State of Knowledge: Ozone

Acknowledgements

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Executive summary

The last major air quality report published was the outcomes of the Metropolitan Air Quality Study in 1997. This current report summarises the knowledge gained since that publication regarding photochemical pollution, as measured by ozone concentration, up to 2004. It includes a description of ozone events in the Sydney, Illawarra, lower Hunter (Newcastle) and Bathurst regions and details air quality modelling investigating events which give rise to ozone exceedences, as well as an investigation of the impact of emissions projected to 2026.

The National Environment Protection (Ambient Air Quality) Measure, hereafter 'AAQ NEPM', sets a standard and goal for both one-hour and four-hour ozone concentrations. The goal for each is no more than one day per calendar year exceeding the standard concentration at each monitoring site. The standard concentration is 0.10 ppm for one-hour ozone and 0.08 ppm for four-hour. Consideration is being given to an eight-hour standard concentration and goal.

Two approaches have been taken to increase understanding of photochemical pollution in New South Wales (NSW). Observations of ozone concentration have been analysed to enhance descriptions of ozone pollution events. An airshed modelling system has been used to simulate four pollution events and, using these simulations, explore the impact on ozone concentration of changes to the emissions, including projections of emissions in future years.

Analysis of observations of ozone concentrations 1994–2004

The concentration of ozone in ambient air has been determined at air quality monitoring sites in NSW by the Department of Environment, Climate Change and Water (DECCW) and its predecessor organisations. Data from monitoring sites in the Sydney, Illawarra and lower Hunter regions for the years 1994 to 2004 are analysed and presented here as is the data from campaign monitoring at Bathurst.

Exceedences of the current AAQ NEPM ozone standards were investigated. Bushfire event days have not been excluded from the analysis in this report. While observations for the lower Hunter and Illawarra are presented, the main focus of this report is an analysis of ozone in the Sydney Basin, as ozone concentrations infrequently exceed the standards in either the Illawarra or the lower Hunter regions. Bathurst reported no exceedences.

Elevated ozone concentrations occur under particular meteorological conditions. Concentrations greater than the standards occur only in the warmer months; in most cases, the maximum temperature on the day was more than 30^{o}C. Other meteorological conditions are necessary for elevated ozone concentrations to occur.

The frequency of the conditions promoting elevated concentrations of ozone varied considerably from year-to-year. There was no trend in the number of exceedence-days each calendar year for the period 1994 to 2004, with the number of days exceeding the four-hour goal varying from as few as one in 1995 to as many as 21 in both 1997 and 2001. Bushfires can be significant in contributing to ozone concentration and this was apparent from the number of exceedence-days during bushfire periods. Climate variability, changes in the monitoring network, and changes in the distribution of sources in a region also complicate trend analysis.

For the 11 years analysed, there were a total of 108 days exceeding the one-hour standard in the Sydney region and 138 days exceeding the four-hour standard. Exceedences were infrequent in the Illawarra and rare in the lower Hunter. The Illawarra region recorded 30 days exceeding the one-hour standard and 41 exceeding the four-hour standard while the lower Hunter reported two days exceeding the one-hour standard and three exceeding the four-hour standard.

Analysis of the Sydney exceedence-days shows that all but seven recording an exceedence of the one-hour standard also recorded an exceedence of the four-hour standard. Conversely, there were 37 days recording an exceedence of the four-hour standard but not exceeding the one-hour standard.

Elevated concentrations of ozone were usually relatively short-lived and often localised. Analysis of the exceedences shows that over half of them were limited to one or two monitoring sites. On days where an exceedence was recorded at more than one site, maximum ozone concentration in the region was most likely to occur in western Sydney. The majority of the exceedences lasted for three hours or less. The longest time period exceeding the one-hour standard was seven hours; for the four-hour standard, it was nine hours.

The data has also been analysed to characterise the time of day ozone concentrations exceeded the standard concentrations. This tended to be in the afternoon, and was earlier in the day for sites in the east of the Sydney Basin (Woolooware, Lindfield, Earlwood, Rozelle and Randwick) and later for sites in the west.

As ozone is formed from the photochemical reaction of oxides of nitrogen (NO_x) and volatile organic compounds (VOCs), it is useful to management of the air environment to describe the influence each precursor has on ozone concentration. The Integrated Empiric Rate (IER) model developed by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) from smog chamber experiments provides a means of characterising an ozone event day as light-limited, in transition or NO_x-limited.

The IER model was used to interpret observational data and showed that regardless of the region or the averaging period, most exceedence-days were NO_x-limited, particularly in western Sydney (92%). This means that reducing NO_x is expected to be effective in reducing ozone concentration for these days. Thirty percent of days in central and eastern Sydney were 'in transition', and these days may not benefit from NO_x control alone.

Bushfires are a potentially significant natural source of both ozone precursors. Concentrations of the precursors within smoke plumes are sufficient to generate ozone concentrations greater than the current standards. Emissions from bushfires are known to have contributed to exceedences of AAQ NEPM standard concentrations. Bushfires near Sydney at the end of 2001 contributed to five of the 19 exceedences of the one-hour ozone standard in that year, and two of the nine exceedences in 2002. While records exist for major bushfire events, a comprehensive record of all bushfire events is needed to assess the true impact on the number of exceedences in Sydney from bushfires.

Modelling

Airshed modelling is used to build on descriptions derived from observations, and to explore possible emission scenarios. The CIT airshed modelling system was used to simulate ozone production for four ozone exceedence-days: 20 December 2000; 12 January 2001; 22 January 2001; and 10 February 2004. The system's performance was evaluated by comparing simulated concentration of ozone against observations for each of these days. For these simulations, results were sufficiently accurate to warrant further use in both augmenting the data-based description of these event days, and in investigating possible emission scenarios.

The results of the simulations showed that these four events fell into three pattern types: 12 January 2001 was an extreme event which showed markedly differing behaviour to the other three days; 20 December 2000 and 22 January 2001 showed closely similar responses to the emissions perturbations; and 10 February 2004 responded between these two patterns. These days account for over 90% of typical chemistry and more than 70% of the typical meteorological conditions which give rise to ozone exceedences in the Sydney Basin.

A co-ordinated series of emission perturbation simulations were then run in three streams. Stream 1 explored scaling of the precursor pollutants with the aim of estimating the overall size of emission reduction required to meet the current AAQ NEPM goal. Stream 2 sought to refine this advice by exploring the significance of emissions by category. Stream 3 simulated future scenarios to indicate possible challenges to air quality from population increases.

Stream 1 showed that an overall reduction of 25% from 2001 rates in both precursors may be sufficient to meet the current AAQ NEPM one-hour goal. This reduction was insufficient to reduce ozone concentrations below the standards for the 12 January 2001 event. Indeed the reduction required for this extreme event may not be achievable using currently considered emission strategies. As this event is relatively rare, compliance with the current AAQ NEPM goal remains possible.

Stream 1 also showed that the optimal strategy for reducing ozone concentration for both 20 December 2000 and 22 January 2001 was to reduce both precursors. This was not the optimal strategy for 10 February 2004, but did reduce ozone concentrations. While reduction in both precursors is important, the results showed a greater sensitivity to volatile organic compounds. This suggests a slightly greater emphasis on reducing these emissions in the short term, but longer term strategies will need to also reduce NO_x emissions.

Stream 2 showed that the Sydney airshed is disproportionately sensitive to the motor vehicle emission category. Reductions in this category will provide greater gains than general reductions. The commercial-domestic category is also significant, as it is a significant source of VOCs.

Stream 3 showed that under current technologies, in order to achieve compliance with the AAQ NEPM ozone standard by 2026, the most significant source to control is motor vehicles. The significant increases in population are a potential challenge for achieving emission reduction targets. Significant emission reductions are anticipated from new control technologies on motor vehicles; however these will be insufficient by themselves and other programs will be needed. Co-generation or distributed electricity plants did not significantly impact on maximum ozone but did highlight a potential impact on the size and duration of the ozone event.

Air quality planning for the Sydney region

The modelling demonstrated that compliance with the ozone standard requires a reduction of 25% from 2001 levels for both VOC and NO_x emissions and that by 2026, exceedences of the ozone standard will still occur. A comparison of the emissions inventory for 2002, 2016 and 2026 showed that, by 2026, VOC emissions will be reduced by 8% and NO_x emissions by 39%. The emissions inventory highlighted that emission reductions for 2026 are only achieved by control of vehicle emissions and that there are other areas which can be targeted for emission control programs.

Future work

Areas identified for further work focus on two areas: the validation of the emissions inventory and the ambient measurements of VOCs to provide additional information to validate the model runs.

1. Introduction

1.1 Definition of ozone

Ozone (O_3) is a colourless, strongly oxidising gas. Ozone occurs in both the stratosphere (10–50 km above the ground) and in the troposphere (ground up to 10 km or so). Ozone in the stratosphere reduces the amount of harmful ultraviolet light entering the Earth's atmosphere (CARB 2005a) and is produced, especially in the ozone layer, from the interaction of ultra-violet light and molecular oxygen.

In the troposphere, ozone is an air pollutant that is harmful to human health and vegetation. Observations and health-based standards presented in this report refer to this ground-level ozone. Ozone in the troposphere is not emitted directly into the air, but is a secondary photochemical pollutant formed when two precursor pollutants – NO_x and VOCs – react in the presence of sunlight. The process of ozone formation is complex and its investigation involves an understanding of the photochemical reactions, the sources of ozone precursor emissions, and the meteorological conditions conducive to ozone formation. Elevated concentrations of ozone occur in Sydney in the warmer months under suitable weather conditions including sufficient sunlight, high temperatures, and favourable wind conditions.

The photochemistry of ozone is highly non-linear. The rate of production of ozone depends largely on the temperature and the ratio of the precursor pollutants (VOCs:NO_x). Precursor emissions contributing to the urban plume, and hence the ozone concentration, vary in both space and time, i.e. they are distributed unevenly through the urban area and vary throughout the day. Complicating this further is the temporal and spatial variation in meteorological processes.

1.2 National Environment Protection (Ambient Air Quality) Measure

Relevant air quality standards are defined by the AAQ NEPM, which was adopted by the NSW Government in 1998. The desired environmental outcome of this NEPM is ambient air quality that allows for the adequate protection of human health and wellbeing. The AAQ NEPM sets standards and goals for several pollutants including two standards for ozone (Table 1). The AAQ NEPM goal for ozone is to maintain ozone concentrations below the standard concentrations set out below, with a goal that it is exceeded on no more than one day a year by 2008.

Table 1: National Ambient Air Quality standards and goals

Pollutant	Averaging period	Maximum concentration*	Goal within 10 years (maximum allowable exceedences)
Photochemical oxidants (as ozone)	1-hour	0.10 ppm	1 day a year
	4-hours	0.08 ppm	1 day a year

* Arithmetic mean concentrations

Source: National Environment Protection Measure and Revised Impact Statement for Ambient Air Quality (NEPC 1998)

1.3 Summary of report

Observational ozone data from DECCW measurement sites in the Sydney, Illawarra and lower Hunter regions are presented in Chapter 2. The numbers of AAQ NEPM ozone exceedence-days, as well as maximum concentrations during the period 1994 to 2004, are presented. While observations for the lower Hunter and Illawarra are presented, the main focus of this report is an analysis of ozone in the Sydney Basin as ozone concentrations rarely exceed the standards in either the Illawarra or the lower Hunter regions. A description of the meteorological processes conducive to the formation of ozone in Sydney is given: Appendix A provides a detailed description of the photochemical reactions involved in ozone formation.

The impacts of a reduction in the one-hour standard from 0.10 ppm to 0.08 ppm are presented. The introduction of an eight-hour standard is being considered as part of the regular review of AAQ NEPM air quality standards. The number of exceedences of an eight-hour standard is calculated for four possible standard concentrations.

While bushfire event days have not been excluded for the analysis in this report, examples of the impact of bushfires on ozone formation are presented.

Results of IER modelling, used to calculate the extent of the photochemical reaction, are also presented in Chapter 2.

Chapter 3 presents results of airshed modelling of the Sydney region. Four exceedence days were chosen as base-case days – 12 and 22 January 2001, 20 December 2000 and 10 February 2004. The model was run to determine how well it replicated observations on base-case days, using current emission and meteorological input files.

Model simulations were then completed using scaled emissions for the ozone precursors, NO_x and VOCs. Twelve scenarios were run with scaling ranging from half the current emissions up to 30% higher than current emissions.

The significance of the two major anthropogenic emission source categories – mobile sources and commercial-domestic – was explored. Variations to motor vehicle emissions included direct scaling of NO_x, application of currently mandated and proposed emissions limits to the current fleet, and scaling motor vehicle usage as measured by kilometres travelled. Variations to commercial-domestic were investigated by using simulations where both NO_x and VOC emissions were halved and doubled.

Future scenarios were then run using altered emissions based on assumptions for expected urban growth and control strategies in 2026.

Chapter 4 discusses the modelling results and the implications for air quality planning for Sydney in order to decrease the number of ozone exceedence-days.

Chapter 5 presents implications for future work. Areas requiring further work include incorporation of the recently updated emissions inventory in further model runs; ambient air quality measurements of hydrocarbons to validate the model results; and further validation of the emissions inventory. Analysis of upper air data currently being collected in western Sydney will assist in better understanding the role of the meteorology in ozone formation in the Sydney Basin.

2. Observational analysis

2.1 Introduction

Observational ozone data from DECCW measurement sites in the Sydney, Illawarra and lower Hunter regions was analysed for the period 1994 to 2004. While results for the lower Hunter, the Illawarra and Bathurst are presented, the main focus of this report is an analysis of ozone in the Sydney Basin, as ozone concentrations rarely exceeded the standards in the Illawarra and the lower Hunter regions, and did not exceed at Bathurst.

Two factors govern the concentrations of photochemical pollution experienced by a region: the emissions and the way they react in the atmosphere; and the meteorology that disperses and transports these emissions and reaction products. In simplistic terms, the emissions of precursor pollutants – VOCs and NO_x – determine the maximum amount of photochemical smog that can be produced under suitable conditions, and the meteorology determines those conditions, and hence when, where and how frequently photochemical pollution episodes occur. A description of the meteorological processes conducive to the formation of ozone in Sydney is given. Results of IER modelling, used to calculate the extent of the photochemical reaction, are also presented for the Sydney region.

In this report, exceedence data are presented as both exceedence-days and station-days. An exceedence-day is a distinct day on which observed ozone concentrations exceed either or both AAQ NEPM standards at one or more sites. A station-day is defined as a day with an exceedence at one site, sites being counted separately. For example, if there are exceedences at five sites on the same day, this is one exceedence-day and five station-days.

Ozone trend data from 1994 to 2004 is presented. Ozone exceedences resulting from the occurrence of bushfires were not excluded as current records of bushfire activity in NSW were inadequate for this type of analysis. While days with bushfires were not excluded from the analysis, this chapter does provide examples of the impact of bushfires on ozone concentrations.

The introduction of an eight-hour standard is being considered as part of the regular review of AAQ NEPM air quality standards. This report investigates the impact of an eight-hour standard on exceedences for four standard concentrations. The impact of reducing the one-hour standard to 0.08 ppm was also investigated.

2.2 Overview of ozone monitoring in NSW

The region has been the subject of two significant scientific investigations of aspects of air quality. These are the Sydney Oxidant Study of the late 1970s and the Metropolitan Air Quality Study (MAQS) from 1992 to 1995.

Prior to MAQS, the network consisted of eight sites in Sydney, located in the eastern and south-west of the basin and one additional site in the Illawarra. MAQS provided the greatest single push for monitoring in NSW. With MAQS, the network was expanded to include monitoring in the urban growth areas in the west, north-west and south-west of Sydney, which previous scientific investigations had suggested would be subject to higher pollutant concentrations than those measured in the then existing network. A major aim of MAQS was to obtain scientific information about the meteorology and chemistry influencing the observed pollution episodes by the strategic placement of sites. MAQS was also responsible for additional monitoring in the Illawarra and the commencement of monitoring in the lower Hunter.

The focus of MAQS and the resulting network was the understanding of photochemical pollution which, as a secondary pollutant, is still the most complex and least understood of the air quality issues in the Sydney region. Photochemical pollution was the primary consideration in the siting of much of the monitoring for MAQS; however the configuration of the network also provided valuable information about particles and other pollutants.

The recent introduction of the AAQ NEPM has provided another focus for the network, driven mostly by reporting requirements and the concept of understanding the exposure of the population to pollutants. The network nominated for AAQ NEPM reporting (as shown in Appendix B) uses existing monitoring sites best suited to its purpose.

The AAQ NEPM has also been the driver for further monitoring in regional centres. Initial ozone monitoring is being carried out at Bathurst on a short-term campaign basis. Bathurst is located some 150 km west of Sydney in the Central Tablelands and on the banks of the Macquarie River, with higher ground rising to the south-west of the city centre. There are no significant industrial sources of air pollution in the region. The relatively cold winters and prevalence of wood heating lead to a potential for exceedences of the AAQ NEPM standard for particle concentrations (PM_{10}). The urban centre has a population of 26,000 and therefore requires at least one station, according to the AAQ NEPM.

The current NSW air quality monitoring network (AQMN) has, as its basis, a core of 13 sites in the Sydney region, with four in the Illawarra and three in the lower Hunter (Appendix C). Note that some sites were not operational for the entire 11-year period (for example Appin, Douglas Park, Kensington, Wentworth Falls and Kurrajong Heights).

New sites include Chullora, which replaced Lidcombe in 2003, and Macarthur, which was commissioned in 2004. Data availability at each site in each year from 1994 to 2004 is given in Appendix C.

2.3 Sydney region

The Sydney region contains the largest population in NSW and Australia. Measurement sites operating in the Sydney region between 1994 and 2004 are shown in Figure 1. Note that some sites were not operational for the entire 11-year period (Appendix C).

The region is essentially a large basin containing complex topography. It is bound by elevated terrain to the north, west and south. Its northern coastal strip extends into and includes the southern part of the Central Coast urban region.

In the Sydney region, ozone exceedences are most likely to occur under the influence of a high pressure system in the central or eastern Tasman Sea, producing light to moderate northerly sector gradient winds over NSW. Under these synoptic conditions, local conditions commonly experienced include high afternoon temperatures, light winds, high solar radiation and mesoscale flows such as drainage flows overnight and sea breezes during the day. In Sydney, peak ozone concentrations are predominantly associated with the passage of the sea breeze front across the basin. Drainage flows, in combination with other flows such as the sea breeze, provide opportunities for the recirculation of pollutants in the region.

The spatial pattern of air quality is determined by the wind regimes and how they interact with the topography. In the west of the region is the Hawkesbury Basin, which is separated from the rest of the region by the Blacktown ridge. Air quality data shows that the north and south of the Hawkesbury Basin have distinct patterns of pollutant concentration, largely because the sea breeze is generally north-easterly.

An emissions inventory was developed as part of MAQS (Carnovale et al. 1997). Emissions from motor vehicles, both domestic and commercial, represent almost 80% of NO_x and nearly half the anthropogenic VOC emitted in the airshed on an annual basis (Carnovale et al. 1997). Domestic and commercial sources are also important, contributing some 40% of anthropogenic volatile organic emissions. Industrial sources are less significant. Bushfires are also intermittent sources of VOCs.

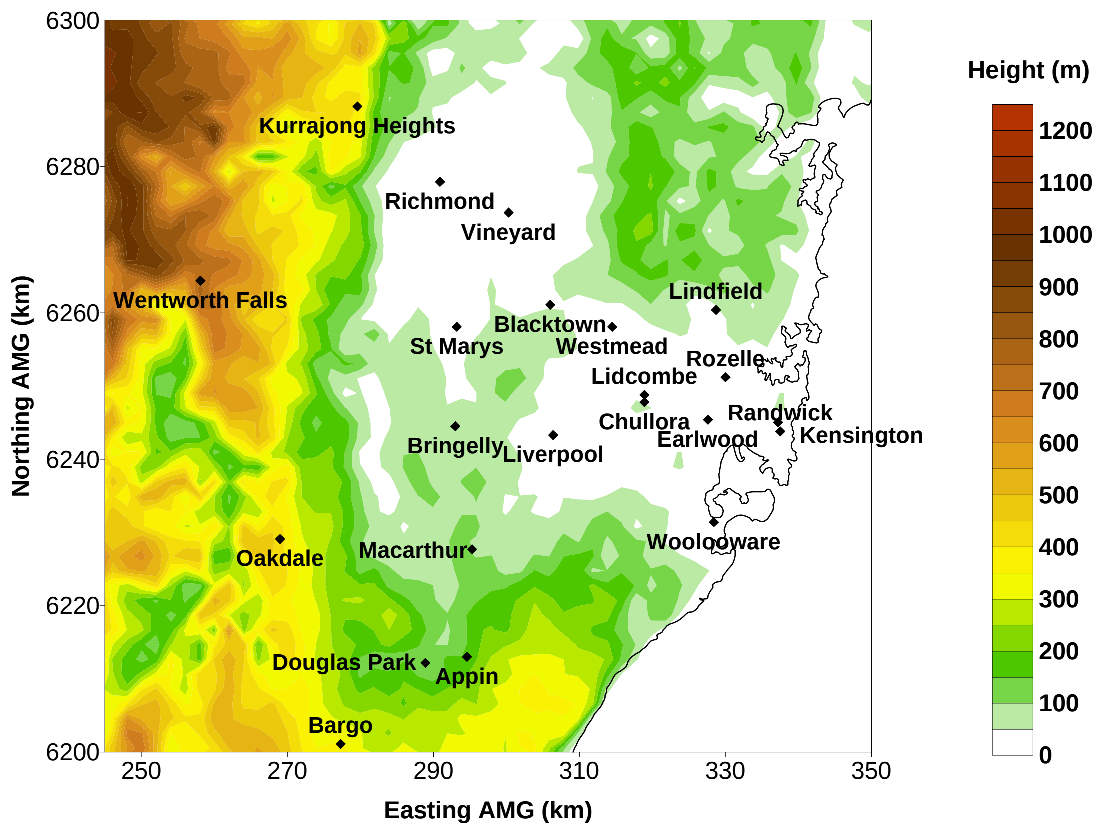


Figure 1: Measurement sites in the Sydney Basin, 1994–2004

2.4 Illawarra region

The Illawarra is the fourth major population centre of NSW. DECCW operates a network of four measurement stations in this region (Figure 2).

It is located on a thin coastal strip with a steep escarpment to the west. The width of the coastal strip increases from north to south until it terminates in a ridge of hills running from the escarpment to the sea. As the significant topographic feature, the escarpment is a major influence on meteorology and hence the region's air quality. It can steer or deflect winds, changing the apparent direction at the surface and also lead to the decoupling of winds above and below the escarpment. As a result, an inversion can form at the top of the escarpment, limiting the dispersion of pollutants in the Illawarra region (Hyde et al. 1997).

The sea breeze is the dominant meteorological influence on elevated concentrations of ozone in the region. In the north of the region, these sea breezes tend to be steered by the topography to become north-north-easterly to north-easterly in direction. In the region's south, sea breezes tend to be more north-easterly to easterly. Return-flow has been observed above the sea breeze in the Illawarra region (Hyde and Prescott 1984). Westerly drainage flows have been observed to develop in the region overnight (Hyde and Prescott 1984) and also have some influence on air quality.

Precursor emissions from local sources can contribute to ozone events in the Illawarra region. Major sources in the Illawarra, apart from motor vehicle traffic, are iron and steel production and associated coke making and primary metallurgical works. The region is only 80 km to the south of the Sydney region and on occasion pollutants are transported between the two, particularly from Sydney to the Illawarra. Most ozone events in the Illawarra occur as a result of the combined effect of both local emissions and the transport of precursors and photochemical smog from other regions.

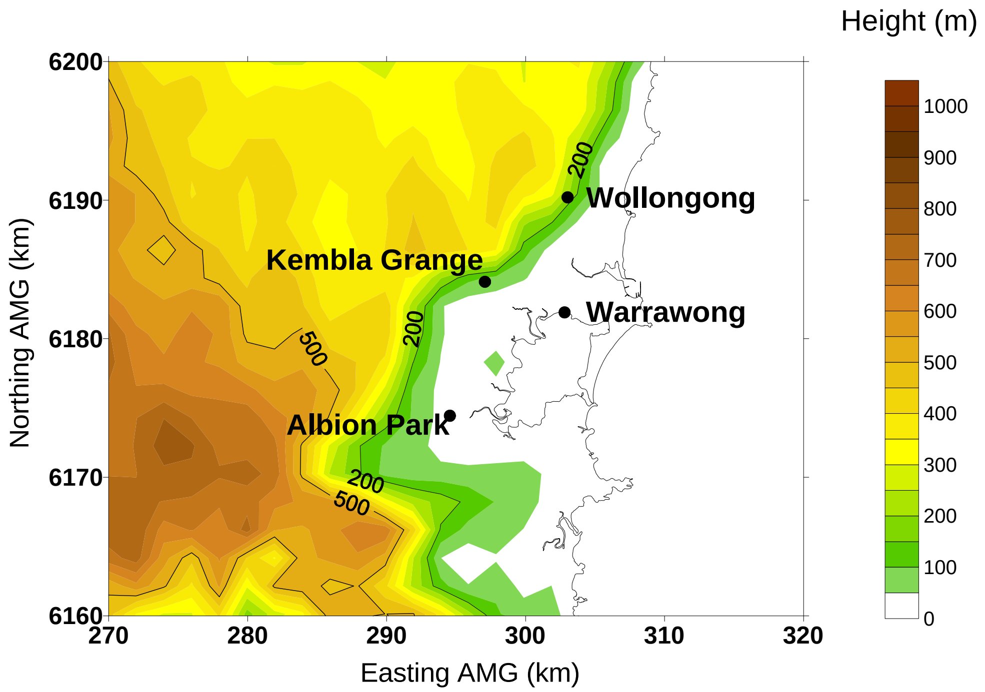


Figure 2: Measurement sites in the Illawarra region, 1994–2004

2.5 Lower Hunter region

The natural lower end of the Hunter region is the second most heavily populated region in NSW with a regional population estimated at over 350,000. DECCW operates three measurement stations in this region (Figure 3). Focusing on Newcastle and its immediate surrounds, the monitoring locations were selected to capture the higher concentrations of regionally significant pollutants and to be in receptor regions for major emission sources.

The lower Hunter Region is defined as the part of the Hunter River valley that opens out to a coastal plain. It is bounded by the coast to the east, and otherwise by the higher terrain enclosing this end of the valley. It is separated from the remainder of the Hunter River valley by the rise in the valley floor north-west of Maitland. The coastal strip extends to the south to include the northern part of the Central Coast urban centre.

Synoptic conditions leading to elevated concentrations of air pollutants are similar to those of Sydney (which is only a hundred kilometres to the south). With a high pressure system in the Tasman Sea, light synoptic winds prevail, allowing the generation of local flows such as katabatic (drainage) flows and sea breezes. Down-valley flows are generated overnight, with up-valley flow established in the afternoon with the onset of the sea breeze (Hyde et al. 1981; Hyde et al. 1997). It is these local flows that have the greatest influence on the distribution and recirculation of pollutants emitted by sources in the region. Sea breezes commence at the coast around mid-morning, reaching up-valley sites late in the afternoon. In the Hunter Valley the sea breeze is generally an easterly flow close to the coast, and is steered more in a south-easterly direction as it penetrates up the valley.

Relatively small variations in the direction of flows can see alterations to this basic pattern. For example, a more north-easterly component in the sea breeze or gradient wind can see emissions from the Newcastle area advected down to the Central Coast and on towards the Sydney airshed. The role of these flows in pollution episodes in the region is also demonstrated by airshed modelling of the lower Hunter region undertaken as part of MAQS (Hyde et al. 1997).

The lower Hunter region is the location of a substantial industrial base including primary metallurgical works, fertiliser manufacturing, and coal-fired power generators. Emissions from a substantial motor vehicle fleet also contribute to pollution concentrations in the region.

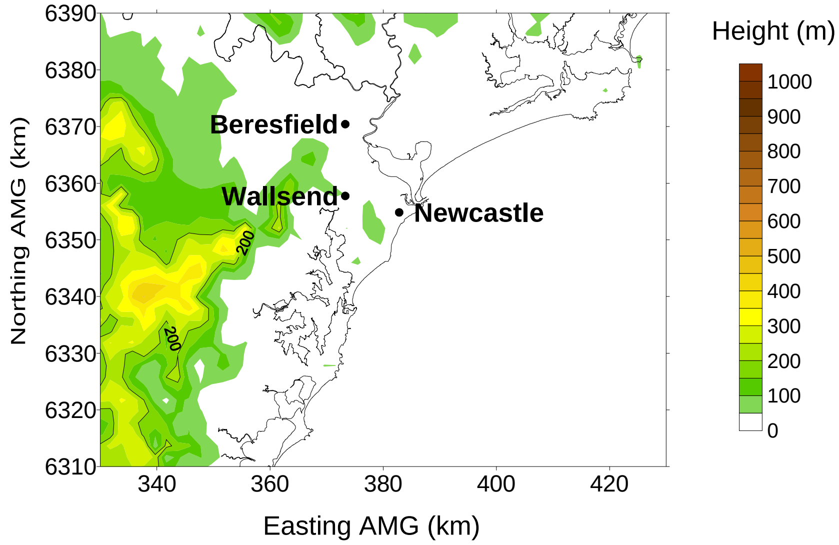


Figure 3: Measurement sites in the lower Hunter, 1994–2004

2.6 Trends: 1994 to 2004

One-hour standard

There are no significant trends in the number of exceedences of the one-hour ozone standard for the period from 1994 to 2004 (Figure 4a/Table 2). Photochemical pollution is of most concern in the Sydney region, where the highest ozone concentrations in the network were measured and where the episodes were the most frequent. Over this period the number of exceedence-days in the Sydney region (108) was significantly higher than the Illawarra (30) and the lower Hunter (2). Ozone concentrations in Sydney exceeded the one-hour standard of 0.10 parts per million (ppm) on up to 19 days per year. Photochemical pollution episodes tended to be considerably less frequent in the Illawarra, where the one-hour standard was exceeded on a maximum of seven days in one year. Exceedences in the lower Hunter were rare with only two days over the entire period recording concentrations above the one-hour standard.

As with the number of exceedences, the one-hour maximums were also higher in Sydney than the other two regions (Figure 4b). Peak one-hour ozone concentrations in Sydney were significantly above the national standards, with concentrations up to 180% of the standard (0.18 ppm in 2001 and 2003). On average, the annual maximum ozone concentrations in the Illawarra were 0.03 ppm lower than Sydney, while those in the lower Hunter were 0.06 ppm lower.

Four-hour standard

As with the one-hour standard, there are no significant trends for exceedences of the four-hour standard over the same time period (Figure 5a). The number of exceedence-days in the Sydney region (138) was significantly higher than the Illawarra (41) and the lower Hunter (3). The four-hour standard of 0.08 ppm was exceeded on up to 21 days per year in Sydney, seven days in the Illawarra and three days in the lower Hunter.

In Sydney, peak four-hour ozone concentrations were double the standard (0.16 ppm in 2003). Peak four-hour concentrations were 0.12 ppm in the Illawarra and 0.13 ppm in the lower Hunter, less than those in Sydney (Figure 5b).

