Sydney air quality study

Program report: Stage 2 – Health impact assessment

Department of Planning and Environment

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Summary

The Sydney Air Quality Study is a 2-stage multi-year research program led by the NSW Department of Planning and Environment (the department), in collaboration with the NSW Environment Protection Authority (the EPA), and the NSW Ministry of Health. Results from Stage I of the study (2017–2019) were released in November 2020 (DPIE 2020). In Stage I, we discussed changes in air quality over the past 2 decades. The results from regional airshed modelling undertaken with the *2008 Calendar year air emissions inventory for the Greater Metropolitan Region in NSW* (NSW EPA 2012) provided insights on the contribution of major sources to air pollution and population exposure in the region.

Results from the Stage 2 (2020–2022) are presented in this report. In Stage 2, the regional airshed model was updated with *2013 Calendar year air emissions inventory for the Greater Metropolitan Region in NSW* (NSW EPA 2019) and major emission sources were classified into: power stations, industry, wood heaters, on-road motor vehicles (exhaust), on-road motor vehicles (non-exhaust), non-road diesel and marine, domestic–commercial. To better understand the adverse health effects associated with air pollution, the modelled source-specific $PM_{2.5}$ concentrations were used to undertake $PM_{2.5}$ exposure modelling by calculating population-weighted annual average $PM_{2.5}$ concentrations over the NSW Greater Metropolitan Area (GMA). This was based on the assumption that the resultant $PM_{2.5}$ concentrations modelled due to each anthropogenic emission source groups in 2013 are representative of long-term exposures to such emissions. The burden of mortality and its associated monetary value were further assessed.

Major findings are:

- Natural and human activities account for 52% (3.36 μg/m^3) and 48% (3.07 μg/m^3), respectively, of population-weighted annual average $PM_{2.5}$ concentrations (that is $PM_{2.5}$ exposure) across the NSW GMA.
    - The 48% human-made source contributions to population-weighted annual average $PM_{2.5}$ concentrations ($PM_{2.5}$ exposure) are made up of following: wood heaters (42%), industry (21%), on-road motor vehicles (exhaust) (13%), power stations (7%), domestic–commercial (7%), non-road diesel and marine emissions (6%), and on-road motor vehicles (non-exhaust) (4%).
- Over the NSW GMA, the following anthropogenic sources are ranked from highest to lowest in terms of their impact on mortality and the associated health cost from premature death or years of life lost: wood heater ($2,046 million, in 2021 Australian dollar value), industry ($1,011 million), on-road motor vehicles (exhaust) ($614 million), power stations ($346 million), domestic–commercial ($331 million), non-road diesel and marine ($302 million), and on-road motor vehicles (non-exhaust) ($218 million). The total quantified impacts from all sources are valued around $4,827 million (in 2021 Australian dollar value) in 2013.

NOTE: All dollar values in this report are 2021 Australian dollar values (AUD 2021).

- Investigations on damage costs (expressed as the monetary health cost associated with changes in a unit amount of emissions) show that based on years of life lost, damage costs from on-road motor vehicles (exhaust) emissions are estimated to be approximately $663,000/tonne, followed by domestic–commercial, wood heaters and on-road motor vehicles (non-exhaust) emissions which are estimated to be $260,000–300,000/tonne. Damage costs from the power stations, non-road diesel and marine and industry emission sources are estimated to be $220,000/tonne, $98,000/tonne and $68,000/tonne, respectively.

1. Introduction

The Sydney Air Quality Study is a multi-year research program led by the NSW Department of Planning and Environment (the department), in collaboration with the NSW Environment Protection Authority (the 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. Results from the first phase of the study (2017–2019) were published in the program report in November 2020 (DPIE 2020).

Determining the health risks caused by ambient air pollution is critical to the development of effective risk-management policies and strategies. The health effects of long-term exposures to ambient concentrations of particulate matter less than 2.5 micrometres in diameter ($PM_{2.5}$) have been well established through epidemiological, clinical and toxicological studies, with health effects reported to include premature mortality, cardiovascular and respiratory risks, and risk of cancer death (WHO 2013; USEPA 2009; IARC 2013).

Stage 2 of the Sydney Air Quality Study is to conduct the health impact assessment based on results from exposure modelling, which provides a quantitative estimate of the levels of people's exposure to air pollutants. Mass concentrations of $PM_{2.5}$ are used as indicators to carry out health assessments. The NSW 2013 calendar year air emissions inventory was released after the completion of the first phase of this study (NSW EPA 2019). The integrated modelling system, consisting of the Conformal Cubic Atmospheric Model (CCAM) and the Chemical Transport Model (CTM), was updated to include the latest emission inventory in order to determine the fields of air pollutant concentrations across the modelling domain.

The current activity consists of carrying out a health risk assessment of air pollution events based on estimated pollutant exposure, population and the relationship between ambient concentrations and health outcomes. This assessment will generate information about the magnitude of the current impacts of the existing air pollution. The health end point considered in this assessment is all-cause premature mortality due to long-term exposure to $PM_{2.5,}$ as recommended by World Health Organization (WHO 2013). Several recent studies have found premature mortality to be the most significant health end point in terms of health costs and driving actions to reduce exposure to $PM_{2.5}$ (Broome et al. 2015; Boulter and Kulkarni 2013; USEPA 2011).

In this report, a model performance evaluation is first presented to review and discuss the results from the updated 2013 regional air quality modelling runs. Based on the new 2013 airshed modelling predictions, updated results from exposure modelling, and an assessment of the burden of mortality attributable to long-term exposure to $PM_{2.5}$ from specific emission source groups will be described and discussed.

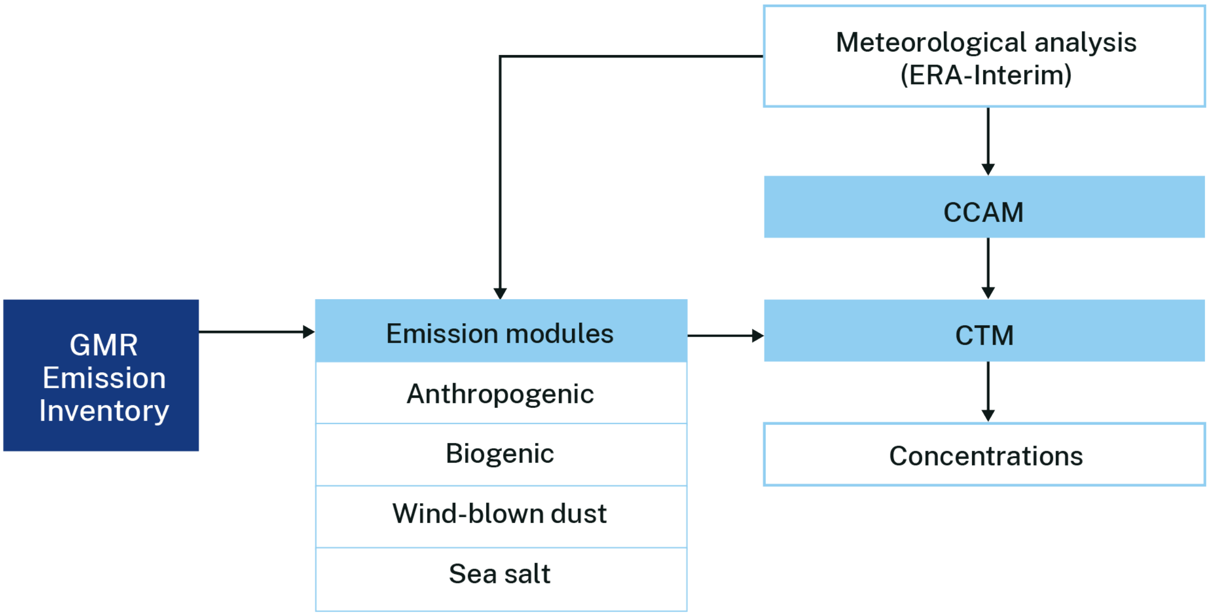
2. Methodology

The methodology of the updated regional airshed modelling, health burden and their monetary value calculations for the health impact assessment are provided in the following section.

2.1 Model descriptions

The coupled Conformal Cubic Atmospheric Model (CCAM) and Chemical Transport Model (CTM) – hereafter referred to as the CCAM–CTM modelling system – was used to generate spatial and temporal concentrations of air pollutants. Meteorological fields including wind velocity, turbulence, temperature, radiation and the water vapour mixing ratios are produced by CCAM. CTM uses the extended carbon bond 5 mechanism (CB05) that consists of 65 gas phase species, 19 aerosol species and 172 reactions. The estimates from the regional air quality model provide the necessary information to calculate the exposure and the associated health impact assessments.

The components of the modelling system (CCAM meteorology module, anthropogenic and natural emission modules, and a CTM) are presented in Figure 1.



ERA-Interim = European Reanalysis Interim; GMR = Great Metropolitan Region.

Figure 1 Schematic diagram of the Conformal Cubic Atmospheric Model (CCAM) and Chemical Transport Model (CTM) – CCAM–CTM modelling system – used in this study

The 3 nested domains used in the modelling are:

- the outermost Australian domain (CTM AUS) at 80 km x 80 km resolution (75 x 65 grid cells)
- the NSW domain (CTM NSW) at 27 km x 27 km (62 x 62 grid cells)
- the innermost Greater Metropolitan Region domain (CTM GMR) at 3 km x 3 km resolution (99 x 99 grid cells).

The European Centre for Medium Range Weather Forecasting (ECMWF) Reanalysis (ERA) Interim product was input into CCAM for the regional meteorological modelling. Model domain configurations are shown in Figure 2.

Figure 2 **Chemical Transport Modelling domains for NSW (CTM NSW) and Greater Metropolitan Region (CTM GMR). The domain of NSW Environment Protection Authority air emissions inventory for the Greater Metropolitan Region (EPA GMR) is also shown.**

2.2 Emission modules

The anthropogenic emissions input into modelling was taken from the EPA *2013 Calendar year air emissions inventory for the Greater Metropolitan Region in NSW* (NSW EPA 2019).

The 2013 NSW EPA air emissions inventory data is segregated into 4 categories comprising 16 major source groups to facilitate regional airshed modelling (Table 1).

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-fired 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.

Table 1 The 4 categories and 16 major source groups segregated from the 2013 NSW EPA 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)

2.3 Emission scenarios

Regional airshed modelling was conducted to predict air pollutant concentrations for the 2013 calendar year based on the emissions scenarios presented in Table 2. These emission scenarios were derived from the 16 major source groups in the 2013 EPA air emissions inventory for the GMR in NSW (Table 1, NSW EPA 2019).

Table 2 The emissions source groups included in each modelled case

Case	Emissions
Base case	All sources – Anthropogenic and natural sources (regional wind-blown dust, biogenic emissions, sea salt)
Natural sources	Regional wind-blown dust, biogenic emissions and sea salt
Biogenic	Biogenic sources
Human-made sources	All anthropogenic sources
Power stations	Coal-power and gas-power generations (groups 11 and 12 in Table 1)
Wood heaters	Residential wood heaters (group 14 in Table 1)
On-road motor vehicles (exhaust)	Petrol exhaust, diesel exhaust, other exhaust, petrol evaporative (groups 1–4 in Table 1)
On-road motor vehicles (non-exhaust)	Non-exhaust particulate matter (group 5 in Table 1)
Non-road diesel and marine	Shipping and commercial boats, industrial vehicles and equipment, aircraft, locomotives, commercial non-road equipment (groups 6–10 in Table 1)
Industry	All point sources except power generation from coal and gas (groups 13 and 15 in Table 1)
Commercial and domestic–commercial	Area source emissions (group 16 in Table 1)

2.4 Population and mortality data

To compute the population-weighted mean $PM_{2.5}$ concentrations and health burden, we used one-year estimates of age- and sex-specific mortality data for the whole NSW Greater Metropolitan Area (GMA, shown in Figure 3). The GMA is as defined in the then Protection of the Environment Operations (Clean Air) Regulation 2010 which included 57 local government areas across the region. The one-year population and death counts were averaged across the 3 years covering 2012 to 2014 to minimise the random variation in annual number of deaths. The sources of these data are listed in Table 3.

The annual number of deaths are averaged across the 3 years to produce mortality rates for 2013.

Table 3 Age-specific and sex-specific data in one-year age groups for the NSW Greater Metropolitan Area covering 2012 to 2014

Data	Data source
Population	NSW Ministry of Health's Secure Analytics for Population Health Research and Intelligence (SAPHaRI) environment from the Australian Bureau of Statistics
Death counts	Australian Coordinating Registry's Cause of Death Unit Record File via the NSW Ministry of Health's SAPHARI environment

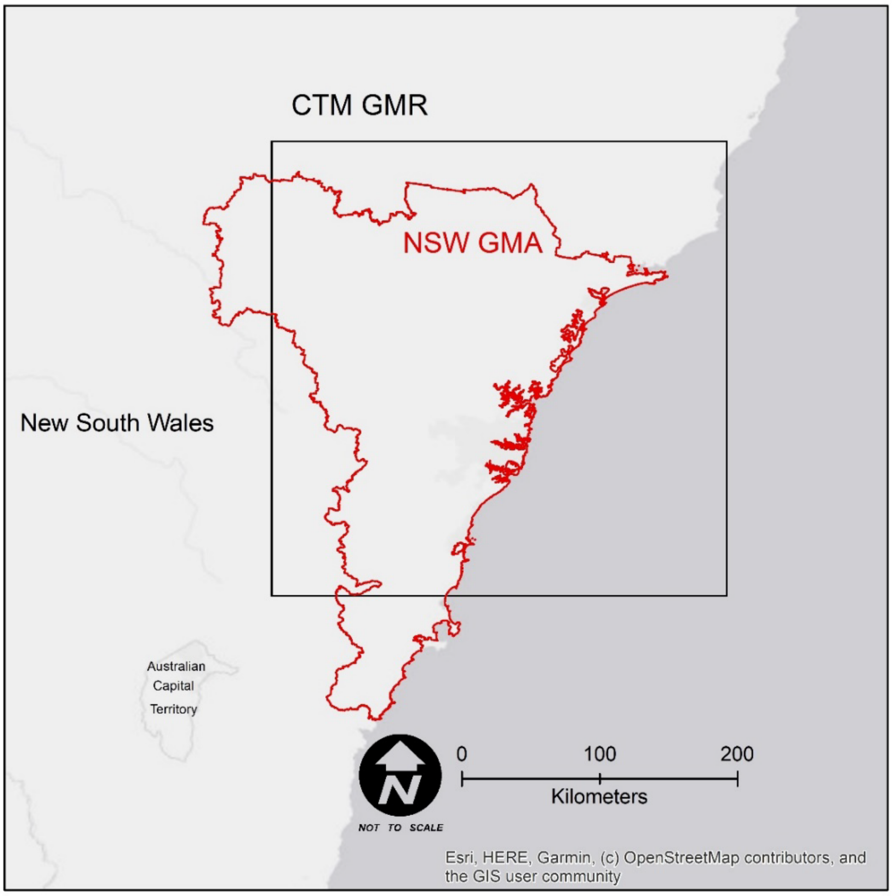


Figure 3 **Chemical Transport Modelling domain for the NSW Greater Metropolitan Region (CTM GMR) and the NSW Greater Metropolitan Area (NSW GMA) domain as defined in the Clean Air Regulation 2010**

The exposure modelling conducted in this study was developed to assess source contributions to population-weighted annual average (pwaa) air pollutant concentrations based on the CCAM–CTM modelling predictions.

Results for the CCAM–CTM modelling system for the 3 x 3 km CTM GMR domain were integrated with the 9 x 9 km CTM NSW domain. Model outputs were then re-gridded to a 1-km resolution to coincide with the Australian Bureau of Statistics' 1-km resolution gridded population data. For each 1-km grid in the NSW GMA (Figure 3), the modelled air pollution concentration was multiplied by the residential population in that 1-km grid. The results were summed across all 1-km grid squares within the NSW GMA and divided by the total population for the NSW GMA to get the NSW GMA population-weighted $PM_{2.5}$ concentration.

Note that the NSW GMA grid points outside of the CTM GMR domain (Figure 3) were taken from the lower resolution CTM NSW domain. This method was compared with computations assuming the areas of the GMA outside of the GMR were empty of population and the difference was negligible.

A population-weighted annual average was calculated as:

$$Population\text{-}weighted\ annual\ average = \frac{\sum(X_i \times P_i)}{P}$$

where X_i is the annual averaged air pollution concentrations in grid square i and P_i is the population in that grid square.

2.5 Health burden calculations

The health burden due to long-term exposures to $PM_{2.5}$ in the NSW GMA from the anthropogenic emission source groups listed in Table 2 were quantified based on the attributable number (AN) of premature deaths, loss of life expectancy (LE) and years of life lost (YLL). The following subsections outline the inputs and steps for computing these 3 metrics and their monetary valuation (as presented in Figure 4).

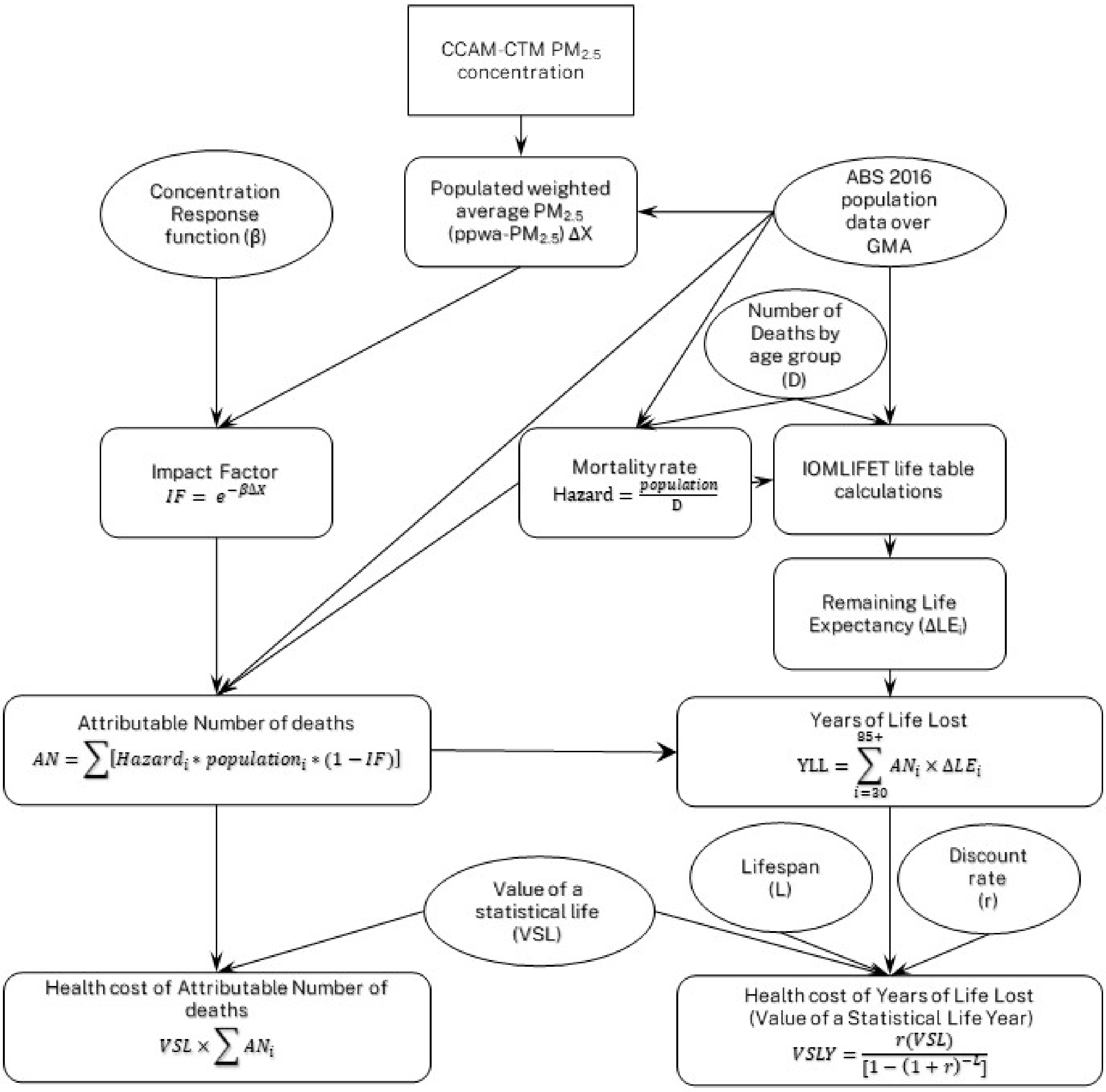


Figure 4 **Schematic of health burden and monetary cost calculations**

2.5.1 IOMLIFET package – spreadsheets for life-table calculations

The health burden estimates were calculated using the IOMLIFET 2013 'life expectancy for all cause death' spreadsheet developed by the Institute of Occupational Medicine (Miller 2013). The World Health Organization's health risk assessment methods for air pollution (WHO 2016) list the IOMLIFET spreadsheets as one of the recommended tools for health impact assessments, and it was adopted for its transparency and adaptability.

The following amendments were made for the NSW health estimates:

- Improved estimates for people aged 85+ by using the Australian Bureau of Statistics' age-specific population data and regressing the logarithms of the hazard rates for the 70–84-year ages following Miller and Hurley (2006).
- To address the inclusion of non-neonatal deaths (that is deaths that occur within the first month) in the NSW health data, the survival probability function for the first year of life (ages 0–1) was changed to:

$$Survival\ probability_i = 1 - \frac{Impacted\ hazard_i}{1 + 0.9 * Impacted\ hazard_i}$$

where age group $i = 0$.

- The survival probability function for the ages one and above were calculated using:

$$Survival\ probability_i = \frac{2 - Impacted\ hazard_i}{2 + Impacted\ hazard_i}$$

2.5.2 Impact factor

Calculation of the health burden is based on an impact factor (IF) which describes the risk associated with each $PM_{2.5}$ exposure scenario. Impact factor is defined as:

$$IF = e^{-\beta \Delta X}$$

where ΔX is the pwaa-$PM_{2.5}$ concentrations for all anthropogenic emission scenarios and β is the concentration–response coefficient.

The β concentration–response coefficient of 0.006 was taken from the meta-analysis of North American and European studies by Hoek et al. (2013) as these regions share similar levels of economic development and mortality to NSW. The value was derived based on the excess all-cause death risk of 6% per 10 µg/m^3 increase in pwaa-$PM_{2.5}$ and a log-linear response curve. We assumed that the concentration–response coefficient relationship is log-linear down to 0 µg/m^3 as there is no threshold for mortality effects. The relative risk associated with a 10 µg/m^3 increase in pwaa-$PM_{2.5}$ recommended by the World Health Organizations' *Health risks of air pollution in Europe project* (WHO 2013) is 1.062 (95% confidence interval of 1.041–1.084).

2.5.3 Mortality rate

The age-specific mortality rate (or hazard) is based on the all-cause deaths per year and population for each age group i.

$$Mortalitiy\ rate_i = \frac{Death\ count_i}{Population_i}$$

Impacted hazard represents how the mortality rate is affected by $PM_{2.5}$ exposure and is calculated by multiplying the mortality rate by the impact factor. For population groups aged under 30 years the impact factor was set to one when computing the impacted hazard to assume no changes to the mortality rate from exposure to $PM_{2.5}$.

