Environment Protection Authority Air Emissions Inventory for the Greater Metropolitan Region in NSW

Category		Major source group
On-road motor vehicles	1	Petrol exhaust
	2	Diesel exhaust
	3	Other exhaust
	4	Petrol evaporation
	5	Non-exhaust particulate matter
Non-road diesel and marine	6	Shipping and commercial boats
	7	Industrial vehicles and equipment
	8	Aircraft (flight and ground operations)
	9	Locomotives
	10	Commercial non-road equipment
Industrial point sources	11	Power generation from coal
	12	Power generation from gas
	13	Other industrial point sources (all point-source emissions except power generation from coal and gas)
Other industrial, commercial and domestic–commercial area sources	14	Residential wood heating
	15	Industrial area fugitive emissions
	16	Other domestic–commercial area source emissions (non-road diesel and marine sources and wood heating are excluded)

Spatial distribution of total PM_{10}, $PM_{2.5}$, NO_x, VOCs, SO_2 and NH_3 emissions released from anthropogenic sources are illustrated in Figure 35. The spots in the north-west quadrants of maps (a), (b) and (e) in Figure 35 represent emissions from coal-fired power stations at Mount Piper and Wallerawang in the Central Tablelands region.

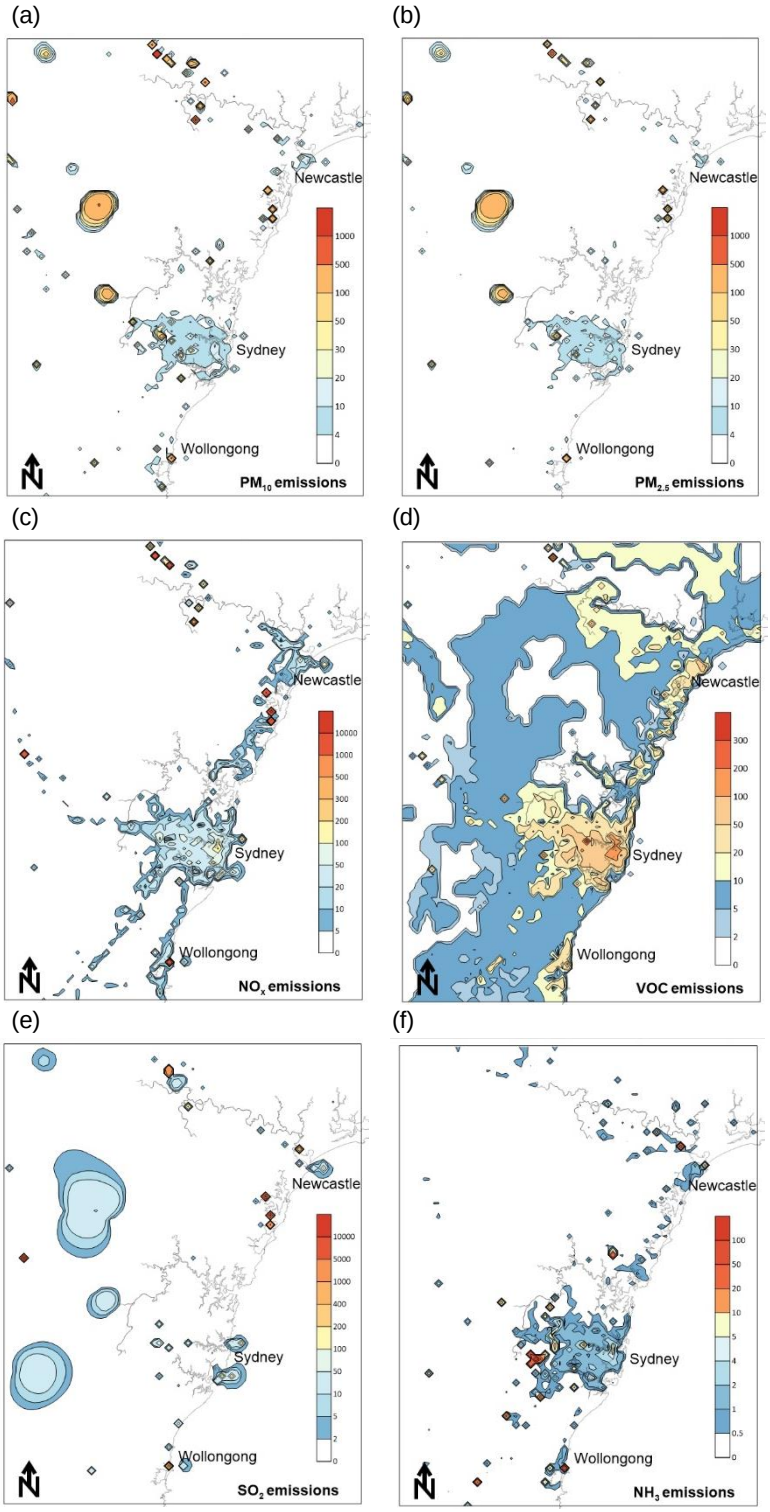


Figure 35 Total emissions (tons/year) of: (a) particulate matter less than 10 micrometres in diameter (PM_{10}); (b) particulate matter less than 2.5 micrometres in diameter ($PM_{2.5}$); (c) nitrogen oxides (NO_x); (d) volatile organic compounds (VOCs); (e) sulfur dioxide (SO_2); and (f) ammonia (NH_3). Source: 2008 NSW Environment Protection Authority Air Emissions Inventory for the NSW greater Metropolitan Region.

5.1.3 Chemical transport modelling

Chemical transport modelling was conducted using the CSIRO CTM (Cope et al. 2004). This CTM is a three-dimensional Eulerian model able to model the emission, transport, chemical transformation, wet and dry deposition of coupled gas-and-aerosol-phase atmospheric systems.

The photochemical mechanisms used in the CTM in this study were an extended version of the carbon bond mechanism (CB05; Sarwar et al. 2008) with updated toluene chemistry (Sarwar et al. 2011). As documented by Cope et al. (2014), secondary inorganic aerosols were assumed to exist in thermodynamic equilibrium with gas phase precursors and were modelled using the ISORROPIA II model (Fountoukis and Nenes 2007). Secondary organic aerosol was modelled using the volatility basis set approach (Donahue et al. 2006). The configurations for the CTM used in this study are summarised in Table 9.

Concentrations of gas and particulate-phase species at the model boundaries were adapted from a global run of the United Kingdom Chemistry and Aerosol scheme (UKCA) for the UK Met Office Unified Model. Chemical boundary conditions for the nested inner domains were then provided by the parent domain CTM runs.

Detailed particle size and component information is required as input into the CTM to simulate particle nucleation, coagulation and condensational growth. Due to the constraints of emissions inventory data, the CTM was run as a single moment model with particle size and chemical speciation information provided for $PM_{2.5}$ and PM_{10}.

Table 9 Configurations of the chemical transport model (CTM) used in this study

Model version: CTM r1057 (released August 2016)		
Model specifications		
Domain	Number of nests	4
	Horizontal resolution (for each nest)	80 kilometres (km), 27 km, 9 km, 3 km
	Number of ‘x’ grid points (for each nest)	75, 60, 60, 60
	Number of ‘y’ grid points (for each nest)	65, 60, 60, 60
	Number of vertical layers	35
	Height of first layer	10 metres
Initial and boundary conditions	Chemical boundary conditions	United Kingdom Chemistry and Aerosol model (UKCA; a mixture of UKCA for particles, and recommendations from Ian Galbally (CSIRO) for VOCs and O_3)
Emissions	Anthropogenic	2008 NSW EPA Air Emissions Inventory for the GMR in NSW
	Biogenic	Calculated in-line with CTM
	Sea-salt	Calculated in-line with CTM
	Dust	Calculated in-line with CTM
Chemical parameterisations	Gas-phase mechanism	Carbon bond mechanism (CB05; Sarwar et al. 2008) with updated toluene chemistry (Sarwar et al. 2011)

	Aerosol modules	Secondary inorganic aerosols were modelled using the ISORROPIA-II model (Fountoukis and Nenes 2007). Secondary organic aerosol was modelled using the volatility basis set approach (Donahue et al. 2006)
	Photolysis scheme	2-dimensional offline scheme (Hough 1988)

5.1.4 Emissions scenarios

Regional airshed modelling was conducted based on the following emissions scenarios to predict air pollutant concentrations for the 2008 calendar year:

1. Base case – emissions from anthropogenic and natural sources (regional wind-blown dust, biogenic emissions, sea salt)
2. Human-made sources – emissions from anthropogenic sources
3. Natural sources – regional wind-blown dust, biogenic emissions and sea salt
4. Power stations – emissions from coal- and gas-power generations (groups 11 and 12 in Table 8)
5. Wood heaters – emissions from residential wood heaters (group 14 in Table 8)
6. On-road motor vehicles – emissions from petrol exhaust, diesel exhaust, other exhaust, petrol evaporative and non-exhaust particulate matter (groups 1–5 in Table 8)
7. Non-road diesel and marine – emissions from shipping and commercial boats, industrial vehicles and equipment, aircraft, locomotives, commercial non-road equipment (groups 6–10 in Table 8)
8. Industry – emissions from all point sources except power generation from coal and gas (group 13 in Table 8)
9. Human-made other – emissions from anthropogenic sources other than groups 1–14 in Table 8, including other commercial and domestic–commercial area source emissions, and industrial area fugitive emissions
10. Biogenic – emissions from biogenic sources
11. Natural other – emissions from regional wind-blown dust and sea salt.

5.2 Model performance evaluation

To assess the performance of the CCAM–CTM modelling system, modelled meteorology and air quality data for 2008 were compared to meteorological and air quality measurements from the NSW Department of Planning, Industry and Environment (DPIE) air quality monitoring stations and the Bureau of Meteorology automatic weather stations. The operational evaluation applied in this study was based on the evaluation framework of Dennis et al. (2010), where model performance metrics were calculated and compared to benchmarks for other modelling studies. The same approach was used by Chang et al (2018) to benchmark and support the application of a modelling system for air quality policy and to inform air quality management in NSW.

5.2.1 Meteorological model performance

CCAM meteorological results were evaluated to assess the model's ability to characterise the meteorological conditions that drive air pollution transport and transformation across the

region. The validation was undertaken for the 2008 CCAM run. CCAM estimates were compared to measurements of temperature, wind speed and wind direction from eight NSW DPIE and six Bureau of Meteorology monitoring stations located across the GMR. Deviations between model predictions and measurements were quantified through statistical tests. CCAM performance metrics were compared to benchmarks for other modelling studies to show whether the CCAM performance was within an acceptable range. Details of this CCAM performance evaluation are presented in Appendix C.

Air temperature was well represented by the CCAM simulation. The CCAM results replicated observed seasonal and diurnal temperature variations. The modelled temperature was slightly warmer but was within referenced benchmarks. The overall diurnal variations and seasonal patterns in the wind field were well represented by the CCAM. Modelled wind speeds were slightly overpredicted, but within reasonable limits of the expected performance of a mesoscale meteorological model used for weather forecasting and research. However, the CCAM simulation tended to predict stronger winds, particularly overnight. This could impact the model's ability to accurately model the dispersion of pollutants and should be considered when assessing the performance of the CTM.

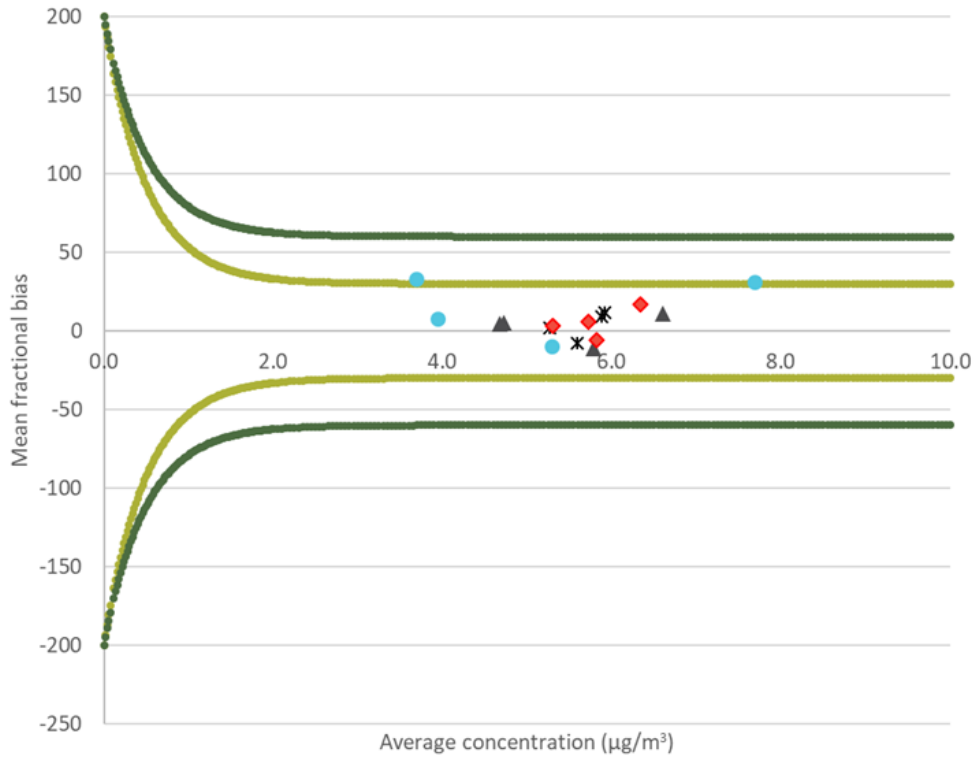
5.2.2 Chemical transport model performance

Air pollutant concentrations modelled for 2008 by the CTM were compared to measured levels from DPIE air quality monitoring stations. Comparisons were made for the Sydney east (Chullora, Earlwood, Lindfield, Randwick and Rozelle sites), Sydney north-west (Prospect, Richmond, St Marys and Vineyard sites), Sydney south-west (Bargo, Bringelly, Liverpool, Macarthur and Oakdale sites), and Illawarra (Albion Park, Kembla Grange and Wollongong sites) regions. The results were then compared with reference criteria to characterise the performance of the CCAM–CTM modelling system. Details of the CTM performance evaluation are presented in Appendix D.

The hourly $PM_{2.5}$ was generally over-predicted by the CTM in the Sydney east region. In contrast, it was under-predicted in north-west and south-west Sydney regions. The model generally predicted the diurnal variation of $PM_{2.5}$ well except in winter.

Bugle plots for hourly $PM_{2.5}$ for predicted–observed pair values across regions in different seasons are shown in Figure 36. Figure 36a shows that $PM_{2.5}$ predictions across regions meet the performance criteria for mean fractional bias (MFB; ± 60%) for all seasons, and most also met the performance goal for MFB (±30%), except the Sydney east and Illawarra regions which were marginally above 30%. Figure 36b shows that $PM_{2.5}$ predictions across regions and seasons met the performance goal (50%) and the performance criteria for mean fractional error (75%).

(a)



(b)

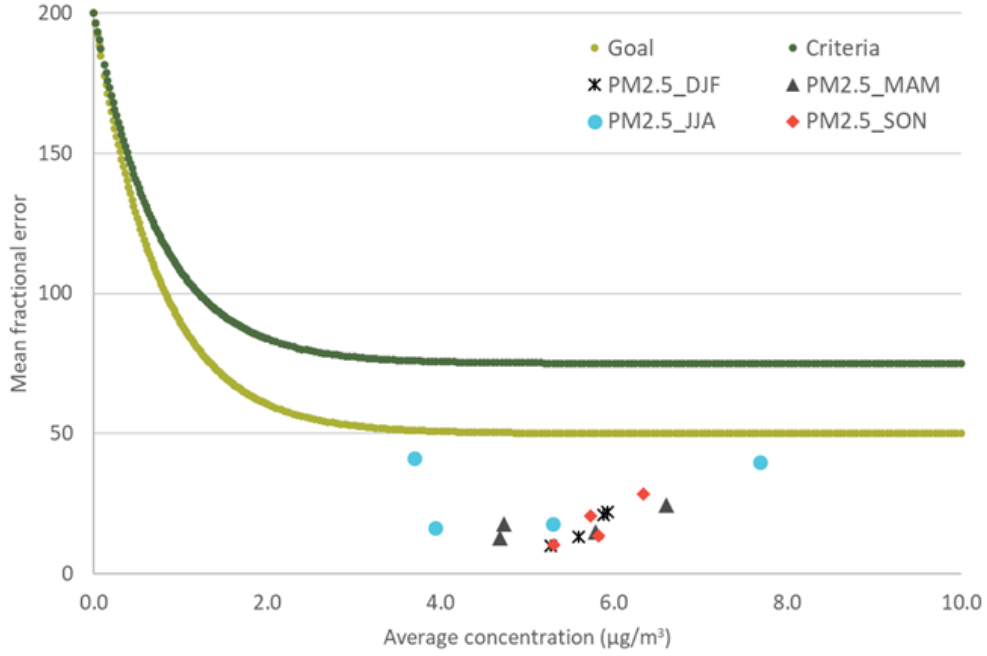


Figure 36 Bugle plots representing (a) mean fractional bias (MFB) and (b) mean fractional error (MFE) for particulate matter less than 2.5 micrometres in diameter ($PM_{2.5}$) for predicted–observed pair values in the east, north-west and south-west Sydney and Illawarra regions for summer (December, January, February (DJF), black asterisk), autumn (March, April, May (MAM), green triangle), winter (June, July, August (JJA), blue dot) and spring (September, October, November (SON), red diamond). The benchmark criteria (dark green lines) and goal (light green lines) for assessing chemical transport model performance are also shown.

The CTM reproduced diurnal variations of ozone well, however ozone is generally under-predicted with the largest negative bias in spring. The model results fell within the benchmark MFB of ±15% (US EPA 2007) across regions for all seasons except spring. The root mean square error (RMSE) in our studies were also well within the15–20 parts per billion reported in most model validation studies (Simon et al. 2012).

Nitrogen dioxide was under-predicted by the model across regions. The CTM generally predicts the diurnal variations of NO_2 well. However, a larger negative bias is found in the predicted midnight peak rather than the morning peak. Better predictions of NO_2 were found in the east and north-west Sydney regions for summer and autumn. The CTM tended to under-predict SO_2 in spring, over-predict SO_2 in autumn, and consistently under-predicted hourly CO across seasons in all regions except the Illawarra.

5.3 Model results and discussion

The CCAM–CTM modelling system was used with 11 emission scenarios and 16 major source groups taken from the 2008 NSW EPA Air Emissions Inventory for the GMR in NSW (see Table 8) to predict air pollution concentrations in the NSW GMR for the 2008 calendar year. Model results are discussed in this section and have also been summarised in Chang et al (2019) and Duc et al. (2018).

5.3.1 Predicted particulate concentrations

The CCAM–CTM predicted average $PM_{2.5}$ concentrations in the GMR domain (9 x 9 kilometres) using various modelling scenarios for the 2008 calendar year, summer (December, January and February) and winter (June, July and August) (Figure 37).

The ‘Base case’ scenario depicts areas of higher $PM_{2.5}$ concentration, which generally co-locates with populated areas; i.e., Sydney, Newcastle and Wollongong regions where annual average $PM_{2.5}$ concentration is below 7 micrograms per cubic meter (µg/m^3). $PM_{2.5}$ over the Sydney region was generally higher in winter. In Newcastle, $PM_{2.5}$ was higher in summer, whereas it did not vary much between seasons in Wollongong. Annual average $PM_{2.5}$ concentrations exceeded the National Environment Protection (Ambient Air Quality) Measure annual average $PM_{2.5}$ of 8 µg/m^3 in the Upper Hunter region (areas of $PM_{2.5}$ greater than 8 µg/m^3 are highlighted with the red contour in Figure 37). The area that showed elevated $PM_{2.5}$ was consistent between summer and winter.

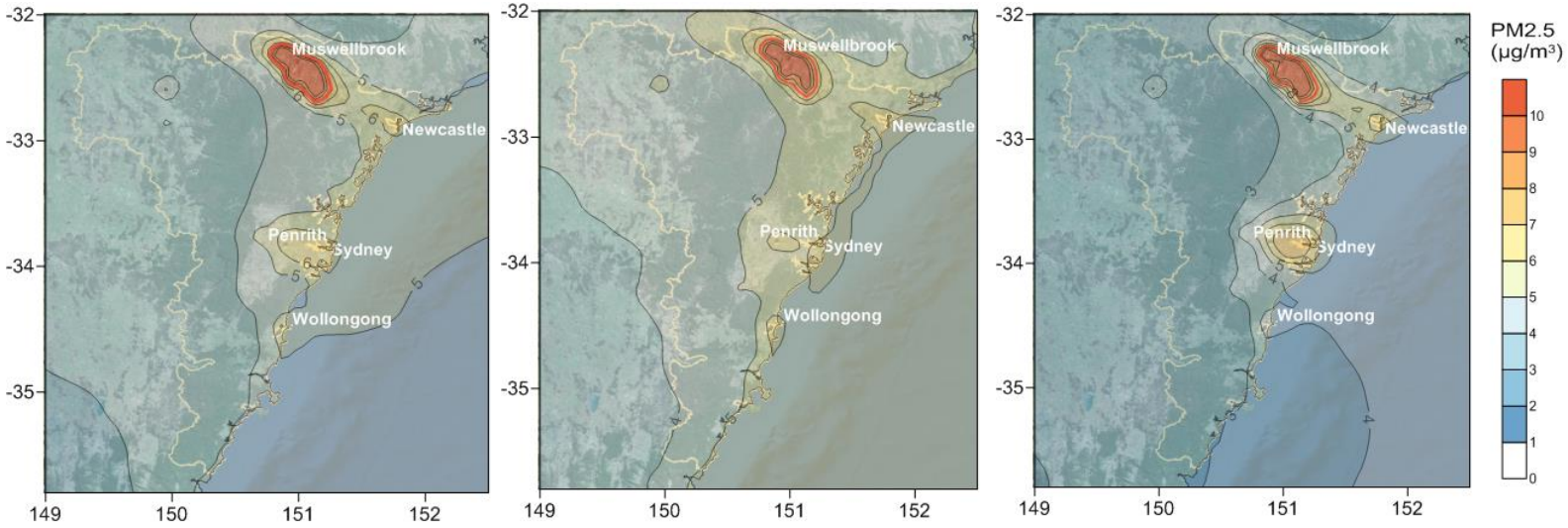
The ‘Natural sources’ scenario depicts contributions to $PM_{2.5}$ concentrations from natural sources including biogenic emissions, sea salt and wind-blown dust. These sources contribute around 4–5 µg/m^3 to the average annual $PM_{2.5}$ concentration in summer and less than 3 µg/m^3 in winter within the NSW GMR. Contributions to $PM_{2.5}$ levels from ‘Human-made sources’ are shown with localised elevated $PM_{2.5}$ concentrations generally coinciding with populated areas consistent with Base case predictions. Human-made sources were predicted to contribute significantly to $PM_{2.5}$ concentrations in the Upper Hunter region. They also contributed significantly to localised elevated $PM_{2.5}$ levels in Sydney, Newcastle and Wollongong, with a greater contribution projected in winter than summer.

‘Industrial sources’, which include all industrial sources except coal and gas power stations, contributed significantly to average $PM_{2.5}$ concentrations in the Upper Hunter region with 7 µg/m^3 in summer and 8 µg/m^3 in winter (Figure 37d). $PM_{2.5}$ concentrations attributed to power station emissions were higher in localised regional areas coinciding with power station locations. Contributions from power stations were less than 1 µg/m^3 to the annual average $PM_{2.5}$, with slightly greater contributions in summer than in winter (Figure 37e). Contributions to average $PM_{2.5}$ levels from power stations were also modelled to be spatially dispersed over the NSW GMR due to emissions occurring from tall stacks and the time taken for chemical transformation of precursors and secondary particle formation (Figure 37e).

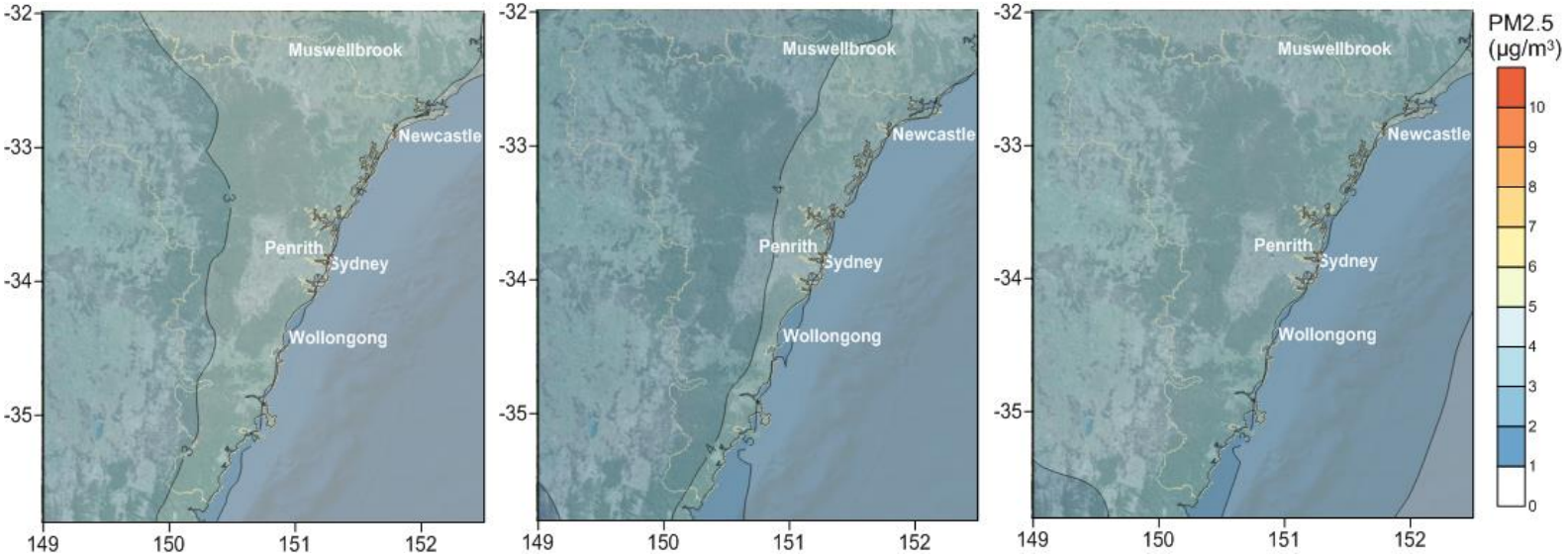
The main human-made sources that contributed to annual average $PM_{2.5}$ in the Sydney region were wood heaters (Figure 37f) and on-road mobile vehicles (Figure 37g). Wood heaters mainly add to $PM_{2.5}$ concentrations in winter when they contribute up to 3 $\mu g/m^3$ and 1 $\mu g/m^3$ in Sydney and Newcastle, respectively. Contributions to average $PM_{2.5}$ concentrations from on-road mobile vehicles appear slightly higher in winter in Sydney (0.5–0.6 $\mu g/m^3$) compared to summer (0.4–0.5 $\mu g/m^3$).

Apart from industrial sources, the 'Non-road diesel sources' made relatively significant contributions of up to 1 $\mu g/m^3$ to average $PM_{2.5}$ concentrations in the Upper Hunter region (Figure 37h). These sources also contributed 0.2 $\mu g/m^3$ to average $PM_{2.5}$ levels off the coast of Sydney and Newcastle.

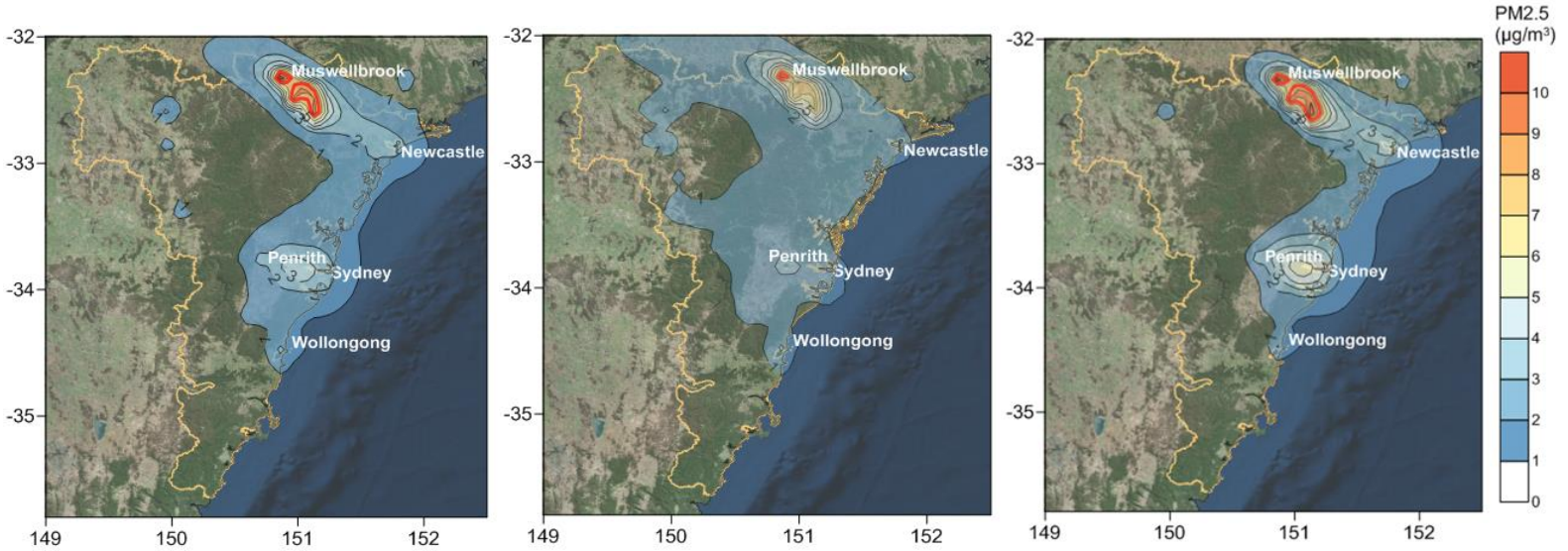
(a) Base case



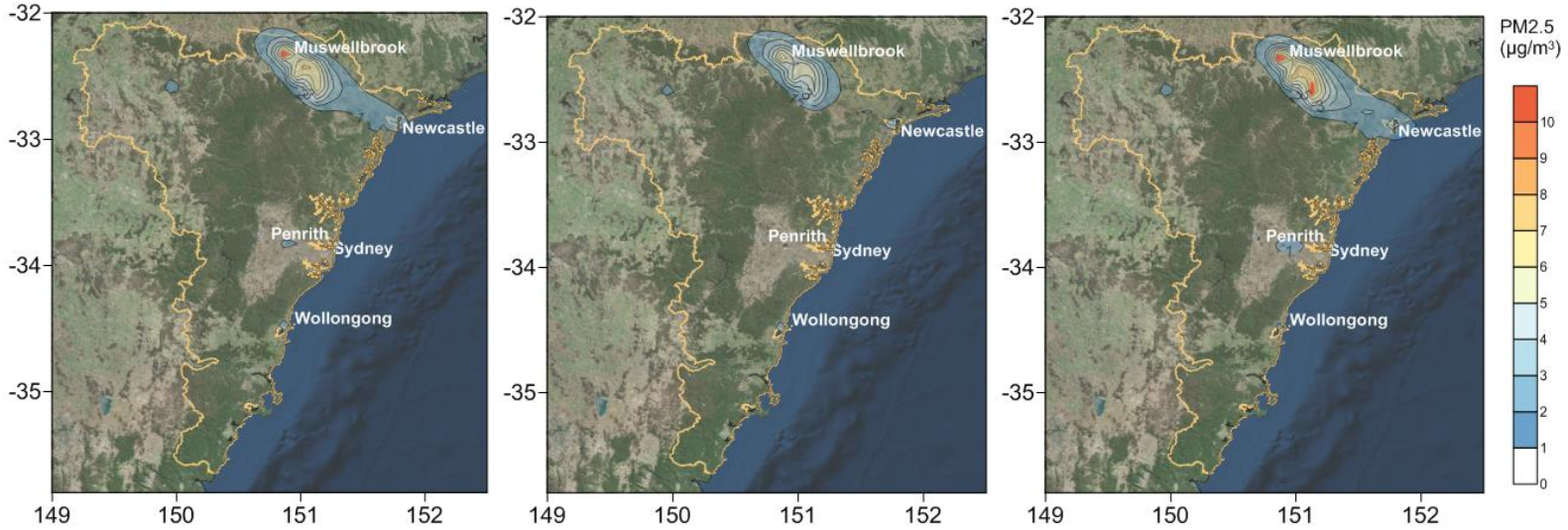
(b) Natural Sources



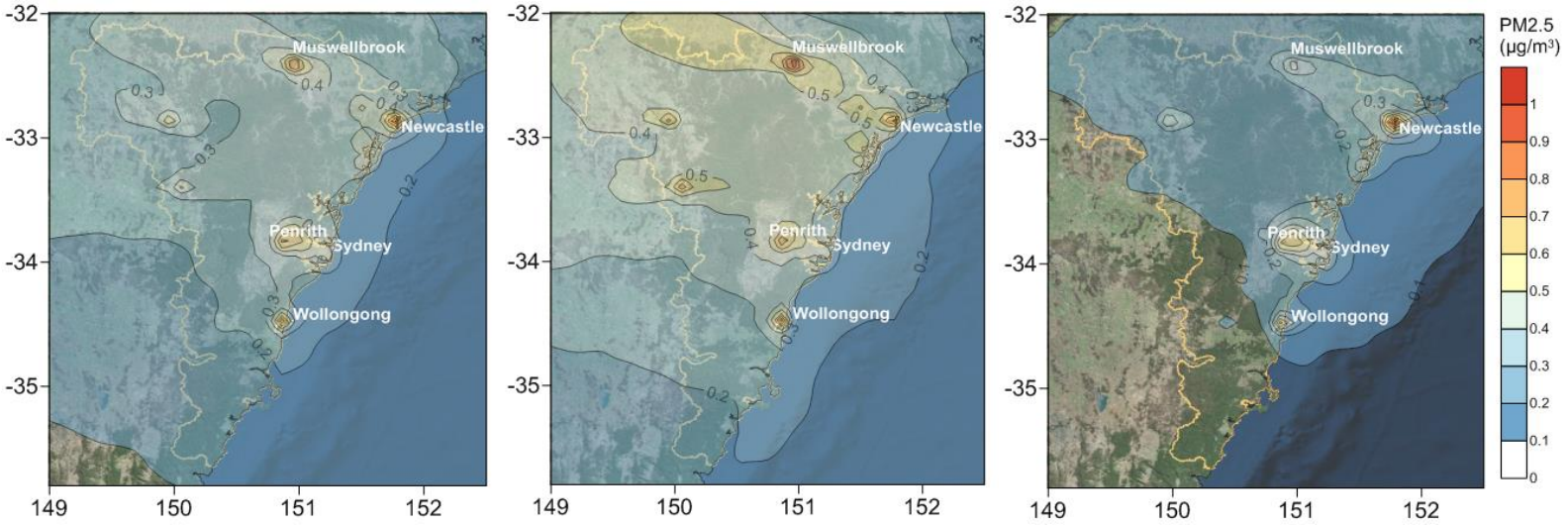
(c) Human-made sources



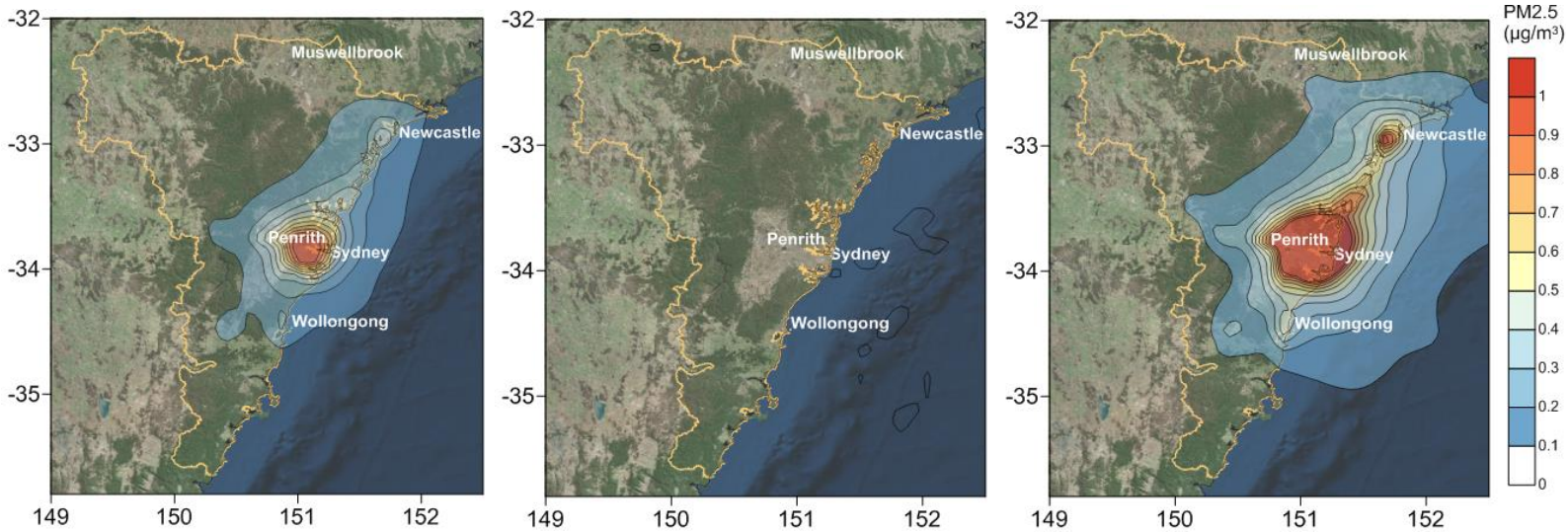
(d) Industrial sources



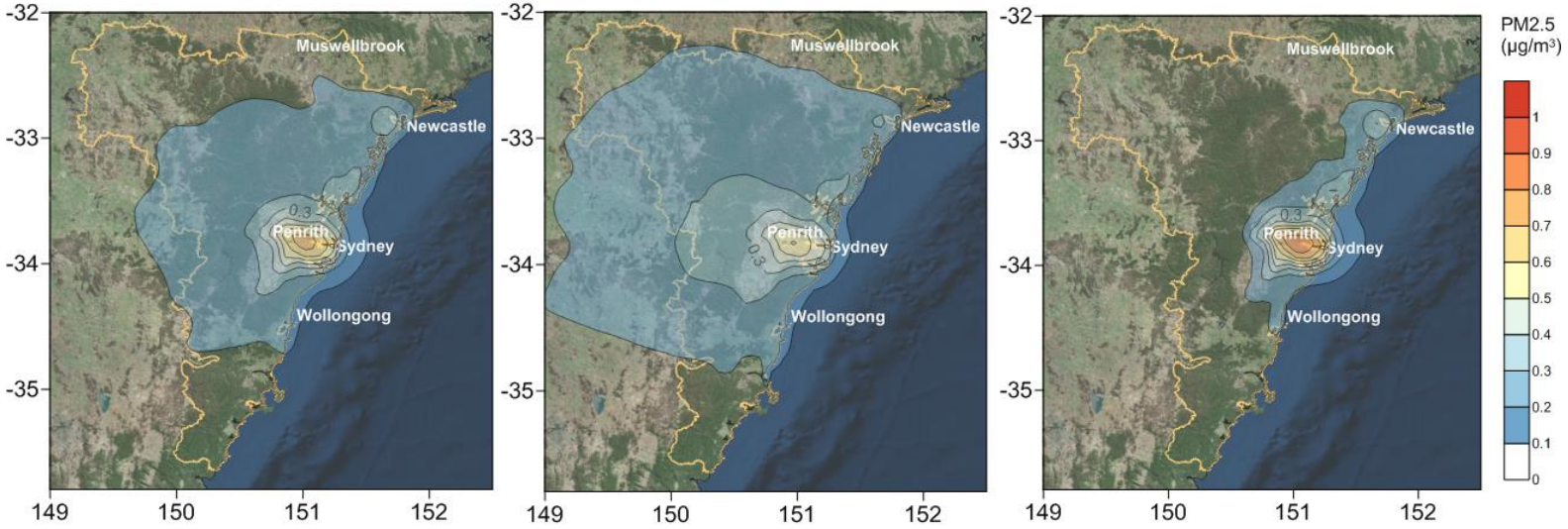
(e) Power stations



(f) Wood heaters



(g) On-road mobile sources



(h) Non-road diesel sources

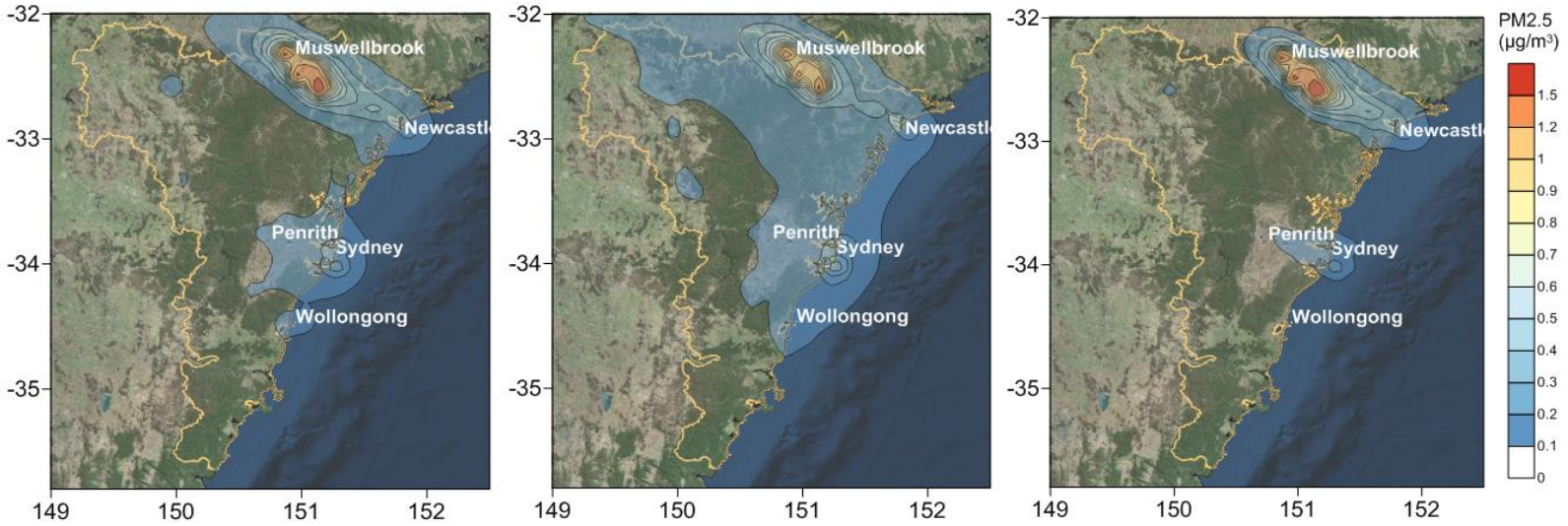


Figure 37 Average concentrations of particulate matter less than 2.5 micrometres in diameter (PM2.5) represented in micrograms per cubic metre (µg/m^3) for the 2008 calendar year (annual; left), summer (December, January, February; centre) and winter (June, July, August; right) predicted by the Conformal Cubic Atmospheric Model and Chemical Transport Model under different modelling scenarios: (a) base case, (b) natural sources, (c) human-made sources, (d) industrial sources, (e) power stations, (f) wood heaters, (g) on-road mobile sources and (h) non-road diesel sources. Areas with source contributions greater than 8 µg/m^3 are highlighted with red contours. The y axis represents latitude and the x axis represents longitude.

5.3.2 Major chemical components of predicted particulate $PM_{2.5}$

To further quantify temporal and spatial variations in $PM_{2.5}$ levels, five key chemical components of $PM_{2.5}$, were assessed. These included:

- particulate nitrate
- particulate ammonium
- particulate sulfate
- sodium
- elemental carbon.

Total $PM_{2.5}$ mass for the GMR domain (9 x 9 kilometres) was also extracted from CCAM–CTM model predictions for the 2008 calendar year at 18 DPIE air quality monitoring stations. The average total modelled $PM_{2.5}$ and the concentration of each major chemical species at the five regions for summer (December, January and February) and winter (June, July and August) in 2008 were calculated (Figure 38).

The regional average modelled $PM_{2.5}$ concentrations in summer were between 5.2–6.1 $\mu g/m^3$. The lowest $PM_{2.5}$ levels were found in the Sydney South-west region and the highest were in the Newcastle region. Particulate sulfate contributed around 0.8−0.95 $\mu g/m^3$ (16%) to the total $PM_{2.5}$ mass, followed by sodium and particulate nitrate which accounted for 0.63–1.06 $\mu g/m^3$ (12–18%) and 0.39–0.44 $\mu g/m^3$ (7–8%), respectively. Elemental carbon made a smaller contribution to the total $PM_{2.5}$ mass (1–3%) compared to other species, and ammonium also played a minor role (less than 0.8 %). Other chemical species, including primary and secondary organic aerosols, accounted for around 60% of the total $PM_{2.5}$ mass and wee integrated into an ‘other’ category (Figure 38).

The regional average modelled $PM_{2.5}$ concentrations in winter were generally lower than those in summer. The most significant drop in total $PM_{2.5}$ mass from summer to winter occurred in the Illawarra region (2.17 $\mu g/m^3$ or 38%). The significant increase in total $PM_{2.5}$ mass in the Sydney East region in winter compared to summer (1.77 $\mu g/m^3$ or 30%), related to an increased concentration of elemental carbon as well as ‘other’ species (including primary and secondary organic aerosols). The trend of an increase in elemental carbon mass and a decrease in particulate sulfate mass from summer to winter was clear in each of the five regions (Figure 38). The mass of sodium also decreased across regions from summer to winter, although it accounted for almost 20% of total $PM_{2.5}$ mass in the Newcastle region. The ‘other’ chemical species had similar proportions in the five regions, making up around 60% of the total $PM_{2.5}$ mass (Figure 38).

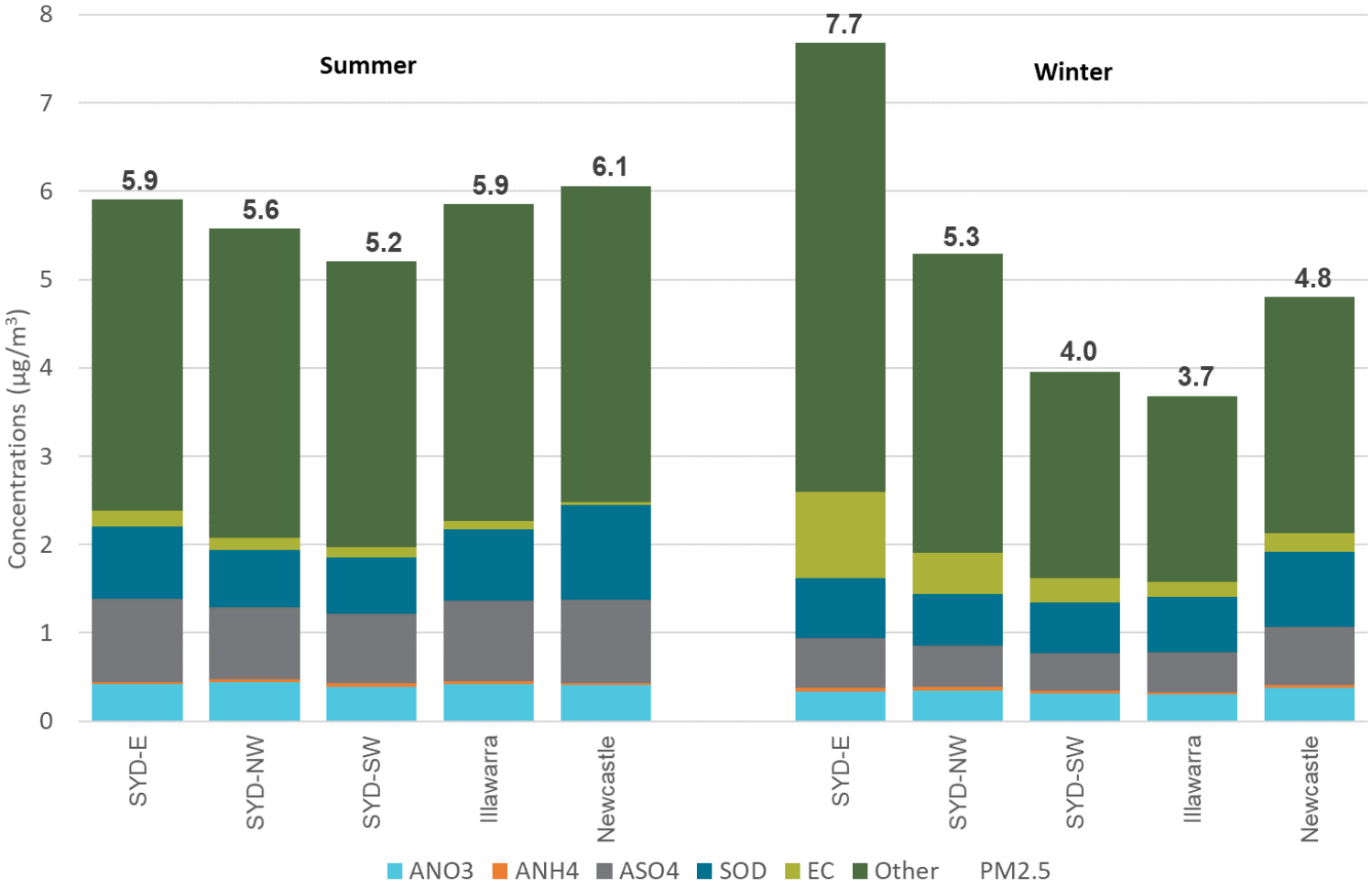
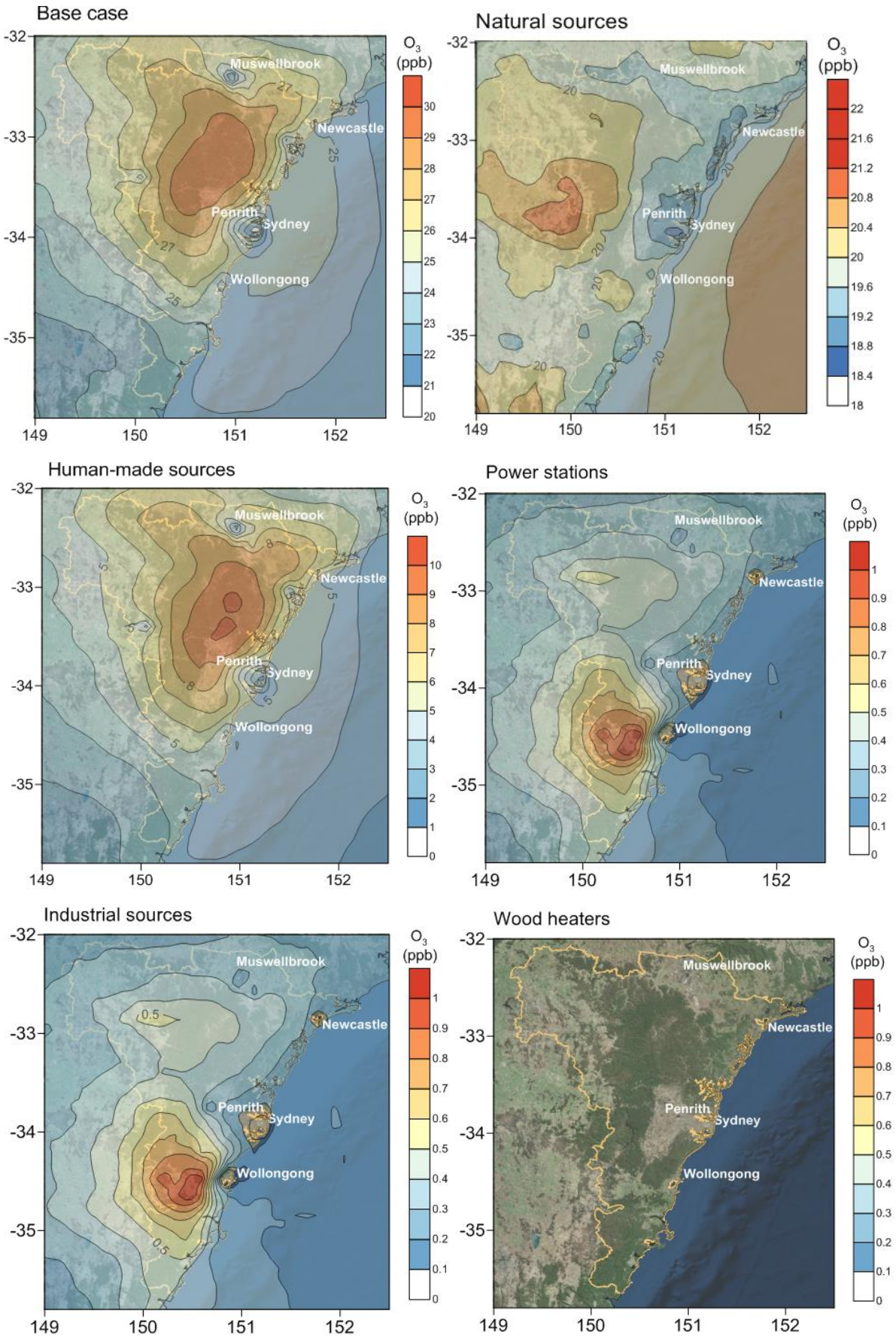


Figure 38 Regional average concentrations of particulate matter less than 2.5 micrometres in diameter ($PM_{2.5}$) (values shown on top of each stacked column), particulate nitrate (ANO_3), ammonium (ANH_4), sulfate (ASO_4), sodium (SOD), elemental carbon (EC) and other species in the Sydney east (SYD-E), Sydney north-west (SYD-NW), Sydney south-west (SYD-SW), Illawarra and Newcastle regions for summer (left) and winter (right) in 2008. µg/m^3 = micrograms per cubic metre.

5.3.3 Predicted ozone concentrations

The CCAM–CTM modelling system predicted average ozone concentrations in the CTM GMR domain (9 x 9 kilometres) for the 2008 calendar year using various modelling scenarios (Figure 39). The ‘Base case’ scenario depicts the area of maximum 1-hour ozone concentrations greater than 30 parts per billion (ppb) generally located over Wollemi National Park, north west of Penrith (Figure 39a). The area of elevated 1-hour ozone concentrations (greater than 20 ppb) in the ‘Natural sources’ scenario (Figure 39b) is consistent with the area; i.e., the Blue Mountains and various national parks where biogenic emissions (VOCs) are higher. The elevated 1-hour ozone concentrations (greater than 10 ppb) in the ‘Human-made sources’ scenario (Figure 39c) is close to the Wollemi National Park area, which correlates with the ‘Base case’ scenario.

Power stations and industrial sources contributed to elevated ozone levels in the south-west and north-west of Sydney whereas emissions from on-road motor vehicles contributed to elevated ozone levels in the broader western Sydney area (Figure 39d–h). Emissions from non-road diesel sources contributed significantly to elevated ozone in the broader Hunter region.