Table 2: Exceedences of the one-hour and four-hour standards

Year	Exceedences of the one-hour standard (> 0.10 ppm)			Exceedences of the four-hour standard (> 0.08 ppm)		
	Sydney	Illawarra	Lower Hunter	Sydney	Illawarra	Lower Hunter
1994	13	4	0	16	5	0
1995	0	0	0	1	0	0
1996	1	0	0	2	0	0
1997	16	7	1	21	7	2
1998	13	3	0	16	6	1
1999	9	1	0	9	1	0
2000	6	3	0	12	7	0
2001	19	3	0	21	4	0
2002	9	2	0	15	4	0
2003	7	4	0	9	4	0
2004	15	3	1	16	3	0

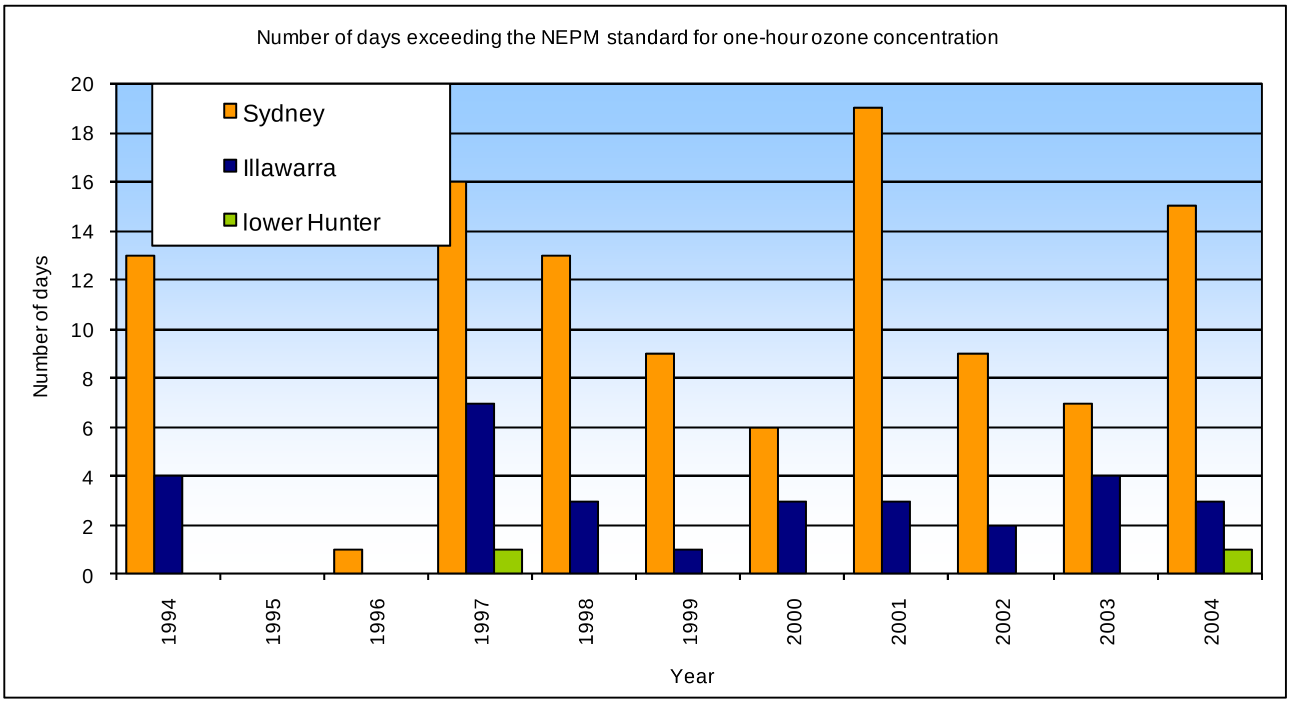
Discussion on trends

The number of days when ozone standards are exceeded in any given year is strongly dependent on the meteorological conditions experienced in that year. As a result, exceedence data is subject to a high level of inter-annual variability. For example, the 1995–96 summer was relatively cool and wet, and as a result there were fewer exceedences of both the one-hour and four-hour standards. The conditions of the 1997–98 summer were hot and dry and therefore conducive to the production of photochemical smog. These conditions also in resulted in major bushfires, the emissions from which were likely to have contributed to some of the exceedences. Similarly, the data for 2001 shows some influence of the bushfires that affected the region in December of that year.

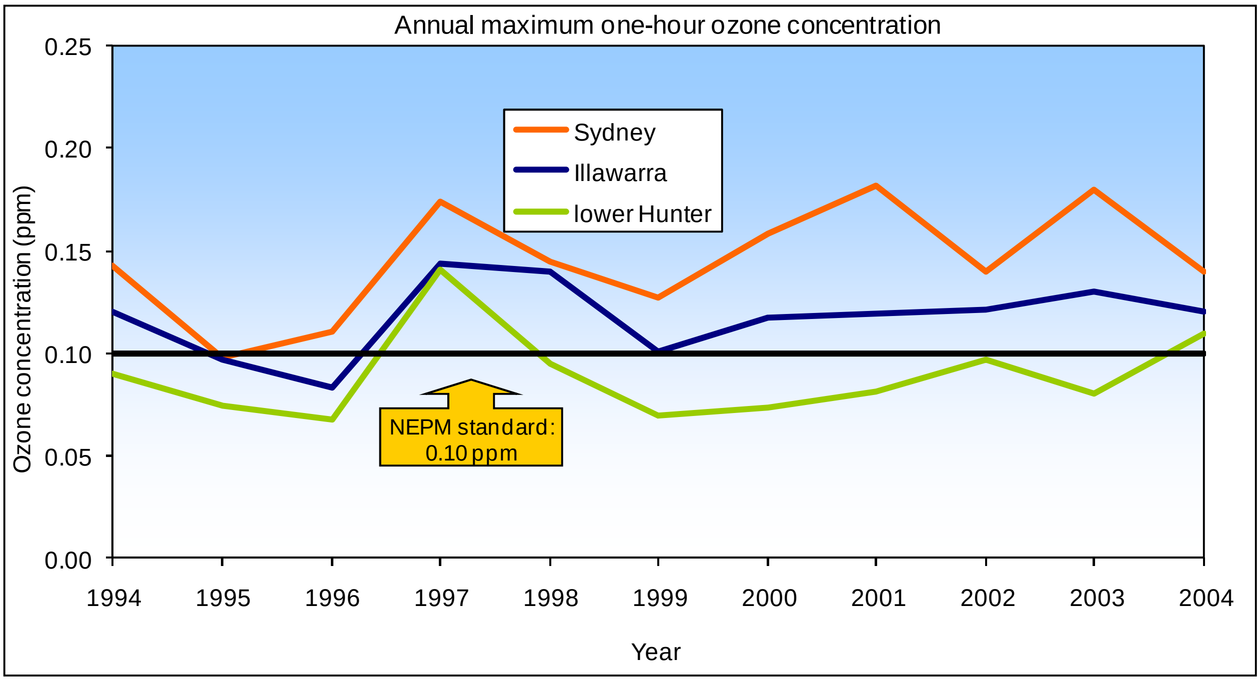
Schere and Hidy (2000) is the foreword to a collection of critical reviews presenting scientific knowledge regarding tropospheric ozone. They noted that despite increasing understanding of the phenomena leading to hourly ozone concentration maxima, there was only limited ability to explain how much of the ozone concentration trend is due to climate variability and how much to changes in precursor emissions. Changes in the monitoring network configuration, monitoring techniques and urban configuration (and hence the distribution of sources) heightens this difficulty. In NSW the monitoring network was expanded prior to 1994 (beginning the study period for this report) to include monitoring in the urban growth areas in the west, north-west and south-west of Sydney. However, there have been some changes to the monitoring network since 1994.

In order to isolate the underlying trend, a number of statistical techniques have been developed that attempt to filter out the meteorological variability. These techniques vary in the way they partition the 'trend' and 'non-trend' variation in the data. Generally these techniques are good at removing the high-frequency signals in the data such as the diurnal and seasonal variations. However, they are limited in their ability to account for the inter-annual variability that occurs as a result of cycles such as the El Niño-Southern Oscillation. This is largely because the period of these cycles is much longer and at present the data record is insufficient to adequately identify and characterise, and therefore filter, their signal. In addition, the time frames of these lower frequency meteorological cycles can be similar to those of the emission changes that the techniques are trying to isolate. In considering the results of these types of analyses, it is important to recognise that some meteorological influence may still be present.

An analysis of an underlying long-term trend for ozone in the Sydney region for the period 1993 to 2000 (Azzi and Duc 2003) shows, for most sites in the region, a slight upward trend with concentrations stabilising over the last two or three years of this period.



(a) Number of one-hour exceedence-days by year



(b) Annual maximum one-hour ozone concentrations

Figure 4: Peak ozone concentrations and exceedences of the one-hour standard, 1994–2004

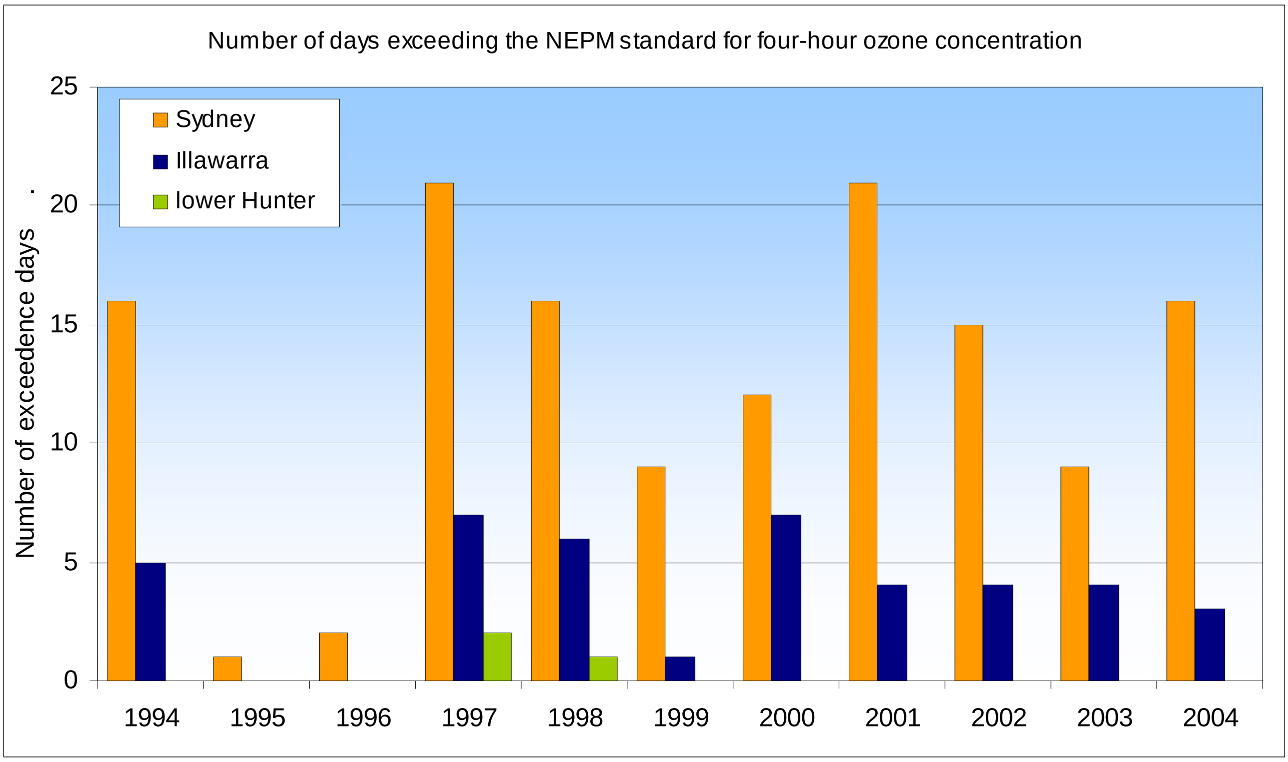
Data from 1994 to 2004 show no significant trends for the one-hour or the four-hour exceedences or maximum concentrations.

The Sydney region had the highest number of ozone exceedence-days for both standards (1994–2004) with a total of 108 for the one-hour standard and 138 for the four-hour standard. The maximum ozone concentration in Sydney was 180% of the one-hour standard and double the four-hour standard.

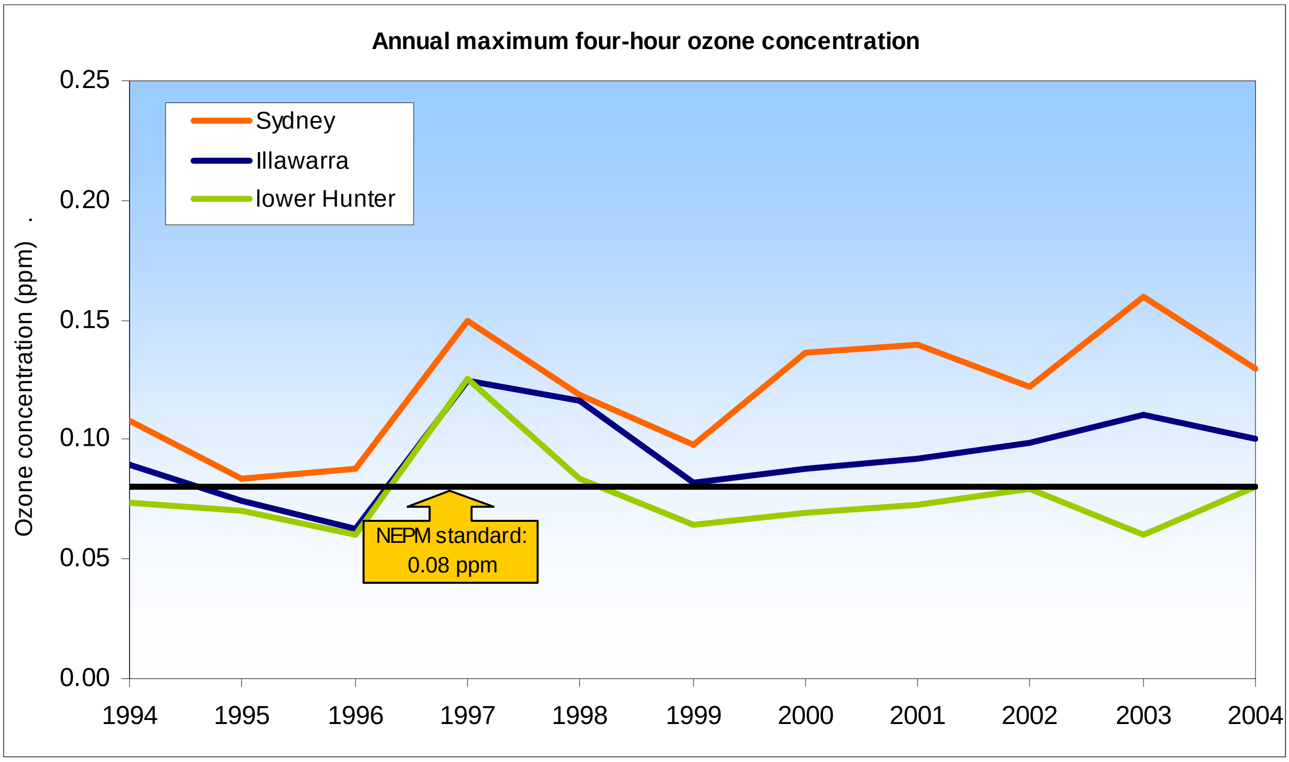
Photochemical pollution episodes tended to be considerably less frequent in the Illawarra region and rare in the lower Hunter.

The number of days when ozone standards are exceeded in any given year is strongly dependent on the meteorological conditions experienced in that year. For example, the summer of 1995–96 was cool and wet, limiting exceedences. In contrast, the summer of 1997–98 was hot and dry therefore conducive to ozone formation.

Climate variability, changes in the monitoring network and changes in the distribution of sources in a region complicate trend analysis.



(a) Number of four-hour exceedence-days by year



(b) Annual maximum four-hour ozone concentrations

Figure 5: Peak ozone concentrations and exceedences of the four-hour standard, 1994–2004

2.7 The role of meteorology in the formation of ozone in Sydney

In the presence of sufficient precursor emissions, photochemical pollution episodes occur when there is adequate sunlight and high enough temperatures to drive the photochemistry, and ventilation is limited so that the dispersion of the resulting pollution is constrained.

Meteorological conditions conducive to ozone formation in Sydney are complex and include both synoptic and mesoscale processes. Meteorological processes can vary in time and space, particularly wind and mixing height. Complex interactions of different air masses determine where and when elevated concentrations of photochemical pollutants occur. Ozone episodes in Sydney occur under several different meteorological regimes and hence peak concentrations can be observed at a range of stations in the monitoring network, depending on the conditions responsible for a particular ozone episode. This is demonstrated by the peak ozone concentrations observed at stations in the current network for the period 1994 to 2004 (Tables 4 and 5).

Synoptic processes

Leighton and Spark (1995) developed a classification scheme for the synoptic weather patterns associated with elevated concentrations of ozone in the Sydney region. Data from 1978–92 was analysed and it was found that episodes of medium to high ozone concentrations most commonly occur under the influence of a high pressure system centred in the Tasman Sea and ridging into NSW, resulting in northerly/north-westerly synoptic winds over Sydney.

A study by Angri and Linfoot (1996) used the classification scheme developed by Leighton and Spark (1995) to determine the most frequently occurring synoptic patterns conducive to ozone formation in Sydney during the period 1993 to 1995. For the 1993–94 study period it was found that a high pressure system in central or eastern Tasman Sea, with an extended ridge to Southern Queensland and light to moderate north-west gradient airflow over NSW, was the most frequently occurring synoptic pattern conducive to the formation of ozone. A col[1] region or extended high pressure ridge covering eastern NSW was found to be the most conducive for the 1994–95 study period. Hart et al. (2005) completed a study of synoptic climatology and photochemical smog episodes in Sydney from 1992 to 2001. Similarly, it was found that elevated ozone was associated with a high pressure system in the central or eastern Tasman Sea.

Mesoscale processes

Solar radiation and temperature influence not only the rate of chemical reactions but also the occurrence, strength and evolution of mesoscale flows, such as sea breezes and drainage flows. Solar radiation contributes to observed temperature through surface heating and also to the temperature structure of the atmosphere and hence mixing of air masses. Wind direction determines where pollutants are transported to, and whether pollutants within them are exposed to other sources en route. The speed of the flow will determine how quickly pollutants are moved around the region, thereby influencing factors such as the time available for chemical reaction, and the entrainment of other pollutants. The depth of the flow will influence the degree to which pollutants are dispersed, which can in turn influence the way the chemistry proceeds. The vertical temperature structure will influence the rate at which flows are eroded or replaced by other flows, and the opportunities for creating multi-layer structure in the lower atmosphere. Layering of flows can provide potential for movement of pollutants above the surface, in directions and at speeds quite different from those apparent at the surface. The interactions between flows can provide opportunities for the recirculation of pollutants.

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[1] A *col* is a region of slightly lower pressure between two high pressure centres. The pressure gradient is small generating light wind and allowing local and mesoscale flows to develop from temperature differences.

The influence of these meteorological factors varies in time and space. For example, at a given time, different parts of the region may experience different wind flows. Similarly, temperatures will vary across the region. A given location will experience diurnal variation in wind flows, temperature, and other meteorological factors. In addition, the characteristics of these factors also vary. For example, a sea breeze will vary in depth, being relatively shallow close to the coast and deepening as it moves inland.

The synoptic patterns conducive to ozone formation in Sydney produce local conditions such as high afternoon temperatures, light winds, high solar radiation and the presence of an afternoon sea breeze. These days also tend to be associated with warm stable air aloft, which limits mixing and the dispersion of pollutants. A ground-based stable layer is often present at inland sites in the morning (Hyde et al. 1997 and references therein). There is the potential for air pollutants to be retained and, possibly, recirculated in the airshed on a time scale of several to tens of hours. These local conditions are important for the formation and transportation of ozone and its precursors in Sydney (Hyde et al. 1997).

Wind flows in Sydney

Seasonally variable wind flow patterns exist within the Sydney airshed, with easterly surface winds dominating in the warmer months. General surface wind flow patterns occurring in Sydney in the morning and afternoon for warmer months (October 1997 to March 1998) are depicted in Figures 6 and 7. Observational wind data recorded at five monitoring stations (Lindfield, Lidcombe, Richmond, Bringelly and Bargo) were chosen to represent geographical spread throughout the airshed. This data has been plotted using wind roses to summarise wind speed, direction, and frequency. Each branch of the wind rose represents wind coming from that direction. The branches of the wind roses are divided into segments of different thickness, which represent wind speed ranges. The length of each segment within a branch is proportional to the frequency of winds blowing within the corresponding range of speeds from that direction (Bureau of Meteorology 2004). The shaded area in the centre represents the percentage of time that winds were calm (less than 0.5 ms^{-1}).

Differences in wind flow patterns between the Hawkesbury and Liverpool basins can be seen. As shown by the wind roses prior to sunrise in the warmer months (Figure 6), calm (up to 50% of the time) or light winds predominate throughout the basin with local flows (katabatic drainage flows) existing. In the afternoon of the warmer months (Figure 7), strong north-easterly to easterly sea breezes predominate and have been seen to extend as far south-west as Bargo at the limit of the monitoring network. Light sea breezes can occur in the eastern part of the basin during the late morning or early afternoon.

Peak ozone concentrations are predominantly associated with the passage of the sea breeze across the basin. However, other meteorological conditions that occur less frequently can also contribute to elevated ozone concentrations in Sydney.

1. Sea breeze

The sea breeze is generally a north-easterly or easterly flow, depending on the direction of the synoptic-scale flow. The direction and strength of the synoptic-scale flow can also influence how far inland the sea breeze penetrates, depending on whether it acts to reinforce the sea breeze or oppose it. In the east of the Sydney region, close to the coast, the onset of the sea breeze can occur around mid-morning. The sea breeze is important in the transport of photochemical pollution, and the passage of the sea breeze front across the Sydney Basin often coincides with the highest concentrations of ozone. Once the front has passed, ozone concentrations tend to fall quite rapidly.

In the Sydney region these north-easterly to easterly sea breezes result in the highest concentrations of ozone being recorded at stations in the west or south-west of the airshed. For example on 3 January 1999, the maximum hourly averaged ozone concentration of 0.11 ppm occurred at Bringelly (Figure 8a), while on 7 January 1999 the maximum hourly averaged ozone concentration of 0.11 ppm occurred at St Marys (Figure 8b).

The sea breeze tends to reach the western and south-western extremes of the basin late in the afternoon (Watt 1986, referenced in Hyde 1997). On any particular occasion, the direction of the sea breeze will vary in different parts of the basin as a result of topographic influences. The north-west of the Sydney Basin can also be influenced by sea breezes originating in the Central Coast area to the north of Sydney (Hyde et al. 1997).

Exceedences of the one-hour ozone standard (1998–2004) have been plotted with the corresponding wind direction at several sites in central or western Sydney (Figure 9). The majority of exceedences at these sites occur under winds from the east or north-east, which are likely to be associated with the sea breeze.

2. Northerly flow in the mornings

Ozone can reach elevated concentrations over several hours prior to the arrival of the sea breeze, particularly in the west of the basin. These episodes occur under the influence of light northerly winds. These wind flows appear to be synoptically derived and are important in that they can support high ozone concentrations over several hours. From limited vertical measurements in the Hawkesbury Basin (EMC 1994; EMC 1995), it appears that this flow is present aloft during the morning and is mixed to the surface as convection develops. These northerly sector flows generally persist until the onset of the sea breeze.

Light northerly winds occurred on 26 February 1998 where the maximum four-hour ozone average was 0.12 ppm, recorded at Westmead (Figure 8c).

This northerly flow is often associated with the presence of an elevated inversion, which could restrict the mixing depth during this pre-sea-breeze period. This is consistent with the near-constant ozone concentrations that can be observed during this period.

Compared to the sea breeze peaks, the particular influences that lead to these pre-sea breeze episodes are not well understood. They may be influenced by recirculation of ozone and/or precursors in drainage flows in the west of the basin. It has also been suggested that transport of precursors and/or ozone from sources outside the Sydney Basin may play some part in the ozone concentrations observed during this period.

3. Drainage flows

Drainage flows at both the local and regional scale have been observed overnight in the Sydney Basin under certain conditions. In general terms, the Hawkesbury Basin experiences south to south-westerly drainage flows on both the local and regional scale. These flows tend to be less clearly defined in the northern extremes of the basin. In the eastern part of the Sydney Basin, drainage flows tend to be dominated by the influence of the Parramatta River valley, resulting in westerly flows.

The frequency of drainage flows in the Sydney Basin, particularly in the east, can vary significantly seasonally, occurring less frequently during summer. Nevertheless, drainage flows appear to be present on the night before many photochemical pollution episodes, particularly in the west of the basin. During these summer events, drainage flows tend to begin breaking down between about 7 am and 8 am, to be replaced by light northerly sector flow. Early work observed the influence of drainage flows in carrying precursors across the basin and offshore during the morning (Hyde et al. 1978b). Modelling carried out for MAQS suggested that drainage flows could be an important influence on the movement of precursors in the region and hence an influence on ozone concentrations during the morning (Hyde et al. 1997). Drainage flows can be important for pollution episodes as, in combination with other flows such as the sea breeze, they provide opportunities for the recirculation of pollutants in the region.

4. Recirculation

Recirculation can be important for pollution episodes as it has the potential to introduce aged pollutants to the airshed, adding to the fresh emissions from that day. For example, measurement campaigns during the 1970s and 1980s identified a sea breeze-drainage flow circulation in the Sydney Basin and showed that it could be important for some ozone events. Precursor pollutants can be trapped within westerly drainage flows and carried offshore during the night and early morning where, after sunrise, they can react to form ozone. This ozone can then be carried back onshore and then possibly inland to the west and south-west by the sea breeze (Hyde et al. 1978b).

On occasion, high concentrations of ozone can occur on the coast or in the east of the Sydney region, either in the sea breeze or under the influence of southerly winds. For example, on 23 January 1998 the maximum hourly average ozone concentration of 0.13 ppm was recorded at Lindfield, occurring under the influence of a sea breeze prior to a southerly change (Figure 8d). Under similar conditions, on 22 February 1998 the maximum hourly averaged ozone concentration of 0.12 ppm was recorded at Woolooware (Figure 8e).

The interaction of the sea breeze and developing drainage flows in the late afternoon to early evening also provides a mechanism for the recirculation of pollutants. As the sea breeze stalls in the late afternoon, the pollutants carried into the outskirts of the basin can become entrained in drainage flows as they form. These flows could then carry the pollutants towards the centre of the basin (Hyde et al. 1978a).

5. The creation of multi-layered flow

Cooler flows will undercut warmer flows, lifting the warmer flow aloft, resulting in a layered structure. The warmer flow aloft effectively caps the surface flow, restricting its depth and limiting dispersion. For instance, a sea breeze of cool maritime air will undercut the warmer synoptic-scale flow.

Similarly, the sea breeze could be undercut by the developing cool drainage flow in the evening, isolating the pollutants from the sea breeze above the nocturnal surface flows. This layer, and any pollutants within it, would then be isolated from the surface and subject to different influences from those at the surface. Pollutants trapped in this layer will be carried downwind, and may be mixed to the surface the following morning as heating erodes the nocturnal temperature inversion and the mixed layer grows.

In the Sydney region it has been suggested that polluted layers aloft could be an important contributor to pre-sea breeze ozone (Hyde et al. 1997). In the west of the basin the increase in ozone concentrations during mid-morning appears to be consistent with the growing boundary layer mixing down ozone from aloft. Ozone could be produced from precursor pollutants present in the layer aloft from sunrise, without interference from fresh NO_x emissions at the surface.

Modelling of the Sydney region (Cope and Lee 2000a; Cope and Lee 2000b) supports the view that the recirculation of sea breeze air within drainage flows can be important. For events in December 1998 and January and February 2000, simulations showed ozone from the previous day’s sea breeze, having been isolated from the surface with the onset of drainage flows, carried back over the western Sydney and fumigated to the surface during the morning. However, on some occasions it was predicted that this remnant ozone aloft would be transported long distances downwind of the urban areas before being fumigated to the surface (Tory et al. 2001).

Winter vertical profiles from a site in the south-west of the basin provided evidence that sea breeze air could be carried back towards the centre of the Sydney Basin by drainage flows (Hyde and Johnson 1990). This could be mixed to the surface as the ground-based inversion breaks down with the heating of the surface during the morning. Analysis of wind records for 1980 (Hyde and Johnson 1990) showed that up to 85% of sea breezes were followed by drainage flows, demonstrating that there is opportunity for pollutants in sea breezes to be recirculated.

Modelling of other episodes shows that photochemical pollution can be carried long distances south during the late afternoon and evening, clearing the basin and leaving little opportunity for recirculation (Cope and Ischtwan 1997; Tory et al. 2001). Cope and Lee (2000b) suggested that the blocking of the sea breeze by elevated terrain to the west could be an important factor in recirculation. Modelling during MAQS (Hyde et al. 1997) also suggested that the blocking of flow by the terrain was important in generating the southerly flow required for recirculation.

While surface observations at many sites in the Sydney region show cooler drainage flows undercutting sea breeze air, this is not always the case. Observations in the Hunter Valley have shown the sea breeze turning with time to become more northerly (Hyde et al. 1981). Surface observations at Badgerys Creek show that, on occasion, the sea breeze will turn in a clockwise direction rather than be undercut by drainage flow (Hyde 1997).

On the basis of modelling during MAQS, Hyde et al. (1997) suggested that southerly drainage flow in the Hawkesbury Basin could interact with northerly synoptic flow aloft, effectively creating a north-south vertical rotor. This would provide a mechanism for pollutants trapped in drainage flows to be transported towards the north, then become entrained in the northerly flow aloft to be carried back over the basin. As the drainage flow breaks down the following morning, these recirculated pollutants could be mixed to the surface (Hyde et al. 1997).

6. Southerly flows

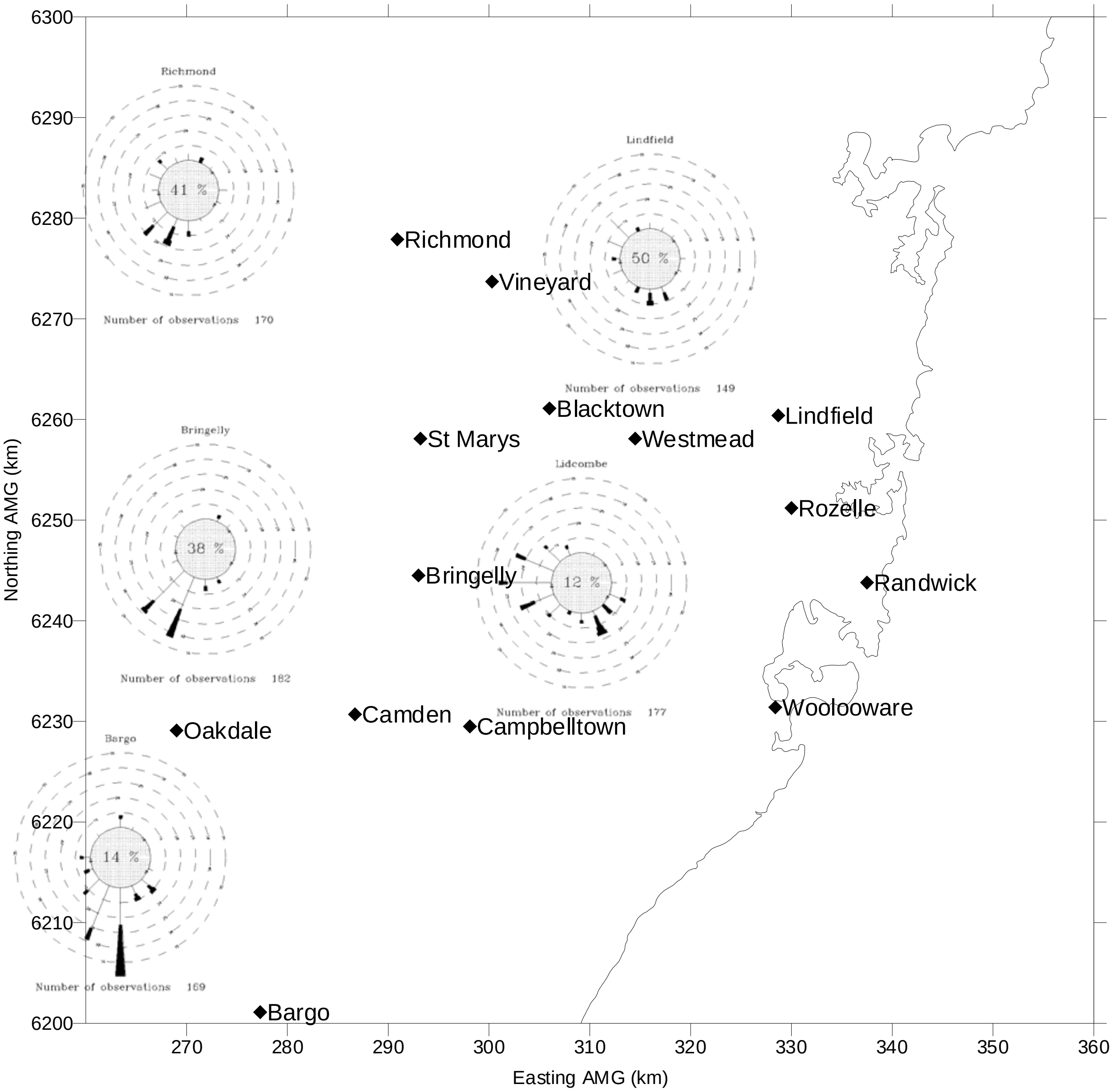
High concentrations of ozone can also occur under the influence of south to south-easterly changes. A strong change will increase ventilation, effectively clearing pollution from the region; however, a weak shallow change can transport pollutants between regions in Sydney.

A weak, shallow south-easterly flow can initially carry clean air into the east of the Sydney Basin, then subsequently entrain polluted air from the central part of the basin and carry it into the west and north-west, resulting in peak ozone concentrations in this area. An example of such an episode occurred on 13 December 1998 and is presented in Figure 8f. The maximum hourly averaged ozone concentration recorded for this day was 0.13 ppm at Vineyard.