2.5.4 Attributable number of deaths

The attributable number (AN) of premature, all-cause deaths is calculated as:

$$Attributable\ number = \sum[mortality\ rate_i * population_i * (1 - IF)]$$

for each age group i over the age of 30 years. The attributable number of deaths over the whole GMA population was computed by summing the age-specific attributable number across the ages 0 to 85+ years.

2.5.5 Loss of life expectancy

The age-specific life-expectancy (LE_i) is computed via the IOMLIFT life tables based on the age-specific mortality rates. The life years remaining per age (change in life expectance ΔLE_i) is calculated based on the survival probability calculated based on the impact factor and mortality rate for each age group.

2.5.6 Years of life lost

Years of life lost (YLL) are a measure of the total amount of time lost by those who died in 2013 as result of exposure to air pollution sources. Years of life lost were calculated as:

$$\text{Years of life lost} = \sum_{i=30}^{85+} AN_i \times \Delta LE_i$$

where AN_i is the attributable number of deaths among people aged i and ΔLE_i is change in life expectancy of people aged i.

2.6 Monetary valuation of health burden

The monetary values of health burden were estimated in AUD 2021 for both the attributable number of deaths and years of life lost metrics.

The monetary value of the burden for the attributable number of deaths was derived using the value of a statistical life (VSL) and the attributable number summed across all population age groups ($\sum AN_i$):

$$Health\ cost\ of\ AN = VSL \times \sum AN_i$$

The monetary value of years of life lost was calculated based on the value of a statistical life year (VSLY) calculated based on value of a statistical life. Jalaludin et al. (2009) recommended that value of a statistical life year be used in place of value of a statistical life in monetising the air pollution effects on premature mortality whenever feasible and practicable to do so.

The value of a statistical life and value of a statistical life year assumptions, sources and values used are shown in Table 4. The method was based on the report on *Air quality and public health benefits of implementing energy efficiency and clean energy measures in NSW* (OEH 2019), where a literature review and sensitivity analysis were carried out for value of a statistical life, value of a statistical life year and discount rates.

2.6.7 Value of a statistical life

The value of statistical life (VSL) is an estimate of the financial value society places on reducing the average number of deaths by one (Jalaludin et al. 2009; OBPR 2014). Value of statistical life is estimated by multiplying the willingness to pay by the estimated rate of avoided deaths in the population (ASCC 2008). Willingness to pay is an estimate of how much an individual is willing to spend in monetary value to avoid health risks.

When considering premature mortality, the health risk to be avoided is death. The values of value of statistical life were estimated using the quarterly consumer price index from the Australian Bureau of Statistics (ABS 2021).

2.6.8 Value of a statistical life year

The value of a statistical life year (VSLY) was calculated using the equation by Aldy and Viscusi (2007):

$$VSLY = \frac{r(VSL)}{[1-(1+r)^{-L}]}$$

where *r* is the discount rate, to account for the health effects occurring over some period, and *L* is the recommended lifespan of 40 years.

Table 4 Assumed values for value of a statistical life, value of a statistical life year, discount rate and the sources they are based on

	Value	Source
Value of a statistical life	$8.3 million (AUD June 2021)	OEH (2019) referencing ASCC (2008)
Discount rate	7%	NSW Treasury (2017)
Value of a statistical life year	~$624,000 (AUD June 2021)	Aldy and Viscusi (2007)

3. Model performance evaluation

To assess the performance of the CCAM–CTM modelling system, the modelled meteorological and air quality data for 2013 were compared to the relevant data from the NSW Department of Planning and Environment's air quality monitoring stations and the Bureau of Meteorology's 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.

3.1 Meteorological model performance

CCAM meteorological results were evaluated to assess the model's ability to characterise the meteorological conditions that prevail across the region and to determine the meteorological conditions conducive to the formation of air pollution episodes. The validation was undertaken for the 2013 CCAM run. CCAM estimates were compared to measurements of temperature, wind speed and wind direction from 8 departmental and 6 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 the CCAM performance evaluation are presented in Appendix A.

3.2 Chemical Transport Model performance

Air pollutant concentrations modelled for 2013 by the CTM were compared to measured levels from departmental air quality monitoring stations. Comparisons were made for the following regions:

- 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
- Newcastle – Newcastle.

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 B.

4. Modelled particulate concentrations

The CCAM–CTM modelling system was used to predict air pollution concentrations for the 2013 calendar year across 11 emission scenarios (Table 2). The 2013 total emissions for selected pollutants by various anthropogenic source groups are summarised in Table 5.

Table 5 Total 2013 emissions (tonnes per year) for selected pollutants by anthropogenic source groups

Source groups	NH_3	CO	NOx	PM_{10}	$PM_{2.5}$	SO_2	VOCs
Human-made sources	7,572	485,378	311,177	102,795	30,765	225,551	137,246
Power stations	232	9,244	141,699	3,730	1,583	198,219	1,284
Wood heaters	409	50,117	728	7,036	6,773	114	8,239
On-road motor vehicles (exhaust)	1,092	115,262	45,085	955	926	126	16,124
On-road motor vehicles (non-exhaust)	0	0	0	1,550	824	0	0
Non-road diesel and marine	37	61,628	58,920	3,263	3,086	10,757	21,300
Industry	4,293	161,903	19,267	82,692	14,947	15,893	11,344
Commercial and domestic–commercial	1,479	69,925	3,308	1,985	1,089	242	75,918

Notes: NH_3 = ammonia; CO = carbon monoxide; NOx = oxides of nitrogen; PM_{10} = particles smaller than 10 micrometres in diameter; $PM_{2.5}$ = particles smaller than 2.5 micrometres in diameter; SO_2 = sulfur dioxide; VOCs = volatile organic compounds.

The CCAM–CTM predicted average $PM_{2.5}$ concentrations in the CTM GMR domain from the 11 different source contribution scenarios for the 2013 calendar year are illustrated in Figure 5.

The 'Base case' scenario (Figure 5a) shows areas of higher $PM_{2.5}$ concentrations corresponding to the densely populated areas of Sydney, Newcastle, Wollongong, and the Upper Hunter region. Annual average $PM_{2.5}$ concentrations exceeded the National Environment Protection Measures for ambient air quality 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 5).

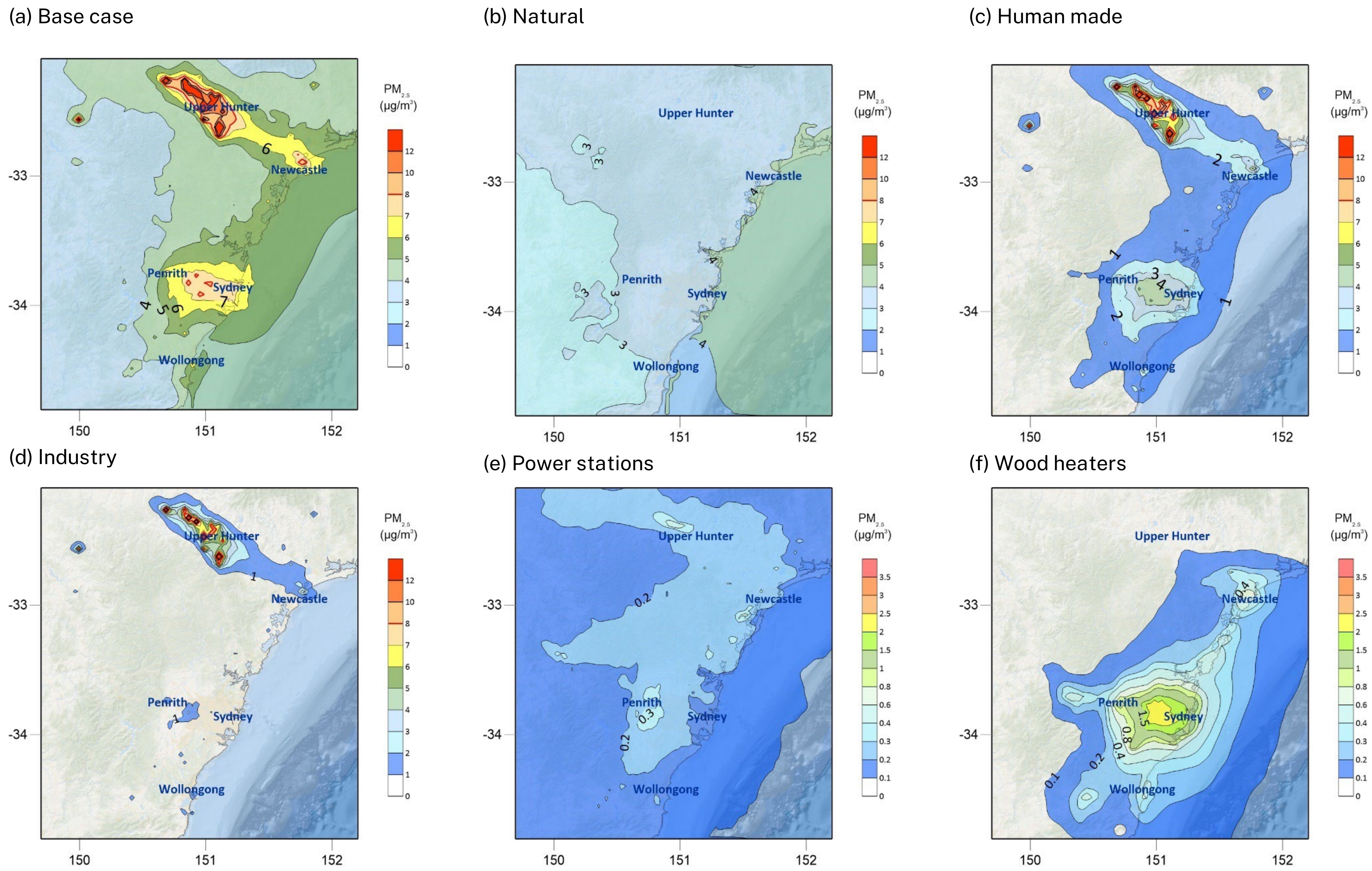
The 'Natural sources' scenario (Figure 5b) shows contributions to $PM_{2.5}$ concentrations from natural sources including biogenic emissions, sea salt and wind-blown dust. These sources contribute around 2–5 µg/m^3 to the average annual $PM_{2.5}$ concentration within the NSW GMR. Contributions to $PM_{2.5}$ levels from 'Human-made sources' (Figure 5c) 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.

‘Industrial sources’ (Figure 5d), which include all industrial sources except coal and gas power stations, contributed significantly to average $PM_{2.5}$ concentrations in the Upper Hunter region. $PM_{2.5}$ concentrations attributed to ‘Power station sources’ (Figure 5e) emissions were higher in localised regional areas coinciding with power station locations. 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.

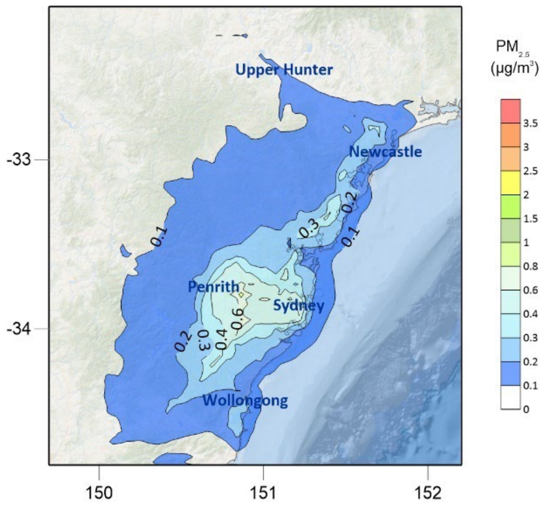
The main human-made sources that contributed to annual average $PM_{2.5}$ in the Sydney region were ‘Wood heaters’ (Figure 5f), ‘On-road motor vehicles (exhaust)’ (Figure 5g) and ‘On-road motor vehicles (non-exhaust)’ (Figure 5h). Contributions to average $PM_{2.5}$ concentrations from on-road motor vehicles exhaust (0.0–1.0 $\mu g/m^3$) are widespread across the GMR, but for non-exhaust sources from motor vehicles the largest $PM_{2.5}$ are seen in the Sydney region.

Apart from industrial sources, ‘Non-road diesel and marine sources’ (Figure 5i) made relatively significant contributions of up to 5 $\mu g/m^3$ to average $PM_{2.5}$ concentrations in the Upper Hunter region. These sources also contributed about 0.4–0.6 $\mu g/m^3$ to average $PM_{2.5}$ levels off the coast of Sydney and Newcastle.

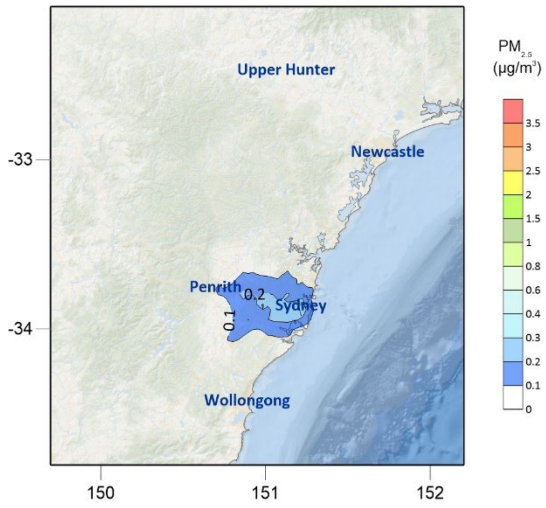
Contributions to average $PM_{2.5}$ concentrations of up to 2.0 $\mu g/m^3$ from ‘Commercial and domestic–commercial sources’ (Figure 5j) can be seen mainly in the Sydney region with a small contribution from Newcastle and Wollongong. Finally, for ‘Biogenic sources’ (Figure 5k), the $PM_{2.5}$ concentrations are spatially widespread as expected with an average $PM_{2.5}$ concentrations of up to 0.8 $\mu g/m^3$.


(a) Base case
(b) Natural
(c) Human made
(d) Industry
(e) Power stations
(f) Wood heaters
Upper Hunter
Newcastle
Penrith
Sydney
Wollongong
PM2.5 (μg/m³)
150
151
152
-33
-34

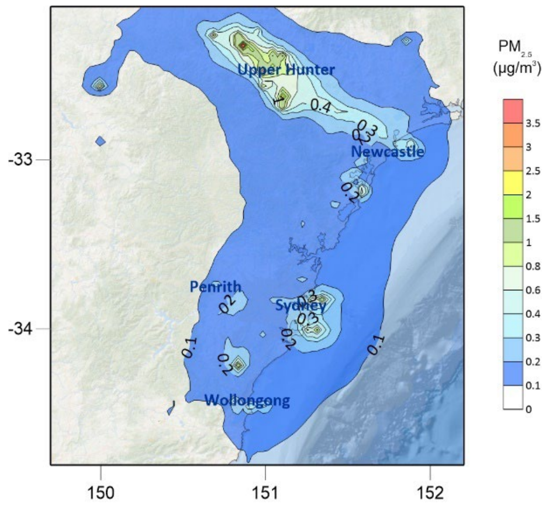
(g) On-road motor vehicles (exhaust)



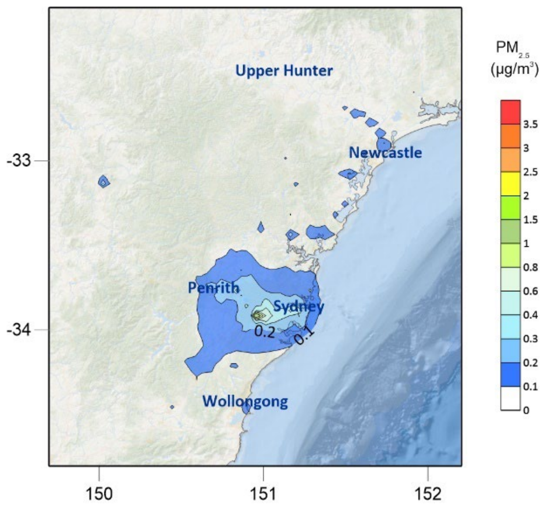
(h) On-road motor vehicles (non-exhaust)



(i) Non-road diesel and marine



(j) Commercial and domestic–commercial



(k) Biogenic

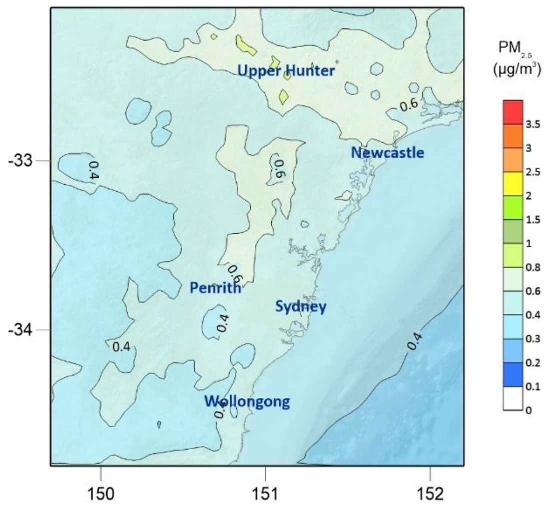


Figure 5 Average concentrations of particulate matter less than 2.5 micrometres in diameter ($PM_{2.5}$) represented in micrograms per cubic metre (µg/m3) for the 2013 calendar year predicted by the CCAM-CTM under different modelling scenarios: (a) base case, (b) natural sources, (c) human-made sources, (d) industry, (e) power stations, (f) wood heaters, (g) on-road motor vehicles (exhaust), (h) on-road motor vehicles (non-exhaust), (i) non-road diesel and marine, (j) commercial & domestic-commercial and (k) biogenic. The y axis represents latitude, and the x axis represents longitude

5. Exposure assessment

Determining the health risks caused by ambient air pollution is critical to the development of effective risk-management policies and strategies. An accurate exposure assessment is essential to better understand the adverse health effects associated with air pollution. The exposure modelling presented in this section provides a quantitative estimate of the level of air pollutants people were exposed to. Results from exposure modelling are also a critical component for the subsequent health impact assessment (see section 6).

Results from the CCAM–CTM modelling system for various emission scenarios (see section 3) were applied to the exposure modelling method to estimate the source contributions to population-weighted air pollutants.

The contribution of natural and human-made sources to the population-weighted annual average $PM_{2.5}$ (pwaa-$PM_{2.5}$) concentrations were calculated (Table 6 and Figure 6). Natural and human-made sources contributed 52% (3.36 μg/m^3) and 48% (3.07 μg/m^3), respectively, to the pwaa-$PM_{2.5}$ (6.43 μg/m^3).

Table 6 **Natural and human-made source contributions to population-weighted annual average $PM_{2.5}$ (pwaa-$PM_{2.5}$) concentrations**

Source	pwaa-$PM_{2.5}$ (μg/m^3)
Natural sources	3.36
Human-made sources	3.07
All sources	**6.43**

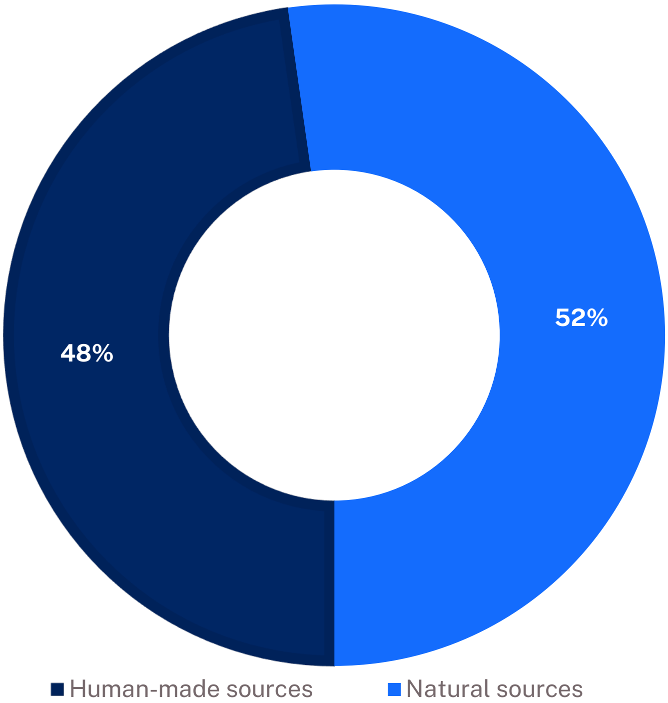


Figure 6 **Percentage contribution natural and human-made sources make to population-weighted annual average $PM_{2.5}$ concentrations**

Human-made sources were further broken down into major groups and their contribution to pwaa-$PM_{2.5}$ concentrations was calculated (Table 7 and Figure 7). Wood heaters, industry, on-road motor vehicles (exhaust) and power stations respectively contributed 1.261, 0.623, 0.379 and 0.213 µg/m^3 to the pwaa-$PM_{2.5}$ concentration, and respectively accounted for 42, 21, 13 and 7% of the total human-made source contribution.

Note that the 2% (0.07 µg/m^3) difference between the sum of the individual modelled sources group pwaa-$PM_{2.5}$ and the base case pwaa-$PM_{2.5}$ (modelled with all sources) is the result of the non-linear processes of the secondary inorganic and organic aerosol formation.

Table 7 **Major human-made source groups and their contributions to population-weighted annual average $PM_{2.5}$ (pwaa-$PM_{2.5}$) concentrations**

Major human-made sources	pwaa-$PM_{2.5}$ (µg/m^3)
Power stations	0.213
Wood heaters	1.261
On-road motor vehicles (exhaust)	0.379
On-road motor vehicles (non-exhaust)	0.134
Non-road diesel and marine	0.186
Industry	0.623

Major human-made sources	pwaa-$PM_{2.5}$ ($\mu g/m^3$)
Domestic-commercial	0.204
Other (model uncertainties associated with non-linear processes)	0.070
All human-made sources	**3.070**

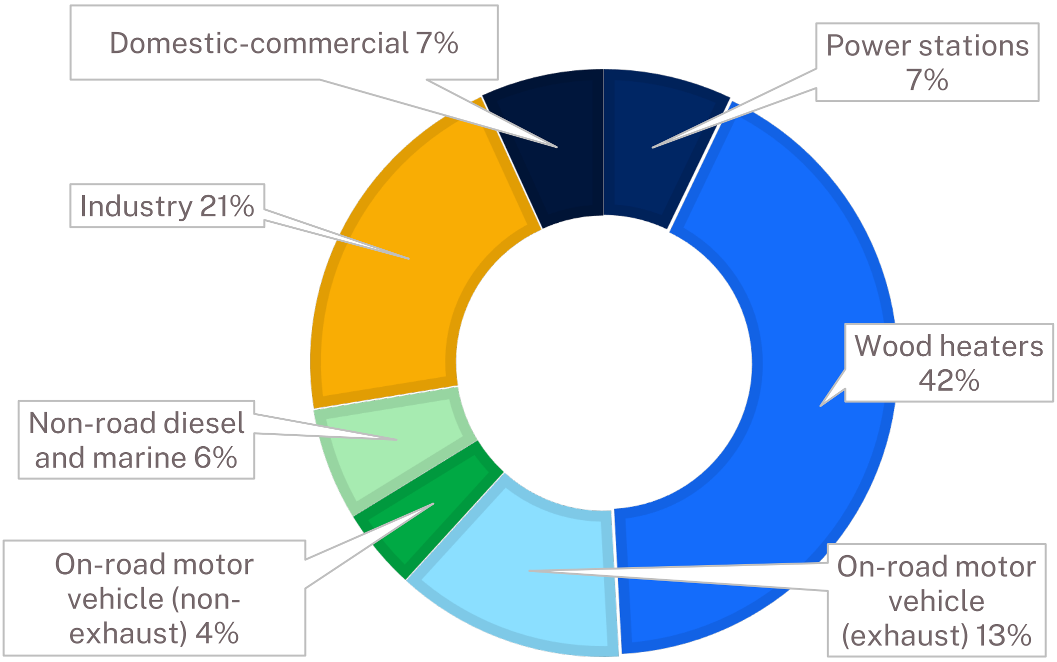


Figure 7 **Major source groups contributions (%) to total human-made sources contribution to population-weighted annual average $PM_{2.5}$ (pwaa-$PM_{2.5}$)**

6. Health impact assessment

The health impact assessment estimates the burden of mortality and its monetary value associated with long-term exposures to $PM_{2.5}$ air pollution (expressed as population-weighted annual average $PM_{2.5}$ concentrations or pwaa-$PM_{2.5}$) from each source group of human-made emissions in the NSW GMA. Estimates assume that the resultant $PM_{2.5}$ concentrations modelled due to each anthropogenic emissions source group in 2013 are representative of long-term exposures to such emissions. This assumption is needed since the health effects of $PM_{2.5}$ pollution may take years to develop.