Base case
Natural sources
Human-made sources
Power stations
Industrial sources
Wood heaters
O3 (ppb)
Muswellbrook
Newcastle
Penrith
Sydney
Wollongong
-32
-33
-34
-35
149
150
151
152

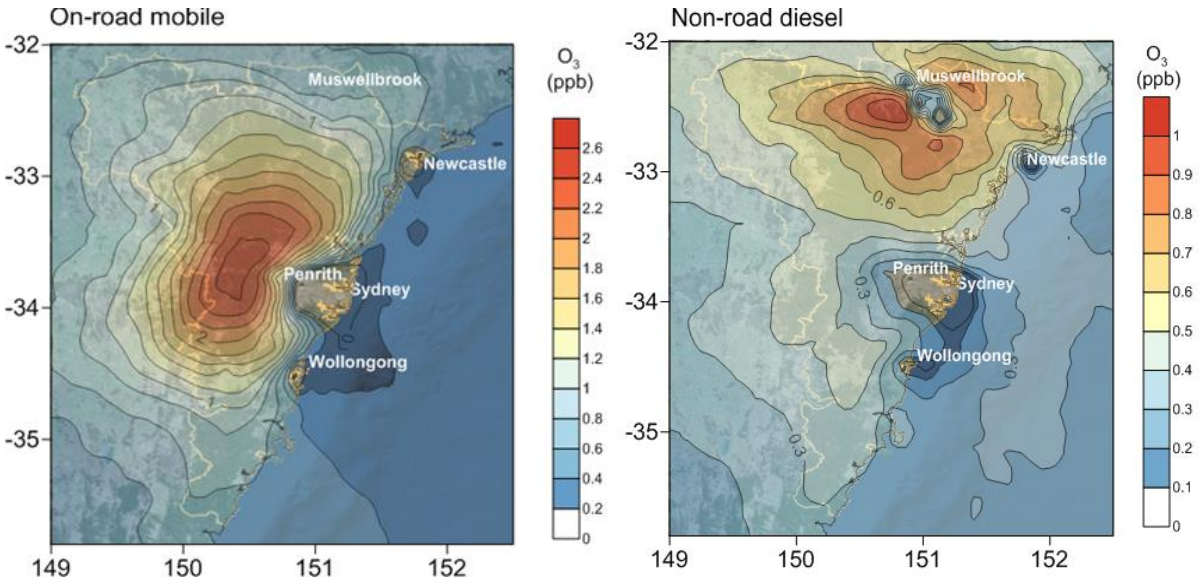
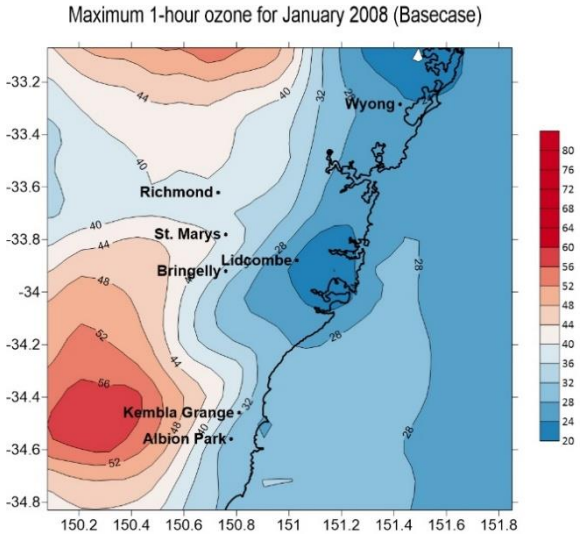


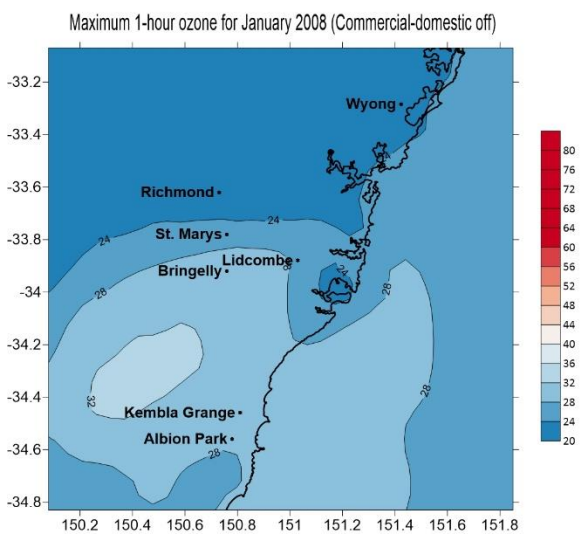
Figure 39 Daily maximum 1-hour ozone (O_3) concentrations in parts per billion (ppb) for 2008 predicted by the Conformal Cubic Atmospheric Model and Chemical Transport Model using various modelling scenarios based on different sources. The y axis represents latitude and the x axis represents longitude.

Ozone is a secondary photochemical pollutant formed from a non-linear reaction between various precursors in the atmosphere. For example, NO_2 precursors, which have a longer lifetime, can be carried on the wind and elevate ozone levels in the downwind region by reacting with VOCs under sunlight. The average daily maximum 1-hour ozone concentrations for January 2008 for four emission scenarios: base case, commercial–domestic sources off, power stations sources off and on-road mobile sources off was modelled (Figure 40). Differences between the spatial patterns of maximum 1-hour ozone for the base case and power stations off scenarios (Figure 40a and c), show that reductions in emissions from power stations may improve the ozone levels in north-west Sydney, the Lower Hunter and Illawarra regions. Differences in the spatial pattern of ozone emissions when emissions from on-road motor vehicles were not included in modelling indicate that reductions in on-road vehicles may improve ozone levels in the south-west Sydney region (Figure 40a and d).

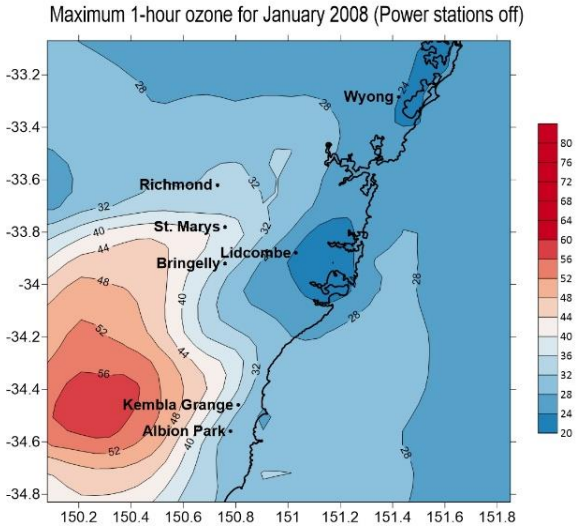
(a)



(b)



(c)



(d)

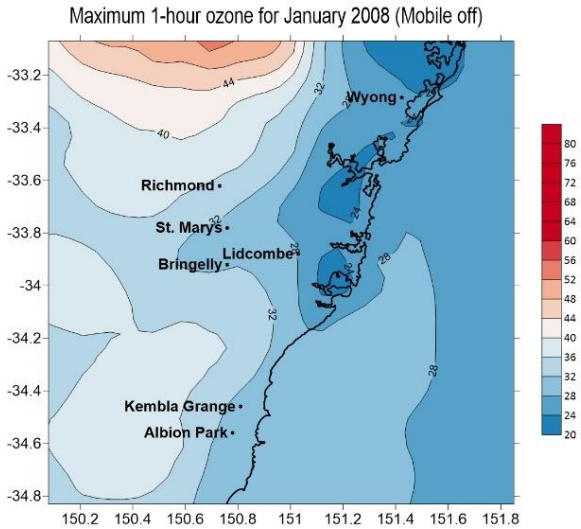


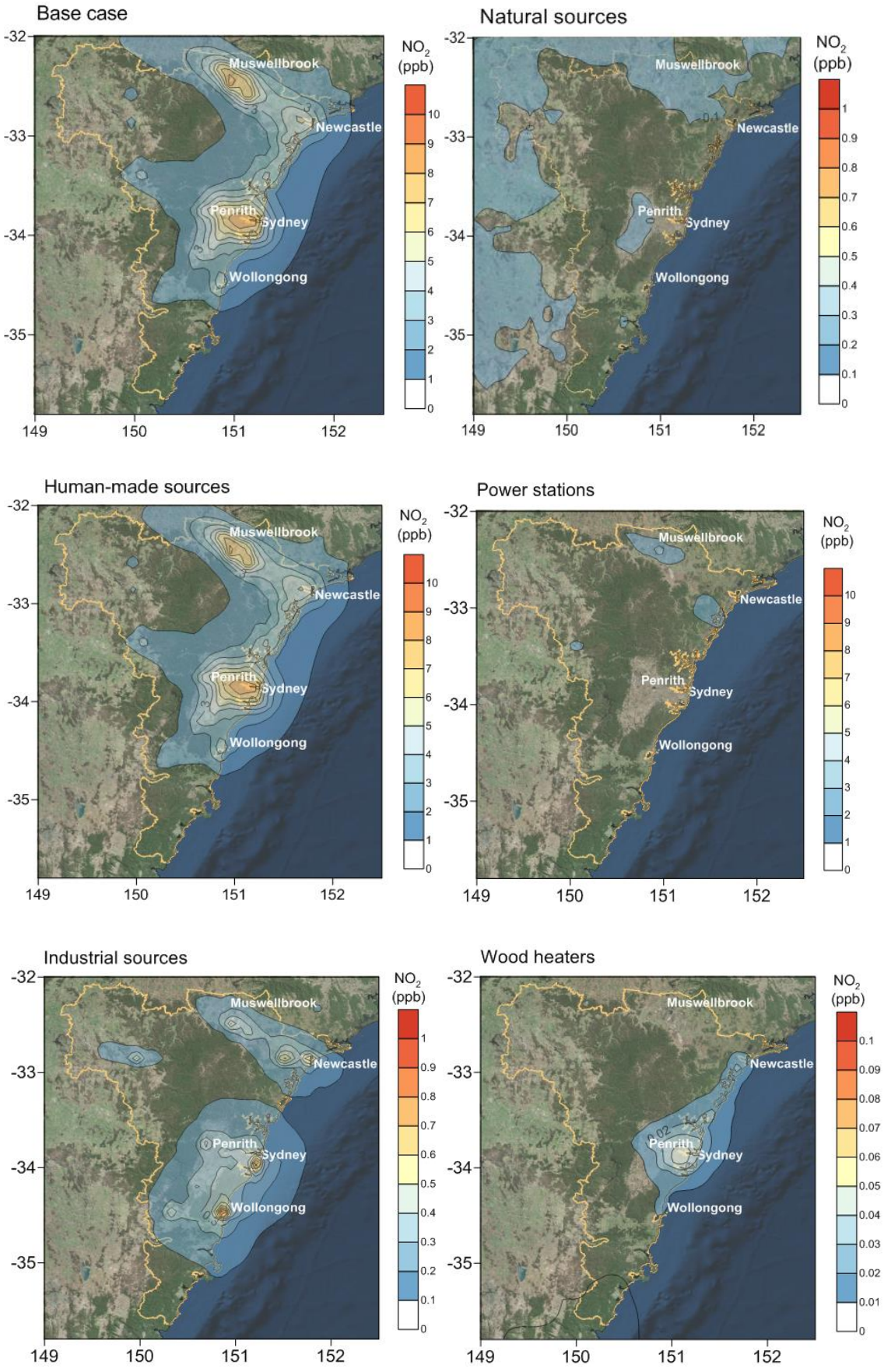
Figure 40 Monthly average of daily maximum 1-hour ozone concentration for January 2018 in (a) base case, (b) commercial-domestic sources off, (c) power station sources off and (d) on-road mobile sources off emission scenarios. The y axis represents latitude and the x axis represents longitude.

5.3.4 Predicted nitrogen and sulfur dioxide concentrations

The annual average predicted NO_2 and SO_2 concentrations for 2008 from various scenarios were modelled for the GMR (Figures 41 and 42).

The NO_2 concentrations for the 'Base case' scenario peaked in the Sydney, Upper Hunter and Newcastle regions. The high NO_2 concentrations (>8 ppb) in the Base case scenario were dominated by 'Human-made sources', especially contributions from 'Power stations', 'On-road mobile' and 'Non-road diesel' sources in these areas. 'Natural sources' and 'Other industrial sources' contributed relatively small portions (<1ppb) to the total NO_2 concentrations, and 'Wood heaters' contributed even less (<0.1 ppb). 'Other industrial sources' made more significant contributions in the Sydney, Upper Hunter, Newcastle and Illawarra regions, and Wood heaters contributed some NO_2 in the Sydney region.

The SO_2 concentrations illustrated in the 'Base case' scenario peaked in regions consistent with peaks found in the 'Human-made sources' scenario, to which power stations are the dominant contributor. Other industrial sources made some contributions to local SO_2 concentrations in the Newcastle and Illawarra regions, and the 'Non-road diesel' scenario demonstrated that shipping emissions contributed to SO_2.


Base case
Natural sources
Human-made sources
Power stations
Industrial sources
Wood heaters
NO2 (ppb)
Muswellbrook
Newcastle
Penrith
Sydney
Wollongong
-32
-33
-34
-35
149
150
151
152

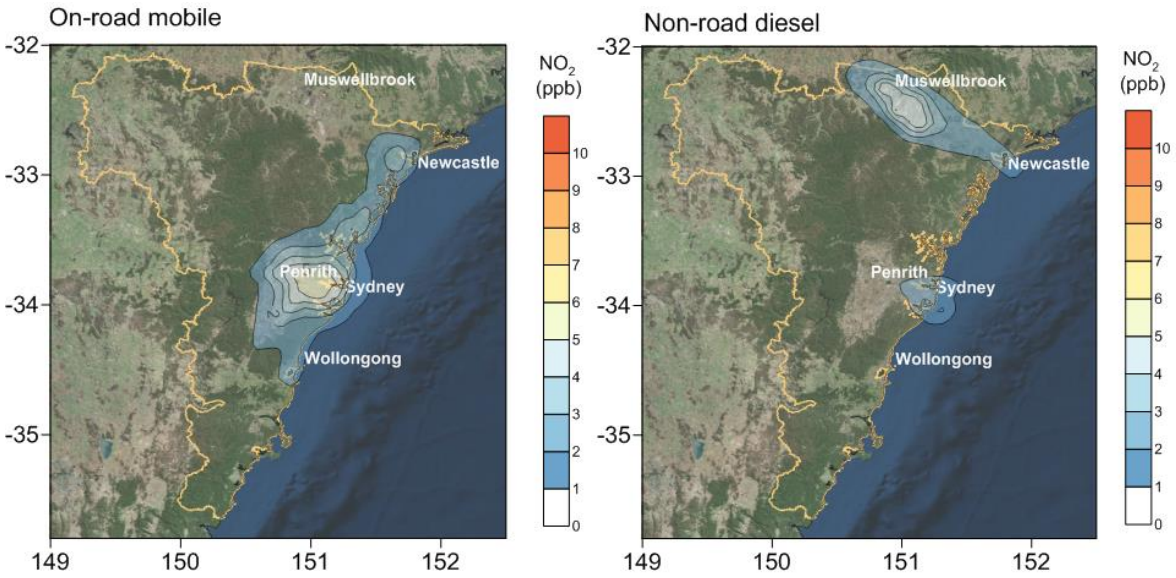
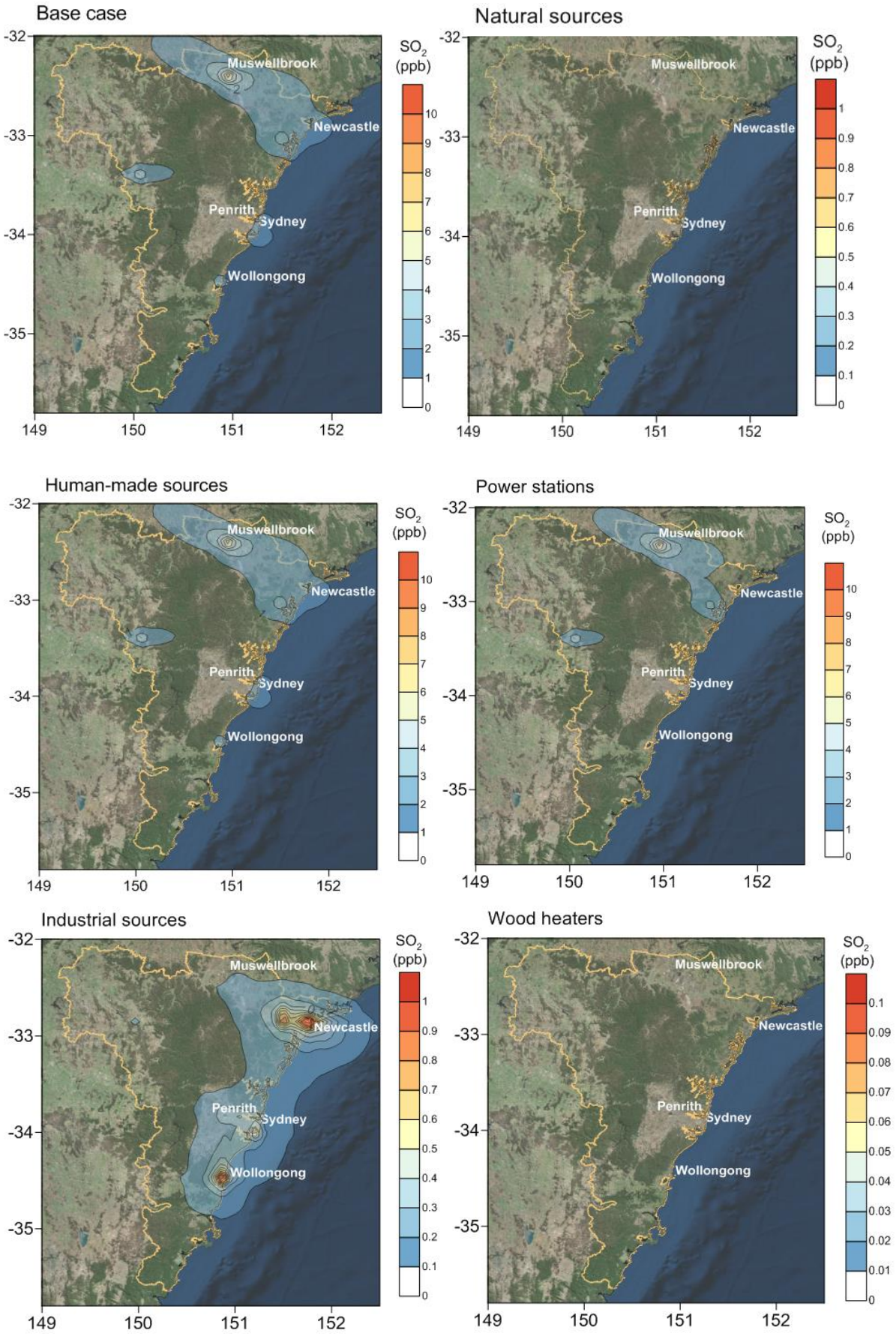


Figure 41 Annual average nitrogen dioxide (NO_2) concentrations parts per billion (ppb) for 2008 across the Greater Metropolitan Region predicted by the Conformal Cubic Atmospheric Model and Chemical Transport Model using various modelling scenarios based on different scenarios on different sources. The y axis represents latitude and the x axis represents longitude.


Base case
Natural sources
Human-made sources
Power stations
Industrial sources
Wood heaters
SO2 (ppb)
Muswellbrook
Newcastle
Penrith
Sydney
Wollongong
-32
-33
-34
-35
149
150
151
152

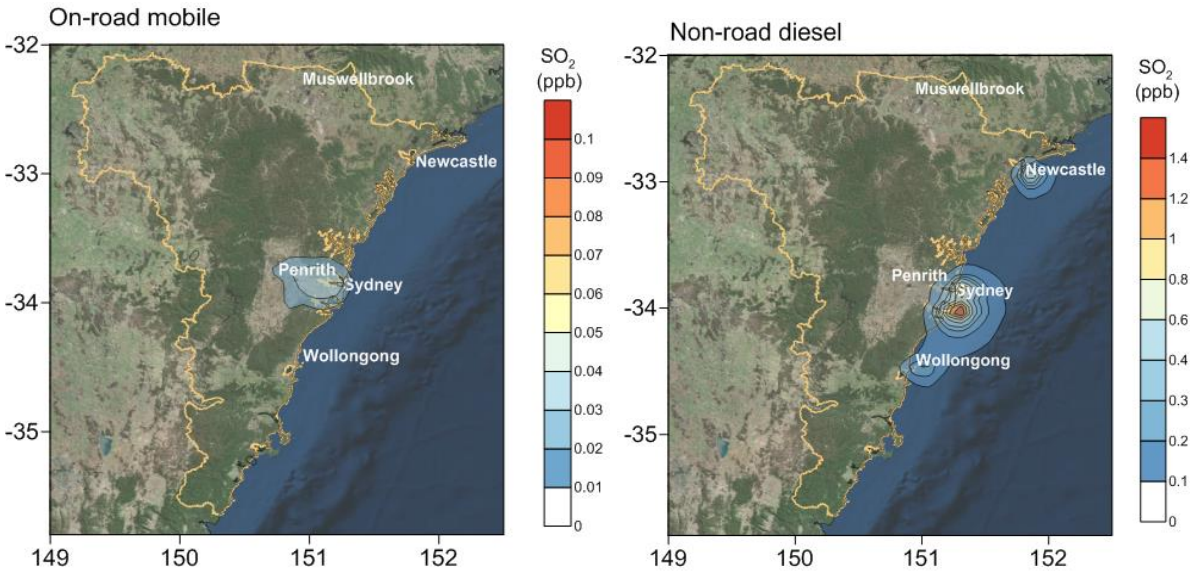


Figure 42 Annual average sulfur dioxide (SO_2) concentrations in parts per billion (ppb) for 2008 across the Greater Metropolitan Region predicted by the Conformal Cubic Atmospheric Model and Chemical Transport Model using various modelling scenarios based on different sources. The y axis represents latitude and the x axis represents longitude.

6. Assessing air pollution exposure

Determining the health risks caused by ambient air pollution is critical to the development of effective risk-management policies and strategies. To better understand the adverse health effects associated with air pollution, accurate exposure assessment is essential. The exposure modelling presented in this section provides a quantitative estimate of the amount of air pollutants people were exposed to. Results from exposure modelling are also a critical component for health impact assessment (HIA).

6.1 Exposure modelling

The exposure modelling conducted in this study was developed to assess population-weighted air pollutant concentrations, including annual average particulate matter less than 2.5 micrometres in diameter ($PM_{2.5}$), annual average nitrogen dioxide (NO_2), annual average sulfur dioxide (SO_2) and hourly maximum ozone (O_3) levels based on the Conformal Cubic Atmospheric Model and Chemical Transport Model (CCAM–CTM modelling system) modelling predictions (see Section 5).

Results for the CCAM–CTM modelling system for the 9 x 9-kilometre (km) Chemical Transport Model Greater Metropolitan Region (CTM GMR) domain were integrated with the 3 x 3-km Chemical Transport Model Greater Sydney (CTM GSYD) domain. Model outputs were then re-gridded to a 1-km resolution to coincide the Australian Bureau of Statistics 1-km resolution gridded population data. For each 1-km grid in the NSW Greater Metropolitan Area (GMA; Figure 34), defined in the Protection of the Environment Operations (Clean Air) Regulation 2010 as 57 Local Government Areas, the modelled air pollutant concentration was multiplied by the usual residential population in that 1-km grid. The result was summed across all 1-km grid squares within the NSW GMA and divided by the total population for the NSW GMA to get the population-weighted $PM_{2.5}$ concentration.

6.2 Population-weighted air pollutant concentrations

Results from the CCAM–CTM modelling system for various emission scenarios (see section 5.1.4) were applied to the exposure modelling method described in section 6.1 to estimate the source contributions to population-weighted air pollutants.

The contribution of natural and human-made sources to the population-weighted annual average $PM_{2.5}$, NO_2, SO_2 and hourly maximum O_3 concentrations were calculated (Table 10 and Figure 43). Natural and human-made sources contributed 60% (3.55 micrograms per cubic metre ($\mu g/m^{3)}$) and 40% (2.41 $\mu g/m^3$) to the population-weighted annual average $PM_{2.5}$ (5.96 µg/m3). Human-made sources dominated the contributions to population-weighted annual average NO_2 and SO_2, with contributions up to 99% and almost 100%, respectively. Human-made sources also accounted for 62% (48.94 parts per billion (ppb)) of the annual average population-weighted hourly maximum ozone levels (78.61 ppb), whereas natural sources made a lower contribution of 38% (29.67 ppb).

Table 2 **Natural and human-made source contributions to population-weighted annual average particles less than 2.5 micrometres in diameter ($PM_{2.5}$), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and hourly maximum ozone (O_3) concentrations**

Source	Annual average $PM_{2.5}$ (µg/m³)	Annual average NO_2 (ppb)	Annual average SO_2 (ppb)	Hourly maximum O_3 (ppb)
Natural sources	3.55	0.06	0.01	29.67
Human-made sources	2.41	5.97	0.76	48.94
All sources	**5.96**	**6.03**	**0.77**	**78.61**

Notes: µg/m3 = micrograms per cubic metre; ppb = parts per billion.

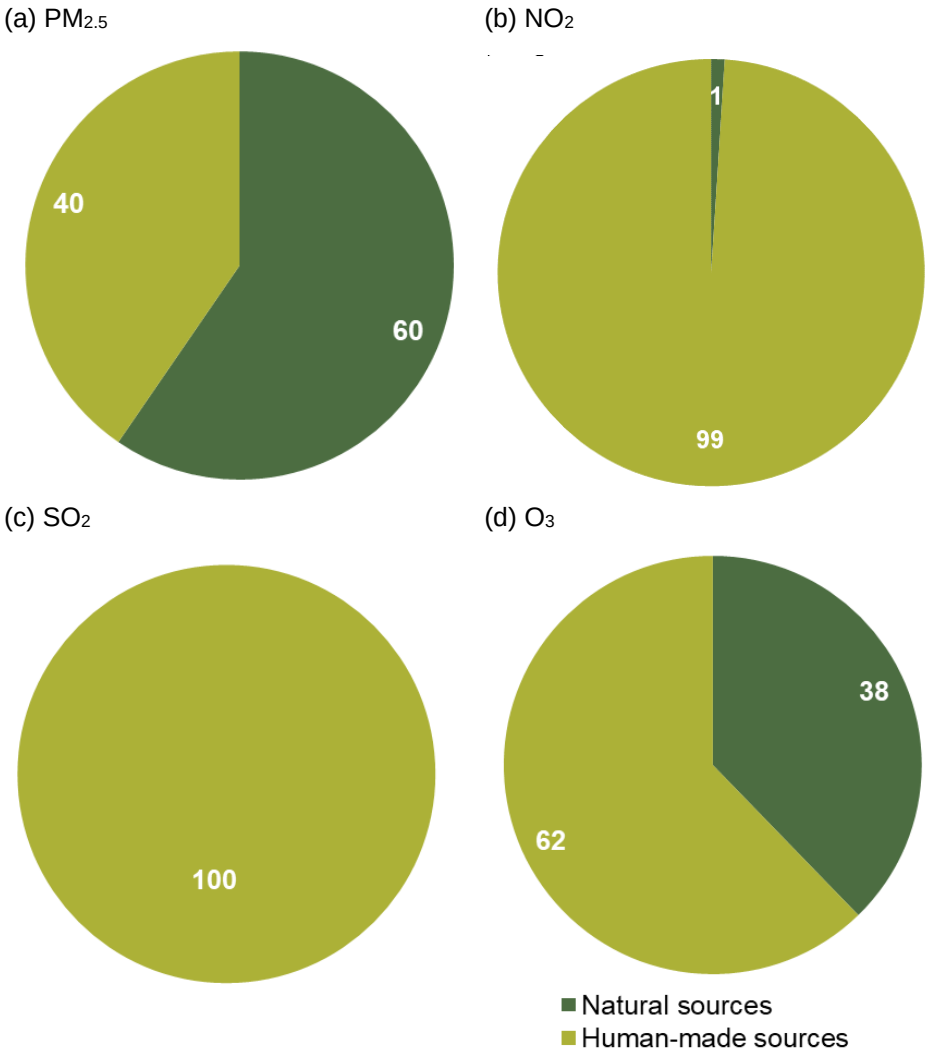


Figure 43 **Percentage contribution natural and human-made sources make to population-weighted: (a) annual average particles less than 2.5 micrometres in diameter ($PM_{2.5}$), (b) annual average nitrogen dioxide (NO_2), (c) annual average sulfur dioxide (SO_2) and (d) hourly maximum ozone (O_3) for the Greater Metropolitan Region.**

Human-made sources were further broken down into major groups and their contribution to population-weighted air pollutants was calculated (Table 11 and Figure 44). Wood heaters, industry, on-road motor vehicles and power stations respectively contributed 0.75, 0.61, 0.46 and 0.42 µg/m^3 the population-weighted annual average $PM_{2.5}$ concentration, and respectively accounted for 31, 26, 19 and 17% of the total human-made source contribution to annual average $PM_{2.5}$ levels.

On-road motor vehicles, non-road diesel and marine, other human-made sources and power stations respectively contributed 3.77, 0.88, 0.56 and 0.43 ppb to population-weighted annual average NO_2 levels, and respectively accounted for 63, 15, 9 and 7% of the total human-made source contribution to annual average NO_2 levels.

Both power stations and industry made significant contributions (0.37 and 0.26 ppb, respectively) to population-weighted annual average SO_2 levels. They also accounted for 83% of the total human-made source contribution to annual average SO_2 levels.

The dominate human-made sources that contributed to population-weighted hourly maximum ozone levels were in the 'other' sources category, followed by power stations and on-road motor vehicles. Other sources accounted for 45% (22.16 ppb), power stations and on-road motor vehicles 28 and 19% (13.65 and 9.16 ppb), respectively, of the total human-made source contribution to hourly maximum ozone levels.

Table 11 Major human-made source groups and their contributions to population-weighted annual average particles less than 2.5 micrometres in diameter ($PM_{2.5}$), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and hourly maximum ozone (O_3) concentrations

Major human-made sources	Annual average $PM_{2.5}$ (µg/m^3)	Annual average NO_2 (ppb)	Annual average SO_2 (ppb)	Hourly maximum O_3 (ppb)
Power stations	0.42	0.43	0.37	13.65
Wood heaters	0.75	0.03	0.00	0.00
On-road motor vehicles	0.46	3.77	0.02	9.16
Non-road diesel and marine	0.15	0.88	0.10	3.06
Industry	0.61	0.30	0.26	0.91
Other	0.02	0.56	0.00	22.16
All human-made sources	**2.41**	**5.97**	**0.75**	**48.94**

Notes: µg/m3 = micrograms per cubic metre; ppb = parts per billion.

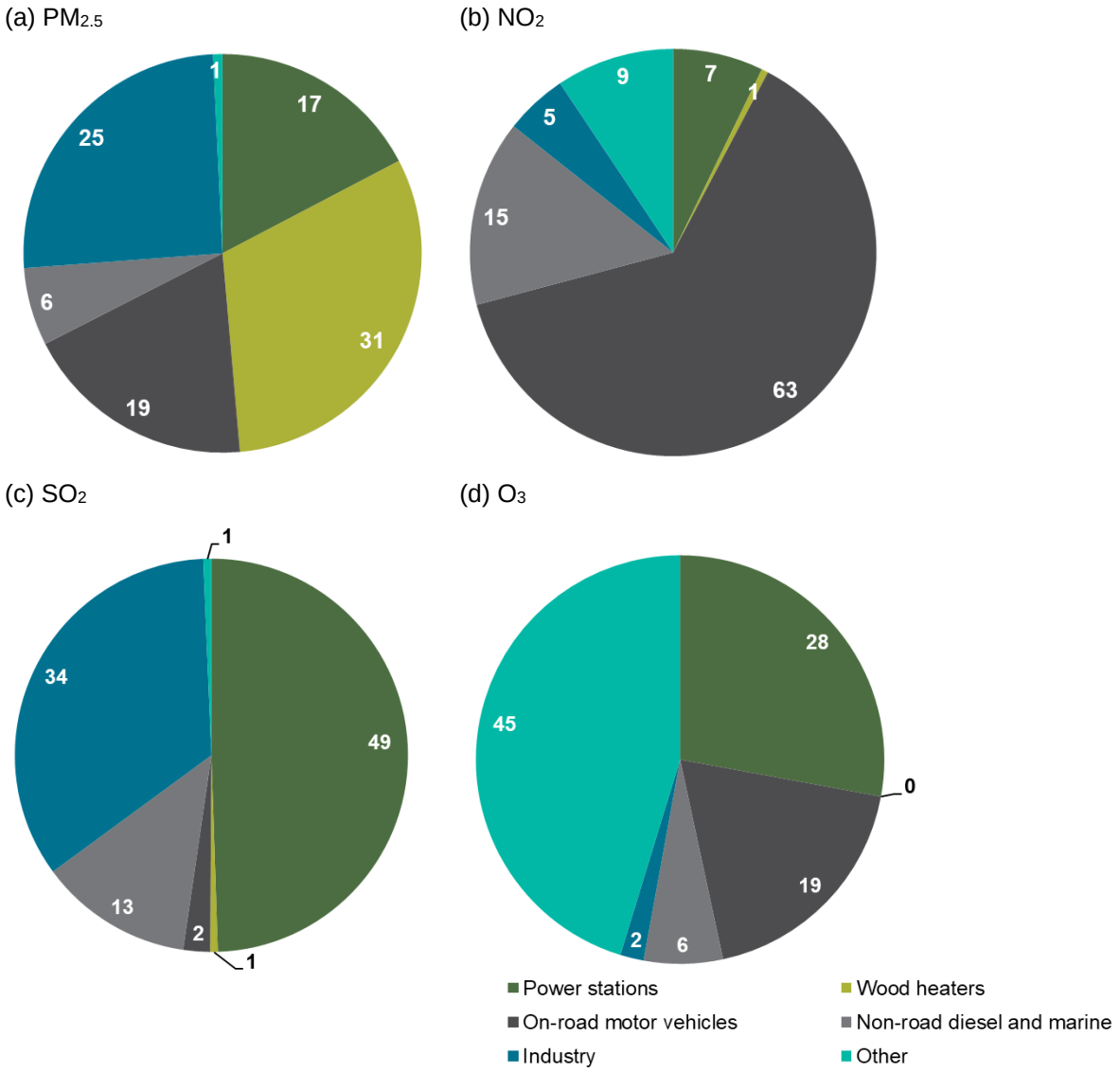


Figure 44 Major source groups contributions (%) to total human-made sources contribution to population-weighted: (a) annual average particles less than 2.5 micrometres in diameter ($PM_{2.5}$), (b) annual average nitrogen dioxide (NO_2), (c) annual average sulfur dioxide (SO_2) and (d) hourly maximum ozone (O_3) for the Greater Metropolitan Region.

7. Conclusions and recommendations

New South Wales has good air quality by international standards, but challenges remain to maintain and improve our air quality. To understand how air pollution varies over time, how it varies across the NSW Greater Metropolitan Region (GMR), what sources contribute to it, and how it affects human health and the environment, a multi-year Sydney Air Quality study led by the Department of Planning, Industry and Environment (DPIE), in collaboration with the NSW Environment Protection Authority (EPA), and the NSW Ministry of Health, was conducted. Findings from the first stage of this project (2017–2019) have been presented in this report.

The study draws on data and information from the NSW DPIE Air Quality Monitoring Network, the NSW Environment Protection Authority (EPA) Air Emissions Inventory for the GMR in NSW and research outcomes from completed studies such as the Sydney Particle Study (NSW OEH 2014c) and the Sydney Particle Characterisation Study (Cohen et al. 2016). Regional air quality and exposure modelling was undertaken to assess how air quality varies across the region, to quantify major source contributions to air pollution and associated population exposure.

The study integrates and expands the evidence base to address gaps in our understanding of air quality and its impacts in the NSW GMR. Major outcomes including a comprehensive evaluation of the performance of the regional airshed modelling system for the NSW GMR, and new insights into major source contributions to fine particles $PM_{2.5}$ and ozone have also been published in multiple peered-reviewed papers which are included in a special issue of the journal *Atmosphere* titled *'Air Quality in New South Wales, Australia'*. Major findings include:

- Air quality has generally been good in the NSW GMR between 2012 and 2018. Air quality was ‘very good’ or ‘good’ for:
    - 69–88% of days in the Sydney and Hunter regions
    - 83–91% of days in the Illawarra
    - 88% or more days on the Central Coast.

  South-west and north-west Sydney experienced more ‘poor’ or worse air quality days due to ozone and particle pollution.
- Regional air quality modelling capabilities have been established for the NSW GMR. The performance of the modelling system used for the NSW GMR was comparable to similar regional airshed models documented in the literature. The benchmarking of the modelling system supports its application in air quality impact assessment and policy scenario modelling to inform air quality management in NSW.
- Regional air quality modelling was undertaken with the 2008 Air Emissions Inventory for the GMR in NSW to investigate major emissions source contributions to fine particles, (particles less than 2.5 micrometres in diameter, $PM_{2.5}$), and ozone. These results found:
    - human activities accounted for 40% of population-weighted annual average $PM_{2.5}$ concentrations across the NSW GMR
    - major sources of human contributions to $PM_{2.5}$ concentrations were from wood heaters (31%), industry (26%), on-road motor vehicles (19%), power stations (17%) and non-road diesel and marine emissions (6%)
    - motor vehicles and commercial–domestic sources contributed significantly to maximum ozone levels in south-west Sydney, whereas emissions from commercial-domestic sources and power generation were major contributors to the ozone formation in north-west Sydney.

The results from this study will contribute to the evidence base the NSW Government relies on to support the development of clean air actions. Health burden analysis based on the source contribution modelling results in this study will be finalised in 2020 to inform the next phase of the study.

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9. Appendix A: Trends in emissions

9.1 Trends in particle emissions over time

Emissions for particulate matter less than 10 micrometres in diameter (PM_{10}) and particulate matter less than 2.5 micrometres in diameter ($PM_{2.5}$) from major source groups across all regions are summarised in Table A3 for the 2003 and 2008 calendar years. The Greater Metropolitan Region includes Sydney, Newcastle, Wollongong and non-urban regions.

9.1.1 Sydney

Total PM_{10} and $PM_{2.5}$ emissions decreased by 15% and 24% in the Sydney region between 2003 and 2008. The greatest percentage decrease in particle emissions in the Sydney region was from off-road mobile sources for PM_{10} and biogenic sources for $PM_{2.5}$. A significant increase in particle emissions from the domestic–commercial sector was found between 2003 and 2008. Residential wood heaters accounted for over 90% of PM_{10} and $PM_{2.5}$ emissions from this sector.

9.1.2 Newcastle

Total PM_{10} and $PM_{2.5}$ emissions increased by 82% and 24% respectively in the Newcastle region between 2003 and 2008. The significant growth in PM_{10} emissions was dominated by biogenic sources, which included wind erosion of exposed areas, agricultural burning, bushfires and prescribed burning. Typical variations occur from year to year, with higher emissions occurring during hotter, dryer years. A growth in particle emissions from industrial sources also contributed to the increased particle emissions in the region.

9.1.3 Wollongong

The total PM_{10} and $PM_{2.5}$ emissions in Wollongong decreased by 1% and 11% respectively between 2003 and 2008. Emissions from biogenic and domestic–commercial sources increased, but emissions from off-road and on-road mobile sources decreased, which resulted in an overall reduction of particle emissions in the region.

9.1.4 Non-urban

Total PM_{10} emissions increased by 51% and total $PM_{2.5}$ emissions decreased by 11% in the non-urban regions. The increase in PM_{10} emissions was dominated by biogenic and industrial sources, whereas the reduction in $PM_{2.5}$ emissions was from industrial, off-road and on-road mobile sources.

9.1.5 Greater Metropolitan Region

The growth of total PM_{10} emissions in the GMR was 33% between 2003 and 2008. It was mainly dominated by increased emissions from biogenic, domestic–commercial and industrial sources. The reduction in emissions from biogenic, commercial, off-road and on-road mobile sources contributed to a total decrease in $PM_{2.5}$ emissions of 14% between 2003 and 2008 in the GMR.

Table A3 **Emissions for particles less than 10 micrometres in diameter (PM_{10}) and particles less than 2.5 micrometres in diameter ($PM_{2.5}$) from major source groups for 2003 and 2008 across all regions in the Greater Metropolitan Region (GMR)**

	Major source groups	PM_{10} emissions			$PM_{2.5}$ emissions		
Region		**2003**	**2008**	**Change**	**2003**	**2008**	**Change**
		(tonnes/year)			**(tonnes/year)**		
Sydney	Biogenic	2,700	3,902	45%	2,331	951	–59%
	Commercial	2,079	1,112	–46%	660	485	–27%
	Domestic–commercial	5,056	6,088	20%	4,889	5,853	20%
	Industrial	7,911	6,215	–21%	3,390	1,935	–43%
	Off-road mobile	3,712	1,019	–73%	1,766	952	–46%
	On-road mobile	2,552	2,110	–17%	2,426	1,553	–36%
	Total	**24,011**	**20,446**	**–15%**	**15,463**	**11,728**	**–24%**
Newcastle	Biogenic	93	689	638%	44	121	174%
	Commercial	169	129	–24%	45	30	–33%
	Domestic–commercial	427	504	18%	412	485	18%
	Industrial	1,706	3,744	119%	808	1,110	37%
	Off-road mobile	468	284	–39%	252	266	6%
	On-road mobile	177	176	–1%	169	131	–22%
	Total	**3,040**	**5,526**	**82%**	**1,730**	**2,144**	**24%**
Wollongong	Biogenic	16	327	1970%	14	90	543%
	Commercial	61	48	–22%	28	14	–50%
	Domestic–commercial	277	334	21%	268	321	20%
	Industrial	2,069	2,099	1%	1,556	1,354	–13%
	Off-road mobile	507	119	–77%	228	112	–51%
	On-road mobile	119	90	–24%	113	68	–40%
	Total	**3,049**	**3,017**	**–1%**	**2,207**	**1,959**	**–11%**
Non-urban	Biogenic	14,630	28,720	96%	12,680	6,176	–51%
	Commercial	1,642	732	–55%	457	167	–64%
	Domestic–commercial	971	1,262	30%	939	1,214	29%
	Industrial	34,844	61,155	76%	7,373	13,273	80%
	Off-road mobile	9,878	2,185	–78%	4,240	2,104	–50%
	On-road mobile	501	417	–17%	479	319	–33%
	Total	**62,466**	**94,472**	**51%**	**26,169**	**23,253**	**–11%**
GMR	Biogenic	17,439	33,638	93%	15,069	7,338	–51%
	Commercial	3,952	2,021	–49%	1,190	695	–42%
	Domestic–commercial	6,731	8,189	22%	6,508	7,873	21%
	Industrial	46,530	73,213	57%	13,127	17,672	35%

	Off-road mobile	14,566	3,607	–75%	6,486	3,433	–47%
	On-road mobile	3,349	2,793	–17%	3,187	2,071	–35%
	Total	**92,567**	**123,462**	**33%**	**45,569**	**39,083**	**–14%**

9.2 Trends in sulfur dioxide, nitrogen oxides, volatile organic compounds and ammonia emissions

Emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOCs) from major sources in all regions in 2003 and 2008 are summarised in Table A.2.

9.2.1 Sydney

Total SO_2, NO_x and VOC emissions decreased by 22%, 21% and 20% respectively in the Sydney region between 2003 and 2008. The greatest percentage change in SO_2 emissions was an increase in emissions from off-road mobile sources, followed by an increase in emissions from commercial sources. There was a significant decrease in SO_2 emissions from industrial sources resulting in an overall decrease in SO_2 emissions across the region. There was a significant increase in NO_x emissions from off-road sources and a significant decrease from commercial sources. Combined with a decrease in NO_x emissions from on-road vehicles, this resulted in an overall decrease in NO_x emissions. The largest magnitude change in Sydney was in VOC emissions with a significant decrease from on-road sources and a slight increase in emissions from domestic–commercial and off-road sources.

9.2.2 Newcastle

Total SO_2 emissions increased by 9% and NO_x and VOC emissions decreased by 4% and 11% respectively in the Newcastle region between 2003 and 2008. Significant growth in SO_2 emissions was seen from biogenic and commercial sources, however these were not significant SO_2 emission sources for the region. Industrial sources contributed the most SO_2 emissions in the Newcastle region, which increased by 10% between 2003 and 2008. The most significant change in NO_x emissions a decrease from commercial sources, whilst the largest contributing source of on-road emissions decreased by 21%. Off-road vehicles had a significant increase in VOC emissions, whereas the largest decrease in VOC emissions was from on-road vehicles.

9.2.3 Wollongong

The total SO_2, NO_x and VOC emissions in the Wollongong region decreased by 14%, 5% and 12% respectively between 2003 and 2008. SO_2 emissions from biogenic and off-road mobile sources increased significantly, whereas emissions from on-road and industrial sources, which made the greatest contribution to emissions in the region, decreased. The largest contributor to NO_x emissions was industrial sources, which slightly decreased. The most significant change in NO_x emissions between 2003 and 2008 was an 87% reduction in emissions from commercial sources. VOC emissions from domestic–commercial and biogenic sources increased and the largest percentage change in VOCs was increased emissions from off-road mobile sources.

9.2.4 Non-urban

In the non-urban region of the GMR the total SO_2 and VOC emissions decreased by 4% and 12% respectively, and total NO_x emissions increased by 18%, between 2003 and 2008. The decrease in total SO_2 emissions was due to a slight decrease in industrial emissions. The

significant increase in total NO_x emissions was mainly due to the increase in NO_x emissions from off-road mobile sources and industrial sources. The decrease in magnitude of total VOC emissions was due to a decrease in biogenic emissions, however the largest percentage change in VOC emissions was a significant increase from off-road mobile sources.

9.2.5 Greater Metropolitan Region

Total SO_2 and VOC emissions in the GMR between 2003 and 2008 decreased by 4% and 16% respectively, and total NO_x emissions increased by 5%. The decrease in magnitude of total SO_2 emissions was dominated by a decrease in SO_2 emissions from industrial sources, however the largest percentage change was an increase in emissions from commercial sources, followed by off-road mobile sources. NO_x emissions increased due to increased emissions from industrial and on-road mobile sources. Reductions in VOC emissions were due to small reductions in biogenic emissions. The largest percentage change in VOC emissions was a significant increase in emissions from off-road mobile sources.

Table A4 Emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOCs) from major source groups in 2003 and 2008 across all regions

Region	Major source groups	$S0_2$ emissions			NO_x emissions			VOC emissions		
		2003	2008	Change	2003	2008	Change	2003	2008	Change
		(tonnes/year)			(tonnes/year)			(tonnes/year)		
Sydney	Biogenic	69	50	–28%	1,585	1,296	–18%	33,989	32,468	–4%
	Commercial	43	108	152%	1,078	344	–68%	9,931	6,685	–33%
	Domestic–commercial	113	131	16%	2,149	2,531	18%	52,009	53,178	2%
	Industrial	10,980	5,574	–49%	14,032	8,906	–37%	13,989	8,050	–42%
	Off-road mobile	1,376	4,725	243%	9,508	16,238	71%	4,797	7,341	53%
	On-road mobile	1,254	210	–83%	65,996	45,392	–31%	50,172	23,512	–53%
	Total	**13,836**	**10,798**	**–22%**	**94,349**	**74,708**	**–21%**	**164,887**	**131,234**	**–20%**
Newcastle	Biogenic	0.5	3	474%	103	126	22%	3,285	3,404	4%
	Commercial	1	2	204%	82	39	–53%	796	476	–40%
	Domestic–commercial	9	11	15%	154	184	20%	3,749	3,757	0%
	Industrial	9,300	10,266	10%	1,728	1,833	6%	1,274	921	–28%
	Off-road mobile	1,270	1,300	2%	2,983	3,548	19%	292	1,303	347%
	On-road mobile	98	15	–85%	4,947	3,902	–21%	3,554	1,678	–53%
	Total	**10,678**	**11,596**	**9%**	**9,997**	**9,632**	**–4%**	**12,951**	**11,539**	**–11%**
Wollongong	Biogenic	0.3	5	1604%	52	71	35%	3,371	3,482	3%
	Commercial	1	1	–26%	94	12	–87%	622	358	–42%
	Domestic–commercial	6	7	18%	107	130	22%	2,625	2,660	1%
	Industrial	10,290	8,494	–17%	7,929	7,784	–2%	788	716	–9%
	Off-road mobile	244	553	126%	908	1,598	76%	233	591	154%

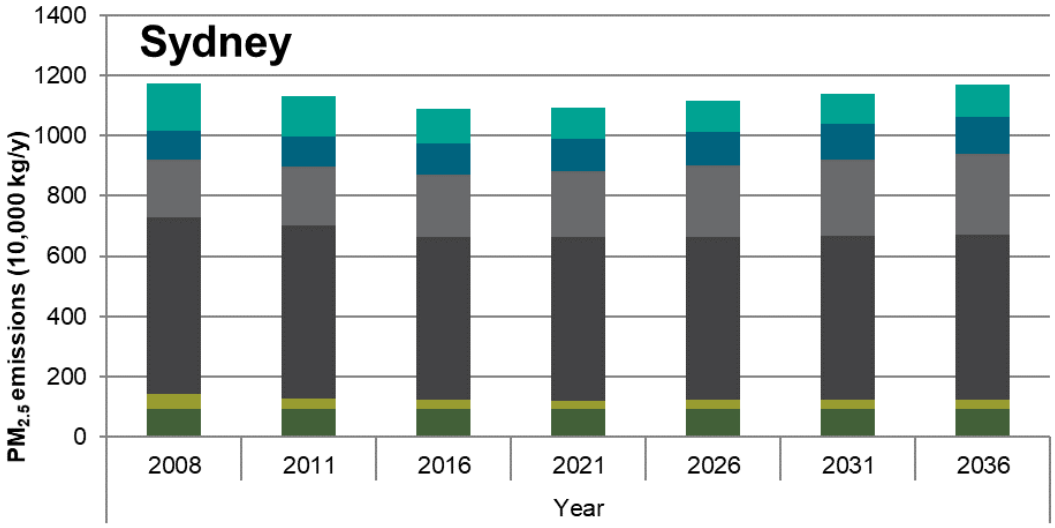
	On-road mobile	59	8	–86%	3,255	2,184	–33%	2,195	879	–60%
	Total	**10,602**	**9,068**	**–14%**	**12,346**	**11,779**	**–5%**	**9,834**	**8,687**	**–12%**
Non-urban	Biogenic	450	259	–42%	11,604	8,319	–28%	151,949	130,284	–14%
	Commercial	20	70	248%	388	106	–73%	2,441	1,904	–22%
	Domestic–commercial	22	26	21%	387	445	15%	8,980	9,213	3%
	Industrial	265,248	256,139	–3%	151,847	172,888	14%	1,734	1,831	6%
	Off-road mobile	1,279	1,246	–3%	10,071	31,826	216%	2,318	8,715	276%
	On-road mobile	249	35	–86%	14,410	9,453	–34%	8,573	3,435	–60%
	Total	**267,267**	**257,774**	**–4%**	**188,706**	**223,038**	**18%**	**175,995**	**155,382**	**–12%**
GMR	Biogenic	520	317	–39%	13,344	9,811	–26%	192,594	169,637	–12%
	Commercial	65	180	180%	1,642	501	–70%	13,790	9,424	–32%
	Domestic–commercial	149	175	17%	2,796	3,290	18%	67,363	68,809	2%
	Industrial	295,819	280,472	–5%	175,537	191,411	9%	17,786	11,519	–35%
	Off-road mobile	4,170	7,824	88%	23,470	53,210	127%	7,640	17,950	135%
	On-road mobile	1,660	269	–84%	88,609	60,932	–31%	64,493	29,504	–54%
	Total	**302,383**	**289,237**	**–4%**	**305,398**	**319,156**	**5%**	**363,666**	**306,843**	**–16%**

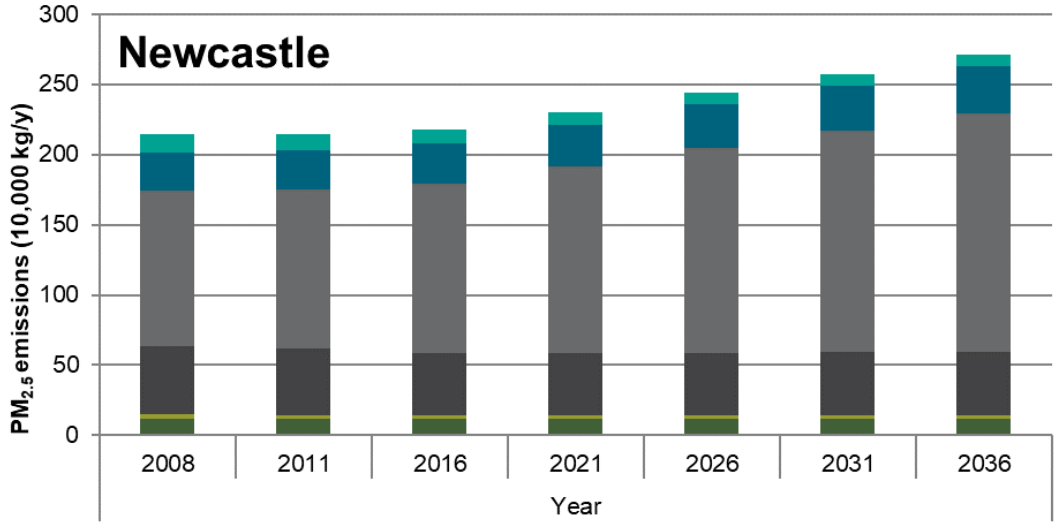
9.3 Projected future trends in emissions

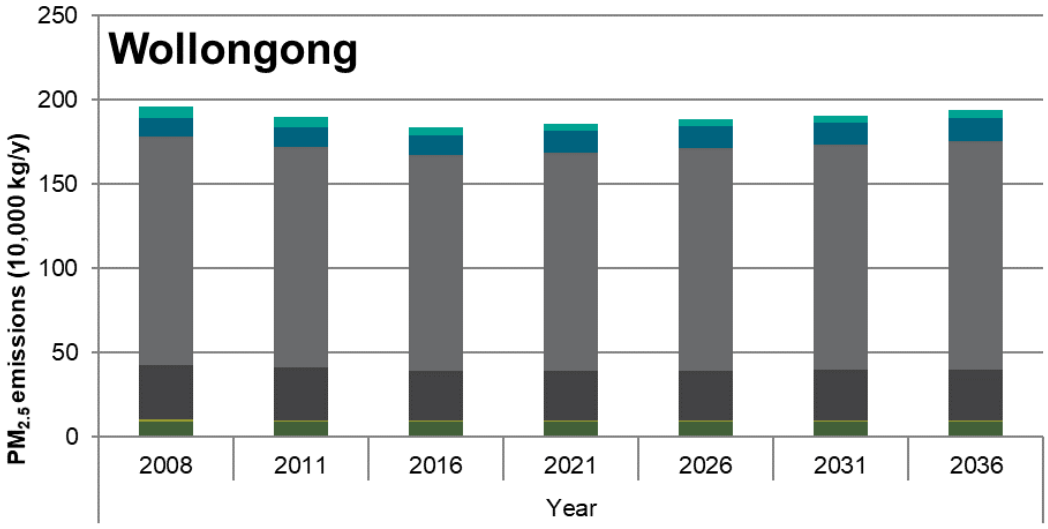
The projections of domestic–commercial sources were based on the energy consumption for residential areas using biomass estimates from the Australian Energy, National and State Projections to 2029–2030, Australian Bureau of Agricultural and Resource Economics (ABARE) research report 06.26 (Cuevas-Cubria and Riwoe 2006). Future on-road mobile emission projections were made using the same methodology used for estimates for the 2008 base year. Assumptions were made regarding emissions performance of the fleet based on known and proposed future emissions relative to the emission data for the current fleet. The total vehicle kilometres travelled used for emission projections was estimated by the Bureau of Transport Statistics. Other projections were based on ABARE primary energy consumption projections for mining, iron and steel in NSW (Cuevas-Cubria and Riwoe 2006).

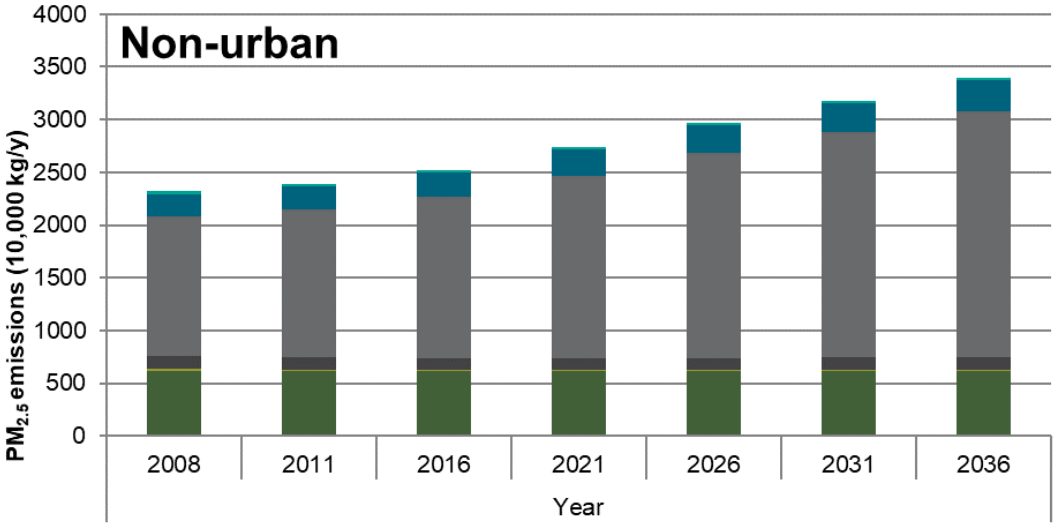
9.3.1 Particulate matter

Projected source contributions to $PM_{2.5}$ emissions across each region were modelled (Figure A.1). Domestic–commercial emissions were the most significant source of $PM_{2.5}$ emissions in the Sydney region in 2008 and are projected to remain relatively stable between 2008 and 2036. These emissions were predominantly from 'solid fuel burning', i.e., residential wood heating. Across all other regions and the GMR, the dominant source of $PM_{2.5}$ was industrial emissions, primarily from coal mining in the Newcastle, non-urban and GMR regions, and iron or steel production in the Illawarra. Industrial sources are also projected to remain relatively stable in the Wollongong region and to slightly increase between 2008 and 2036 in other regions.