7. Alongshore flow

North-north-easterly alongshore flows are often observed at the surface at coastal sites on ozone days. Limited observations of the vertical structure on such occasions show highly stable conditions above this flow (Hyde et al. 1997). Measurements from the Central Coast show an alongshore flow present above a shallow offshore flow at the surface (Physick and Noonan 1992). Alongshore flow could be important in influencing pollution episodes because it offers the potential for pollutants to be carried along the coast.

There are occasions when these alongshore flows persist overnight. On these days the opportunity for the development of an offshore-onshore drainage flow–sea breeze circulation will be restricted, allowing little opportunity for recirculation of pollutants.



The shaded area in the centre represents calms

Calms are winds less than 0.5 ms^{-1}

Minimum frequency is 1 per cent

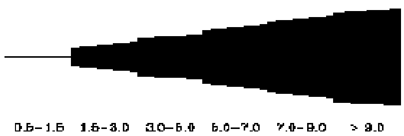


Figure 6: Morning wind rose plots for Sydney during the warmer months, October 1997 to March 1998 (Hour 6)

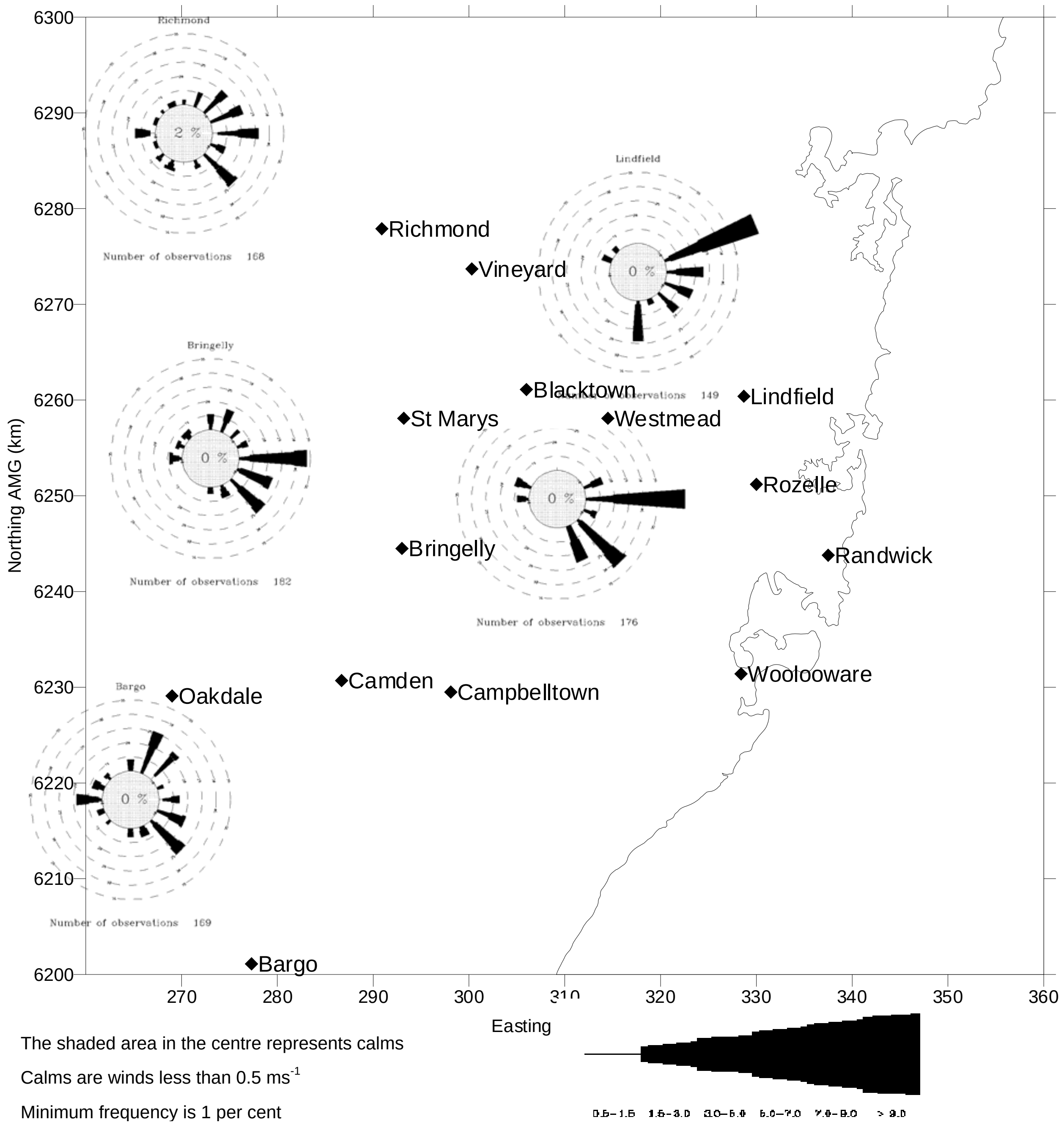


Figure 7: Afternoon wind rose plots for Sydney during the warmer months, October 1997 to March 1998 (Hour 15)

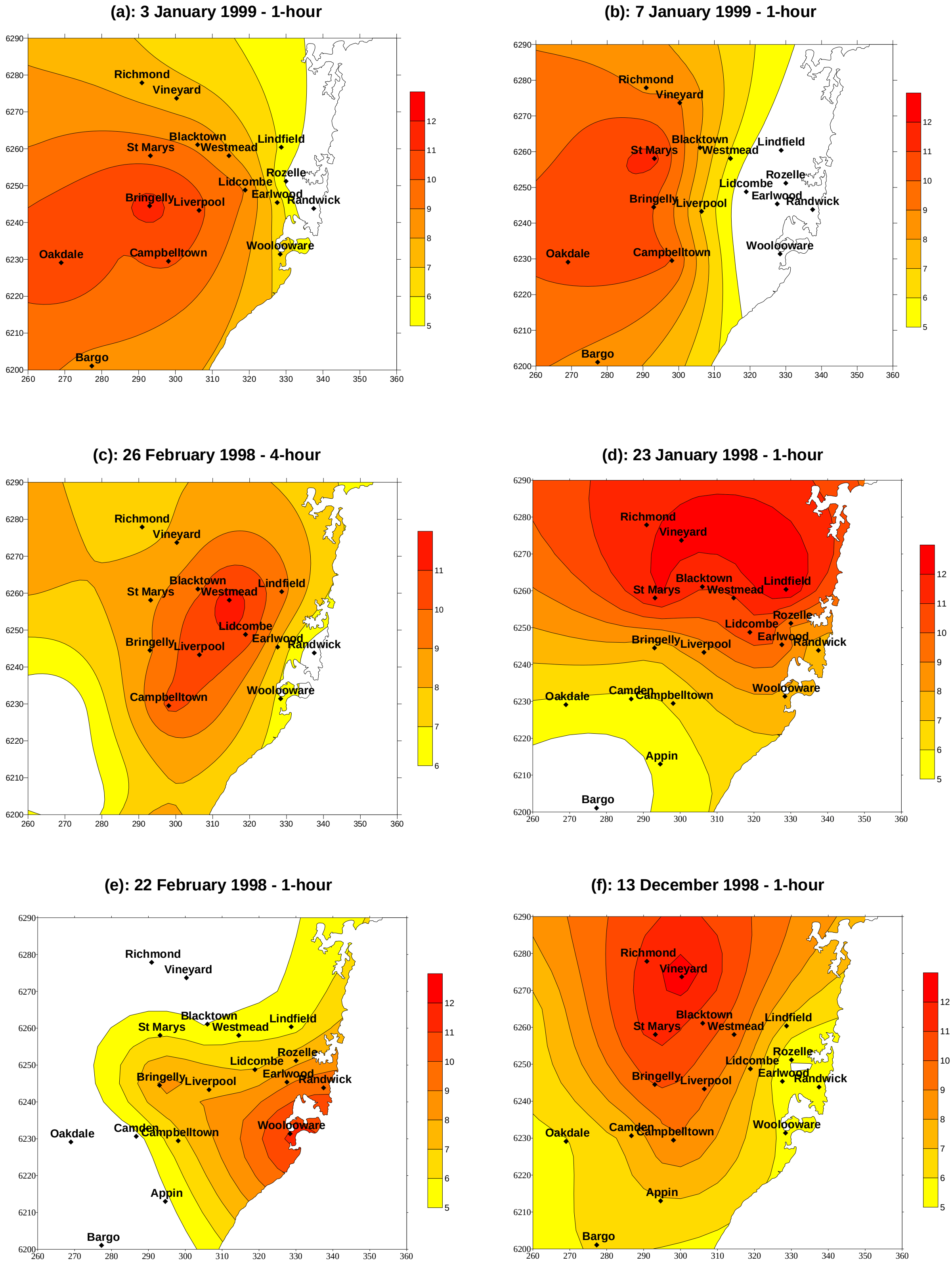


Figure 8: Contours of maximum one-hour and four-hour ozone concentrations (pphm) for a range of days

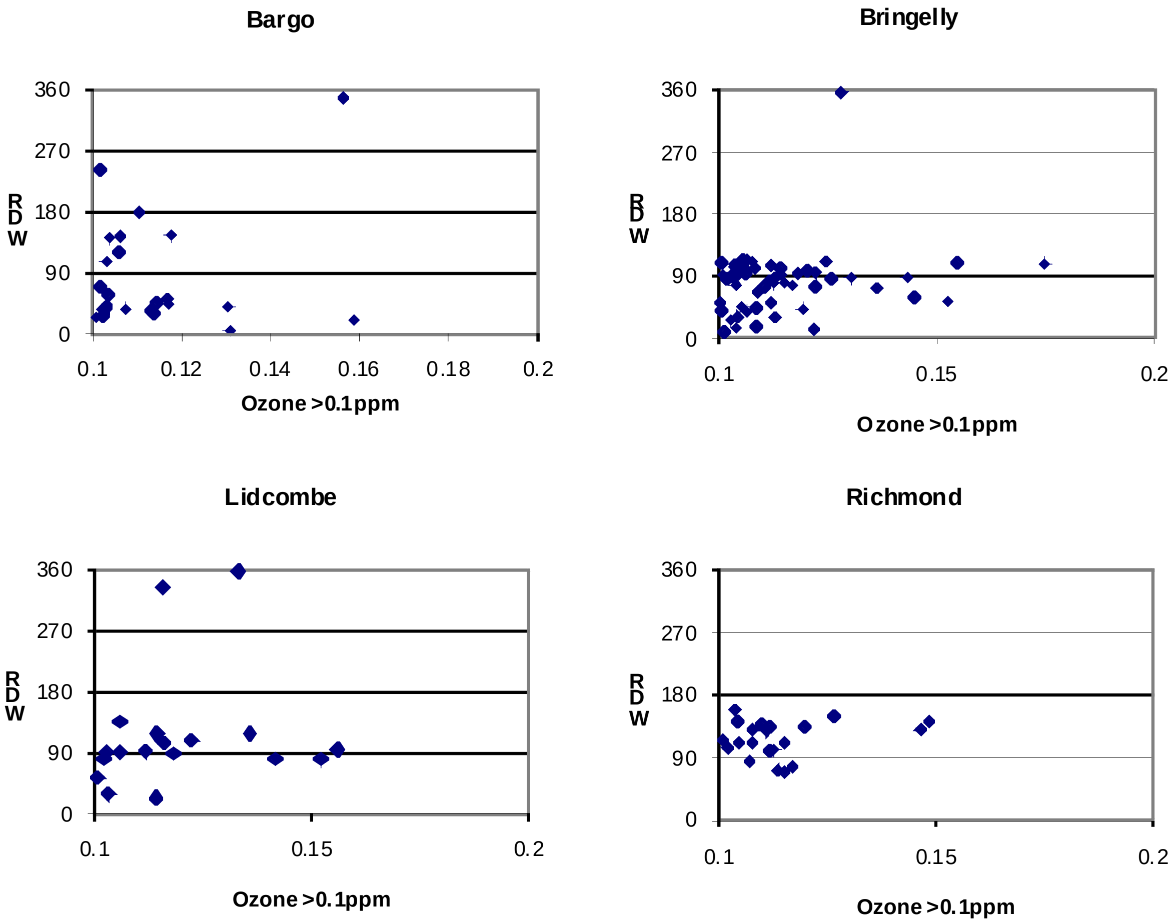


Figure 9: Exceedences of the one-hour ozone standard plotted with corresponding wind direction, 1998–2004

Both synoptic and mesoscale processes are important for the formation of ozone.

Ozone exceedences are most likely to occur under the influence of a high pressure system in the central or eastern Tasman Sea, producing light to moderate northerly sector gradient winds over NSW.

Under these synoptic conditions, local conditions commonly experienced in Sydney include high afternoon temperatures, light winds, high solar radiation and mesoscale flows such as drainage flows overnight and sea breezes during the day.

In Sydney, peak ozone concentrations are predominantly associated with the passage of the sea breeze front across the basin. Drainage flows in combination with other flows such as the sea breeze provide opportunities for the recirculation of pollutants in the region. Other wind flows, such as southerly flows, northerly flows in the morning and multi-layered flows, can also contribute to elevated ozone concentrations in Sydney.

2.8 Resulting diurnal ozone patterns in Sydney

As a result of the meteorological processes and wind flows described above, ozone concentrations vary throughout the day, resulting in particular diurnal ozone patterns. The most obvious feature of many photochemical pollution episodes is the high concentrations of ozone associated with the passage of the sea breeze across the basin. However, concentrations of ozone can also be elevated before the arrival of the sea breeze, particularly at inland sites – north-west, west and south-west of the Sydney Basin. At these sites, as described during MAQS (Hyde et al. 1997), a fairly clear sequence is frequently recognisable: concentrations begin increasing during the morning, sometimes rapidly; concentrations can then plateau; concentrations rise sharply with the onset of the sea breeze; then fall gradually through the remainder of the afternoon or evening. Hyde et al. (1997) classified periods in this sequence as 'morning ozone', 'regional ozone' and 'sea breeze ozone', presented in schematic form in Figure 10. Some days exhibit all three periods while, on other days, one or more of the periods are absent. These periods were characterised as follows:

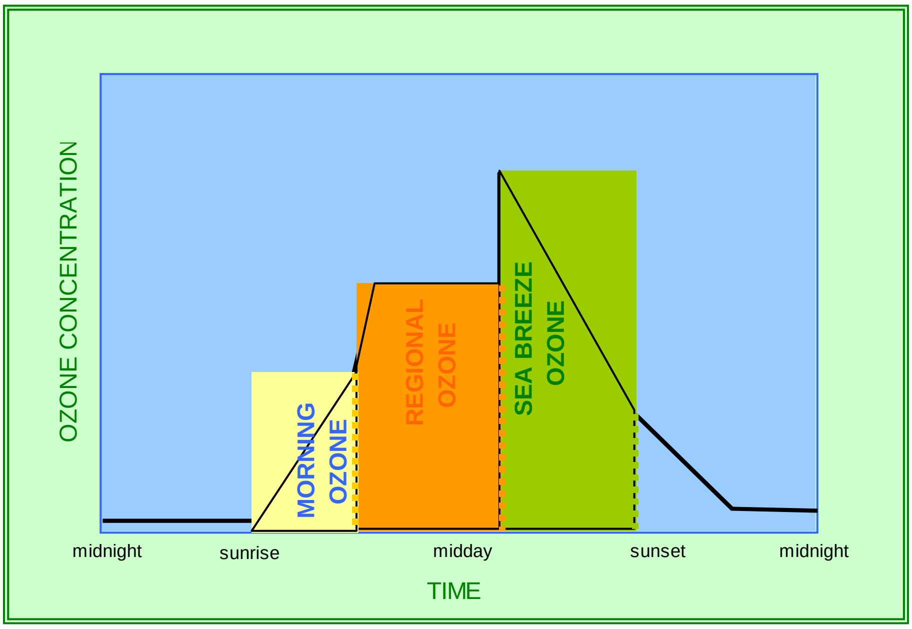
- Morning ozone was characterised by increasing concentrations of ozone soon after sunrise, within the deepening of the surface layer. It was found to occur under a range of wind directions but was commonly associated with northerly sector winds, particularly in the west of the basin. MAQS investigators suggested that morning ozone was most likely to occur as a result of local emissions, and that the recirculation of emissions trapped overnight in drainage flows might be an influence on morning ozone (Hyde et al. 1997).
- Regional ozone (or pre-sea breeze ozone) was the term used to refer to ozone occurring under the influence of synoptic-scale winds, before the arrival of the sea breeze. Regional ozone occurs widely, particularly in the west of the basin, and is generally associated with northerly sector winds. It is characterised by a period when the concentration of ozone increases almost linearly with time (often at a rate more rapid than would be expected from the reaction of precursors alone), followed by a period when it remains relatively constant. Ozone concentrations during this 'plateau' can reach concentrations of up to 0.08 ppm.

As discussed, this regional ozone might occur as a result of ozone formed in a layer aloft being mixed to the surface with the deepening of the boundary layer.

Patterns in pre-sea-breeze ozone at sites closer to the coast are generally less well defined. This is partly because the onset of the sea breeze is earlier and, as a result, there is less temporal separation to give a clear distinction between periods. However, Hyde et al. (1997) suggested that a pre-sea breeze period, with possible mixing to the surface of layers aloft, could also be an influence on ozone concentrations at coastal sites.

- Sea-breeze ozone: photochemical smog trapped and transported in the sea breeze is an obvious feature on many ozone event days. The onset of the sea breeze is accompanied by a sharp rise in ozone concentrations, most obvious at inland sites. The passage of the sea breeze front is also characterised by a change in wind direction (from variable winds to stable easterly flow); an increase in wind speed; and a drop in temperature. Peak ozone concentrations are frequently measured during the passage of the sea breeze front and concentrations tend to fall rapidly after the front has passed.

Figure 11 provides examples of both regional and sea breeze ozone at sites in the west of the Sydney Basin. It can be seen that the time of peak ozone at each site corresponds with the passage of the sea breeze front (shown by the increase in wind speed and change in direction). Figure 12 shows the progression of the sea breeze passage from east to west across the Sydney Basin during the afternoon of 26 February 1998. The sea breeze front (shown by the increase in wind speed and change in direction to easterly) corresponds with peak ozone concentration, firstly at Lidcombe at 1 pm, then Blacktown at 3 pm, Richmond at 5 pm and Wentworth Falls at 7 pm.



Adapted from Hyde et al. (1997)

Figure 10: Schematic of the generic diurnal variation in ozone concentrations at inland sites in Sydney for an ozone event under the influence of northerly sector synoptic-scale flows

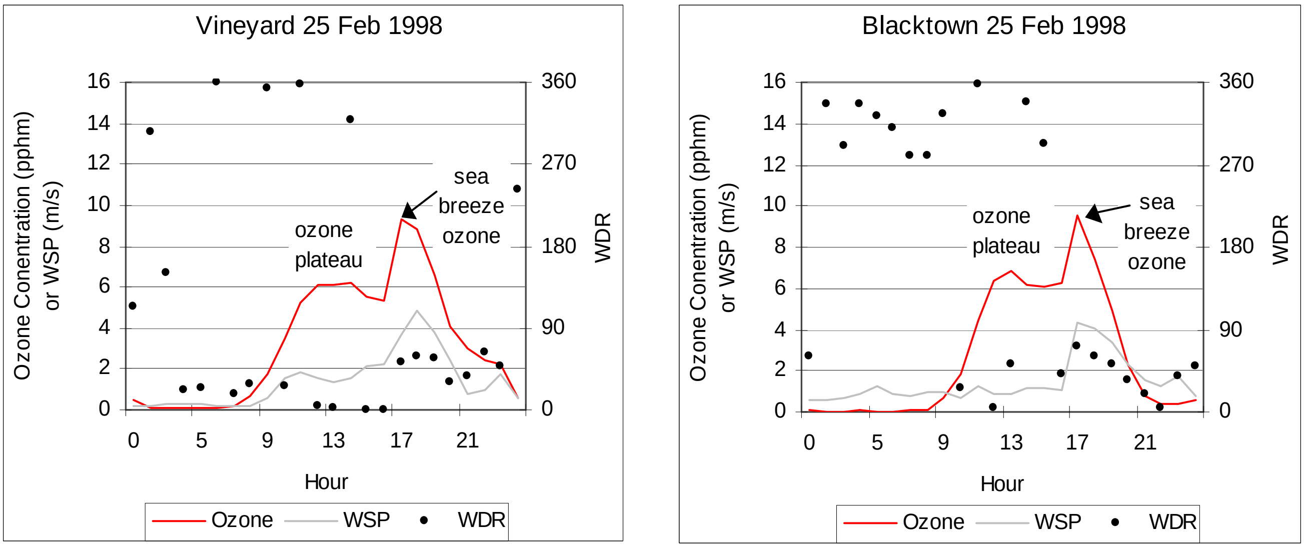
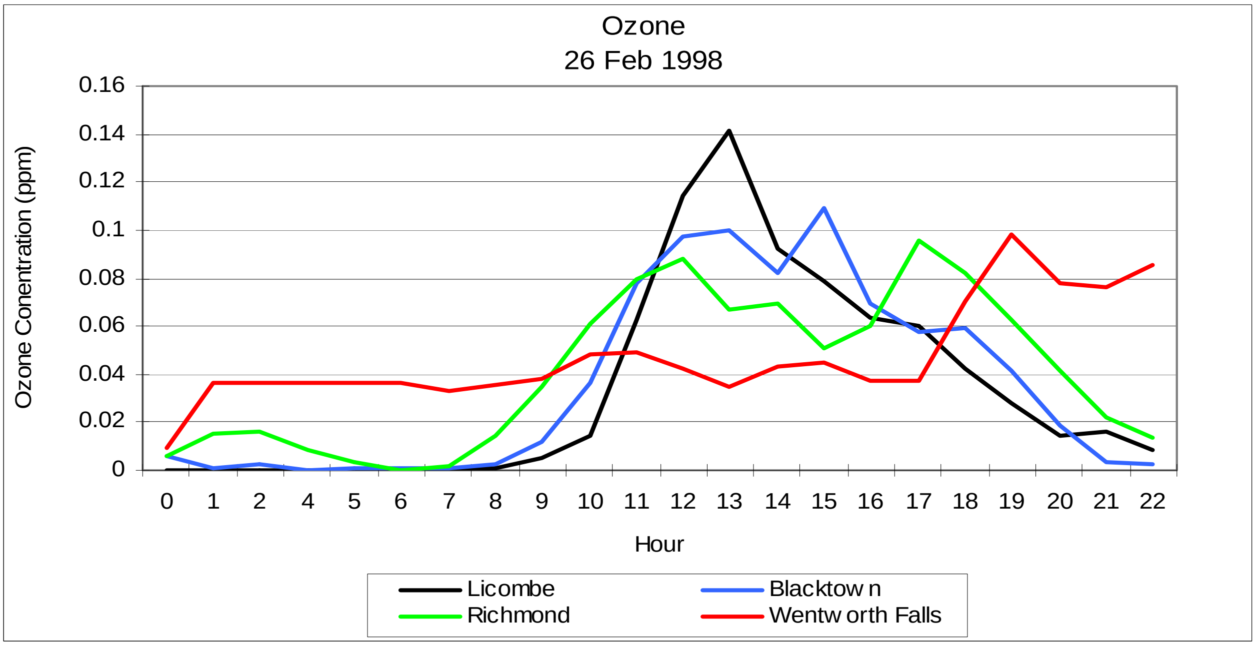


Figure 11: Examples of regional and sea breeze ozone, 25 February 1998



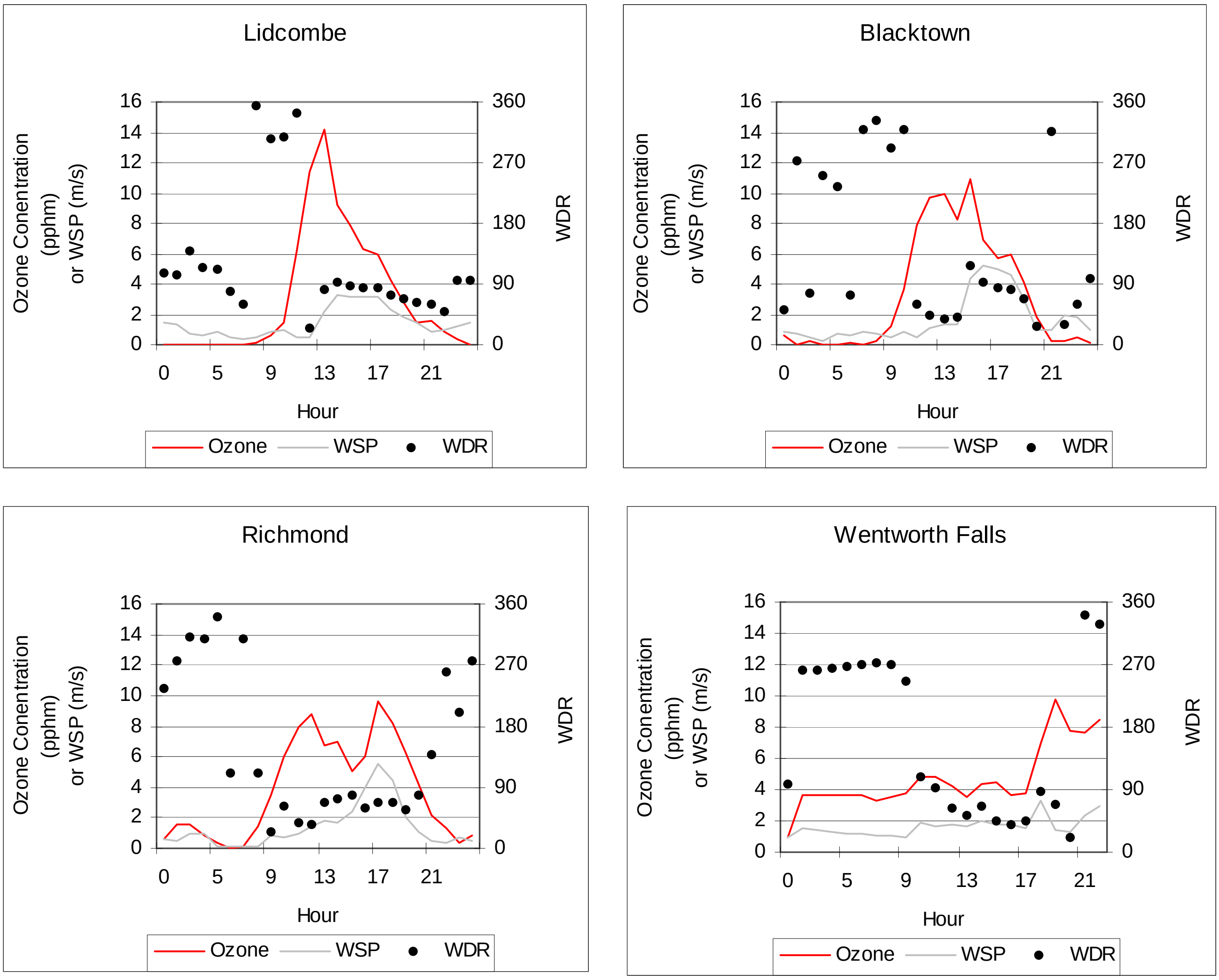


Figure 12: Example of sea breeze ozone, 26 February 1998

2.9 Data analysis: Sydney region 1994–2004

Sydney site analysis

Table 3 presents the number of exceedence-days and station-days for the Sydney region for each standard. Exceedence-days and station-days are separated into datasets for days when only the one-hour standard was exceeded, when only the four-hour standard was exceeded, and when both standards were exceeded.

During the period 1994 to 2004, there were 145 distinct exceedence-days in Sydney when ozone concentrations exceeded one or both of the current AAQ NEPM standards. There were 108 distinct exceedence-days for the one-hour standard and 138 for the four-hour standard. The majority of these days (101) reported exceedences of both the one-hour and four-hour standard on the same day. The data for station-days shows similar results.

The one-hour standard was exceeded without an exceedence of the four-hour standard on only seven days. Of these, one day occurred in April and one in October each with exceedences at one site only, accounting for the only one-hour exceedence-days in these two months (see Figure 17). On another day, a sharp short-lived peak was recorded at 8 am at Woolooware, which was also unusual. These types of events are rare and not well understood. It can be concluded that the current four-hour standard captures the majority of the one-hour exceedences (assuming the current AAQ NEPM standard).

The more usual one-hour peaks, due to the passage of the sea breeze front, are captured by the four-hour standard. However, the four-hour standard was exceeded on an additional 37 days without an exceedence of the one-hour standard, therefore capturing additional events. These additional four-hour exceedences could be the result of one-hour peaks just below the current one-hour standard or could be occurring under different meteorological regimes.

Table 3: Exceedences of the current AAQ NEPM standards for the Sydney region, 1994–2004

Averaging period	Exceedence-days	Station-days*
One-hour only	7	19
Four-hour only	37	174
One and four-hour	101	252
Total one-hour	108	271
Total four-hour	138	426
Total exceedence-days	**145**	**445**

* Station-day: an exceedence represents one day at one site

Data was examined for peak concentrations and exceedences of the current ozone one-hour and four-hour AAQ NEPM standards at each site between 1994 and 2004 (Table 4). Note that some stations were not operating for the entire 11 years (see Appendix C for data availability by year).

Analysis of the data shows that Bringelly reported the greatest number of exceedences of both the one-hour and four-hour standard. Oakdale had the second highest number of exceedence days for the one-hour standard and St Marys for the four-hour standard. Excluding sites with shorter measurement record periods, the sites with the fewest exceedences include Rozelle, Randwick and Earlwood for both standards.

The peak one-hour ozone concentration in Sydney was 0.18 ppm measured at both Blacktown and Westmead. The maximum four-hour concentration of 0.16 ppm was recorded at Blacktown.

Table 4: Maximum ozone concentrations and number of exceedence-days at each site in Sydney, 1994–2004

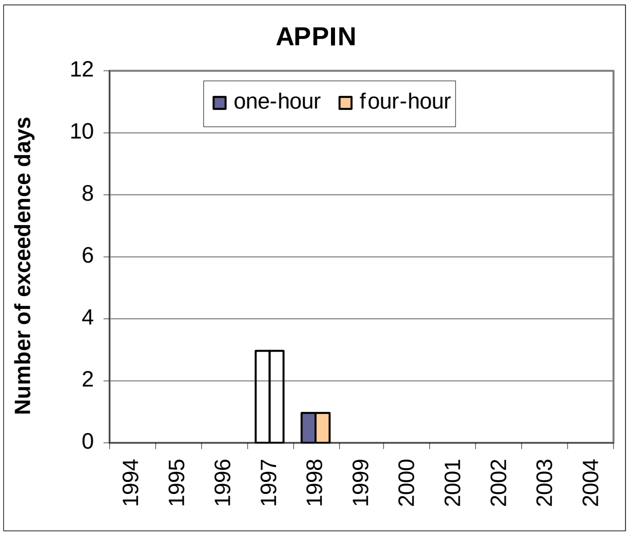
Site	Number of exceedence-days One-hour standard (0.10 ppm)	Maximum one-hour ozone concentration (ppm)	Number of exceedence-days Four-hour standard (0.08 ppm)	Maximum four-hour ozone concentration (ppm)
Appin[3]	4	0.11	4	0.09
Bargo[1]	24	0.16	38	0.13
Blacktown	22	0.18	30	0.16
Bringelly	42	0.17	64	0.13
Chullora[2]	1	0.10	4	0.09
Douglas Park[3]	2	0.14	3	0.11
Earlwood	2	0.13	6	0.09
Kensington[3]	0	0.07	0	0.06
Kurrajong Heights[3]	5	0.13	8	0.11
Lidcombe[2]	12	0.17	16	0.14
Lindfield	9	0.16	19	0.12
Liverpool	24	0.15	34	0.13
Macarthur[4]	0	0.099	1	0.08
Oakdale[1]	35	0.15	44	0.13
Randwick	6	0.17	8	0.15
Richmond	15	0.15	24	0.14
Rozelle	1	0.12	3	0.09
St Marys	27	0.16	47	0.14
Vineyard	17	0.14	30	0.12
Wentworth Falls[3]	0	0.098	2	0.08
Westmead	12	0.18	24	0.14
Woolooware	11	0.16	17	0.13
Total number of station-day exceedences	**271**	–	**426**	–

Each site was counted once for every day the ozone concentrations were exceeded.
[1] Bargo and Oakdale began in 1996
[2] Lidcombe (ceased operation in 2002) and was replaced by Chullora (began in 2003)
[3] Douglas Park (1994), Kensington (1994–95), Appin (1995–98), Wentworth Falls (1998–99), Kurrajong Heights (2000–2003)
[4] Macarthur began in 2004

Figure 13 presents the number of exceedence-days each year at each site for both the one-hour and four-hour standards. As discussed in the trends section above, the number of days when ozone standards are exceeded in any given year is strongly dependent on the meteorological conditions experienced in that year. Again, the impacts of a cooler and wetter summer (1995–96) and a hotter drier summer (1997–98 and 2001) are evident in this site-specific trend analysis.