A summary of major source contributions to the pwaa-$PM_{2.5}$ concentrations, the estimates of the burden of mortality (attributable number of premature deaths, years of life lost) attributable to each source, and their health costs over the NSW GMA are presented in Table 8.

Table 8 The annual burden of mortality related to long-term exposure to $PM_{2.5}$ from major sources in the NSW Greater Metropolitan Area

Source group	pwaa-$PM_{2.5}$ (µg/m^3)	Attributable number (AN) of premature deaths	Health cost based on AN (AUD 2021, million)	Years of life lost (YLL)	Health costs based on YLL (AUD 2021, million)
Wood heaters	1.26	269	2,239	3,279	2,046
Industry	0.62	133	1,108	1,619	1,011
On-road motor vehicle (exhaust)	0.38	81	674	984	614
On-road motor vehicle (non-exhaust)	0.13	29	239	350	218
Power stations	0.21	46	380	555	346
Non-road diesel and marine	0.19	40	331	483	302
Domestic-commercial	0.20	44	363	531	331
All human sources	**3.07**	**603**	**5,020**	**7,733**	**4,827**

The wood heater emissions have the greatest pwaa-$PM_{2.5}$ across the GMA and result in an estimated 269 attributable number of premature deaths with a health cost of $2,239 million. The associated years of life lost are 3,279 with health cost of $2,046 million.

The next largest source of emissions is industry, with an estimated pwaa-$PM_{2.5}$ concentration of 0.62 µg/m^3. The attributable number of premature deaths is 133 with an estimated health cost of $1,108 million. There are 1,619 projected years of life lost associated with the industry emissions at a health cost of $1,011 million.

On-road motor vehicle emission sources contributed 0.38 and 0.13 pwaa-$PM_{2.5}$ across the GMA from exhaust and non-exhaust emissions, respectively, (0.51 pwaa-$PM_{2.5}$ combined). The combined attributable number of premature deaths and years of life lost were 110 and 1,334, respectively. The associated health cost of these were $913 million and $832 million, respectively.

Non-road diesel and marine, power stations and domestic commercial pwaa-$PM_{2.5}$ were around 0.2 µg/m^3. The attributable number of premature deaths associated with each source were around 40–46 and had a predicted health cost between $331 million and $380 million. The years of life lost for these 3 sources were between 483 and 555 at a health cost around $302–346 million.

It should be noted that these health costs due to emissions from different sources do not include health costs due to morbidity effects from these sources (for example hospitalisations due to respiratory, cardio-vascular and stroke diseases) besides mortality effect.

7. Damage costs

Another way to assess the scale of the air quality impacts from each emission source is to estimate the damage costs from the health burden calculations (attributable number of premature deaths and years of life lost). Damage costs can be expressed as the monetary health cost associated with changes in a unit amount of emissions ($/tonne). $PM_{2.5}$ emissions from major sources in 2013 (see Table 5) were 6,773 tonnes for wood heaters, 14,947 tonnes for industry, 926 tonnes for on-road motor vehicle (exhaust), 824 tonnes for on-road motor vehicle (non-exhaust), 1,583 tonnes for power stations, 3,086 tonnes for non-road diesel and marine, and 1,089 tonnes for domestic–commercial. For each emission source group, the damage costs are estimated in AUD 2021 per tonne (Table 9).

Table 9 The damage costs of long-term exposure to $PM_{2.5}$ for major sources in the NSW Greater Metropolitan Area

Source group	Damage costs (AUD 2021 health costs per tonne of emissions per source)	
	Attributable number of premature deaths	Years of life lost
Wood heaters	330,550	302,151
Industry	74,097	67,625
On-road motor vehicle (exhaust)	727,509	663,566
On-road motor vehicle (non-exhaust)	290,579	264,880
Power stations	239,875	218,703
Non-road diesel and marine	107,242	97,770
Domestic–commercial	333,631	304,176

Notes: An example of damage cost (based on attributable number of premature deaths) for wood heaters ($330,550/tonne) is derived from health cost for this source ($2,239 million in Table 8) divided by $PM_{2.5}$ emissions from wood heaters in 2013 (6,773 tonnes).

Based on attributable number of premature deaths, damage costs for wood heaters and domestic–commercial emissions are estimated to be ~$330,000/tonne each (Table 9). Based on the years of life lost approach, damage costs for wood heater emissions are estimated to be approximately $300,000/tonne.

The highest damage cost from attributable number of premature deaths is from the on-road motor vehicle exhaust source of $727,509/tonne, and $663,566/tonne when using years of life lost. Non-exhaust on-road damage costs for both estimation methods are around $260,000–$291,000/tonne. For power stations, the damage costs range between $220,000–240,000/tonne.

The lowest damage cost of all source groups come from non-road diesel and marine and industry, ranging between $68,000 and $107,000/tonne, with smaller costs for the years of life lost method over attributable number of premature deaths approach.

8. Conclusion

The Sydney Air Quality Study is a 2-stage multi-year research program led by the NSW Department of Planning and Environment (the department), in collaboration with the NSW Environment Protection Authority (the EPA), and the NSW Ministry of Health. Findings from the second stage of this project (2020–2022) are presented in this report.

Understanding the health risks caused by ambient air pollution is critical to the development of effective risk-management policies and strategies. Particulate matter less than 2.5 µm in diameter ($PM_{2.5}$) is a pollutant that has a broad spectrum of effects on health that may include mortality and cardiovascular and respiratory illness. To identify and quantify source contributions to $PM_{2.5}$, in the second stage of the study, the regional airshed model was updated with *2013 Calendar year air emissions inventory for the Greater Metropolitan Region in NSW* (NSW EPA 2019) and major human-made emission sources were classified into: power stations, industry, wood heaters, on-road motor vehicles (exhaust), on-road motor vehicles (non-exhaust), non-road diesel and marine, and domestic–commercial.

To better understand the adverse health effects associated with air pollution, the modelled source-specific $PM_{2.5}$ concentrations were used to undertake $PM_{2.5}$ exposure modelling by calculating population-weighted annual average $PM_{2.5}$ concentrations over the NSW Greater Metropolitan Area (GMA). Results show natural and human activities account for 52% (3.36 µg/m^3) and 48% (3.07 µg/m^3) of $PM_{2.5}$ exposure, respectively. Major sources of human contributions to $PM_{2.5}$ exposure were from wood heaters (42%), industry (21%), on-road motor vehicles (exhaust) (13%), power stations (7%), domestic–commercial (7%), non-road diesel and marine emissions (6%), and on-road motor vehicles (non-exhaust) (4%).

Subsequent health impact assessment and associated damage costs estimations are shown in similar studies (OEH 2019; Broome et al. 2020; Mazaheri et al. 2021). The economic costs are estimated based on the most current value of a statistical life for the attributable number of premature deaths, and on the value of a statistical life year and discount rate for years of life lost to take into account the population age structure in which earlier life years are more costly than later years.

The assessment shows that the human-made emission source groups that cause the most impact on mortality and the associated economic cost from premature death or years of life lost are wood heaters, industry, on-road motor vehicle (exhaust), power stations, domestic–commercial, non-road diesel and marine, and on-road motor vehicle (non-exhaust). The corresponding health costs based on years of life lost are $2,046 million, $1,011 million, $614 million, $346 million, $331 million, $302 million, $218 million (AUD 2021), respectively.

The damage costs expressed as the monetary health cost associated with changes in a unit amount of emissions for each emission source group were also investigated. Based on years of life lost, damage costs from on-road motor vehicle (exhaust) emissions are estimated to be approximately $663,000/tonne, followed by domestic–commercial, wood heaters and on-road motor vehicle (non-exhaust) emissions which are estimated to be roughly $260,000–300,000/tonne. Damage costs from the power stations, non-road diesel and marine emission and industry sources are estimated to be $220,000/tonne, $98,000/tonne and $68,000/tonne, respectively.

The results from this study will contribute to the evidence base the NSW Government relies on to support the development of clean air actions.

Appendix A: Conformal Cubic Atmospheric Model performance

Validation of the Conformal Cubic Atmospheric Model (CCAM) meteorological results for 2013 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 and Environment and Bureau of Meteorology (BoM) monitoring stations. Seasons are defined by months: summer – December, January, February (DJF); autumn – March, April, May (MAM); winter – June, July, August (JJA); and spring – September, October, November (SON).

Table 10 Locations of Department of Planning and Environment (DPE) air quality monitoring stations and Bureau of Meteorology (BoM) weather stations selected for this study

Site location	Provider	Latitude	Longitude
Bargo	DPE	-34.307	150.580
Prospect	DPE	-33.795	150.910
Newcastle	DPE	-32.910	151.758
Singleton	DPE	-32.557	151.177
Muswellbrook	DPE	-32.272	150.886
Wyong	DPE	-33.279	151.432
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

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 (see 'Graphical performance evaluation' section) and statistical metrics (see 'Statistical performance evaluation' section) 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.

Graphical performance evaluation

The graphical performance evaluation of the CCAM meteorological results for 2013 looks at discrete probability density functions and the seasonal diurnal (daily) averaged time-series for temperature, relative humidity and wind speeds. 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.

Discrete probability density functions

Discrete probability density functions for seasonally averaged temperature, relative humidity and wind speed were calculated at Wyong, Prospect, Camden Airport and Sydney Airport.

The probability density functions for temperature plots generally show close agreement across all seasons and stations (Figure 8). The model slightly underpredicts temperatures between 10 and 25 degrees Celsius for all sites except Camden Airport where the model overpredicts temperatures. Additionally, at the Camden Airport site the model underpredicts the frequency of temperatures below 10 degrees Celsius.

Figure 9 shows a tendency for the model to have more-frequent occurrences of lower relative humidity conditions compared to the observations. At the other end of the scale, the model tends to have less-frequent occurrences of higher relative humidity. There is little seasonal variability seen in the probability density functions of relative humidity.

For wind speeds (Figure 10) the model underpredicts in the range 0–2 metres per second (m/s) across all sites, with the exception of Sydney Airport where the model overpredicts in this range. Additionally, the model overpredicts wind speeds greater than approximately 2 m/s across all sites except Sydney Airport where they underpredict wind speeds.

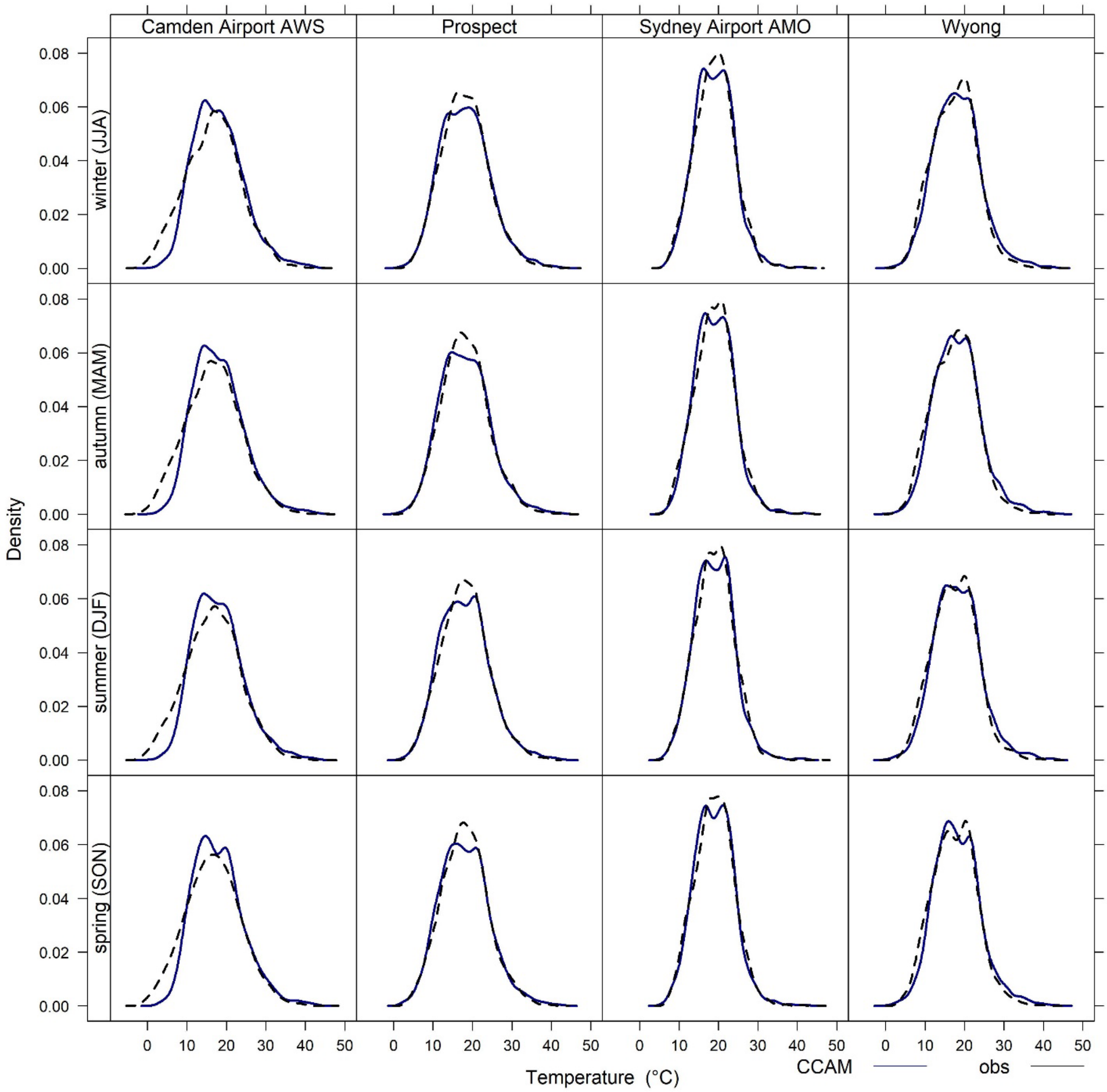


Figure 8 **Seasonal discrete probability density function plots for temperature (degrees Celsius [°C]) at Camden Airport, Prospect, Sydney Airport and Wyong**

Figure notes: CCAM = Conformal Cubic Atmospheric Model; DJF = December, January, February; JJA = June, July, August; MAM = March, April, May; Obs = observed; SON = September, October, November.

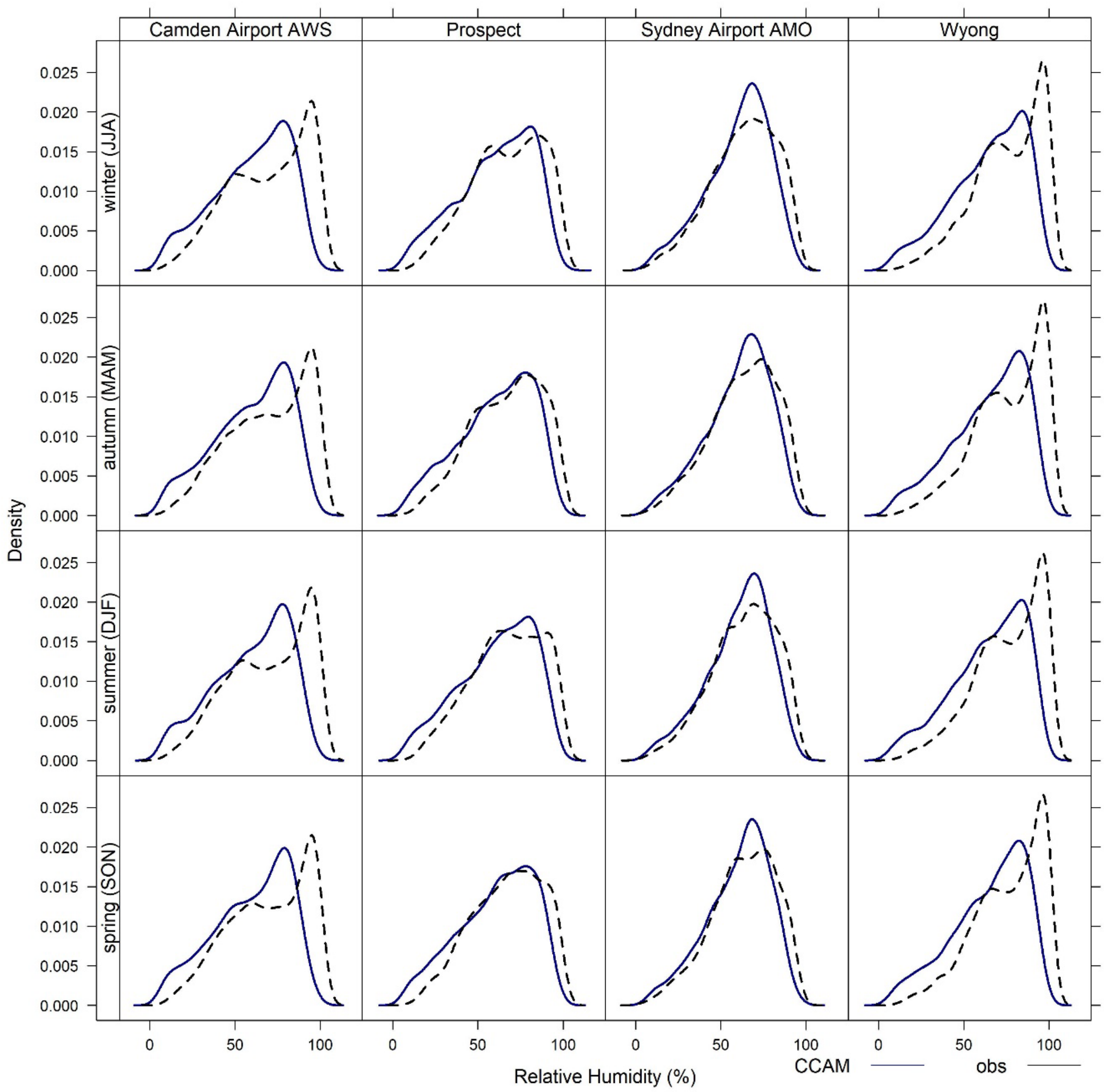


Figure 9 **Seasonal discrete probability density function plots for relative humidity (%) at Camden Airport, Prospect, Sydney Airport and Wyong**

Figure notes: CCAM = Conformal Cubic Atmospheric Model; DJF = December, January, February; JJA = June, July, August; MAM = March, April, May; Obs = observed; SON = September, October, November.

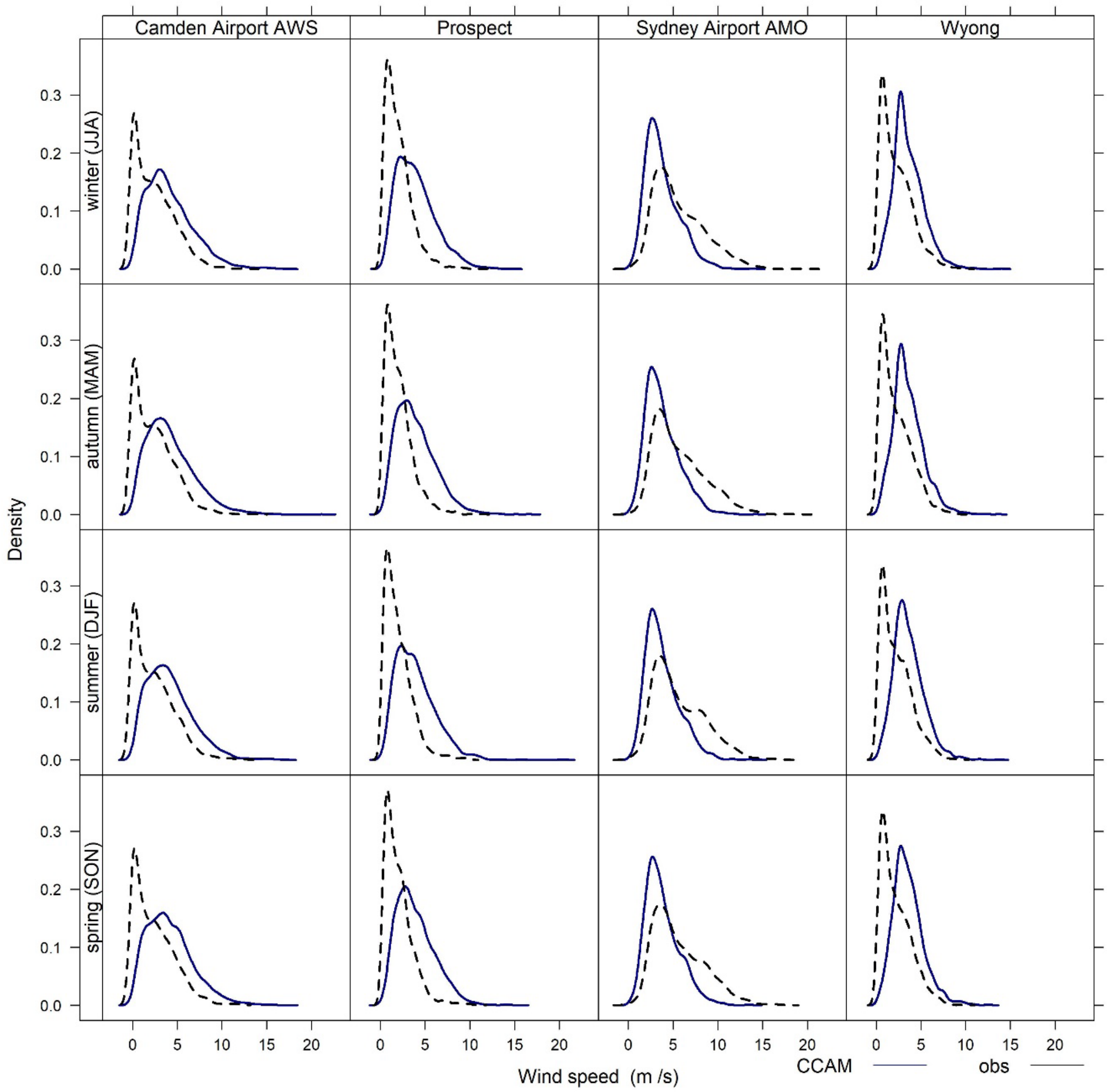


Figure 10 **Seasonal discrete probability density function plots for wind speed (metres per second [m/s]) at Camden Airport, Prospect, Sydney Airport and Wyong**

Figure notes: CCAM = Conformal Cubic Atmospheric Model; DJF = December, January, February; JJA = June, July, August; MAM = March, April, May; Obs = observed; SON = September, October, November.