Newcastle
300
250
200
150
100
50
0
PM2.5 emissions (10,000 kg/y)
2008
2011
2016
2021
2026
2031
2036
Year


Wollongong
250
200
150
100
50
0
PM2.5 emissions (10,000 kg/y)
2008
2011
2016
2021
2026
2031
2036
Year


Non-urban
4000
3500
3000
2500
2000
1500
1000
500
0
PM2.5 emissions (10,000 kg/y)
2008
2011
2016
2021
2026
2031
2036
Year

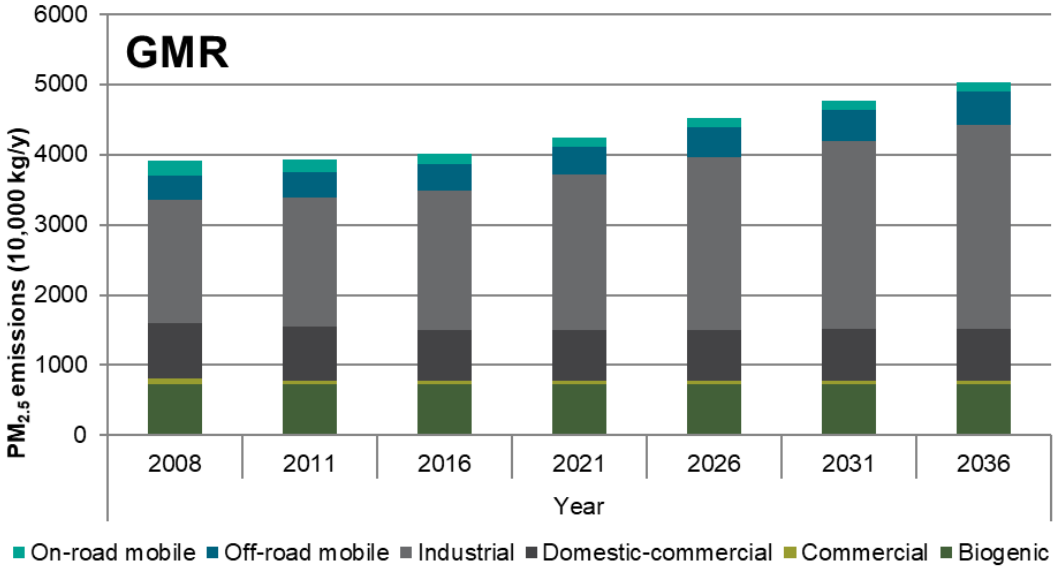
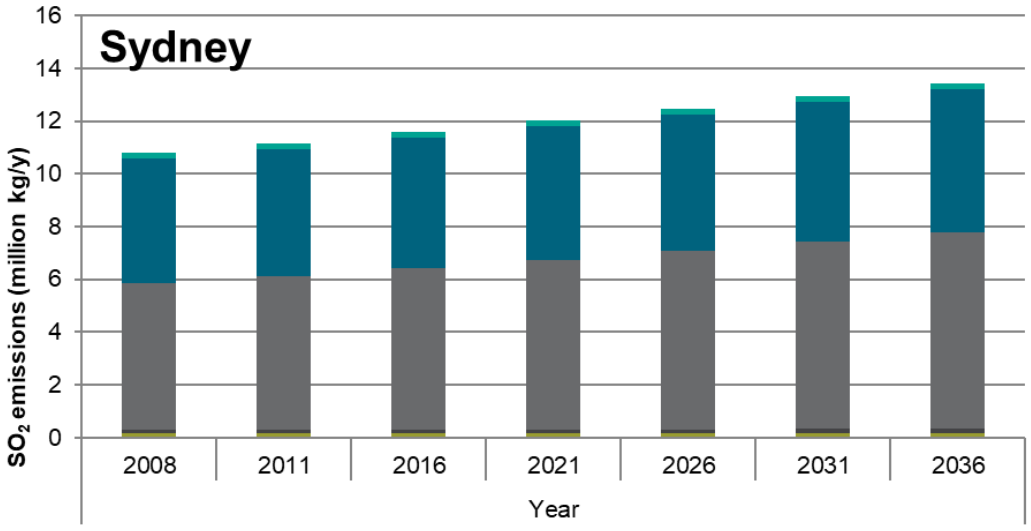
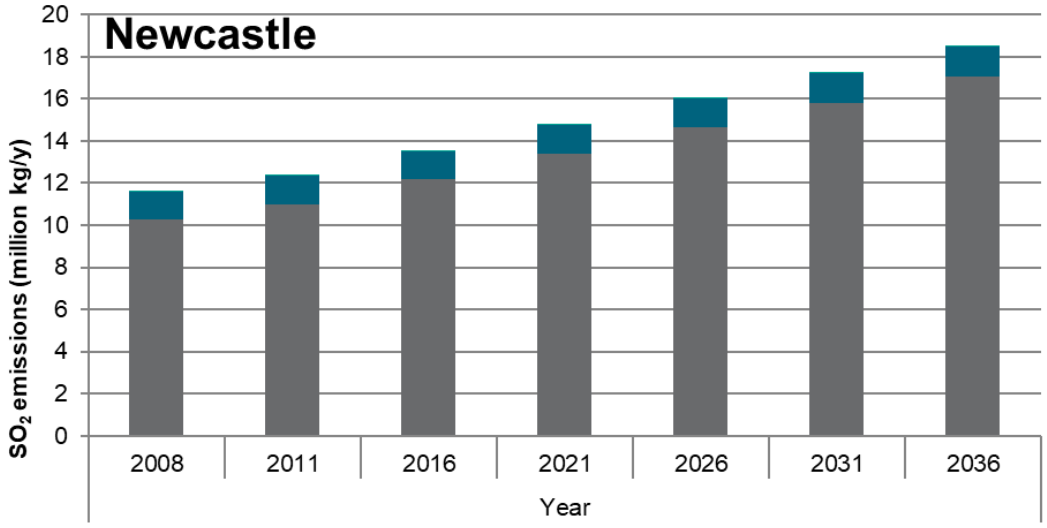


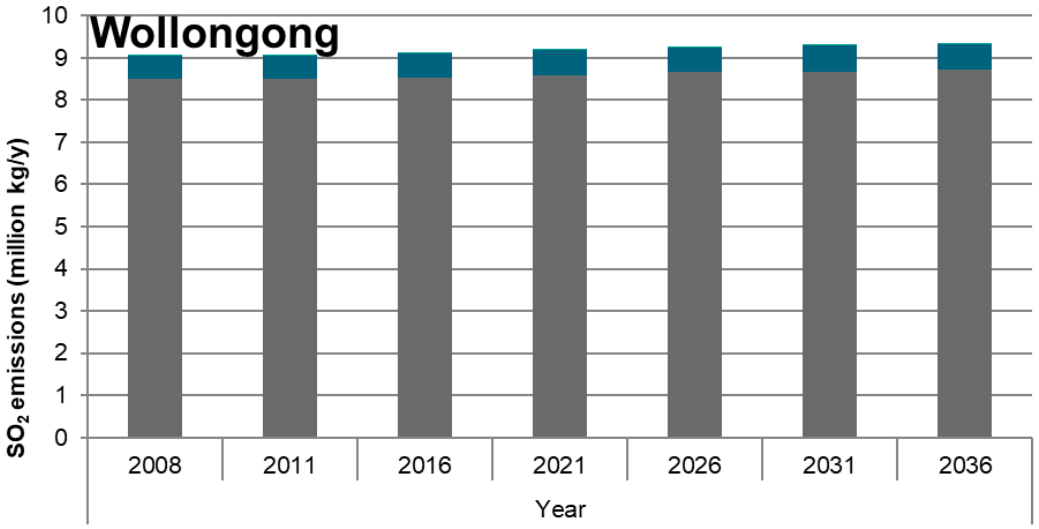
Figure A1 Modelled and projected source contributions for particles less than 2.5 micrometres in diameter ($PM_{2.5}$) for each region in the NSW Greater Metropolitan Region (GMR) between 2008 and 2036. kg/y = kilograms per year.

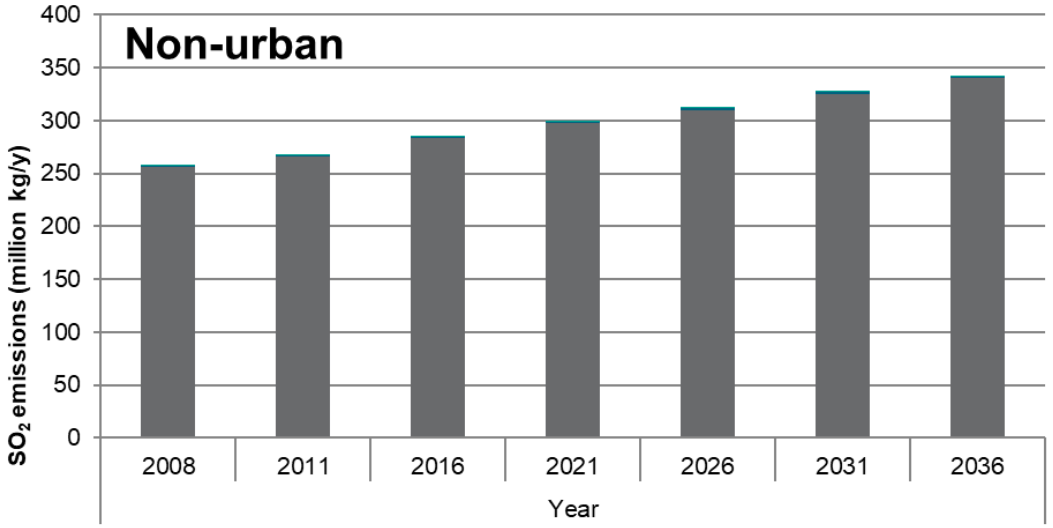
9.3.2 Sulfur dioxide

Projected source contributions to SO_2 emissions across each region were modelled (Figure A.2). Industrial emissions were the most significant source of SO_2 emissions across all regions in 2008 and are projected to remain relatively stable between 2008 and 2036, although increasing in the Newcastle and the GMR. The sources of the industrial emissions were dominated by the production of petroleum and fuel in Sydney, aluminium production in Newcastle, iron or steel production in the Illawarra and coal-fired power stations in the non-urban and GMR regions.




Newcastle
20
18
16
14
12
10
8
6
4
2
0
SO2 emissions (million kg/y)
2008
2011
2016
2021
2026
2031
2036
Year


Wollongong
10
9
8
7
6
5
4
3
2
1
0
SO2 emissions (million kg/y)
2008
2011
2016
2021
2026
2031
2036
Year


Non-urban
400
350
300
250
200
150
100
50
0
SO2 emissions (million kg/y)
2008
2011
2016
2021
2026
2031
2036
Year

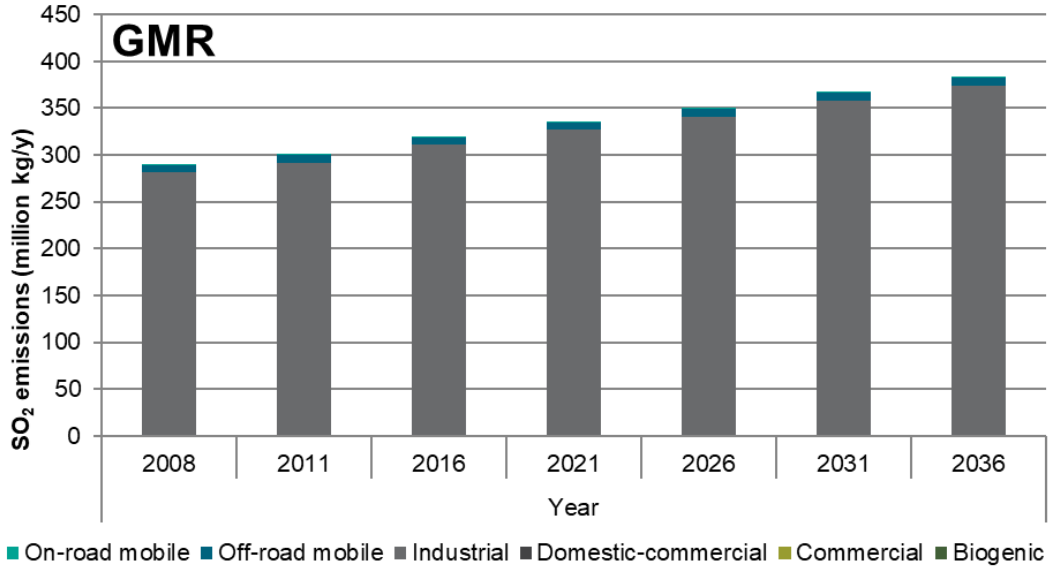
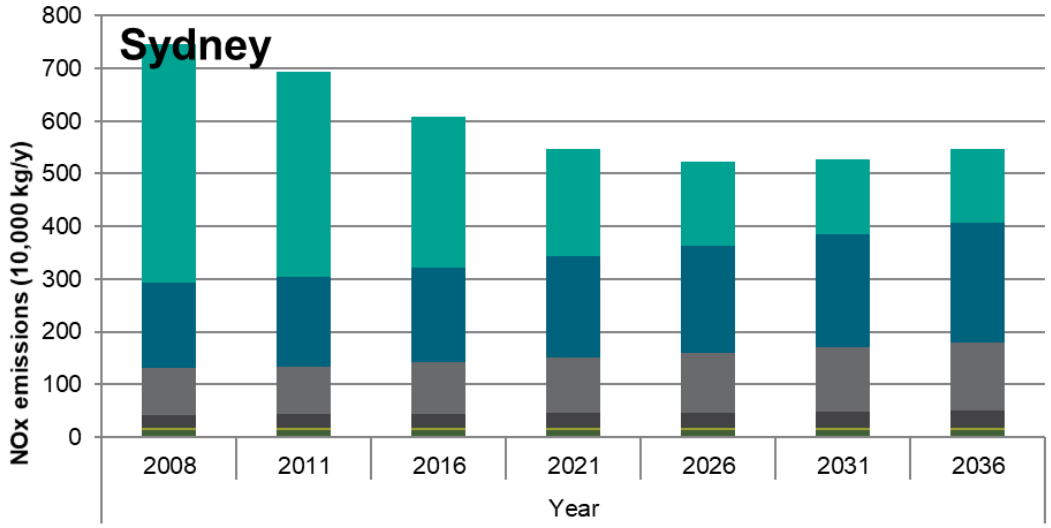
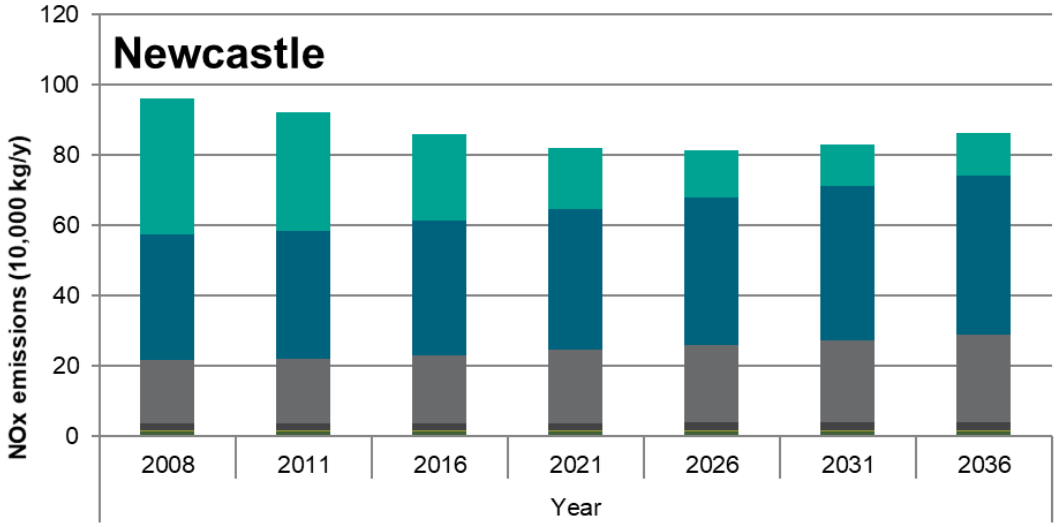


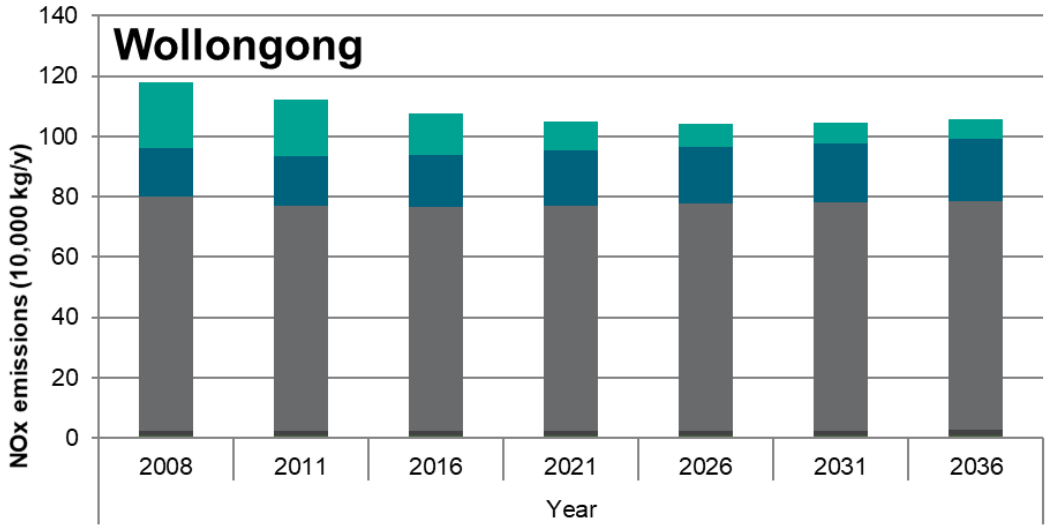
Figure A2 Modelled and projected source contributions for sulfur dioxide (SO_2) for each region in the NSW Greater Metropolitan Region (GMR) between 2008 and 2036. kg/y = kilograms per year.

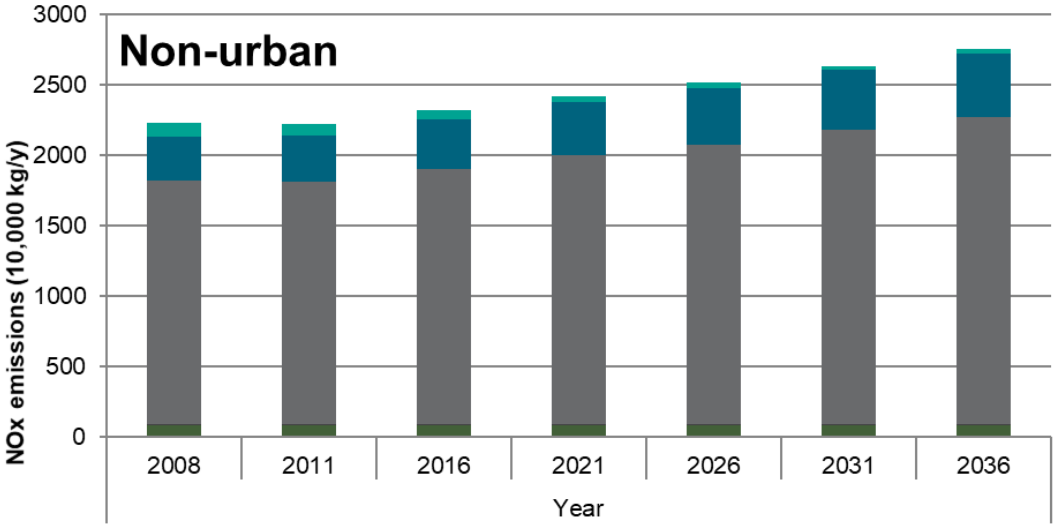
9.3.3 Nitrogen oxides

Projected source contributions to NO_x emissions across each region were modelled (Figure A.3). On-road mobile emissions were the most significant source of NO_x emissions in the Sydney region in 2008 and are projected to decrease between 2008 and 2036. The predominant contributor to on-road mobile NO_x emissions in Sydney is passenger vehicle petrol exhaust. Off-road mobile emissions of NO_x are dominated by shipping, which is the most significant source in the Newcastle region. Industrial emissions are the predominant source of NO_x in the Wollongong region, and is dominated by iron or steel production. In the non-urban region and GMR, industrial emissions from coal-fired power stations are the biggest contributors to NO_x.




Newcastle
NOx emissions (10,000 kg/y)
120
100
80
60
40
20
0
2008
2011
2016
2021
2026
2031
2036
Year


Wollongong
NOx emissions (10,000 kg/y)
140
120
100
80
60
40
20
0
2008
2011
2016
2021
2026
2031
2036
Year


Non-urban
NOx emissions (10,000 kg/y)
3000
2500
2000
1500
1000
500
0
2008
2011
2016
2021
2026
2031
2036
Year

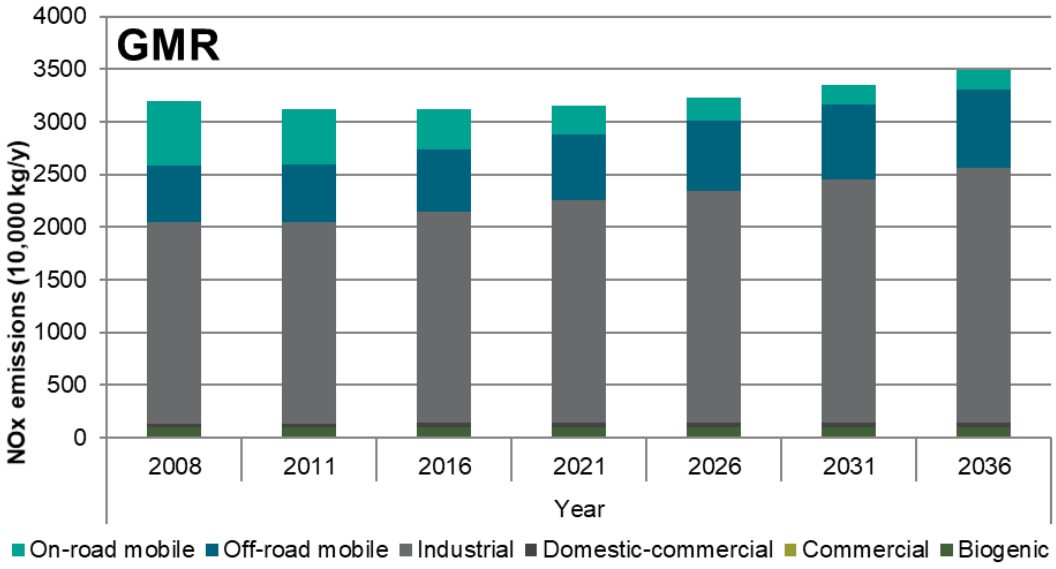
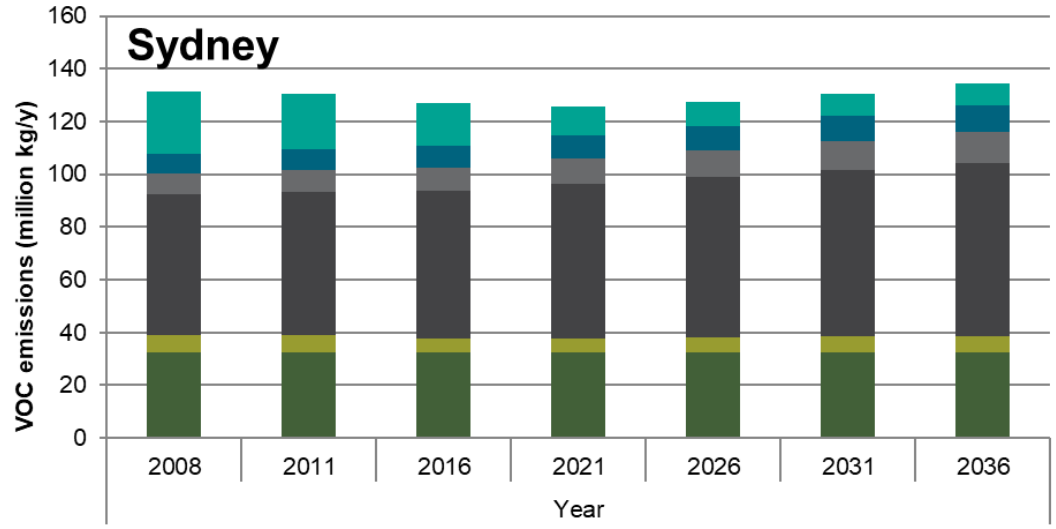
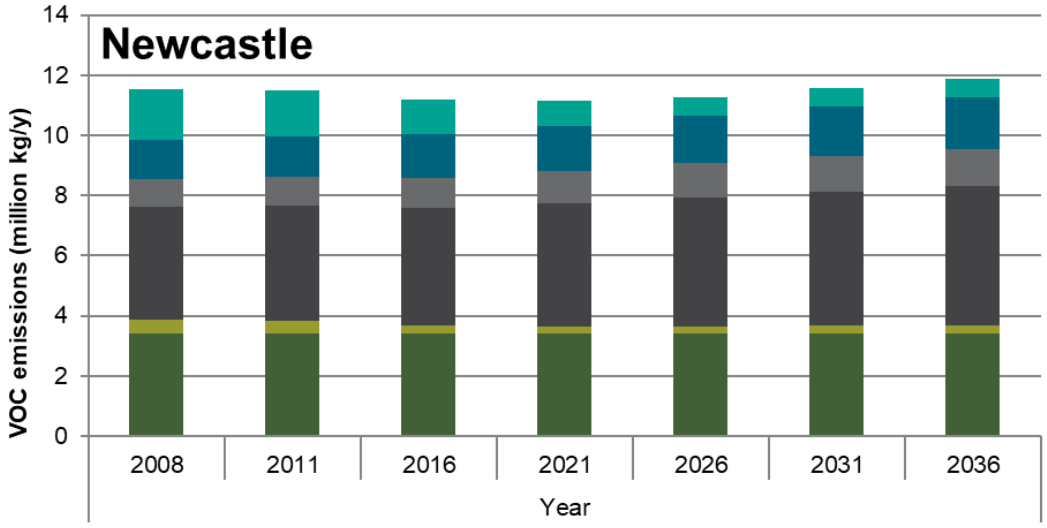


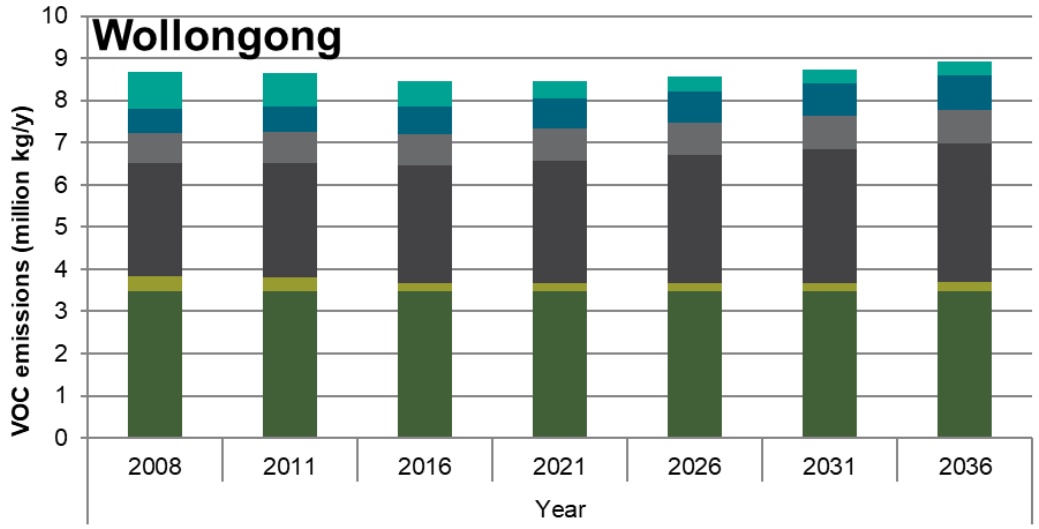
Figure A3 Modelled and projected source contributions for nitrogen oxides (NOx) for each region in the NSW Greater Metropolitan Region (GMR) between 2008–2036.

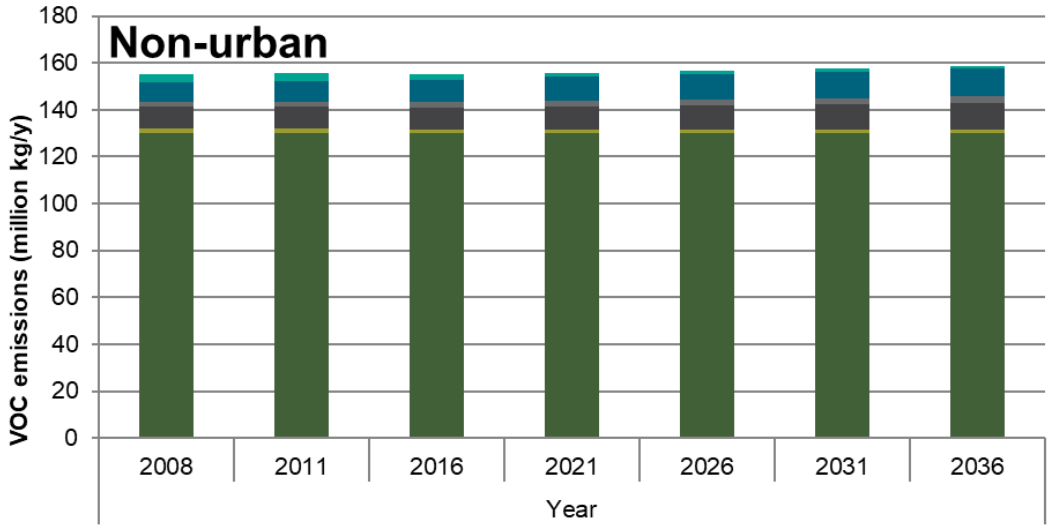
9.3.4 Volatile organic compounds

Projected source contributions to VOC emissions across each region were modelled (Figure A.4). In Sydney, Newcastle and Wollongong the dominant source for VOCs were domestic–commercial emissions. In non-urban areas biogenic sources dominated as the contributor to VOC emissions because there are fewer domestic–commercial sources. Biogenic emissions are dominated by vegetation and are projected to remain stable. The domestic–commercial emissions of VOCs are predominantly from the use of solvents and aerosols.




Newcastle
VOC emissions (million kg/y)
0
2
4
6
8
10
12
14
2008
2011
2016
2021
2026
2031
2036
Year


Wollongong
VOC emissions (million kg/y)
0
1
2
3
4
5
6
7
8
9
10
2008
2011
2016
2021
2026
2031
2036
Year


Non-urban
VOC emissions (million kg/y)
0
20
40
60
80
100
120
140
160
180
2008
2011
2016
2021
2026
2031
2036
Year

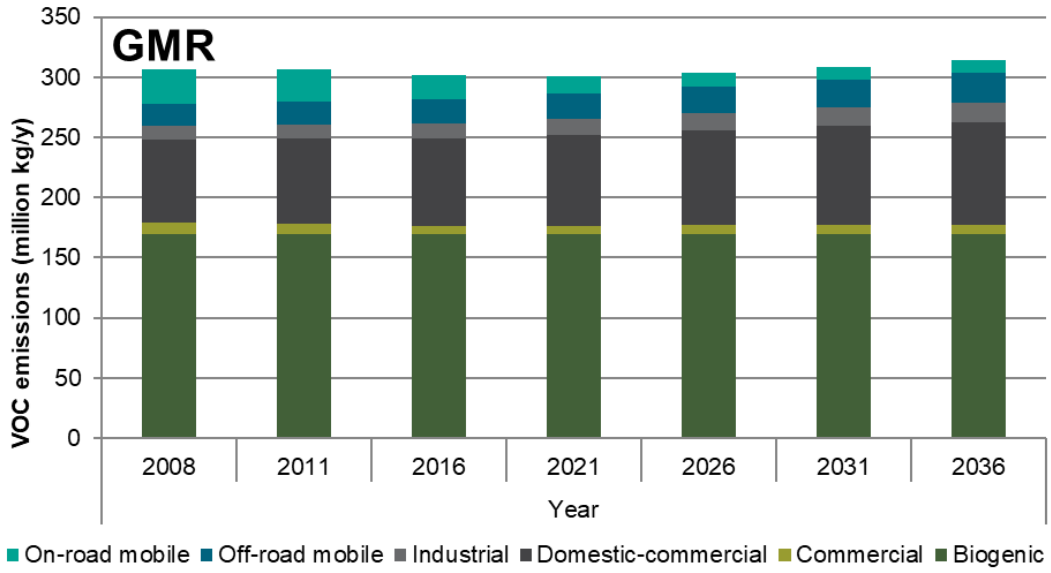
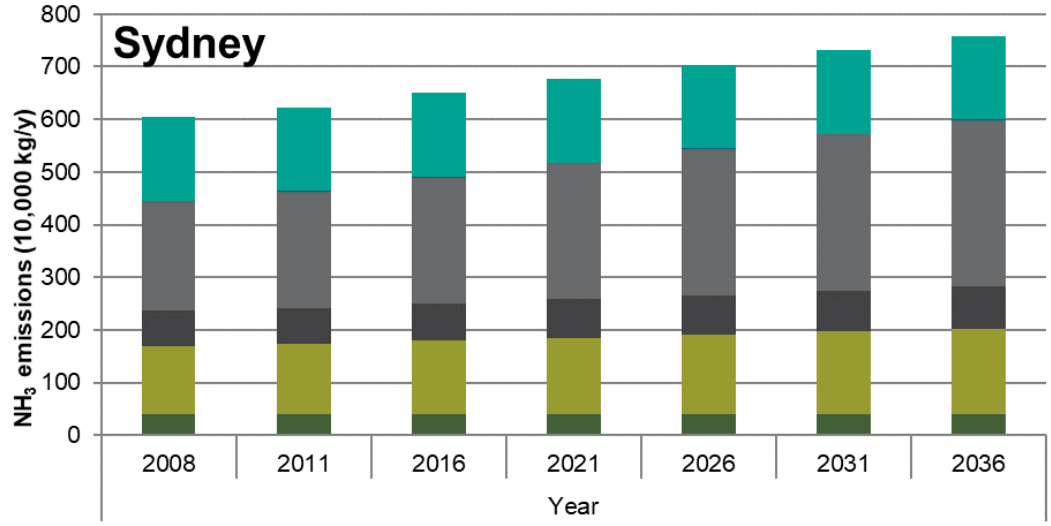
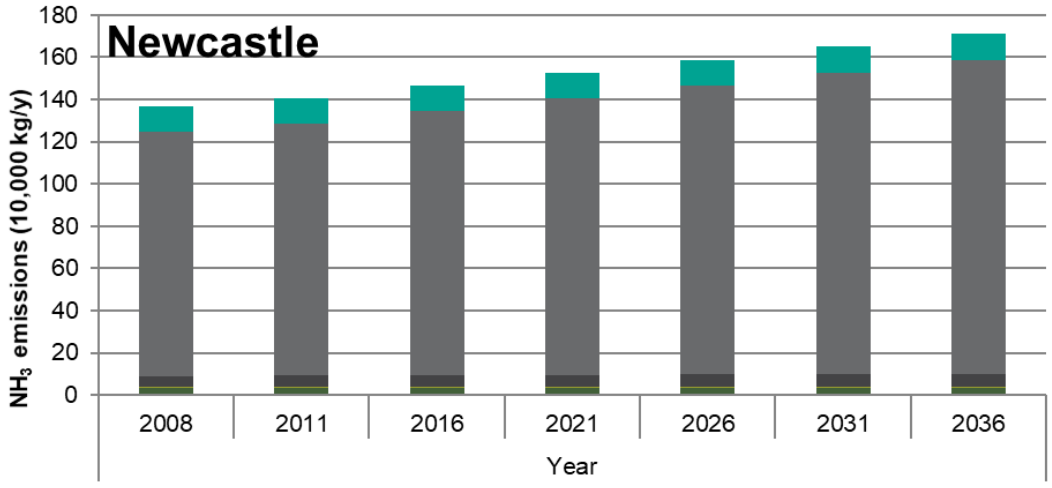


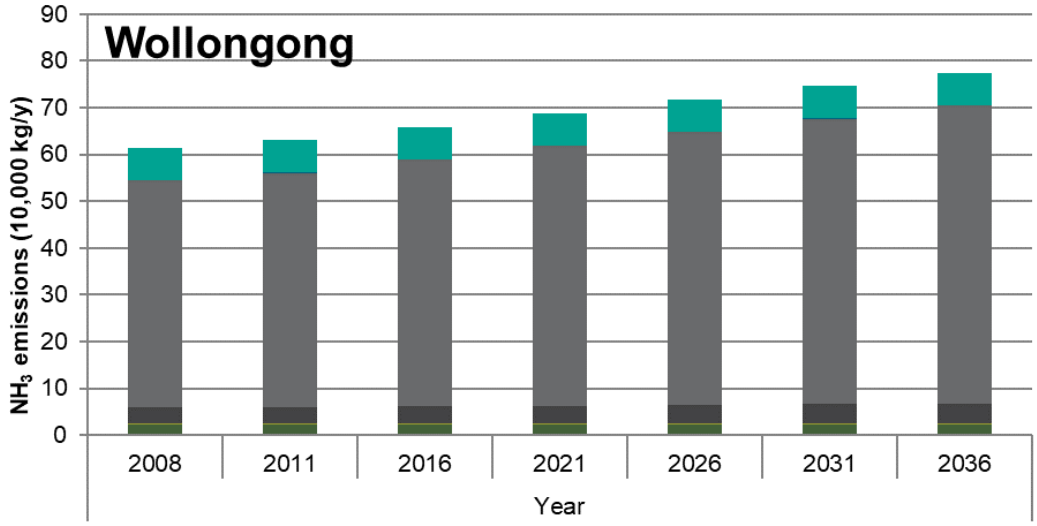
Figure A4 Modelled and projected source contributions for volatile organic compounds (VOCs) for each region in the NSW Greater Metropolitan Region between 2008 and 2036.

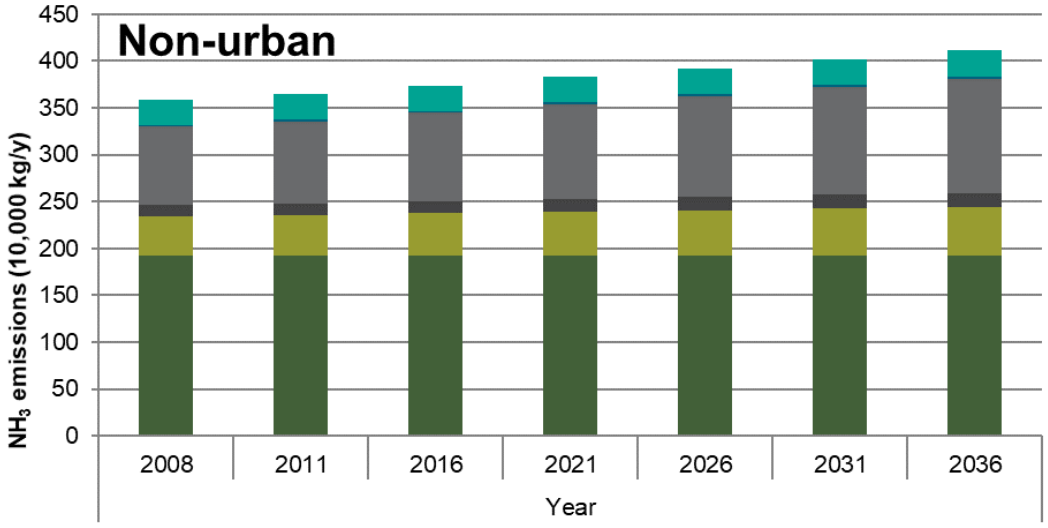
9.3.5 Ammonia

Projected source contributions to NH_3 emissions across each region were modelled (Figure A.5). Industrial emissions are the major contributors to NH_3 in the Sydney, Newcastle, Wollongong regions and the GMR. The source of these emissions is mainly waste disposal (application to land) in Sydney and the GMR, slaughtering or processing of animals Newcastle and iron or steel production in Wollongong. In non-urban regions, biogenic emissions dominated in 2008 and are projected to remain stable across the 28-year period. Soil is the most significant contributor to biogenic NH_3 emissions in non-urban areas.




Newcastle
180
160
140
120
100
80
60
40
20
0
NH3 emissions (10,000 kg/y)
2008
2011
2016
2021
2026
2031
2036
Year


Wollongong
90
80
70
60
50
40
30
20
10
0
NH3 emissions (10,000 kg/y)
2008
2011
2016
2021
2026
2031
2036
Year


Non-urban
450
400
350
300
250
200
150
100
50
0
NH3 emissions (10,000 kg/y)
2008
2011
2016
2021
2026
2031
2036
Year

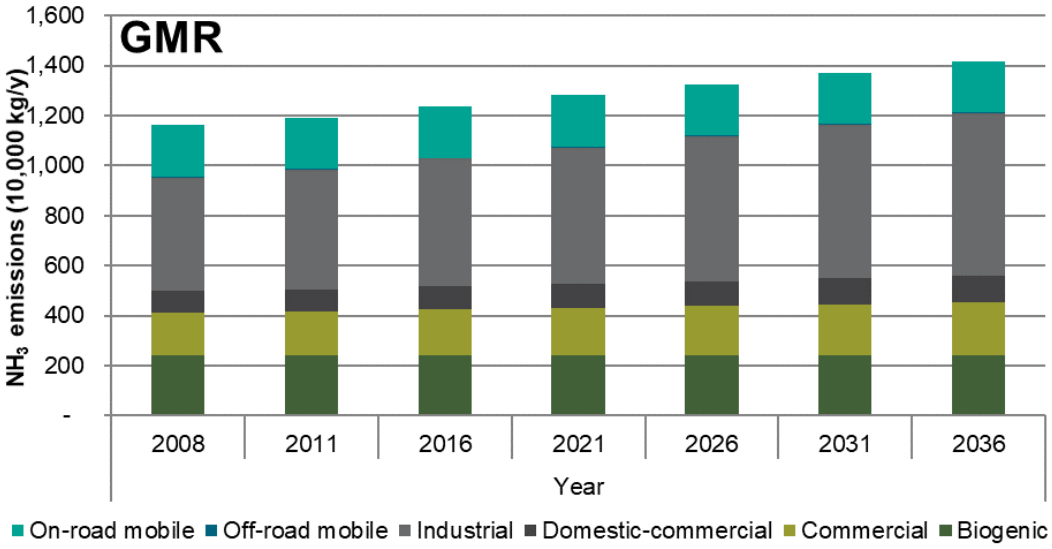


Figure A5 Modelled and projected source contributions for ammonia (NH3) for each region in the NSW Greater Metropolitan Region between 2008 and 2036.

9.4 Reference

Cuevas-Cubria C and Riwoe D 2006, Australian Energy: National and State Projections to 2029–30, Australian Bureau of Agricultural and Resource Economics Research Report 06.26 Prepared for the Australian Government Department of Industry, Tourism and Resources, Canberra.

10. Appendix B: Source-dependent fractions for major source groups used in emission modelling

Table B1 The source-dependent fractions for major source groups used in emission modelling

Major source groups	$PM_{2.5}/PM_{10}$	EC/PM_{10}	OC/PM_{10}	DU/PM_{10}	$LEVO/PM_{10}$	SO_3/PM_{10}	SO_3/SO_x	IOLE/OLE	ALDX/ALD2	ETHA/PAR	PTOL/TOL	PXYL/XYL	PBNZ/TOL
Diesel exhaust	0.970	0.329	0.401	0.270	0.0	0.0285	0.03	0.374	0.145	0.0	0.77	0.48	0.31
Petrol exhaust	0.953	0.283	0.635	0.083	0.0	0.044	0.03	0.185	0.34	0.085	0.77	0.48	0.31
Other exhaust	0.953	0.283	0.635	0.083	0.0	–1.0	0.03	0.491	0.650	0.123	0.77	0.48	0.31
Petrol evaporation	0.953	0.283	0.635	0.083	0.0	–1.0	0.03	0.491	0.650	0.123	0.77	0.48	0.31
Shipping and commercial boats	0.970	0.008	0.191	0.156	0.0	0.645	0.00	0.0	0.0	0.0	0.77	0.48	0.31
Industrial vehicles and equipment	0.970	0.643	0.237	0.120	0.0	–1.0	0.03	0.0	0.0	0.0	0.77	0.48	0.31
Aircraft	0.844	0.76	0.24	0.0	0.0	–1.0	0.03	0.0	0.0	0.0	0.77	0.48	0.31
Locomotives	0.970	0.771	0.176	0.053	0.0	–1.0	0.03	0.0	0.0	0.0	0.77	0.48	0.31
Commercial non-road equipment	0.970	0.643	0.237	0.120	0.0	–1.0	0.03	0.0	0.0	0.0	0.77	0.48	0.31
Non-exhaust particulate matter	0.532	0.01	0.094	0.893	0.0	0.0135	0.00	0.0	0.0	0.0	0.0	0.0	0.0
Residential wood heaters	0.963	0.151	0.419	0.431	0.25	–1.0	0.03	0.0	0.0	0.0	0.77	0.48	0.31
Industrial area fugitives	0.170	0.005	0.1	0.9	0.0	0.001	0.00	0.0	0.0	0.0	0.0	0.0	0.0
Other domestic–commercial area source (excluding non-road and wood heaters)	0.300	0.100	0.100	0.800	0.0	–1.0	0.03	0.0	0.0	0.0	0.77	0.48	0.31

Notes: ALD2 = acetaldehyde; ALDX = all other higher aldehydes; EC = elemental carbon; ETHA = ethane; DU = dust; IOLE = internal olefin species; LEVO = levoglucosan; OC = organic carbon; OLE = olefins; PAR = paraffins; PBNZ = p-benzene; $PM_{2.5}$ = particles less than 2.5 micrometres in diameter; PM_{10} = particles less than 10 micrometres in diameter; PTOL = p-toluene; PXYL = p-xylene; SO_3 = sulfur trioxide; SO_x = sulfur oxides; TOL = toluene; XYL: xylene.

11. Appendix C: Conformal Cubic Atmospheric Model performance

Validation of the Conformal Cubic Atmospheric Model (CCAM) meteorological results for 2008 was used to assess its ability to predict the meteorological conditions that drive the transportation and chemical transformation of pollutants in the Greater Metropolitan Region (GMR) of NSW. Three key meteorological parameters, temperature, wind speed and wind direction, were used for the CCAM validation against a selection of Department of Planning, Industry and Environment (DPIE) and Bureau of Meteorology monitoring stations (Table C.1).

Table C1 Locations of Department of Planning, Industry and Environment (DPIE) air quality monitoring stations and Bureau of Meteorology (BoM) weather stations selected for this study

Site location	Provider	Latitude	Longitude
Bargo	DPIE	–34.307	150.580
Bringelly	DPIE	–33.919	150.760
Chullora	DPIE	–33.894	151.050
Prospect	DPIE	–33.795	150.910
Randwick	DPIE	–33.933	151.240
Richmond	DPIE	–33.618	150.750
Wollongong	DPIE	–34.419	150.890
Newcastle	DPIE	–32.910	151.758
Badgerys Creek	BoM	–33.897	150.728
Bankstown Airport	BoM	–33.918	150.986
Camden Airport	BoM	–34.039	150.689
Richmond Royal Australian Air Force (RAAF)	BoM	–33.600	150.776
Sydney Airport	BoM	–33.947	151.173
Williamtown RAAF	BoM	–32.793	151.836

This validation was considered an operational evaluation where model estimates were compared to observations and deviations were quantified through statistical tests. As part of this operational evaluation a selection of graphical analytics (Section 1) and statistical metrics (Section 2) were used to measure the overall performance of the modelling. The statistical metrics could then be compared to other modelling study benchmarks to indicate whether the model was within an acceptable range of performance.

11.1 Graphical performance evaluation

The graphical performance evaluation of the CCAM meteorological results for 2008 looked at discrete probability density functions (PDFs) and the seasonal diurnal (daily) averaged time-series for temperature and winds. Wind rose plots were included to provide a comparison to investigate whether there were differences in the frequency of wind direction

and wind speeds. These tools enabled visual investigation of important time-scale variability throughout the modelling period and gauge whether there was a correlation between the CCAM and other observations.

11.1.1 Discrete probability density functions

Discrete PDFs for seasonally averaged temperature and wind speed were calculated at Chullora, Prospect, Camden Airport, and Sydney Airport.

The PDFs for temperature generally showed close agreement and were relatively consistent across seasons and stations (Figure C.1). The model slightly under and over-predicted temperature at different times of the day. This trend was more noticeable for temperatures between 10 and 30°C.

For wind speeds, the model clearly over-predicted in the 0–2 metres per second range across all sites, except for Sydney Airport where there was close agreement (Figure C.2).

The model captured the seasonal variability and range of temperatures quite well. This indicated that the influence of meteorology on photochemical processes would be well represented by the model. The over-prediction of higher wind speeds and under-prediction of lower wind speeds would impact the ability of the model to predict the dispersion and transport of pollutants in chemical transport modelling.

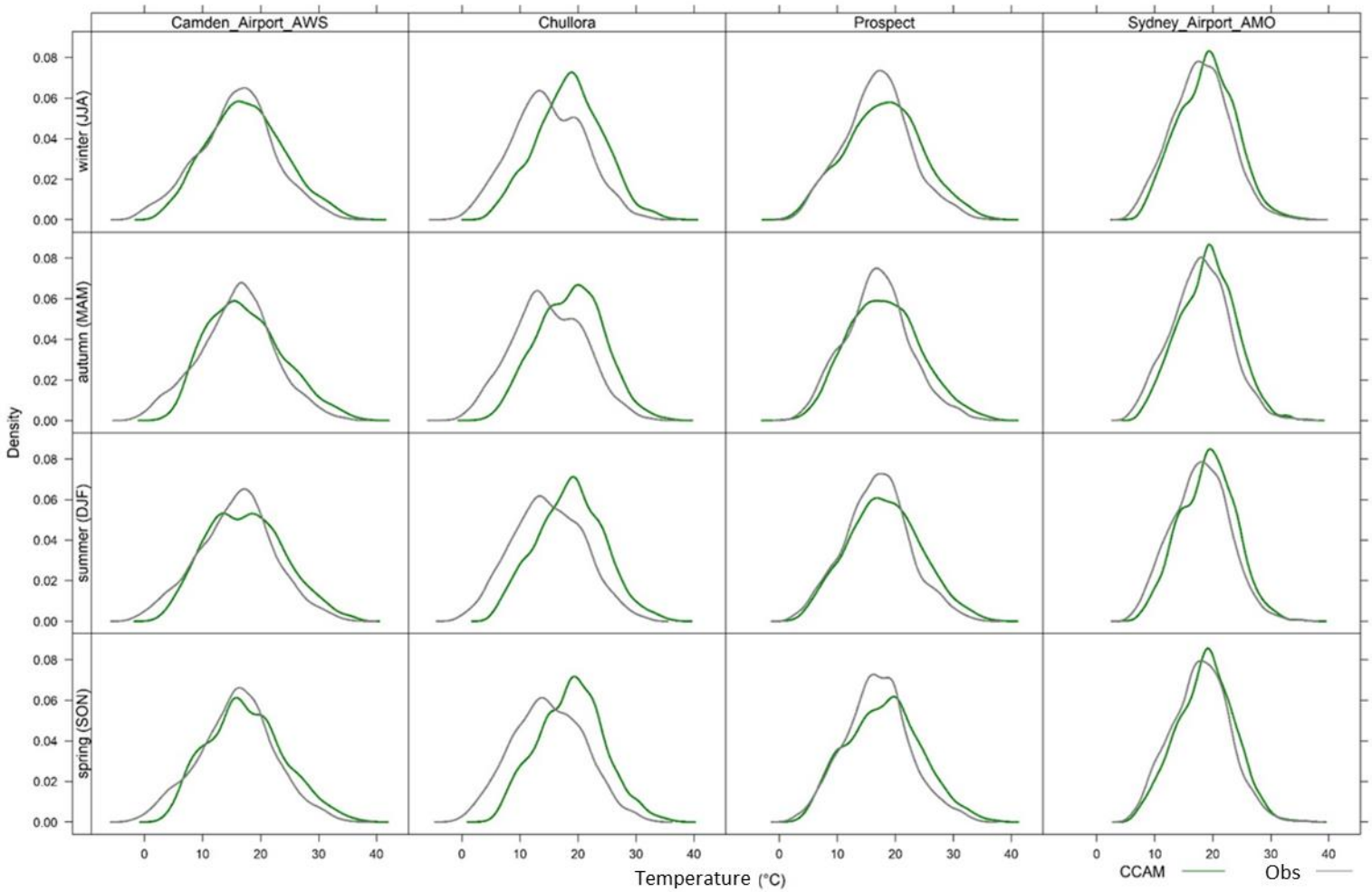


Figure C1 Seasonal discrete probability density function plots for temperature (degrees Celsius (deg C)) at Chullora, Prospect, Camden and Sydney Airport. CCAM = Conformal Cubic Atmospheric Model; DJF = December, January, February; JJA = June, July, August; MAM = March, April, May; Obs = observed; SON = September, October, November.

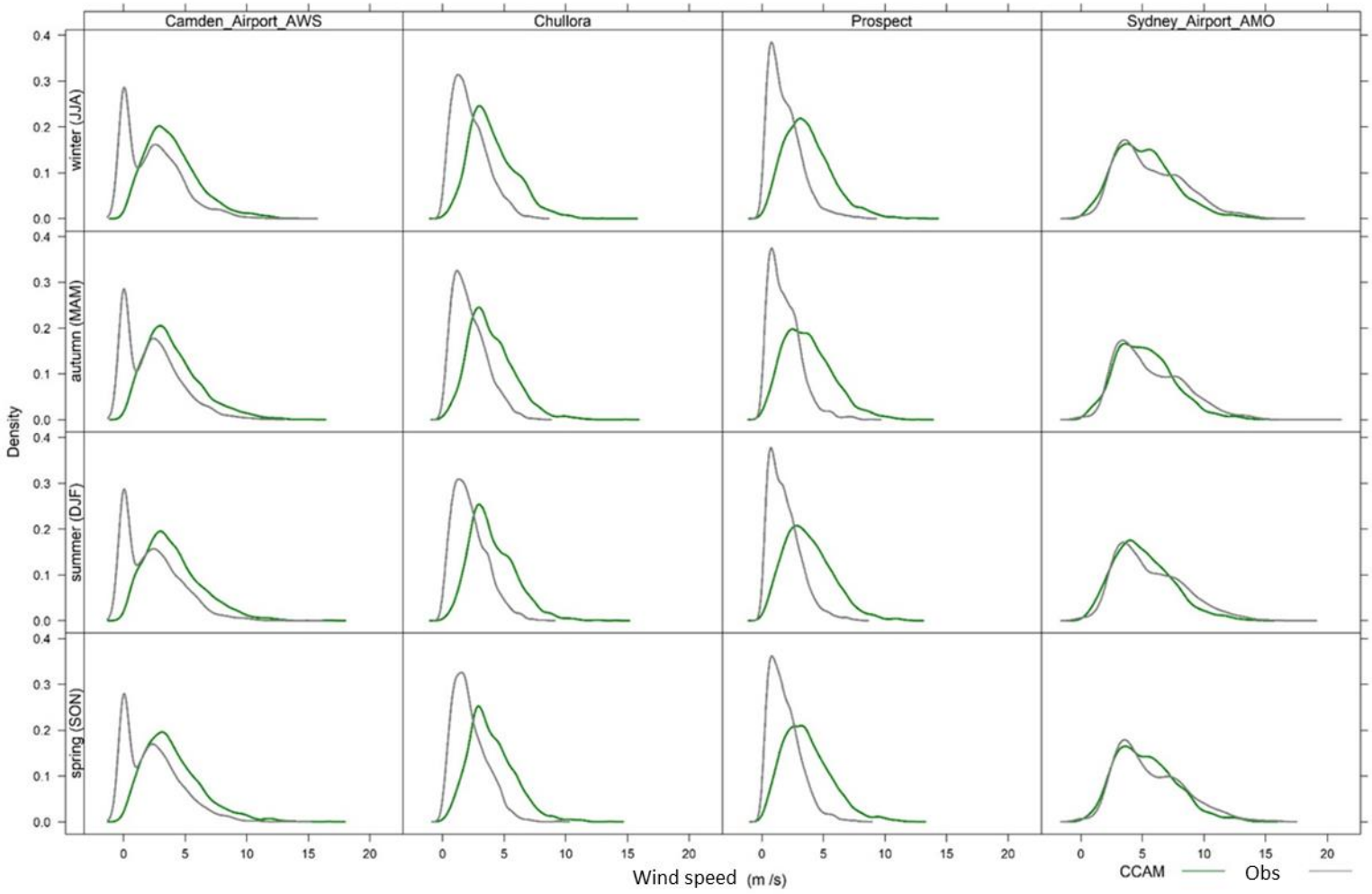


Figure C2 Seasonal discrete probability density function plots for wind speed (metres per second (m/s)) at Chullora, Prospect, Camden and Sydney Airport. CCAM = Conformal Cubic Atmospheric Model; DJF = December, January, February; JJA = June, July, August; MAM = March, April, May; Obs = observed; SON = September, October, November.

11.1.2 Temporal plots

Monthly and diurnal temperature plots for the DPIE (Figure C.3a and b) and BoM (Figure C.4a and b) monitoring stations show the overall variability of the model slightly over-predicted temperature throughout the year and the day. At all stations the modelled temperatures were warmer than the CCAM observations, however this over-prediction is unlikely to be significant in terms of impact on air quality. The largest bias in the predicted monthly temperatures occurred in winter at the Chullora DPIE station and the Williamtown RAAF BoM station. Throughout the day, maximum temperatures were slightly warmer than the model predicted, which could impact the formation of photochemical species in the chemical transport modelling. A notable deviation from observations was for the warmer temperatures overnight, which may be associated with the model's inability to simulate stable conditions overnight. This could impact subsequent air quality modelling on the dispersion of pollutants (Monk et al 2019).