Individual sites in Sydney have recorded exceedences of the one-hour ozone standard on a maximum of nine days at Bringelly in 2001, followed by Oakdale with eight exceedence-days in 1997. The four-hour standard was exceeded on a maximum of 12 days at both Bringelly in 2001 and Oakdale in 1997, followed by 11 exceedence-days at St Marys in 2001. Even the most recent data for 2004 shows exceedences of up to seven days a year at a site for both standards. This data shows that Sydney is far from complying with the AAQ NEPM goal of exceedences on no more than one day a year at a site.

High ozone concentrations and exceedences of the standards occur across the whole of Sydney, and the differences between regions are generally relatively small. However, this data demonstrates that exceedences of the current one-hour and four-hour ozone standard occur more frequently in western Sydney.


APPIN
one-hour
four-hour
Number of exceedence days
12
10
8
6
4
2
0
1994
1995
1996
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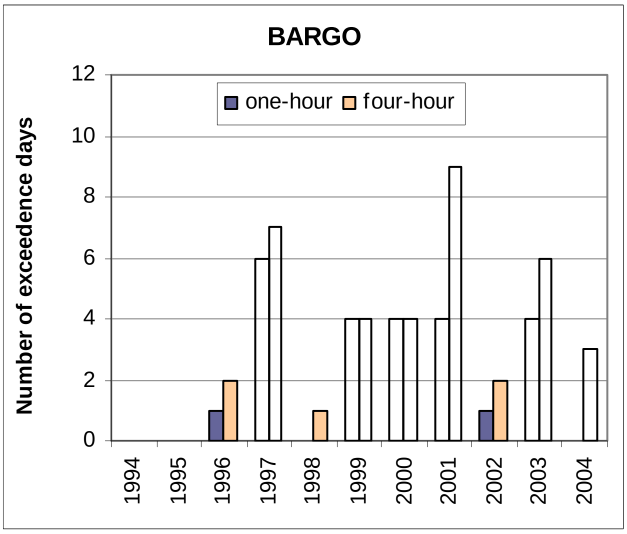
BARGO
one-hour
four-hour
Number of exceedence days
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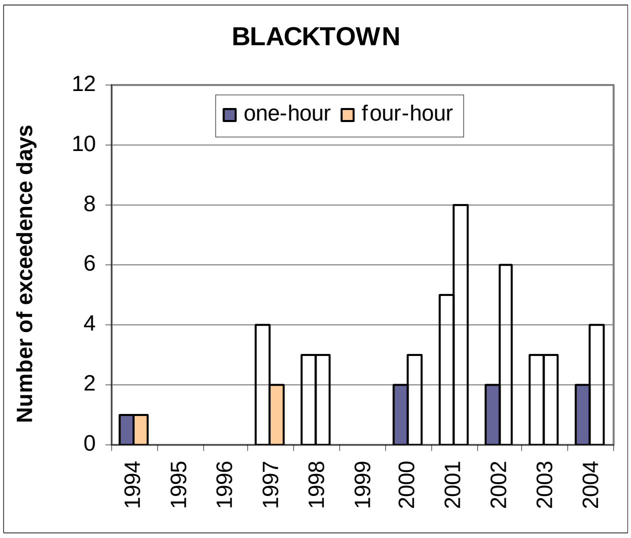
BLACKTOWN
one-hour
four-hour
Number of exceedence days
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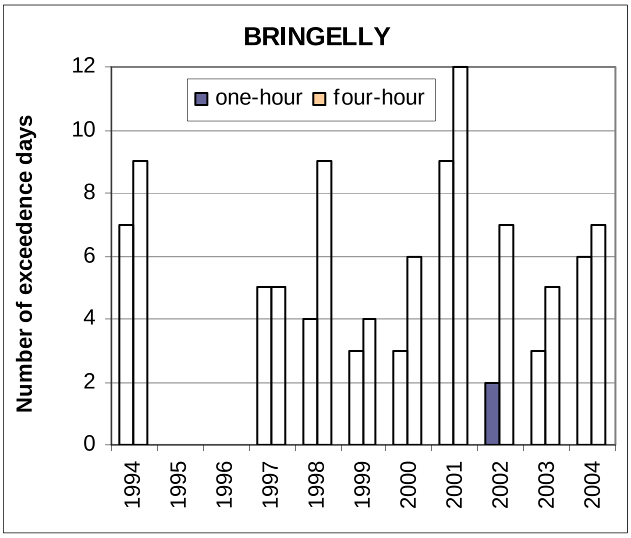
BRINGELLY
one-hour
four-hour
Number of exceedence days
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10
8
6
4
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0
1994
1995
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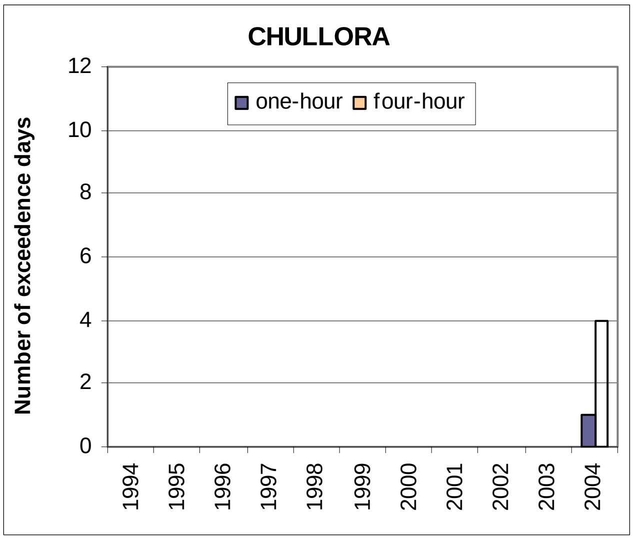
2004


CHULLORA
one-hour
four-hour
Number of exceedence days
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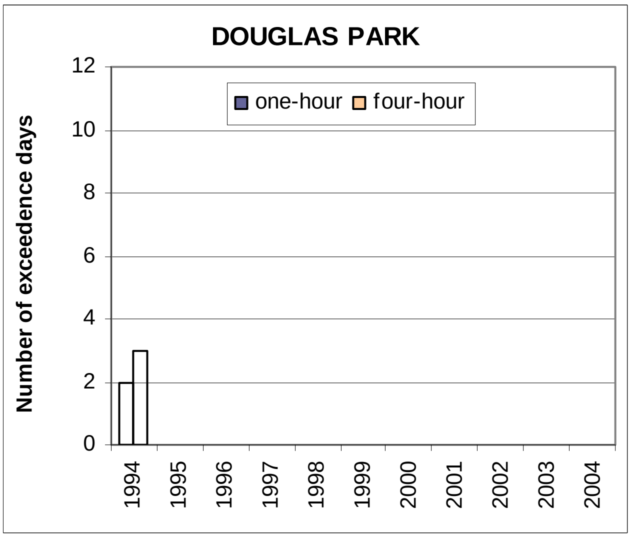
2004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one-hour
four-hour
Number of exceedence days
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8
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2
0
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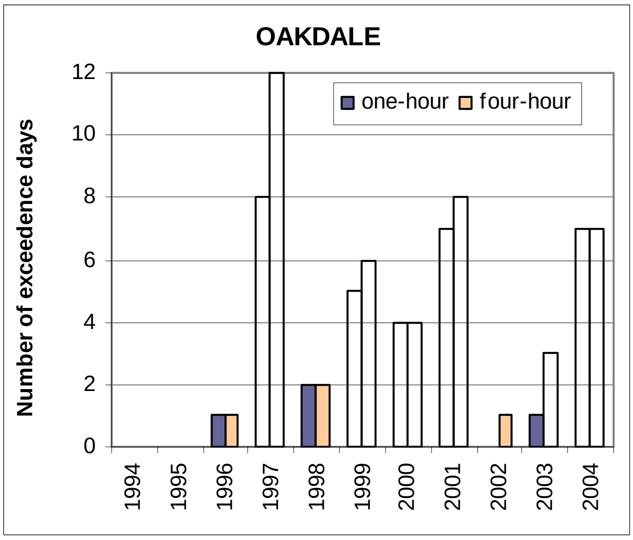
2002
2003
2004


OAKDALE
Number of exceedence days
one-hour
four-hour
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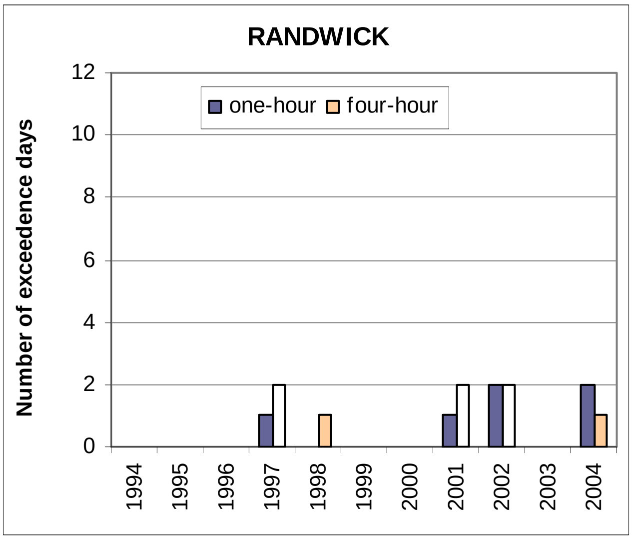
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Number of exceedence days
one-hour
four-hour
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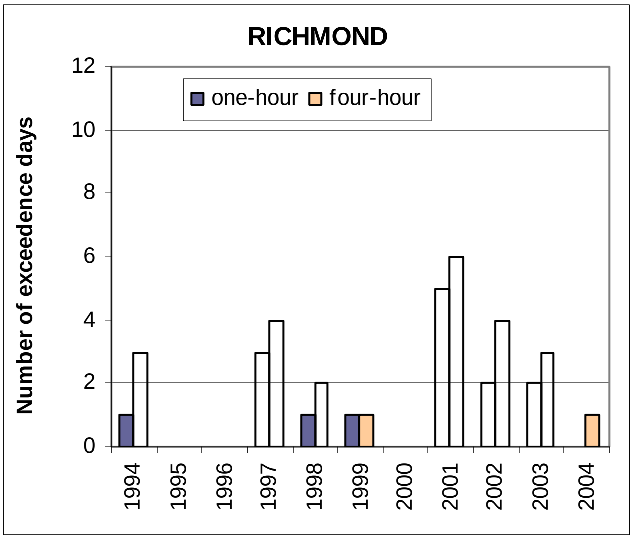
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Number of exceedence days
one-hour
four-hour
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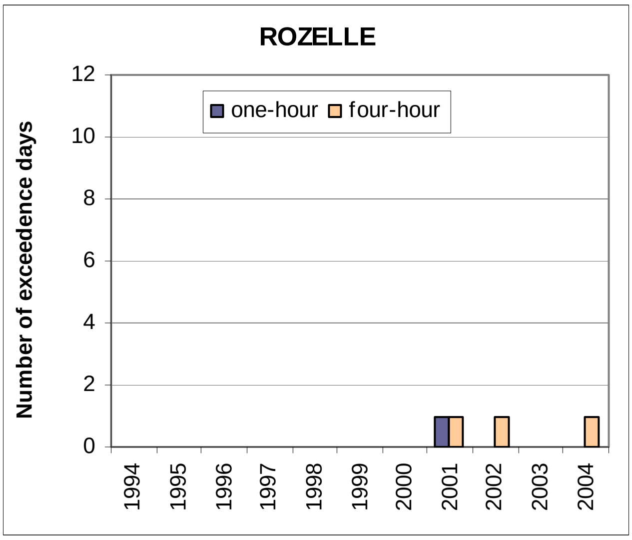
2004


ROZELLE
Number of exceedence days
one-hour
four-hour
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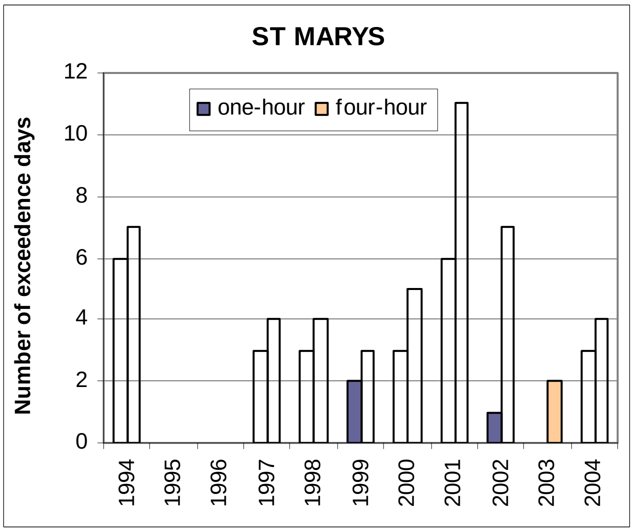
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Number of exceedence days
one-hour
four-hour
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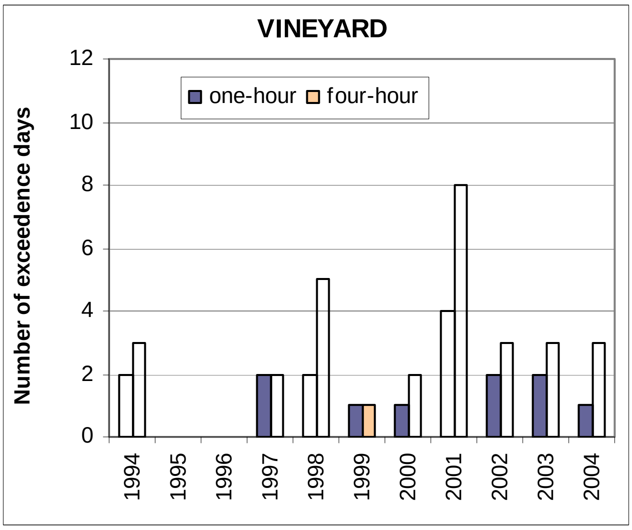
VINEYARD
Number of exceedence days
one-hour
four-hour
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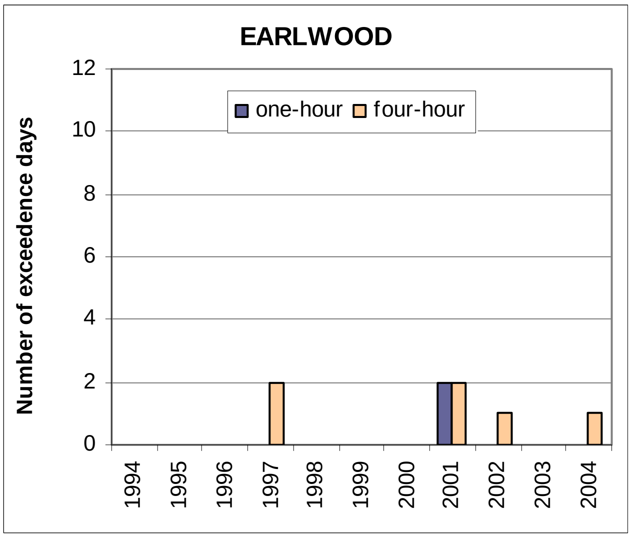
EARLWOOD
Number of exceedence days
one-hour
four-hour
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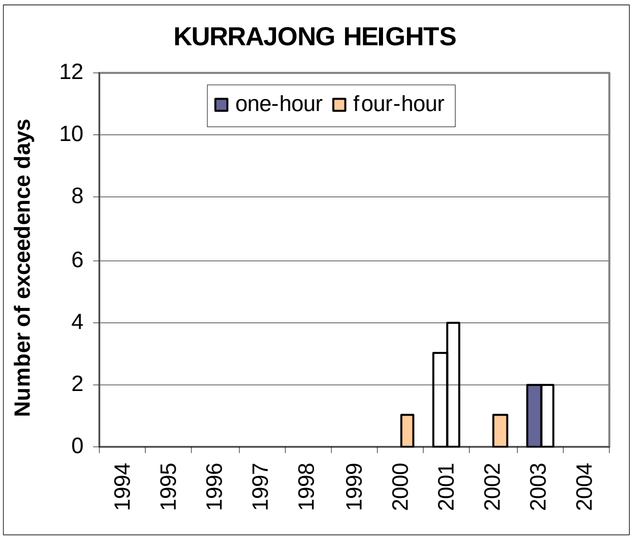
KURRAJONG HEIGHTS
Number of exceedence days
one-hour
four-hour
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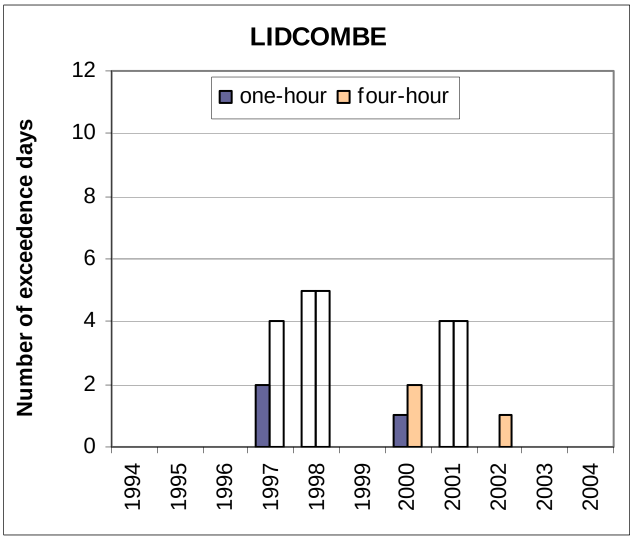
LIDCOMBE
Number of exceedence days
one-hour
four-hour
0
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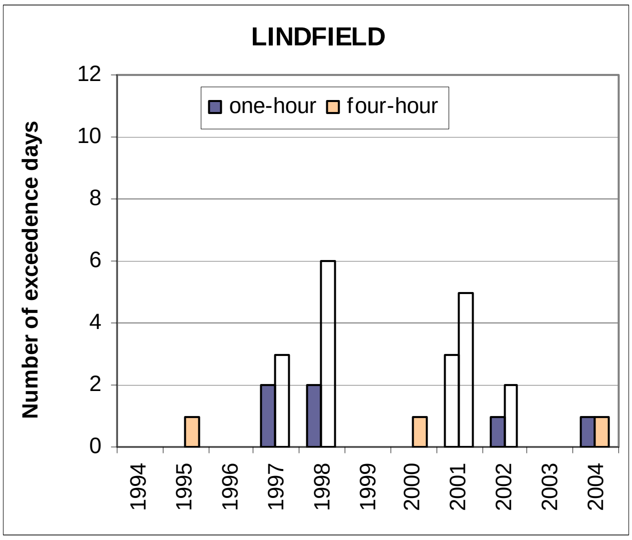
LINDFIELD
Number of exceedence days
one-hour
four-hour
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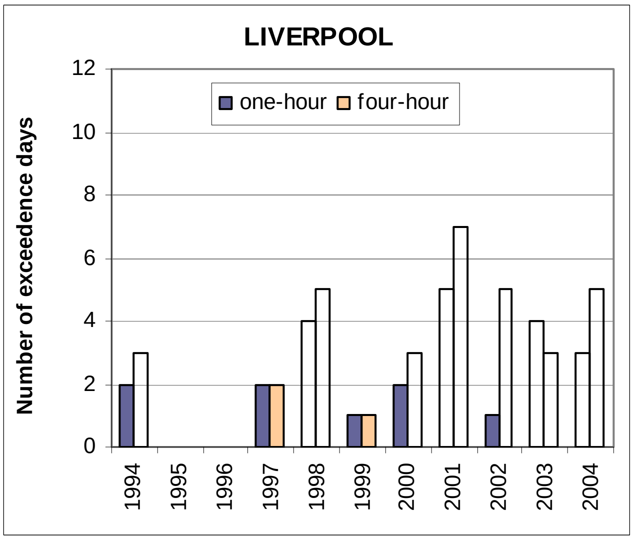
LIVERPOOL
Number of exceedence days
one-hour
four-hour
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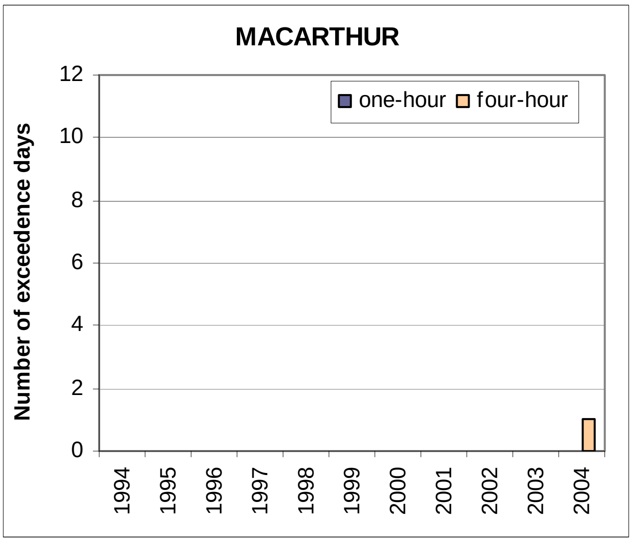
MACARTHUR
Number of exceedence days
one-hour
four-hour
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2
4
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1994
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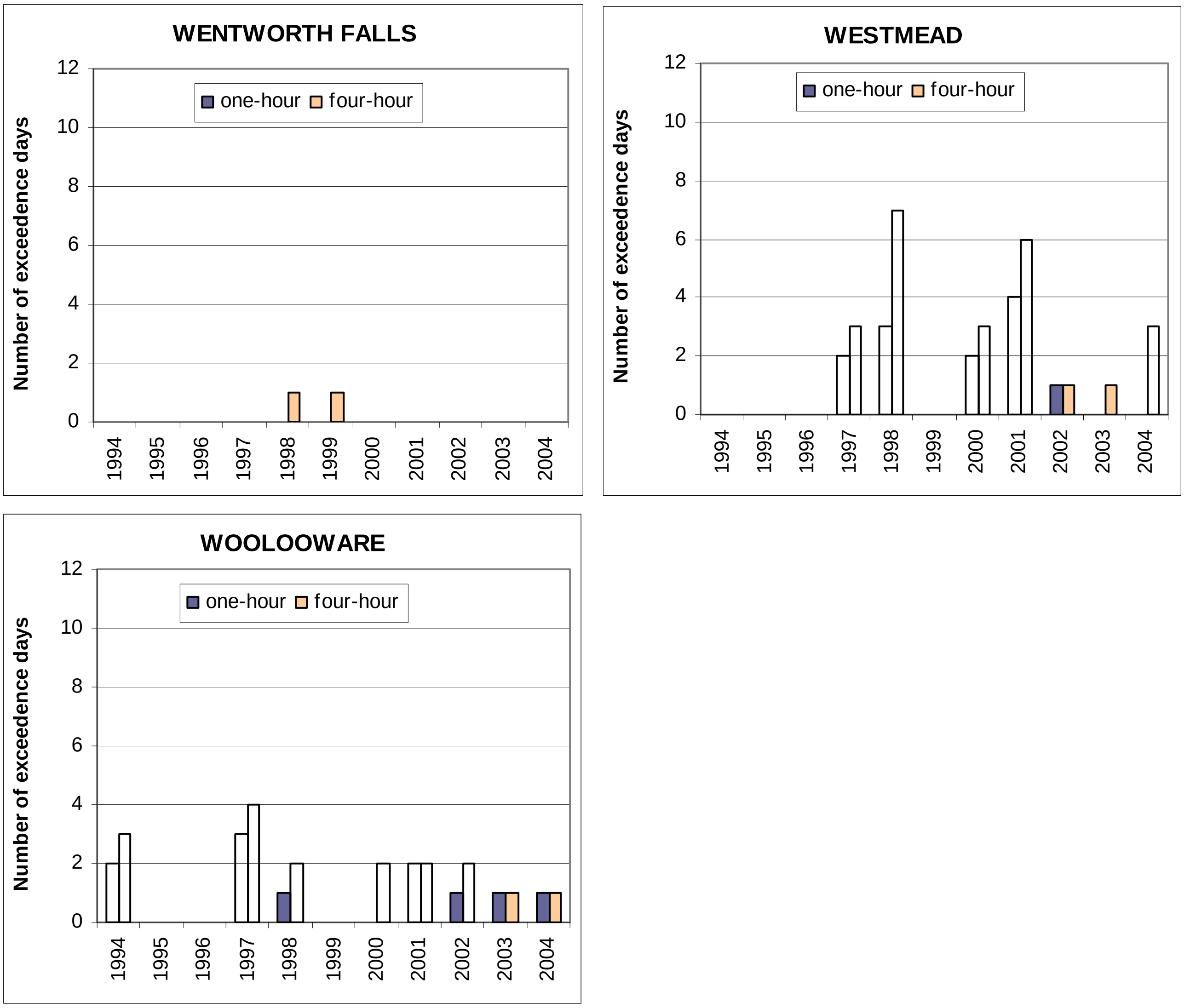


Figure 13: Number of exceedence-days each year at each site

The one-hour exceedences associated with the passage of the sea breeze front are also captured by the current four-hour standard. The current one-hour standard was exceeded alone on only seven days, demonstrating that the current four-hour standard captures the majority of one-hour exceedence-days.

However, the four-hour standard was exceeded on 37 days without an exceedence of the one-hour standard, showing additional events possibly occurring under different meteorological regimes.

Peak ozone concentrations and exceedences of the standards can occur across the whole of Sydney. However, exceedences of the one-hour and four-hour ozone standard occur more frequently in western Sydney.

The maximum number of exceedence-days at a site in one year was nine days for the one-hour standard and 12 days for the four-hour standard. This data indicates that Sydney is far from complying with the NEPM goal of exceedences on no more than one day a year at a site.

Geographic extent of exceedences

The number of stations exceeding the standard in a region is an indirect measure of the geographic extent of an ozone event. For the Sydney region exceedences of both the one-hour and four-hour standard can occur over a relatively large area, but most frequently occur at a single site.

From 1994 to 2004, there were 108 days where one-hour ozone concentrations were greater than 0.10 ppm. Exceedences occurred at one site only on 42 of these days (39%). The remaining 66 days had exceedences of the one-hour standard at multiple sites up to a maximum of 12 sites (Figure 14).

Exceedences of the four-hour standard show the same pattern. Exceedences of the four-hour standard occurred at one site only on 47 (34%) of the 138 exceedence-days. The remaining 91 days had exceedences of the four-hour standard at multiple sites up to a maximum of 13 sites.

Exceedences at eight or more sites on a particular day are infrequent with such widespread exceedence occurring on only two calendar days for the one-hour standard and 11 for the four-hour standard.

The high number of days with exceedences at one site only highlights the difficulty of assessing trend data when the monitoring network is altered.

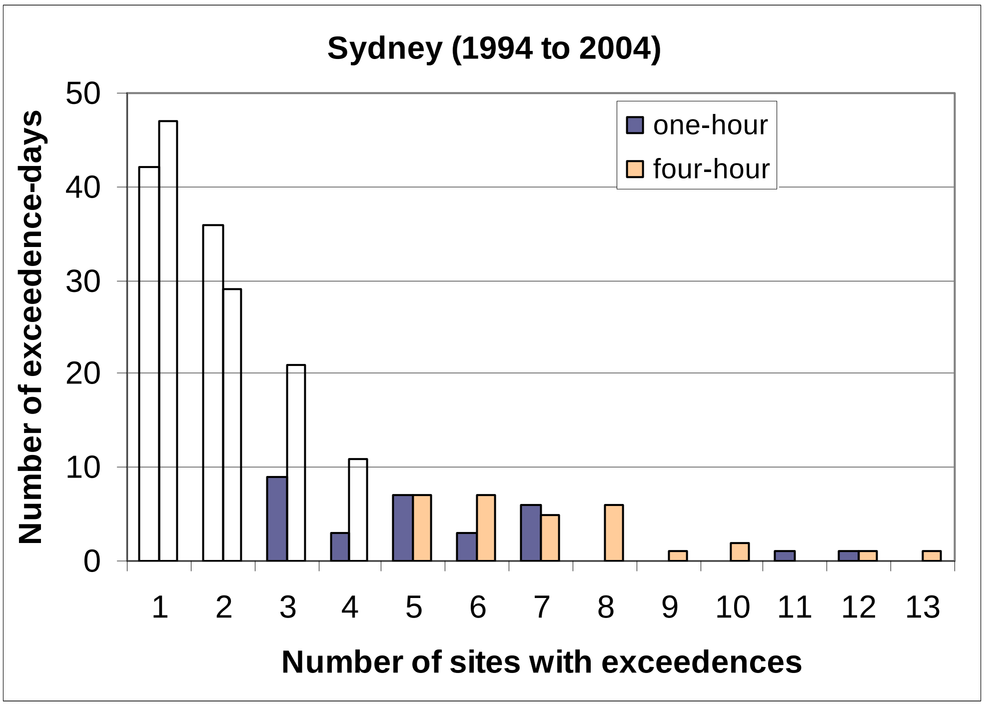


Figure 14: Number of sites with exceedences

> Over three-quarters of the exceedence days had exceedences at only one or two sites (78% of exceedence-days for the one-hour standard and 76% for the four-hour standard).
>
> In the Sydney Basin the largest number of sites exceeding the one-hour standard on a particular day was 12 out of the 16 sites operating at the time, while for the four-hour standard it was 13 out of 16 sites.

The number of days where exceedences occurred at one site only is given in Table 5. For example, the one-hour ozone standard was exceeded only at Bringelly on seven days. Bringelly had the highest number of days with exceedences at one site only for the one-hour standard and Oakdale and Woolooware for the four-hour standard.

Table 5: Frequency of the maximum ozone concentration on exceedence-days at each site

	Number of exceedence-days One-hour			**Number of exceedence-days Four-hour**		
	Exceedences recorded at one site only	Maximum ozone recorded on days where multiple sites exceeded	Total	Exceedences recorded at one site only	Maximum ozone recorded on days where multiple sites exceeded	Total
Appin	1	0	1	0	2	2
Bargo	6	6	12	6	8	14
Blacktown	0	4	4	1	2	3
Bringelly	7	9	16	5	17	22
Douglas Park	1	1	2	1	2	3
Kurrajong Heights	0	2	2	0	1	1
Lidcombe	3	2	5	3	6	9
Lindfield	1	1	2	1	3	4
Liverpool	3	8	11	2	9	11
Macarthur	0	0	0	0	1	1
Oakdale	6	17	23	9	13	22
Randwick	3	1	4	2	3	5
Richmond	1	2	3	2	1	3
Rozelle	0	0	0	0	1	1
St Marys	1	6	7	2	11	13
Vineyard	2	3	5	4	4	8
Westmead	1	3	4	0	5	5
Woolooware	6	1	7	9	2	11
Total exceedence-days	**42**	**66**	**108**	**47**	**91**	**138**

Kensington recorded no exceedence days in the two years it operated and is excluded from the table.
Chullora and Earlwood recorded exceedences, but were not the maximum concentration on these days and are omitted.

Table 5 also presents the number of days a particular site recorded the maximum ozone concentration when more than one site exceeded the standard. For example, Oakdale recorded the maximum ozone concentration on 17 days when more than one site exceeded the one-hour standard. Oakdale, Bringelly and Liverpool most frequently recorded the maximum on days when multiple sites exceeded the one-hour standard. Bringelly, Oakdale, St Marys and Liverpool most frequently recorded the maximum ozone concentration on days when multiple sites exceeded the four-hour standard. On days when exceedences were recorded at more than one site, it was found that sites in the west more frequently recorded the maximum ozone concentration.

There were no occasions where exceedences occurred at Wentworth Falls, Chullora and Earlwood alone. Also, these sites never reported the highest concentration in the Sydney Basin on a day when multiple sites exceeded.

Duration of exceedence

The duration of an ozone event is defined as the number of hours that exceeded the standard. Durations ranged from one hour to nine hours. Table 6 presents the count of station-days for each duration.

The two most frequently occurring durations for exceedences of the one-hour standard were one hour and two hours, and for the four-hour standard they were two hours and three hours. The longer durations for the longer averaging period were, in part, inherent in the calculation method, i.e. calculations are based on the previous four hours for a four-hour standard, where a one-hour peak can contribute to an exceedence for several hours.

Exceedences of the one-hour standard for a duration of seven hours occurred at Blacktown and Bringelly. Ozone concentrations were above the four-hour standard for a maximum of nine hours at Randwick and eight hours at Vineyard, St Marys, Richmond and Blacktown.