Temporal plots

Monthly and diurnal temperature plots for the Department of Planning and Environment (Figure 11) and BoM (Figure 12) stations show a close agreement throughout the year and the day, capturing the overall variability. At all BoM stations the temperatures are warmer than the observations from April onwards and largest at the Newcastle Department of Planning and Environment station and Camden Airport BoM station. Throughout the day the maximums temperatures in CCAM are slightly warmer and later, which could impact the formation of photochemical species in the chemical transport modelling. The other notable deviation from observations are the warmer temperatures overnight (which are largest at the BoM stations).

The CCAM has a consistently drier relative humidity compared to the observations at both the departmental and BOM measurement stations (Figure 13 and Figure 14). The greatest difference appears in October, whilst the smallest (overestimation at some sites) occurs consistently during February. Diurnally, the modelled relative humidity appears to be drier throughout the entire day compared to observations with the greatest deviation overnight. The exceptions occur at Bankstown and Sydney Airport between 7 am and 1 pm where the relative humidity is on average slightly higher than observed.

For winds, the temporal comparison between the CCAM and observations for the modelling period is presented for wind speed, zonal and meridional wind components. A useful evaluation of wind direction is a comparison of wind roses at each station, which is presented in the section below.

The wind speed plots (Figure 15 and Figure 16) show a consistent overprediction at most stations. The exception is Sydney Airport where the modelled monthly average wind speeds are underpredicted. This underprediction at Sydney Airport is consistent with the probability density function plots seen in Figure 10. The diurnal plots highlight the overestimation of modelled wind speeds are generally largest overnight. There is an underestimation of wind speeds in CCAM at Bankstown Airport between 7 am and 3 pm and across the day at Sydney Airport.

In general, due to the differences between the Department of Planning and Environment and BoM monitoring networks (from instrumentation and local terrain influences), the wind speeds observed from the department’s Air Quality Monitoring Network are known to be lower than those recorded at BoM sites. This is seen clearly in the wind speed plots and explains why there is a slightly closer agreement with BoM wind speed observations. The difference is also greatest at the inland sites as the wind speeds are not as high as the coastal sites. The model doesn’t appear to capture this difference in wind speeds between the coast and inland.

Zonal and meridional wind monthly averaged plots (Figures 17–20) show that the model captures the overall pattern of winds throughout the year, that is, more westerly components during winter months and easterly components during summer. Diurnally, the zonal winds capture the sea breeze and the model amplitude is too large, which is likely dominated by the wind speed overpredictions. The diurnally averaged meridional winds show less agreement with the observations; however, there is little variability across the day in the observations and no definite shift through the day from north to south as in the sea breeze–influenced zonal winds.

Wind roses

Wind rose plots presented in Figure 21 provide a comparison between the model and the observed frequency of wind direction and wind speed at each station. It is clear from the wind rose plots that the model has a higher frequency of faster winds speeds than observed. Additionally, a comparison between the mean wind speeds shows there is an at least 1.5 m/s difference between the observations and CCAM, which is smaller between the BoM sites as their measured wind speeds tend to be higher. The predominant wind directions are well captured at most stations.

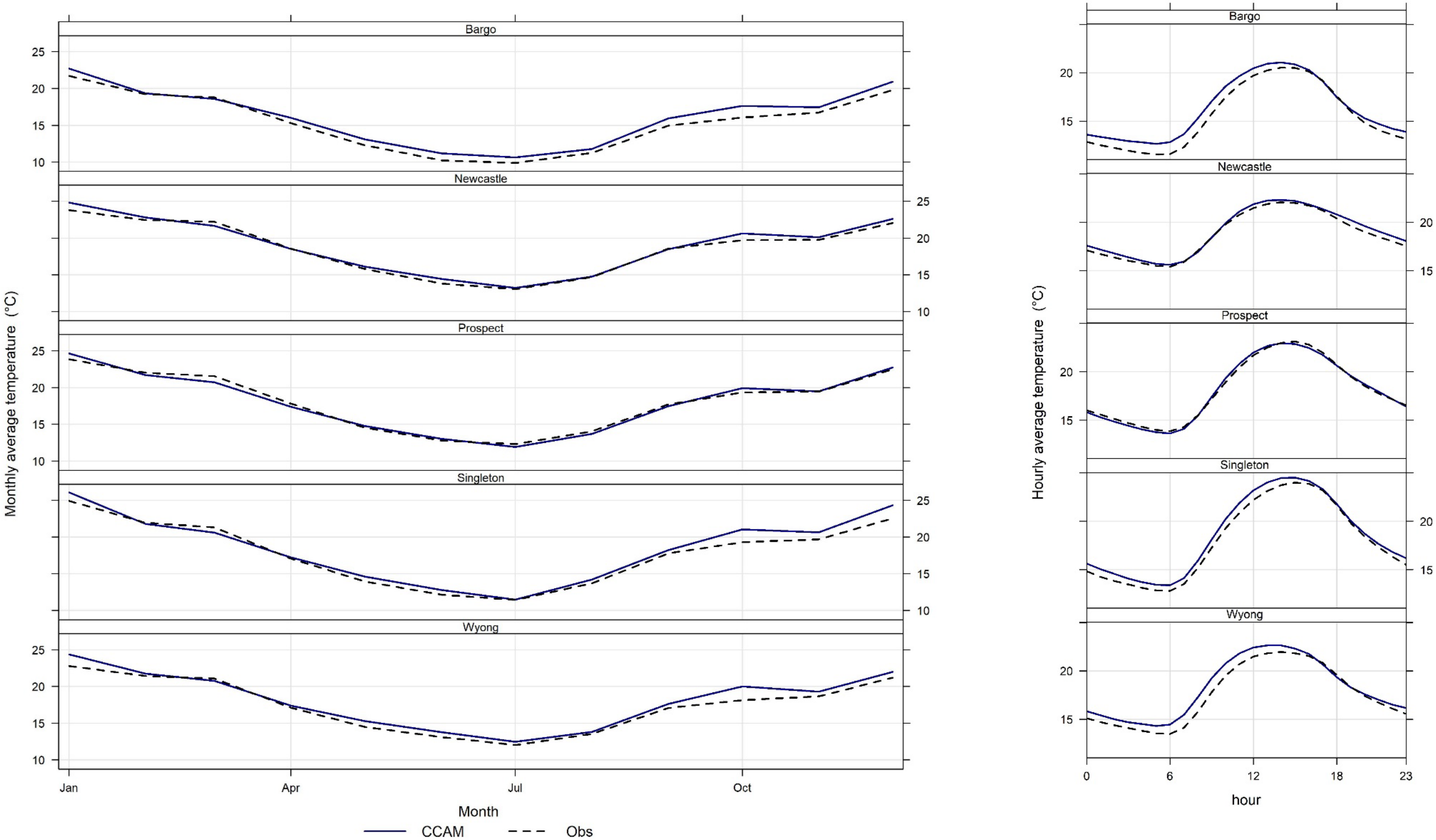


Figure 11 **Monthly average temperature (°C) plots (left) and diurnal average temperature (°C) plots (right) for a selection of Department of Planning and Environment air quality monitoring stations**

Figure notes: CCAM = Conformal Cubic Atmospheric Model; Obs = observed. Blue lines represent Conformal Cubic Atmospheric Model predictions and black dashed lines represent temperatures observed at monitoring stations.

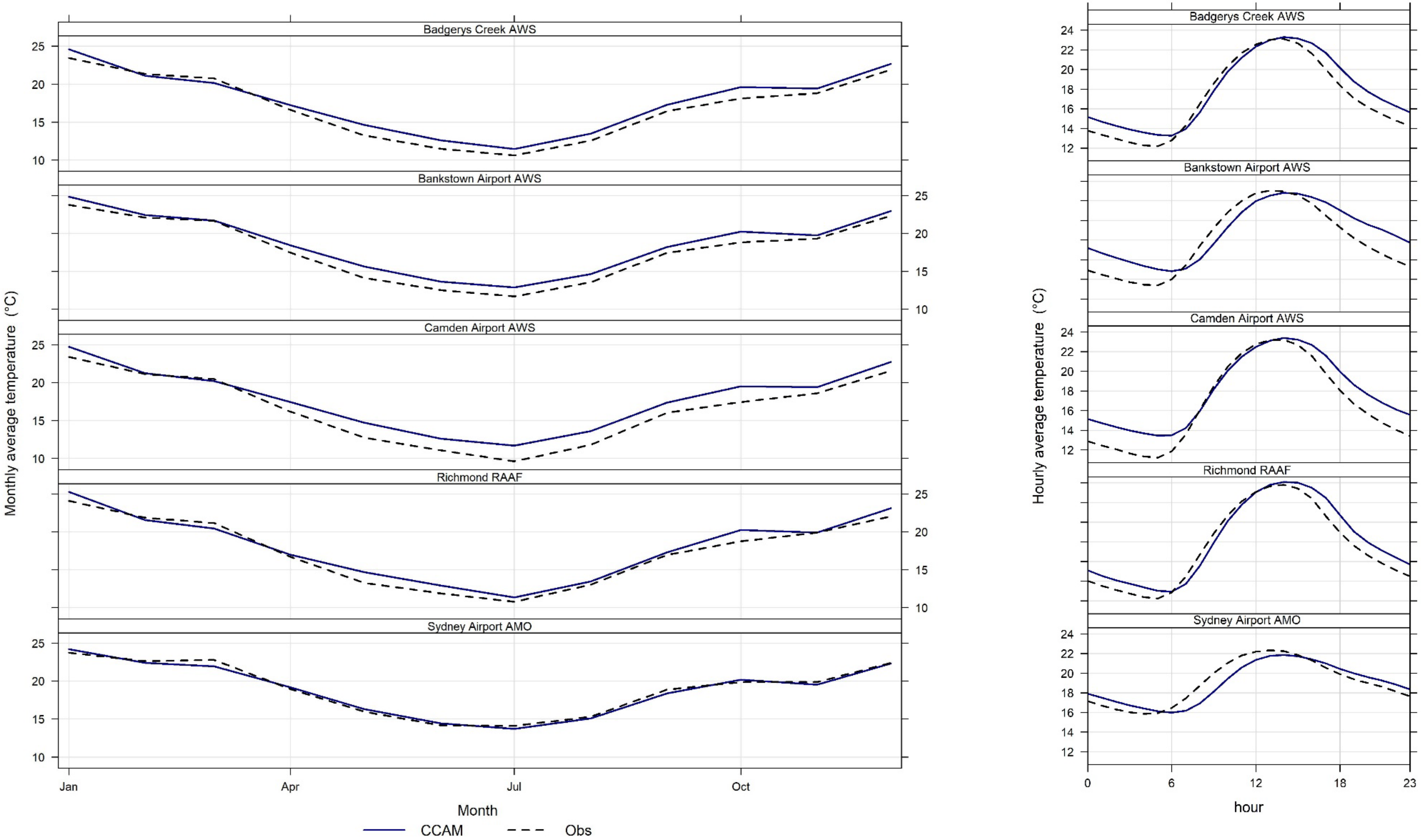


Figure 12 **Monthly average temperature (°C) plots (left) and diurnal average temperature (°C) plots (right) for Bureau of Meteorology stations**

Figure notes: AMO = Airport Meteorological Office; AWS = Automatic Weather Station; CCAM = Conformal Cubic Atmospheric Model; Obs = observed; RAAF = Royal Australian Air Force. Blue lines represent Conformal Cubic Atmospheric Model predictions and black dashed lines represent temperatures observed at monitoring stations.

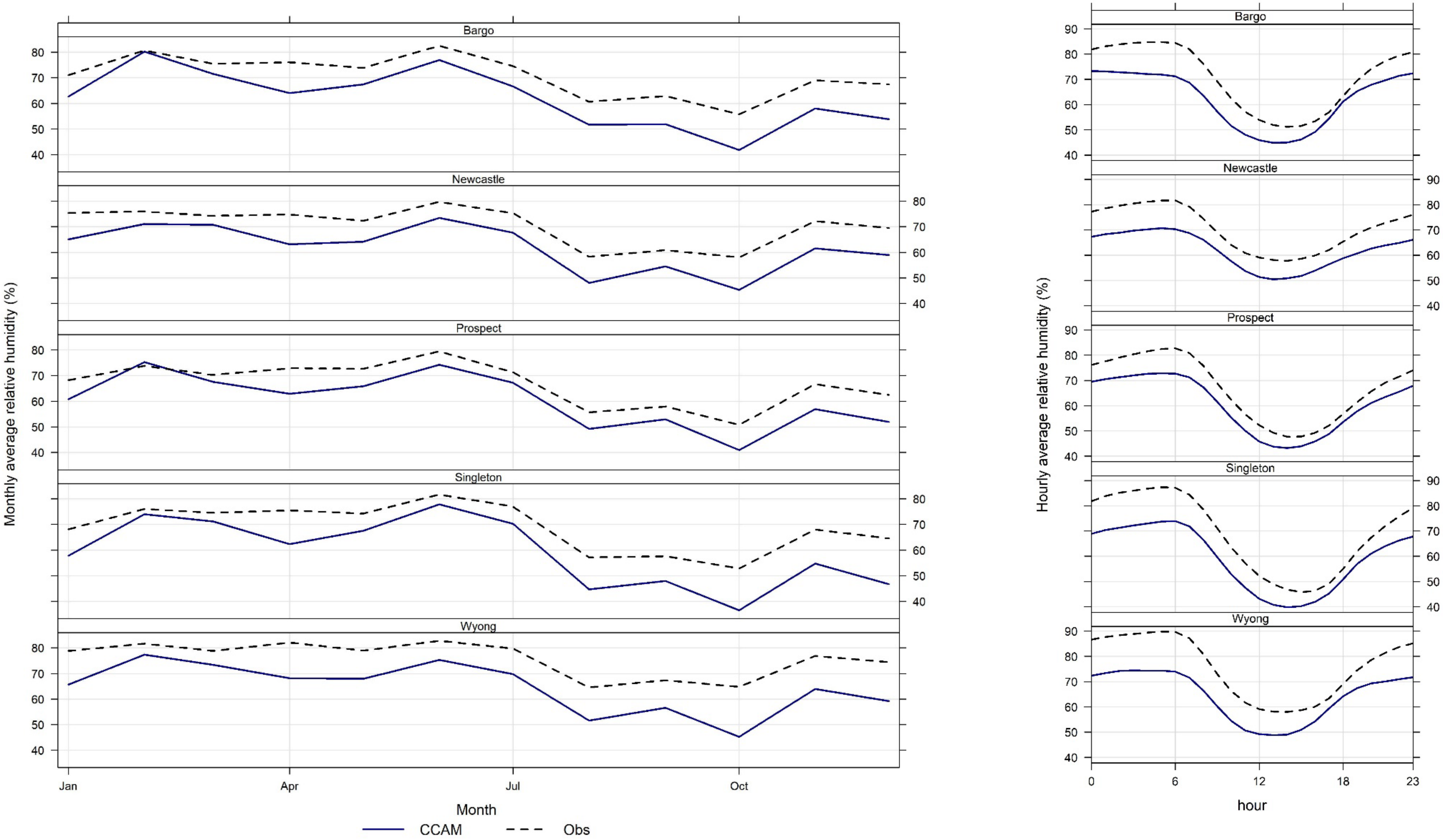


Figure 13 **Monthly average relative humidity (%) plots (left) and diurnal average relative humidity (%) plots (right) for a selection of Department of Planning and Environment air quality monitoring stations**

Figure notes: CCAM = Conformal Cubic Atmospheric Model; Obs = observed. Blue lines represent Conformal Cubic Atmospheric Model predictions and black dashed lines represent relative humidity observed at monitoring stations.

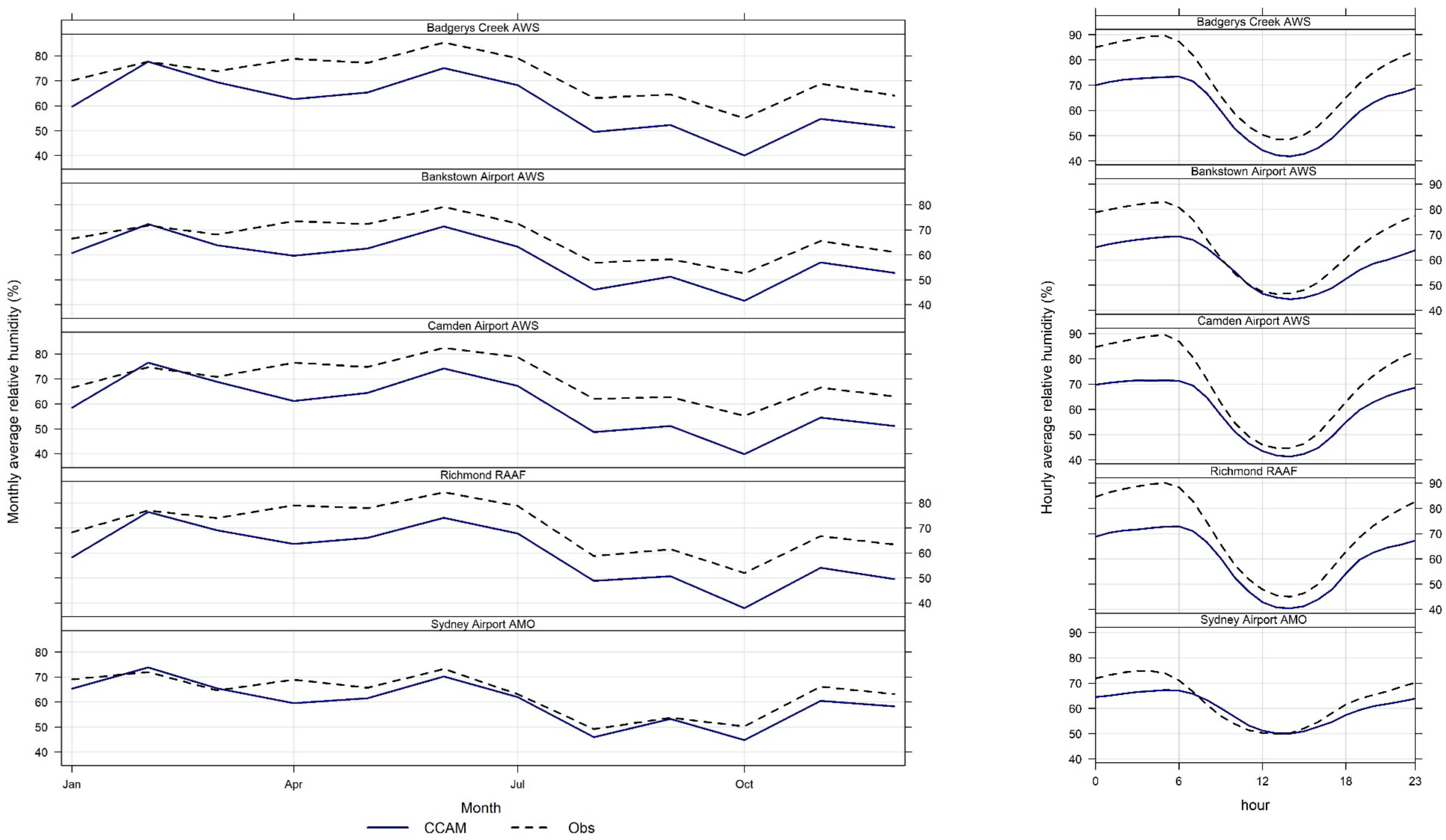


Figure 14 **Monthly average relative humidity (%) plots (left) and diurnal average relative humidity (%) plots (right) for Bureau of Meteorology stations**

Figure notes: AMO = Airport Meteorological Office; AWS = Automatic Weather Station; CCAM = Conformal Cubic Atmospheric Model' Obs = observed; RAAF = Royal Australian Air Force. Blue lines represent Conformal Cubic Atmospheric Model predictions and black dashed lines represent relative humidity observed at monitoring stations.

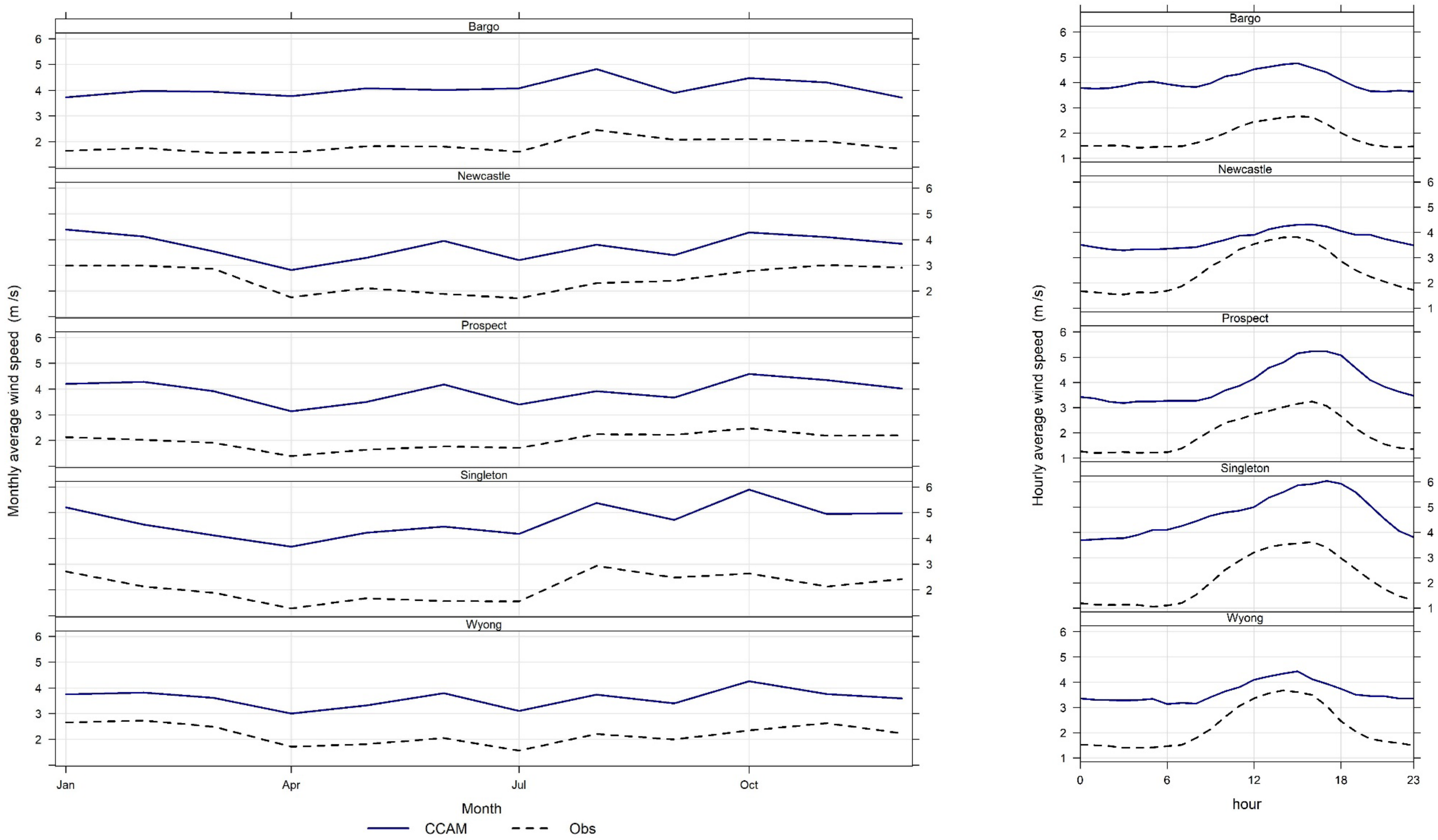


Figure 15 **Monthly average wind speed (metres per second [m/s]) plots (left) and diurnal average wind speed (m/s) plots (right) for a selection of Department of Planning and Environment air quality monitoring stations**

Figure notes: CCAM = Conformal Cubic Atmospheric Model; Obs = observed. Blue lines represent Conformal Cubic Atmospheric Model predictions and black dashed lines represent wind speeds observed at monitoring stations.