For winds, a temporal comparison between the CCAM and monitoring station observations for the modelling period was presented for wind speed, zonal and meridional wind components. The wind speed plots show a consistent over-prediction of 1–2 metres per second at most stations, with a slightly higher over-prediction of 2–3 metres per second at the Richmond and Bringelly stations (Figures C.5 and C.6). The exception was Sydney Airport, where there was close agreement between the modelled and observed monthly average wind speed, particularly during autumn and winter months. This was consistent with the PDF plots for Sydney Airport (Figure C.2).

In general, because of differences between the DPIE and BoM monitoring networks (from instrumentation and influences of local terrain), the wind speeds observed by the DPIE Air Quality Monitoring Network are lower than those recorded at BoM sites. This can be seen clearly in the wind speed plots and explains why there is a closer agreement between the CCAM simulation and BoM wind speed observations.

Monthly averaged zonal (Figures C.7 and C.8) and meridional (Figures C.9 and C.10) wind plots capture the overall pattern of winds throughout the year; i.e. more southerly and westerly components occur during winter months and more easterly and northerly components occur during summer. The CCAM simulation has a much larger amplitude, regardless of the direction of the wind, which would largely be attributable to the over-prediction of wind speeds. Diurnally, zonal winds capture the sea breeze and the model amplitude is too large, which again is likely to be due to over-prediction of the wind speed. The diurnally averaged meridional winds show less agreement with observations, however there is little variability across the day in the observations and no definite shift throughout the day from north to south as for the sea breeze-influenced zonal winds.

11.1.3 Wind roses

A more useful evaluation of wind direction is a comparison of wind roses at each station. Wind rose plots provide a comparison between the model and the observed frequency of wind direction and wind speed at each station (Figure C.11). It is clear from the wind rose plots that the model predicted faster winds speeds more often than in the observations. Additionally, a comparison of the mean wind speeds showed there was at least a 1 metre per second difference between observations and CCAM. The predominant wind directions were well captured by the model at Bargo, Chullora, Newcastle, Prospect and most BoM stations.

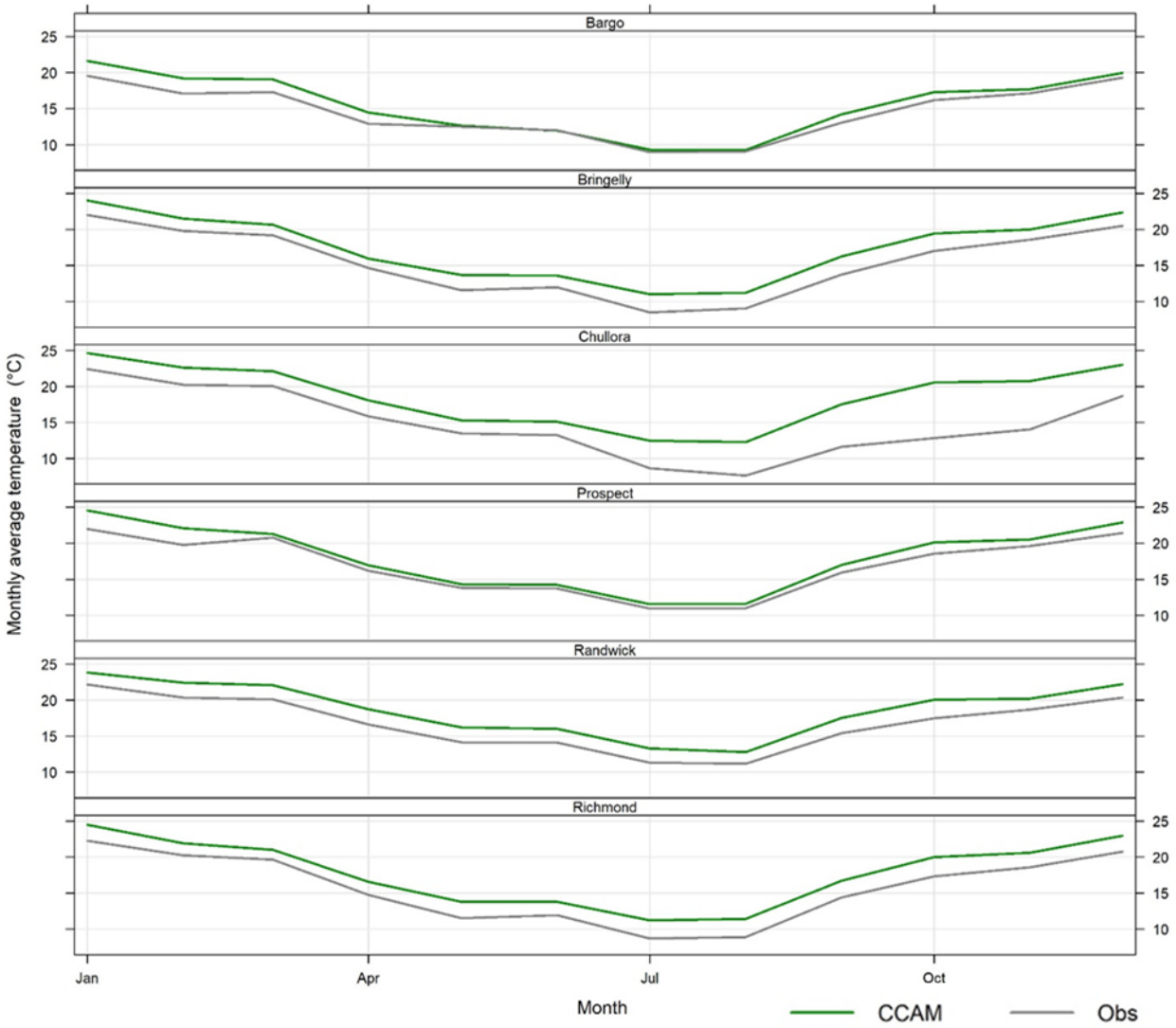


Figure C3a Monthly average temperature plots for a selection of Department of Planning, Industry and Environment air quality monitoring stations. CCAM = Conformal Cubic Atmospheric Model; Obs = observed.

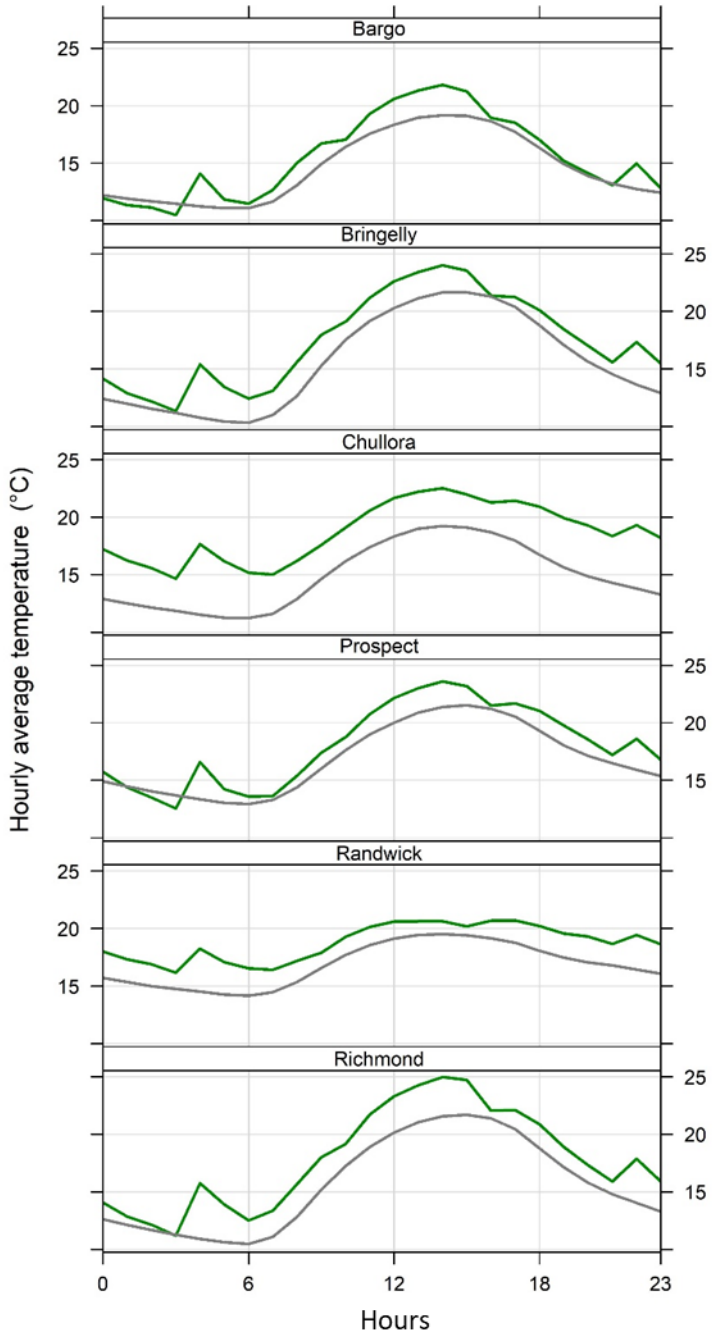


Figure C3b Diurnal average temperature plots for a selection of Department of Planning, Industry and Environment air quality monitoring stations. Green lines represent Conformal Cubic Atmospheric Model predictions and grey lines represent temperatures observed at monitoring stations.

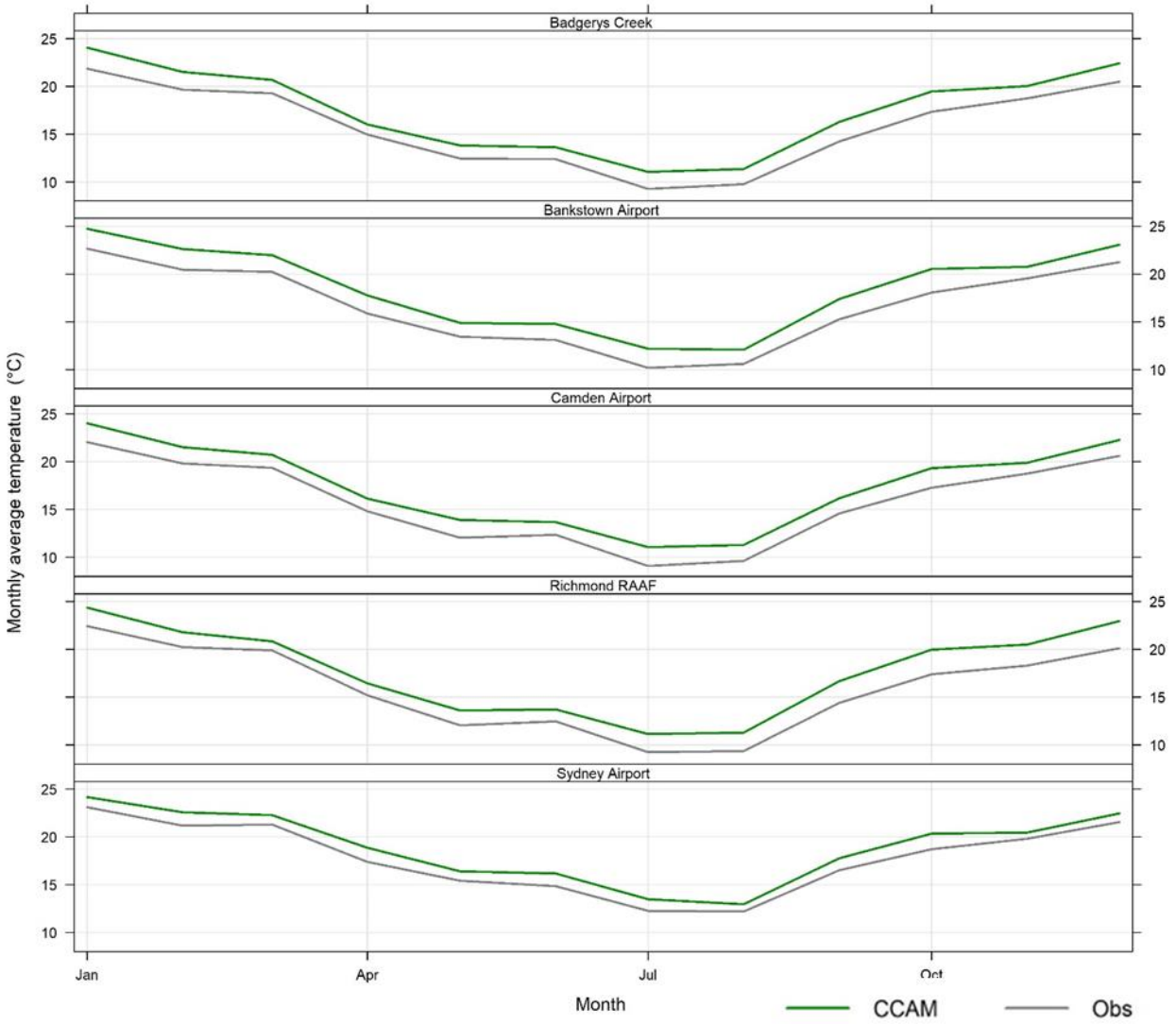


Figure C4a Monthly average temperature plots for Bureau of Meteorology stations; CCAM = Conformal Cubic Atmospheric Model. Obs = observed; RAAF = Royal Australian Air Force.

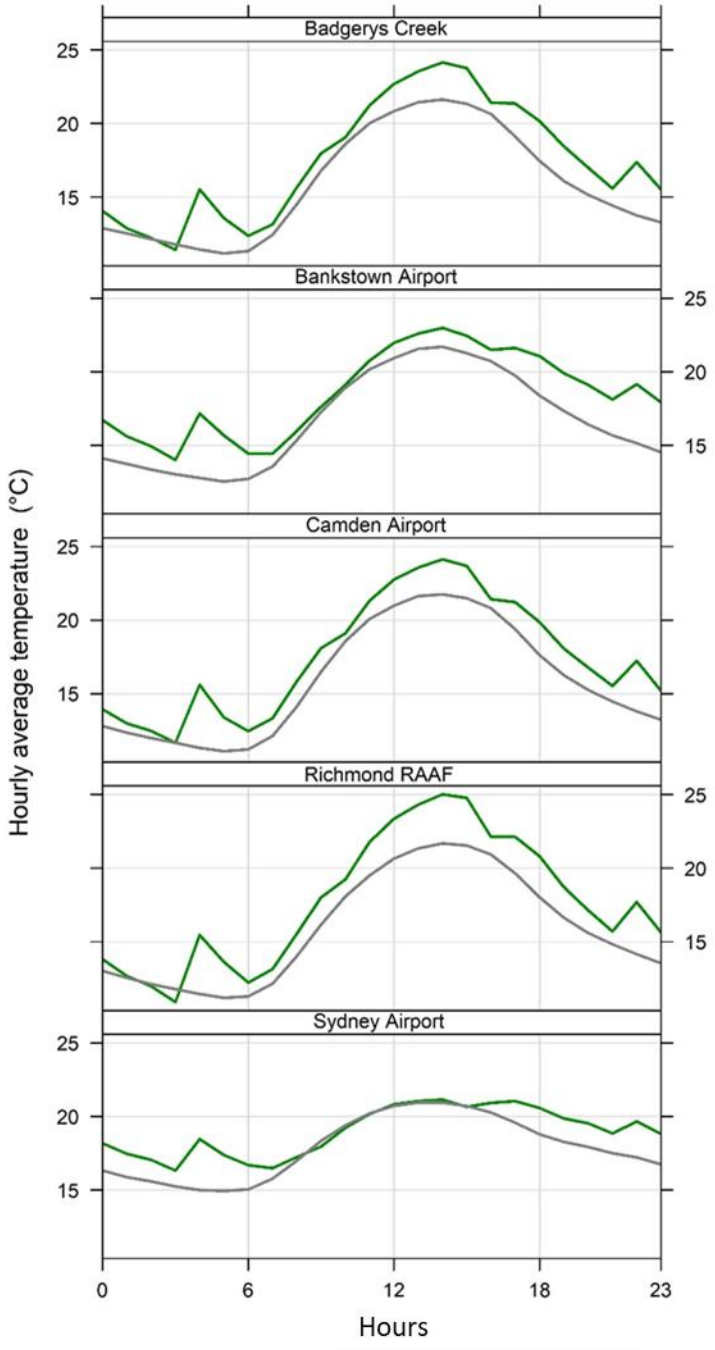


Figure C4b Diurnal average temperature plots for Bureau of Meteorology stations; green lines represent Conformal Cubic Atmospheric Model predictions and grey lines represent temperatures observed at monitoring stations. RAAF = Royal Australian Air Force.

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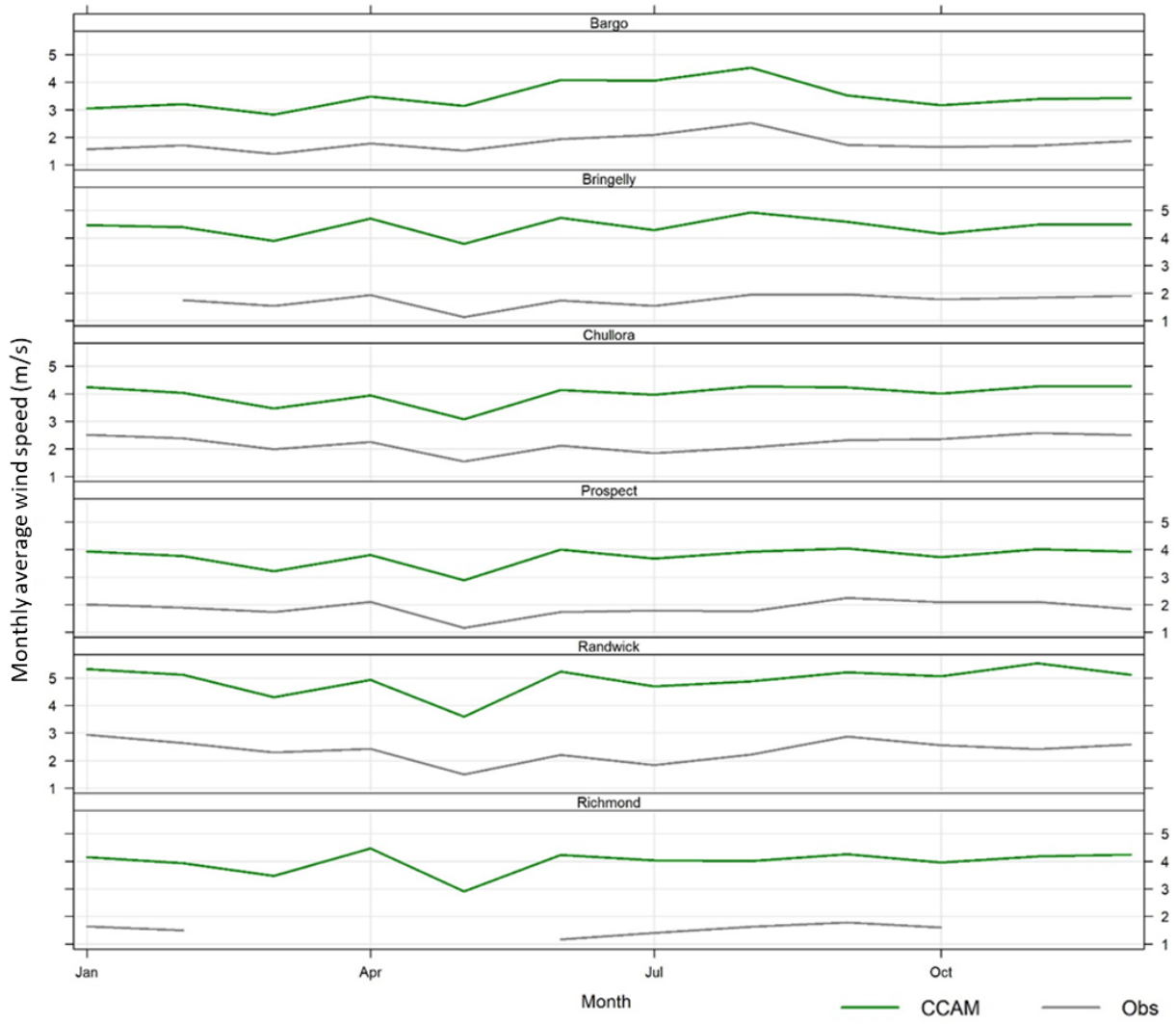


Figure C5a Monthly average wind speed plots for a selection of Department of Planning, Industry and Environment air quality monitoring stations. CCAM = Conformal Cubic Atmospheric Model. m/s = metres per second; Obs = observed.

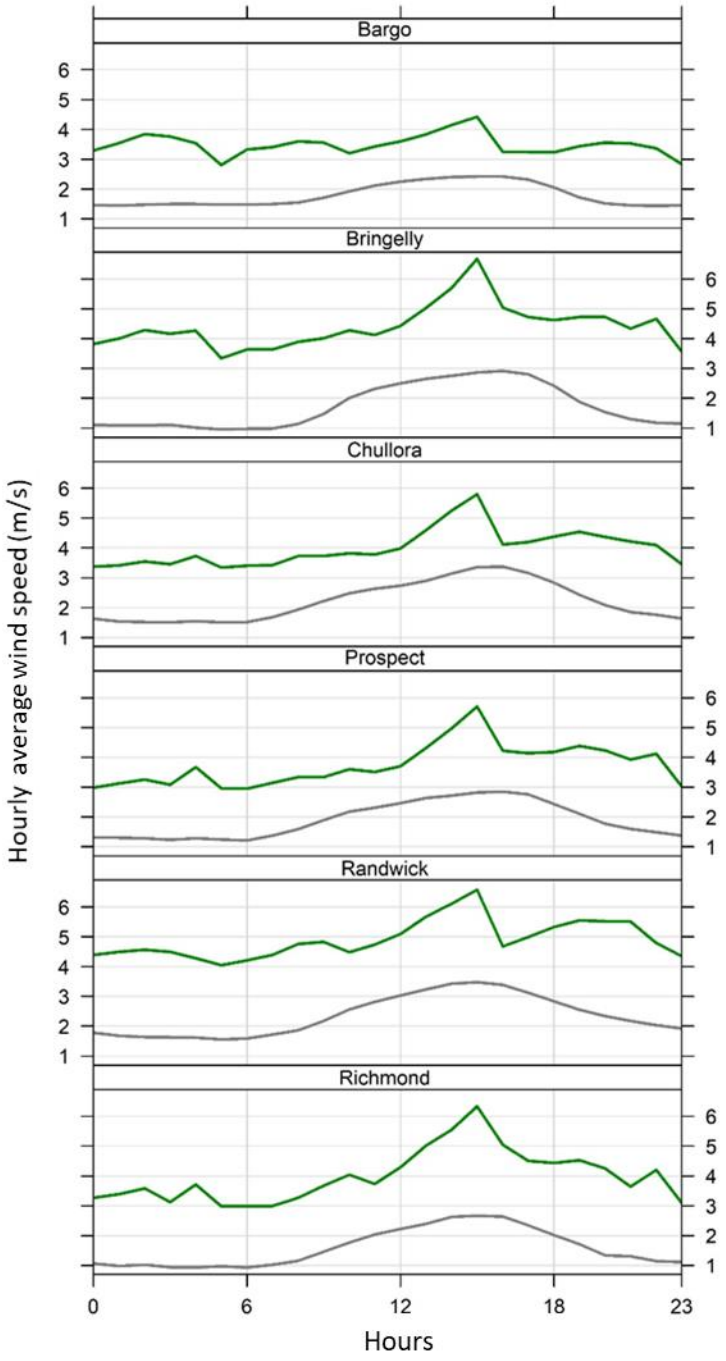


Figure C5b Diurnal average wind speed plots for a selection of Department of Planning, Industry and Environment monitoring stations. Green lines represent Conformal Cubic Atmospheric Model predictions and grey lines represent wind speeds observed at monitoring stations. m/s = metres per second.

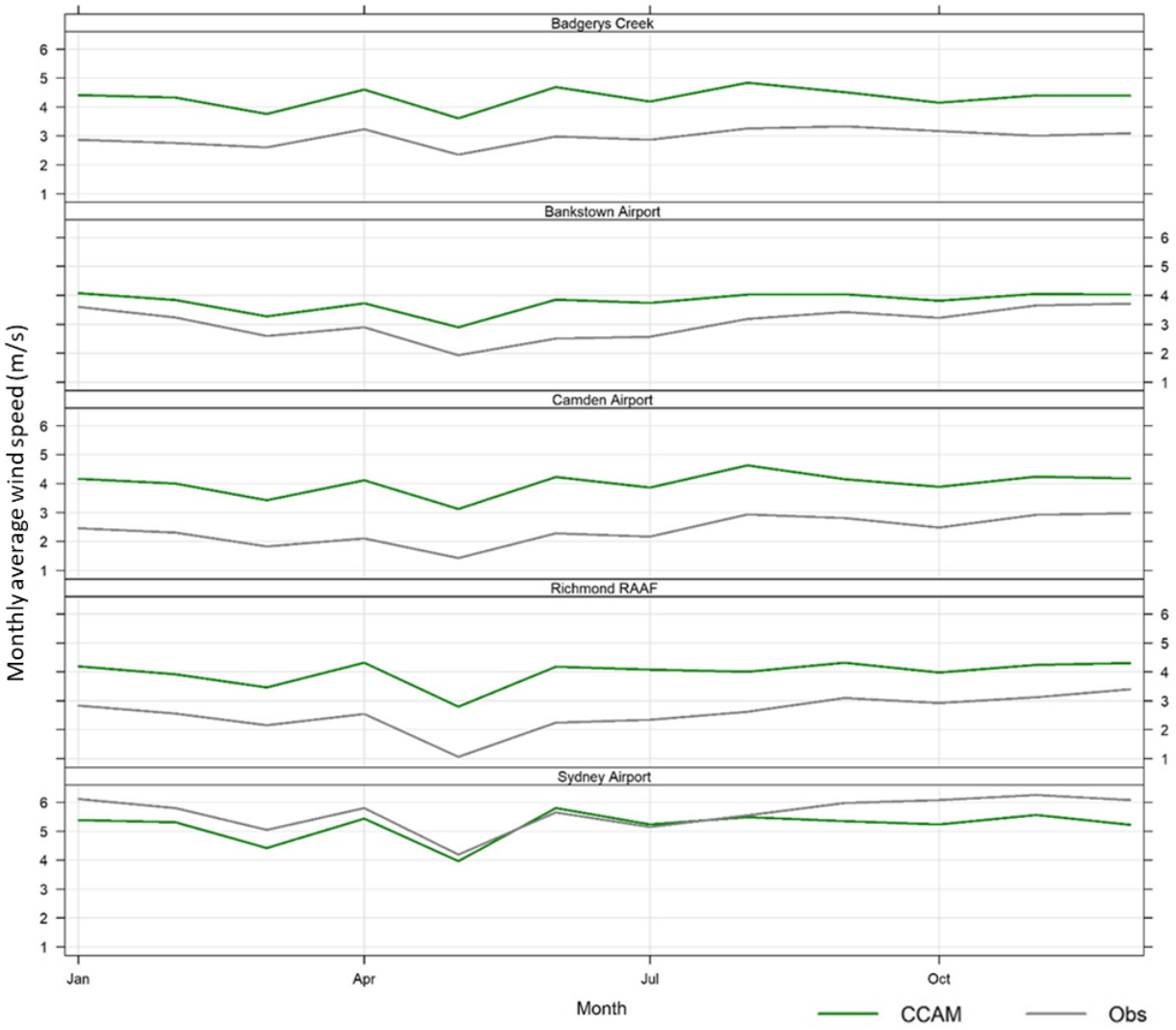


Figure C6a Monthly average wind speed plots for Bureau of Meteorology stations; CCAM = Conformal Cubic Atmospheric Model. m/s = metres per second; Obs = observed; RAAF = Royal Australian Air Force.

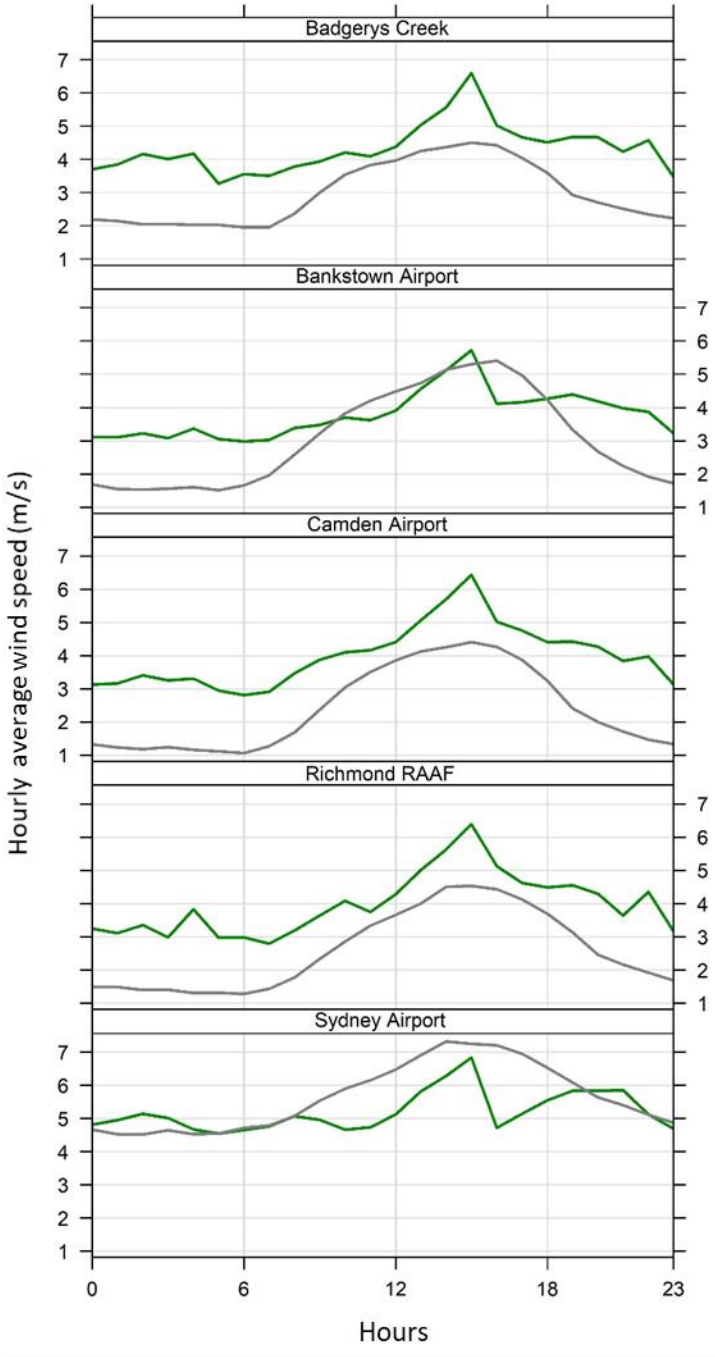


Figure C6b Diurnal average wind speed plots for Bureau of Meteorology stations; green lines represent Conformal Cubic Atmospheric Model predictions and grey lines represent wind speeds observed at monitoring stations. m/s = metres per second; RAAF = Royal Australian Air Force.

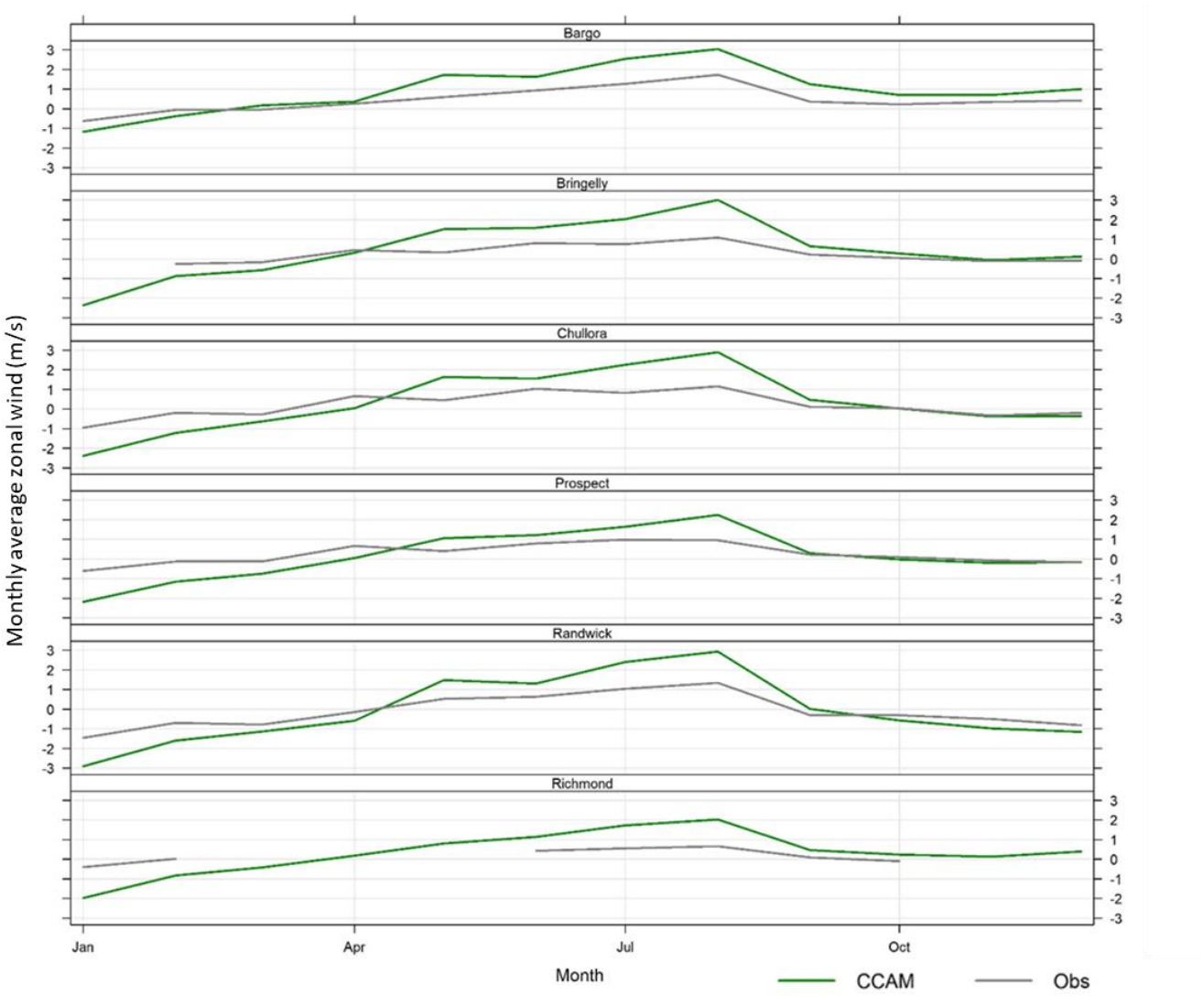


Figure C7a Monthly average zonal wind plots for a selection of Department of Planning, Industry and Environment. CCAM = Conformal Cubic Atmospheric Model. m/s = metres per second; Obs = observed.

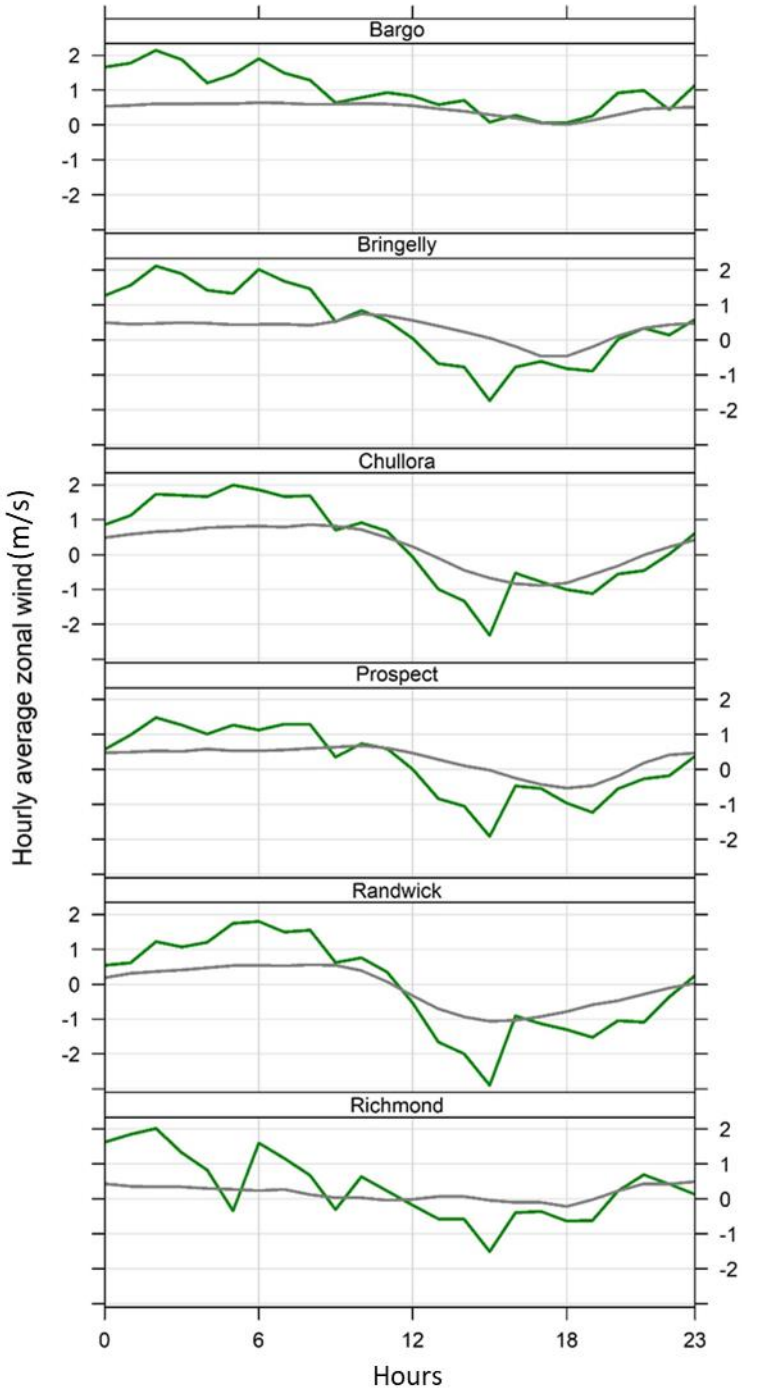


Figure C7b Diurnal average zonal wind plots for a selection of Department of Planning, Industry and Environment monitoring stations. Green lines represent Conformal Cubic Atmospheric Model predictions and grey lines represent zonal wind observed at monitoring stations. m/s = metres per second.

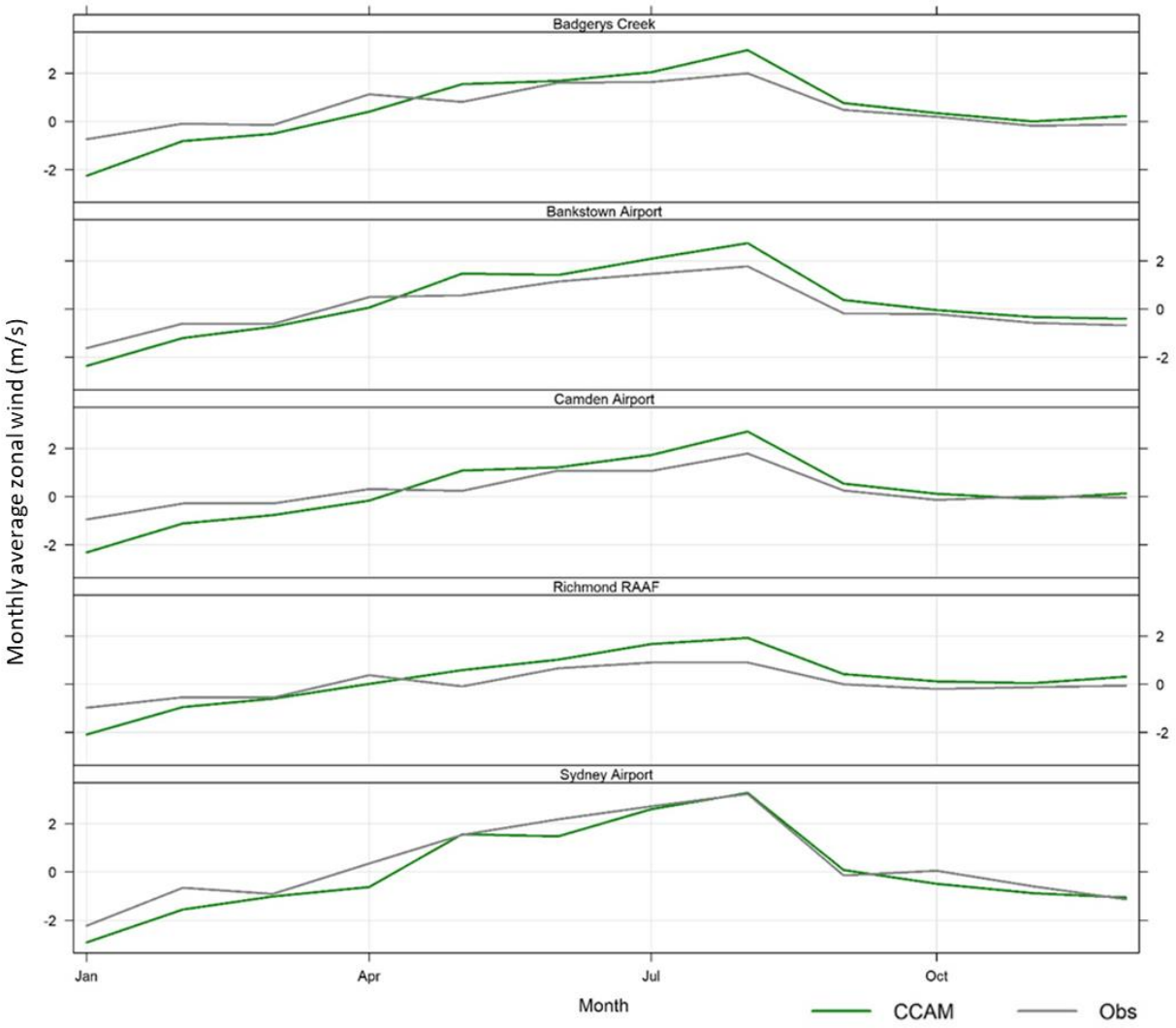


Figure C8a Monthly average zonal wind plots for Bureau of Meteorology stations; CCAM = Conformal Cubic Atmospheric Model. m/s = metres per second; Obs = observed; RAAF = Royal Australian Air Force.

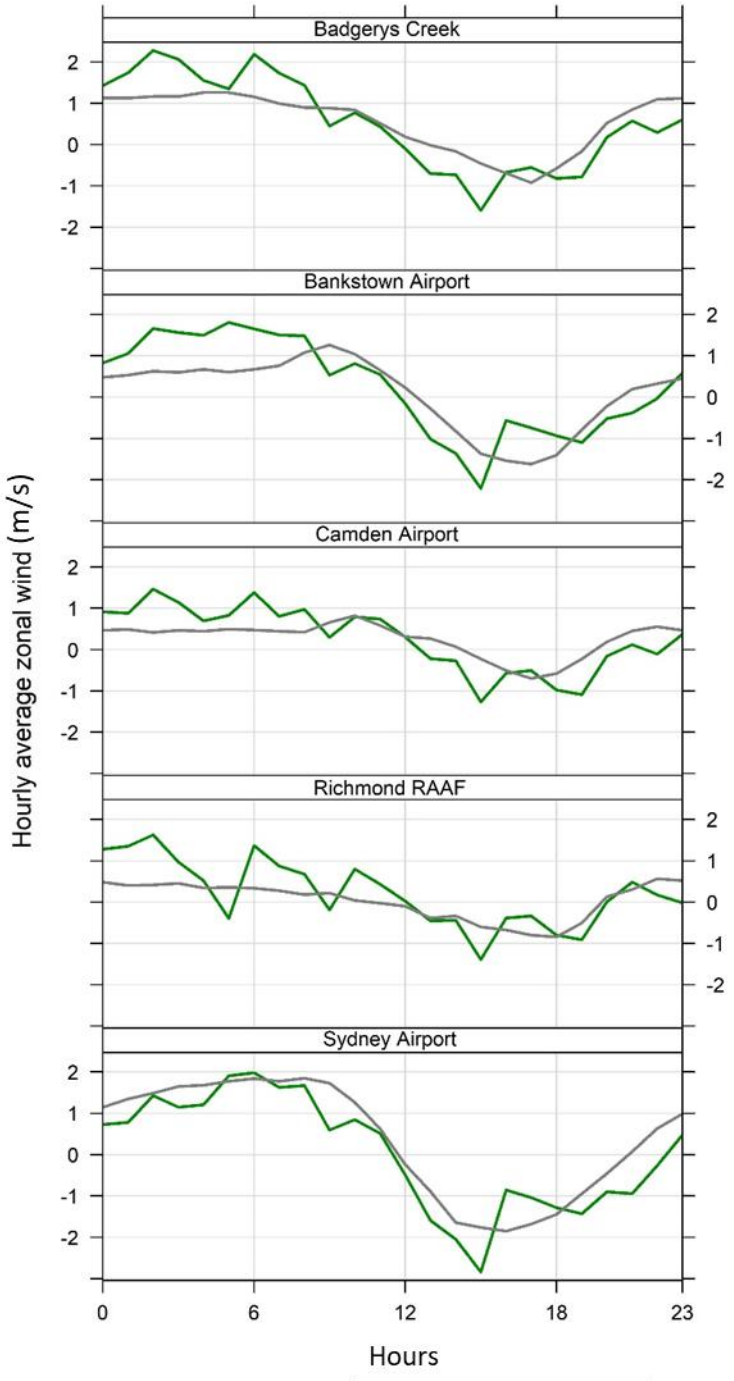


Figure C8b Diurnal average zonal wind plots for Bureau of Meteorology stations; green lines represent Conformal Cubic Atmospheric Model predictions and grey lines represent zonal wind observed at monitoring stations. m/s = metres per second; RAAF = Royal Australian Air Force.

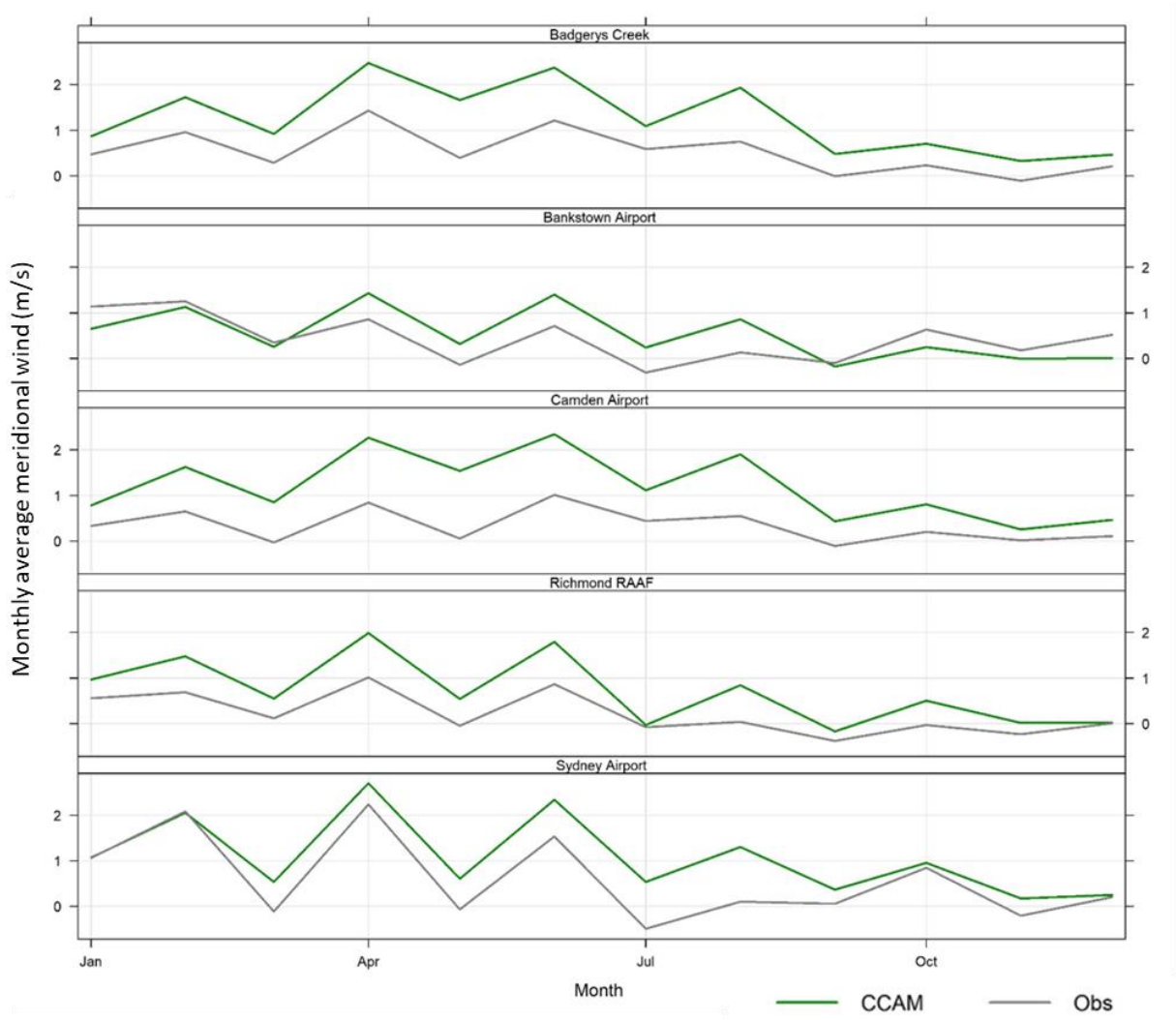


Figure C9a Monthly average meridional wind plots for a selection of Department of Planning, Industry and Environment monitoring stations. CCAM = Conformal Cubic Atmospheric Model; m/s = metres per second; Obs = observed.

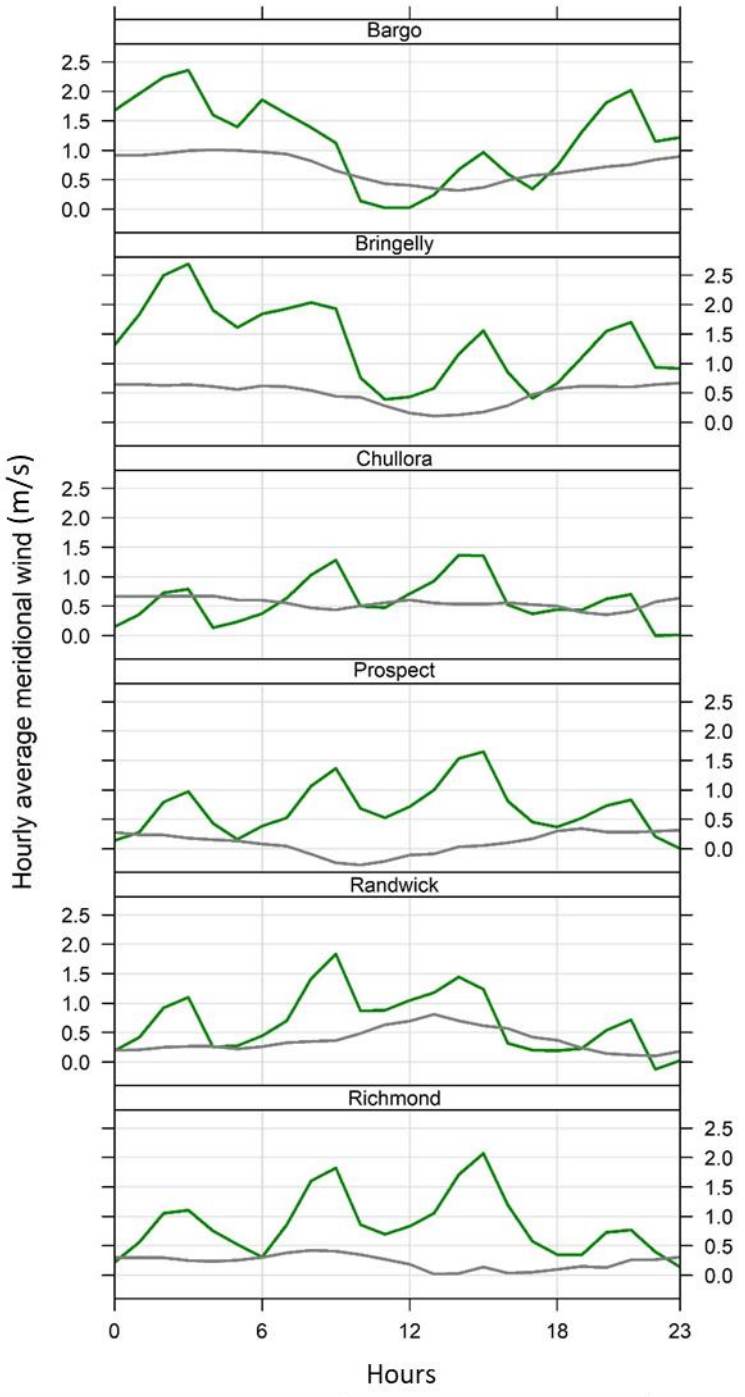
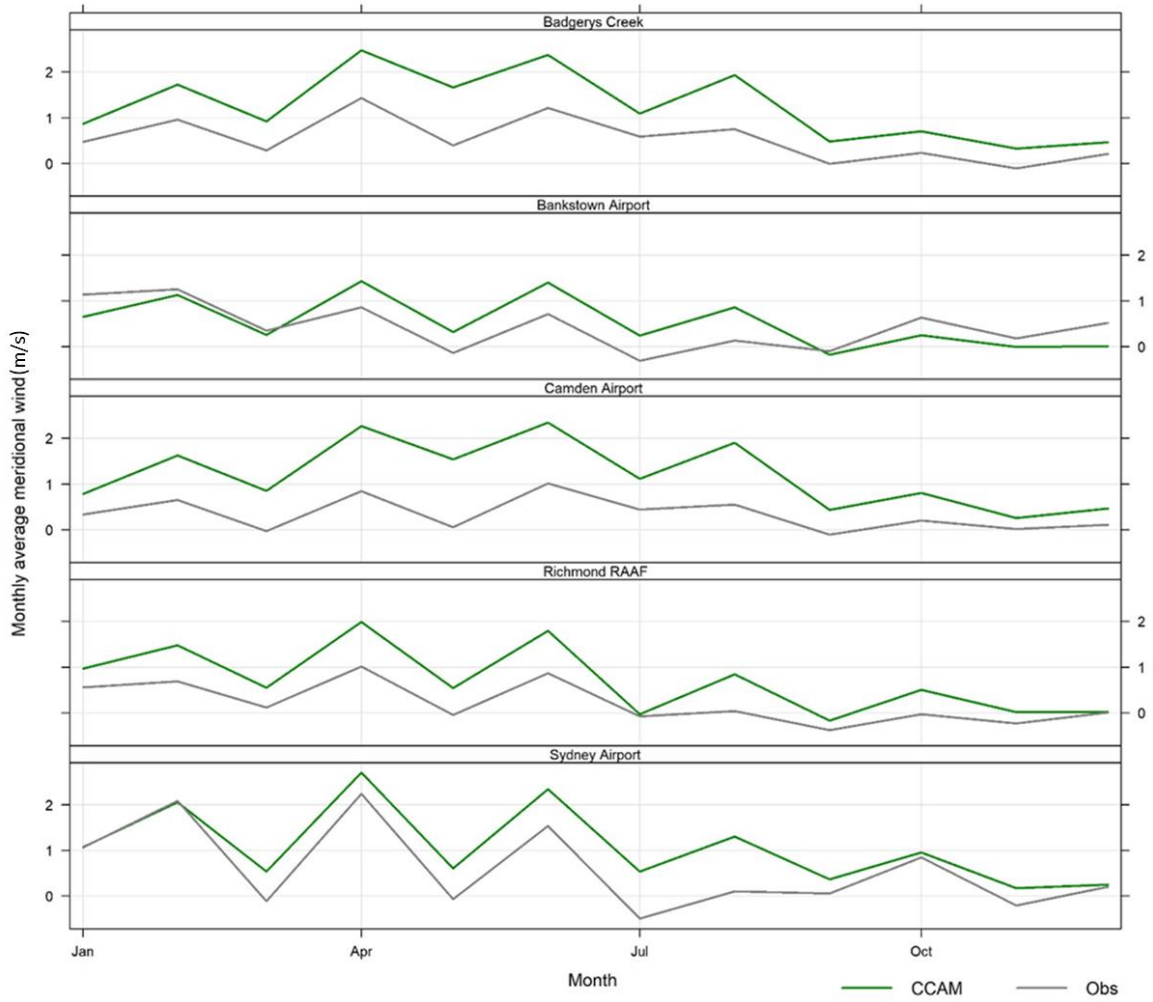


Figure C9b Diurnal average meridional wind plots for a selection of Department of Planning, Industry and Environment monitoring stations. Green lines represent Conformal Cubic Atmospheric Model predictions and grey lines represent meridional wind observed at monitoring stations; m/s = metres per second.