Table 6: Duration of ozone event for each station-day

Duration	One-hour 0.10 ppm	Four-hour 0.08 ppm
1 hour	137	75
2 hours	82	126
3 hours	25	99
4 hours	18	71
5 hours	6	32
6 hours	1	11
7 hours	2	7
8 hours	–	4
9 hours	–	1
Total	**271**	**426**

Exceedences at one site only are the most frequently occurring type of ozone event.

When exceedences were recorded at more than one site, it was found that sites in the west more frequently recorded the maximum ozone concentration.

The majority of exceedences have durations of three hours or less. However, on rare occasions, ozone concentrations above the standard can persist for up to seven hours for the one-hour standard and nine hours for the four-hour standard.

Hour of maximum ozone

Figure 15 shows the hour of the maximum observed ozone concentration on each day a standard was exceeded at each site. For example, at Blacktown on 12 January 2003 ozone concentrations exceeded the one-hour standard for five hours (representing one station-day), where the maximum one-hour ozone concentration was recorded at hour 14. On this day the four-hour standard was exceeded for six hours, where the maximum four-hour ozone concentration was recorded at hour 15. These are called the hour of maximum exceedence.

The hour of maximum exceedence for each of the 271 station-days for the one-hour standard and 426 station-days for the four-hour standard are presented in Figure 15. The most frequent hour of maximum exceedence for one-hour ozone was hour 14, while that for four-hour ozone was hour 16. Indeed further analysis not presented here shows that these are also the hours with the highest count of exceedences. That is, for one-hour ozone, hour 14 is the most common hour to exceed the standard and the hour most commonly reporting maximum ozone concentration on an exceedence-day. For four-hour ozone, this is true for hour 16.

Exceedences in the early hours of the morning (at 5 am for the one-hour and 6 am for the four-hour) were both recorded at Woolooware on 28 December 2001 during a major bushfire event in Sydney.

Because the AAQ NEPM labels an exceedence using the end time of the period, it is expected that the hour of maximum concentration for four-hour ozone will be later than that for one-hour ozone. If exceedences were labelled using the central hour, then both the one-hour and four-hour maximum concentrations would occur at hour 14.

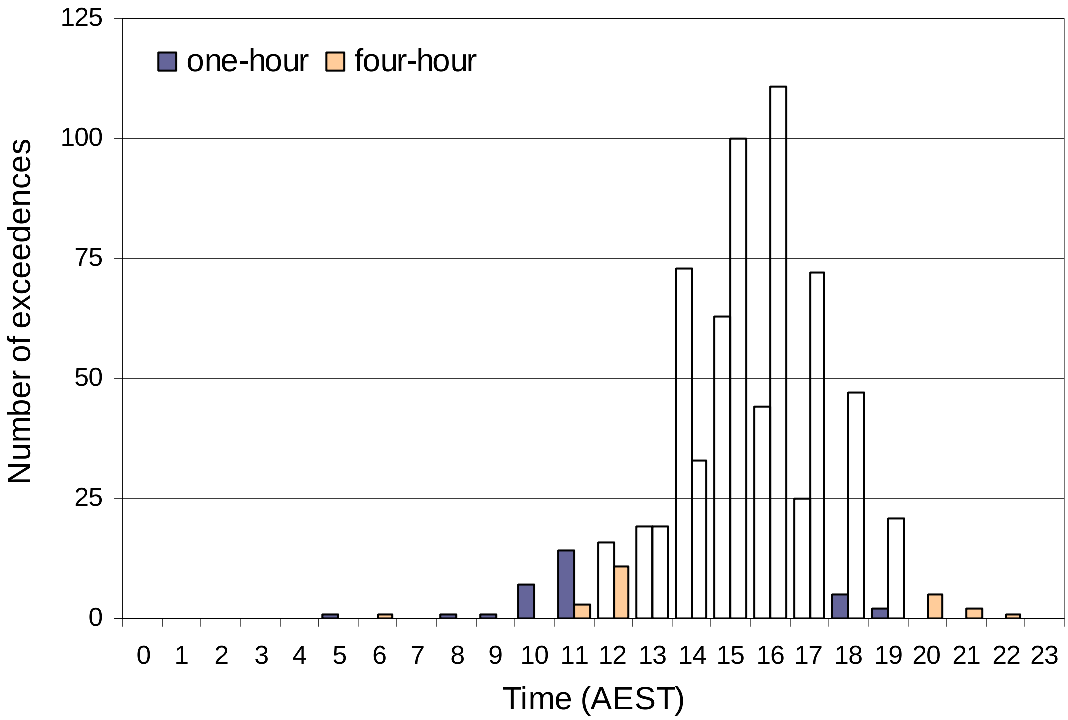


Figure 15: Hour of maximum ozone exceedence for each station-day

Among exceedence days, maximum ozone concentration was most frequently observed at hour 14 for the one-hour standard and hour 16 for the four-hour standard.

If the exceedences were referenced by the central hour, then the hour with the highest number of maximum exceedences would be hour 14 for both standards.

It is more useful to compare the hour of maximum exceedence by site within each averaging period (Tables 7 and 8) rather than comparing between averaging periods. The hours with the highest number of maximum exceedences are generally before hour 14 for sites in the east of the basin (Woolooware, Lindfield, Earlwood, Rozelle and Randwick) for both averaging periods. Maximum exceedences in the west occur more frequently later in the day. For example, the highest number of maximum exceedences occurs latest at Bargo and Kurrajong Heights for the one-hour and at Wentworth Falls, Bargo and Oakdale for the four-hour. These results are consistent with current understanding of meteorological processes in the Sydney Basin where short-term peak ozone concentrations are often associated with the passage of a sea breeze front from the east to the west.

Table 7: Frequency of hour of maximum one-hour ozone exceedence at each site

One-hour max	**≤ 10am**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**TOTAL**
Appin						**2**	1		1		4
Bargo	1		1			7	5	**8**	1	1	24
Blacktown		1	2	1	**9**	**9**					22
Bringelly		1		2	11	**16**	10	2			42
Chullora						**1**					1
Douglas Park					**1**	**1**					2
Earlwood		**1**	**1**								2
Kurrajong Heights					**2**	**2**				1	5
Lidcombe		3	2	1	**5**	1					12
Lindfield	1	1	2	1	4						9
Liverpool		1		5	**10**	3	5				24
Oakdale			1	1	2	3	**13**	12	3		35
Randwick		1			**2**	**2**	1				6
Richmond		1	1	1	**6**	1	1	1			15
Rozelle	1										1
St Marys			1	4	7	**11**	4				27
Vineyard	1	1	2		**6**	4	2	1			17
Westmead		2		2	**6**		2				12
Woolooware	**3**	1	**3**	1	2			1			11
Total	10	14	16	19	**73**	63	44	25	5	2	271

The hour with greatest frequency of maximum exceedence is in **bold**
Neither Kensington nor Macarthur recorded an exceedence of the one-hour standard.

Table 8: Frequency of hour of maximum four-hour ozone exceedence at each site

Four-hour max	**≤ 10am**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**TOTAL**
Appin							1	**2**	1					4
Bargo			1	2	2	3	5	7	**11**	5	1	1		38
Blacktown				1	3	**10**	7	6	2	1				30
Bringelly			1		3	12	**25**	14	8	1				64
Chullora				1			**2**	1						4
Douglas Park						**2**		1						3
Earlwood		1			**2**	1	1		1					6
Kurrajong Heights							2	**3**		1	2			8
Lidcombe					2	**9**	4	1						16
Lindfield			1	2	3	4	**6**	3						19
Liverpool			1	1	2	**13**	10	6	1					34
Macarthur							**1**							1
Oakdale				1	2	5	6	11	**13**	5		1		44
Randwick			1		1	**2**	**2**		1	1				8
Richmond		1	1	3	1	**6**	4	**6**		2				24
Rozelle			**2**						1					3
St Marys			1	3	5	14	**15**	5	3	1				47
Vineyard				3	1	8	**9**	1	2	4	2			30
Wentworth Falls									1				**1**	2
Westmead			2		1	7	**10**	3	1					24
Woolooware	1	1		2	**5**	4	1	2	1					17
Total	1	3	11	19	33	100	**111**	72	47	21	5	2	1	426

The hour with greatest frequency of maximum exceedence is in **bold.**

The hours with the highest number of maximum exceedences are generally earlier in the day for sites in the east of the basin (Woolooware, Lindfield, Earlwood, Rozelle and Randwick) and later for sites in the west for both averaging periods.

Correlation between ozone and temperature: Sydney data analysis

As discussed, suitable weather conditions such as sufficient sunlight, high temperatures and favourable wind conditions, are important to the formation of ozone. The importance of these higher temperatures was assessed using exceedence data from the Sydney region between 1994 and 2004.

Hourly ozone concentrations greater than 0.10 ppm were plotted against the corresponding temperature at that hour (Figure 16). There were 498 hours where the one-hour ozone concentration was greater than 0.10 ppm and of these 455 had valid temperature data. The average temperature for these hours was 33.4^{o}C, and the temperature was higher than 30^{o}C for 81% of them. The greatest maximum temperature at the time of an hourly exceedence was 43.2^{o}C. This supports other evidence that temperature and solar radiation play an important role in ozone formation. The two exceedences with corresponding temperatures below 20^{o}C occurred at Woolooware in the early morning as a result of bushfire activity.

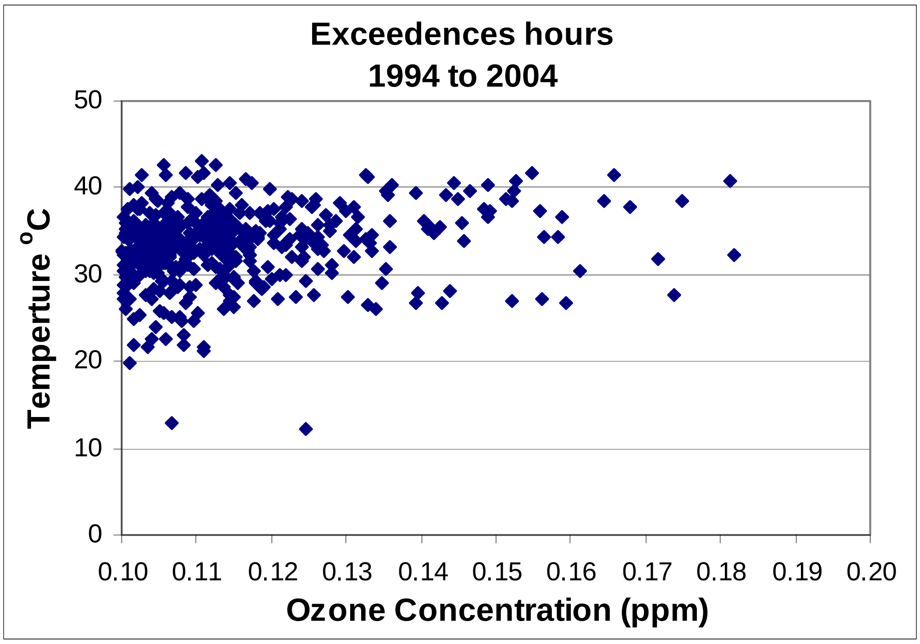


Figure 16: Correlation between ozone concentration and temperature

Further analysis of all data recorded when temperatures exceeded 30^{o}C shows that the average ozone concentration was 0.049 ppm (less than half of the one-hour standard). This demonstrates that higher temperatures alone did not result in an ozone exceedence; other meteorological conditions and sufficient precursor emissions were also needed.

Temperatures were greater than 30^{o}C for the majority of exceedences of the one-hour standard (> 80%). However, it was also found that these higher temperatures alone did not result in exceedences of the one-hour ozone standard. This highlights the importance of other meteorological mechanisms and precursor emissions.

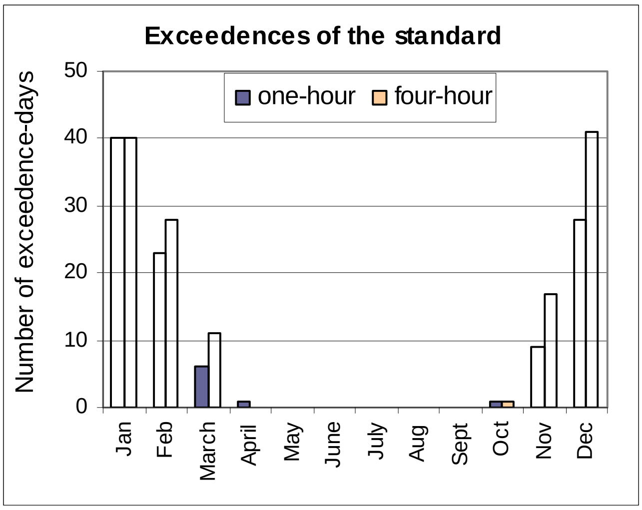
Exceedences by month: Sydney

Figure 17 provides the number of exceedence-days and station-days occurring each month for each standard. There are no exceedences of either ozone standard in the cooler months, from May to September, for the entire 11-year period. This demonstrates that daily temperatures and other conditions are not sufficient to produce photochemical smog during these cooler months.

For the one-hour standard, the month with the most exceedence-days and station-days was January. December and February had the next highest frequency.

For the four-hour standard, January and December had the highest number of exceedence-days (with only one day difference). While the highest number of station-days also occurred in January and December, there was a greater difference between them with January having more. This occurred because exceedences occurring in January were more widespread, occurring at more sites on the same day. For example, in January there were eight exceedence days with exceedences at only one site compared with 20 days in December with exceedences at one site only.

Meteorological conditions are more conducive to ozone formation in the warmer months. In addition to meteorological conditions, an increase in emissions of precursor pollutants may also contribute to ozone exceedences. About 30% of the total VOC emissions in the Sydney Basin for an average summer day are biogenic (Carnovale et al. 1997).



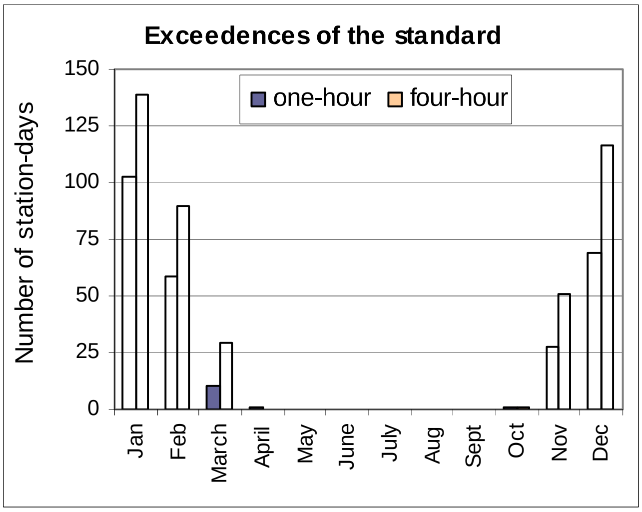


Figure 17: Number of exceedence-days and station-days each month, 1994–2004

Exceedences of both the one-hour and four-hour ozone standards occur throughout the warmer months only, peaking in January and December.

Day of week analysis: Sydney

An analysis of the number of exceedence-days occurring on each day of the week found little variation (Figure 18). The day with the highest number of exceedences was Thursday for the one-hour standard and Saturday for the four-hour standard. The lowest number of exceedences occurred on Sunday and Monday for the one-hour standard and Monday for the four-hour standard.

Thursday had the highest number of station-day exceedences for the one-hour standard and Friday for the four-hour standard. Monday had the lowest number of station-day exceedences for both the one-hour and four-hour standards.

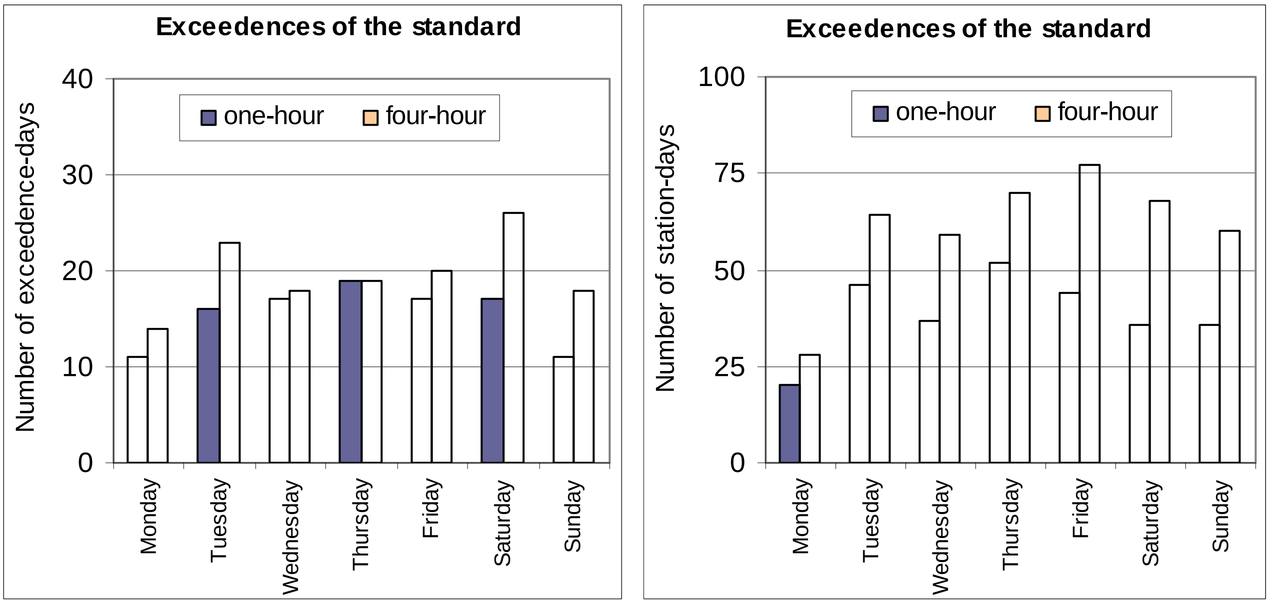


Figure 18: Number of exceedence-days and station-days for each day of the week

No significant trends were found for exceedences of either standard on different days of the week.

2.10 Investigation of the impacts of different standards

Investigation of the impacts of a one-hour standard at 0.08 ppm

The impact of reducing the one-hour standard concentration to 0.08 ppm was investigated. Table 9 presents the number of exceedence-days for the current one-hour standard of 0.10 ppm compared with the number of days for a one-hour standard of 0.08 ppm. A reduction in the one-hour goal to 0.08 ppm would have more than doubled the number of exceedence-days over the last 11 years for all regions. Such a goal generates an additional 140 exceedence-days in the Sydney region, an extra 53 in the Illawarra region and an extra 10 in the lower Hunter region for these 11 years (1994–2004).

Investigation of the impacts of an eight-hour ozone standard in Sydney

The introduction of an eight-hour standard is being considered as part of the regular review of air quality standards. The impact on exceedences if the concentration chosen for an eight-hour standard was 0.06, 0.065, 0.07 and 0.08 ppm has been assessed. These concentrations were chosen to represent a range of international 8-hour ozone standards – WHO 0.06 ppm, Canada 0.065 ppm, California 0.07 ppm and USA 0.08 ppm (WHO 2000; CCME 2000; CARB 2005b; US EPA 1997).

During the period 1994 to 2004 the eight-hour ozone concentration of 0.06 ppm was exceeded on 205 days (790 station-days) in the Sydney region. This compares with 108 days (271 station-days) for the one-hour standard and 138 days (426 station-days) for the four-hour standard. Table 10 shows the number of exceedence-days in each year for each of the four possible eight-hour standard concentrations. As with the one-hour and four-hour standards, 1995 and 1996 had the fewest exceedences.

Table 9: Number of exceedence-days one-hour > 0.10 ppm and one-hour > 0.08 ppm

	Sydney	Sydney	Illawarra	Illawarra	Lower Hunter	Lower Hunter
Year	**One-hour > 0.10 ppm**	**One-hour > 0.08ppm**	**One-hour > 0.10 ppm**	**One-hour > 0.08ppm**	**One-hour > 0.10 ppm**	**One-hour > 0.08ppm**
1994	13	29	4	6	0	1
1995	0	8	0	4	0	0
1996	1	5	0	2	0	0
1997	16	34	7	10	1	3
1998	13	26	3	11	0	2
1999	9	25	1	6	0	0
2000	6	22	3	11	0	0
2001	19	31	3	9	0	1
2002	9	26	2	12	0	3
2003	7	14	4	5	0	0
2004	15	28	3	7	1	2

Table 10: Number of exceedence-days for four possible eight-hour standard concentrations in the Sydney region

Year	Eight-hour > 0.06 ppm	Eight-hour > 0.065 ppm	Eight-hour > 0.07 ppm	Eight-hour > 0.08 ppm
1994	19	15	11	3
1995	2	0	0	0
1996	7	2	0	0
1997	27	20	13	6
1998	19	13	10	7
1999	18	14	8	0
2000	20	14	9	3
2001	25	20	15	9
2002	29	16	11	4
2003	15	12	7	2
2004	24	16	11	3
Total	**205**	**142**	**95**	**37**

Tables 11 and 12 show the number of exceedence-days and station-days, respectively, for these four standard concentrations for the eight-hour averaging period. These days were separated into datasets representing days when any one of the current one-hour standard, the current four-hour standard or the eight-hour concentrations were exceeded; any two were exceeded; and days when all three were exceeded, resulting in seven datasets.

In total there were 209 exceedence-days (814 station-days) when ozone concentrations exceeded at least one of the current one-hour and four-hour AAQ NEPM standards or the eight-hour ozone concentration of 0.06 ppm. This compares with the total of 145 exceedence-days (445 station-days) for just the one-hour and four-hour standards. Setting an eight-hour standard of 0.06 ppm would result in another 64 days (369 station-days) exceeding a standard. This suggests that an eight-hour standard at 0.06 ppm is stricter than the current one-hour and four-hour standards.

Table 11 shows that there are only four distinct exceedence-days that are not captured by an eight-hour concentration of 0.06 ppm (three days for the one-hour only and one day for the one-hour and four-hour combined). This indicates that an eight-hour concentration of 0.06 ppm would capture nearly every distinct ozone exceedence day that the current one-hour and four-hour AAQ NEPM standards capture. That is, an eight-hour standard concentration of 0.06 ppm would capture the sea breeze episodes that the one-hour and four-hour standards capture, as well as additional ozone episodes resulting possibly from different meteorological mechanisms.

Note that while an eight-hour standard of 0.06 ppm alone would capture most distinct exceedence-days, it would not capture these exceedences at every site (Table 12). It can be seen that 24 station-days are not captured by an eight-hour standard at 0.06 ppm. These days, however, represent less than three per cent of station days overall. This is of importance as the AAQ NEPM goals are based on allowable exceedences per year at each site.

An eight-hour standard at 0.065 ppm would capture an extra 17 exceedence-days and at 0.07 ppm an additional five exceedence-days. An eight-hour concentration of 0.08 ppm does not capture any extra exceedence-days, indicating that it would be less strict than the current one-hour or four-hour standards.

Table 11: Number of exceedence-days in the Sydney region for current AAQ NEPM standards and four possible eight-hour standard concentrations, 1994–2004

Averaging period	Eight-hour > 0.06 ppm	Eight-hour > 0.065 ppm	Eight-hour > 0.07 ppm	Eight-hour > 0.08 ppm
1-hour only	3	7	7	7
4-hour only	0	7	21	37
8-hour only	64	17	5	0
1 and 4-hour	1	6	27	64
1 and 8-hour	4	0	0	0
4 and 8-hour	37	30	16	0
All averaging periods	100	95	74	37
All 1-hour	108	108	108	108
All 4-hour	138	138	138	138
All 8-hour	205	142	95	37
Total	**209**	**162**	**150**	**145**

Table 12: Number of station-days in the Sydney region for four possible eight-hour standard concentrations, 1994–2004

Averaging period	Eight-hour > 0.06 ppm	Eight-hour > 0.065 ppm	Eight-hour > 0.07 ppm	Eight-hour > 0.08 ppm
1-hour only	10	16	18	19
4-hour only	4	28	80	165
8-hour only	369	152	33	0
1 and 4-hour	10	31	69	156
1 and 8-hour	9	3	1	0
4 and 8-hour	170	146	94	9
All averaging periods	242	221	183	96
All 1-hour	271	271	271	271
All 4-hour	426	426	426	426
All 8-hour	790	522	311	105
Total	**814**	**597**	**478**	**445**

Analysis assuming an eight-hour ozone standard of 0.06 ppm

Further analysis of data assuming an eight-hour ozone standard of 0.06 ppm is presented for the Sydney region. Table 13 presents the maximum eight-hour concentration at each site as well as the number of exceedences at each site of a standard of 0.06 ppm.

The maximum eight-hour concentration of 0.12 ppm was recorded at Randwick and Blacktown. All eight-hour concentrations greater than 0.09 ppm corresponded with exceedences of both the one-hour and four-hour standard.

The highest numbers of exceedences of an eight-hour standard concentration of 0.06 ppm were recorded at Bringelly, St Marys, Bargo and Oakdale.

Table 14 presents the duration of ozone exceedences for each averaging period. The durations for the one-hour and four-hour standards have been repeated here for comparison. The durations of the exceedences increase as the averaging periods increase. The one-hour standard was exceeded for only one or two hours on the majority of station-days whereas the eight-hour ozone concentration of 0.06 ppm was exceeded for four or five hours on the highest number of station-days. Sites with the longest durations of the eight-hour averaging period were Oakdale (13 hours), Randwick (12 hours), Kurrajong Heights, Blacktown and Oakdale (11 hours). The longer durations as the averaging period increases are, in part, inherent in the calculation method. Each time the eight-hour concentration was greater than 0.06 ppm for 10 hours or longer there was a corresponding exceedence of the one-hour standard.

Table 13: Maximum eight-hour ozone concentrations and number of days with a maximum eight-hour concentration greater than 0.06 ppm at each site in Sydney, 1994–2004

Site	Maximum concentration: eight-hour (ppm)	Number of exceedence-days: eight-hour concentration (at 0.06 ppm)
Appin	0.08	9
Bargo	0.10	75
Blacktown	0.12	59
Bringelly	0.11	105
Chullora	0.07	6
Douglas Park	0.07	3
Earlwood	0.08	14
Kensington	0.05	0
Kurrajong Heights	0.10	16
Lidcombe	0.10	29
Lindfield	0.10	46
Liverpool	0.10	53
Macarthur	0.07	2
Oakdale	0.11	72
Randwick	0.12	16
Richmond	0.11	55
Rozelle	0.08	9
St Marys	0.11	78
Vineyard	0.10	65
Wentworth Falls	0.08	7
Westmead	0.09	48
Woolooware	0.10	23
Total number of station-day exceedences	–	790
Number of distinct days (as represented in trend graphs)	–	205

Table 14: Duration of ozone event for each station-day in the Sydney region

Duration	One-hour 0.10 ppm	Four-hour 0.08 ppm	Eight-hour 0.06 ppm
1 hour	137	75	52
2 hours	82	126	93
3 hours	25	99	126
4 hours	18	71	129
5 hours	6	32	129
6 hours	1	11	110
7 hours	2	7	70
8 hours	–	4	34
9 hours	–	1	29
10 hours	–	–	13
11 hours	–	–	3
12 hours	–	–	1
13 hours	–	–	1
Total	**271**	**426**	**790**

Figure 19 shows the hour of the maximum observed ozone concentration for each station-day where the one-hour standard (271 station-days), the four-hour standard, (426 station-days) and an eight-hour standard of 0.06 ppm (790 station-days) were exceeded. The hour of maximum exceedence is defined in this report as ‘the hour recording the highest ozone concentration on each day when the standard was exceeded at each site’.

The most frequent hour of maximum exceedence for one-hour ozone was hour 14; that for four-hour ozone was hour 16; and that for eight-hour ozone (at 0.06 ppm) was hour 18.

Because the AAQ NEPM labels an exceedence using the end time of the period, it is expected that the hour of maximum concentration for eight-hour ozone will be later than that for one-hour or four-hour ozone. If exceedences were labelled using the central hour then the one-hour, four-hour and eight-hour maximum concentrations would all occur at hour 14.

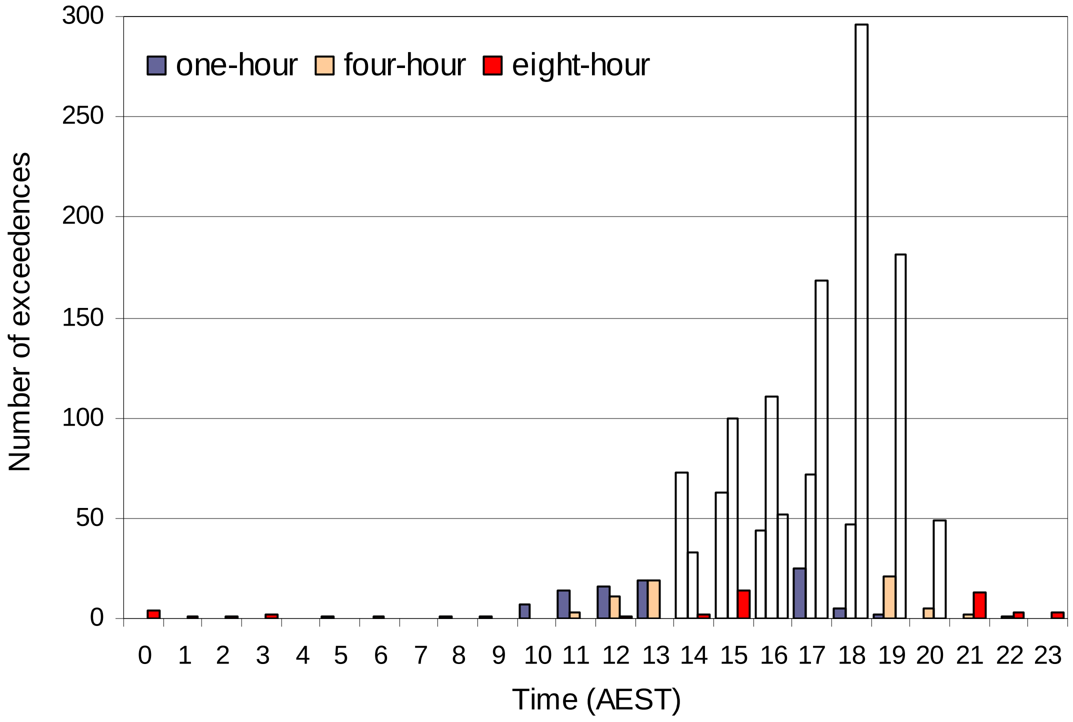


Figure 19: Hour of maximum ozone exceedences in the Sydney region, 1994–2004

It is therefore more useful to compare the hour of maximum exceedences by site within each averaging period (Table 15). The highest number of maximum exceedences occurs latest at sites in the west of the basin – Kurrajong Heights, Oakdale and Wentworth Falls (represented by the hours in the 'less than 11 am' column as they occurred in the early hours of the morning as a result of ozone concentrations the previous afternoon). These results are consistent with current understanding of meteorological processes in the Sydney Basin where short-term peak ozone concentrations are often associated with the passage of a sea breeze front from the east to the west.

A one-hour goal of 0.08 ppm would have resulted in an additional 140 exceedence days in the Sydney region, an extra 53 in the Illawarra region and an extra 10 in the lower Hunter region over the period 1994 to 2004.

An eight-hour standard of 0.06 ppm would result in an extra 64 exceedence-days, at 0.065 ppm an extra 17 days, and at 0.07 ppm an extra five days. At 0.08 ppm there would be no exceedence-days that either the current one-hour or four-hour standard did not capture.

An eight-hour concentration at 0.06 ppm would be stricter than the current one-hour and four-hour standards, and stricter than an eight-hour concentration of 0.08 ppm.

The highest eight-hour ozone concentrations were recorded at Blacktown (0.12 ppm), Randwick (0.12), Bringelly (0.11), Richmond (0.11), Oakdale (0.11) and St Marys (0.11).

Assuming an eight-hour ozone standard of 0.06 ppm:

- The most exceedence-days were recorded at Bringelly then St Marys, Bargo and Oakdale
- Exceedences most frequently lasted for four or five hours; the maximum duration was 13 hours.
- Maximum exceedences were most frequently observed at hour 18. However, if the exceedences were referenced by the central hour then maximum exceedences would most frequently be observed at hour 14.
- Hours with the highest number of maximum exceedences are generally earlier in the day for sites in the east of the basin, and later for sites in the west.