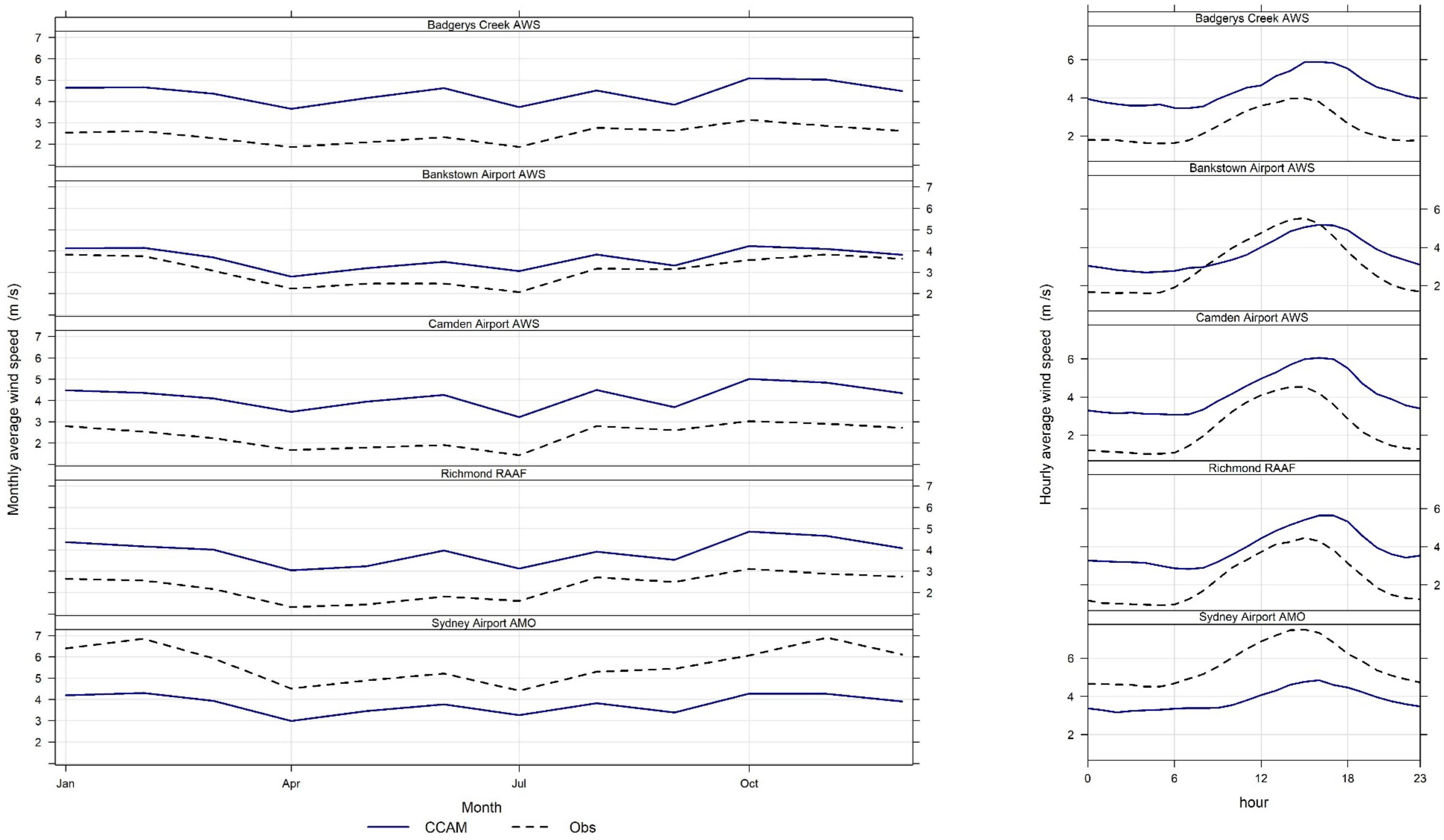


Figure 16 **Monthly average wind speed (metres per second [m/s]) plots (left) and diurnal average wind (m/s) speed plots (right) for Bureau of Meteorology stations**

Figure notes: AMO = Airport Meteorological Office; AWS = Automatic Weather Station; CCAM = Conformal Cubic Atmospheric Model; Obs = observed; RAAF = Royal Australian Air Force. Blue lines represent Conformal Cubic Atmospheric Model predictions and black dashed lines represent wind speeds observed at monitoring stations.

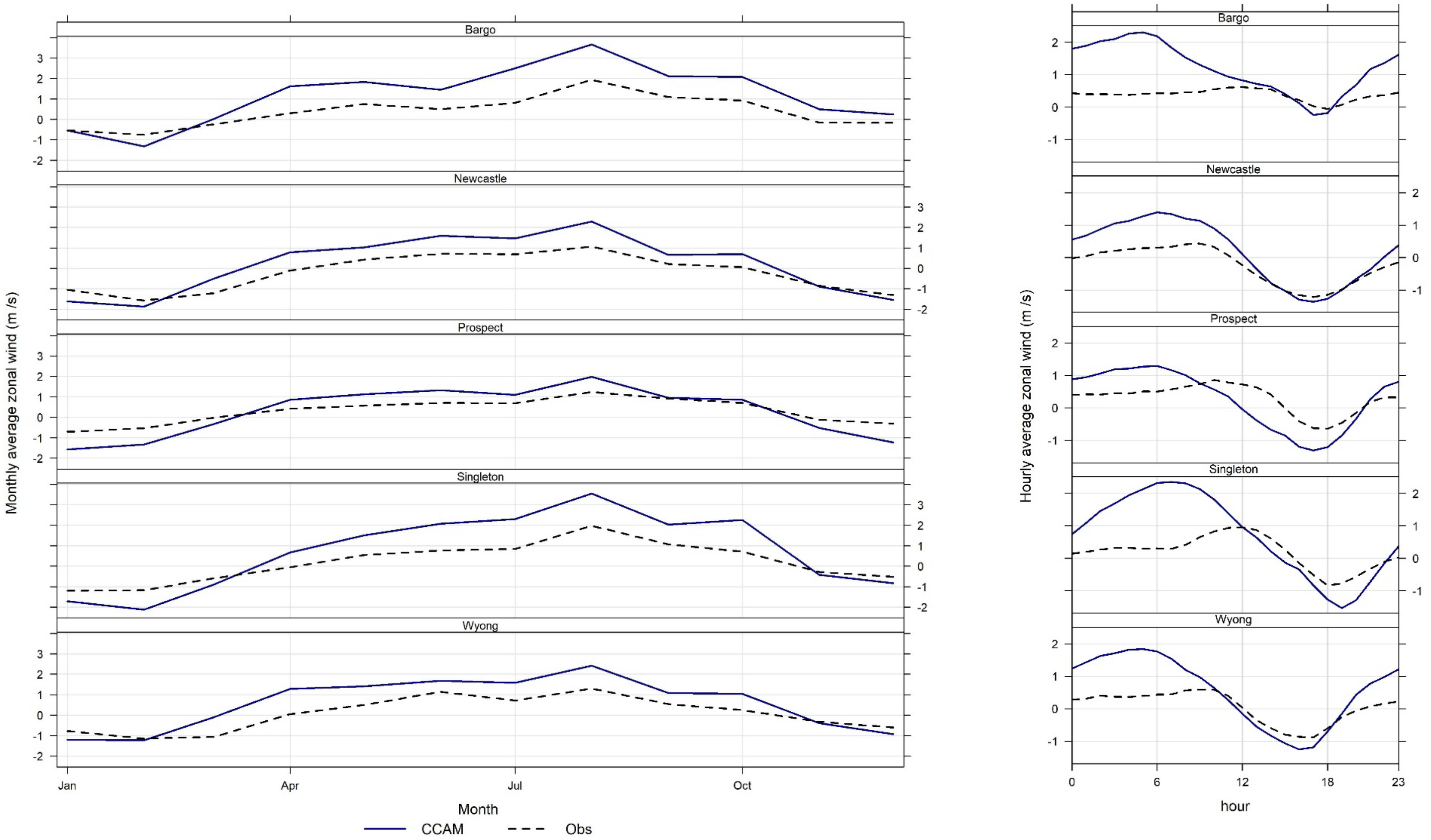


Figure 17 **Monthly average zonal wind speed (metres per second [m/s]) plots (left) and diurnal average zonal wind speed (m/s) plots (right) for a selection of Department of Planning and Environment air quality monitoring stations**

Figure notes: CCAM = Conformal Cubic Atmospheric Model; Obs = observed. Blue lines represent Conformal Cubic Atmospheric Model predictions and black dashed lines represent zonal wind observed at monitoring stations.

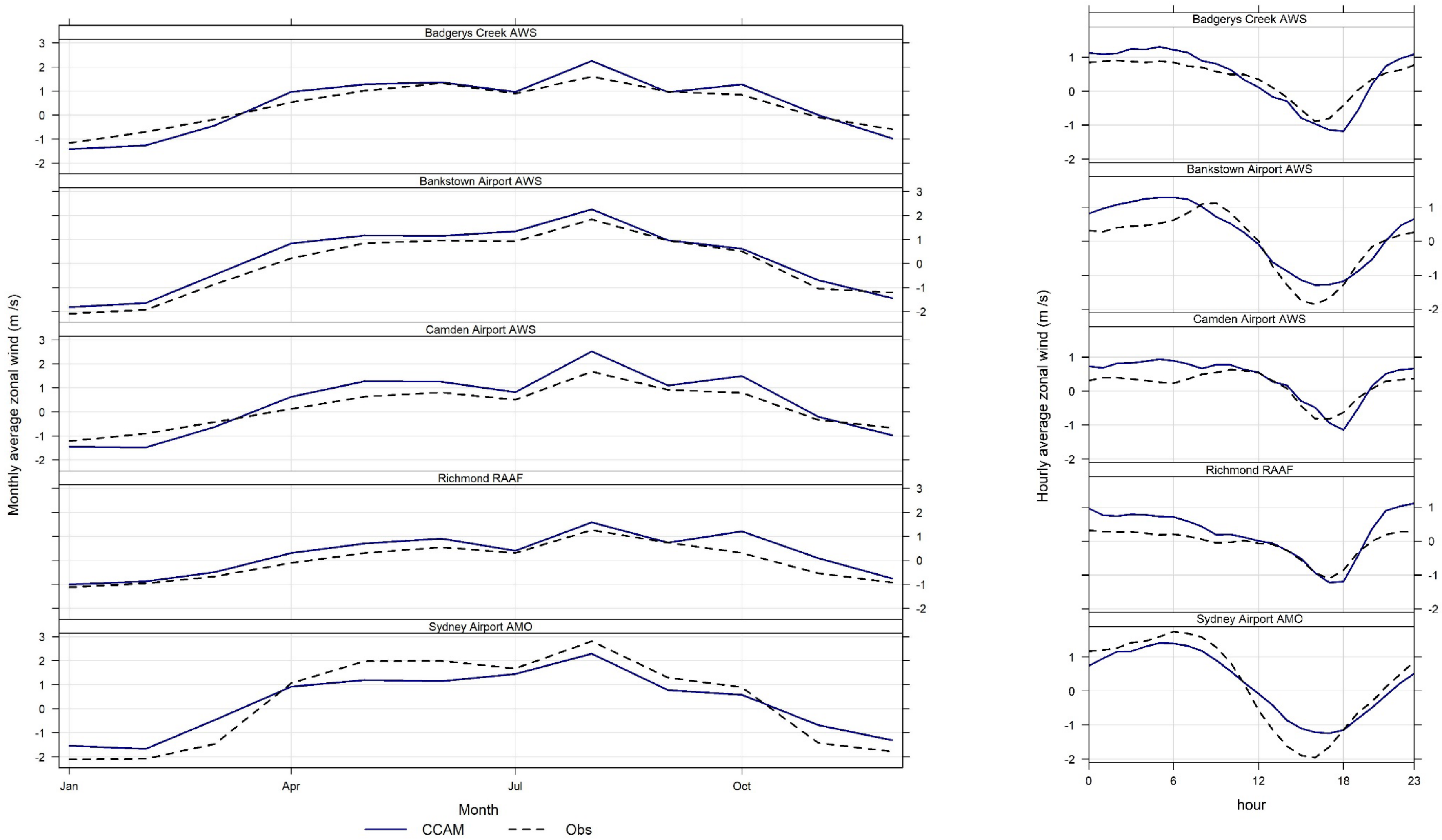


Figure 18 **Monthly average zonal wind speed (metres per second [m/s]) plots (left) and diurnal average zonal wind speed (m/s) plots (right) for Bureau of Meteorology stations**

Figure notes: AMO = Airport Meteorological Office; AWS = Automatic Weather Station; CCAM = Conformal Cubic Atmospheric Model; Obs = observed; RAAF = Royal Australian Air Force. Blue lines represent Conformal Cubic Atmospheric Model predictions and black dashed lines represent zonal wind observed at monitoring stations.

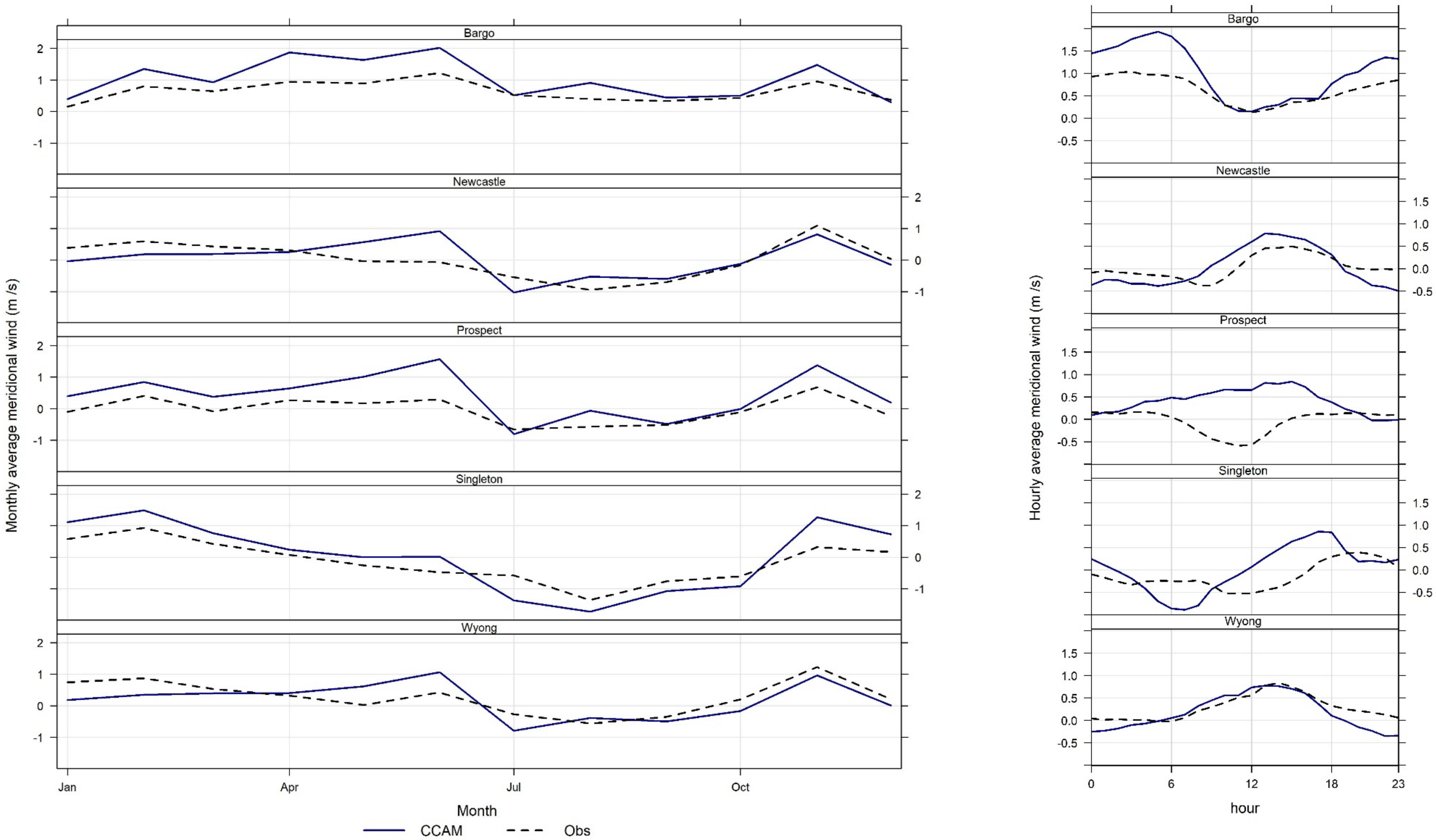


Figure 19 **Monthly average meridional wind speed (metres per second [m/s]) plots (left) and diurnal average meridional wind speed (m/s) plots (right) for a selection of Department of Planning and Environment air quality monitoring stations**

Figure note: CCAM = Conformal Cubic Atmospheric Model; Obs = observed. Blue lines represent Conformal Cubic Atmospheric Model predictions and black dashed lines represent meridional wind observed at monitoring stations.

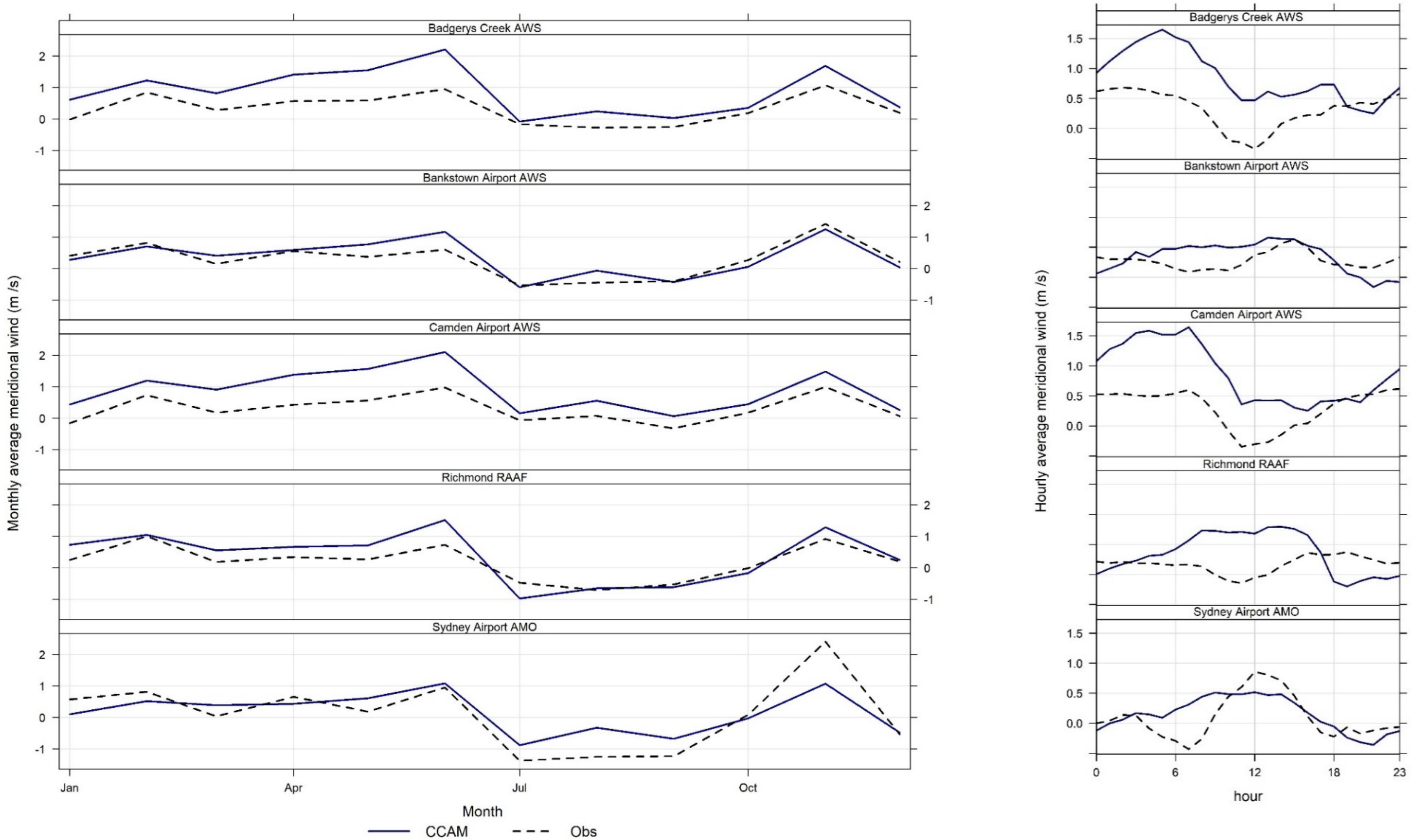


Figure 20 **Monthly average meridional wind speed (metres per second [m/s]) plots (left) and diurnal average meridional wind speed (m/s) plots (right) for Bureau of Meteorology stations**

Figure notes: AMO = Airport Meteorological Office; AWS = Automatic Weather Station; CCAM = Conformal Cubic Atmospheric Model; Obs = observed; RAAF = Royal Australian Air Force. Blue lines represent Conformal Cubic Atmospheric Model predictions and black dashed lines represent meridional wind observed at monitoring stations.