FigureC10a Monthly average meridional wind plots for Bureau of Meteorology stations; CCAM = Conformal Cubic Atmospheric Model. m/s = metres per second; Obs = observed; RAAF = Royal Australian Air Force.

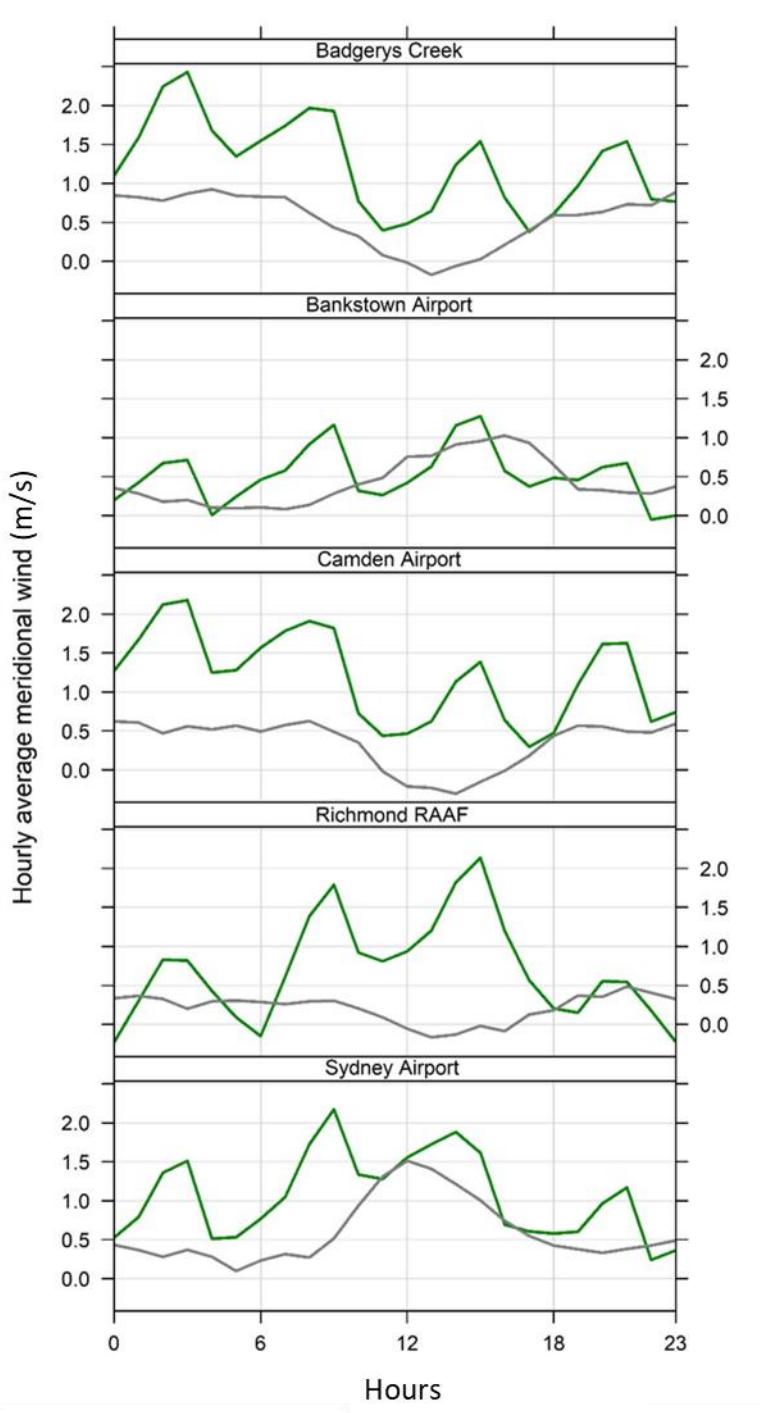


Figure C10b Diurnal average meridional wind plots for Bureau of Meteorology stations; green lines represent Conformal Cubic Atmospheric Model predictions and grey lines represent meridional wind observed at monitoring stations. m/s = metres per second; RAAF = Royal Australian Air Force.

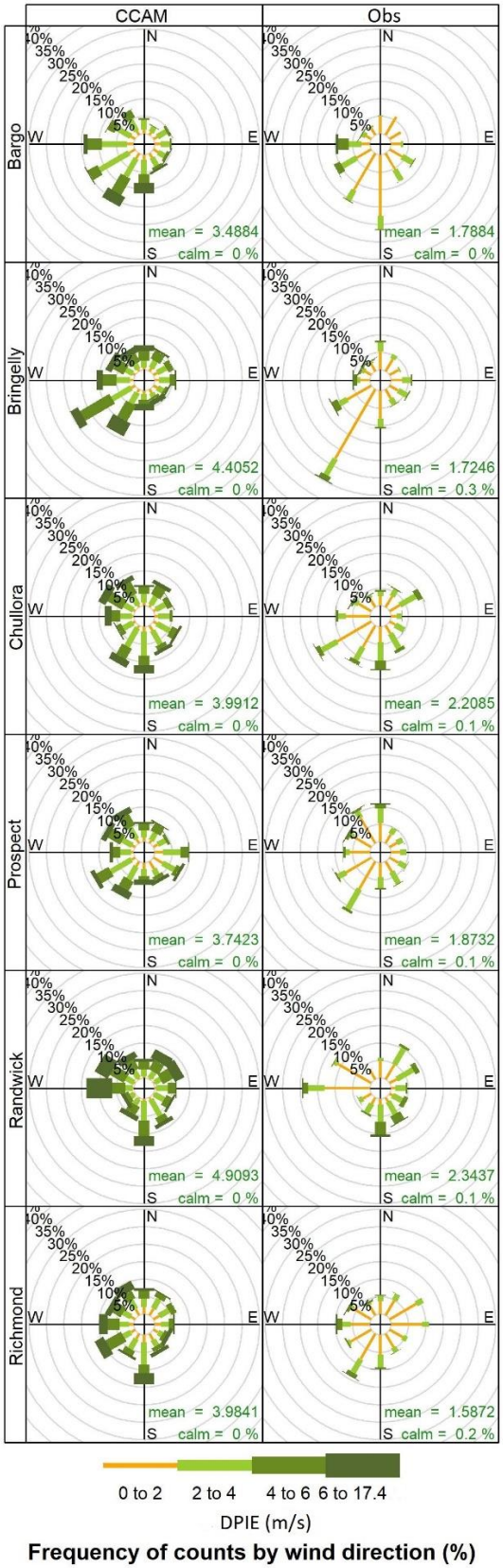


Figure C11a Comparison of Conformal Cubic Atmospheric Model (CCAM) versus observation (Obs) wind rose plots at selected Department of Planning, Industry and Environment monitoring stations. Calm represents any data with wind speed = 0 or wind direction = 0; mean represents mean wind speed; m/s = metres per second.

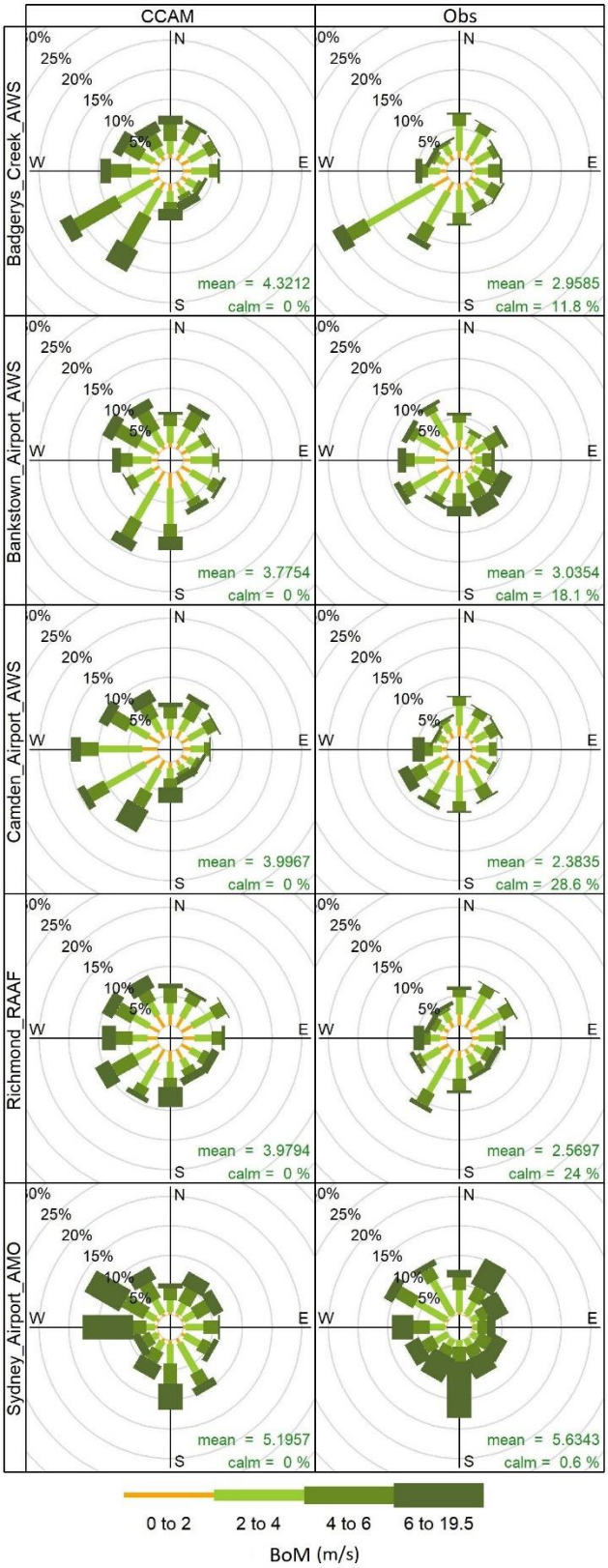


Figure C11b Comparison of Conformal Cubic Atmospheric Model (CCAM) versus observation (Obs) wind rose plots at BoM stations. Calm represents any data with wind speed = 0 or wind direction = 0; mean represents mean wind speed; m/s = metres per second; RAAF = Royal Australian Air Force.

11.2 Statistical performance evaluation

The model performance for the entire period was assessed with several single statistical metrics (Table C.2). For the CCAM validation modelling period, the mean bias (MB; positive or negative deviation from the mean), mean (gross) error (MGE; overall deviation from the mean) and index of agreement (IOA) are presented for each parameter at a selection of DPIE and BoM monitoring stations.

Benchmarks provide an acceptable range of values to measure model performance against. Due to the uncertainties in the modelling, it is not a case of pass–fail and knowledge of biases or shortcomings in the model provide users with a measure of the range of uncertainty in the data. Benchmarks help to understand whether modelling results are good or poor, relative to a range of other model applications (Tesche et al. 2002).

The most commonly referenced meteorological benchmarks in the literature have been established by Emery et al. (2001). The modelling by Emery et al. (2001) was conducted over the eastern and mid-west of the United States, where the terrain is considered flat and 'simple'. For more complex terrain, benchmarks provided by McNally (2009) and Kemball–Cook et al. (2005) may be more appropriate. CCAM performance statistics for temperature and wind speed predictions for 2008 are shown in Table C.3.

Table C2 Summary of statistical metrics used to validate the Conformal Cubic Atmospheric Model

Name	Equation	Perfect agreement
Mean bias (MB)	$MB = \frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)$	0
Mean gross error (MGE)	$MGE = \frac{1}{n}\sum_{i=1}^{n}\lvert M_i - O_i\rvert$	0
Pearson correlation coefficient (R)	$R = \frac{\sum_{i=1}^{n}((O_i-\bar{O})(M_i-\bar{M}))}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2\sum_{i=1}^{n}(M_i-\bar{M})^2}}$ $= \frac{\sum_{i=1}^{n}((O_i-\bar{O})(M_i-\bar{M}))}{\sigma_O\sigma_M}$	1
Index of agreement (IOA)	$IOA = 1 - \frac{\sum_{i=1}^{n}(M_i-O_i)^2}{\sum_{i=1}^{n}(\lvert M_i-\bar{O}\rvert+\lvert O_i-\bar{O}\rvert)^2}$	1
Centred root mean square error (CRMSE)	$CRMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left((M_i-\bar{M})-(O_i-\bar{O})\right)^2}$	0

Note: Notations reference the model (*M*) and observation (O) concentrations for the index (*i*) covering the number of data point pairs (*n*).

Table C3 Conformal Cubic Atmospheric Model performance statistics for temperature and wind speed at selected monitoring stations

Parameter	Temperature			Wind speed		
Stations	MB	MGE	IOA	MB	MGE	IOA
Ideal value	0	0	1	0	0	1
Benchmark (simple)	≤±0.5	≤±2	≥0.8	≤±0.5	≤±2	≥0.6
Benchmark (complex)	≤±1	≤±3	–	≤±1.5	≤±2.5	–
Bargo	0.94	1.93	0.95	1.71	1.81	0.63
Prospect	1.13	1.91	0.96	1.86	2.03	0.59
Newcastle	1.76	2.22	0.91	3.50	3.62	0.42
Wollongong	1.12	1.73	0.94	2.20	2.34	0.53
Badgerys Creek	1.63	2.43	0.94	1.34	1.89	0.70
Bankstown Airport	1.82	2.41	0.93	0.72	1.69	0.74
Camden Airport	1.66	2.44	0.94	1.61	2.05	0.72
Richmond Royal Australian Air Force (RAAF)	1.84	2.58	0.94	1.40	1.97	0.73
Sydney Airport	1.12	1.77	0.95	–0.45	1.56	0.83

Note: Orange indicates predictions that met complex terrain benchmarks, green represents predictions that met the more stringent simple terrain benchmarks.

Taylor diagrams provide a visual comparison of the performance of different stations, experiments or variables. The Taylor diagram presents the correlation coefficient (R; linear relationship) and centred root mean square error (CRMSE; overall accuracy) as metrics of similarity, and the standard deviation (σM and σO; spread from the mean) representing amplitude of the variation of model results versus observations on a single diagram.

Taylor diagrams for temperature, wind speed, U-component and V-component across seasons were developed for all monitoring stations (Figure C.12a–d). Optimal performance occurs when model results are closest to the observed results (purple dot on the x-axis). Between the seasons for all variables there was a small spread in the performance statistics, indicating that the performance of the model was consistent throughout the year.

The performance of CCAM for temperature was good, with correlations around 0.9 and CRMSE well below 1. The standard deviations of the model were also close to the centre line, indicating a similar amplitude of variation between CCAM and observations. The model performance for each station was clustered close together, which indicated there were no spatial biases in the ability of CCAM to simulate temperature across the Sydney basin.

The ability of CCAM to predict wind speed was relatively similar between stations, particularly during spring and winter. Lindfield was a clear outlier with consistently lower correlations, higher CRMSE and standard deviations. For most stations the correlations were between 0.4–0.6 and the CRMSE was predominantly under 2.0, except for Lindfield. The CCAM performance was worst at Lindfield and Oakdale, whereas it performed best at Sydney and Bankstown Airports.

Zonal and meridional winds have a greater spread across Taylor diagrams and the best performance of the model appears to be during spring and summer, with the worst performance during autumn and winter. The correlations were between 0.6–0.8 and the

CRMSE was less than 2, except for Lindfield as seen in the wind speed plots (Figure C.12). The best representation of wind speed was at Sydney and Bankstown Airports. This would largely be influenced by the higher wind speeds recorded at these stations as CCAM predicted much stronger wind speeds, as seen in the previous analysis.

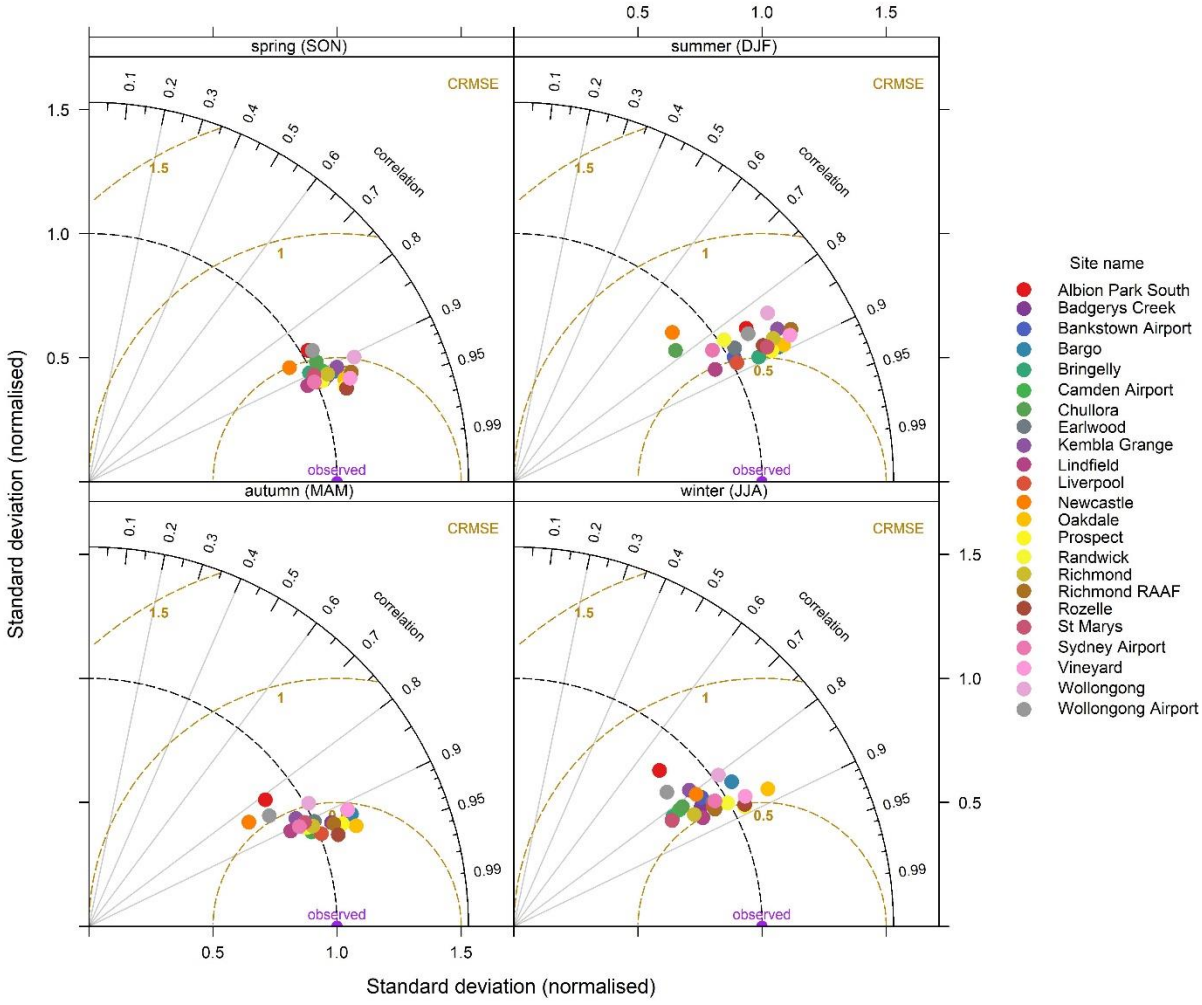


Figure C12a Seasonal Taylor diagram for temperature for all Department of Planning, Industry and Environment and Bureau of Meteorology monitoring stations. CRMSE = centred root mean square error; DJF = December, January, February; JJA – June, July, August; MAM = March, April, May; RAAF = Royal Australian Air Force; SON = September, October, November.

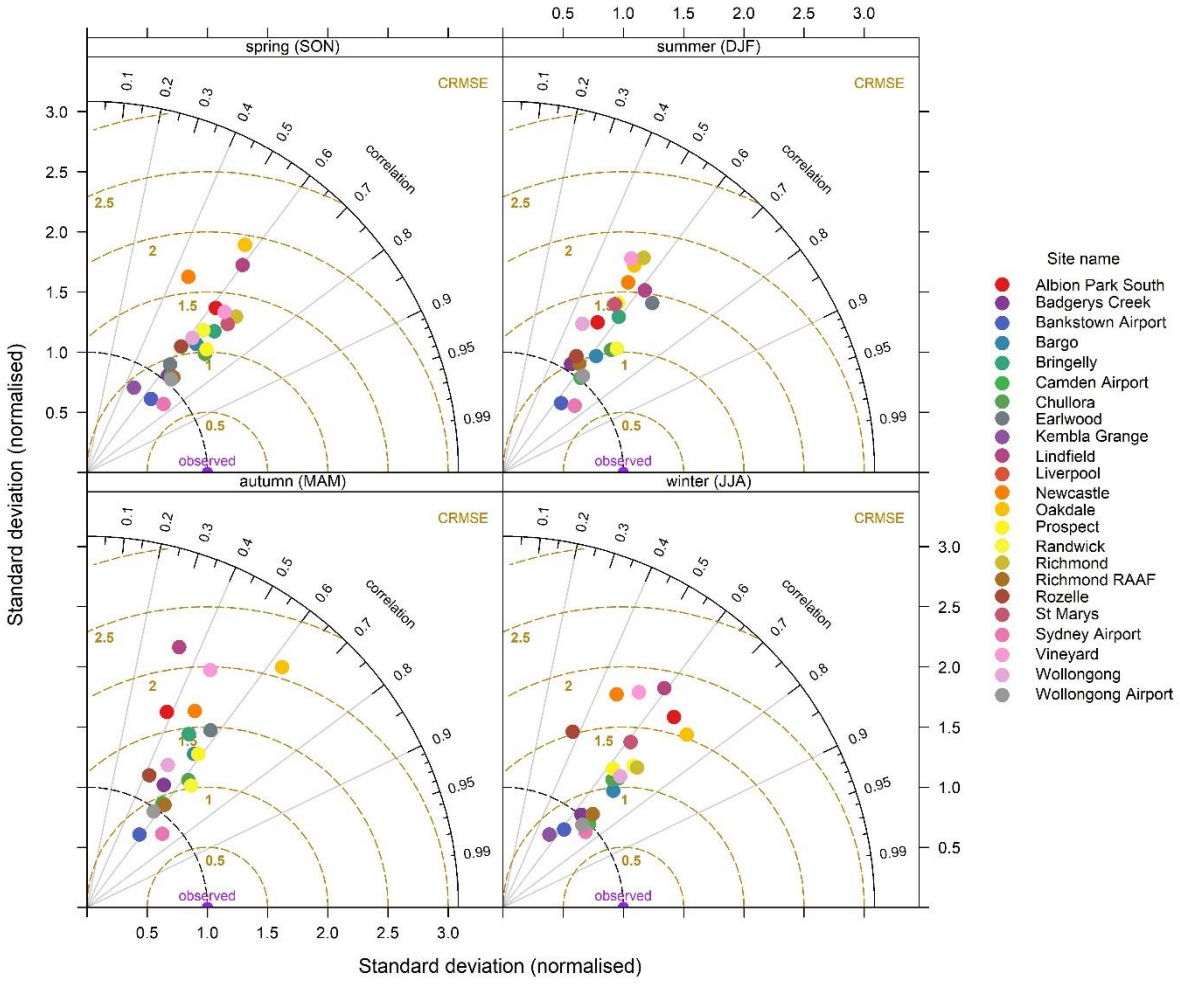


Figure C12b Seasonal Taylor diagram for wind speed for all Department of Planning, Industry and Environment and Bureau of Meteorology monitoring stations. CRMSE = centred root mean square error; DJF = December, January, February; JJA – June, July, August; MAM = March, April, May; RAAF = Royal Australian Air Force; SON = September, October, November.

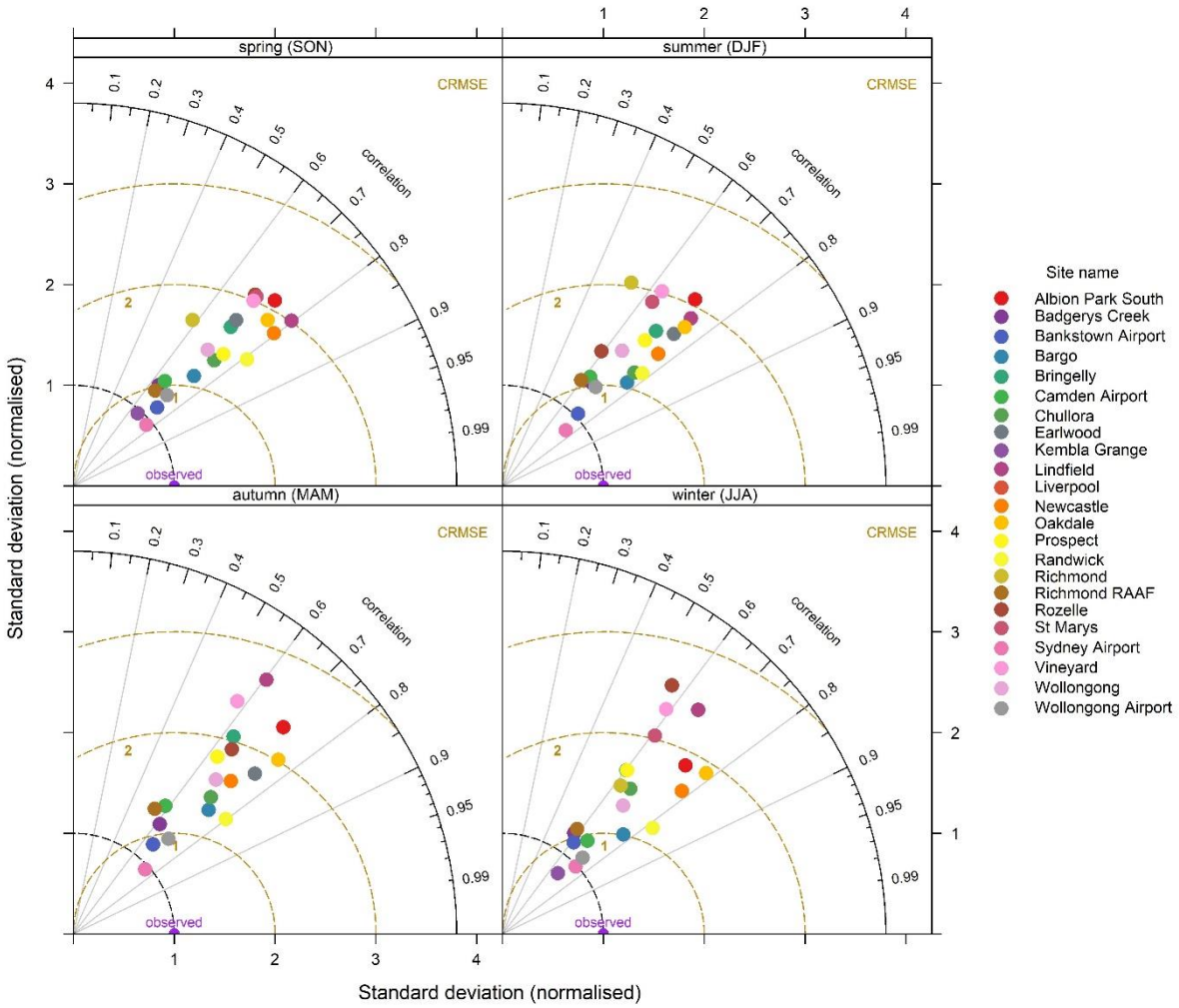


Figure C12c Seasonal Taylor diagram for U wind component for all Department of Planning, Industry and Environment and Bureau of Meteorology monitoring stations. CRMSE = centred root mean square error; DJF = December, January, February; JJA – June, July, August; MAM = March, April, May; RAAF = Royal Australian Air Force; SON = September, October, November.

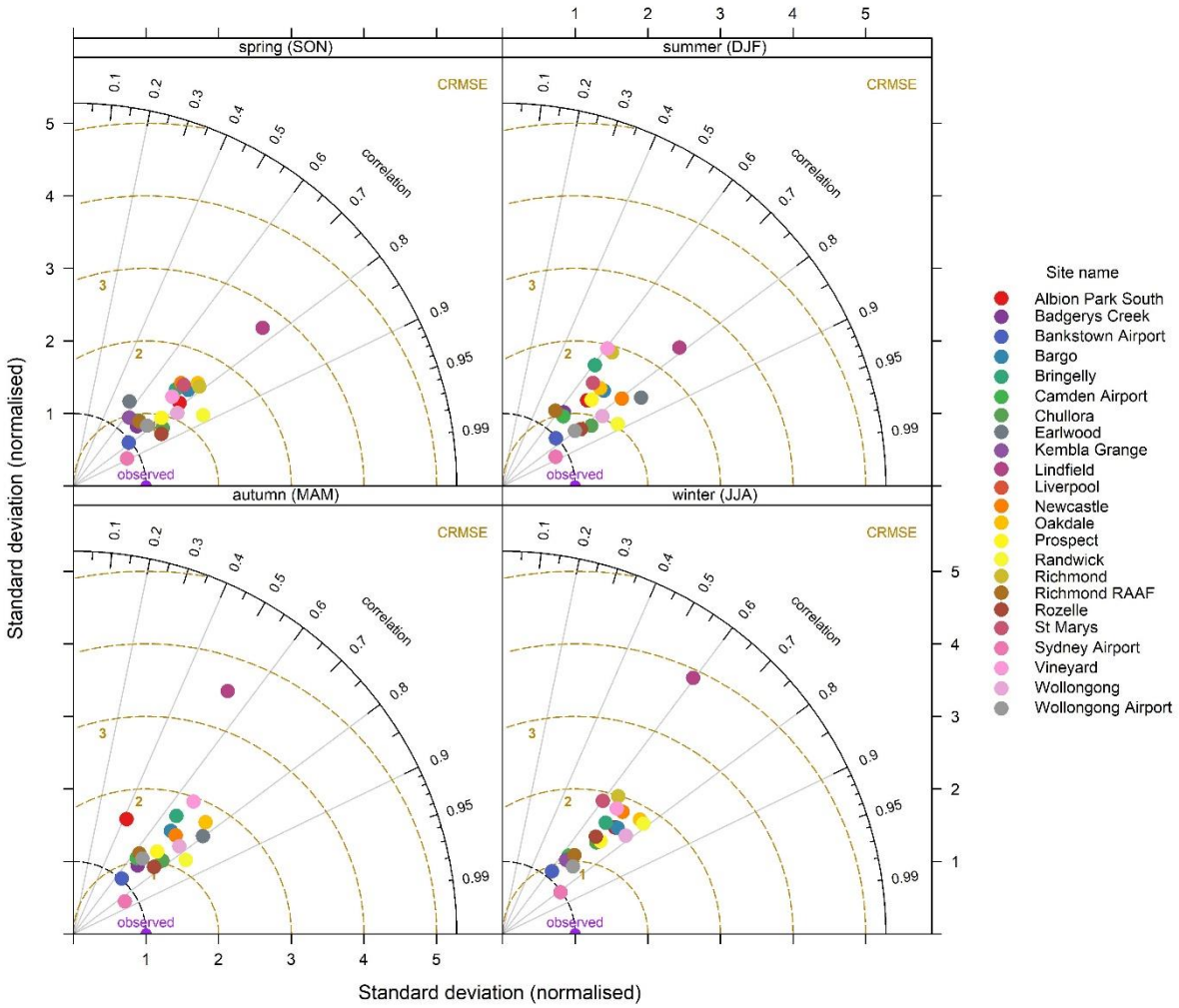


Figure C12d Seasonal Taylor diagram for V wind component for all Department of Planning, Industry and Environment and Bureau of Meteorology monitoring stations. CRMSE = centred root mean square error; DJF = December, January, February; JJA – June, July, August; MAM = March, April, May; RAAF = Royal Australian Air Force; SON = September, October, November.

11.3 Validation of upper air profile prediction

11.3.1 Upper air prediction

There are 35 levels in the CCAM simulation. As with many meteorological models, the level is in sigma level coordinate. The 35 sigma levels are:

1, 0.998, 0.994, 0.985, 0972, 0.954, 0.933, 0.909, 0.882, 0.851, 0.819, 0.784, 0.747, 0.708, 0.668, 0.627, 0.585, 0.543, 0.5, 0.457, 0.415, 0.373, 0.332, 0.292, 0.253, 0.216, 0.181, 0.149, 0.118, 0.091, 0.067, 0.046, 0.029, 0.015, 0.006, 0.001.

These levels correspond to the following approximate heights (metres):

0, 10, 50, 130, 240, 390, 570, 790, 1000, 1300, 1600, 2000, 2400, 2800, 3300, 3700, 4300, 4900, 5500, 6100, 6800, 7600, 8400, 9200, 10000,11000, 12000, 14000, 15000, 17000, 18000, 21000, 24000, 28000, 34000, 42000.

11.3.2 Radiosonde data at Sydney Airport

The BoM uses the 1013.25 hPa (hectopascal) universal standard for atmospheric pressure as at zero height (sea level tidal average). Sometimes pressure above this level was calculated as negative height (which for our purpose had to be reset to 0 metres high). The boundary layer height calculated from observation was based on the height of the temperature inversion.

11.3.3 Comparison results

It is expected that the temperature and wind profiles are modulated differently depending on the season. Here, we selected one typical month for each season: January, April, July and October. The results show that predicted CCAM temperature profiles were accurate when compared to observations at Sydney Airport across all seasons. Note that July has the lowest mixing height, as derived from temperature inversion, whereas January has the highest mixing height.

January 2008

Results for January 2008 for CCAM upper air prediction were compared with observations at Sydney airport (Figure C.13a and b). The prediction was for each hour for the whole month at 35 levels (sigma from 0.998 to 0.001, which is from 10 to 42,000 metres). Observations were conducted for 2 hours each day (at 4:00 and 19:00) at several heights (up to 16,000 metres).

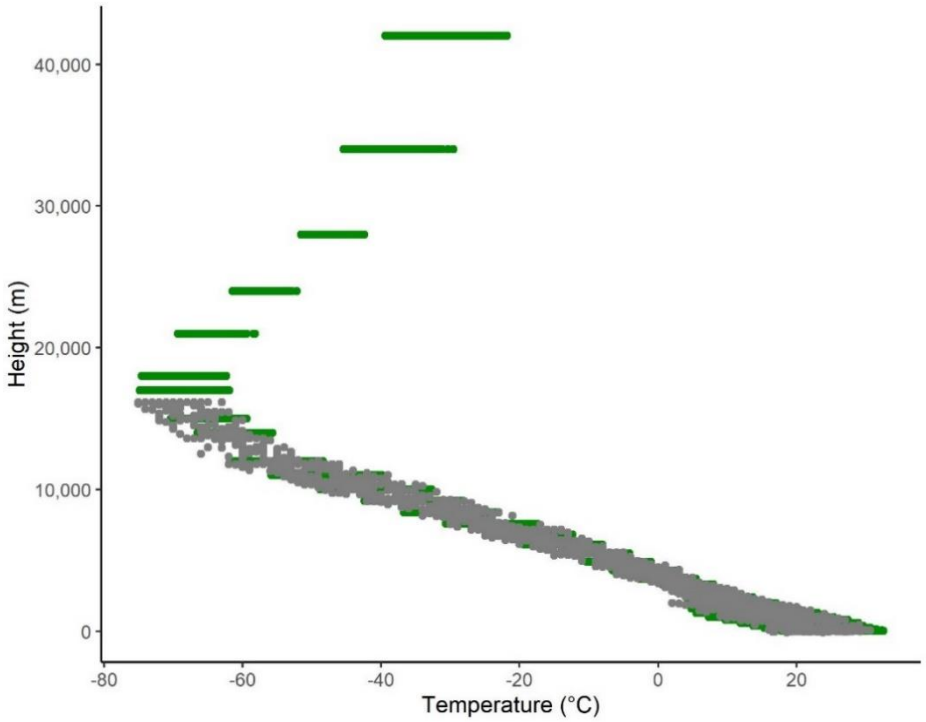


Figure C13a January 2008 Conformal Cubic Atmospheric Model (CCAM)-predicted temperature profiles versus observation at Sydney Airport; green indicates CCAM prediction and grey represent Bureau of Meteorology radiosonde observation. m = metres.

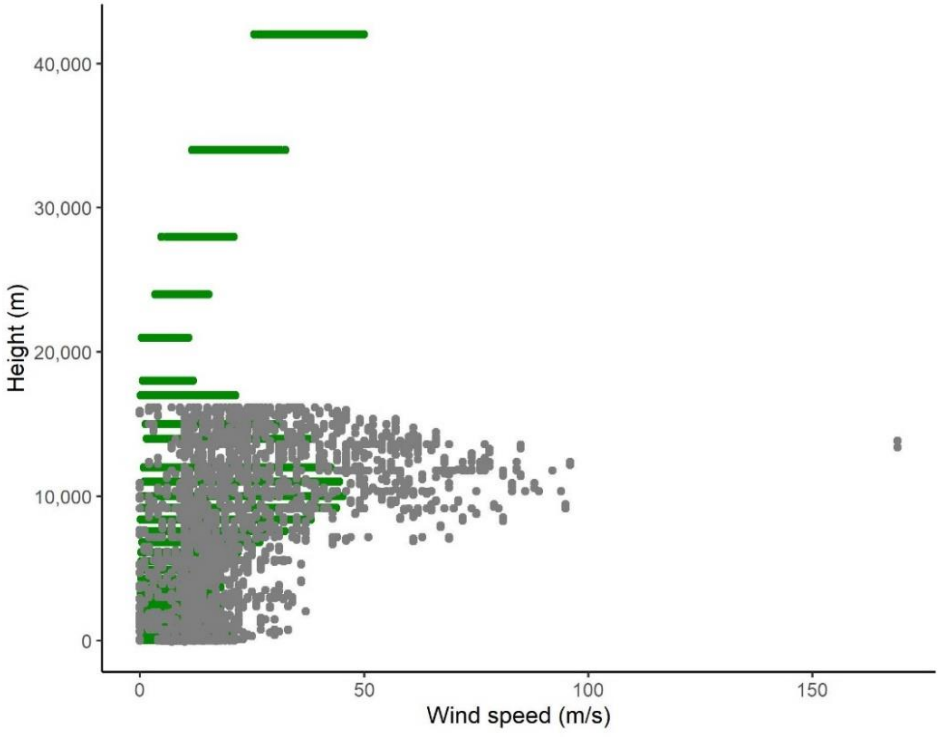


Figure C13b January 2008 Conformal Cubic Atmospheric Model (CCAM) predicted wind speed profiles versus observation at Sydney Airport; green indicates CCAM prediction and grey dots represent Bureau of Meteorology radiosonde observation. m = metres; m/s = metres per second.

The CCAM prediction for temperature profile was accurate, whereas wind speed profiles tended to be under-predicted, especially for heights above 7000 metres (jet steam level, which has a wind speed up to 100 metres per second). It is also instructive to compare the temporal mean across different heights for temperature and wind speed (Figure C.14), and the spatial profile at a specific data and time (Figure C.15)

It is interesting to note that the profile of radiosonde temperature observation data for January did not extend high enough to calculate the mixing height from temperature inversion, whereas the CCAM prediction did. The temperature profiles for 1/1/008 19:00 and 2/1/2008 4:00 showed that the temperature inversion occurred at about 17,500 metres.

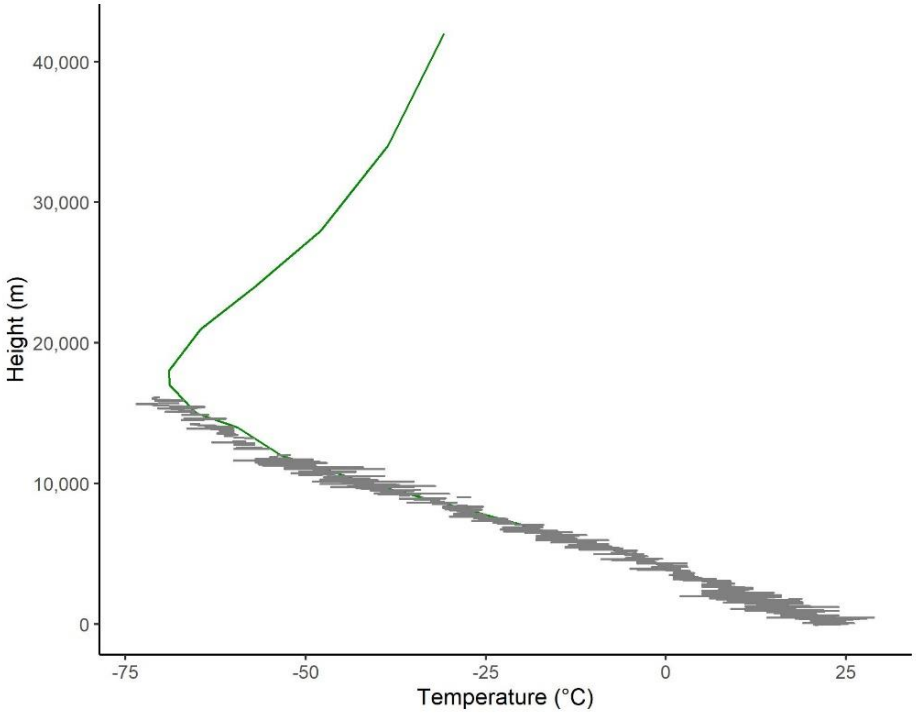


Figure C14a Temporal mean profiles of Conformal Cubic Atmospheric Model (CCAM) and observation temperature at Sydney Airport for January 2008; green line indicates CCAM prediction and grey lines represent Bureau of Meteorology radiosonde observation.

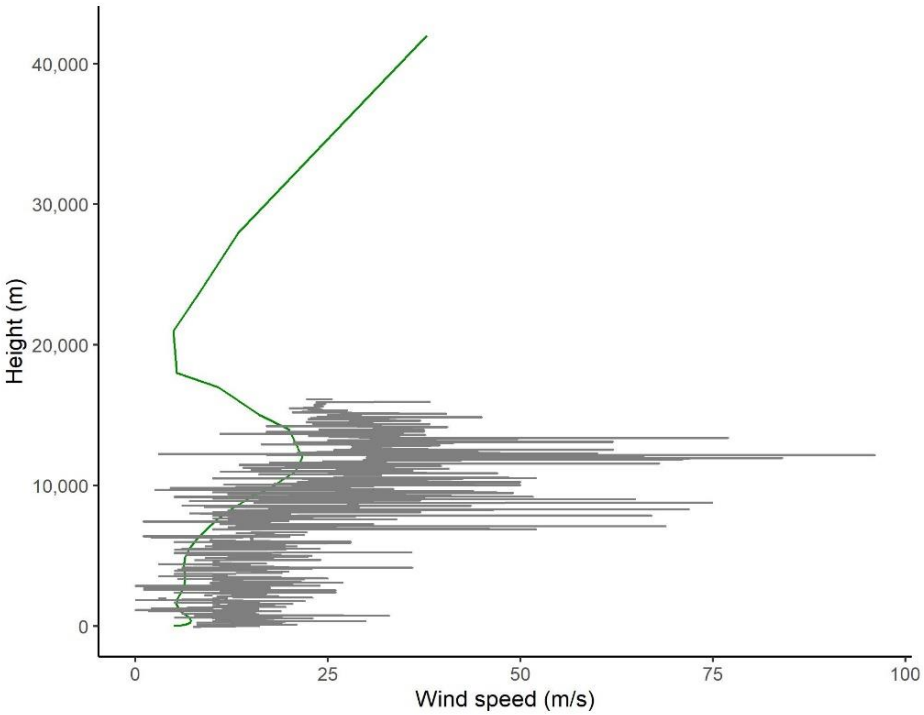


Figure C14b Temporal mean profiles of Conformal Cubic Atmospheric Model (CCAM) and observation wind speed at Sydney Airport for January 2008; green line indicates CCAM prediction and grey lines represent Bureau of Meteorology radiosonde observation.

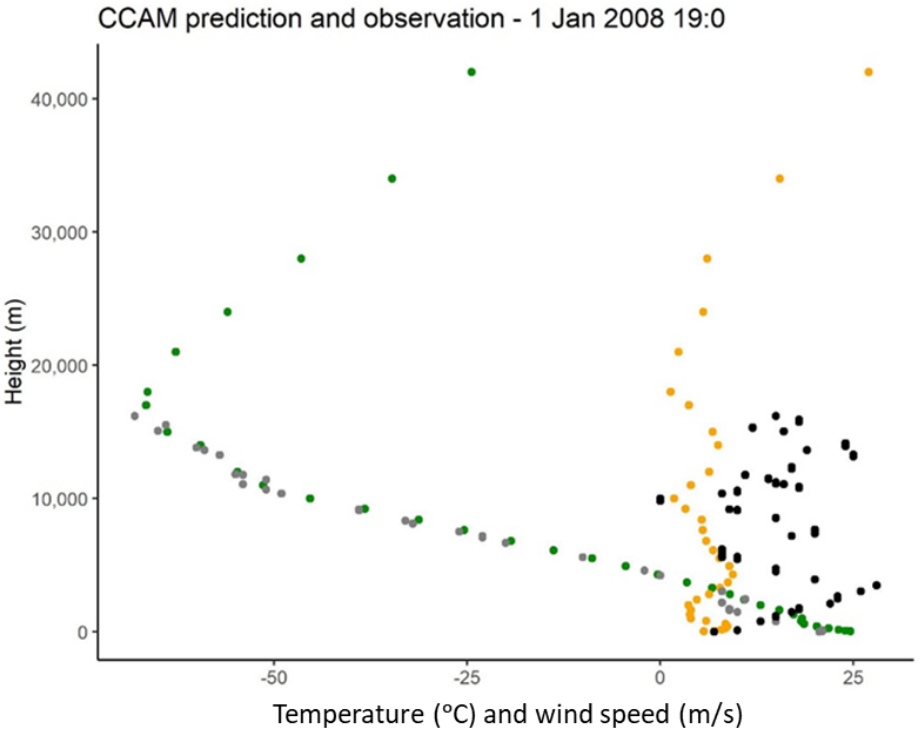


Figure C15a Temperature (green dots indicate Conformal Cubic Atmospheric Model (CCAM) predictions and grey dots represent observations) and wind speed (orange dots indicate CCAM predictions and black dots represent observations) profiles at Sydney Airport on 01/01/2008 19:00. m = metres; m/s = metres per second.

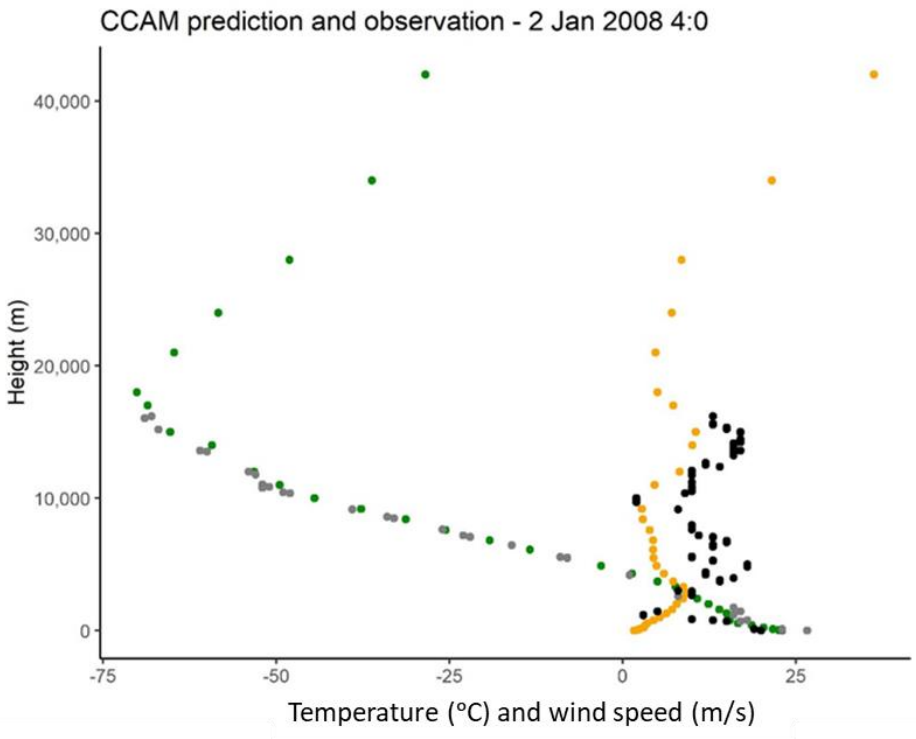


Figure C15b Temperature (green dots indicate Conformal Cubic Atmospheric Model (CCAM) predictions and grey dots represent observations) and wind speed (orange dots indicate CCAM predictions and black dots represent observations) profiles at Sydney Airport on 02/01/2008 19:00. m = metres; m/s = metres per second.

April 2008

Results for April 2008 for CCAM upper air prediction were compared with observation at Sydney airport (Figure C.16a and b). The temporal means at different heights for temperature and wind speed for April 2008 were compared (Figure C.17a and b). The temperature profiles for 1/4/2008 19:00 and 2/4/2008 4:00 show that the temperature inversion occurred at about 15,000 metres (Figure C.18a and b).

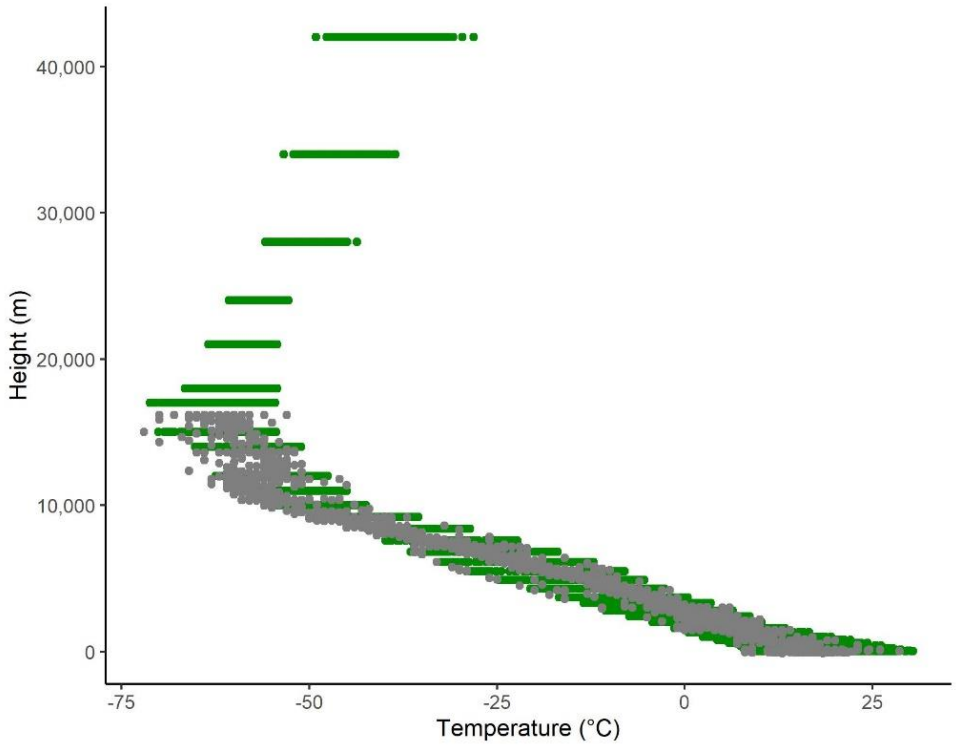


Figure C16a April 2008 Conformal Cubic Atmospheric Model (CCAM) predicted temperature profiles versus observation at Sydney Airport. Green indicates CCAM prediction and grey represents Bureau of Meteorology radiosonde observation. m = metres.

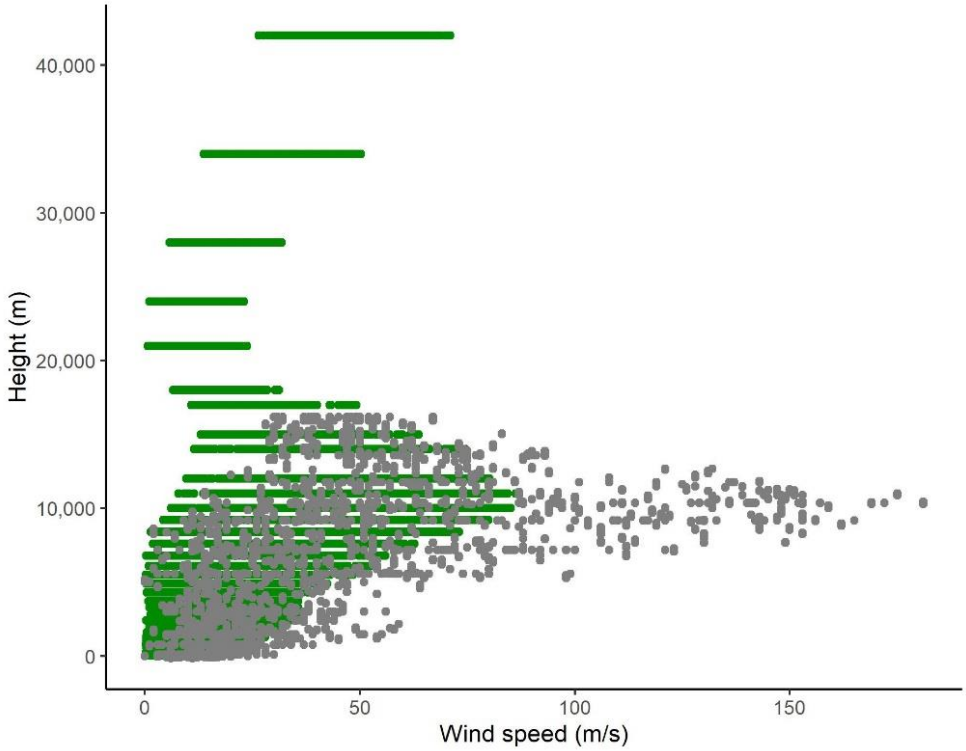


Figure C16b April 2008 Conformal Cubic Atmospheric Model (CCAM) predicted wind speed profiles versus observation at Sydney Airport. Green indicates CCAM prediction and grey represents Bureau of Meteorology radiosonde observation. m = metres; m/s = metres per second.

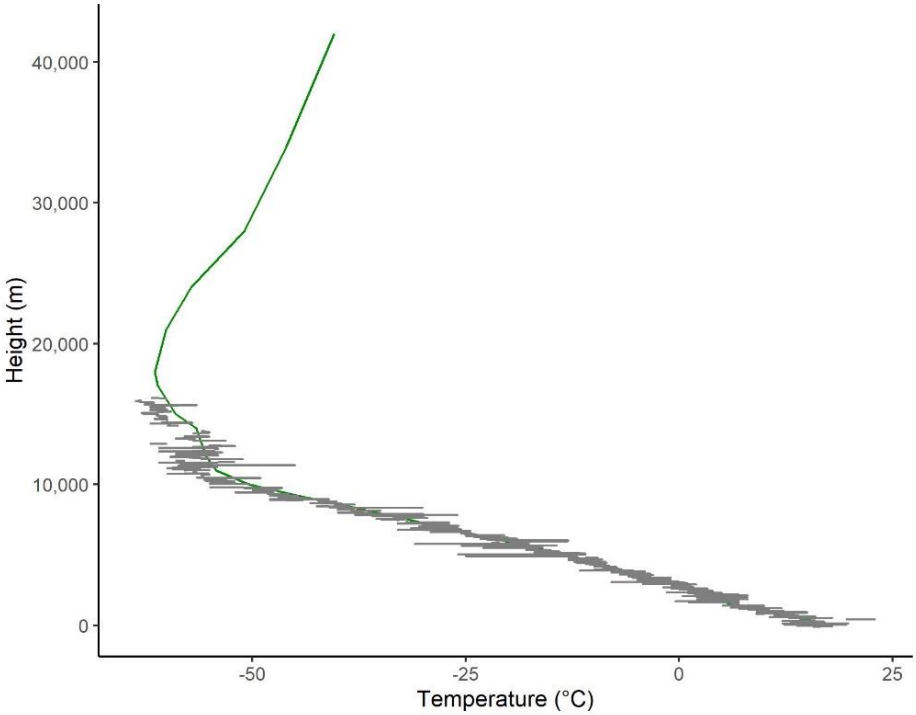


Figure C17a Temporal mean profiles of Conformal Cubic Atmospheric Model (CCAM) and observation temperature at Sydney Airport for April 2008. Green line indicates CCAM prediction and grey lines represent Bureau of Meteorology radiosonde observation.