Table 15: Frequency of hour of maximum eight-hour ozone at each site

Eight-hour	≤ 11am	12	13	14	15	16	17	18	19	20	21	22	23
Appin							3	2	**4**				
Bargo					3	3	10	14	**29**	10	5		1
Blacktown						6	13	**26**	13	1			
Bringelly						6	23	**46**	27	2		1	
Chullora						1	1	**3**	1				
Douglas Park							1	**2**					
Earlwood					1	1	**5**	**5**	2				
Kurrajong Heights	1						3	**4**	3	**4**	1		
Lidcombe						2	4	**19**	4				
Lindfield					1	5	15	**22**	2	1			
Liverpool					2	4	12	**27**	8				
Macarthur								**2**					
Oakdale	3			1	1	1	8	16	**18**	14	6	2	2
Randwick						1	4	**5**	**5**		1		
Richmond					1	4	11	**21**	14	4			
Rozelle						2	3	**4**					
St Marys					1	7	19	**32**	16	3			
Vineyard					2	2	15	**20**	19	7			
Wentworth Falls	**4**								1	2			
Westmead					1	5	10	**20**	11	1			
Woolooware		1		1	1	2	**8**	6	4				

The hour with greatest frequency of maximum exceedence is in **bold.**

2.11 IER analysis: 1994 to 2003

IER modelling (Johnson 1984) was used to calculate the extent of the photochemical reaction. Software developed by Blanchard (1995), using the original IER algorithms, was used in this study, as were daytime hourly (07:00 to 18:00) ozone and NO_x measurements. Background ozone was assumed to be 0.015 ppm. Data from 2004 was not included in this analysis as quality assurance on this data was completed recently.

Extent ranges from 0 to 1, and indicates how far towards the NO_x-limited regime the photochemistry has progressed. Blanchard (2000) interprets the extent calculated from the IER model as follows:

- A value less than 0.6 indicates the air is in the light-limited regime.
- A value between 0.6 and 0.9 indicates the air is in the transitional to NO_x-limited regimes.
- A value greater than 0.9 indicates the air is in the NO_x-limited regime.

For the IER analysis, the eight-hour exceedences are based on a standard of 0.06 ppm. NO_x data was used to calculate the extent of reaction (Johnson et al. 1997). Only those station-days with both valid ozone and NO_x data were included in this study, resulting in a total of 666 station-days, representing 176 distinct days. Table 16 presents the number of exceedence-days at each site for this reduced data set.

For the IER analysis, measurement sites in the Sydney Basin were grouped into three regions – east, central and west (Figure 20). The eastern region represents sites that are located close to the coast. Sites west of the Blacktown ridge represent the western region and the remainder of sites (Blacktown, Chullora, Lidcombe, Liverpool and Westmead) fall into the central region.

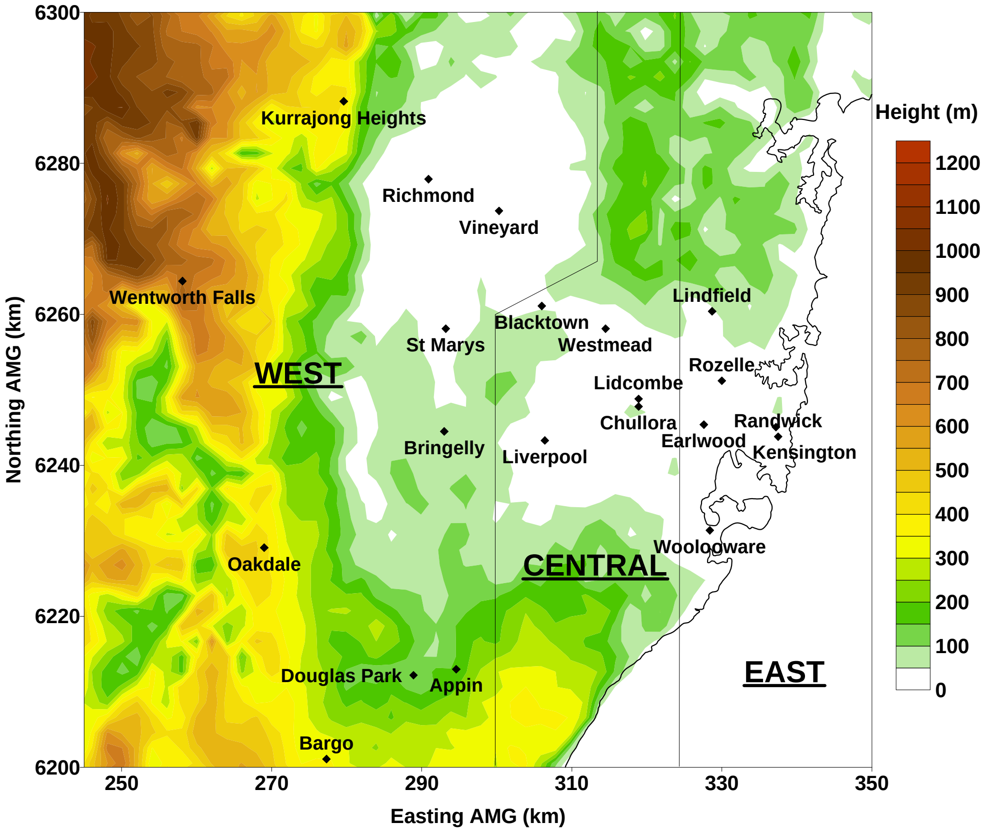


Figure 20: Regional boundaries defined for the IER analysis

Extent results are based on IER modelling of observations from these station-days (666 in total) and represent the extent at the hour of maximum ozone. Table 17 shows the distribution of extent of reaction at maximum hourly ozone concentration, on days where either the current standards were exceeded or the eight-hour concentration was greater than 0.06 ppm.

Table 16: Number of exceedences where IER could be calculated, 1994–2003

Site	Number of days exceeding the one-hour standard	Number of days exceeding the four-hour standard	Number of days exceeding eight-hour concentration of 0.06 ppm
Appin	3	3	8
Bargo	22	29	56
Blacktown	19	25	50
Bringelly	33	52	82
Chullora	0	0	0
Douglas Park	2	3	3
Earlwood	2	5	11
Kensington	0	0	0
Kurrajong Heights	3	6	11
Lidcombe	11	14	27
Lindfield	7	17	39
Liverpool	18	25	41
Oakdale	27	36	62
Randwick	4	6	13
Richmond	15	23	49
Rozelle	1	2	5
St Marys	24	41	66
Vineyard	16	27	58
Wentworth Falls	0	1	6
Westmead	12	21	38
Woolooware	9	14	19
Total station-days west	145	221	401
Total station-days central	60	85	156
Total station-days east	23	44	87
Total number of station-days exceeding	228	350	644
Number of distinct days	91	117	173

Table 17: Frequency of extent at hourly maximum ozone for each dataset

Averaging period	Light-limited (%)	Transitional (%)	NO_x-limited (%)
One-hour only	0	33	67
Four-hour only	0	75	25
Eight-hour only	1	17	83
One- and four-hour	0	67	33
One- and eight-hour	0	25	75
Four- and eight-hour	0	22	78
All averaging periods	2	17	81
Total	**1**	**19**	**80**

Table 18 explores this data further by presenting the frequency for each extent category at the time of maximum ozone for each exceedence type by geographic region. The data shows that the air mass was in the transitional regime at the hour of maximum ozone for 19% of station-days and was NO_x-limited for 80% of station-days for the entire Sydney region. Very few exceedence events were in the light-limited regime across Sydney. The number of exceedences in each frequently occurring category increased from the east to the west. Figure 21 presents the total number of days in each regime for each site, with Rozelle, Earlwood, Lidcombe and Woolooware having the highest number of days in the transitional regime. The majority of days at all other sites were in the NO_x-limited regime at the hour of maximum ozone on days with an exceedence.

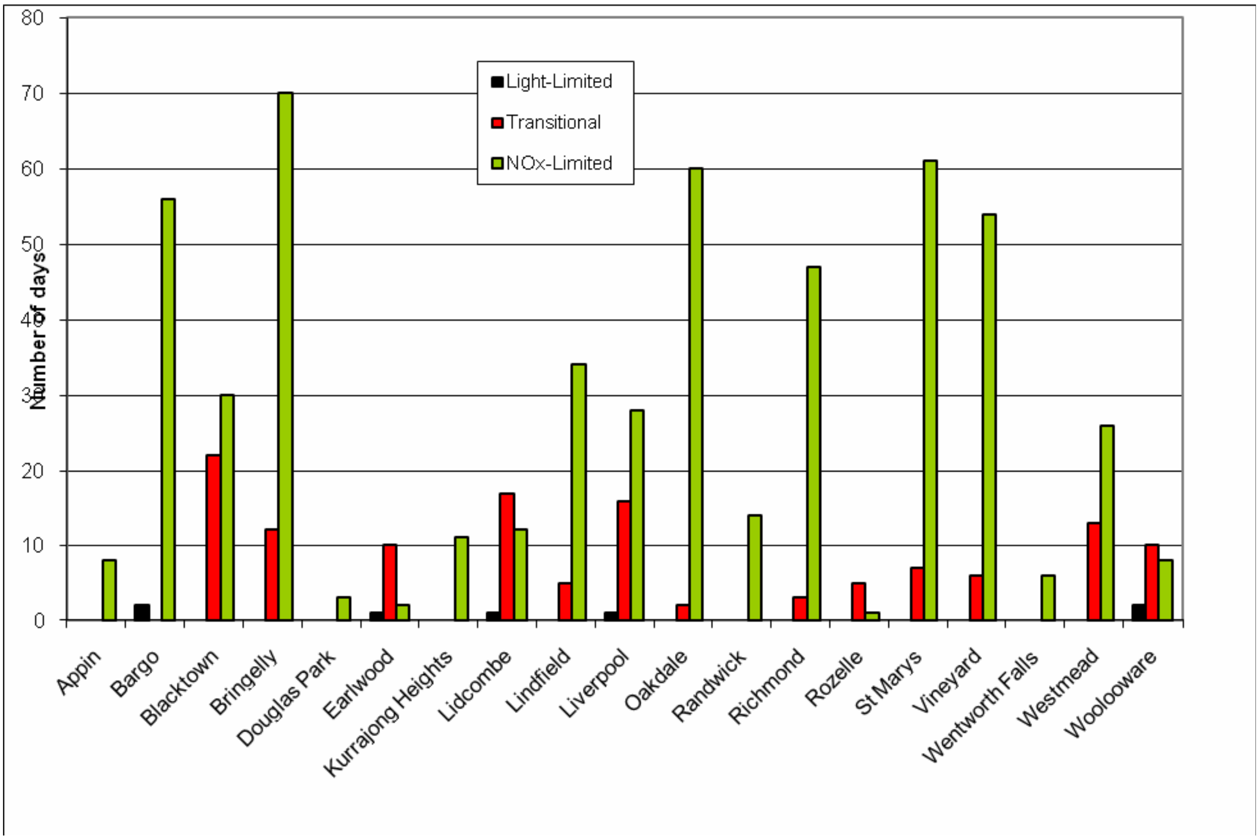


Figure 21: Distribution of extent at hour of maximum ozone on exceedence days

Table 18: Distribution of extent of reaction at hourly maximum ozone for days where either current AAQ NEPM standard was exceeded or the eight-hour ozone concentration was greater than 0.06 ppm

Region		One-hour only	Four-hour only	Eight-hour only	One-hour and four-hour	One-hour and eight-hour	Four-hour and eight-hour	All averaging periods	Totals
West	Light-limited	0	0	0	0	0	0	2	2
	Transitional	1	0	10	2	0	10	7	30
	NO_x-limited	3	0	170	1	3	73	126	376
	Totals	4	0	180	3	3	83	135	408
Central	Light-limited	0	0	2	0	0	0	0	2
	Transitional	2	2	24	1	1	13	25	68
	NO_x-limited	3	1	49	1	0	15	27	96
	Totals	5	3	75	2	1	28	52	166
East	Light-limited	0	0	1	0	0	0	2	3
	Transitional	0	1	16	3	0	6	4	30
	NO_x-limited	0	0	31	1	0	14	13	59
	Totals	0	1	48	4	0	20	19	92
Total	Light-limited	0	0	3	0	0	0	4	7
	Transitional	3	3	50	6	1	29	36	128
	NO_x-limited	6	1	250	3	3	102	166	531
	Totals	9	4	303	9	4	131	206	666

Figure 22 shows the frequency of extent at the hour of maximum ozone for each region in Sydney. The proportion of station-days in the NO_x-limited regime was highest in western Sydney (92%). In central and eastern Sydney, however, over 30% of station-days were in the transitional regime (extent between 0.6 and 0.9). Duc et al. (2003) reports similar results, finding that sites in western Sydney had higher frequencies of elevated ozone in the NO_x-limited regime.

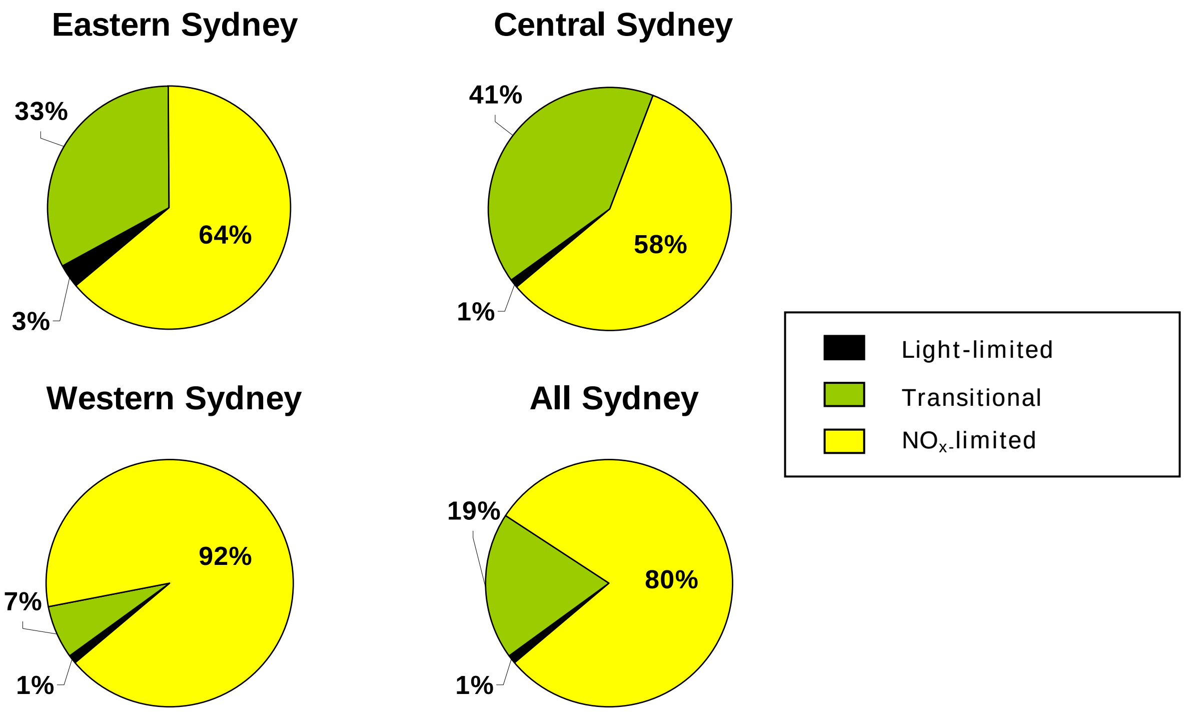


Figure 22: Frequency of extent at hourly maximum ozone for each region

These results – based on observations and IER modelling – show that in Sydney, ozone exceedences can occur in both the light-limited and NO_x-limited regimes, although the frequency of light-limited events is very low.

Computer simulation of a subset of these days indicates that the situation is more complicated. Johnson and Spencer (2005) show differing behaviour among three simulated ozone event days. While reducing NO_x emissions resulted in a decrease in maximum ozone concentration on two days, control of both VOCs and NO_x was more effective. On the other modelled event day, a substantial reduction of NO_x emissions was needed before maximum ozone concentration decreased. This demonstrates the complexity of ozone formation in an urban airshed and shows that no single control strategy is effective for all ozone events in Sydney.

Blanchard (2000) shows that extent of reaction alone is insufficient as an indicator of sensitivity of ozone concentration in a region with complex meteorology and emission changes. A significant proportion of VOC emissions in the Sydney region are from biogenic sources and much of these are located to the west of Sydney. However, anthropogenic VOC emissions dominate in central and eastern Sydney. The combination of the variation in the reactivity of biogenic and anthropogenic VOC emissions with the complex meteorological conditions observed in Sydney, may account for the differences between observed and modelled ozone events. Regardless of the region or the averaging period, the highest proportion of station-days was in the NO_x-limited regime. This is particularly true in western Sydney where 92% of station-days are NO_x-limited. In central and eastern Sydney however, over 30% of station-days had an extent in the transitional regime. This indicates that controlling NO_x would likely reduce the frequency of exceedences in western Sydney; however, NO_x control alone may not necessarily reduce the frequency of exceedences elsewhere in Sydney. Duc et al. (2003) also concluded that reducing ozone concentrations through NO_x control alone is not effective for the entire Sydney region.

Results of observational analysis, together with results of event simulation, have shown that no single control strategy is effective for all ozone events or for the entire Sydney region.

IER modelling was used to calculate the extent of the photochemical reaction using Sydney data between 1994 and 2003.

Results shows that, regardless of the region or the averaging period, the highest proportion of station-days were in the NO_x-limited regime.

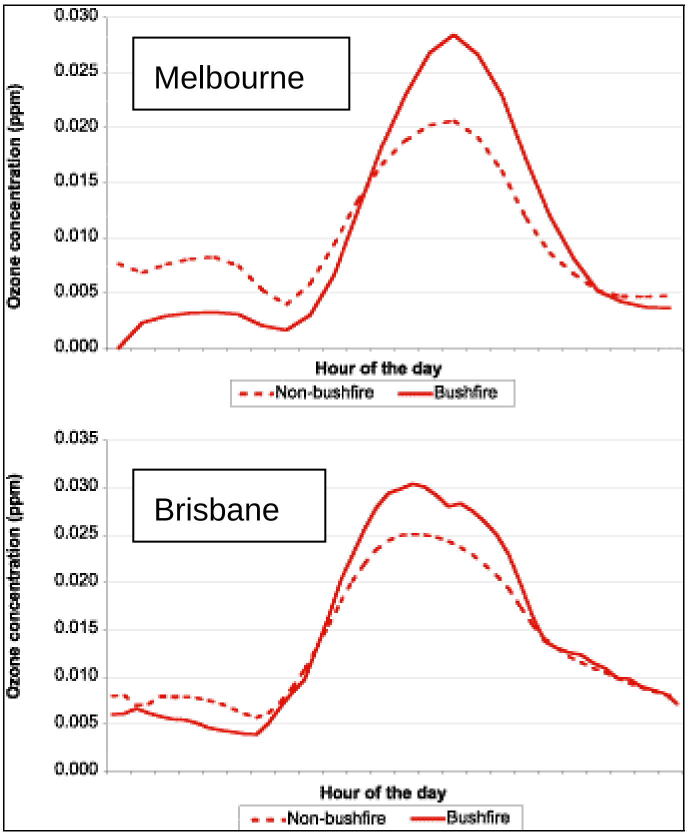
This is particularly true in western Sydney where 92% of station-days are NO_x-limited. In central and eastern Sydney however, over 30% of station days had an extent in the transitional regime.

This indicates that controlling NO_x would likely reduce the frequency of exceedences in western Sydney, but NO_x control alone may not necessarily reduce the frequency of exceedences elsewhere in Sydney.

2.12 The impact of bushfire events on ozone concentrations

Major bushfire events can have a significant impact on air quality. During bushfires, PM_{10} concentrations increase, often exceeding goals, and visibility is reduced (as measured by nephelometer). Ozone concentrations can also increase during bushfire events due to the emissions of ozone pre-cursors (NO_x and VOCs) from the fire.

Analysis of data from Melbourne and Brisbane concluded that fires contribute to many occasions when elevated ozone concentrations are recorded (AATSE 1997). Figure 23 shows that average ozone concentrations in Melbourne and Brisbane are higher when there are bushfires in the region than on other occasions. The effect is more marked if only days conducive to ozone formation are selected.



Source: DEHC 2001

Figure 23: Ozone concentrations in Melbourne and Brisbane with and without bushfires

Bushfires in Sydney

In January 2003 there were major bushfires in and around Canberra and the southern parts of NSW. Since 1994 there have been three major bushfire events in NSW with widespread fire activity both within and surrounding the Sydney Basin. There have also been numerous smaller bushfires in Sydney where impacts on air quality can only be seen at one or two sites.

Major bushfire events in Sydney since 1994 include:

1. 27 December 1993 to 16 January 1994

The NSW Rural Fire Service (1998) has documented the major bushfire event occurring in the summer of 1993–94. It is reported that more than 800 fires started in NSW between 27 December 1993 and 16 January 1994, the majority along the coast or nearby ranges. Fires began in the Hunter Region, Wingecarribee, Shoalhaven and Wollongong areas in December, then in the Gosford and Wyong areas, Ingleburn and the Royal National Park south of Sydney.

The greatest number of fires occurred 5–9 January 1994. A deep low pressure system was located south of Tasmania, maintaining hot dry westerly winds over NSW during this period. Maximum temperatures above 35°C, relative humidity around 13%, and winds gusting to 70 km per hour promoted rapid fire spread. On 6 January the first major outbreaks of fire in the Sydney metropolitan area occurred, including those in the Lane Cove River Park and within the Sutherland Council area. Temperatures were well into the 40s with humidity less than 20% and winds gusting over 50 km per hour. Fires were also burning in the Blue Mountains and Warringah. Intrusion by fire into heavily populated suburbs of Sydney, Wollongong and Gosford occurred in a manner never before documented.

2. 1–5 December 1997

Bushfires near the Sydney Basin were located in Lithgow and then in Sydney's southern suburbs including Menai. Fires were also burning in the Hunter Valley, the Hawkesbury River region and the Blue Mountains. More than 400 bushfires burned across Australia's eastern seaboard, fanned by strong winds and high temperatures. On 5 December rain fell across the state, bringing fires on the city's outskirts and across the state under control (NSW Fire Brigades).

3. 24 December 2001 to 7 January 2002

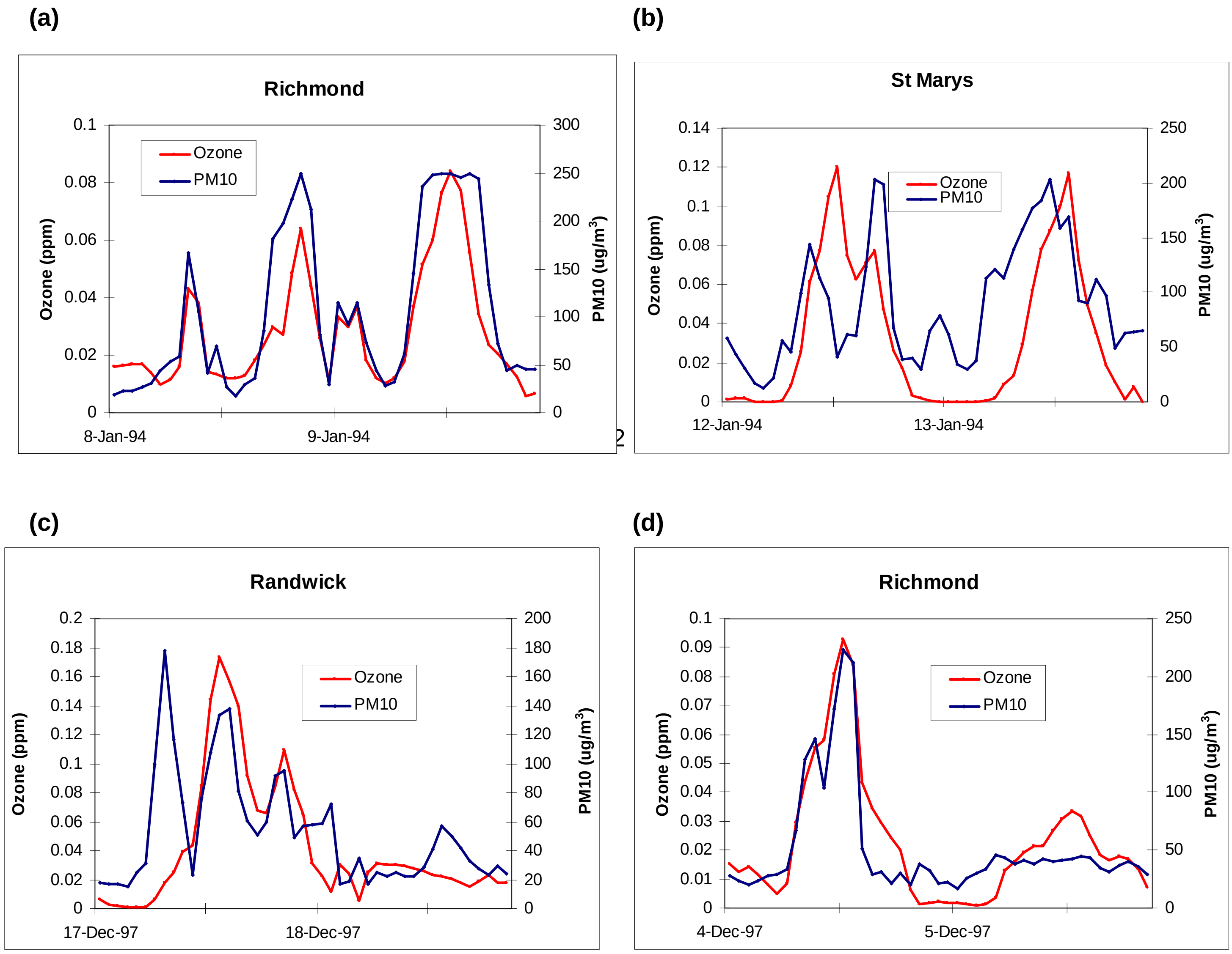
The 2001–02 Christmas bushfire emergency officially began on 24 December 2001 with the outbreak of major bushfires in the Cessnock, Blue Mountains, Hawkesbury and Penrith areas. The main fire activity ended on 7 January 2002 following heavy overnight rain around Sydney. Fires were still burning in the South Coast region until 11 January 2002 (NSW Fire Brigades). These fires are reported to have been more intense than the 1994 fires.

The impact on ozone

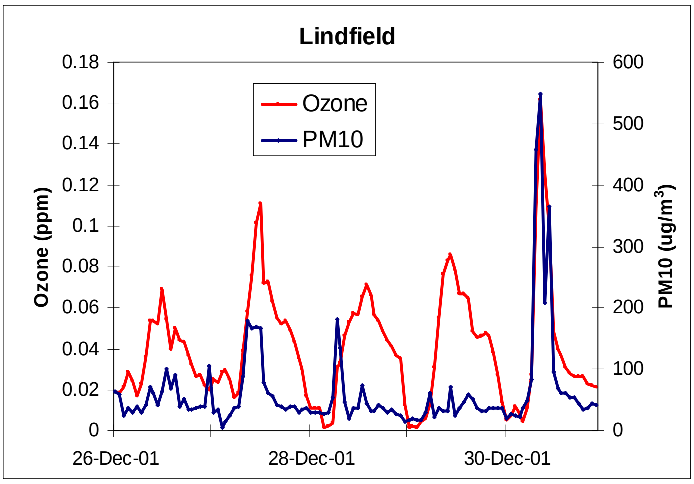
Figure 24 shows examples of the impact of these major bushfire events on ozone concentrations in Sydney. Figures 24a–b show ozone and PM_{10} concentrations during the 1994 bushfires in Sydney. In these examples ozone concentrations tend to follow PM_{10} concentration. Figure 24c provides an example of ozone on a day that falls outside of the major bushfire events. Bushfire activity on this day is assumed due to the concentrations of particles. Figures 24d–f provide examples of ozone and particle concentrations at sites in the Sydney region during the 1997 and 2001–02 bushfire events. The 2001 bushfires contributed to five of the 19 exceedences of the one-hour ozone standard in 2001 and two of the nine exceedences in 2002. The highest ozone concentration measured since 1994 was 0.18 ppm, which was recorded at Westmead on 30 December 2001 (Figure 24f) and then again at Blacktown in January 2003.

Figure 24g shows ozone concentrations exceeded the one-hour standard at hours five and six in the morning on 28 December 2001 at Woolooware. Ozone does not usually reach these concentrations at this hour in the morning as precursor pollutants have not been exposed to enough sunlight to react photochemically. This unusual diurnal pattern for ozone, particularly on December 28, and the increase in nephelometer (decreased visibility) are evidence that bushfires led to this ozone exceedence.

While bushfires can have an impact on ozone concentrations, the increase in precursor emissions from bushfires alone will not necessarily lead to an ozone exceedence. For example, hazard reduction burning throughout the cooler months does not usually lead to ozone exceedences (see Figure 14). This is due to lower temperatures in these months and meteorological conditions that are not conducive to ozone formation.



(e)



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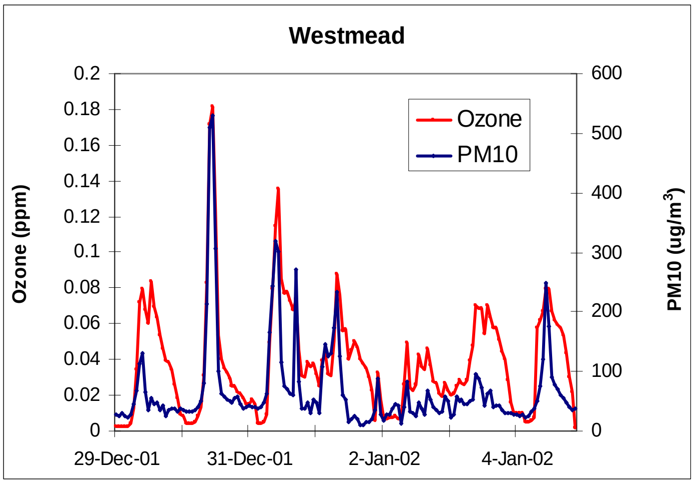

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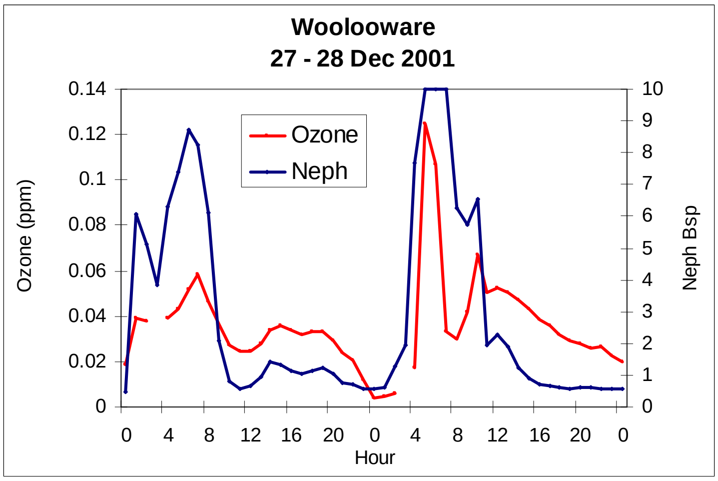


Figure 24: Examples of the impact of bushfires on ozone concentrations in Sydney

Bushfires are a natural source of ozone precursors (NO_x and VOCs) that can react to form ozone at concentrations that exceed the current standards. Bushfires near Sydney in the summer of 2001–02 contributed to five of the 19 exceedences of the one-hour ozone standard in that year, and two of the nine exceedences in 2002.

While records exist for major bushfire events, a comprehensive record of all bushfires is needed to assess their true impact on the number of exceedences in Sydney.

The increase in precursor emissions from bushfires alone does not necessarily lead to an ozone exceedence if meteorological conditions are not suitable (e.g. hazard reduction burning throughout the cooler months does not usually lead to ozone exceedences).

2.13 Lower Hunter 1994–2004

Ozone concentrations in the lower Hunter region rarely exceed the current AAQ NEPM standards. The exceedences of the standards at each monitoring station in the lower Hunter are shown in Table 19.

There were only two exceedence-days for the one-hour standard (17 December 1997 at two sites and 21 February 2004 at all three sites). The four-hour standard was exceeded on three days during this time period (17–18 December 1997 and 2 January 1998).