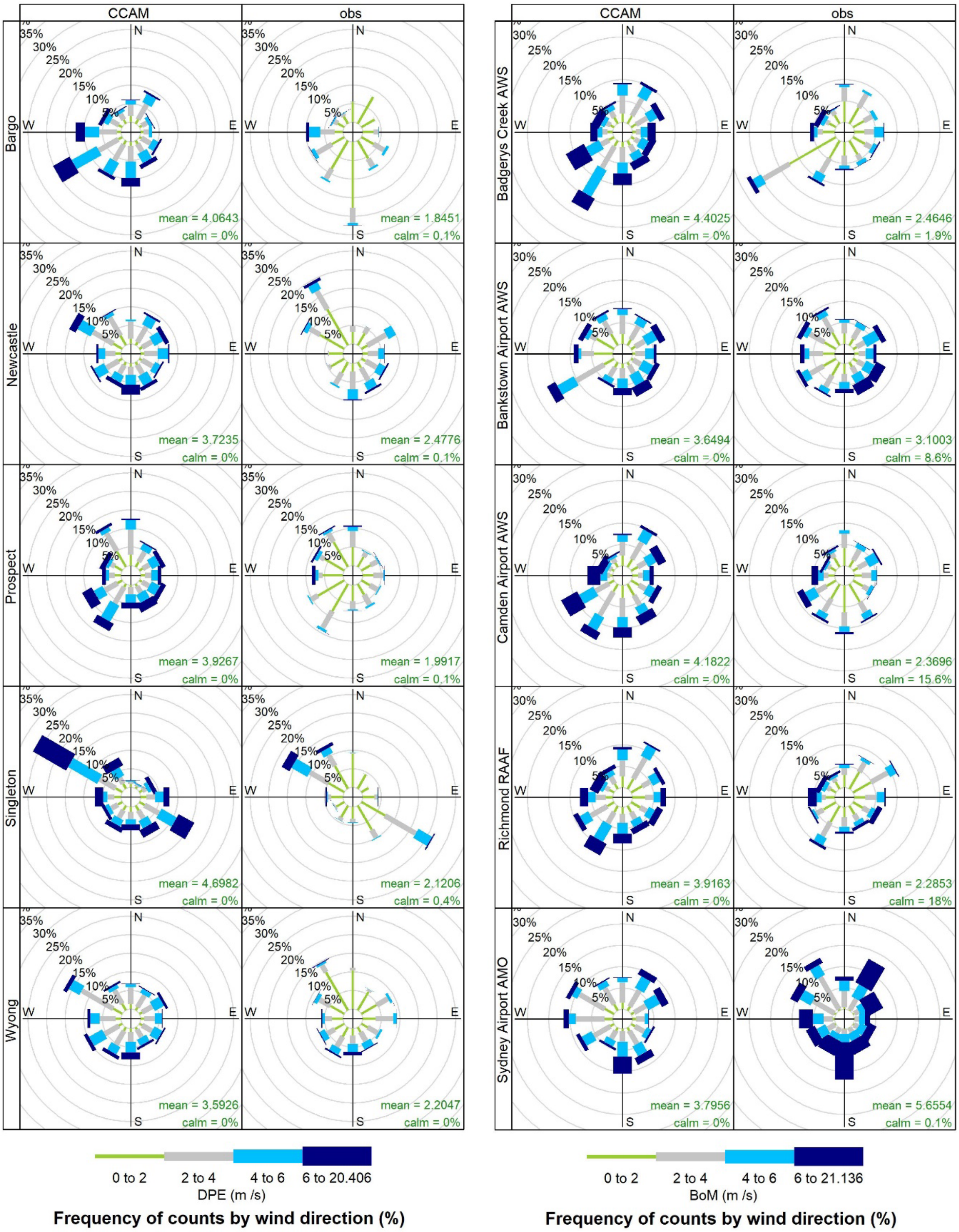


Figure 21 **Comparison of Conformal Cubic Atmospheric Model (CCAM) versus observation (Obs) wind rose plots at selected Department of Planning and Environment monitoring stations (left) and Bureau of Meteorology stations (right).**

Figure notes: calm represents any data with wind speed = 0 or wind direction = 0; mean represents mean wind speed; m/s = metres per second.

Statistical performance evaluation

The model performance for the entire period was assessed with several single statistical metrics (Table 11). 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 Department of Planning and Environment and BoM stations. The performance metrics presented are for temperature, wind speed and relative humidity. A statistical evaluation of wind direction is not included due to the complexity from errors at low wind speeds (Jimenez and Dudhia 2013).

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 2013 are shown in Table 12.

Taylor diagrams allow 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 (σ_M and σ_O; spread from the mean) representing amplitude of the variation of model results versus observations on a single diagram.

Table 11 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).

Performance statistics

The performance statistics for temperature further confirm what was demonstrated in the graphical evaluation, that is, there are positive biases across most sites, except Prospect and Sydney Airport. Comparing the mean bias values against the benchmarks, only one site does not meet the more relaxed conditions for complex terrain. For mean (gross) error, all sites meet the complex benchmarks and all the Department of Planning and Environment sites even meet the simple terrain benchmarks. The index of agreement for all stations is close to the ideal value of 1 and well over the benchmark. Overall, the metrics indicate that, while there are positive biases for temperature, they are small (<1°C) and meet the benchmarks for reasonable model performance.

The performance of the wind speed has a strong positive mean bias for all sites except Sydney Airport. Whilst there is a strong positive bias it does meet the benchmarks for complex terrain at Newcastle, Wyong, Bankstown Airport and are within 1 m/s at all remaining sites. The mean (gross) error meets benchmarks for complex terrain at all stations and simple terrain at Newcastle, Wyong and Bankstown Airport. The index of agreement meets benchmarks for all sites except Bargo, Prospect and Singleton which are very close. These statistics illustrate that the CCAM simulation of wind speeds are within reasonable range for model performance.

For relative humidity there are no benchmarks (mixing ratio has been used to represent atmospheric moisture in Emery et al. 2005); however, it is clear the modelling system is drier than the observations, with negative mean bias across all sites. The mean (gross) error ranges between 11.2 and 15.05, while the index of agreement sits between 0.78 at Wyong and 0.87 at Prospect.

Table 12 **Conformal Cubic Atmospheric Model performance statistics for temperature and wind speed at selected monitoring stations**

Parameter	Temperature			Wind speed			Relative humidity		
Stations	**MB**	**MGE**	**IOA**	**MB**	**MGE**	**IOA**	**MB**	**MGE**	**IOA**
Ideal value	0	0	1	0	0	1	0	0	1
Benchmark (simple)	≤±0.5	≤±2	≥0.8	≤±0.5	≤±2	≥0.6	n/a	n/a	n/a
Benchmark (complex)	≤±1	≤±3	n/a	≤±1.5	≤±2.5	n/a	n/a	n/a	n/a
Bargo	0.75	1.73	0.96	2.23	2.32	0.54	–8.64	13.18	0.84
Prospect	–0.02	1.63	0.97	1.93	2.17	0.58	–6.29	11.22	0.87
Newcastle	0.31	1.58	0.95	1.25	1.72	0.62	–8.60	12.56	0.80
Singleton	0.61	1.99	0.96	2.58	2.77	0.60	–9.72	13.64	0.86
Wyong	0.65	1.79	0.95	1.40	1.75	0.65	–11.43	14.72	0.78
Badgerys Creek	0.74	2.24	0.95	1.94	2.29	0.63	–11.23	14.95	0.82

Parameter	Temperature			Wind speed			Relative humidity		
Stations	**MB**	**MGE**	**IOA**	**MB**	**MGE**	**IOA**	**MB**	**MGE**	**IOA**
Bankstown Airport	0.88	2.38	0.93	0.55	1.65	0.75	–8.05	13.37	0.81
Camden Airport	1.26	2.56	0.93	1.81	2.26	0.68	–9.89	15.04	0.81
Richmond RAAF	0.63	2.37	0.95	1.63	2.18	0.70	–10.69	15.05	0.83
Sydney Airport	–0.08	1.72	0.94	–1.86	2.23	0.66	–3.26	11.45	0.83

Notes: MB = mean bias; MGE = mean (gross) error; IOA = index of agreement. Light grey shading indicates predictions that met complex terrain benchmarks; dark grey shading represents predictions that met the more stringent simple terrain benchmark; n/a = not applicable.

Taylor diagrams

The Taylor diagrams in Figures 22–26 show all the stations for each parameter and season. The optimal performance is when the model results are closest to the observed (purple dot on the x-axis). Between the seasons for all variables there is little difference in the performance statistics, indicating that the model performance is consistent throughout the year.

For relative humidity (Figure 22) the model performance clusters close together with the greatest spread seen in summer when the highest centred root mean square error is slightly over 1. The correlation coefficients are between 0.7 and 0.9.

The performance of CCAM for temperature (Figure 23) is good, with correlations between 0.8 and 0.9 and centred root mean square error is well below 1. The standard deviations of the model are also close to the centre line, indicating a similar amplitude of variation between CCAM and observations. The model performance for each station is clustered close together which indicates there are not any spatial biases in the CCAM's ability to simulate temperature across the Sydney Basin.

The performance of the wind speed (Figure 26) has more spread between stations. For most stations the correlations are between 0.4 and 0.75 and the centred root mean square error are predominantly under 1.5. The performance is worst at Singleton, Bargo and Prospect, while it is best at Sydney and Bankstown airports, which is consistent with the other statistics presented in Table 12.

The zonal and meridional winds (Figure 24 and Figure 25) have a greater spread across the Taylor diagrams with little variability between seasons. The correlations are between 0.4 and 0.8 and the centred root mean square error are less than 2. As with wind speed, the best representation of winds is at Sydney and Bankstown airports. This would largely be influenced by the higher wind speeds recorded at these stations as CCAM has much strong wind speeds, as seen in the previous analysis.

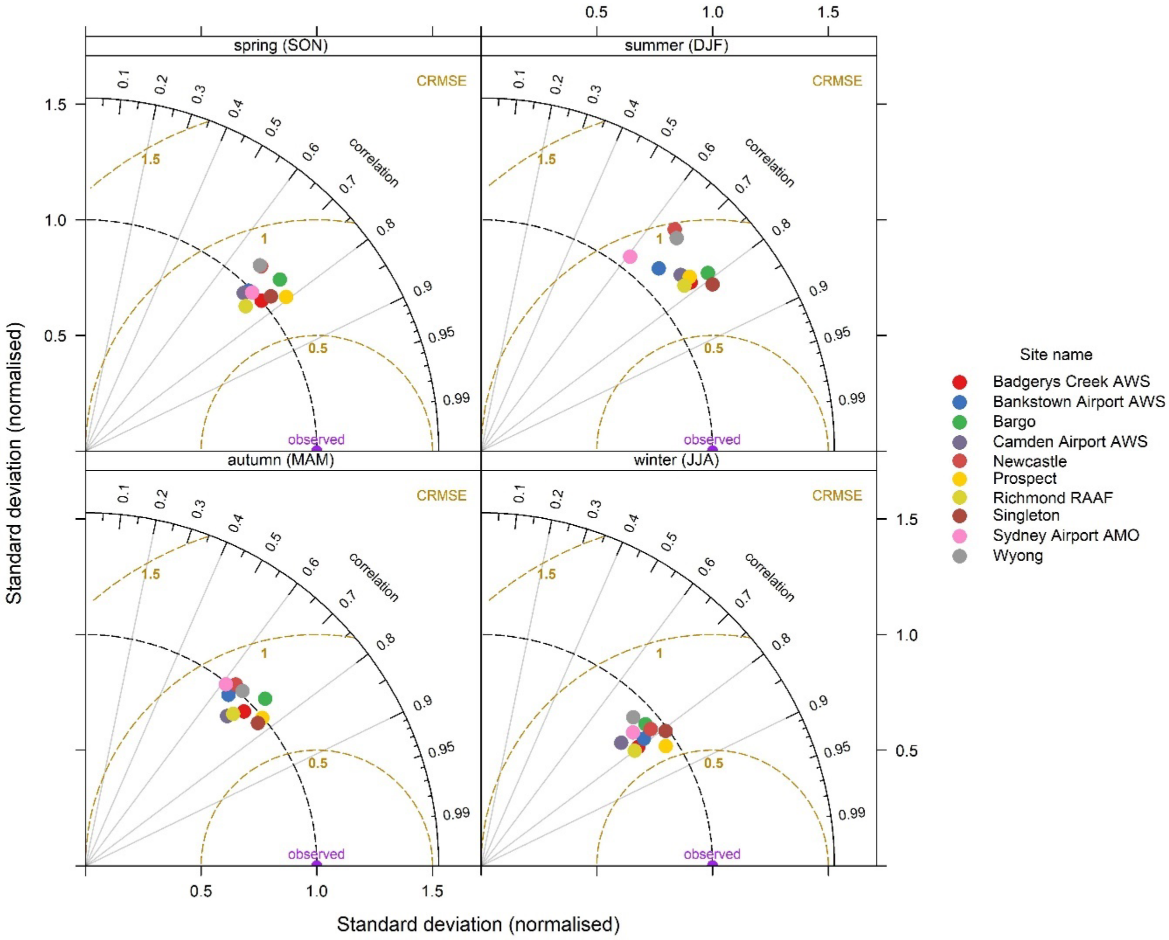


Figure 22 **Seasonal Taylor diagrams for relative humidity for all Department of Planning and Environment and Bureau of Meteorology monitoring stations**

Figure notes: AMO = Airport Meteorological Office; AWS = Automatic Weather Station; 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.

Seasonal Taylor diagrams for temperature for all Department of Planning and Environment and Bureau of Meteorology stations (indicated by different coloured circles). Top left is spring, top right is summer, bottom left is autumn and bottom right is winter.

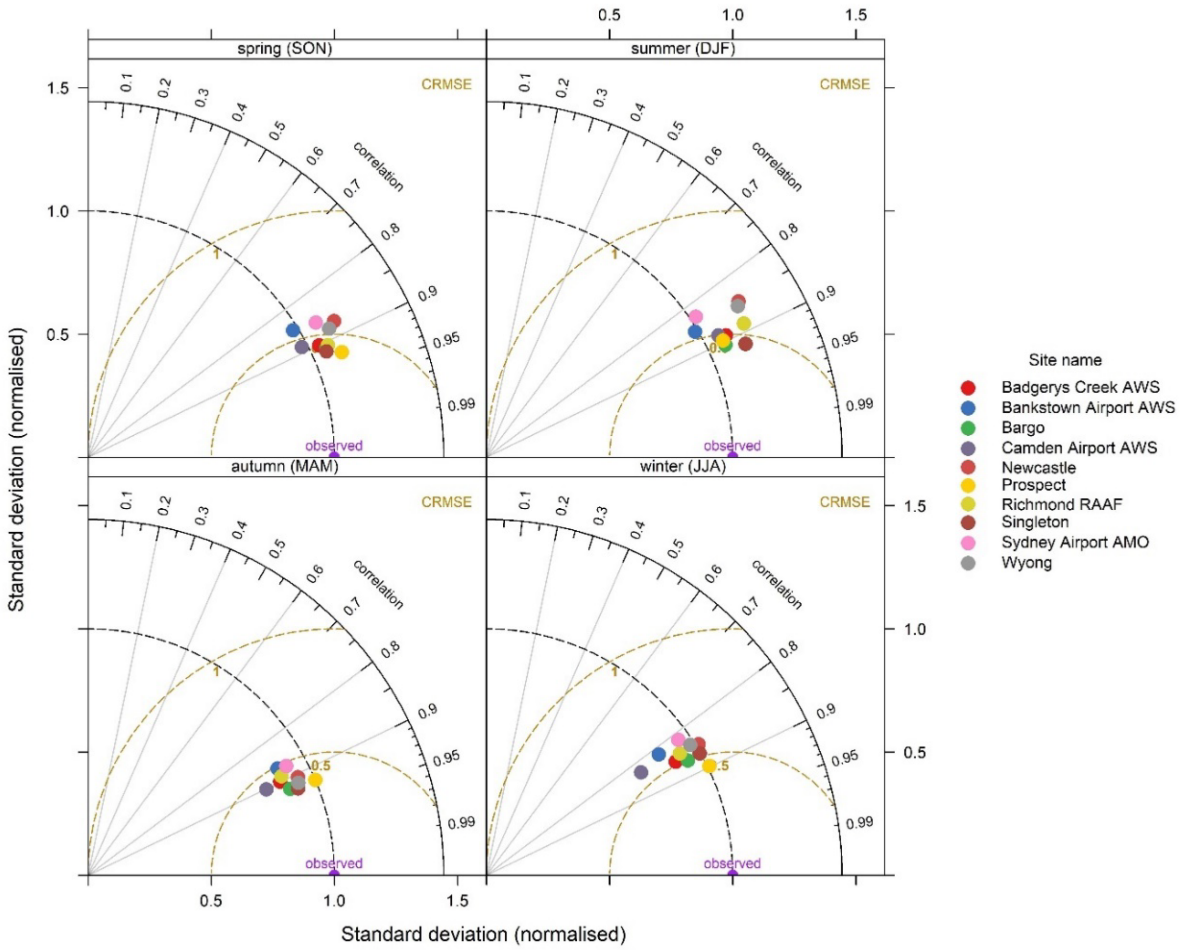


Figure 23 Seasonal Taylor diagrams for temperature for all Department of Planning and Environment and Bureau of Meteorology monitoring stations

Figure notes: AMO = Airport Meteorological Office; AWS = Automatic Weather Station; 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.

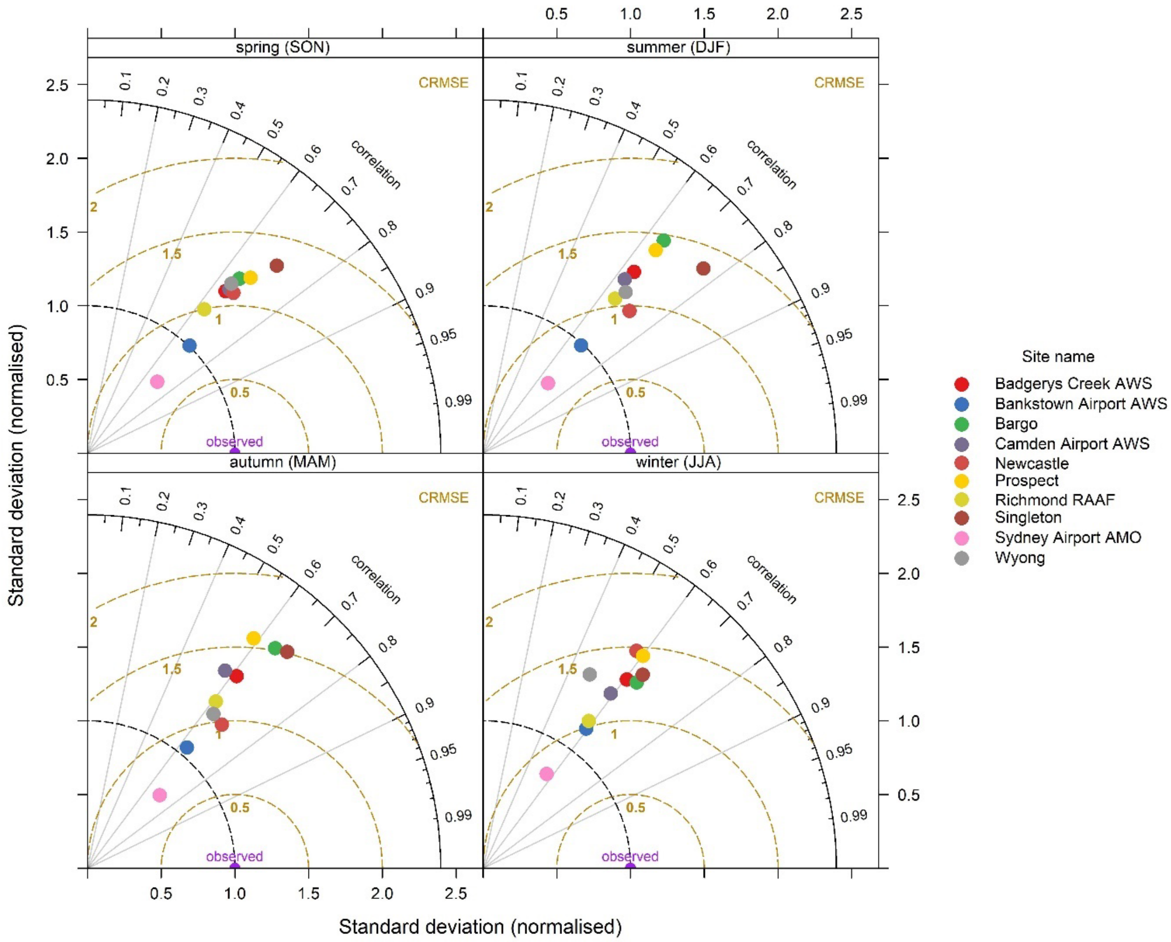


Figure 24 **Seasonal Taylor diagrams for zonal wind component for all Department of Planning and Environment and Bureau of Meteorology monitoring stations**

Figure notes: AMO = Airport Meteorological Office; AWS = Automatic Weather Station; 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.

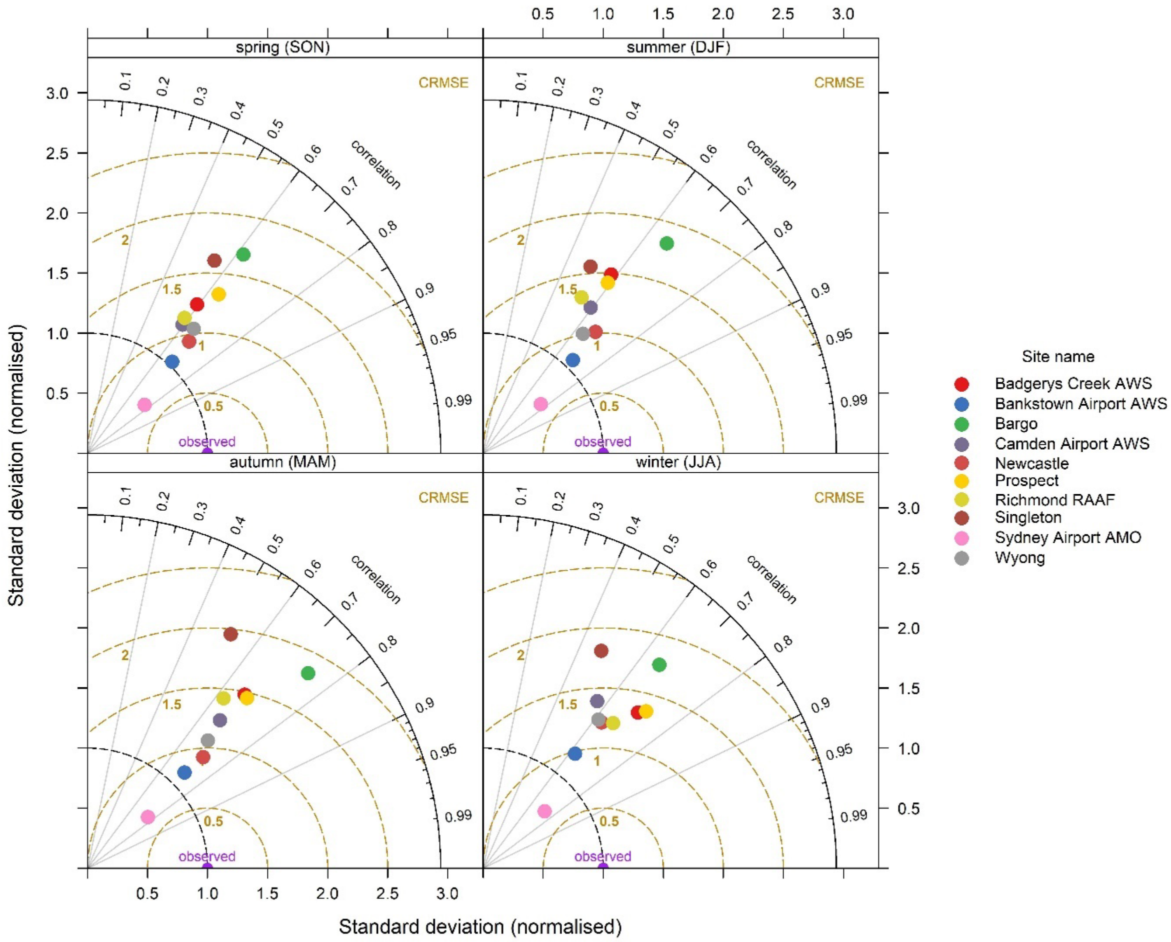


Figure 25 **Seasonal Taylor diagrams for meridional wind component for all Department of Planning and Environment and Bureau of Meteorology monitoring stations**

Figure notes: AMO = Airport Meteorological Office; AWS = Automatic Weather Station; 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.