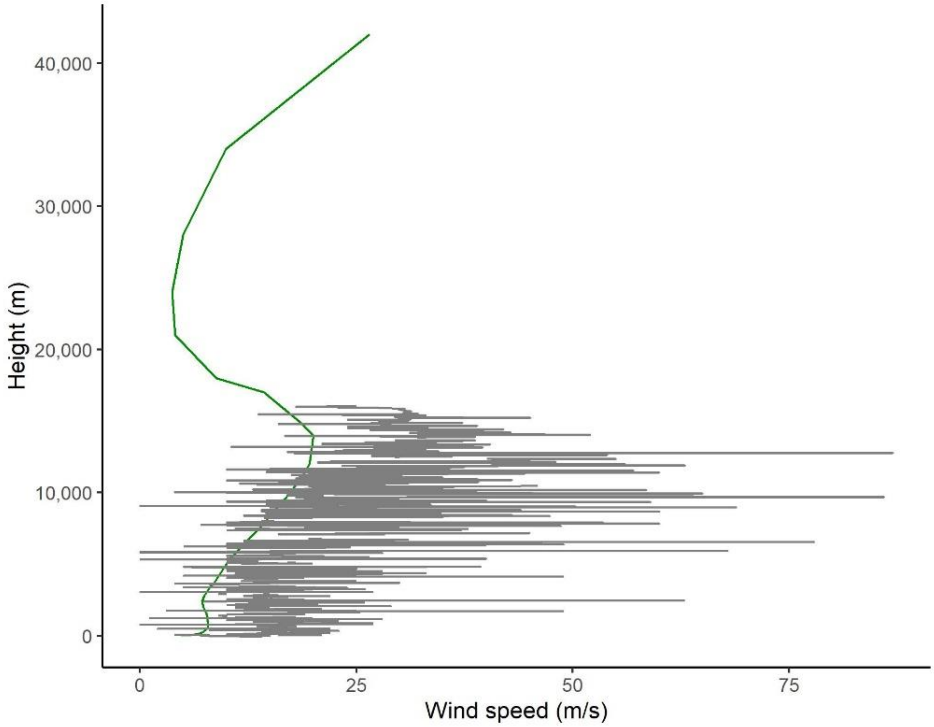


Figure C17b Temporal mean profiles of Conformal Cubic Atmospheric Model (CCAM) and observation wind speed at Sydney Airport for April 2008. Green line indicates CCAM prediction and grey lines represent Bureau of Meteorology radiosonde observation.

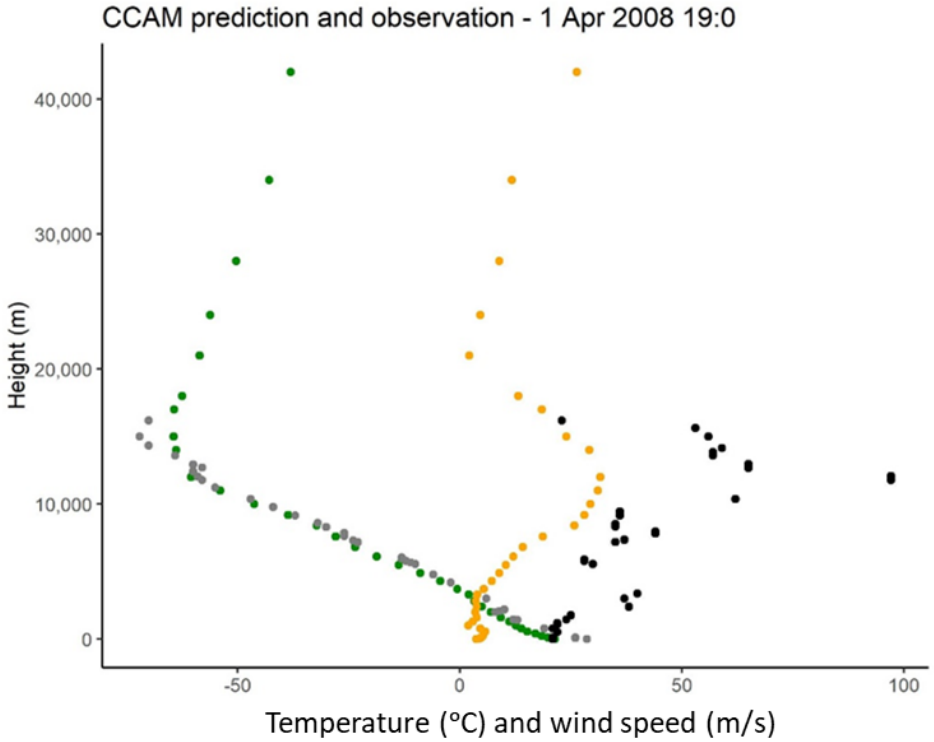


Figure C18a Temperature (green dots indicate Conformal Cubic Atmospheric Model (CCAM) predictions and grey dots represent observations) and wind speed (orange dots indicate CCAM predictions and black dots represent observations) profiles at Sydney Airport on 01/04/2008 19:00. m = metres; m/s = metres per second.

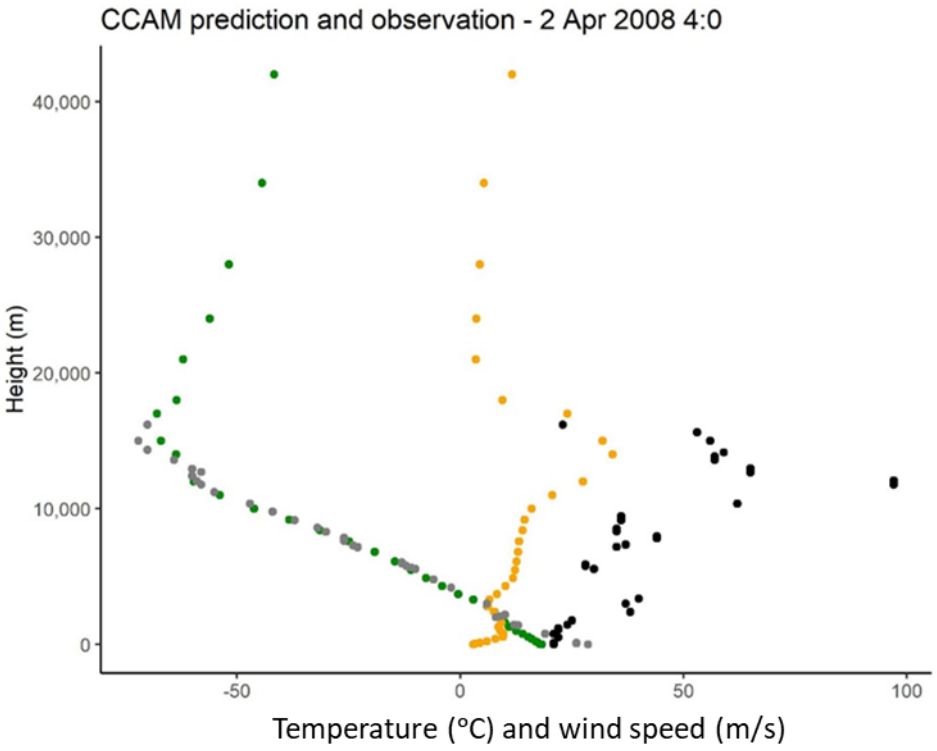


Figure C18b Temperature (green dots indicate Conformal Cubic Atmospheric Model (CCAM) predictions and grey dots represent observations) and wind speed (orange dots indicate CCAM predictions and black dots represent observations) profiles at Sydney Airport on 02/04/2008 04:00. m = metres; m/s = metres per second.

July 2008

Validation of results for CCAM upper air prediction compared with observation at Sydney airport for July 2008 was conducted (Figures C.19 and 20). Temperature profiles for 1/7/2008 20:00 and 2/7/2008 05:00 showed that the temperature inversion occurred at about 11,000 metres (Figure C.21). As indicated by the temperature profiles, the mixing height during July was lower than that for January and April.

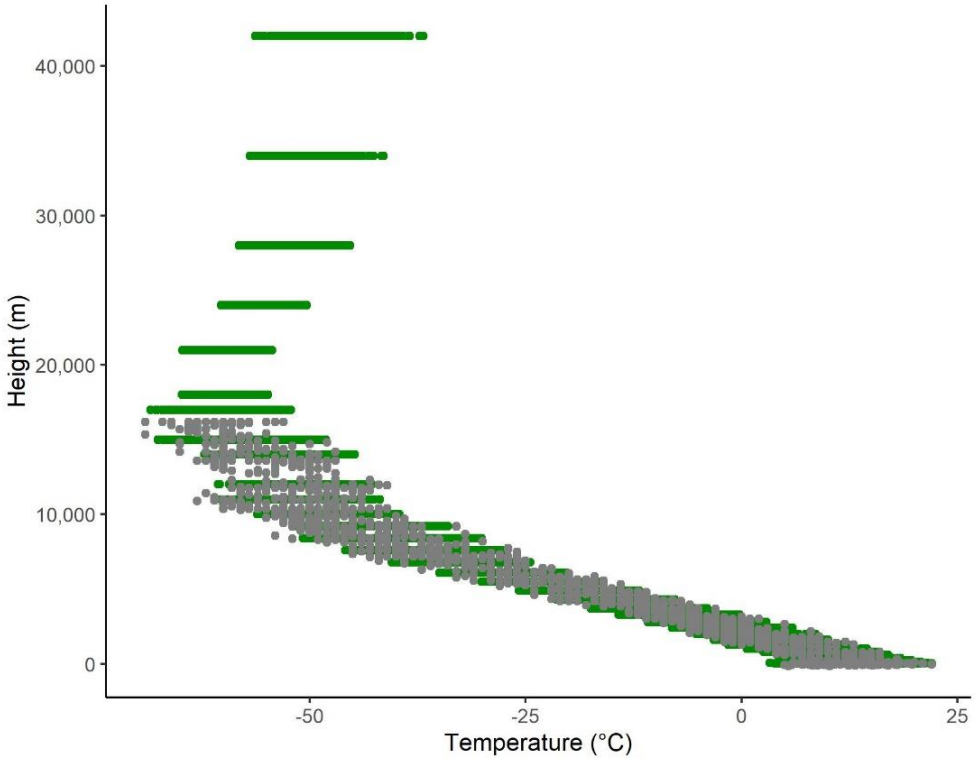


Figure C19a July 2008 Conformal Cubic Atmospheric Model (CCAM) predicted temperature profile versus observation at Sydney Airport. Green indicates CCAM prediction and grey represents Bureau of Meteorology radiosonde observation. m = metres.

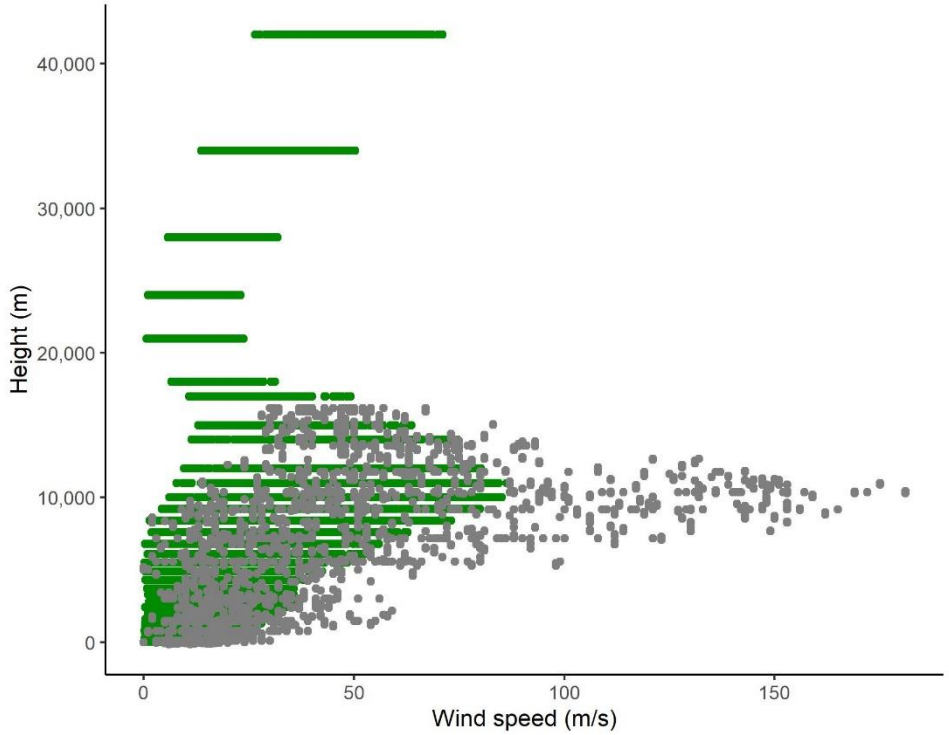


Figure C19b July 2008 Conformal Cubic Atmospheric Model (CCAM) predicted wind speed profiles versus observation at Sydney Airport. Green indicates CCAM prediction and grey represents Bureau of Meteorology radiosonde observation. m = metres; m/s = metres per second.

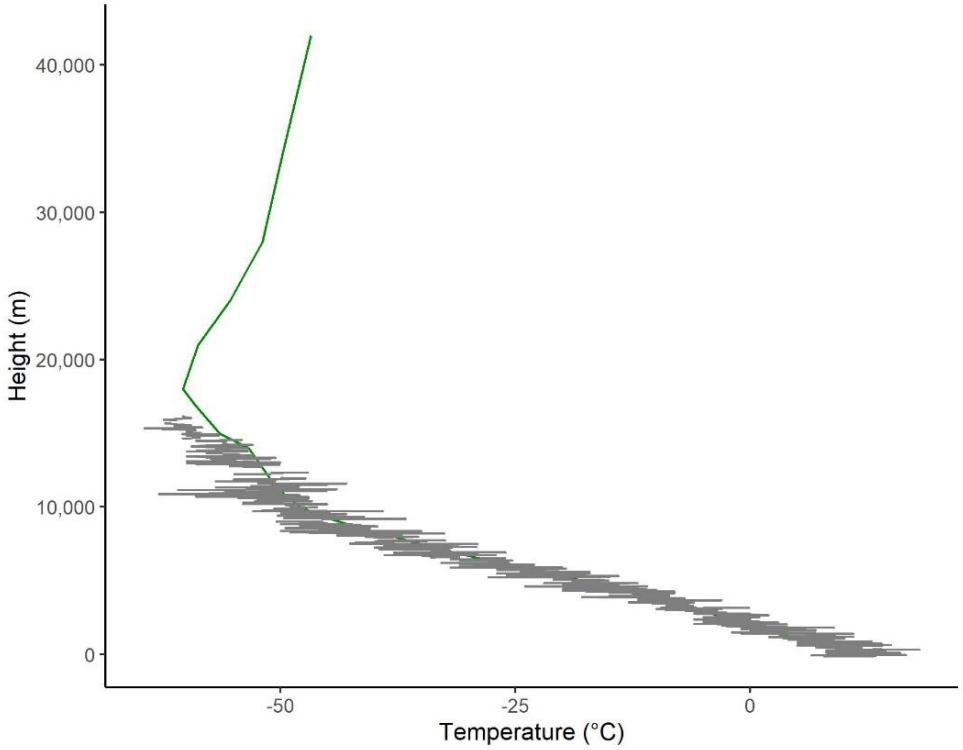


Figure C20a Temporal mean profiles of Conformal Cubic Atmospheric Model and observation temperature at Sydney Airport for July 2008. Green line indicates CCAM prediction and grey lines represent Bureau of Meteorology radiosonde observation.

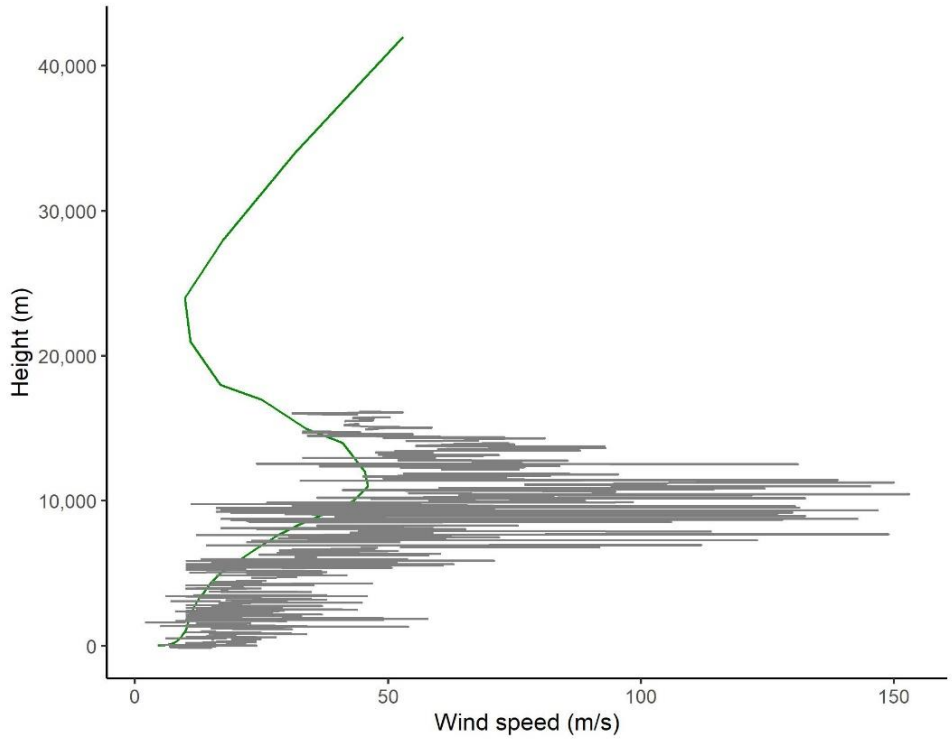


Figure C20b Temporal mean profiles of Conformal Cubic Atmospheric Model (CCAM) and observation wind speed at Sydney Airport for July 2008. Green line indicates CCAM prediction and grey lines represent Bureau of Meteorology radiosonde observation.

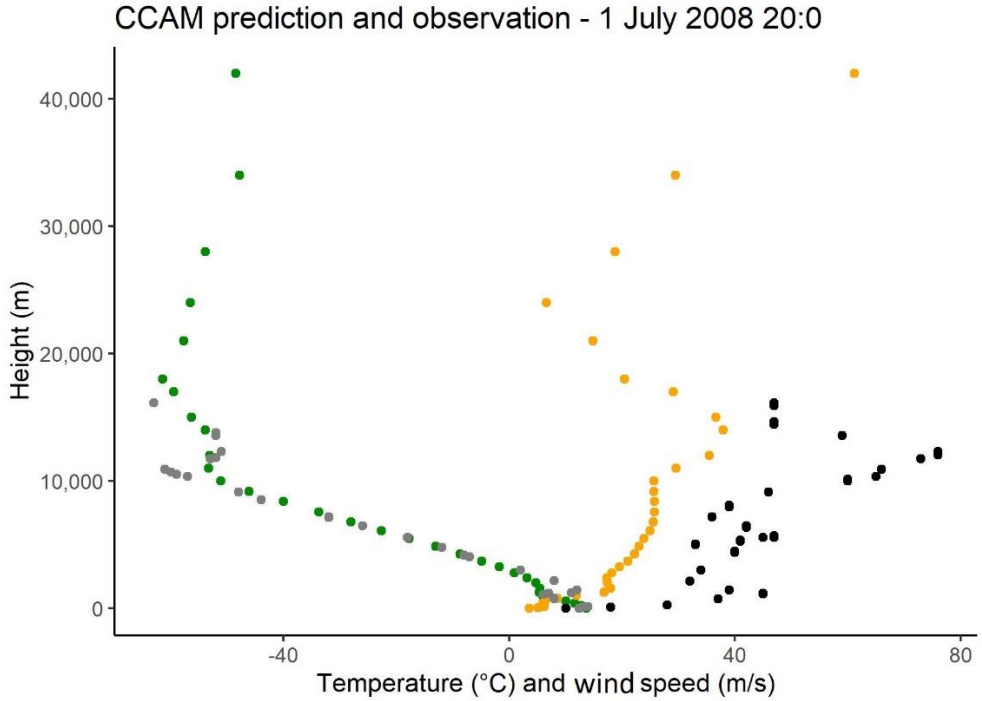


Figure C21a Temperature (green dots indicate Conformal Cubic Atmospheric Model (CCAM) predictions and grey dots represent observations) and wind speed (orange dots indicate CCAM predictions and black dots represent observations) profiles at Sydney Airport on 01/07/2008 20:00. m = metres; m/s = metres per second.

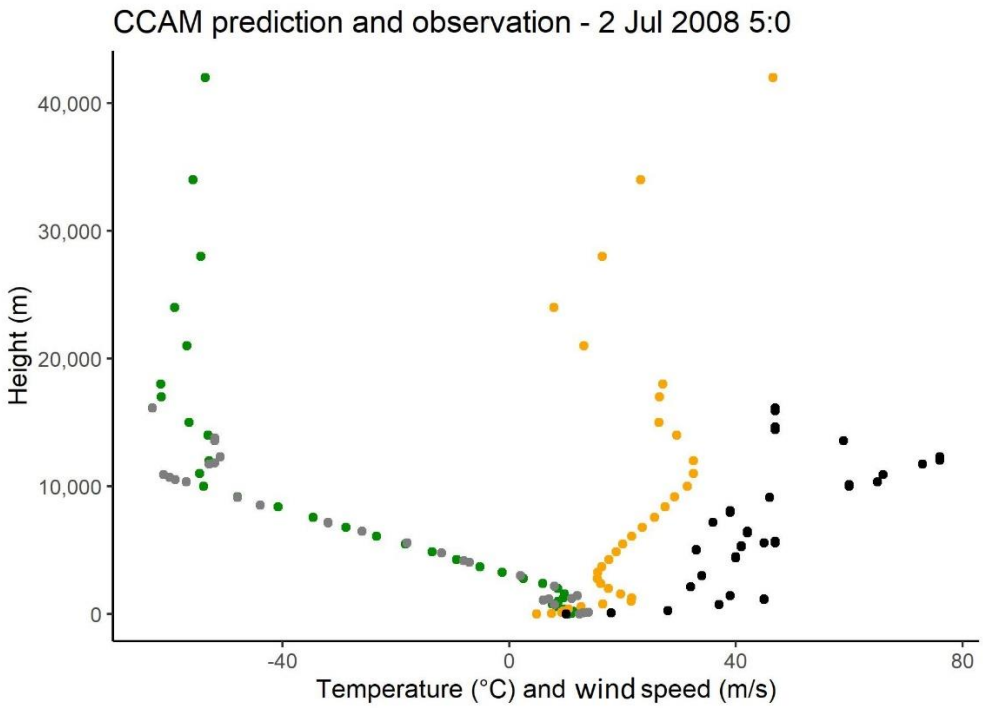


Figure C21b Temperature (green dots indicate Conformal Cubic Atmospheric Model (CCAM) predictions and grey dots represent observations) and wind speed (orange dots indicate CCAM predictions and black dots represent observations) profiles at Sydney Airport on 02/07/2008 05:00. m = metres; m/s = metres per second.

October 2008

Validation of results for CCAM upper air prediction compared with observation at Sydney airport for October 2008 was conducted (Figures C.22 and C.23). Temperature profiles for 1/10/2008 20:00 and 2/10/2008 5:00 show that the temperature inversion occurred at about 1500 metres (Figure C.24).

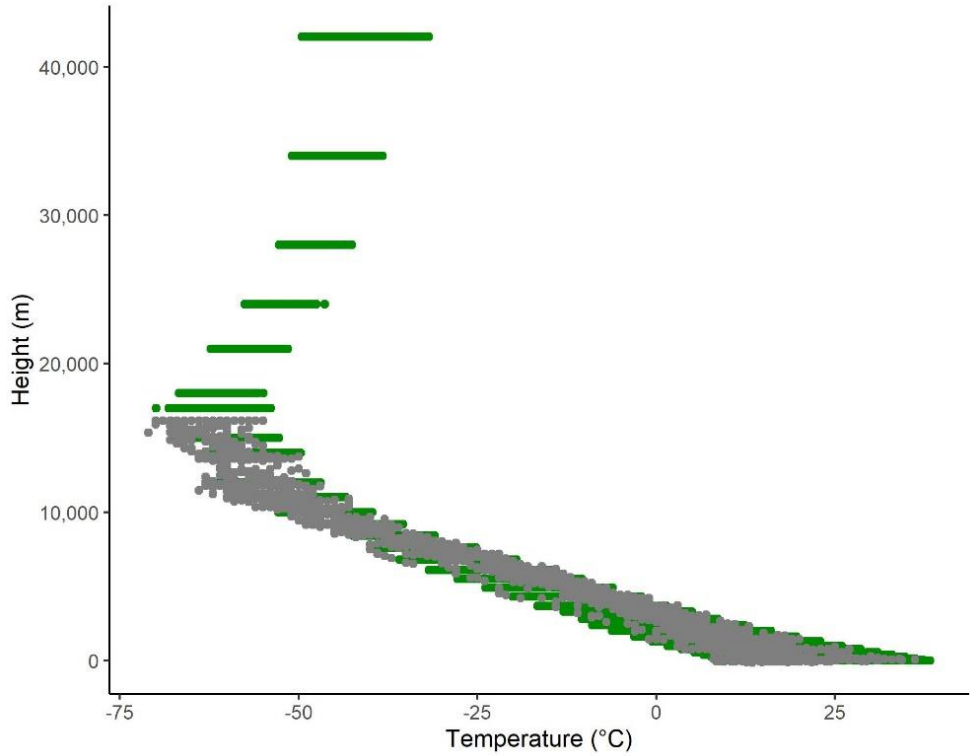


Figure C22a October 2008 Conformal Cubic Atmospheric Model (CCAM) predicted temperature profiles versus observation at Sydney Airport. Green dots indicate CCAM prediction and grey dots represent Bureau of Meteorology radiosonde observation. m = metres.

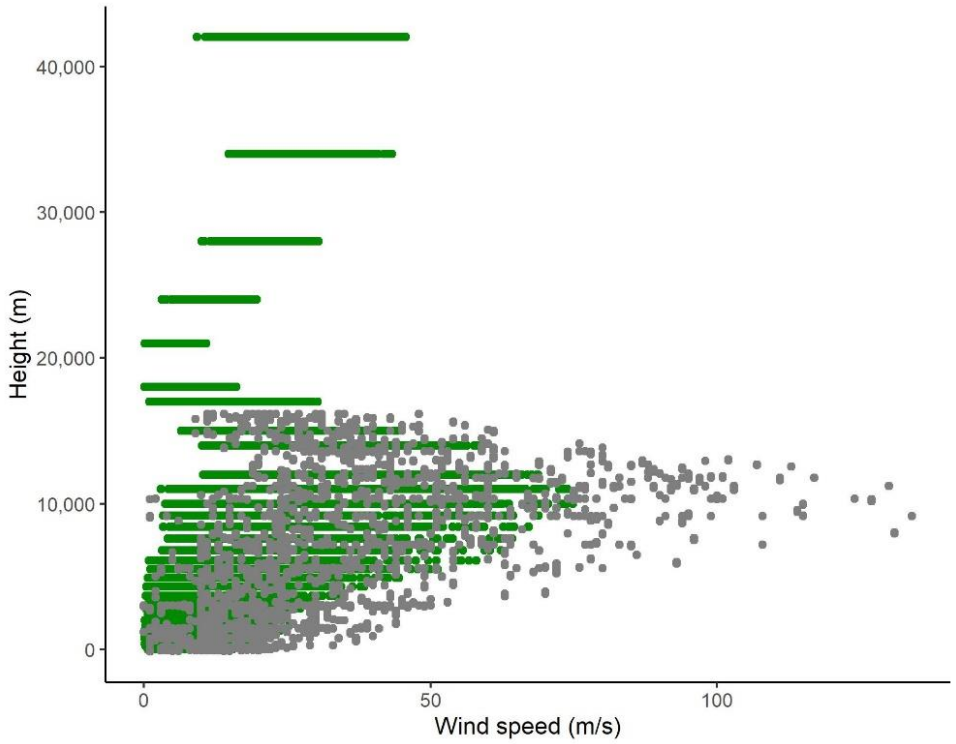


Figure C22b October 2008 Conformal Cubic Atmospheric Model (CCAM) predicted wind speed profiles versus observation at Sydney Airport. Green dots indicate CCAM prediction and grey dots represent Bureau of Meteorology radiosonde observation. m = metres; m/s = metres per second.

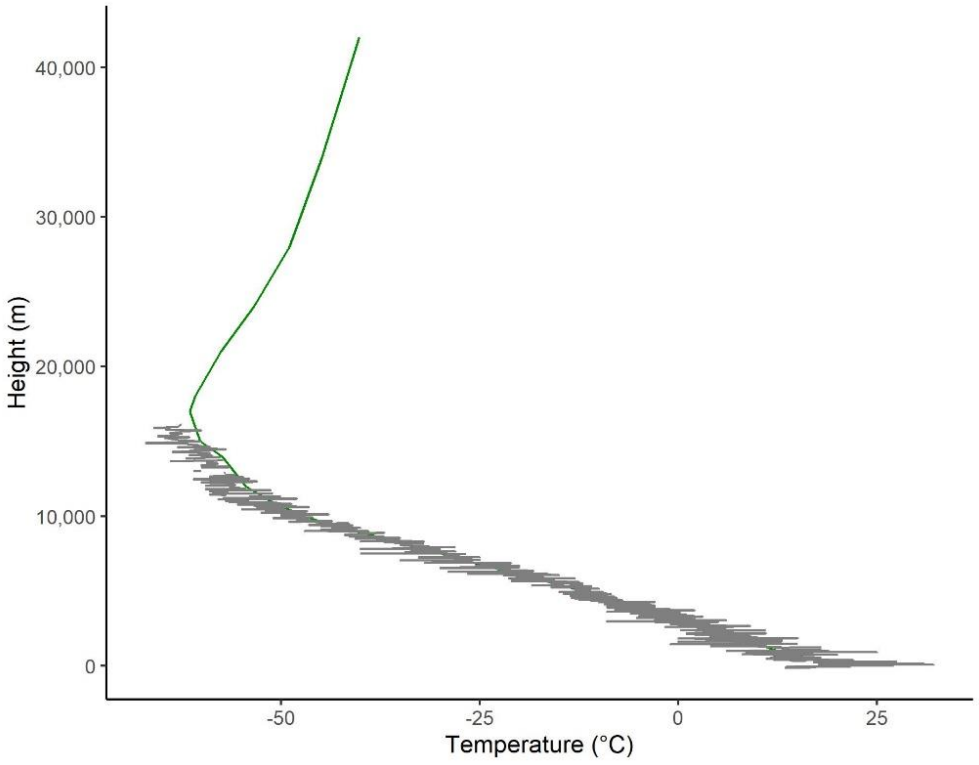


Figure C23a Temporal mean profiles of Conformal Cubic Atmospheric Model (CCAM) and observation temperature at Sydney Airport for October 2008. Green line indicates CCAM prediction and grey lines represent Bureau of Meteorology radiosonde observation.

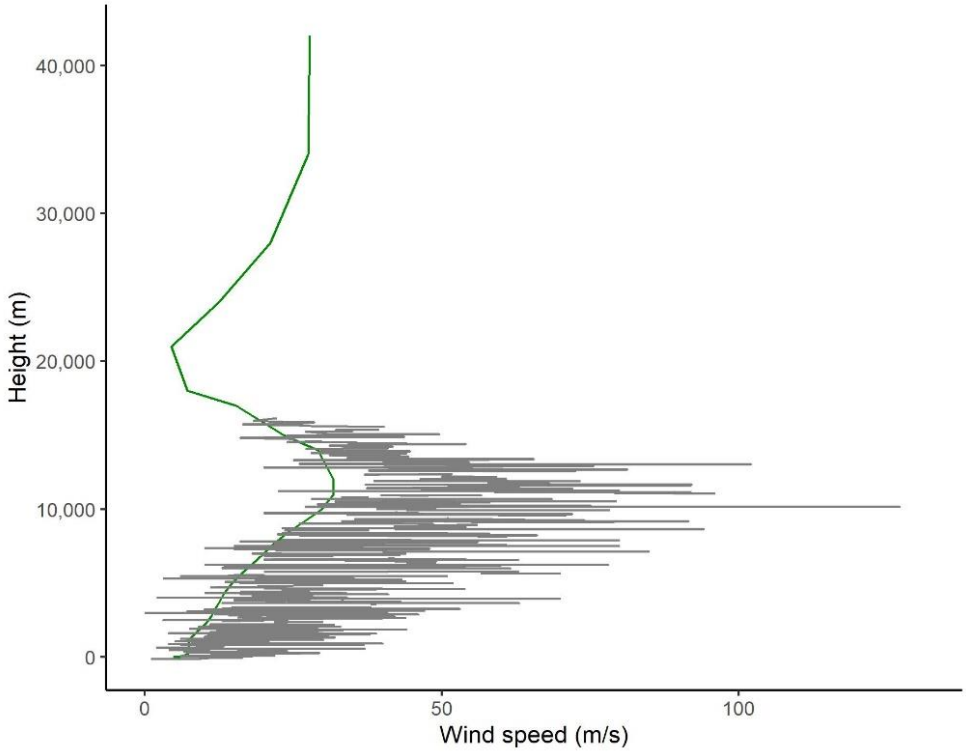


Figure C23b Temporal mean profiles of Conformal Cubic Atmospheric Model and observation wind speed at Sydney Airport for October 2008. Green line indicates CCAM prediction and grey lines represent Bureau of Meteorology radiosonde observation.

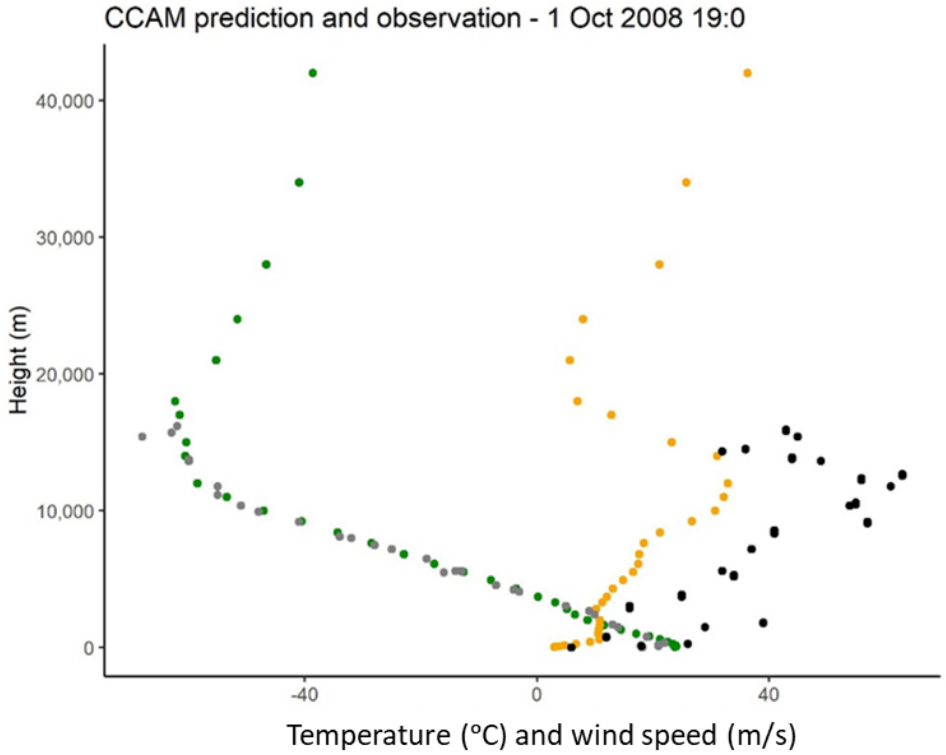


Figure C24a Temperature (green dots indicate Conformal Cubic Atmospheric Model (CCAM) predictions and grey dots represent observations) and wind speed (orange dots indicate CCAM predictions and black dots represent observations) profiles at Sydney Airport on 01/10/2008 19:00. m = metres; m/s = metres per second.

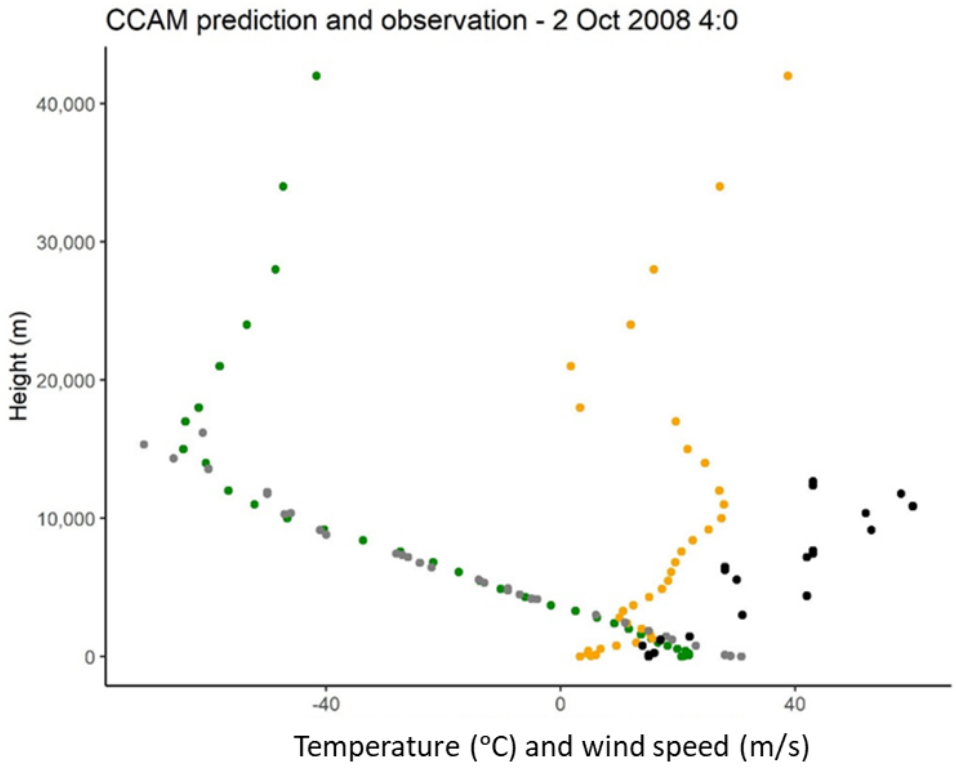


Figure C24b Temperature (bright green dots indicate Conformal Cubic Atmospheric Model (CCAM) predictions and grey dots represent observations) and wind speed (orange dots indicate CCAM predictions and black dots represent observations) profiles at Sydney Airport on 02/10/2008 04:00. m = metres; m/s = metres per second.

Conclusions

Temperatures were well represented by the CCAM simulation, with seasonal and daily cycles captured. Temperatures were slightly warmer in the model compared to observations, but meet the referenced model benchmarks. Positive biases are not expected to have a large impact on the photochemistry of the chemical transport model.

Wind speed and direction were over-predicted by the CCAM simulation, but overall the average cycle through the year and daily averages were captured. Although wind speed were too fast, they were within reasonable limits of the expected performance of a mesoscale meteorological model. Stronger overnight winds could impact the dispersion of pollutants under stable conditions. This should be considered when assessing the performance of the chemical transport model.

11.4 References

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Kemball-Cook S, Jia Y, Emery C, Morris R 2005, Alaska MM5 Modeling for the 2002 Annual Period to Support Visibility Modeling. ENVIRON International Corporation: Novato, CA, USA.

Monk K, Guérette E-A, Paton-Walsh C, Silver JD, Emmerson KM, Utembe SR, Cope ME 2019, Evaluation of regional air quality models over Sydney and Australia: Part 1 – Meteorological Model Comparison, *Atmosphere*, 10(7), p374.

McNally DE 2009, 12km MM5 Performance Goals. Alpine Geophysics, LLC: Arvada, CO, USA.

Tesche TW, DE McNally and DC Tremback 2002, Operational evaluation of the MM5 Meteorological Model over the continental United States: Protocol for annual and episodic evaluation. US EPA, Washington, DC, USA.

12. Appendix D: Chemical Transport Model performance

12.1 General guidance

Many performance metrics can be used to examine the performance of air quality models. However, there is no universal agreement among the modelling community on the best-practice to evaluate model performance. Dennis et al. (2010) comprehensively reviewed methods and tools that are widely used to evaluate regional-scale numerical photochemical modelling. The general guidance and procedure used to evaluate of the Chemical Transport Model (CTM) used in this study mainly follows the 'operational evaluation' proposed as an evaluation framework by Dennis et al. (2010).

The traditional metrics-based evaluation was first undertaken in our study; i.e., CTM predictions were compared with observations and deviations were quantified through statistics. The magnitudes of statistics were then compared with reference criteria to characterise the CTM performance. Measures for metrics used included the mean bias (MB), the mean error (ME), the normalised mean bias (NMB), the normalised mean error (NME), the mean fractional bias (MFB), the mean fractional error (MFE), the root mean square error (RMSE), the correlation coefficient (R), the index of agreement (IOA) and Skill_V (Table D.1).

We also conducted a graphical evaluation, which included time-series comparison and spatial distribution. This helped visualise and measure how well the model reproduced temporal and spatial variations for various pollutants. The model evaluation in this study mainly focused on predictions in the most inner domain (3 x 3 kilometres), which covers the NSW Greater Metropolitan Region (GMR).

Table D1 Metrics used to quantify chemical transport model performance

Metrics	Mathematical expression	Range
Mean bias (MB)	$MB = \frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)$	–∞ to +∞
Mean error (ME)	$ME = \frac{1}{n}\sum_{i=1}^{n}\lvert M_i - O_i\rvert$	0 to +∞
Normalised mean bias (NMB)	$NMB = \frac{1}{n}\sum_{i=1}^{n}\frac{(M_i - O_i)}{O_i}$	–100% to +∞
Normalised mean error (NME)	$NME = \frac{1}{n}\sum_{i=1}^{n}\frac{\lvert M_i - O_i\rvert}{O_i}$	0% to +∞
Mean fractional bias (MFB)	$MFB = \frac{1}{n}\sum_{i=1}^{n}\frac{(M_i - O_i)}{\frac{(M_i + O_i)}{2}}$	–200 to 200%
Mean fractional error (MFE)	$MFE = \frac{1}{n}\sum_{i=1}^{n}\frac{\lvert M_i - O_i\rvert}{\frac{(M_i + O_i)}{2}}$	0 to 200%

Root mean square error (RMSE)	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)^2}$	0 to +∞
Correlation coefficient (R)	$R = \frac{\sum_{i=1}^{n}((O_i-\bar{O})(M_i-\bar{M}))}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2 \sum_{i=1}^{n}(M_i-\bar{M})^2}}$	–1 to 1
Index of agreement (IOA)	$IOA = 1 - \frac{\sum_{i=1}^{n}(M_i-O_i)^2}{\sum_{i=1}^{n}(\lvert M_i-\bar{O}\rvert+\lvert O_i-\bar{O}\rvert)^2}$	0 to 1
Skill_V	$Skill\_V = \frac{Standard\ deviation\ of\ predictions}{Standard\ deviation\ of\ observations}$	Near 1 indicates skill

Ambient air quality data was provided by the NSW Department of Planning, Industry and Environment (DPIE) Air Quality Monitoring Network. The locations of monitoring sites that provided observations used for this evaluation represent Sydney east (Chullora, Earlwood, Lindfield, Randwick and Rozelle), Sydney north-west (Prospect, Richmond, St Marys and Vineyard), Sydney south-west (Bargo, Bringelly, Liverpool, Macarthur and Oakdale), Illawarra (Albion Park, Kembla Grange and Wollongong) and Newcastle (Newcastle) regions (Figure D1). Ozone (O_3), nitrogen oxides (NO_x, NO, NO_2), particles less than 10 micrometres in diameter (PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO) and visibility were monitored at all sites. Measurements of particles less than 2.5 micrometres in diameter ($PM_{2.5}$) were only available at five sites: Chullora, Earlwood, Richmond, Liverpool and Wollongong.

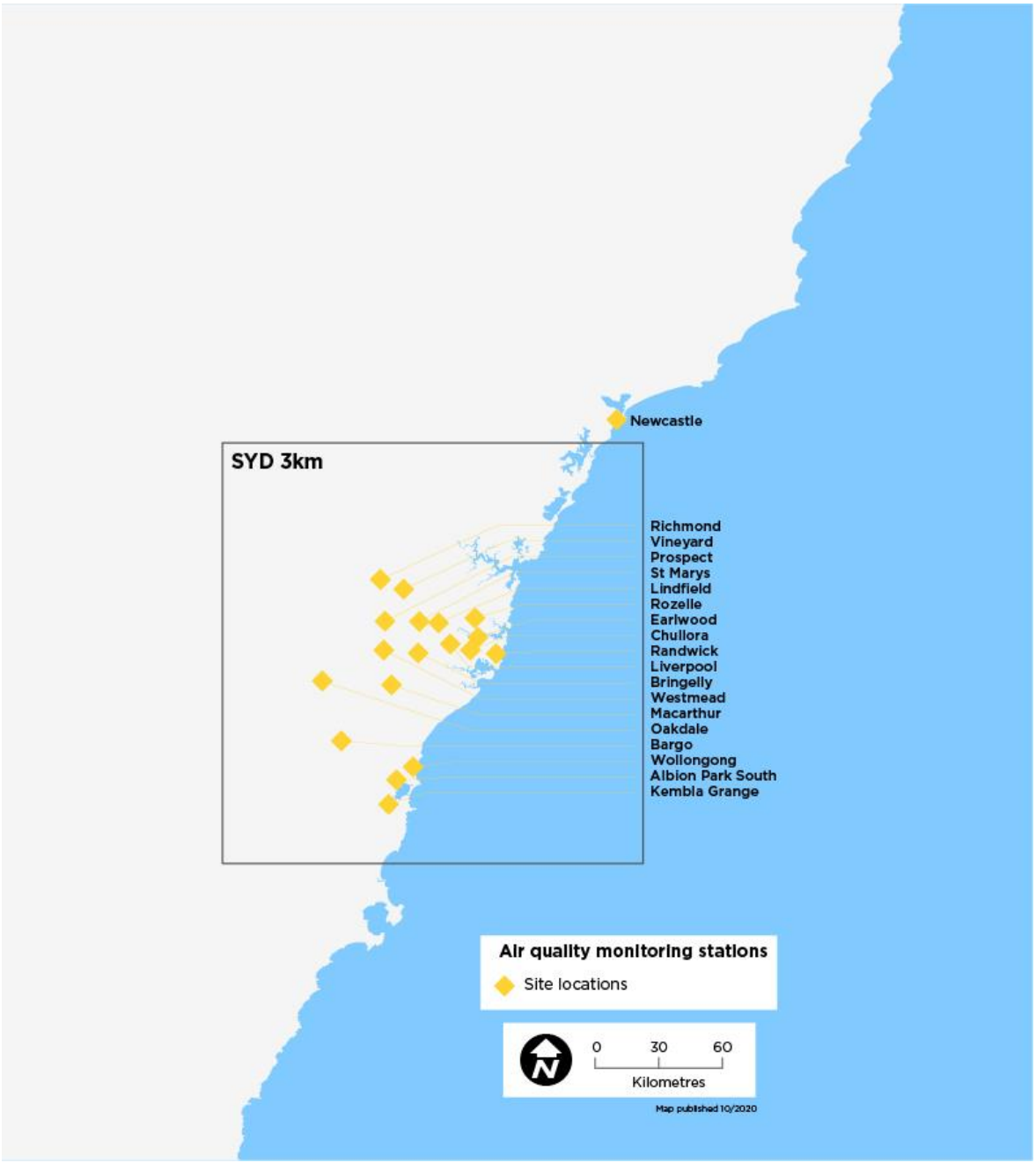


Figure D1 Location of 18 Department of Planning, Industry and Environment air quality monitoring stations. Stations are located within the innermost domain used for Conformal Cubic Atmospheric Model–Chemical Transport Model simulation with a horizontal resolution of 3 kilometres (SYD 3-km), except the Newcastle station.

12.2 Model evaluation

Summaries of CTM model performance for predicting O_3, $PM_{2.5}$, NO_2, $SO_2$and CO levels in 2008 are provided in this section. Summaries have been disaggregated into seasons and are for Sydney east, Sydney north-west, Sydney south-west, Illawarra and Newcastle sub-regions. Seasons are defined by months: December, January, February (DJF, summer), March, April, May (MAM, autumn), June, July, August (JJA, winter) and September, October, November (SON, spring). The model evaluation consists of:

- The quantitative performance statistics summary based on paired hourly predictions and observations. As discussed in Boylan and Russell (2006), MB and ME are defined as

the average difference between all predicted–observed pairs, and the error only includes absolute deviation between the two. The NMB and NME normalise the MB and ME by the mean of observations, and they assume observations are the absolute truth. The NMB ranges from –100 % to +∞, whereas the NME range is from 0 % to +∞, which results in overpredictions artificially being given more weight than underpredictions. The MFB is defined as the bias normalised by the mean of paired predictions–observations; accordingly, the MFE can be defined in a similar way. Among the six metrics used, the MFB and MFE are the least biased. The IOA is a measure of the ratio of the error magnitudes to the sum of the difference between predicted and observed mean and the difference between observation and the observed mean. The IOA ranges from 0 to 1, where 1 would present a perfect agreement. The Skill_V is estimated by the ratio between the standard deviation of predictions and observations, and when it approaches 1 it indicates skills in the model.

- The Quantile–Quantile (QQ) plot, which is used to demonstrate similarity between the distribution of predicted and observed concentrations. The data are unpaired in time and space. Both datasets are sorted from lowest to highest value and the new pairs are plotted. If the datasets have a similar distribution the plotted values will fall along a 1:1 line. Values over the 1:1 line indicate general model over-simulation and values under the 1:1 line indicate general model under-simulation. The overall model tendencies are displayed in QQ plots and the model's general capability to simulate low, average, or high values becomes apparent (Thunis et al, 2012).
- The Taylor diagram (2001), which allows different statistical indicators to be represented in a single plot –R, the centred root-mean-square error (CRMSE), and the standard deviation of model predictions.
- The Bugle plot, which displays the MFB and the MFE versus 'average concentration' (the average of mean predicted and mean observed concentrations) along with the corresponding model performance goal and criterion. The goals and criterion are plotted as an exponential curve in function of concentration, as proposed by Boylan and Russell, 2006.

12.2.1 Ozone

Table D.2 summarises the quantitative performance statistics for predicted hourly O_3, along with the mean and standard deviation of predicted values and observations in each sub-region for different seasons. The MB shows that hourly O_3 is generally under-predicted across regions, and the largest negative bias can be found in spring.

The US Environment Protection Agency (US EPA) recommended benchmarks for MFB and MFE of ±15 and 35% for ozone predictions (US-EPA 2007). Results in Table D.2 show that the MFB for the majority of the regions fell within the benchmark of MFB of ±15% (highlighted with orange) for all seasons except SON; however, the MFE for Newcastle in summer complied with the benchmark MFE of 35% (Table D.2, highlighted with green). MFEs for other regions during DJF were a little larger than 35%. The MFE fell far outside 35% for autumn, winter and spring across all regions. Simon et al. (2012) reported that RMSEs were in the range of 15–20 parts per billion (ppb) for hourly O_3 concentrations in most model validation studies; the RMSEs in our studies are far under that. The Skill_V for most regions fell within the values of 0.8 to 1.2 during summer, which demonstrates a good agreement between the observed and modelled standard deviations.

Figure D.2 represents the QQ plot for predicted and observed hourly O_3 concentration during different seasons. The CTM under-predicted higher O_3 values across seasons, since plotted values fell under the 1:1 line indicating general model under-prediction. The overall tendency of the model to under-predict ozone levels became more apparent with higher O_3 concentrations in summer and autumn.

Figure D.3 represents the diurnal variations for predicted and observed hourly O_3 concentrations during each season at Chullora (Sydney east), Richmond (Sydney north-west), Bringelly (Sydney south-west), Wollongong (Illawarra) and Newcastle (Newcastle). The CTM reproduced diurnal variations of ozone well across seasons and regions. However, the CTM predictions were worse in spring because O_3 peaks across regions were not captured.

The predicted and observed O_3 represented in a Taylor diagram (Figure D.4) generally shows better correlations in the range of 0.4–0.8 in summer, and worse correlations in the range of 0.2–0.6 across the other seasons. In terms of better correlations, along with lower normalised standard deviation and lower CRMSE, the model performance in predicting O_3 levels for summer were better than for other seasons.

12.2.2 Particulate matter

Table D.3 summarises the quantitative performance statistics for the predicted hourly $PM_{2.5}$, along with the mean and standard deviation of predicted values and observations in each sub-region, except for Newcastle ($PM_{2.5}$ measurements are not available at the Newcastle site). The MB shows that hourly $PM_{2.5}$ is generally over-predicted in the Sydney east region; in contrast, it is under-predicted in the Sydney north-west and south-west regions. The relatively high correlation coefficient (R>0.50) and high IOA (>0.6) occur in the Sydney east and south-west regions in autumn. The Skill_V in the Sydney east region in autumn and winter also fell within the values of 0.8 to 1.2, which demonstrates a good agreement between observed and modelled standard deviations.

The QQ plot for predicted and observed hourly $PM_{2.5}$ concentrations for different seasons shows that the CTM under-predicted higher values since plotted values fell under the 1:1 line (Figure D.5). The model's tendency to under-predict became more apparent with higher $PM_{2.5}$ concentrations in the cooler months (JJA and SON).

Figure D.6 represents the seasonal diurnal variations for predicted and observed hourly $PM_{2.5}$ concentration at Chullora (Sydney east), Richmond (Sydney north-west) and Wollongong (Illawarra). The CTM generally predicted the diurnal variation well at Chullora and Wollongong for most months (DJF, MAM and SON); however, a significant negative bias was found for predicted $PM_{2.5}$ at Richmond across seasons.

The predicted and observed $PM_{2.5}$ concentrations presented in a Taylor diagram (Figure D.4) generally show better correlations in the range of 0.3–0.5 in summer and autumn, and worse correlations in the range of 0.2–0.3 in winter (JJA). In terms of better correlations along with lower normalised standard deviation and lower CRMSE, the model performance in $PM_{2.5}$ predictions for summer and autumn were better than that for other seasons.

12.2.3 Nitrogen dioxide

Table D.4 summarises the statistical analysis of the predicted hourly NO_2 performance, along with the mean and standard deviation of predicted values and observations in each sub-region. Negative MB occurred across regions for all the seasons. Better model results occurred for NO_2 predictions for Sydney east and north-west regions in summer and autumn, where MFB fell by ±10% and MFE was below 60%. The Skill_V in Sydney east and north-west regions also fell within the values of 0.8 to 1.2, which demonstrates there was good agreement between observed and modelled standard deviations.

The QQ plot for predicted and observed hourly NO_2 concentrations shows the CTM under-predicted NO_2 for all seasons (Figure D.7). A smaller negative bias was found during autumn and winter, and a larger bias was found in spring.

The CTM generally predicted diurnal variations for hourly NO_2 concentrations well across seasons and regions compared with observed NO_2 levels (Figure D.8). However, a larger

negative bias was found in predictions for midnight NO_2 peak compared to the morning peak.

The predicted and observed NO_2 presented in a Taylor diagram (Figure D.4) generally showed better correlations in the range of 0.5–0.8 for summer and autumn. In terms of better correlations along with lower normalised standard deviation and lower CRMSE, the model performance in NO_2 predictions for summer was better than that for other seasons.

12.2.4 Sulfur dioxide

Table D.5 summarises the statistical analysis of the predicted hourly SO_2 performance, along with the mean and standard deviation of predicted values and observations in each sub-region. Generally, the CTM under-predicted hourly SO_2 in spring, and over-predicted SO_2 in autumn.

The QQ plot for predicted and observed hourly SO_2 concentration during different seasons shows the CTM had a consistent bias to under-predict SO_2 in all seasons (Figure D.10). Differences between predictions and observations increase for values above 10.

Seasonal diurnal variations for predicted and observed hourly SO_2 concentration at Chullora (Sydney East), Richmond (Sydney North-West) and Wollongong (Illawarra) (Figure D.10).

12.2.5 Carbon monoxide

Table D.6 summarises the statistical analysis of the predicted hourly CO performance, along with the mean and standard deviation of predicted values and observations in each sub-region. Generally, the CTM consistently under-predicted hourly CO across seasons in all the regions except for the Illawarra.

The QQ plot for predicted and observed hourly CO concentration during different seasons shows that the CTM over-predicted CO at values roughly above 600 ppb in summer and values above 1200 in spring, whereas it under-predicted CO at values roughly below 2000 ppb in autumn and winter (Figure D.11). The differences between predictions and observations generally increased for values above 1000 ppb.

Seasonal diurnal variations for predicted and observed hourly CO concentration at Chullora (Sydney East) and Wollongong (Illawarra) were plotted (Figure D.12).

The predicted and observed CO levels presented in a Taylor diagram (Figure D.4) generally show poor correlation in the range of 0.3–0.5 in summer and autumn, and worse correlations in the range of 0.2–0.3 in winter. In terms of better correlations along with lower normalised standard deviation and lower CRMSE, the model performance in CO predictions for summer and autumn were better than for other seasons.