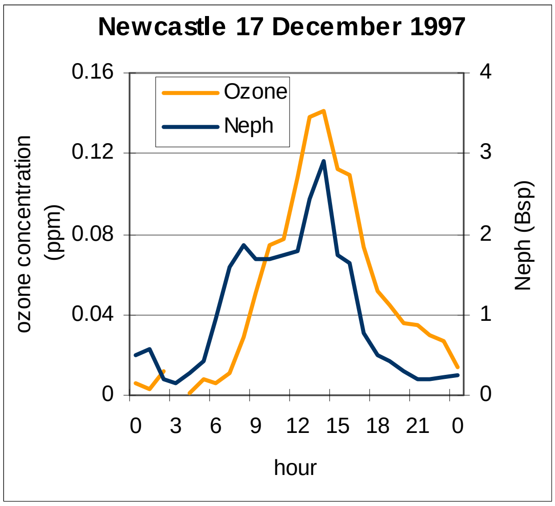
Table 19: Number of exceedence-days at each site, lower Hunter, 1994–2004

Site	Number of exceedence-days One-hour standard	Maximum one-hour concentration (ppb)	Number of exceedence-days Four-hour standard	Maximum four-hour concentration (ppm)
Newcastle	2	0.14	1	0.13
Beresfield	1	0.10	0	0.0798
Wallsend	2	0.13	3	0.11
Number of station-days	5	–	4	–
Number of distinct days	2	–	3	–

Analysis of particle data recorded on these ozone days show that each of the ozone exceedences in the lower Hunter region are likely to be associated with bushfires.

17–18 December 1997

On 17 December 1997 nephelometer readings were high (a maximum of 2.9) at Newcastle at the time of the ozone exceedence (Figure 25). At Wallsend, PM_{10} concentrations reached 188 µg/m^3 at the time of maximum ozone. These particle concentrations suggest bushfire activity at this time.



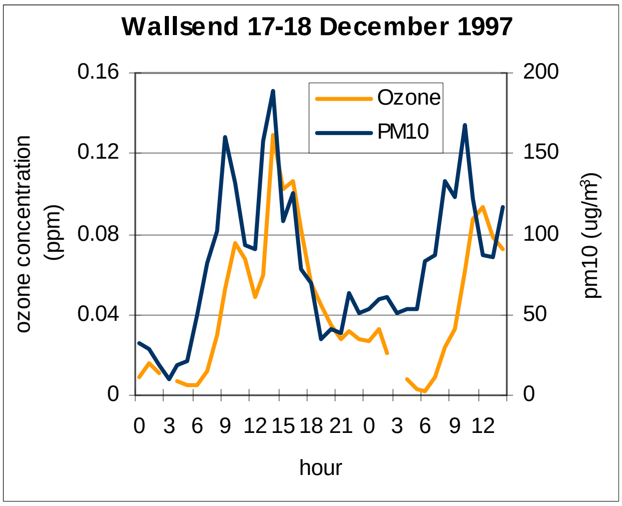


Figure 25: Ozone and particle concentrations in the lower Hunter, 17–18 December 1997

2 January 1998

One-hour ozone concentrations were just below the standard, with a maximum of 0.095 ppm, at Wallsend on 2 January 1998 (Figure 26). The four-hour standard was exceeded for two hours at this site. A maximum of 8.69 Bsp was recorded and hourly PM_{10} concentrations reached 243.8 µg/m^3. The maximum temperature at Wallsend was 33°C. Thunderstorms and accompanying lightning strikes on the previous night (1 January 1998) were responsible for starting fires in widely spread parts of the state (Australian Weather News 1998). Bushfires were burning in the Myall State Forest north of Newcastle.

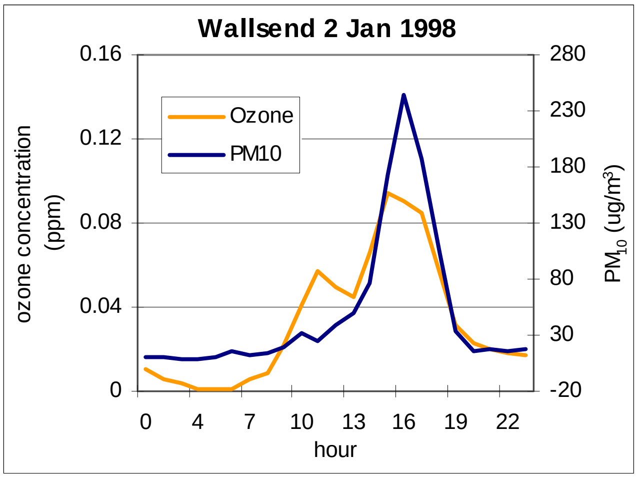


Figure 26: Ozone and particle concentrations at Wallsend, 2 January 1998

21 February 2004

There were exceedences of the one-hour standard for ozone on 21 February 2004 at each of the stations in the lower Hunter, with a maximum of 0.11 ppm at Newcastle. There were no exceedences of the four-hour standard. Nephelometer readings were high, indicating possible bushfire activity in the area (Figure 27).

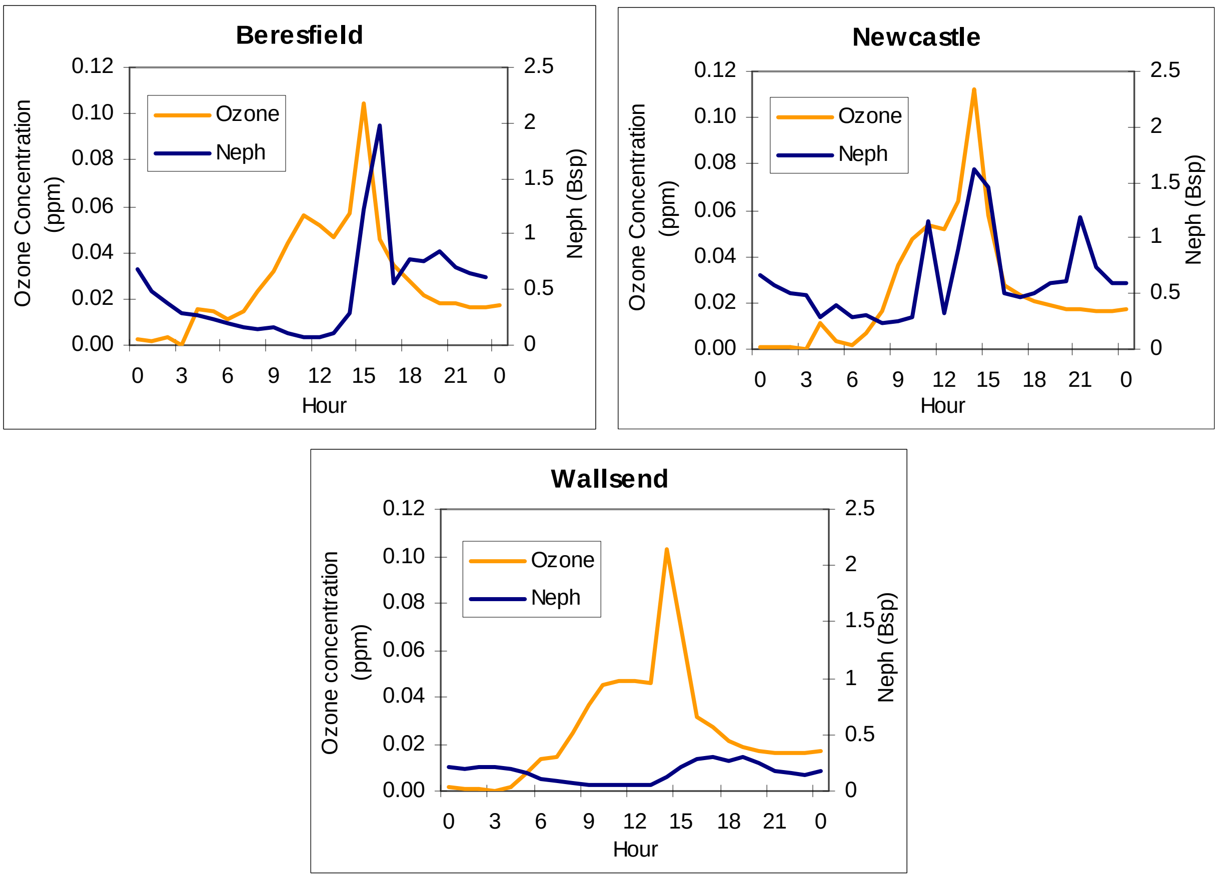


Figure 27: Ozone and particle concentrations at the lower Hunter sites, 21 February 2004

2.14 Illawarra 1994–2004

Ozone in the Illawarra region can occur as a result of photochemical smog produced from local emissions, or from smog or precursors transported down the coast from the Sydney region. It appears that most ozone events in the Illawarra occur as a result of the combined effect of these two factors. The sea breeze, generally north-easterly in direction, is the dominant meteorological influence on elevated concentrations of ozone in the region. Figure 28 presents exceedences of the one-hour ozone standard along with the corresponding wind direction, showing that the majority of exceedences are associated with a north-easterly flow.

Based on data from 1994 to 2004, Kembla Grange records the greatest number of exceedences of both the one-hour and four-hour AAQ NEPM standards for ozone (Table 20). Albion Park (the station furthest downwind of sources) has the second highest number of exceedence events. Emissions of NO_x may reduce ozone concentrations on a local scale close to the source by titration: fresh NO_x emissions react with ozone reducing its concentration. However, at some distance downwind this NO_x can produce more ozone. On many event days this potential is realised by the time the plume arrives at the Albion Park monitoring station.

The fewest exceedences were recorded at Warrawong with six days exceeding the one-hour standard and 12 days exceeding the four-hour standard.

Tables 21 and 22 present the number of exceedence-days by year for each site. The years with the fewest exceedences were 1995, 1996 and 1999 for all sites in the Illawarra. This is consistent with observations in the Sydney region and the meteorological conditions in those years. The most exceedence-days in a calendar year was five days at Albion Park in 1997 for the one-hour standard and six days at Kembla Grange in 1998 for the four-hour standard.

Table 20: Number of exceedence-days at each site, Illawarra, 1994–2004

Site	Number of exceedence-days one-hour standard	Maximum one-hour concentration	Number of exceedence-days four-hour standard	Maximum four-hour concentration
Wollongong	12	0.12	17	0.11
Kembla Grange	18	0.14	26	0.12
Warrawong	6	0.13	12	0.12
Albion Park	14	0.14	23	0.12
Number of station-days	50	–	78	–
Number of distinct days	30	–	41	–

Table 21: Number of days exceeding the one-hour standard each year

One-hour ozone	Wollongong	Albion Park*	Kembla Grange	Warrawong
1994	2	1	1	1
1995	0	0	0	0
1996	0	0	0	0
1997	4	5	4	2
1998	1	2	2	0
1999	0	0	1	0
2000	1	1	3	0
2001	1	0	2	0
2002	2	0	0	2
2003	0	4	2	0
2004	1	1	3	1

* Changed site location in 1998

Table 22: Number of days exceeding the four-hour standard each year

Four-hour ozone	Wollongong	Albion Park*	Kembla Grange	Warrawong
1994	3	1	1	1
1995	0	0	0	0
1996	0	0	0	0
1997	4	5	5	4
1998	1	5	6	0
1999	0	1	1	0
2000	3	4	4	3
2001	1	1	2	0
2002	2	1	1	2
2003	1	4	3	1
2004	2	1	3	1

* Changed site location in 1998

The Illawarra region is strongly influenced by sea breezes. In the north of the region these tend to be steered by the topography to become north-north-easterly to north-easterly in direction. In the south of the region sea breezes tend to be more north-easterly to easterly. Figure 28 shows the hourly ozone exceedences with the wind direction at that time for data recorded between 1997 and 2004. It can be seen that the majority of exceedences occurred under these north-easterly flows.

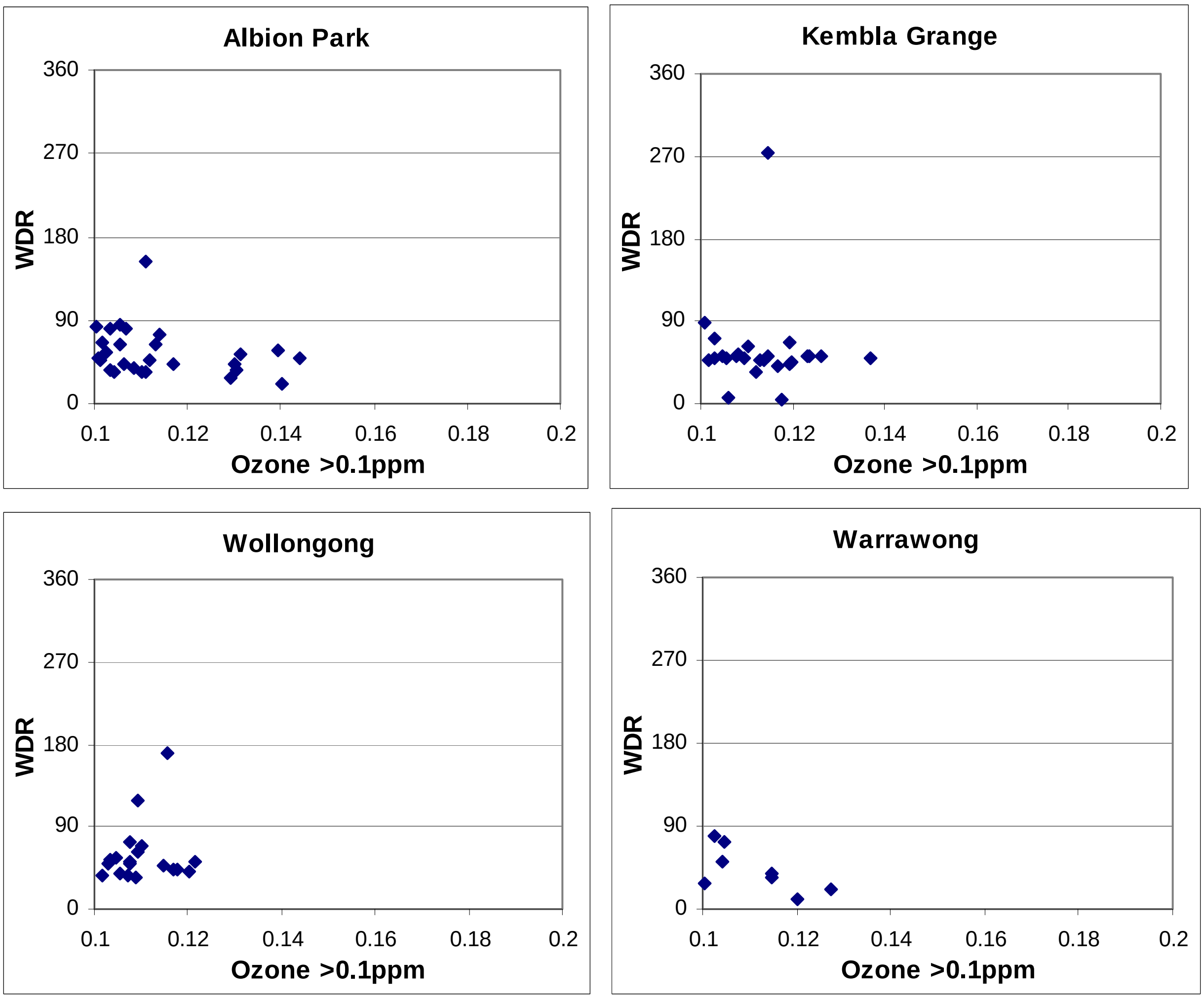


Figure 28: Hourly data for one-hour ozone exceedences and corresponding wind direction in the Illawarra, 1997–2004

2.15 Bathurst

Bathurst is located some 150 km west of Sydney in the Central Tablelands and on the banks of the Macquarie River, with higher ground rising to the south-west of the city centre. There are no significant industrial sources of air pollution in the region. The urban centre has a population of 26,000.

The measurement site was built in 2001 as part of the NSW AAQ NEPM monitoring network. Data from 2001 to 2004 has been analysed and is presented here.

Ozone concentrations at Bathurst are generally low and there were no exceedences of either the one-hour or four-hour standards (Table 23). The highest one-hour ozone concentration of 0.09 ppb was recorded on the 2 January 2004. The highest four-hour concentration, 0.07 ppb, was also recorded on this day.

Table 23: Ozone at Bathurst, 2001–2004

	Number of exceedences One-hour	Maximum one-hour concentration (ppm)	Number of exceedences Four-hour	Maximum four-hour concentration (ppm)
2001	0	0.06	0	0.06
2002	0	0.06	0	0.06
2003	0	0.06	0	0.05
2004	0	0.09	0	0.07

2 January 2004

One-hour ozone concentrations reached 0.09 ppm on 2 January 2004 at Bathurst (Figure 29). Particle readings were less than 0.4 Bsp, indicating that there was no bushfire event nearby. Peak ozone concentrations occurred at hour 21, corresponding with a change in wind direction (from westerly to northerly) and an increase in wind speed.

On this day, maximum one-hour ozone concentrations in Sydney were 0.079 ppm at Richmond and 0.087 ppm at Oakdale. This day also had the maximum four-hour average for this year.

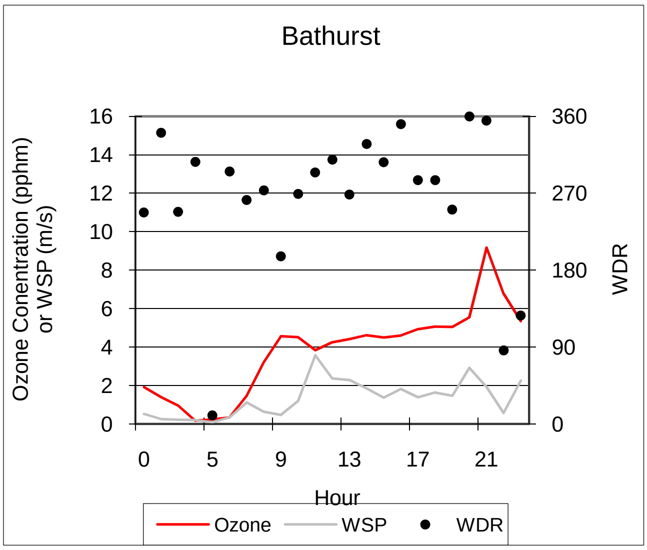


Figure 29: Ozone concentrations in Bathurst, 2 January 2004

Those hours with a concentration greater than 0.05 ppm were examined to find which hour of the day had the most occurrences of these elevated concentrations. Figure 28 shows that elevated concentrations occur in the afternoon with hour 17 recording the most.

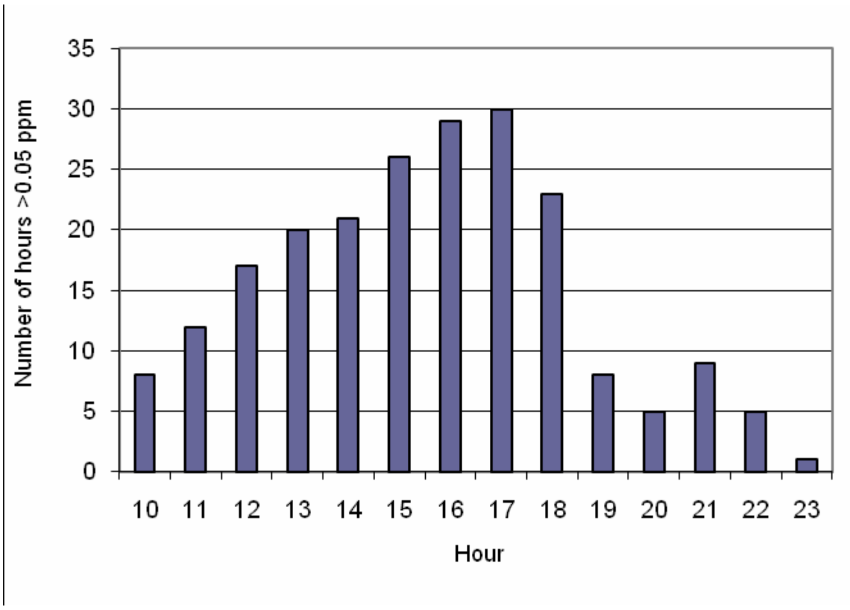


Figure 30: Hour of ozone concentration greater than 0.05 ppm at Bathurst

Figure 31 shows ozone concentrations greater than 0.05 ppm with the corresponding wind direction at that time. It can be seen that there is no particular direction associated with these elevated ozone concentrations.

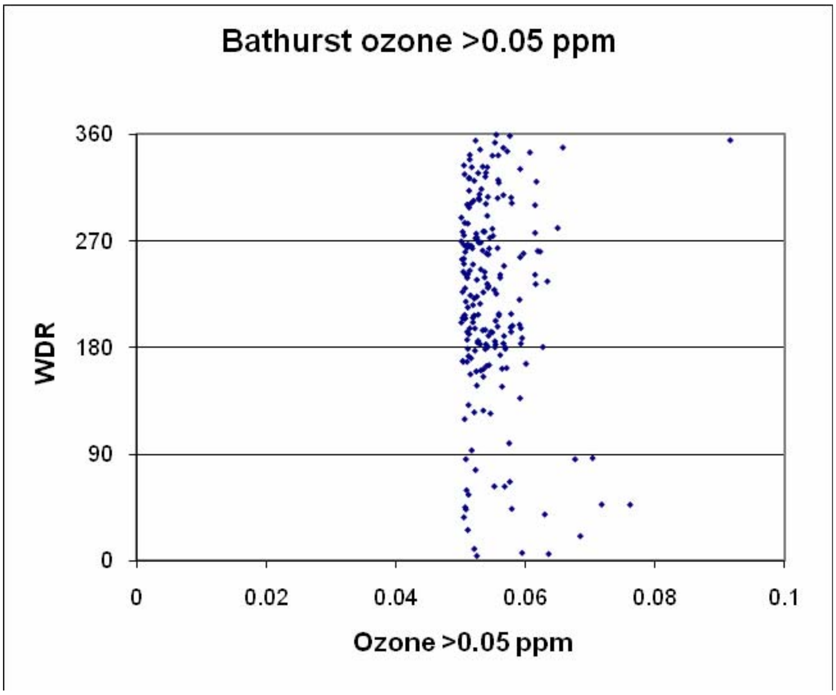


Figure 31: Ozone concentration greater than 0.05 ppm with corresponding wind direction in Bathurst

3. Modelling

3.1 Introduction

Context

Generation of photochemical smog is complex in several ways. The photochemistry of ozone is highly non-linear and the relationship between concentrations of the two precursors (NO_x and VOCs) and resulting maximum ozone concentration is best described as a function of both NO_x, and the VOCs to NO_x ratio. These emissions contributing to the urban plume, and hence the ozone concentration, vary in both space and time. They are distributed very unevenly through the urban area, and vary throughout the day. Motor vehicles are currently the largest source in the Sydney Basin.

Complicating the temporal and spatial variations in emissions is the temporal and spatial variation in meteorology, particularly wind and mixing height. Furthermore, a range of meteorological conditions favour ozone production resulting in a number of categories of ‘ozone exceedence-days’.

Photochemistry describes the maximum ozone concentration that can be formed under given conditions due to the precursors NO_x and VOCs. The CIT airshed modelling system is used to simulate this complex system. Its utility arises from how well it replicates both observations of ozone concentration and the observation-derived significant processes contributing to those concentrations (get it right for the right reason).

The emissions themselves are usefully divided into categories: mobile sources; (major) industrial; commercial-domestic; and biogenic. Each category contributes to ozone production but to different degrees that are not linear functions of their relative contribution to total emissions.

The approach to providing advice regarding management of the air environment therefore needs to consider the relative significance of the emission categories, and the potential impact of emissions changes in each category on ozone exceedence-days. In order to investigate the impacts of emissions and hence give advice, it is necessary for the airshed modelling system to simulate, as accurately as possible, existing ozone exceedence-days.[2] These simulations are known as base-case days.

Once a number of base-case days have been created, the emissions can then be systematically altered in order to provide advice for air management strategies. This advice is built up, stepwise.

Step 1: Using the base-case days, determine the photochemical state of the urban plume for these days. This step attempts to answer the question: Is the ozone concentration reduced most by reducing either precursor or both? This part of the picture is provided by the results of simulations where emissions are scaled and suggests in broad terms the overall strategy.

Step 2: Explore the significance of the source categories. Given a particular broad approach to reducing emissions, is it more effective to reduce them in any one category? Furthermore, does the urban plume develop in such a way that changing one category in isolation alters the spatio-temporal relationships and hence the photochemical state? If so, is this so sufficiently different that the overall strategy needs also to change? Given a particular broad approach, how important are the specific actions enacting that approach?

Step 3: Explore likely and possible future scenarios. Given current control strategies and expected urban growth, what will the photochemical state be in 20 years time? Is this such that the overall strategy will need to change? Does anticipating this suggest a different optimal path for managing the urban environment?

2 An ozone exceedence-day is one on which observed ozone concentrations exceed either or both AAQ NEPM ozone standards – one-hour concentration of 0.10 ppm; four-hour concentration of 0.08 ppm.

To the limits of the ability of the airshed modelling system to replicate processes and the degree to which the emissions perturbations remain within the set of conditions where the airshed modelling system represents the photochemistry, the steps above are explored with three streams of simulations.

The first stream explores the relationship of precursors to resulting maximum ozone concentration for a number of ozone exceedence-days.

The second stream explores the significance of emission categories by scaling emissions in each source.

The third simulates ozone exceedence-days using emissions projections for future years based on particular assumptions regarding population growth and emission control actions, with additional scenarios exploring the significance of these assumptions.

Metrics used to characterise photochemical pollution

Ozone concentration is used to represent photochemical pollution. AAQ NEPM sets standards for one-hour and four-hour ozone concentration (100 ppb and 80 ppb, respectively). Photochemical pollution varies in severity, spatial extent, and duration and several metrics are used to represent these. The simplest metric of severity is the maximum concentration. The greater the maximum concentration, the more severe the event. A useful measure of spatial extent is the area exceeding a threshold, in this case the AAQ NEPM standard. Duration has several metrics, and in this report it is combined with a spatial measure to generate a dosage. For the modelling results, this is presented as the total number of grid-cell-hours exceeding the AAQ NEPM standard.

Summary of the 2002 emissions inventory

Emissions are usefully divided into four categories: mobile sources; (major) industrial; commercial-domestic; and biogenic. The contribution of each of these to total emissions of NO_x and VOCs is given in Table 24. Figure 32 shows the model domain with the Sydney urban domain embedded within the map. Note that the Sydney domain excludes significant industrial sources, particularly coal-fired power stations. These are included in the full modelling domain and are the largest source of NO_x for that larger region.

Table 24: Anthropogenic emissions in the Sydney region for a high oxidant day, 2002

	VOCs		**NO_x**	
	kg/day	**% of anthropogenic**	**kg/day**	**% of anthropogenic**
Mobile sources	150,431	44	156,777	74
Commercial-domestic	139,200	41	16,346	8
Industrial	50,000	16	39,000	18
Total (kg/day)	**339,631**	**100**	**212,123**	**100**

Percentages may not add to 100 due to rounding

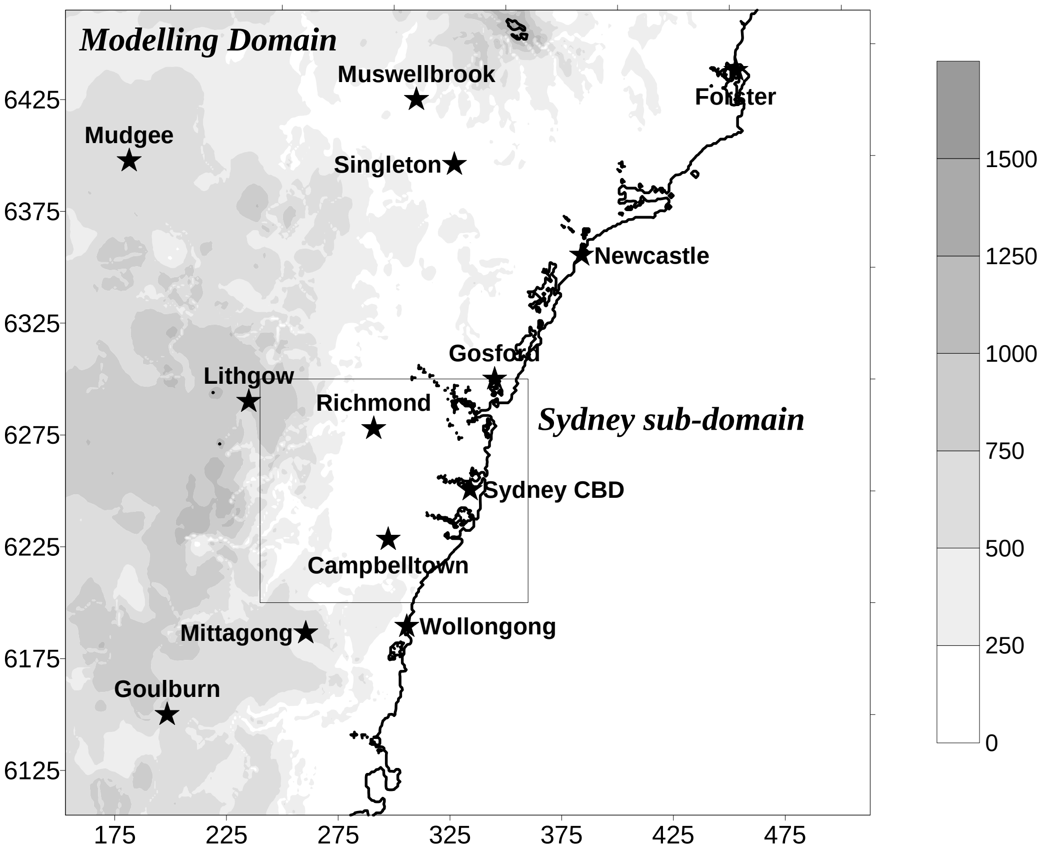


Figure 32: Modelling domain and Sydney sub-region

Airshed modelling system

A photochemical airshed modelling system is a numerical model designed to simulate the processes generating elevated concentrations of photochemical pollution (usually measured as ozone). Such systems generally have four components: a geographical database; an emissions inventory; a meteorology model; and a photochemical model. In such a system the emissions react to produce photochemical pollution according to the photochemical model while being transported on winds determined from the meteorology model. The geographical database provides location and surface information used by the other three components. Such systems are computationally intensive and generally limited to simulation of particular pollution events.

The airshed modelling system used in this work is that developed initially as part of MAQS (Cope and Ischtwan 1997), with recent improvements reported in CSIRO Energy Technology (2002). The system uses CIT as the photochemistry model (McRae et al. 1992a, b and c) and either TAPM version 2 (Hurley 2002) or CALMET (Scire et al. 1997) as the meteorology model. The chemical reaction module is the LCC model. Johnson and Spencer (2003) and Spencer and Duc (2003) provide a more detailed description of the system and examples of its use.

The ability of the modelling system to replicate the real-world processes is assessed by comparing simulated concentrations of pollutants to observations for the simulated event. Where the system shows sufficient skill in replicating observations, the event day is suitable for investigating changes to emissions and is termed a base-case day. The response of the urban plume to changed emissions may vary across the range of meteorological conditions generating elevated concentrations of ozone. It is desirable for a range of base-case days to be developed to capture this range of response.

To investigate the impact of changes to emissions, emission scenarios are developed describing these changes and then used in simulations of base-case days. The model's simulation of the effect of the change in emissions is shown by the differences in simulated concentration between the emission scenario and the base-case.

For simulation of the greater metropolitan area of NSW, airshed modelling is conducted on a domain extending from the Hunter Valley in the north to the southern boundary of the Illawarra (Figure 32). In this report, results are presented on a sub-domain called the Sydney region, defined in Australian Map Grid coordinates (km) as a regular rectangle with the south-west corner at (240, 6200) and north-east corner at (360, 6300), Figure 33.

Characteristics of the base-case modelling

The meteorological component of the model was run on a three-km x three-km grid domain, spanning 360 km north-south and east-west. Four base-case days were created. TAPM was used to simulate the meteorology of one day, and Calmet the other three. Some upper air TAPM output was incorporated into two of the Calmet runs.

The motor vehicle component of the emissions came from the Transport Data Centre. Motor vehicle emissions were calculated on a one-km x one-km grid using emission data representing the mix of vehicles in 2001 and the estimates of road usage by vehicle category for that year. Further details of the setup configuration can be found in Appendix E.

For the other emissions:

- Commercial-domestic sources increase from 1994 estimates in proportion to population increase.
- Industrial emissions were held constant.
- Biogenic emissions were held constant.
- The chemical component of the CIT model used is the LCC.

Factors to consider for uncertainty

The results presented here are only as reliable as the model's ability to accurately represent the days; therefore it is important to consider the uncertainty in the model output.

This model is limited by potential errors in the following components:

- resolution
- land-use categorisation
- meteorology
- chemistry
- emissions inventory.

These components of the model both individually and collectively try to capture all the important facets of the physical dynamics of ozone formation and distribution. They are far from absolute and there is a possibility that negative errors in one component compensate for positive errors in another. Furthermore, uncertainty in the emission inventory means that emission reduction strategies should not be read exactly, but looked upon in broad terms. The airshed model is best understood to be a generalisation tool which gives a good depiction of ozone formation and can be used to advise broadly on emission control strategies.