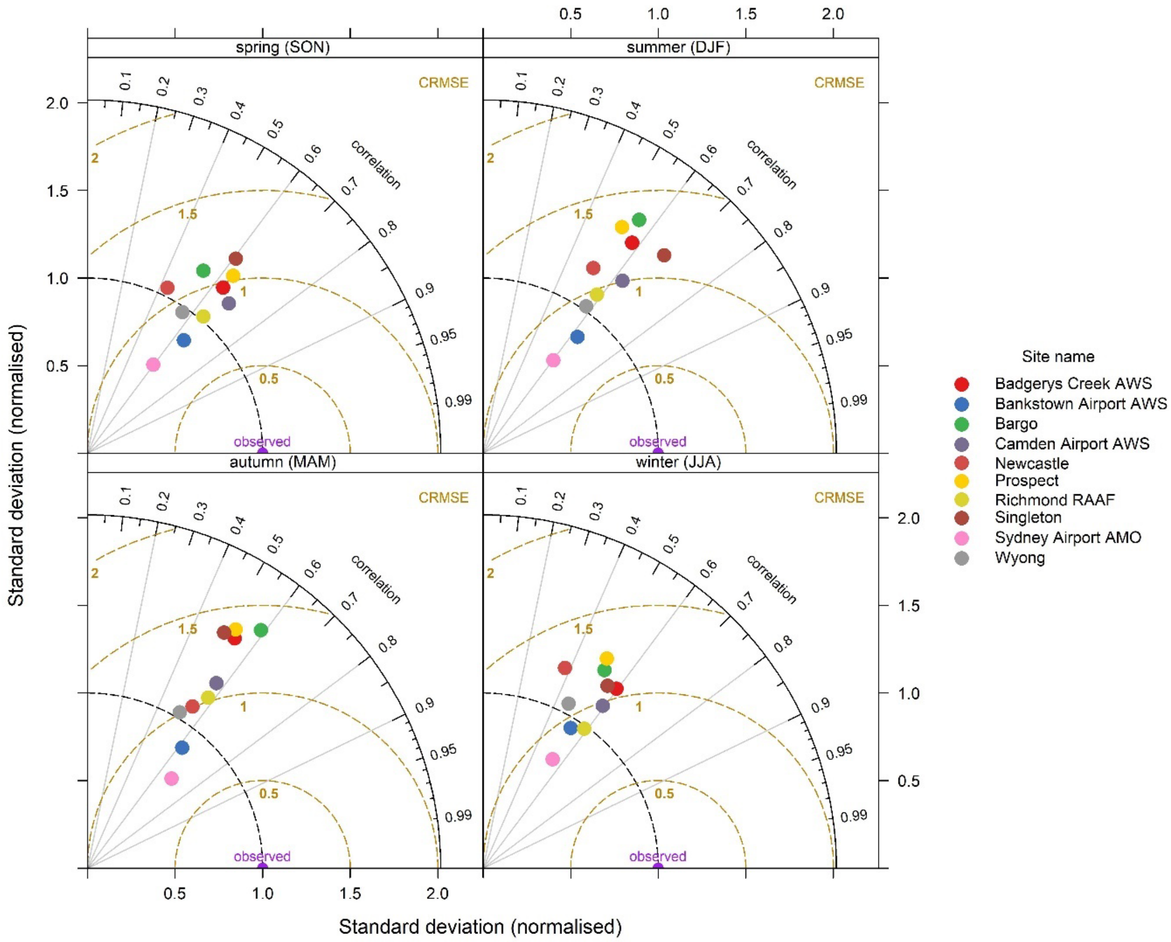


Figure 26 **Seasonal Taylor diagrams for wind speed for all Department of Planning and Environment and Bureau of Meteorology monitoring stations**

Figure notes: AMO = Airport Meteorological Office; AWS = Automatic Weather Station; 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.

Conclusions

Temperatures are well represented by the CCAM simulation, and the seasonal and daily cycle are captured. The temperatures are slightly warmer in the model overnight but meet the referenced model benchmarks at almost all stations. With biases and centred root mean square error below 1.5°C, it is not expected that the positive biases will have a large impact on the photochemistry of the chemical transport model.

CCAM has less atmospheric moisture than observed, which is more pronounced overnight. This may impact on photochemistry and aerosol formation in the subsequent chemical transport modelling via reductions in afternoon convection or the formation of non-precipitating cloud.

Winds are overpredicted, particularly overnight; however, the average cycle through the year and daily averages are captured. Additionally, whilst too fast, the wind speeds are within reasonable limits of the expected performance of a mesoscale meteorological model at most stations. The stronger winds overnight could impact on the dispersion of pollutants under stable conditions. This should be considered when assessing the performance of the chemical transport model.

Appendix B: Chemical Transport Model performance

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, that is, 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 13).

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 13 **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%

Metrics	Mathematical expression	Range
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 shows skill

Ambient air quality data was provided by the NSW Department of Planning and Environment Air Quality Monitoring Network. The locations of monitoring sites that provided observations used for this evaluation represent the following regions:

- 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
- Newcastle – Newcastle (Figure 27).

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 5 sites: Chullora, Earlwood, Richmond, Liverpool and Wollongong.

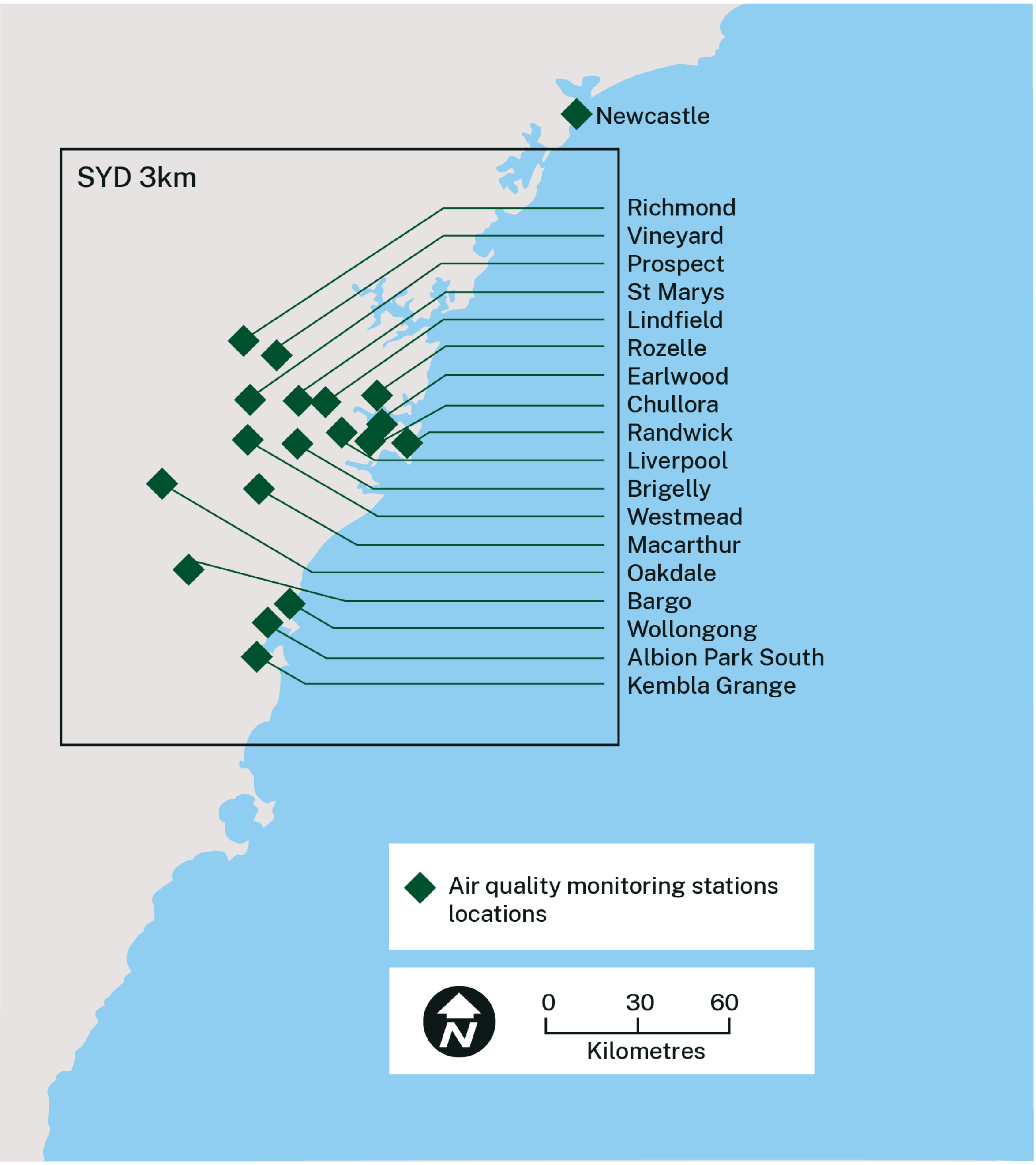


Figure 27 **Location of 18 Department of Planning and Environment air quality monitoring stations. Stations are located within the innermost domain used for Conformal Cubic Atmospheric Model–Chemical Transport Model simulation with a horizontal resolution of 3 kilometres**

Model evaluation

Summaries of CTM model performance for predicting ozone and $PM_{2.5}$ levels in 2013 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 subregions. Seasons are defined by months: summer – December, January, February (DJF); autumn – March, April, May (MAM); winter – June, July, August (JJA); and spring – September, October, November (SON).

The quantitative performance statistics summary is based on paired hourly predictions and observations. As discussed in Boylan and Russell (2006), mean bias and mean error are defined as the average difference between all predicted–observed pairs, and the error only includes absolute deviation between the 2. The normalised mean bias and normalised mean error normalise the mean bias and mean error by the mean of observations, and they assume observations are the absolute truth. The normalised mean bias ranges from –100% to +∞, whereas the normalised mean error range is from 0% to +∞, which results in overpredictions artificially being given more weight than underpredictions. The mean fractional bias is defined as the bias normalised by the mean of paired predictions–observations; accordingly, the mean fractional error can be defined in a similar way. Among the 6 metrics used, the mean fractional bias and mean fractional error are the least biased. The index of agreement 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 index of agreement ranges from 0 to 1, where 1 would present a perfect agreement.

Ozone

Table 14 summarises the quantitative performance statistics for the predicted hourly ozone, along with the mean and standard deviation of predicted values and observations at selected air quality stations. Predicted ozone concentrations were generally higher than observations, with lowest mean bias for 0.14 ppb (parts per billion) at Randwick and highest mean bias for 6.92 ppb at Bringelly.

The US Environment Protection Agency (USEPA) recommended the benchmarks of mean fractional bias and mean fractional error are ±15% and 35% for ozone predictions (USEPA 2007). Results in Table 14 show that the mean fractional bias for Oakdale, Randwick and Rozelle fell within the benchmark of mean fractional bias of ±15% (highlighted with yellow). However, only mean fractional error for Oakdale complies the benchmark of mean fractional error of 35% (highlighted with green). Simon et al. (2012) reported the root mean square errors are in the range of 15–20 ppb for hourly ozone concentrations in most of model validation studies, and the root mean square error in our studies are far under that.

Figure 28 is the diurnal variations for predicted and observed hourly ozone concentration in each season at Chullora (Sydney east), Richmond (Sydney north-west), Bringelly (Sydney south-west), Wollongong (Illawarra) and Newcastle (Newcastle). Generally, the CTM can reproduce the diurnal variations of ozone well across seasons and regions.

Figure 29 is the time-series for predicted and observed hourly ozone concentrations.

Particulate matter

Table 15 summarises the quantitative performance statistics for the predicted hourly $PM_{2.5}$, along with the mean and standard deviation of predicted values and observations at selected air quality stations. The mean bias shows that hourly $PM_{2.5}$ is generally underpredicted except for Singleton.

Figure 30 is the seasonal diurnal variations for predicted and observed hourly $PM_{2.5}$ concentration at Chullora (Sydney east), Richmond (Sydney north-west) and Wollongong (Illawarra). CTM generally predict the diurnal variation well at Chullora and Wollongong in summer (DJF), autumn (MAM) and spring (SON); however, a significant negative bias can be found in the predicted $PM_{2.5}$ at Richmond across seasons.

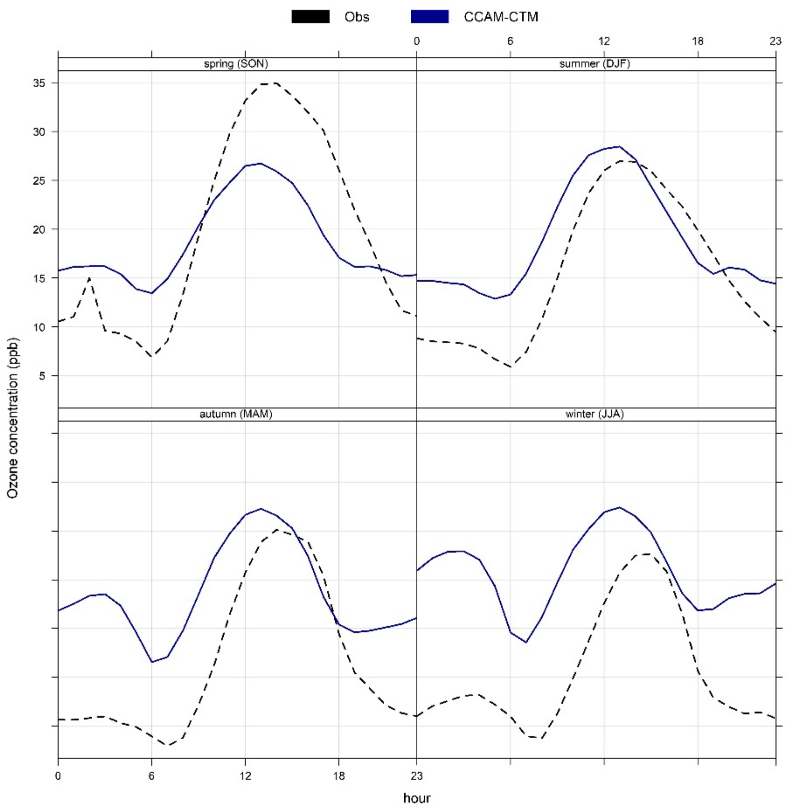
Figure 31 is the time series for predicted and observed hourly $PM_{2.5}$ concentrations.

Table 14 **Quantitative performance statistics for predicted hourly ozone (O_3) concentration (parts per billion [ppb]) against observation at a selection of Department of Planning and Environment air quality monitoring stations**

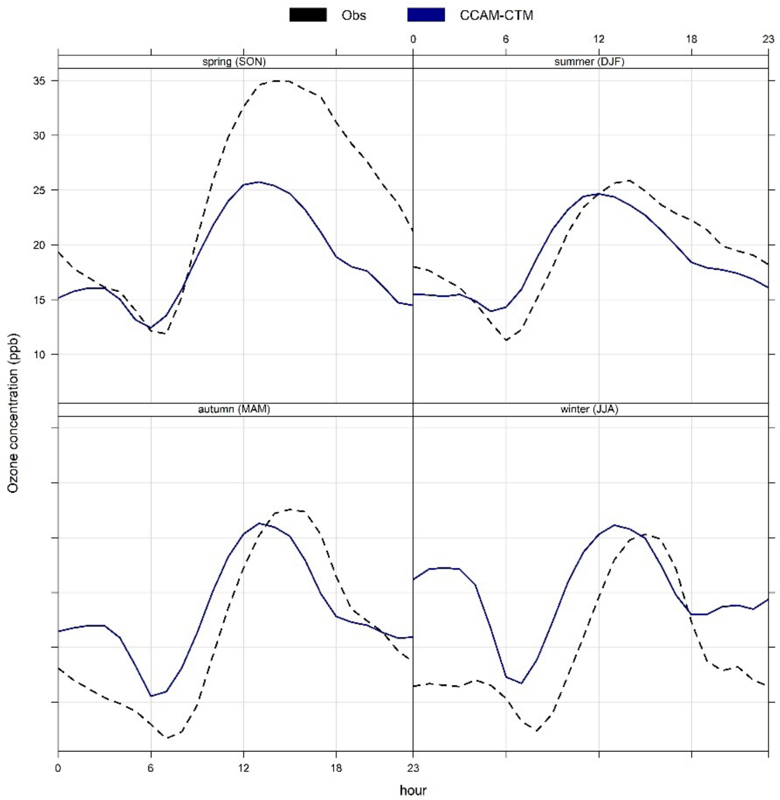
Site	Mean obs	Mean CTM	SD obs	SD CTM	MB	NMB	MFB	ME	NME	MFE	RMSE	r	IOA
Albion Park Sth	20.04	24.67	11.59	6.40	4.64	0.23	0.32	9.59	0.48	0.49	12.39	0.29	0.49
Bargo	20.32	24.90	13.00	6.99	4.66	0.23	0.36	9.87	0.49	0.53	12.84	0.41	0.52
Bringelly	16.68	23.53	13.41	8.17	6.92	0.41	0.53	11.45	0.69	0.72	14.27	0.41	0.47
Camden	18.75	24.65	13.72	7.53	6.00	0.32	0.43	11.44	0.61	0.62	14.53	0.34	0.47
Campbelltown West	14.91	21.59	13.09	8.24	6.79	0.46	0.62	10.67	0.72	0.78	13.16	0.52	0.50
Chullora	14.37	19.19	11.86	8.50	4.88	0.34	0.48	8.86	0.62	0.68	11.23	0.55	0.54
Earlwood	15.12	18.47	11.79	8.10	3.31	0.22	0.37	8.73	0.58	0.65	11.25	0.47	0.55
Kembla Grange	18.87	23.35	11.03	7.15	4.52	0.24	0.32	8.55	0.45	0.48	11.21	0.43	0.52
Lindfield	15.66	20.56	10.94	7.88	4.91	0.31	0.42	8.51	0.54	0.60	10.84	0.51	0.52
Liverpool	14.86	18.98	13.56	9.12	4.24	0.29	0.55	9.14	0.62	0.77	11.65	0.60	0.58
Oakdale	24.78	26.73	9.71	6.20	1.97	0.08	0.11	7.20	0.29	0.27	9.32	0.41	0.49
Prospect	17.28	19.41	13.40	8.74	2.13	0.12	0.28	8.95	0.52	0.59	11.47	0.55	0.58
Randwick	18.81	18.86	11.19	7.91	0.14	0.01	0.12	7.59	0.40	0.48	9.94	0.50	0.57
Richmond	18.85	25.52	13.17	6.68	6.76	0.36	0.46	11.66	0.62	0.61	14.34	0.33	0.46
Rozelle	17.16	17.58	10.00	8.46	0.44	0.03	0.04	7.63	0.44	0.51	9.84	0.44	0.53
St Marys	17.11	22.13	13.79	8.35	5.07	0.30	0.45	10.83	0.63	0.68	13.41	0.46	0.52
Vineyard	18.66	23.61	13.19	7.62	5.01	0.27	0.40	10.76	0.58	0.61	13.35	0.39	0.49
Wollongong	18.22	22.47	11.27	7.12	4.25	0.23	0.32	8.86	0.49	0.50	11.42	0.41	0.50
Newcastle	17.81	22.09	11.10	6.82	4.42	0.25	0.37	8.61	0.48	0.54	11.12	0.44	0.52
Wyong	17.34	22.91	12.03	7.33	5.67	0.33	0.44	10.23	0.59	0.62	12.83	0.38	0.48

Notes: MFB within ±15% is highlighted with yellow; MFE <35% is highlighted with green. SD = standard deviation; MB = mean bias; NMB = normalised mean bias; MFB = mean fractional bias; ME = mean error; NME = normalised mean error; MFE = mean fractional error; RMSE = root mean square error (RMSE); r = correlation coefficient; IOA = index of agreement (IOA).