Table D2 **Quantitative performance statistics for predicted hourly O_3 concentration (ppb) against observation in the sub-regions across the NSW Greater Metropolitan Region during different seasons**

Ozone	Months	Mean CTM	SD CTM	Mean Obs	SD Obs	MB	NMB	MFB	ME	NME	MFE	RMSE	r	IOA	SKILLv
Sydney East	DJF	15.1	9.6	15.5	10.3	–0.2	–0.01	12%	5.6	0.36	46%	7.5	0.72	0.63	0.93
Sydney NW	DJF	16.5	11.7	16.8	12.7	0.0	0.00	13%	6.4	0.38	45%	8.5	0.77	0.68	0.92
Sydney SW	DJF	16.4	11.0	17.6	12.6	–0.9	–0.05	9%	6.3	0.36	47%	8.4	0.75	0.67	0.87
Illawarra	DJF	17.0	8.3	16.2	9.8	0.9	0.06	16%	5.9	0.36	41%	7.8	0.65	0.60	0.85
Newcastle	DJF	18.6	7.6	19.2	9.8	–0.4	–0.02	6%	6.1	0.32	34%	7.8	0.63	0.59	0.77
Sydney East	MAM	9.6	7.1	11.7	10.2	–2.0	–0.16	13%	6.1	0.52	76%	7.9	0.67	0.66	0.69
Sydney NW	MAM	11.6	9.1	12.6	11.4	–1.1	–0.08	22%	6.9	0.55	83%	8.8	0.67	0.63	0.80
Sydney SW	MAM	12.7	8.4	14.8	11.1	–1.9	–0.12	6%	6.5	0.46	57%	8.5	0.68	0.62	0.77
Illawarra	MAM	14.8	5.6	14.5	10.2	0.4	0.02	26%	7.7	0.53	65%	9.3	0.44	0.56	0.56
Newcastle	MAM	17.4	5.8	14.0	9.8	3.5	0.25	43%	8.1	0.58	65%	9.8	0.40	0.52	0.60
Sydney East	JJA	9.4	6.6	11.7	10.0	–2.3	–0.20	7%	6.6	0.57	87%	8.5	0.59	0.63	0.66
Sydney NW	JJA	11.0	6.7	13.2	10.6	–2.2	–0.15	10%	7.7	0.59	82%	9.4	0.56	0.60	0.63
Sydney SW	JJA	12.6	6.3	16.6	9.5	–4.0	–0.22	–1%	7.8	0.49	70%	9.4	0.51	0.45	0.69
Illawarra	JJA	15.6	4.8	19.5	9.8	–3.9	–0.20	–4%	8.9	0.46	56%	10.4	0.28	0.47	0.49
Newcastle	JJA	16.5	6.2	15.4	9.7	1.1	0.07	25%	7.3	0.47	54%	8.9	0.45	0.57	0.64
Sydney East	SON	13.2	8.1	19.9	11.4	–6.5	–0.33	–23%	9.3	0.47	65%	11.2	0.61	0.49	0.71
Sydney NW	SON	14.2	9.4	20.9	12.3	–6.4	–0.30	–22%	9.3	0.45	61%	11.2	0.69	0.54	0.76
Sydney SW	SON	14.4	8.7	21.8	12.1	–7.3	–0.33	–23%	9.9	0.46	61%	11.9	0.64	0.46	0.72
Illawarra	SON	16.0	6.6	21.8	11.2	–5.7	–0.26	–16%	9.9	0.45	54%	11.6	0.46	0.45	0.59
Newcastle	SON	17.9	7.1	23.6	9.7	–5.5	–0.23	–18%	8.8	0.37	42%	10.4	0.49	0.44	0.73

Notes: DJF = December January, February; MAM = March, April, May; JJA = June, July, August; ppb = parts per billion; SON = September, October, November; orange cells = mean fractional bias (MFB) within ±15%; green cell = mean fractional error (MFE) <35%; red cells = index of agreement (IOA) >0.6 or 0.8 < Skill_V < 1.2.

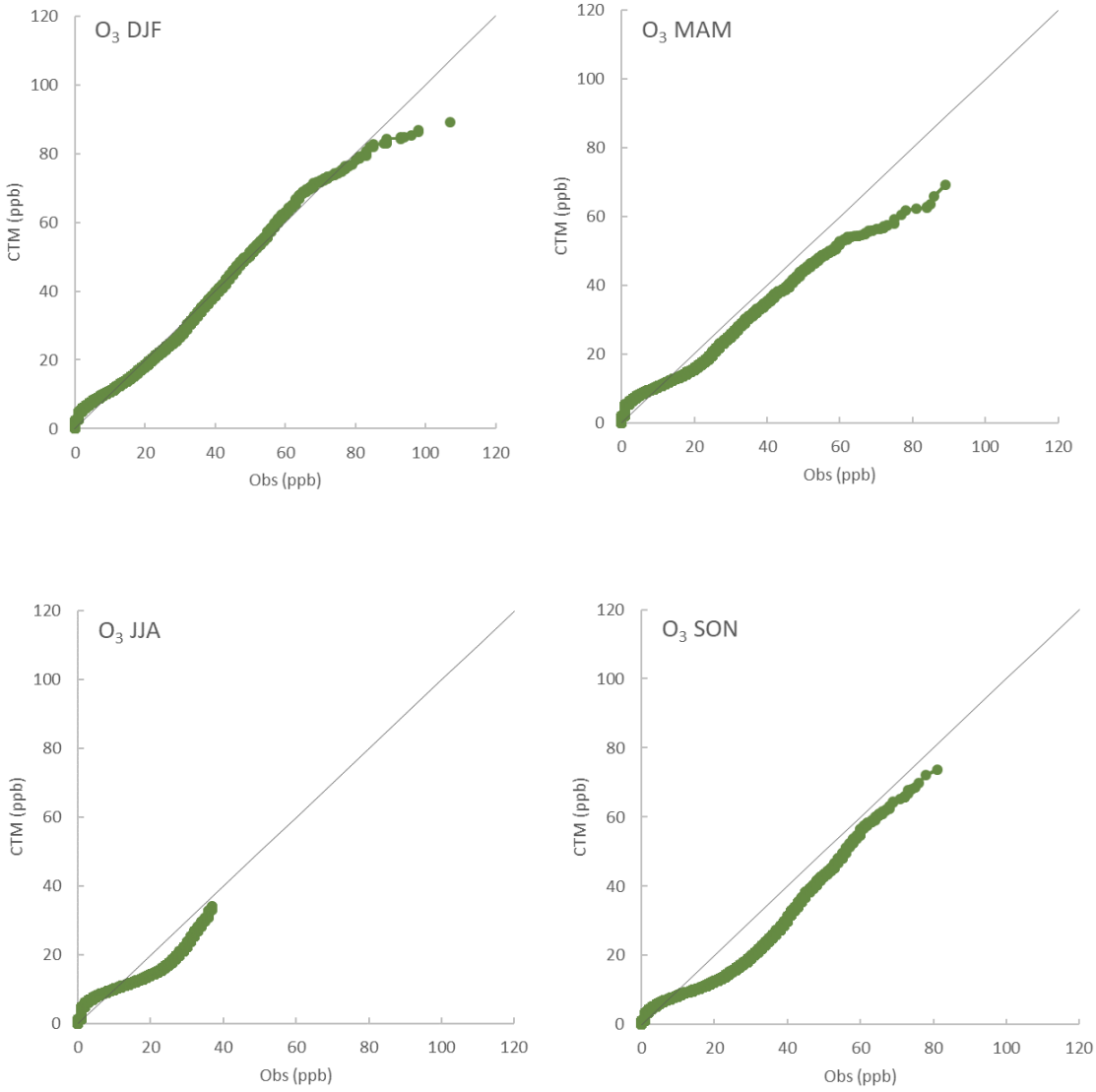
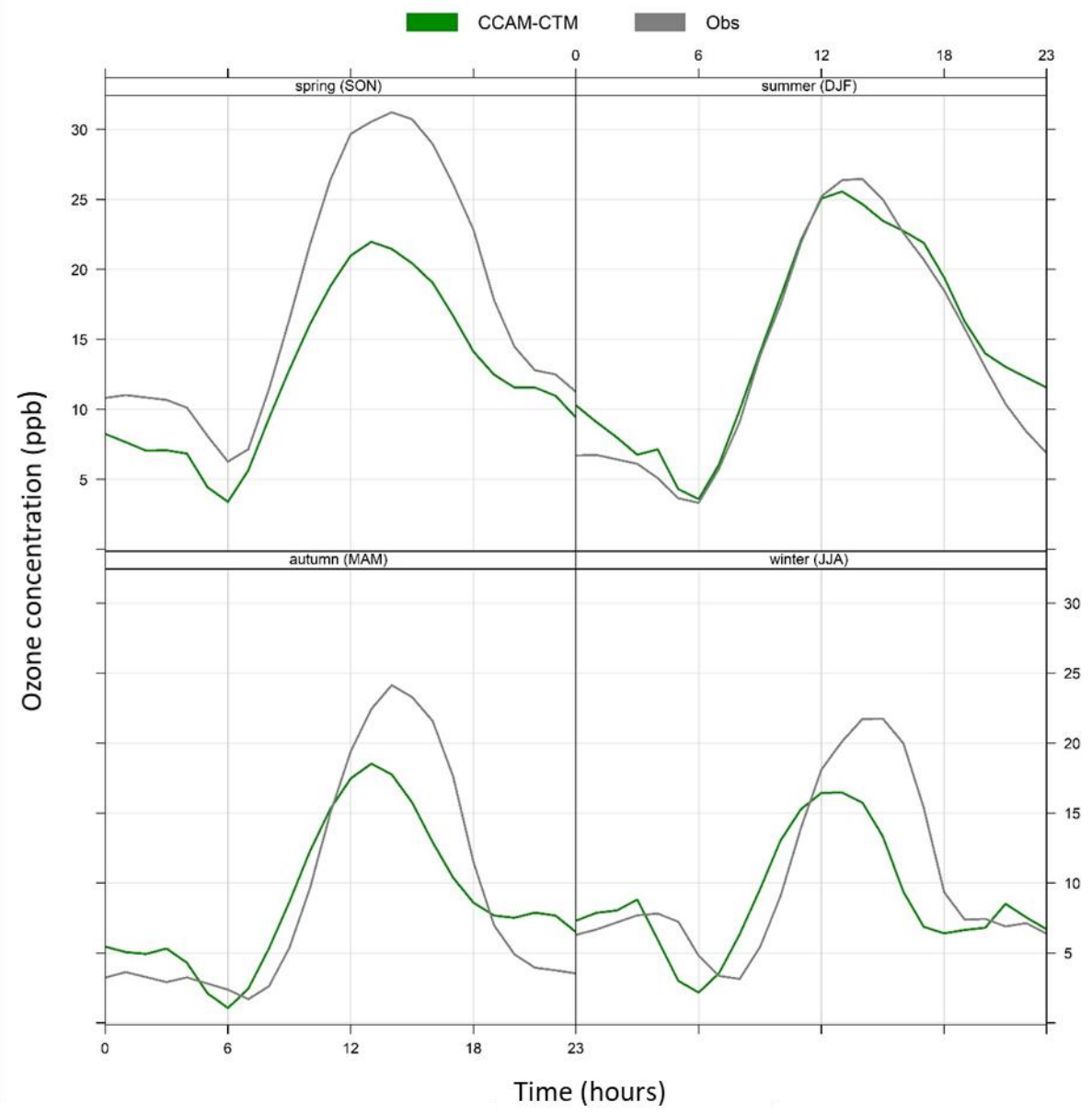


Figure D2 Quantile-quantile plots for predicted (chemical transport model (CTM)) and observed (Obs) hourly ozone (O_3) concentration during different seasons for all monitoring stations in the NSW Greater Metropolitan Region; grey line represents 1:1 line. DJF = December, January, February (summer); MAM = March, April, May (autumn); JJA = June, July, August (winter); ppb = parts per billion; SON = September, October, November (spring).

(a)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
Ozone concentration (ppb)
Time (hours)
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6
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18
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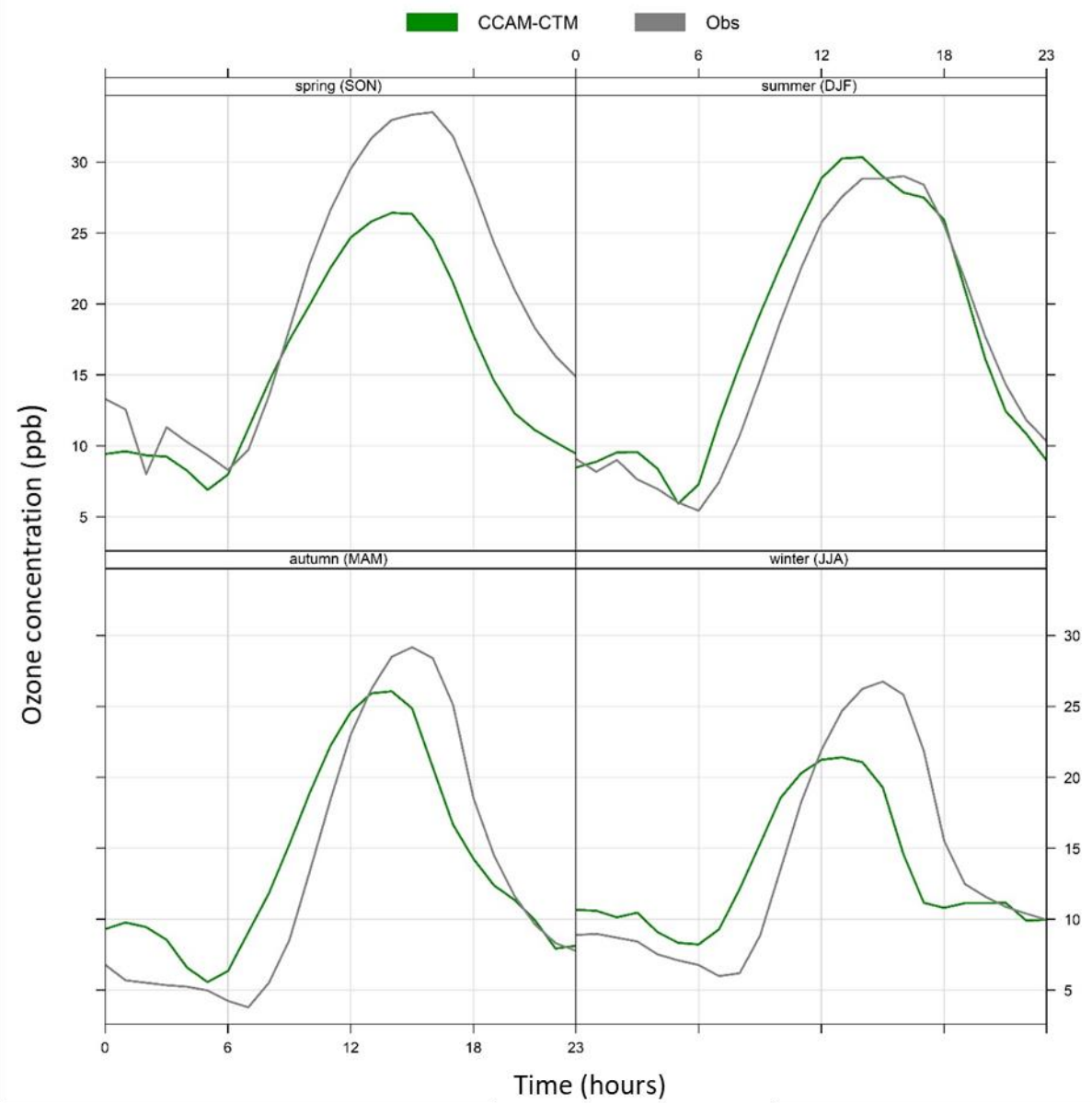
25
30

(b)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
Ozone concentration (ppb)
Time (hours)
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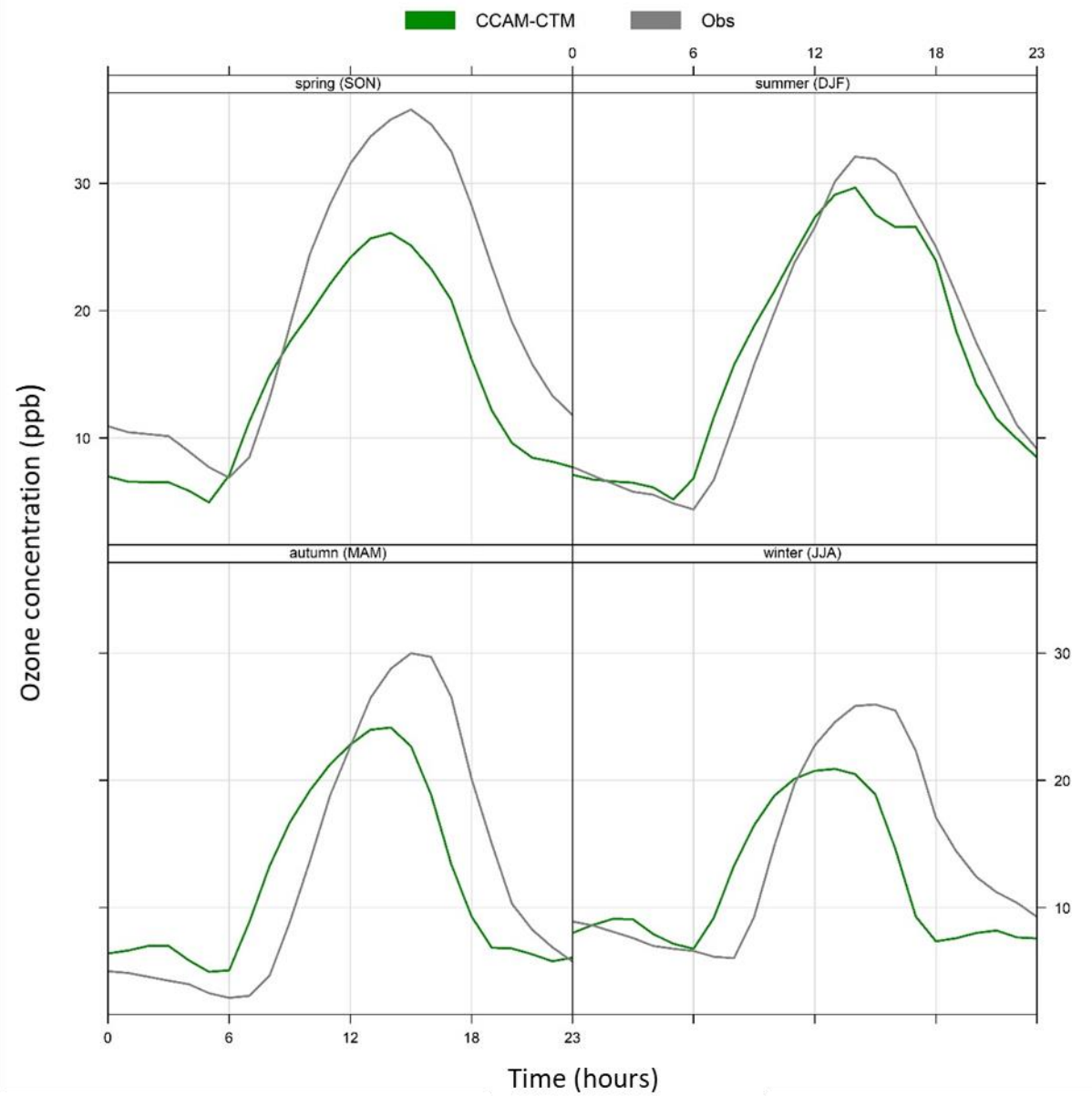
(c)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
Ozone concentration (ppb)
Time (hours)
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23
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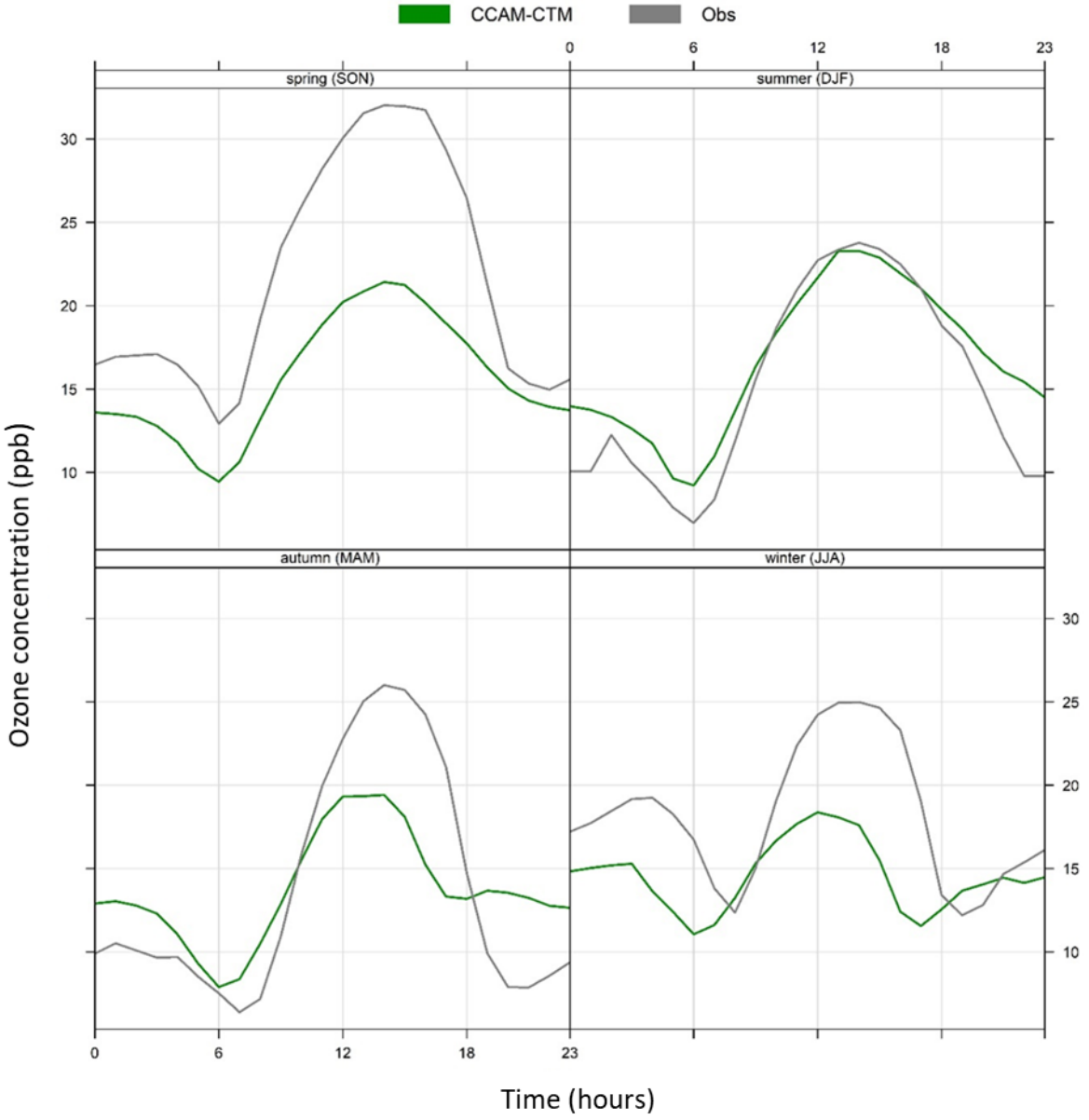
20
30

(d)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
Ozone concentration (ppb)
Time (hours)
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6
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10
15
20
25
30

(e)

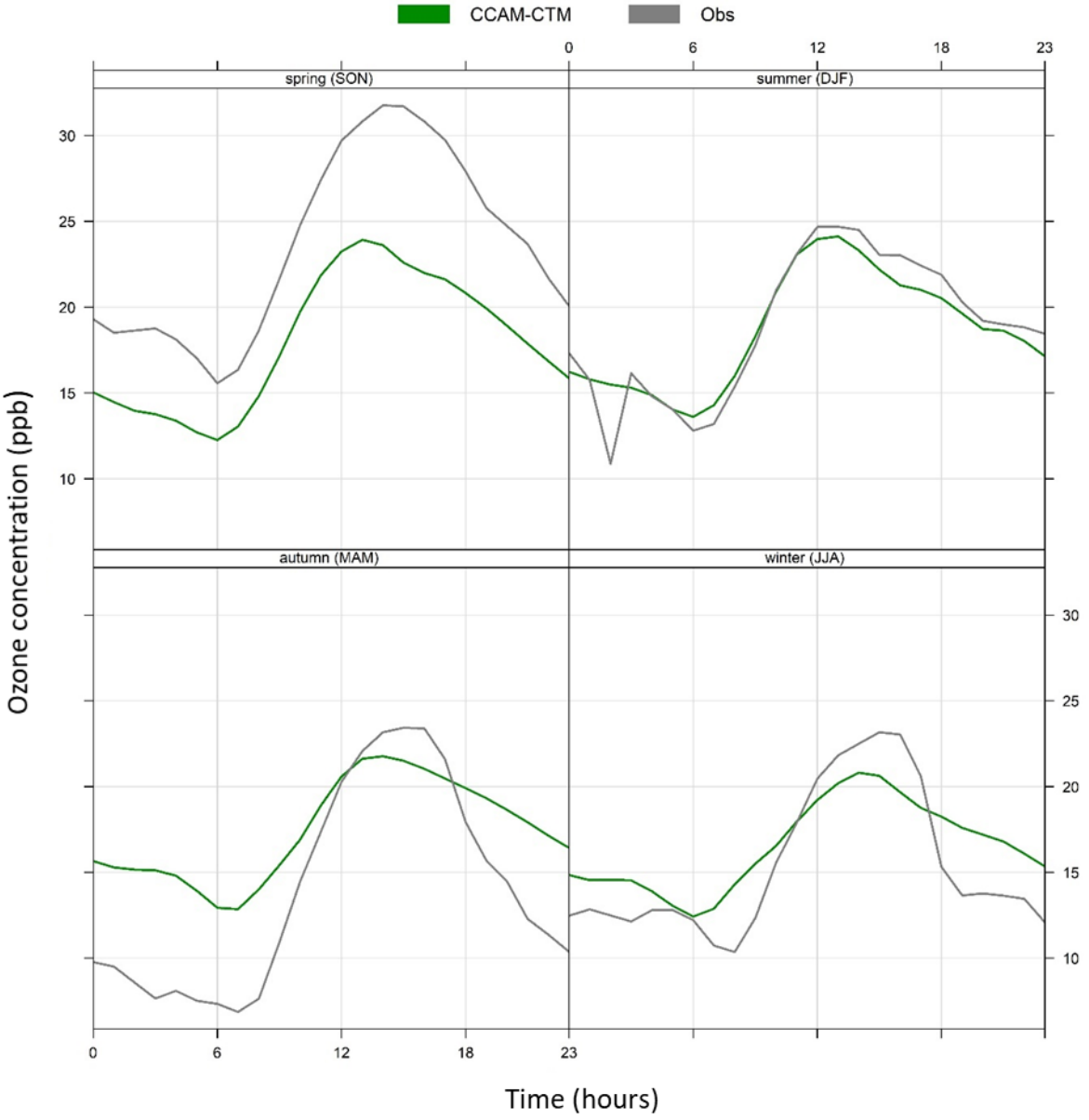


Figure D3 Seasonal diurnal variations for predicted (CCAM–CTM; green) and observed (Obs; grey) hourly ozone (O_3) concentration in parts per billion (ppb) at (a) Chullora, (b) Richmond, (c) Bringelly, (d) Wollongong and (e) Newcastle. CCAM–CTM = Conformal Cubic Atmospheric Model–chemical transport model; DJF = December, January, February; JJA – June, July, August; MAM = March, April, May; SON = September, October, November.

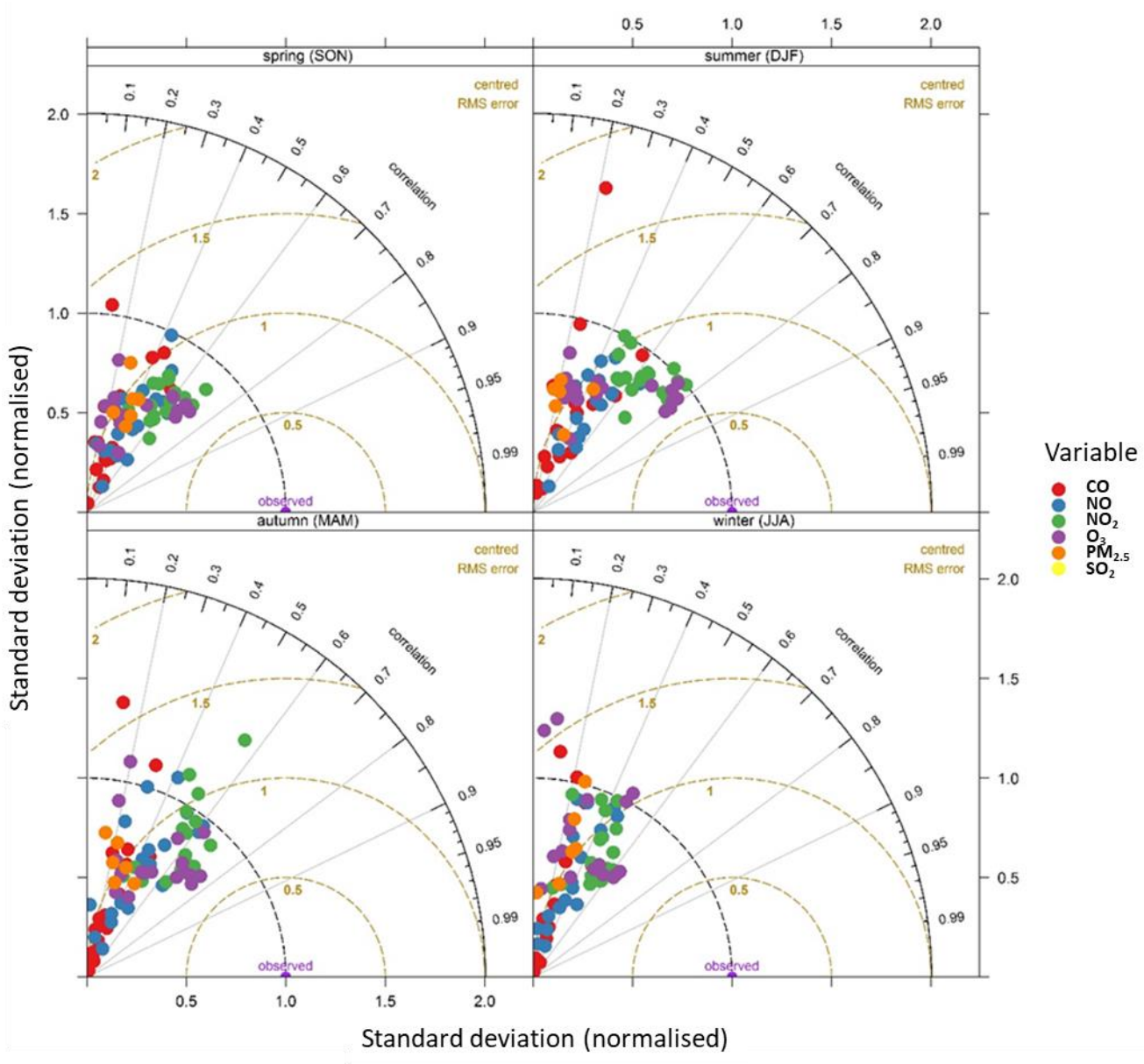


Figure D4 **Taylor diagrams of hourly carbon monoxide (CO), nitric oxide (NO) and nitrogen dioxide (NO_2), ozone (O_3), particles less than 2.5 micrometres in diameter ($PM_{2.5}$) and sulfur dioxide (SO_2) for predicted–observed pairs of values at all 18 stations across the NSW Greater Metropolitan Region. DJF = December, January, February; JJA – June, July, August; MAM = March, April, May; SON = September, October, November.**

Table D3 Quantitative performance statistics for predicted hourly concentration of particles less than 2.5 micrometres in diameter ($PM_{2.5}$; $\mu g/m^3$) against observation in the sub-regions across NSW Greater Metropolitan Region during different seasons

$PM_{2.5}$	Months	Mean CTM	SD CTM	Mean Obs	SD Obs	MB	NMB	MFB	ME	NME	MFE	RMSE	r	IOA	SKILLv
Sydney East	DJF	5.9	2.6	5.4	3.7	0.7	0.14	12%	2.5	0.5	22%	3.5	0.46	0.54	0.71
Sydney NW	DJF	5.6	2.6	7.5	4.0	–2.4	–0.32	–8%	3.4	0.5	13%	4.5	0.37	0.44	0.61
Sydney SW	DJF	5.3	2.5	6.2	4.0	–0.4	–0.06	2%	2.6	0.4	10%	3.6	0.47	0.56	0.68
Illawarra	DJF	5.9	2.8	6.1	4.4	0.2	0.03	9%	3.2	0.5	21%	4.3	0.34	0.53	0.63
Newcastle	DJF	6.1	2.6	NA	NA										
Sydney East	MAM	6.6	4.5	6.7	5.5	0.3	0.04	11%	3.4	0.51	25%	4.7	0.59	0.59	0.87
Sydney NW	MAM	5.8	3.1	8.0	4.5	–3.5	–0.43	–11%	4.0	0.50	15%	5.5	0.32	0.40	0.45
Sydney SW	MAM	4.7	2.4	6.6	5.5	–0.5	–0.07	5%	3.2	0.50	13%	4.8	0.52	0.61	0.62
Illawarra	MAM	4.7	2.5	5.2	4.2	0.0	0.01	5%	2.8	0.54	18%	3.8	0.46	0.56	0.59
Newcastle	MAM	4.8	2.0	NA	NA										
Sydney East	JJA	7.7	5.6	5.3	5.7	2.8	0.53	31%	5.0	0.94	40%	6.5	0.47	0.41	1.02
Sydney NW	JJA	5.3	3.2	6.6	4.2	–3.0	–0.45	–10%	3.8	0.57	18%	5.3	0.09	0.40	0.44
Sydney SW	JJA	3.9	2.1	6.5	6.1	–0.1	–0.01	8%	4.0	0.63	16%	5.4	0.49	0.57	0.62
Illawarra	JJA	3.7	1.7	3.3	3.5	1.3	0.38	33%	2.9	0.89	41%	4.0	0.17	0.39	0.60
Newcastle	JJA	4.8	2.1	NA	NA										
Sydney East	SON	6.3	2.6	5.6	5.1	1.0	0.18	17%	3.7	0.66	28%	5.4	0.19	0.46	0.52
Sydney NW	SON	5.8	2.4	7.1	3.7	–2.0	–0.29	–6%	3.3	0.46	13%	4.4	0.17	0.40	0.54
Sydney SW	SON	5.3	2.2	6.5	7.5	–0.4	–0.06	3%	3.5	0.54	10%	7.5	0.18	0.51	0.35
Illawarra	SON	5.7	2.5	6.4	4.9	–0.2	–0.03	6%	3.5	0.55	20%	4.9	0.25	0.52	0.53
Newcastle	SON	6.3	2.3	NA	NA										

Notes: CTM = chemical transport model; DJF = December, January, February; IOA = index of agreement; JJA = June, July, August; MAM = March, April, May; MB = mean bias; MFB = mean fractional bias; ME = mean error; MFE = mean fractional error; NMB = normalised mean bias; NME = normalised mean error; NW = north-west; RMSE = root square mean error; SD = standard deviation; SON = September, October, November; SW = south-west; red = index of agreement (IOA) >0.6 or 0.8 < Skill_V <1.2.

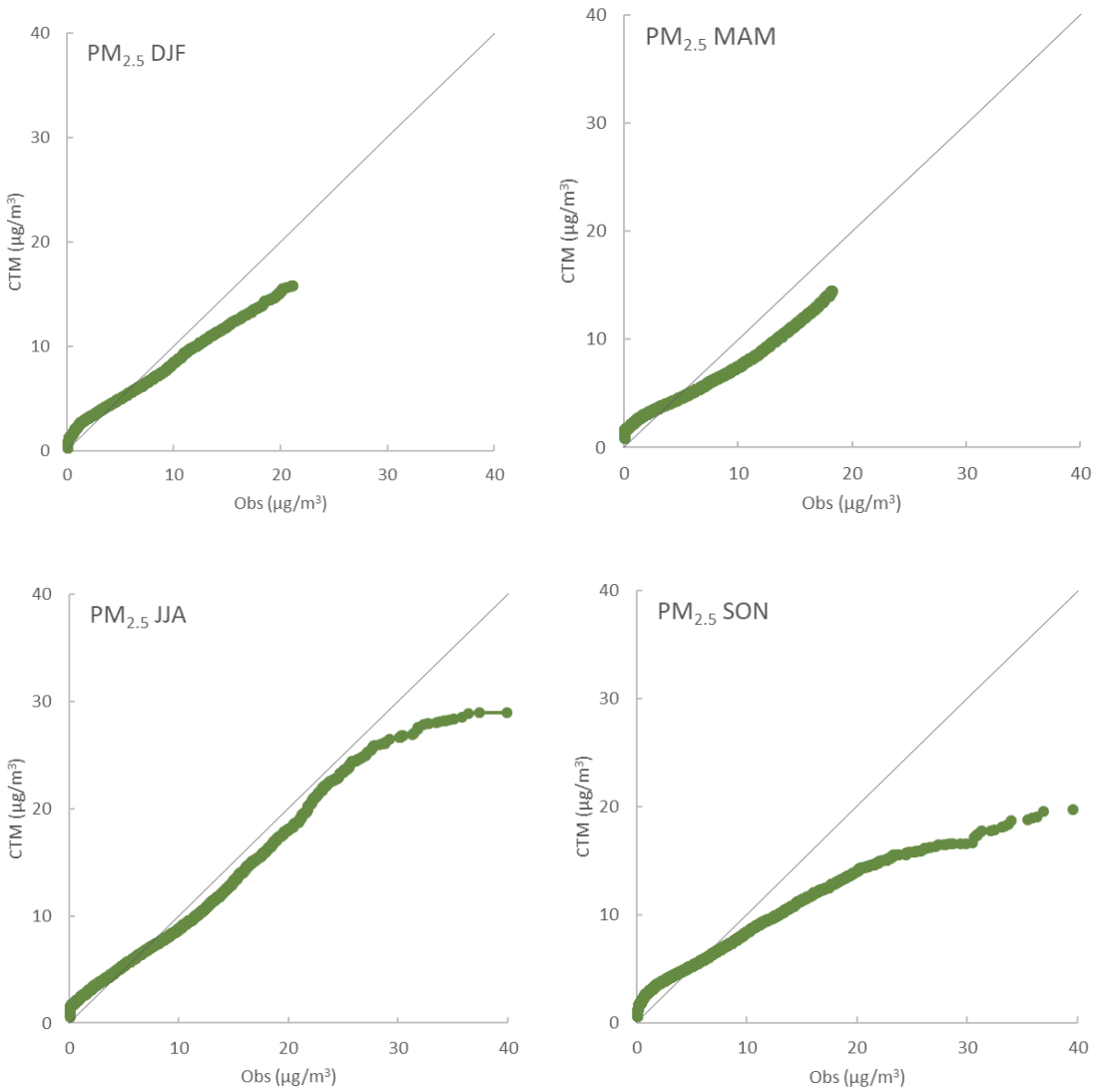
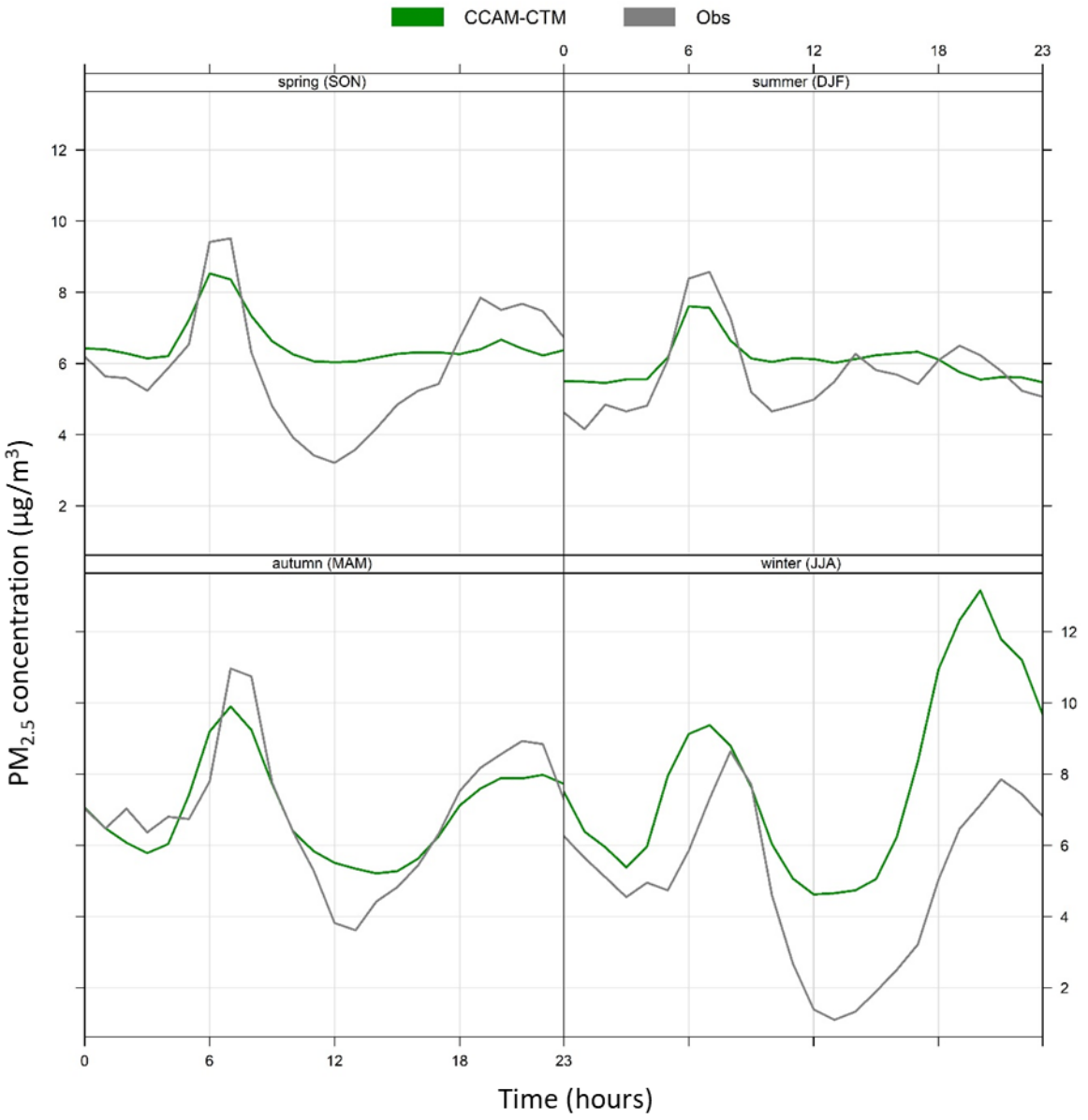
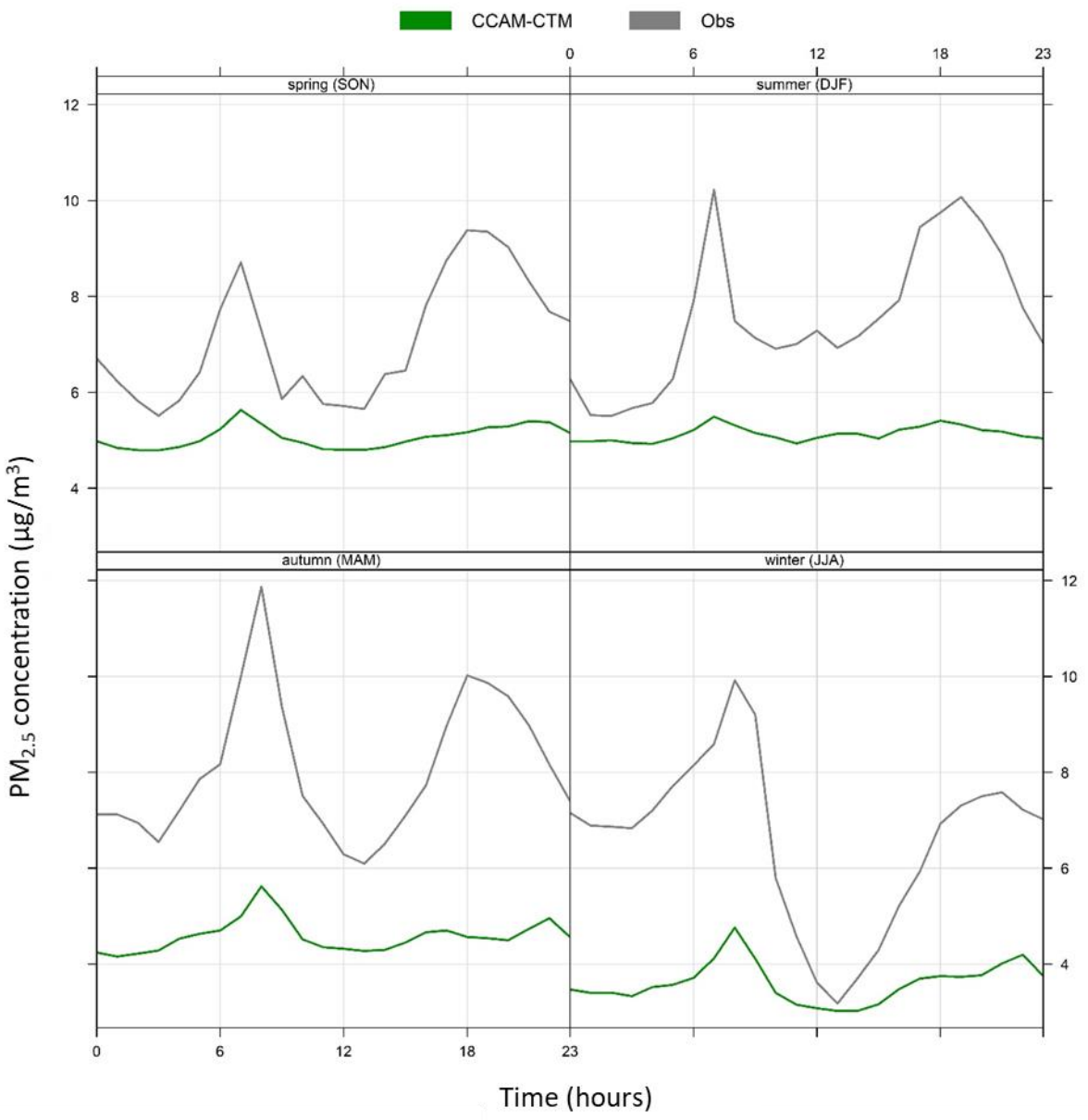


Figure D5 Quantile-quantile plots for predicted (chemical transport model (CTM) and observed (Obs) hourly levels of particles less than 2.5 micrometres in diameter (PM 2.5) concentration during different seasons for all the monitoring stations in the NSW Greater Metropolitan Region; grey line represents 1:1 line. DJF = December, January, February (summer); MAM = March, April, May (autumn); JJA = June, July, August (winter); ppb = parts per billion; SON = September, October, November (spring).

(a)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
PM2.5 concentration (µg/m3)
Time (hours)
0
6
12
18
23
2
4
6
8
10
12

(b)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
PM2.5 concentration (µg/m3)
Time (hours)
0
6
12
18
23
4
6
8
10
12

(c)

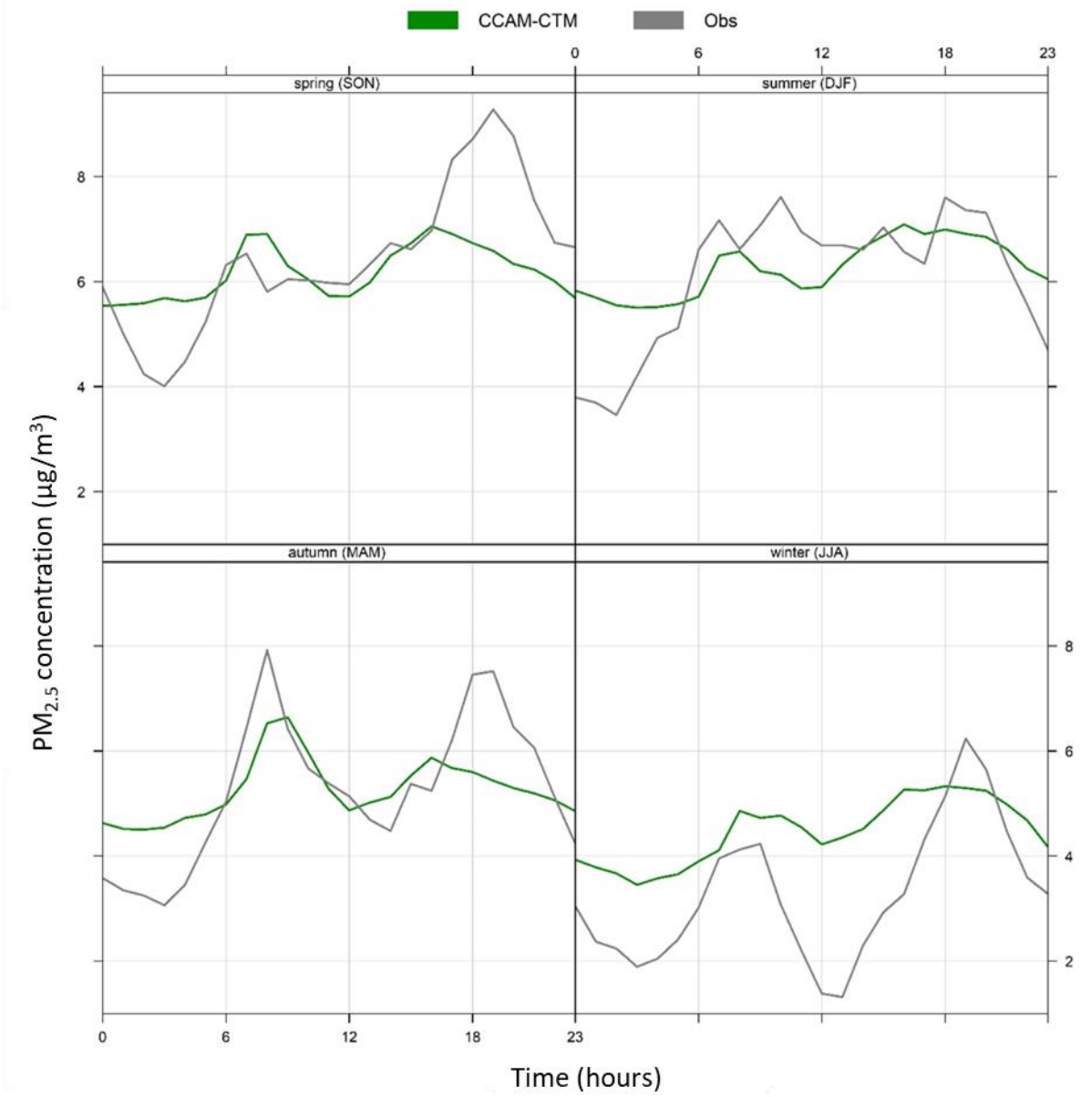


Figure D6 Seasonal diurnal variations for predicted (CCAM–CTM; green) and observed (obs; grey) hourly concentrations (microgram per cubic metre (µg/m3) of particles less than 2.5 micrometres in diameter (PM2.5) at (a) Chullora, (b) Richmond and (c) Wollongong. CCAM–CTM = Conformal Cubic Atmospheric Model–chemical transport model; DJF = December, January, February; JJA – June, July, August; MAM = March, April, May; SON = September, October, November.

Table D4 Quantitative performance statistics for predicted hourly nitrogen dioxide (NO_2) concentration (ppb) against observation in the sub-regions across the NSW Greater Metropolitan Region during different seasons

NO_2	Months	Mean CTM	SD CTM	Mean Obs	SD Obs	MB	NMB	MFB	ME	NME	MFE	RMSE	r	IOA	SKILLv
Sydney East	DJF	5.9	4.0	6.4	4.7	–0.5	–0.05	5%	3.1	0.5	48%	4.4	0.53	0.58	0.85
Sydney NW	DJF	4.1	2.8	5.1	3.9	–1.1	–0.20	–6%	2.7	0.5	60%	3.9	0.40	0.54	0.72
Sydney SW	DJF	3.6	3.0	4.6	4.0	–1.1	–0.02	5%	2.5	0.9	78%	3.7	0.55	0.58	0.77
Illawarra	DJF	3.2	2.6	4.4	4.0	–1.2	–0.22	–6%	2.7	0.6	64%	4.0	0.49	0.56	0.70
Newcastle	DJF	1.2	1.5	4.1	3.6	–2.9	–0.70	–83%	3.1	0.8	100%	4.2	0.51	0.46	0.42
Sydney East	MAM	9.9	6.7	11.6	7.1	–1.3	–0.11	–8%	5.1	0.45	40%	6.8	0.55	0.56	0.96
Sydney NW	MAM	6.4	4.7	7.7	5.4	–1.0	–0.10	–5%	4.2	0.58	56%	5.7	0.42	0.50	0.88
Sydney SW	MAM	5.1	4.5	7.3	5.4	–2.0	–0.27	–31%	3.8	0.59	66%	5.4	0.57	0.53	0.87
Illawarra	MAM	4.2	3.9	6.5	5.2	–2.2	–0.32	–38%	4.0	0.63	77%	5.6	0.48	0.51	0.77
Newcastle	MAM	2.2	2.5	8.0	6.3	–5.8	–0.73	–108%	5.9	0.74	116%	8.0	0.51	0.44	0.40
Sydney East	JJA	10.1	6.8	13.8	7.7	–3.6	–0.25	–29%	6.9	0.50	47%	8.8	0.42	0.47	0.88
Sydney NW	JJA	5.7	4.7	7.8	5.8	–1.9	–0.23	–1%	4.7	0.64	67%	6.5	0.35	0.48	0.82
Sydney SW	JJA	4.1	3.7	7.3	5.6	–3.2	–0.48	–59%	4.4	0.65	88%	6.1	0.47	0.49	0.68
Illawarra	JJA	3.3	3.1	6.1	5.4	–2.7	–0.45	–36%	4.0	0.68	70%	5.8	0.41	0.55	0.60
Newcastle	JJA	3.5	3.0	10.3	7.1	–6.9	–0.67	–75%	7.2	0.69	84%	9.5	0.39	0.41	0.42
Sydney East	SON	6.9	4.7	9.4	7.3	–2.6	–0.26	–9%	4.6	0.50	58%	6.7	0.56	0.61	0.64
Sydney NW	SON	4.4	3.3	6.1	5.0	–1.9	–0.30	–13%	3.4	0.57	60%	5.1	0.44	0.55	0.66
Illawarra	SON	3.4	2.9	7.1	6.2	–2.8	–0.36	–20%	4.3	0.61	62%	6.6	0.39	0.56	0.52
Newcastle	SON	1.8	2.0	6.7	5.9	–5.0	–0.75	–94%	5.2	0.77	109%	7.1	0.61	0.46	0.35
Sydney SW	SON	4.0	3.5	7.0	6.0	–3.2	–0.47	–53%	4.0	0.61	80%	6.0	0.55	0.56	0.61

Notes: CTM = chemical transport model; DJF = December, January, February; IOA = index of agreement; JJA = June, July, August; MAM = March, April, May; MB = mean bias; MFB = mean fractional bias; ME = mean error; MFE = mean fractional error; NMB = normalised mean bias; NME = normalised mean error; NW = north-west; RMSE = root square mean error; SD = standard deviation; SON = September, October, November; SW = south-west red-coloured cells = index of agreement (IOA) > 0.6 or 0.8 < Skill_V < 1.2

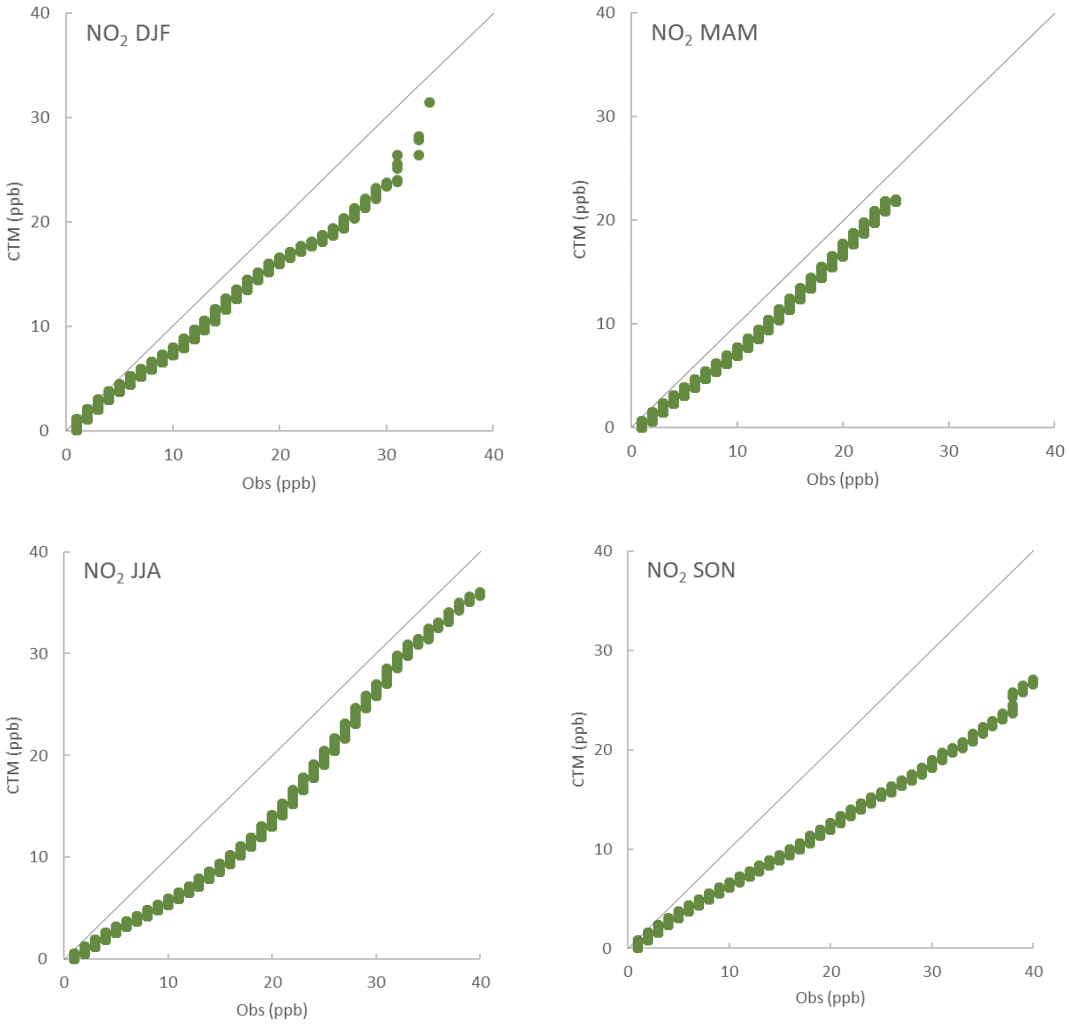
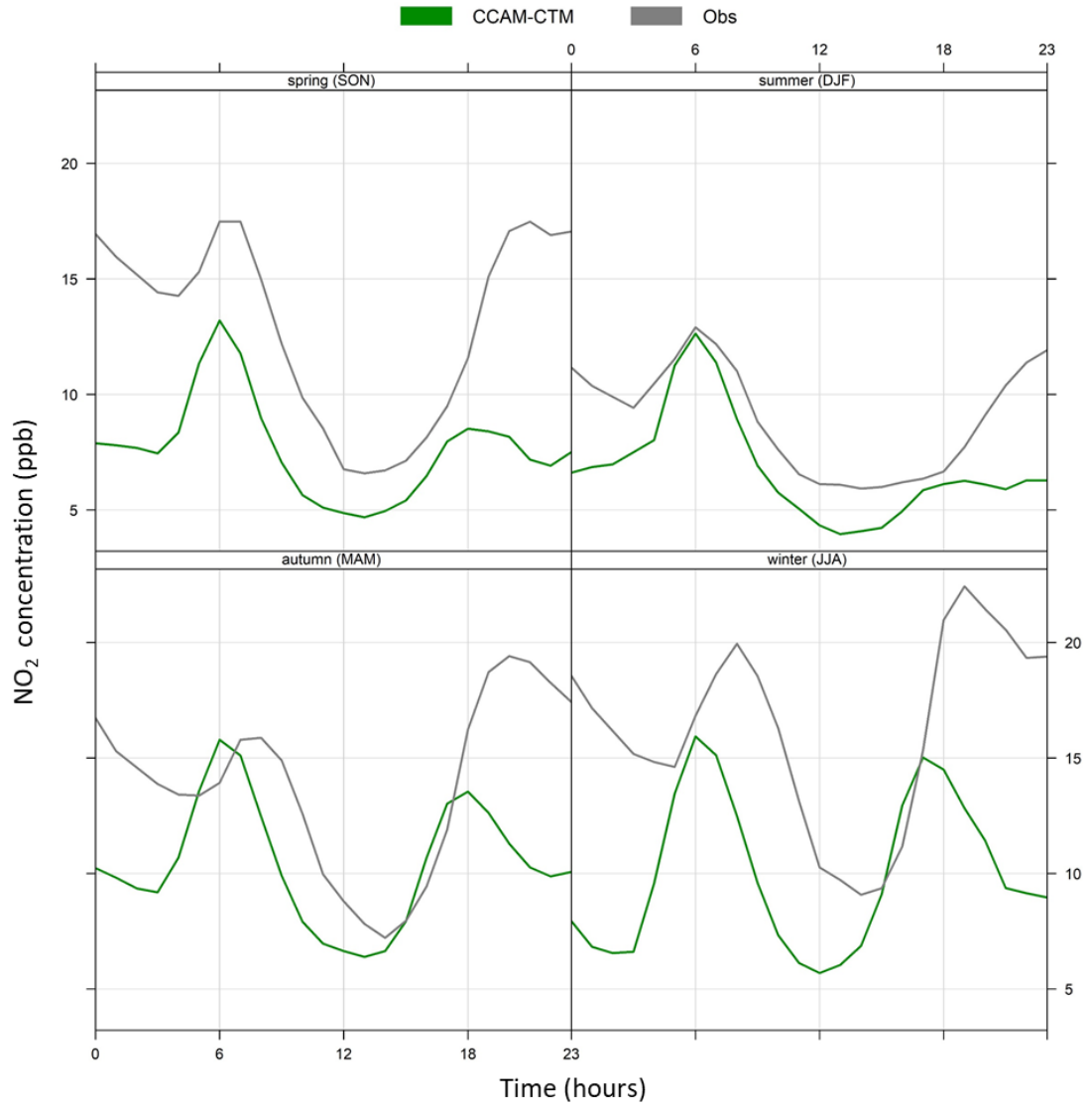
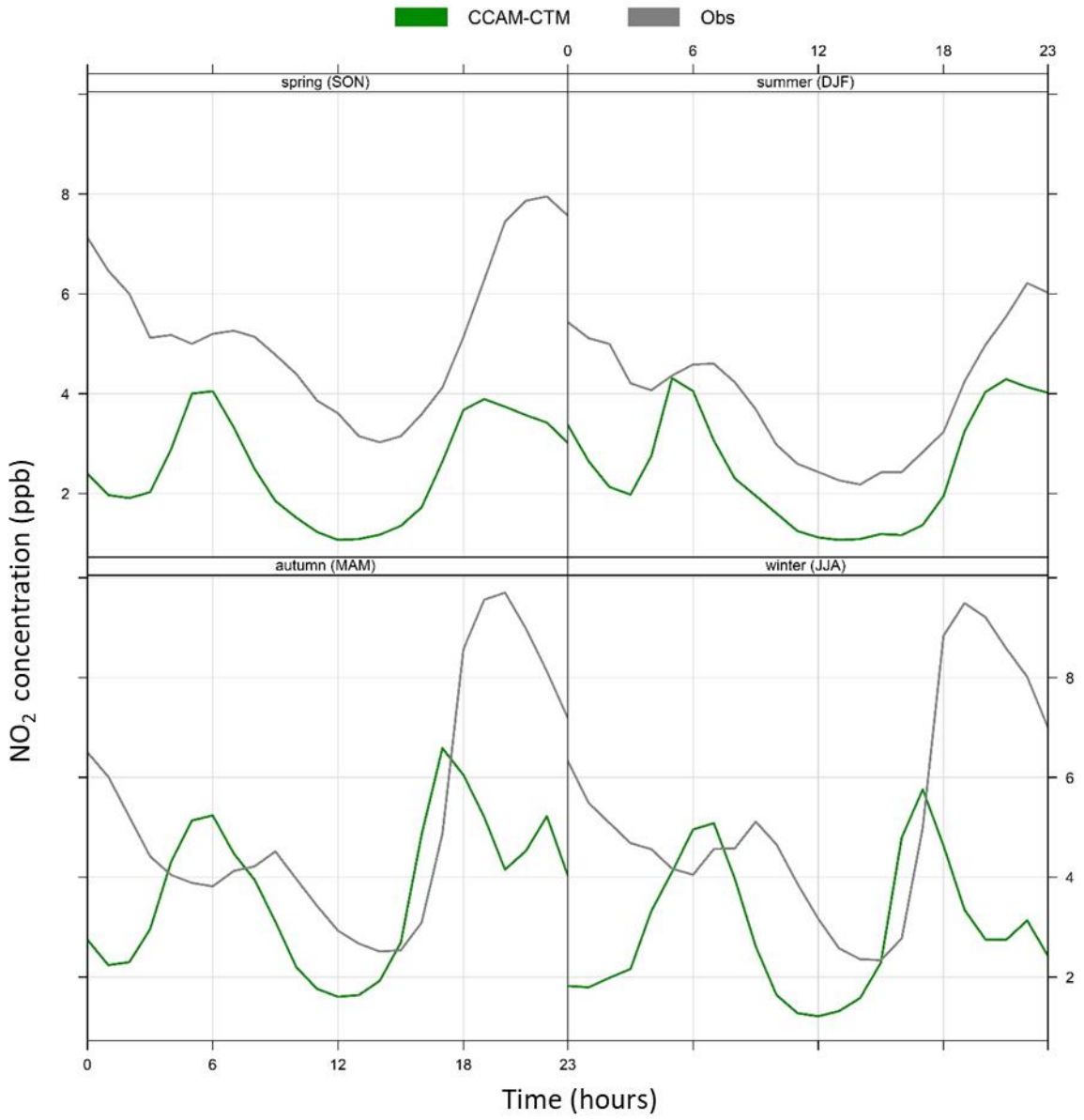


Figure D7 Quantile-quantile plots for predicted (chemical transport model (CTM)) and observed (Obs) hourly nitrogen dioxide (NO_2) concentrations during different seasons for all the monitoring stations in the NSW Greater Metropolitan Region; grey line represents 1:1 line. DJF = December, January, February (summer); MAM = March, April, May (autumn); JJA = June, July, August (winter); ppb = parts per billion; SON = September, October, November (spring).

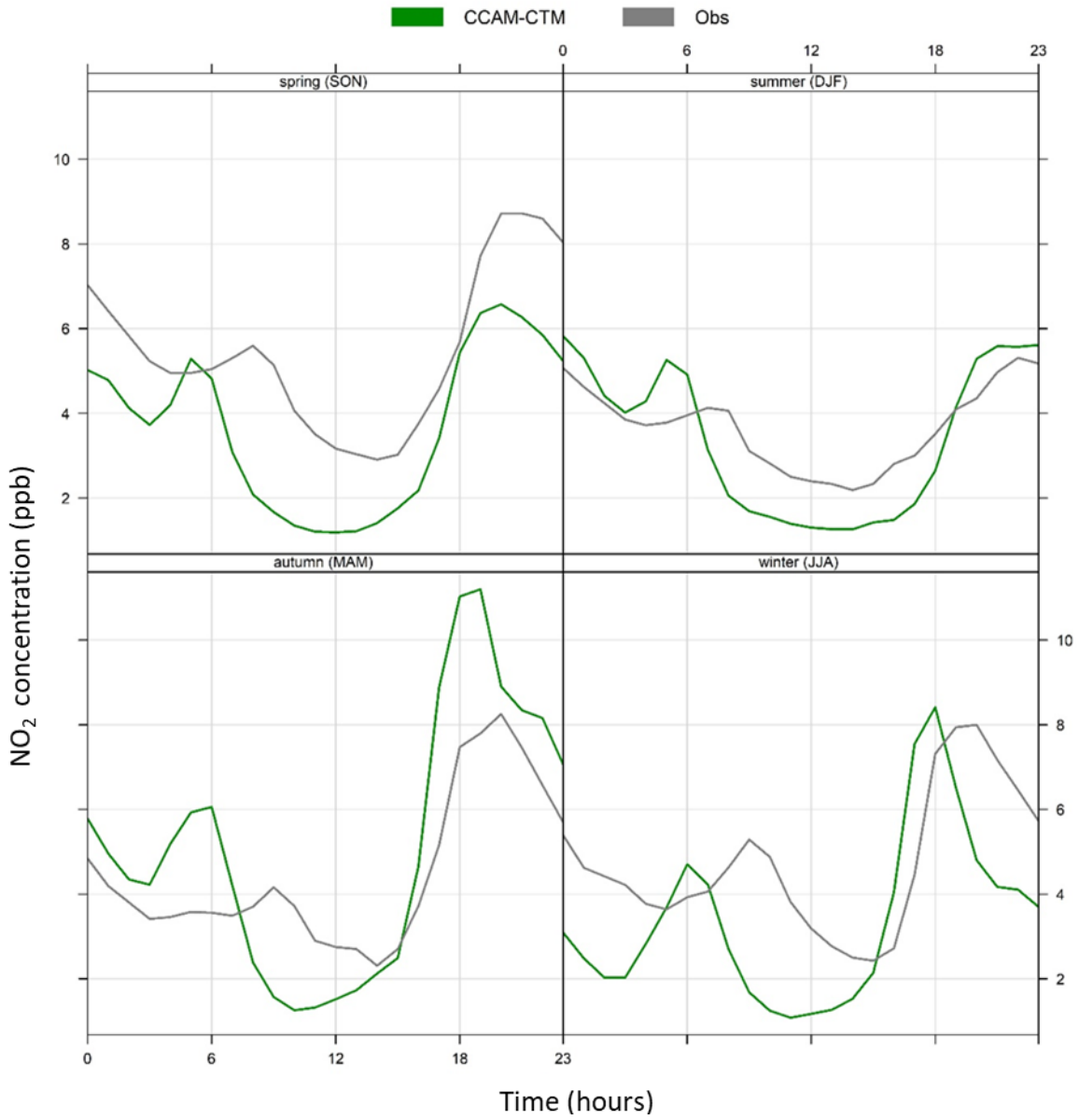
(a)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
NO_2 concentration (ppb)
Time (hours)
0
6
12
18
23
5
10
15
20

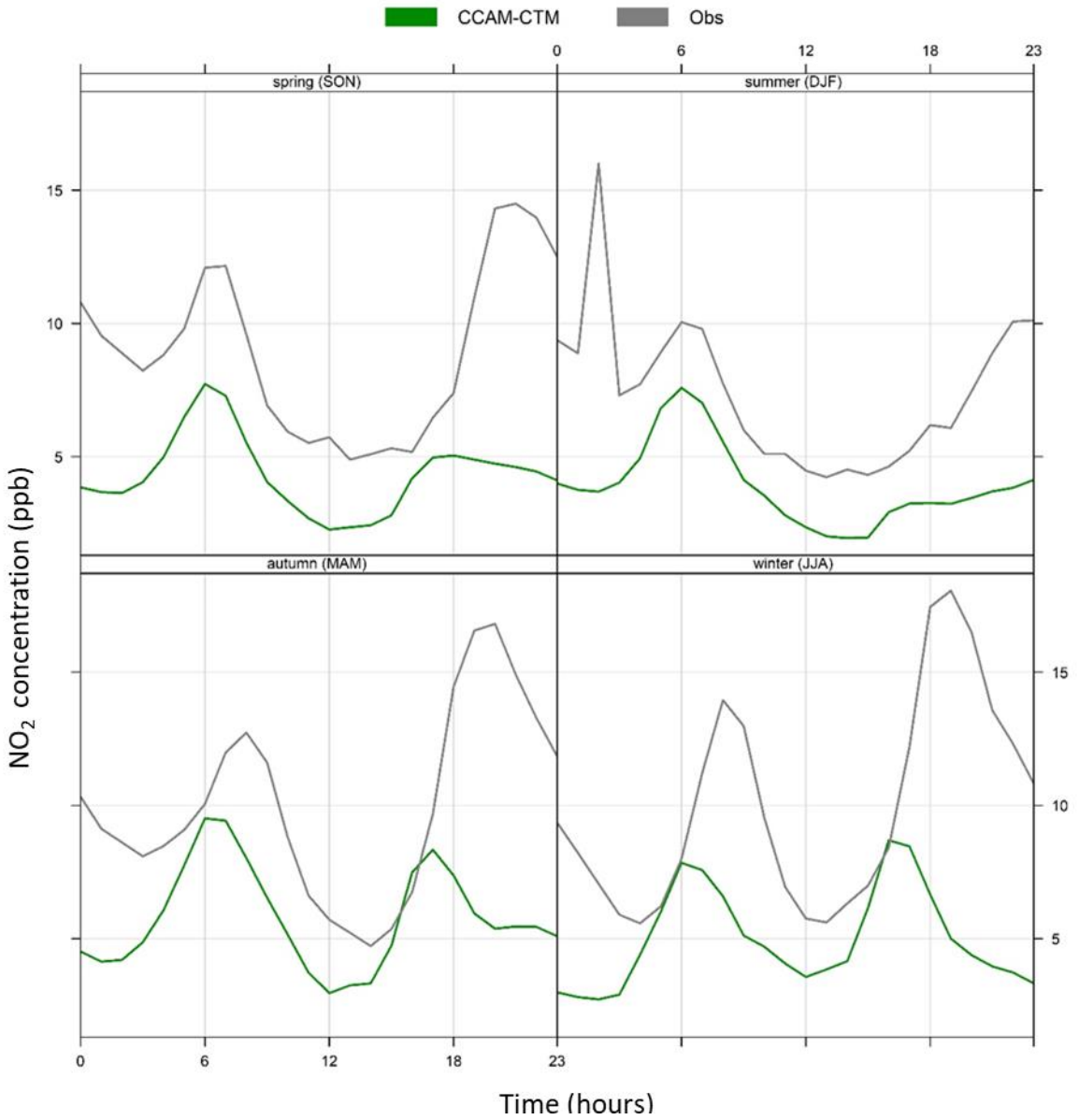
(b)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
NO_2 concentration (ppb)
Time (hours)
0
6
12
18
23
2
4
6
8

(c)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
NO_2 concentration (ppb)
Time (hours)
0
6
12
18
23
2
4
6
8
10

(d)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
NO_2 concentration (ppb)
Time (hours)
0
6
12
18
23
5
10
15

(e)

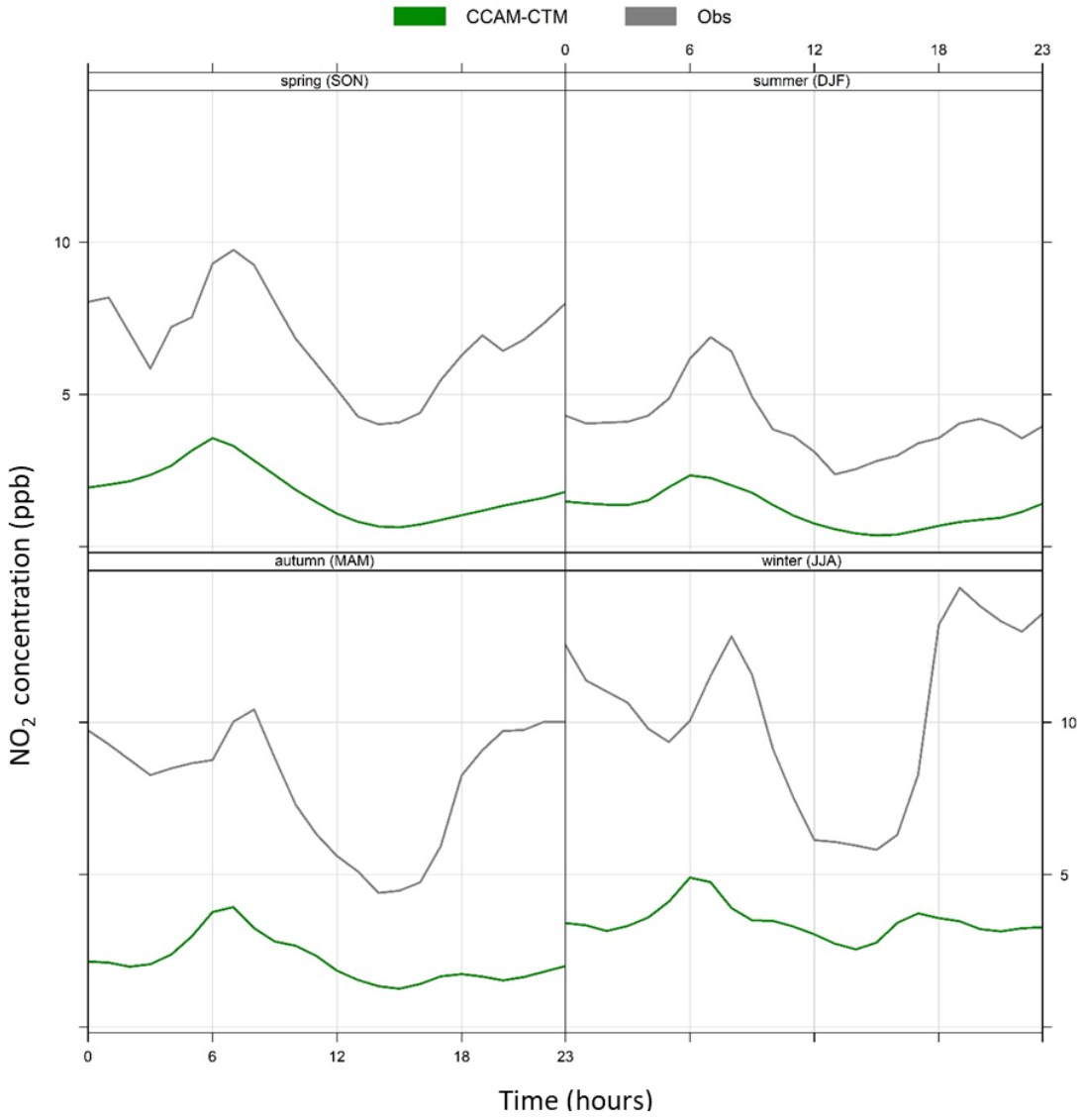


Figure D8 Seasonal diurnal variations for predicted (CCAM–CTM; green) and observed (obs; grey) hourly nitrogen dioxide (NO_2) concentration in parts per billion (ppb) at (a) Chullora, (b) Richmond, (c) Bringelly, (d) Wollongong and (e) Newcastle. CCAM–CTM = Conformal Cubic Atmospheric Model–chemical transport model; DJF = December, January, February; JJA = June, July, August; MAM = March, April, May; SON = September, October, November.

Table 5 Quantitative performance statistics for predicted hourly sulfur dioxide (SO_2) concentrations (parts per billion) against observation in the sub-regions across the NSW Greater Metropolitan Region during different seasons

SO_2	Months	Mean CTM	SD CTM	Mean Obs	SD Obs	MB	NMB	MFB	ME	NME	MFE	RMSE	r	IOA	SKILLv
Sydney East	DJF	0.69	0.94	0.40	1.40	0.31	0.79	62%	0.84	2.10	96%	1.34	0.44	0.50	0.67
Sydney NW	DJF			NA	NA										
Sydney SW	DJF	0.44	0.60	0.91	0.99	–0.47	–0.46	–70%	0.91	1.05	89%	1.18	0.21	0.25	0.61
Illawarra	DJF	1.06	1.41	0.92	2.45	0.20	0.69	–34%	1.78	2.37	41%	2.62	0.34	0.45	0.60
Newcastle	DJF	0.68	1.07	0.50	2.58	0.21	0.42	51%	1.30	2.60	55%	2.41	0.37	0.54	0.41
Sydney East	MAM	0.86	1.00	0.60	1.72	0.29	0.46	8%	1.16	1.91	55%	1.76	0.29	0.49	0.58
Sydney NW	MAM	0.55	0.69	0.32	1.04	0.22	0.92	72%	0.71	2.43	104%	1.12	0.25	0.42	0.73
Sydney SW	MAM	0.42	0.60	0.17	1.12	0.27	8.10	72%	0.75	15.61	114%	1.17	0.25	0.41	0.54
Illawarra	MAM	1.07	1.54	0.52	2.10	0.52	1.05	38%	1.29	2.53	73%	2.40	0.33	0.44	0.77
Newcastle	MAM	1.10	1.53	1.93	2.96	–0.81	–0.42	20%	1.51	0.79	130%	2.77	0.45	0.59	0.52
Sydney East	JJA	0.55	0.99	0.83	1.11	–0.33	–0.40	44%	0.78	0.94	144%	1.29	0.25	0.53	0.82
Sydney NW	JJA	0.43	0.65	0.21	0.77	0.21	1.37	79%	0.59	3.07	112%	0.95	0.16	0.29	1.00
Sydney SW	JJA	0.22	0.46	0.01	0.93	0.21	14.38	9%	0.64	44.52	61%	0.95	0.27	0.46	0.49
Illawarra	JJA	0.24	0.75	0.46	0.82	–0.22	–0.47	74%	0.47	1.02	172%	0.97	0.29	0.60	0.91
Newcastle	JJA	1.66	1.86	1.96	2.70	–0.33	–0.17	11%	1.77	0.91	104%	2.76	0.30	0.47	0.69
Sydney East	SON	0.68	0.92	0.97	1.53	–0.30	–0.31	25%	0.81	0.84	62%	1.45	0.42	0.58	0.60
Sydney NW	SON	0.53	0.70	0.81	1.51	–0.26	–0.29	34%	0.80	1.02	72%	1.50	0.32	0.58	0.47
Sydney SW	SON	0.44	0.61	1.28	1.16	–0.84	–0.66	–53%	0.99	0.77	136%	1.36	0.42	0.39	0.53
Illawarra	SON	0.56	1.06	1.46	3.19	–0.89	–0.61	–18%	1.79	1.23	107%	2.98	0.47	0.58	0.33
Newcastle	SON	1.04	1.38	0.28	2.96	0.77	2.80	–96%	2.04	7.45	92%	2.80	0.41	0.47	0.47

Notes: CTM = chemical transport model; DJF = December, January, February; IOA = index of agreement; JJA = June, July, August; MAM = March, April, May; MB = mean bias; MFB = mean fractional bias; ME = mean error; MFE = mean fractional error; NMB = normalised mean bias; NME = normalised mean error; NW = north-west; RMSE = root square mean error; SD = standard deviation; red = index of agreement (IOA) >0.6 or 0.8< Skill_V <1.2.

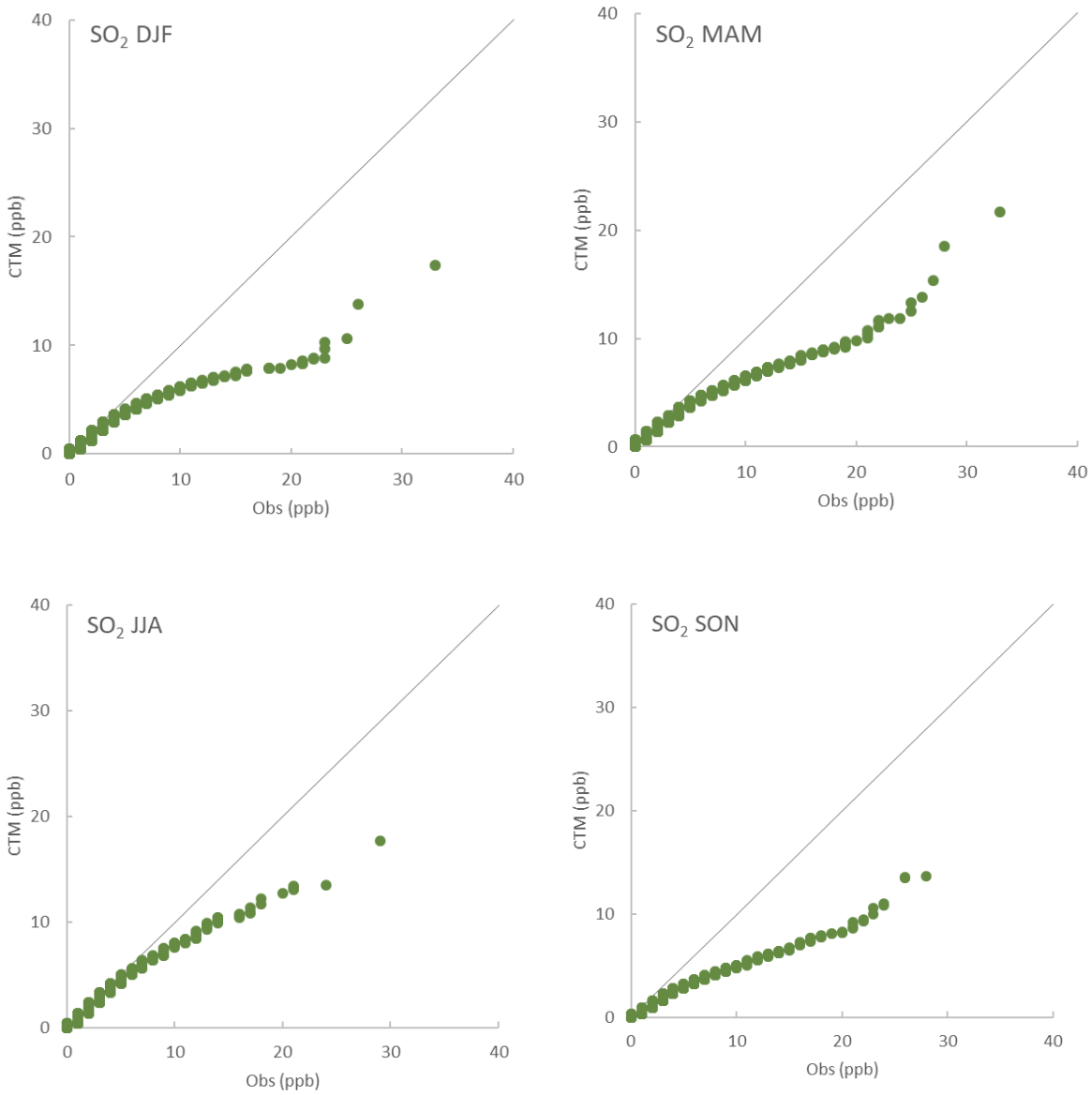
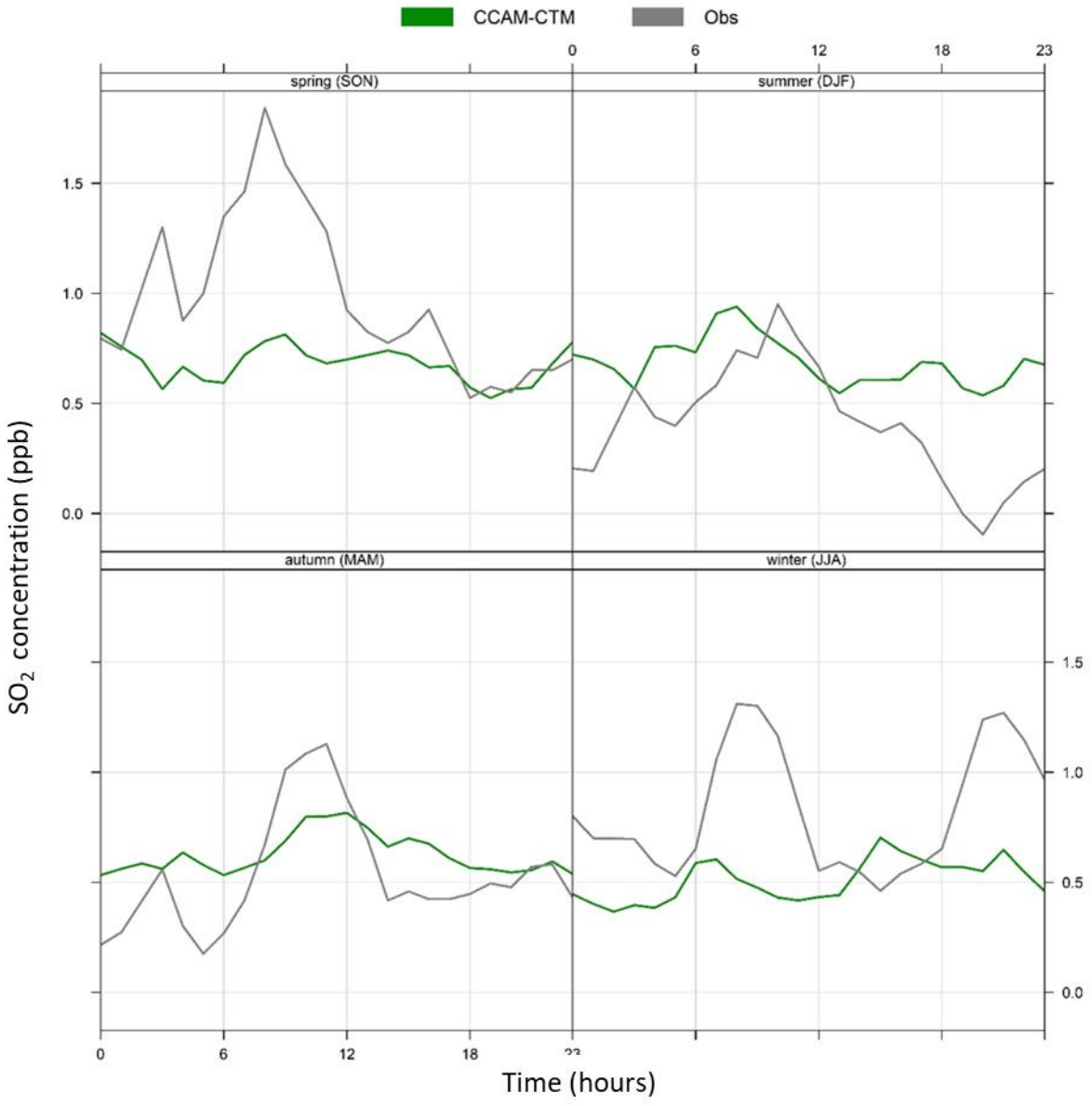
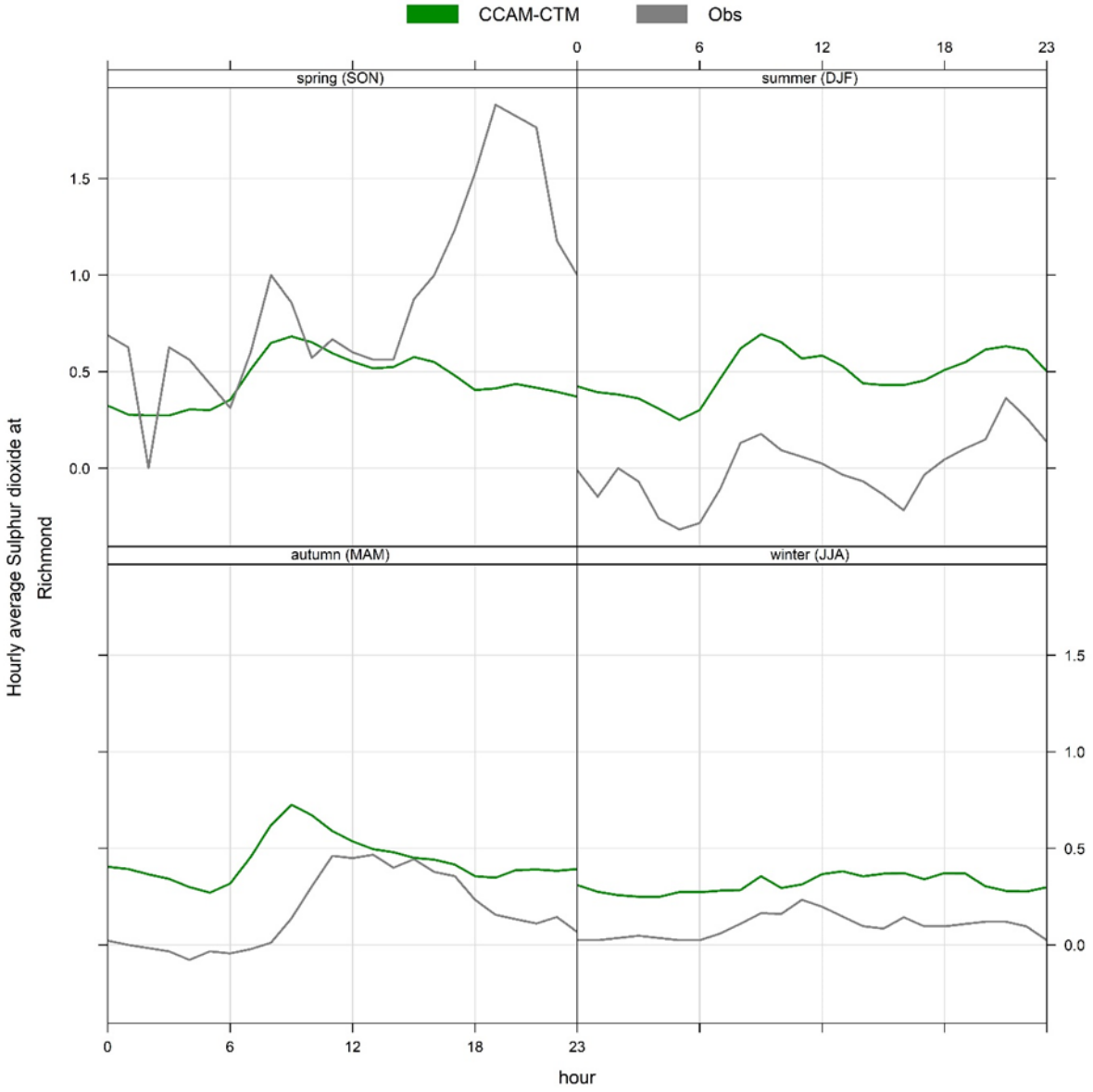


Figure D9 Quantile-quantile plots for predicted (chemical transport model (CTM)) and observed (Obs) hourly sulfur dioxide (SO_2) concentration during different seasons for all the monitoring stations in the NSW Greater Metropolitan Region; grey line represents 1:1 line. DJF = December, January, February (summer); MAM = March, April, May (autumn); JJA = June, July, August (winter); ppb = parts per billion; SON = September, October, November (spring).

(a)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
SO_2 concentration (ppb)
Time (hours)
0
6
12
18
23
0.0
0.5
1.0
1.5

(b)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
Hourly average Sulphur dioxide at Richmond
hour
0
6
12
18
23
0.0
0.5
1.0
1.5

(c)

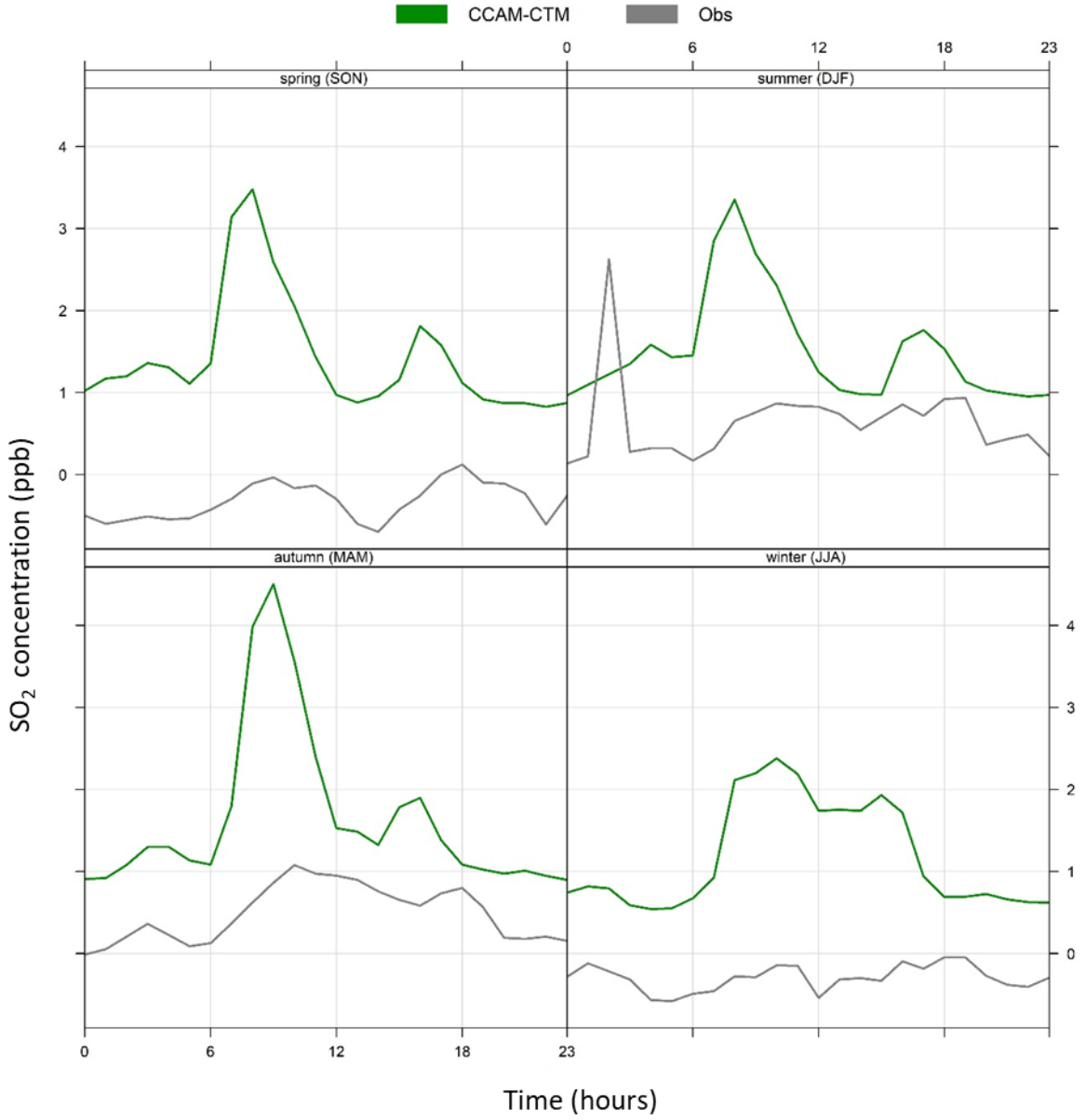


Figure D10 Seasonal diurnal variations for predicted (CCAM–CTM; green) and observed (obs; grey) hourly sulfur dioxide (SO_2) concentration in parts per billion (ppb) at (a) Chullora, (b) Richmond and (c) Wollongong. CCAM–CTM = Conformal Cubic Atmospheric Model–chemical transport model; DJF = December, January, February; JJA – June, July, August; MAM = March, April, May; SON = September, October, November.

Table D6 **Quantitative performance statistics for predicted hourly carbon monoxide (CO) concentration (parts per billion) against observation in the sub-regions across NSW Greater Metropolitan Region during different seasons**

CO	Months	Mean CTM	SD CTM	Mean Obs	SD Obs	MB	NMB	MFB	ME	NME	MFE	RMSE	r	IOA	SKILLv
Sydney East	DJF	98.1	59.3	161.3	131.5	–48.2	–0.30	–76%	98.4	0.6	41%	135.6	0.33	0.52	0.50
Sydney NW	DJF	81.6	37.0	57.7	161.1	39.9	0.69	–108%	117.5	2.0	70%	163.5	0.20	0.48	0.29
Sydney SW	DJF	84.9	59.9	127.7	118.9	–32.3	–0.25	–37%	96.2	0.8	39%	126.6	0.22	0.45	0.52
Illawarra	DJF	193.0	254.9	118.8	185.9	115.3	0.97	129%	217.7	1.8	181%	345.4	0.22	0.10	1.60
Newcastle	DJF	56.3	17.1	330.7	130.0	-274.7	–0.83	–117%	274.7	0.8	117%	303.5	0.13	0.15	0.13
Sydney East	MAM	162.0	142.9	238.5	300.2	–49.3	–0.18	105%	190.9	0.83	165%	293.6	0.35	0.56	0.51
Sydney NW	MAM	107.8	62.2	186.3	314.2	–41.7	–0.22	74%	197.9	1.06	126%	292.7	0.40	0.57	0.28
Sydney SW	MAM	100.3	75.0	264.4	249.6	-139.2	–0.45	–76%	186.3	0.70	35%	281.2	0.29	0.47	0.45
Illawarra	MAM	200.5	295.9	170.2	257.0	93.3	0.55	23%	264.0	1.55	81%	422.2	0.13	0.26	1.37
Newcastle	MAM	62.4	23.1	408.9	271.3	-346.5	–0.85	–128%	346.5	0.85	128%	435.0	0.39	0.04	0.09
Sydney East	JJA	177.1	141.9	274.0	318.4	–75.0	–0.25	–70%	209.4	0.80	80%	323.5	0.30	0.54	0.48
Sydney NW	JJA	101.5	63.8	260.9	356.2	-119.3	–0.46	130%	248.3	0.95	221%	360.2	0.30	0.55	0.27
Sydney SW	JJA	85.6	59.4	261.4	313.1	-144.0	–0.30	97%	219.9	1.01	195%	345.6	0.28	0.51	0.33
Illawarra	JJA	134.8	195.0	92.5	249.6	129.7	1.40	–156%	256.0	2.77	119%	378.2	0.12	0.23	1.12
Newcastle	JJA	66.6	24.2	307.3	294.7	-240.7	–0.78	–102%	243.6	0.79	96%	373.1	0.44	0.35	0.08
Sydney East	SON	114.5	78.3	183.6	183.3	–54.0	–0.29	91%	137.4	0.74	173%	195.0	0.19	0.49	0.48
Sydney NW	SON	87.3	40.5	116.9	192.4	–9.4	–0.08	–143%	119.7	1.02	192%	181.3	0.34	0.54	0.27
Sydney SW	SON	85.5	53.8	121.6	181.4	–20.0	0.13	–97%	128.2	1.36	113%	187.4	0.25	0.51	0.40
Illawarra	SON	179.1	252.1	182.3	289.3	33.2	0.18	–50%	265.7	1.46	29%	394.3	0.12	0.36	1.03
Newcastle	SON	62.9	20.0	231.1	111.3	-168.1	–0.73	–97%	170.8	0.74	105%	197.4	0.47	0.01	0.18

Notes: CTM = chemical transport model; DJF = December, January, February; IOA = index of agreement; JJA = June, July, August; MAM = March, April, May; MB = mean bias; MFB = mean fractional bias; ME = mean error; MFE = mean fractional error; NMB = normalised mean bias; NME = normalised mean error; NW = north-west; RMSE = root square mean error; SD = standard deviation; red = index of agreement (IOA) >0.6 or 0.8< Skill_V <1.2.

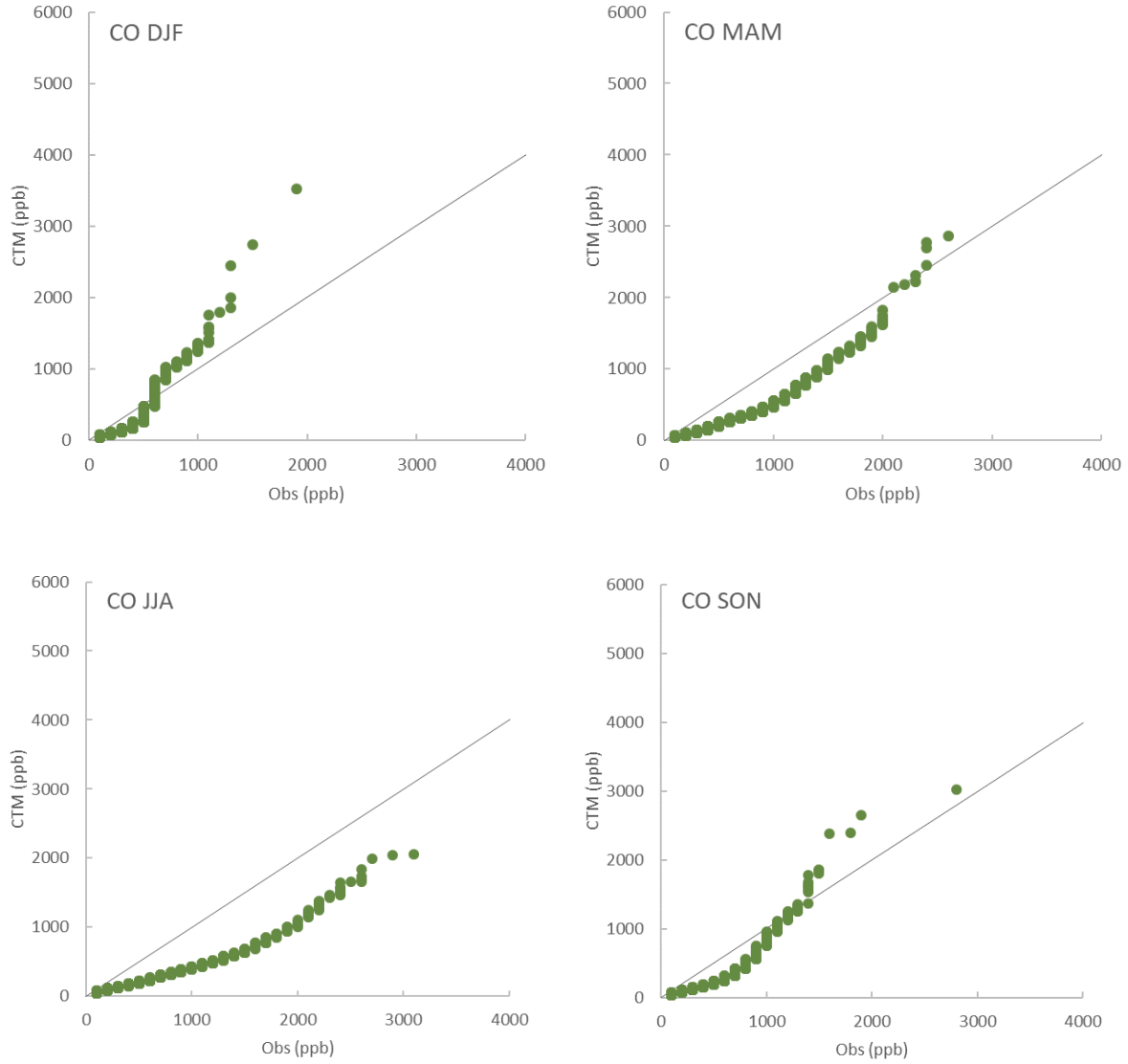
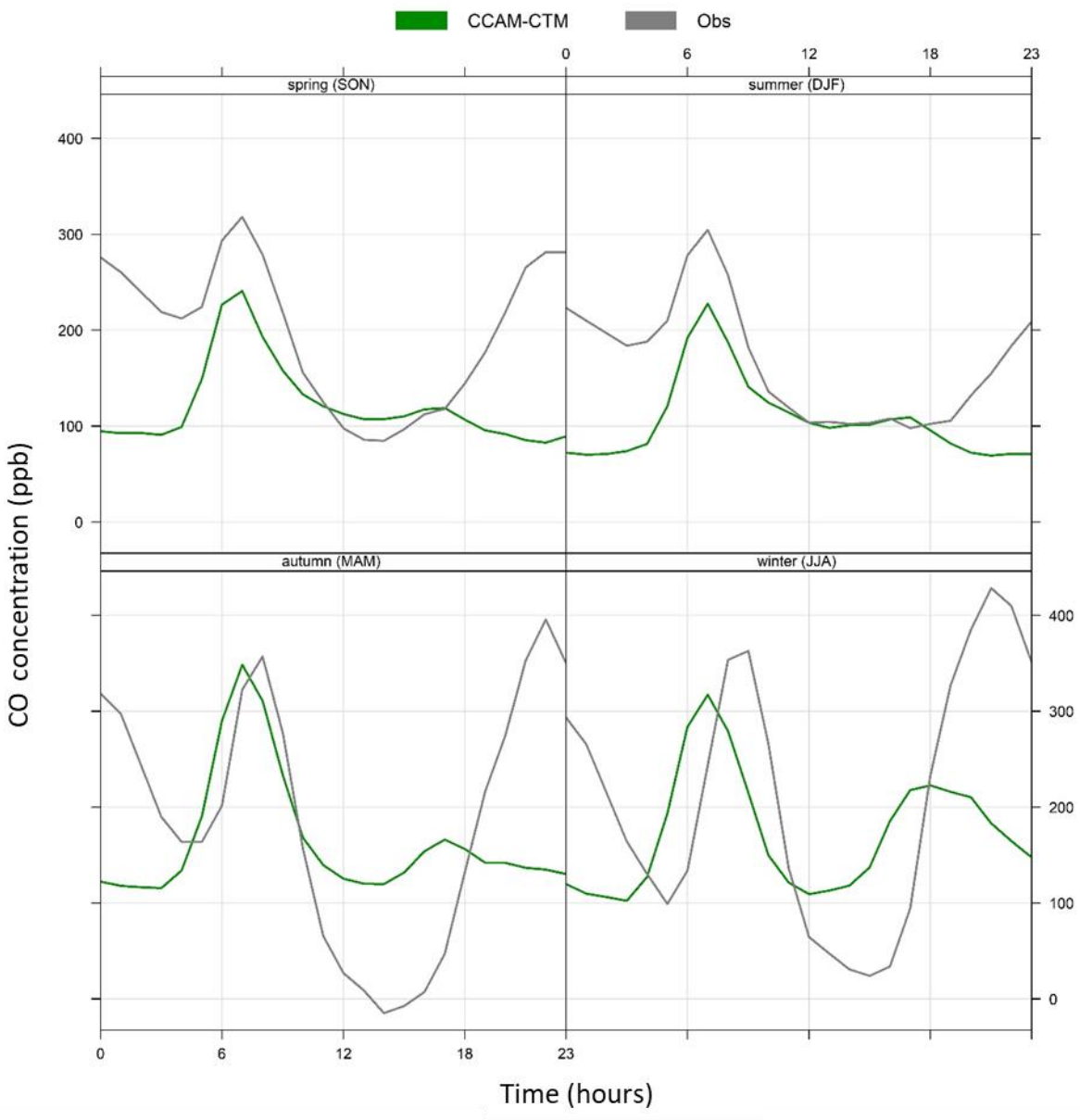


Figure D11 Quantile-quantile plots for predicted (chemical transport model (CTM))and observed (Obs) hourly carbon monoxide (CO) concentration during different seasons for all the monitoring stations in the NSW Greater Metropolitan Region; grey line represents 1:1 line. DJF = December, January, February (summer); MAM = March, April, May (autumn); JJA = June, July, August (winter); ppb = parts per billion; SON = September, October, November (spring).

(a)


CCAM-CTM
Obs
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
CO concentration (ppb)
Time (hours)
0
6
12
18
23
100
200
300
400

(b)

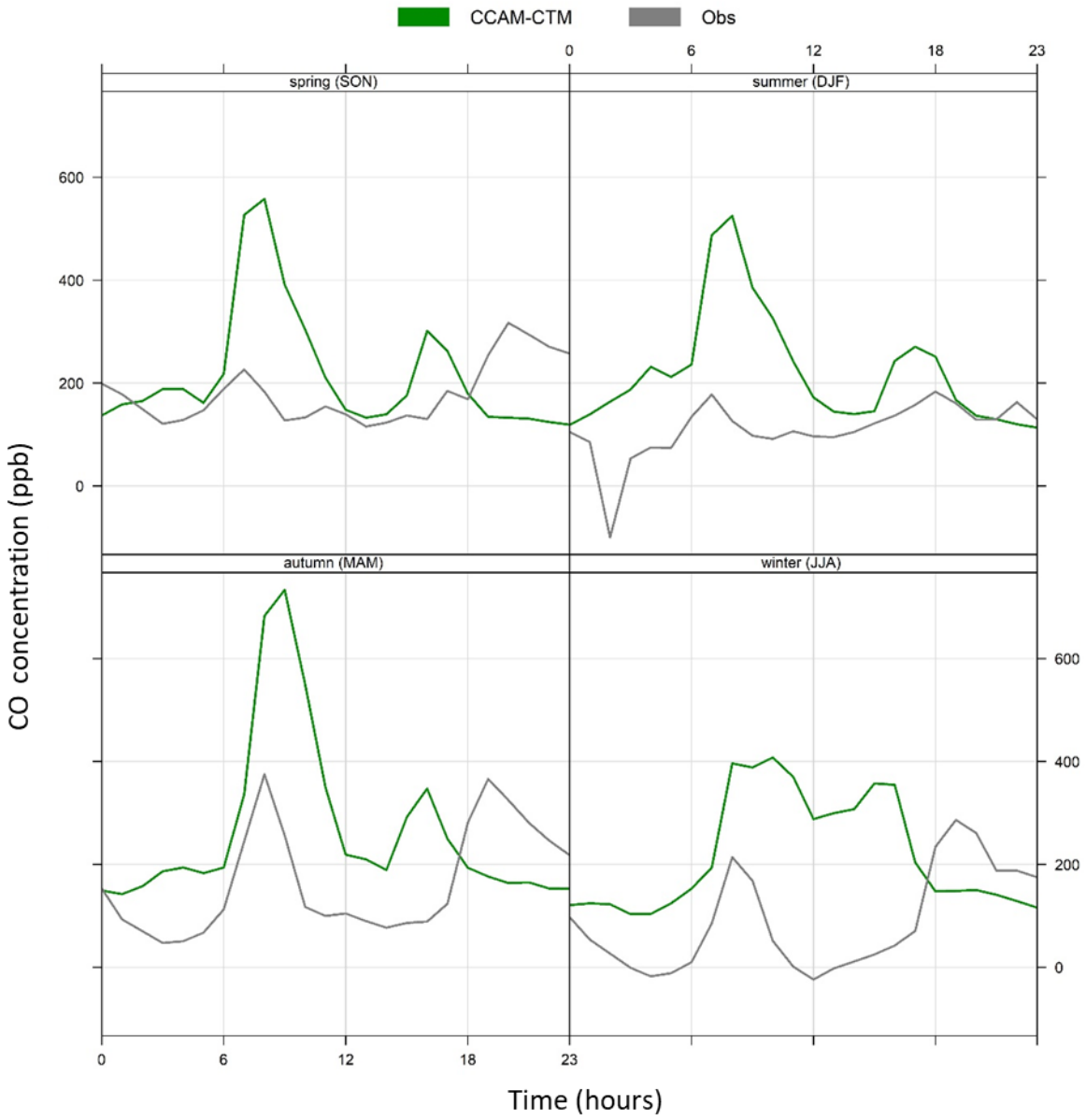


Figure D12 Seasonal diurnal variations for predicted (CCAM–CTM; green) and observed (obs; grey) hourly carbon monoxide (CO) concentration in parts per billion (ppb) at (a) Chullora and (b) Wollongong. CCAM–CTM = Conformal Cubic Atmospheric Model–chemical transport model; DJF = December, January, February; JJA – June, July, August; MAM = March, April, May; SON = September, October, November.