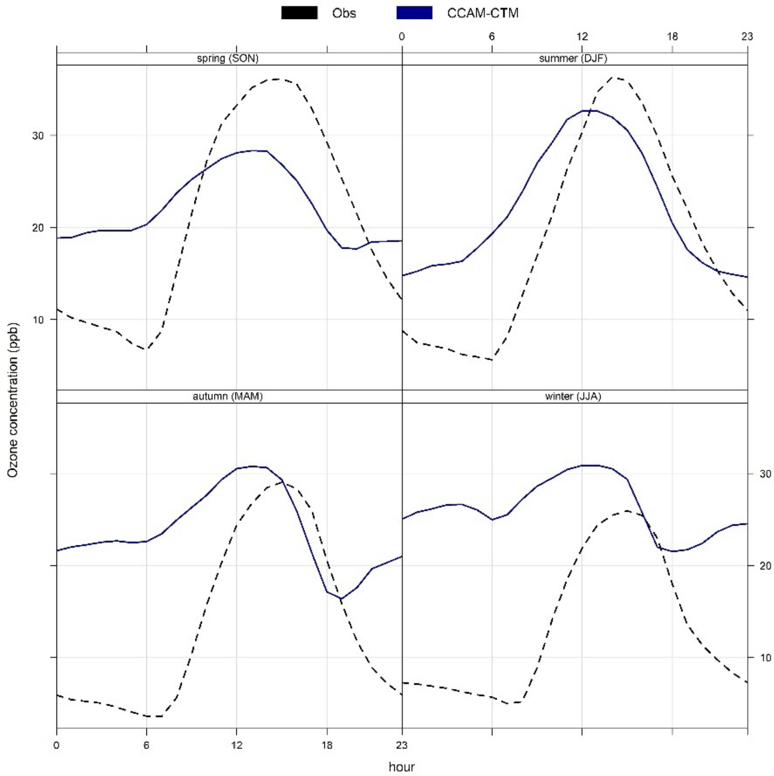
(a)


Obs
CCAM-CTM
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
Ozone concentration (ppb)
hour
0
6
12
18
23
5
10
15
20
25
30
35

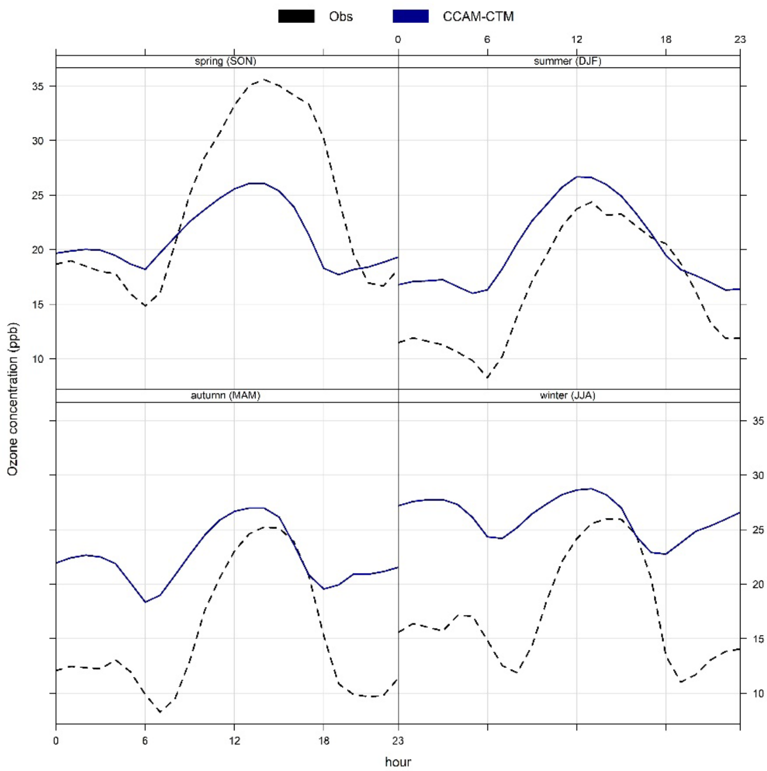
(b)


Obs
CCAM-CTM
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
Ozone concentration (ppb)
hour
0
6
12
18
23
10
15
20
25
30
35

(c)


Obs
CCAM-CTM
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
Ozone concentration (ppb)
hour
0
6
12
18
23
10
20
30

(d)


Obs
CCAM-CTM
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
Ozone concentration (ppb)
hour
0
6
12
18
23
10
15
20
25
30
35

(e)

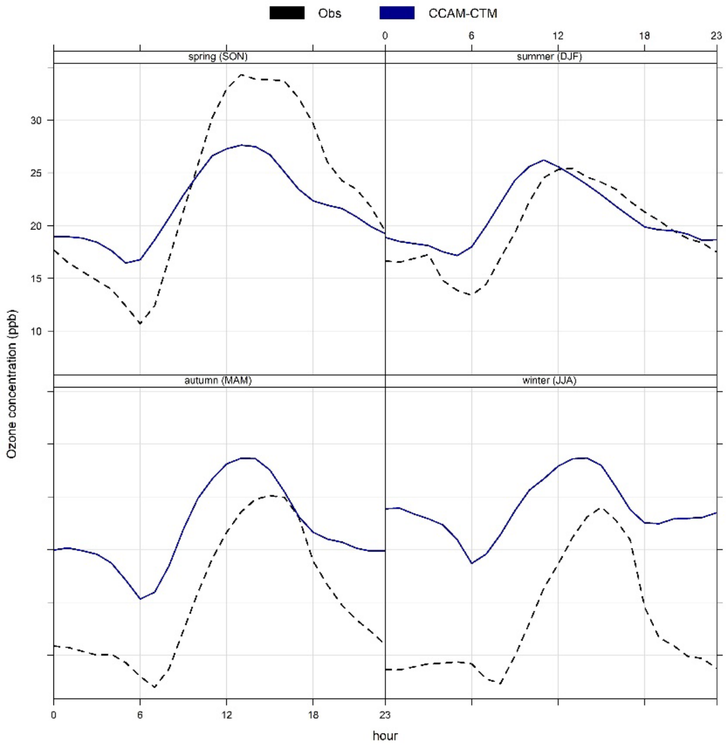


Figure 28 **Seasonal diurnal variations for predicted (CCAM–CTM; blue) and observed (Obs; dashed black) hourly ozone (O_3) concentration in parts per billion (ppb) at (a) Chullora, (b) Richmond, (c) Bringelly, (d) Wollongong and (e) Newcastle**

Figure notes: 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.

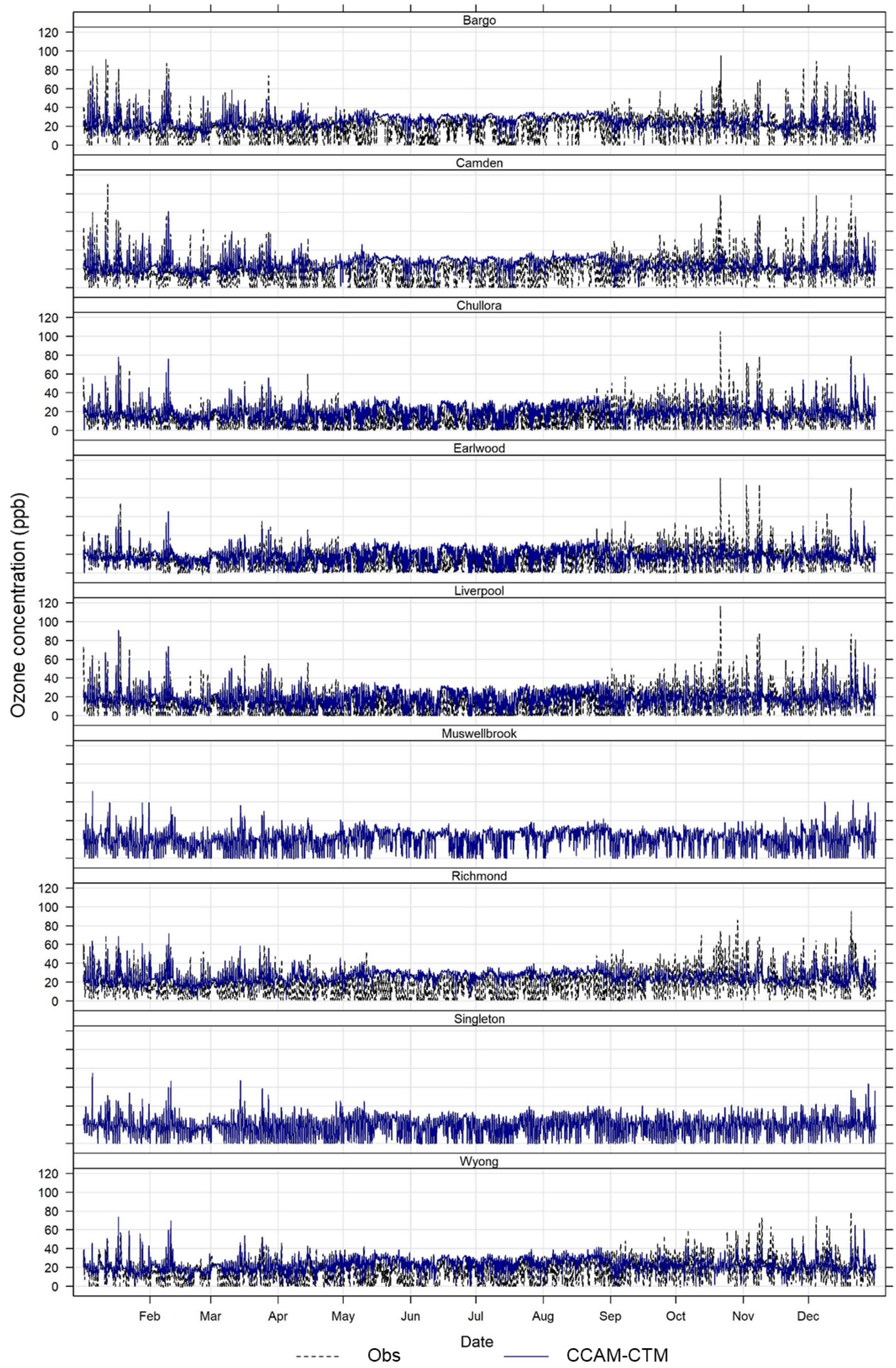


Figure 29 **Time-series of predicted (CCAM-CTM; blue) and observed (Obs; black) hourly ozone (O_3) concentration in parts per billion (ppb) at a selection of Department of Planning and Environment air quality monitoring stations**

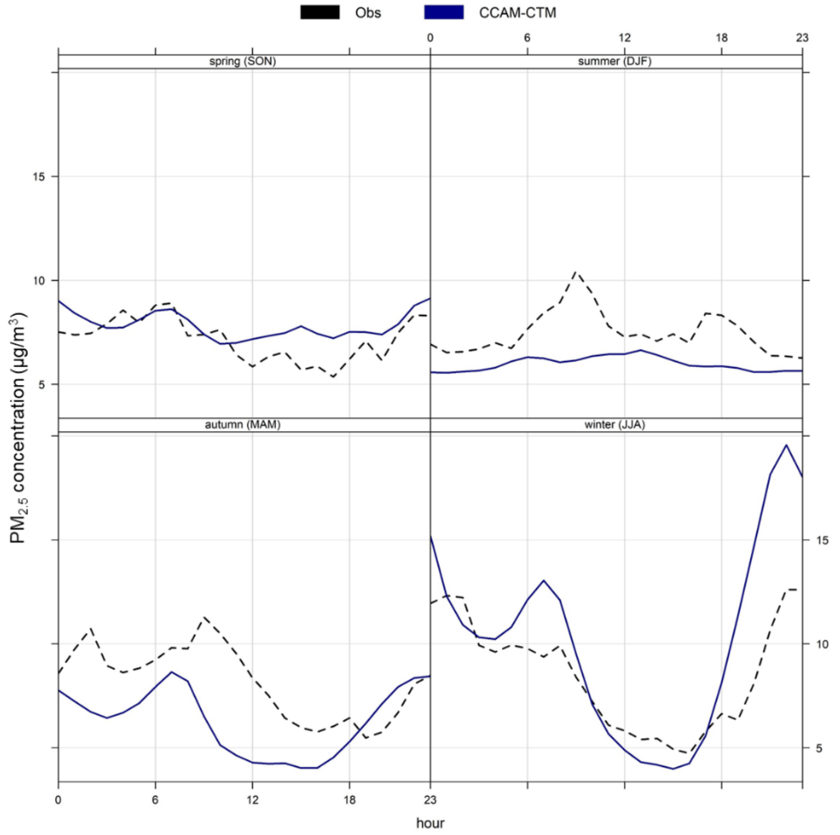
Notes: CCAM–CTM = Conformal Cubic Atmospheric Model–chemical transport model.

Table 15 **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 at a selection of Department of Planning and Environment air quality monitoring stations**

Site	Mean obs	Mean CTM	SD obs	SD CTM	MB	NMB	MFB	ME	NME	MFE	RMSE	r	IOA
Camden	5.96	5.20	5.14	5.89	−0.78	−0.13	0.24	4.33	0.73	1.09	7.01	0.22	0.43
Chullora	7.92	7.61	5.69	7.91	−0.25	−0.03		5.23	0.66		8.15	0.33	0.39
Earlwood	7.42	7.36	5.79	7.68	−0.01	0.00		4.95	0.67		7.99	0.34	0.42
Liverpool	8.95	7.15	7.76	6.80	−1.72	−0.19	0.17	5.85	0.65	0.90	8.66	0.31	0.49
Richmond	6.93	5.11	6.56	5.64	−1.90	−0.27		4.86	0.70		8.25	0.13	0.44
Wollongong	7.08	4.79	6.35	5.02	−2.36	−0.33		5.06	0.71		7.56	0.20	0.46
Singleton	7.55	9.20	6.46	9.73	1.65	0.22		6.20	0.82		10.35	0.26	0.31
Muswellbrook	9.23	7.74	8.95	9.20	−1.32	−0.14	−0.13	7.66	0.83	0.87	12.62	0.07	0.33
Wyong	6.16	5.50	5.34	5.84	−0.69	−0.11		4.59	0.74		7.00	0.20	0.43

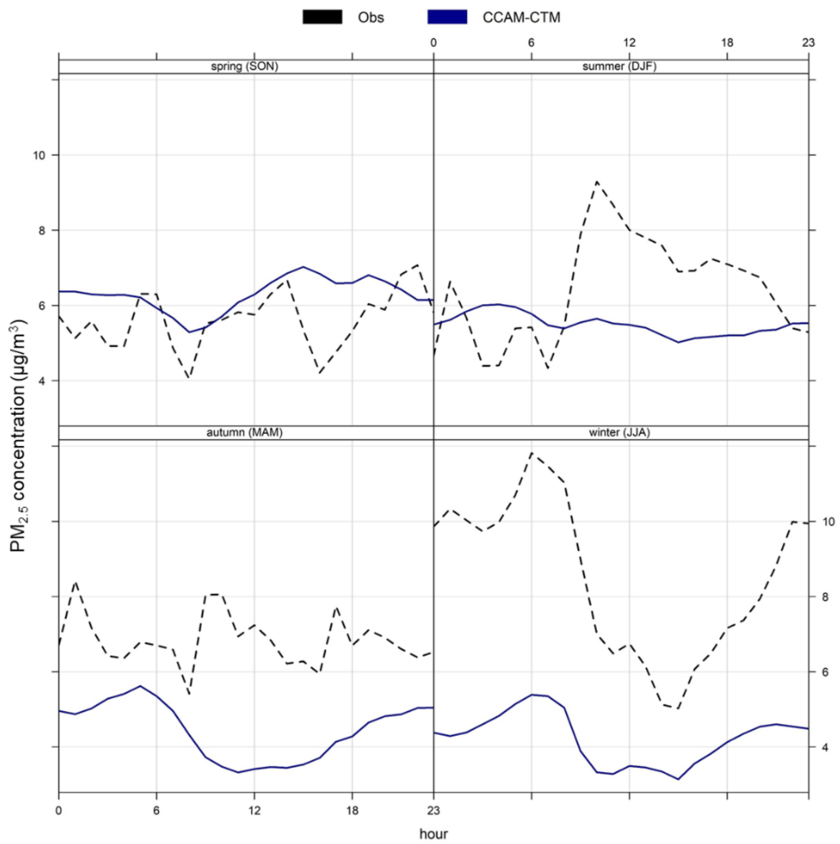
Note: SD = standard deviation; MB = mean bias; NMB = normalised mean bias; MFB = mean fractional bias; ME = mean error; NME = normalised mean error; MFE = mean fractional error; RMSE = root mean square error (RMSE); r = correlation coefficient; IOA = index of agreement (IOA).

(a)



Obs
CCAM-CTM
spring (SON)
summer (DJF)
autumn (MAM)
winter (JJA)
PM2.5 concentration (µg/m3)
hour
0
6
12
18
23
5
10
15

(b)



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

(c)

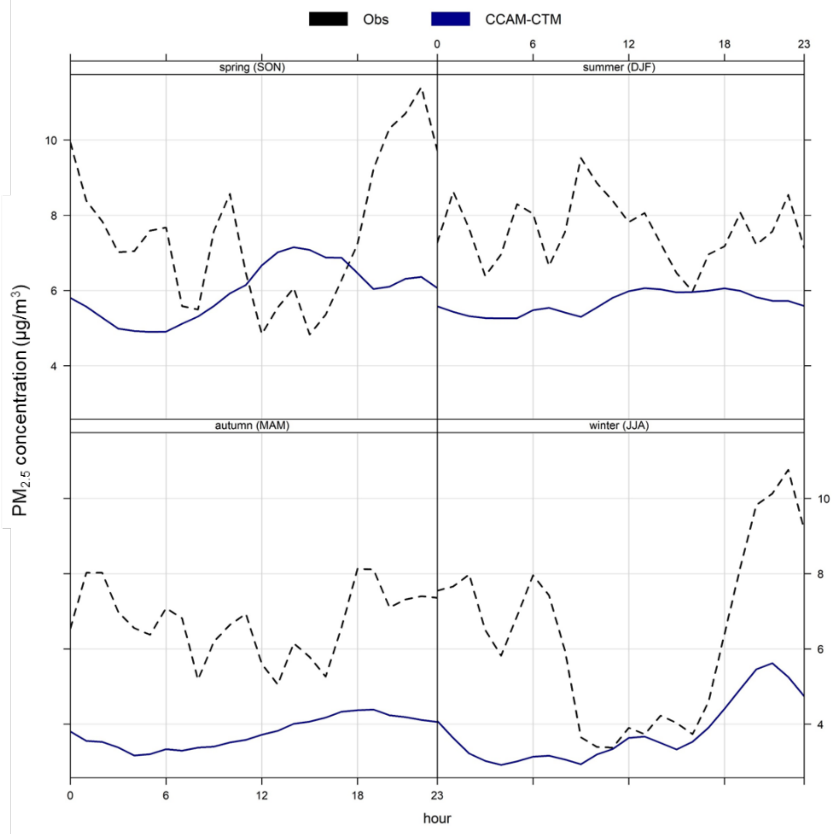


Figure 30 **Seasonal diurnal variations for predicted (CCAM–CTM; blue) and observed (Obs; dashed black) hourly concentrations (microgram per cubic metre (µg/m³) of particles less than 2.5 micrometres in diameter ($PM_{2.5}$) at (a) Chullora, (b) Richmond and (c) Wollongong**

Figure notes: 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.

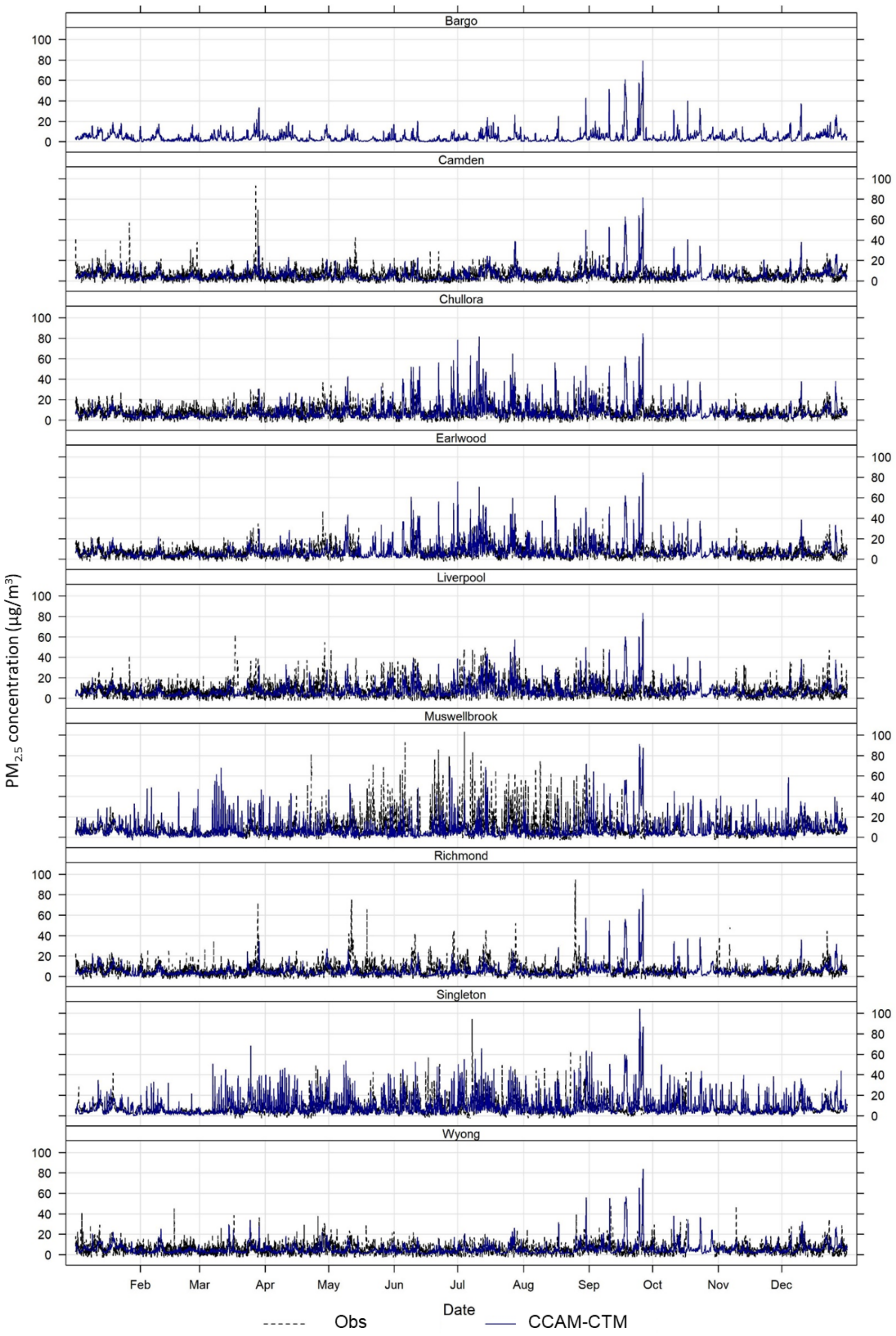


Figure 31 Time series of predicted (CCAM-CTM; blue) and observed (Obs; black) hourly concentrations (microgram per cubic metre [µg/m³]) of particles less than 2.5 micrometres in diameter ($PM_{2.5}$) at a selection of Department of Planning and Environment air quality monitoring stations

Figure notes: CCAM–CTM = Conformal Cubic Atmospheric Model–chemical transport model.

List of abbreviations

Abbreviation	Meaning
°C	degrees Celsius
µg/m^3	micrograms per cubic metre
AN	attributable number of premature deaths,
AUD 2021	Australian dollars at 2021 value
BoM	Bureau of Meteorology
CCAM	Conformal Cubic Atmospheric Model
CO	carbon monoxide
CRMSE	centred root mean square error
CTM	Chemical Transport Model (CTM),
DJF	summer – December, January, February
DPE	Department of Planning and Environment
EPA	NSW Environment Protection Authority (the EPA)
ERA-Interim	European Reanalysis Interim
GMA	NSW Greater Metropolitan Area (GMA)
GMR	NSW Greater Metropolitan Region (GMR)
IF	impact factor
IOA	index of agreement
IOMLIFET	Institute of Occupational Medicine LIFE Table
JJA	winter – June, July, August
LE	life expectancy
m/s	metres per second
MAM	autumn – March, April, May
MB	mean bias (positive or negative deviation from the mean)
ME	mean error
MFB	mean fractional bias
MFE	mean fractional error
MGE	mean (gross) error (MGE; overall deviation from the mean)
NEPM	National Environment Protection Measure
NMB	normalised mean bias
NME	normalised mean error
NO_x, NO, NO_2	nitrogen oxides
O_3	ozone
$PM_{2.5}$	particulate matter less than 2.5 micrometres in diameter
PM_{10}	particulate matter less than 10 micrometres in diameter

Abbreviation	Meaning
ppb	parts per billion
pwaa-$PM_{2.5}$	population-weighted annual average $PM_{2.5}$ concentrations
R	correlation coefficient
SO_2	sulfur dioxide
SON	spring – September, October, November
VOCs	volatile organic compounds
VSL	value of a statistical life
VSLY	value of a statistical life year
YLL	years of life lost

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More information

- Air Quality Monitoring Network – Department of Planning and Environment webpage
- National Environment Protection (Ambient Air Quality) Measure (NEPM)