3.2 Base-case ozone exceedence-days

The DECCW monitoring data record for the years 1997 to 2004 was screened to identify all days on which observed ozone concentration exceeded either AAQ NEPM goal for ozone (100 ppb one-hour and 80 ppb four-hour). These events were screened by removing all days with known bushfire activity along with those which experience indicated would be outside the capability of the modelling system. The monitoring network for Sydney is shown in Figure 33.

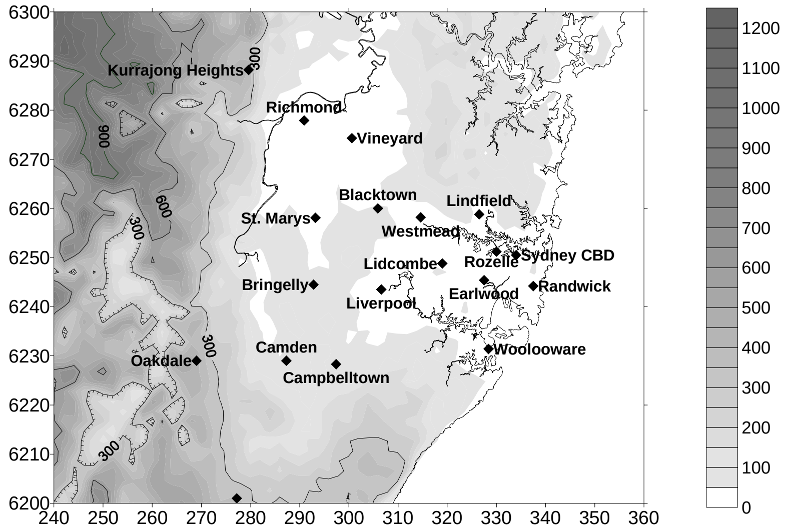


Figure 33: Monitoring stations in Sydney

The base-case simulations have been assessed using statistical measures recommended by Tesche et al. (1990), and shown in Table 25. The measures used are defined in Appendix D. Four ozone exceedence-days have been simulated with sufficient accuracy by the airshed modelling system to qualify as base-case simulations. Table 25 shows that the base-case statistics fall within the recommended criteria. However, this was not the only metric used to determine whether to classify a day as a base-case. Comparison of the diurnal time series of ozone and other observations at DECCW monitoring stations to values predicted in the simulation were also taken into account. This gives a good indication of how well the meteorology has been captured, particularly the sea breeze.

Table 25: Base-case performance statistics

	Overall bias (%)	Gross error (%)	Paired in space gross relative error (%)
Tesche criteria	*–15 to 15*	*< 35*	
20 Dec 2000	–14	16	19
12 Jan 2001	–7	10	14
22 Jan 2001	–4	7	10
10 Feb 2004	–2	5	10

The three base-case days occurred under the influence of a high-pressure system with hot, sunny conditions and light northerly synoptic flows. These conditions are recognised as being conducive to photochemical pollution episodes in the Sydney region (e.g. Hyde et al. 1997, Leighton and Spark, 1995, Hyde et al. 1997). Days of this type have also been successfully modelled in previous studies e.g. Cope and Ischtwan (1997), Johnson and Spencer (2003). For example, 10 February 2004 had light, overnight southerly flows followed by a sea breeze.

While there are similarities in the synoptic-scale meteorological conditions on three of these days, observational records show differences in both the maximum ozone concentration and the spatial distribution of elevated concentrations of ozone. Characteristics of the days are summarised in Table 26 with further description following.

Cluster analysis was carried out on the observational data set of high ozone events to determine how many types of days occur. The cluster was carried out in two separate ways, one based on the chemistry and the other on the meteorology. The cluster based on the chemistry uses both the ozone concentration and the extent value to categorise the smog potential.

Using the data from 1994 to 2001 for days with maximum ozone concentration greater than 80 ppb and excluding bushfire-related days, the cluster analysis identified three event day groups. Three of the base-case days belong to the first cluster group which accounts for 84% of all event days. The other base-case day belongs to the second cluster group which accounts for 14% of all event days. Therefore we can say that we have covered 98% of the ozone potential days based on the chemistry.

The cluster based on meteorological conditions uses a variety of meteorological parameters defining both synoptic-scale and more local influences to characterise the ozone exceedence-days. The cluster analysis identified one synoptic category which accounted for 70% of the pollution episodes since 1992. The details of the cluster analysis are still being evaluated but all the modelling days fall within this cluster so, at a bare minimum, the modelled days account for 70% of the days based on meteorology.

These two cluster analyses provide confidence that predominant conditions giving rise to high ozone events are included in this work.

Table 26: Summary of base-case days

	20 Dec 2000	**12 Jan 2001**	**22 Jan 2001**	**10 Feb 2004**
Day of the week	Wednesday	Friday	Monday	Tuesday
Maximum one-hour ozone (ppb)	115 (Oakdale)	126 (Bringelly)	103 (Bringelly)	107 (Oakdale)
Number of hours ozone > 100 ppb	1 (hour 17)	6 (hours 13–18)	1 (hour 16)	2 (hours 15 & 17)
Number of sites ozone > 100 ppb	1: Oakdale (SW)	5: St Marys (NW); Blacktown (NW); Liverpool (SW); Bringelly (SW); Oakdale (SW)	1: Bringelly (SW)	2: Bringelly (SW); Oakdale (SW)
Number of sites ozone 80-100 ppb	1: Bringelly (SW)	5: Lidcombe (CE); Westmead (NW); Vineyard (NW); Richmond (NW); Bargo (SW)	5: St Marys (NW); Blacktown (NW); Vineyard (NW); Liverpool (SW); Oakdale (SW)	3: Liverpool (SW); St Marys (NW); Westmead (NW)

Details of the days

20 December 2000

Maximum one-hour ozone concentrations on 20 December 2000 exceeded 80 ppb at two sites in the Sydney region, with only one site in the far south-west of the basin exceeding the AAQ NEPM one-hour standard of 100 ppb. The maximum one-hour ozone concentration on this day was 115 ppb. Table 27 compares simulated and observed maximum ozone concentration for sites in the Sydney region.

Interpolated contours of maximum ozone concentration are shown in Figure 34. Note that as the maximum occurred at the edge of the observational network, data interpolation outside the network is potentially misleading.

Simulated maximum one-hour concentrations for 20 December 2000 are shown in Figure 35. The figures give a visual representation of observed and simulated, but they are not intended for a visual comparison due to their differing resolutions. The observation plot is created from 15 data points, whereas the simulation has 14,400 data points (one for each grid-cell). Any visual comparison should be taken only from a very general perspective.

Table 27: Observed and simulated maximum ozone concentrations, 20 December 2000 (ppb)

Site	Region	Observed	Simulated
Randwick	CE	48	48
Rozelle	CE	47	56
Lindfield	CE	77	61
Liverpool	SW	77	88
Lidcombe	CE	79	80
Blacktown	NW	67	80
Bringelly	SW	86	90
Earlwood	CE	70	63
Woolooware	CE	68	54
Richmond	NW	71	61
Bargo	SW	57	55
Kurrajong	NW	73	71
St Marys	NW	73	85
Vineyard	NW	76	64
Westmead	NW	74	75
Oakdale	SW	115	97
Correlation		**0.778**	

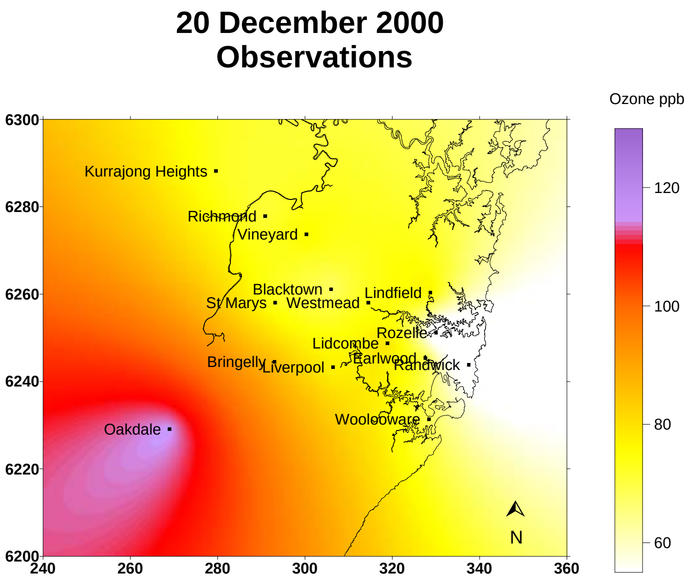


Figure 34: Contours of maximum one-hour ozone concentrations based on interpolation of observations

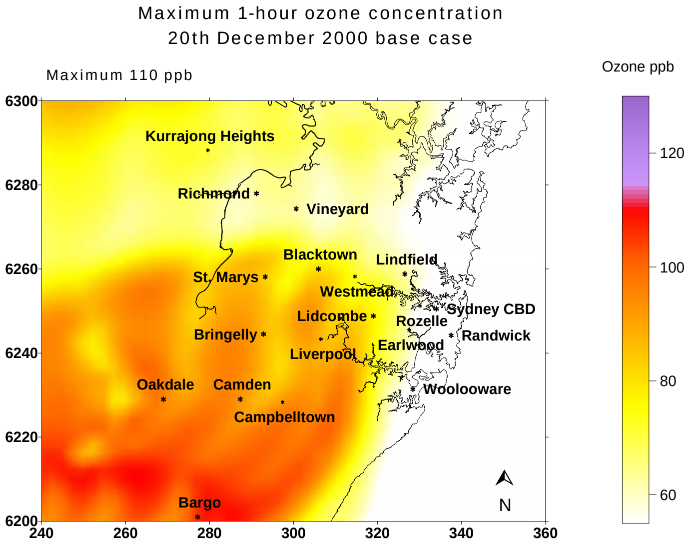


Figure 35: Simulated maximum one-hour ozone concentrations

12 January 2001

The 12 January 2001 ozone event was the most extreme of the base-case days, recording the highest maximum one-hour ozone concentration (126 ppb) and the greatest area exceeding AAQ NEPM ozone standards. In addition, concentrations above the standard occurred for longer periods in both the south-west and the north-west. On this day, concentrations greater than 80 ppb were also the most widespread, occurring throughout the Sydney Basin. Interpolated contours of maximum ozone concentration are shown in Figure 36. Note that as the maximum occurred at the edge of the observational network, data interpolation outside the network is potentially misleading.

Simulated maximum one-hour concentrations for 12 January 2001 are shown in Figure 37. To aid assessment of the simulation, Table 28 compares simulated and observed maximum ozone concentration for sites in the Sydney region.

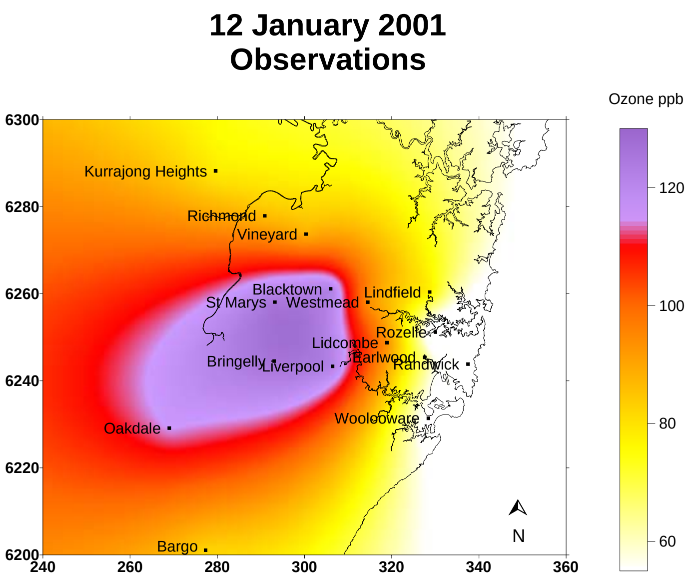


Figure 36: Contours of maximum one-hour ozone concentrations based on interpolation of observations

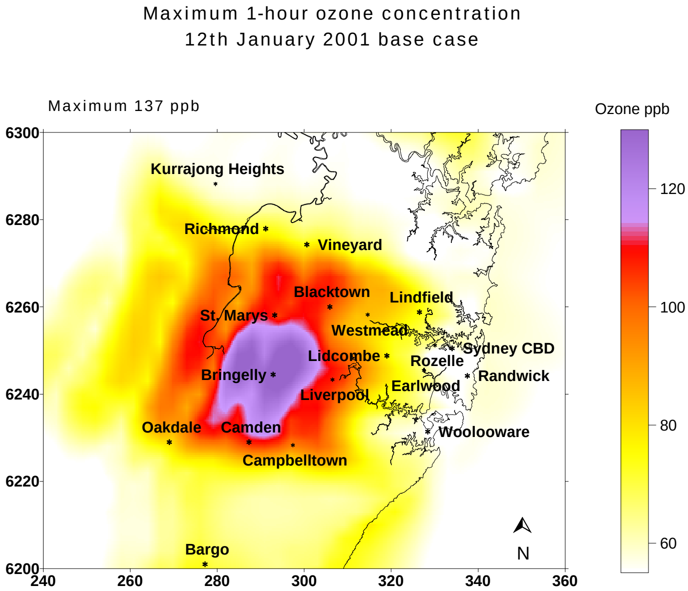


Figure 37: Simulated maximum one-hour ozone concentrations

Table 28: Observed and simulated maximum ozone concentrations, 12 January 2001 (ppb)

Site	Region	Observed	Simulated
Randwick	CE	40	49
Rozelle	CE	43	53
Lindfield	CE	78	72
Liverpool	SW	122	102
Lidcombe	CE	94	82
Blacktown	NW	123	99
Bringelly	SW	126	120
Earlwood	CE	65	66
Woolooware	CE	51	54
Oakdale	SW	115	75
Richmond	NW	86	77
St Marys	NW	126	101
Vineyard	NW	88	84
Westmead	SW	93	82
Correlation		**0.874**	

22 January 2001

The maximum one-hour ozone concentration on 22 January 2001 was the lowest of the four base-case days and, like 20 December 2000, exceeded the AAQ NEPM standard at only one site in the south-west. However, sites recording concentrations greater than 80 ppb were more widespread, occurring in both the south-west and north-west regions. The maximum one-hour ozone concentration on this day was 103 ppb and interpolated contours of maximum ozone concentration are shown in Figure 38. Note that data interpolation outside the monitoring network is potentially misleading as it reflects the interpolation scheme used and not the processes generating photochemical smog.

Simulated maximum one-hour concentrations for 22 January 2001 are shown in Figure 39. To aid assessment of the simulation, Table 29 compares simulated and observed maximum ozone concentration for sites in the Sydney region.

Table 29: Observed and simulated maximum ozone concentrations, 22 January 2001 (ppb)

Site	Region	Observed	Simulated
Randwick	CE	34	42
Lindfield	CE	53	56
Liverpool	SW	88	81
Lidcombe	CE	60	60
Blacktown	NW	83	82
Bringelly	SW	103	100
Earlwood	CE	51	52
Woolooware	CE	40	47
Kurrajong	NW	80	78
St Marys	NW	99	99
Vineyard	NW	84	71
Westmead	NW	61	71
Oakdale	SW	82	100
Correlation		**0.933**	

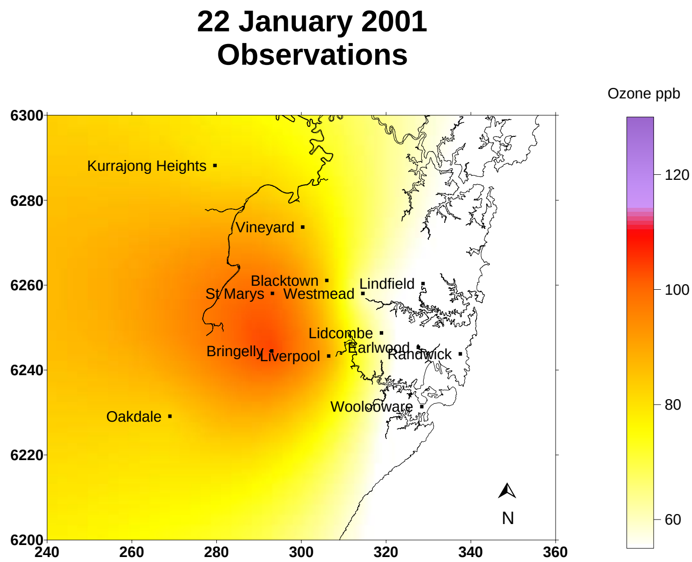


Figure 38: Contours of maximum one-hour ozone concentrations based on interpolation of observations

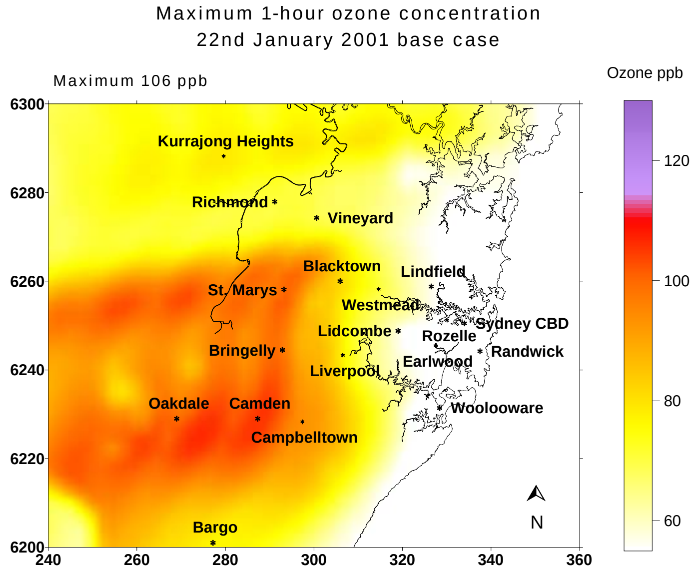


Figure 39: Simulated maximum one-hour ozone concentrations

10 February 2004

The 10 February 2004 ozone event lies between 20 December 2000 and 22 January 2001 in terms of both maximum observed concentration and geographic extent of concentrations over 80 ppb. It differs in that two stations recorded a concentration greater than 100 ppb, whereas only one station is found for the other two events. Interpolated contours of maximum ozone concentration are shown in Figure 40. Note that as the maximum occurred at the edge of the observational network, data interpolation outside the network is potentially misleading.

Simulated maximum one-hour concentrations for 10 February 2004 are shown in Figure 40. To aid assessment of the simulation, Table 30 compares simulated and observed maximum ozone concentration for sites in the Sydney region.

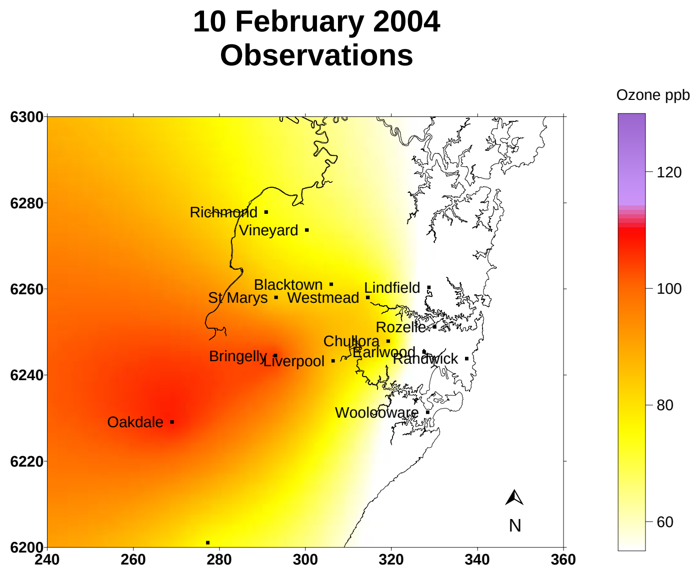


Figure 40: Contours of maximum one-hour ozone concentrations based on interpolation of observations

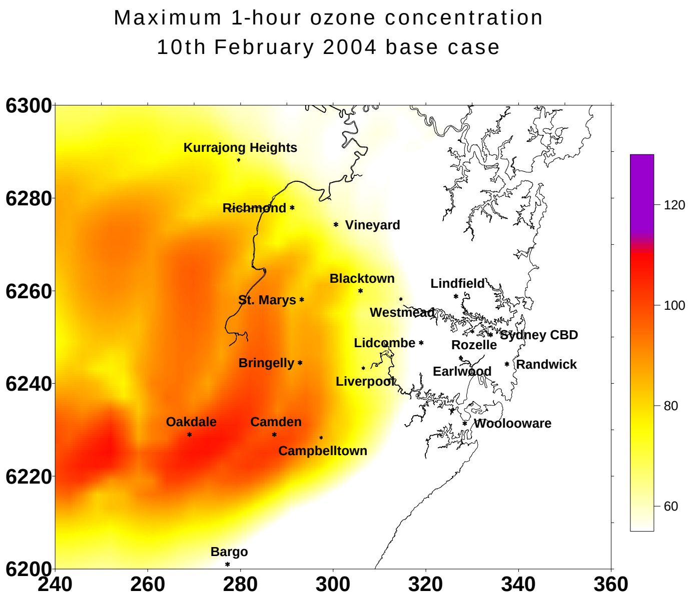


Figure 41: Simulated maximum one-hour ozone concentrations

Model performance

In general, the model under-performs in the mid-morning growth of ozone, particularly for 10 February 2004 and 12 January 2001. However the plume is consistent with the observations, albeit slightly smaller, with the maximums similar to the observations except on the fringes of the plume. This suggests that the forced meteorology has simulated the sea breeze correctly, but the morning growth of the boundary layer has probably been too fast and hindered ozone production.

Therefore, the model can quite sufficiently reproduce the maximum ozone for these base-case days both spatially and temporally, but care is needed when analysing any emission control strategies from the perspective of the four-hour standard. The following streams of sensitivity studies will be analysed using the one-hour ozone concentrations.

Table 30: Observed and simulated maximum ozone concentrations, 10 February 2004 (ppb)

Site	Region	Observed	Simulated
Randwick	CE	36	34
Rozelle	CE	36	33
Lindfield	CE	50	43
Liverpool	SW	84	70
Blacktown	NW	79	73
Bringelly	SW	104	88
Earlwood	CE	43	42
Woolooware	CE	35	34
Richmond	NW	74	74
St Marys	NW	83	82
Vineyard	NW	72	69
Westmead	NW	80	62
Oakdale	SW	107	103
Bargo	SW	75	52
Correlation		**0.954**	

The results of this analysis can be summarised as follows:

- Four base-case days have been established.
- Three of these days account for 84% and the fourth day 14% of the typical chemistry characteristics which give rise to ozone exceedences in the Sydney Basin.
- The four base-case days account for at least 70% of the meteorological conditions which give rise to ozone exceedences in the Sydney Basin.

3.3 Stream 1: VOCs to NO_x ratio – investigation of the relationship between ozone precursor emissions and maximum ozone concentration for the base-case days

Emissions used by the airshed modelling system can be globally scaled. A coordinated series of 12 simulations has been completed for the ozone event days. These consider scalings as low as 50% of current emissions and as high as increases of 30% on 2001 emissions. Results for each ozone exceedence-day are summarised in Tables 31–34.

Table 31: Simulated maximum ozone concentrations, 12 January 2001

VOCs MAQS	NO_x MAQS	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
1.3	1.3	144.2	100.1	166	104	204	226
1.3	1.0	178.7	117.7	227	193	327	532
1.0	1.3	105.4	82.5	20	7	20	9
1.0	1.0	136.7	96.6	136	81	161	164
1.0	0.7	160.3	109.6	192	143	264	392
1.0	0.5	153.5	108.4	194	176	266	472
0.8	0.5	141.9	99.6	137	99	178	261
0.7	1.0	98.7	78.1	0	0	0	0
0.7	0.7	127.2	90.3	89	45	101	80
0.5	1.0	87.8	73.9	0	0	0	0
0.5	0.8	92.4	74.1	0	0	0	0
0.5	0.5	116.5	83.8	48	19	48	30

Table 32: Simulated maximum ozone concentrations, 20 December 2000

VOCs MAQS	NO_x MAQS	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
1.3	1.3	121.8	102.6	530	662	741	1458
1.3	1.0	121.5	100.8	395	545	518	1169
1.0	1.3	114.5	96.8	270	441	340	842
1.0	1.0	109.9	94.2	186	371	213	667
1.0	0.7	106.7	91.9	22	210	22	323
1.0	0.5	99.7	87.7	0	62	0	88
0.8	0.5	95.0	83.4	0	19	0	21
0.7	1.0	103.3	88.8	25	176	25	244
0.7	0.7	97.2	84.1	0	51	0	63
0.5	1.0	98.7	84.7	0	51	0	64
0.5	0.8	95.1	82.8	0	21	0	23
0.5	0.5	86.2	76.1	0	0	0	0

Table 33: Simulated maximum ozone concentrations, 22 January 2001

VOCs MAQS	NO_x MAQS	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
1.3	1.3	115.7	96.4	250	419	302	1116
1.3	1.0	112.9	93.6	214	399	241	1018
1.0	1.3	107.2	91.0	70	276	72	602
1.0	1.0	106.2	89.3	79	263	79	550
1.0	0.7	100.8	84.9	7	144	7	247
1.0	0.5	94.6	80.8	0	9	0	9
0.8	0.5	91.3	78.6	0	0	0	0
0.7	1.0	98.5	84.4	0	103	0	146
0.7	0.7	94.9	81.1	0	18	0	18
0.5	1.0	92.2	80.6	0	44	0	56
0.5	0.8	91.8	79.5	0	0	0	0
0.5	0.5	86.0	75.0	0	0	0	0

Table 34: Simulated maximum ozone concentrations, 10 February 2004

VOCs MAQS	NO_x MAQS	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
1.3	1.3	107.5	82.5	11	39	11	56
1.3	1.0	119.9	88.2	132	182	137	347
1.0	1.3	88.1	73.0	0	0	0	0
1.0	1.0	108.2	85.0	54	108	54	173
1.0	0.7	112.2	85.5	48	25	48	32
1.0	0.5	109.6	87.2	32	27	33	40
0.8	0.5	102.5	81.0	3	3	3	3
0.7	1.0	84.0	70.1	0	0	0	0
0.7	0.7	94.6	75.8	0	0	0	0
0.5	1.0	75.5	70.0	0	0	0	0
0.5	0.8	80.9	68.2	0	0	0	0
0.5	0.5	86.4	70.8	0	0	0	0

These tables show that the ozone event days have differing responses to scaling emissions. This result implies differing conditions in the urban plume presumed to arise from the interaction of the differing spatio-temporal distribution of each precursor, and the particular weather conditions for each day. As would be expected, reducing VOC emissions results in decreased maximum ozone concentrations due to reduced photochemical production.

The response to NO_x emissions is not so straightforward. In some cases, reducing NO_x emissions results in increased maximum ozone concentration, even though analysis of observations found that the maximum ozone in the western Sydney region for these events was NO_x-limited. This implies that there is a NO_x-rich environment in the morning, inhibiting photochemistry. For this condition, a reduction in NO_x emissions generates a less NO_x-rich environment and photochemistry proceeds earlier. For some events, this may lead to greater maximum ozone concentrations and these greater concentrations are expected to occur at locations other than those of the base-case. Of note for events showing this behaviour, is the occurrence of elevated concentrations of ozone which are not NO_x-limited and therefore have potential to generate greater ozone concentrations.

Both the 12 January 2001 and 10 February 2004 events show increased maximum ozone for moderately decreased NO_x emissions. For both days, analysis of observations found stations for which maximum concentrations exceeded 80 ppb and were not NO_x-limited. This suggests that greater concentrations would be generated were the photochemistry to proceed earlier or faster or both. It follows from the deduction of NO_x-rich conditions, that reducing NO_x emissions allows photochemistry to proceed earlier.

The 12 January 2001 event is the most extreme in both severity and spatial extent, and very substantial reductions in NO_x emissions are required to achieve a reduction in maximum ozone concentration. Indeed, halving NO_x emissions at no scaling of VOC emissions generated maximum ozone concentrations greater than with no scaling. Within the scalings used, reducing NO_x emissions resulted in increased maximum ozone concentration, except for reducing NO_x emissions from 0.7 to 0.5 at no scaling of VOCs.

The 20 December 2000 and 22 January 2001 events are quite similar. Neither shows behaviour suggesting the NO_x-rich conditions found for the other two events. For these two events, a reduction in either precursor resulted in reduced maximum ozone concentrations.

These results are presented in Figures 42–45 as ozone isopleths plotted against scaled emissions of VOCs (x-axis) and NO_x (y-axis). Data points are displayed as a filled diamond, the contours being generated using kriging at a resolution of 0.01 (81 rows and 81 columns). The diagram shows the relationship between each pre-cursor and maximum ozone concentration for the day in question. These can vary among event days because they include the effect of meteorology.

For comparison, an example EKMA diagram based on smog chamber experiments is shown in Figure 46. This is an adaptation of a figure from Lawson (2002). This figure presents the EKMA diagram, annotated to indicate the location of the four event days diagnosed from the emission sensitivity simulations for these days. Further description of this plot can be found in Appendix A.

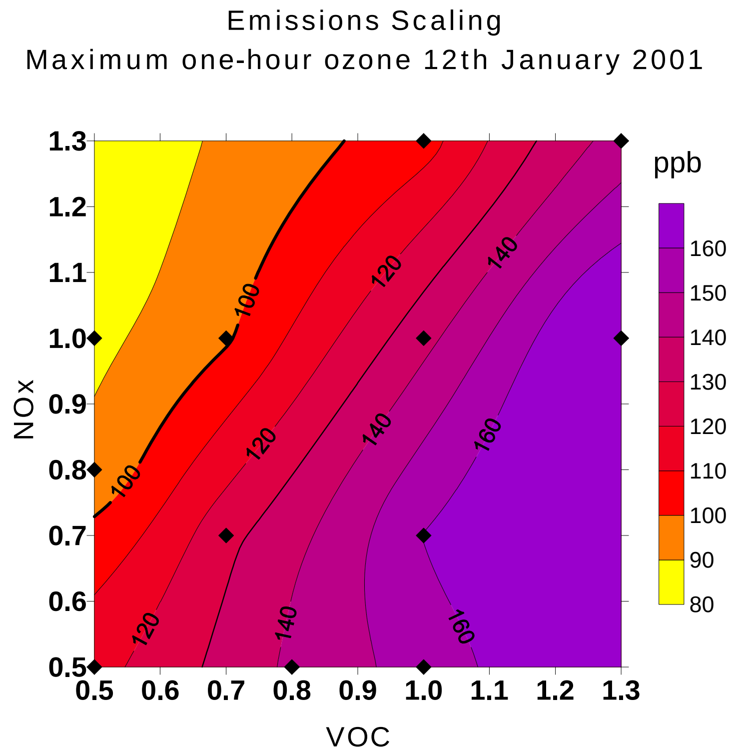


Figure 42: Ozone isopleths, 12 January 2001

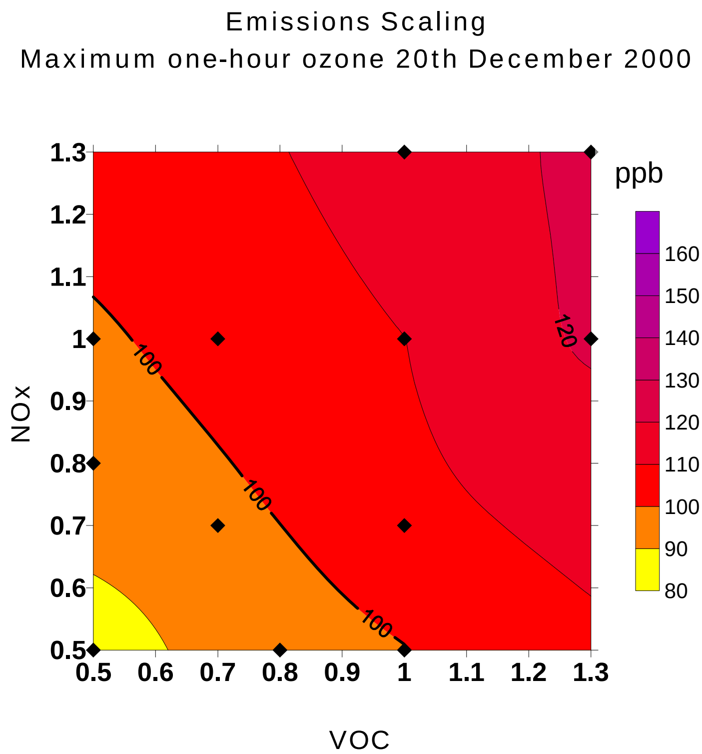


Figure 43: Ozone isopleths, 20 December 2000

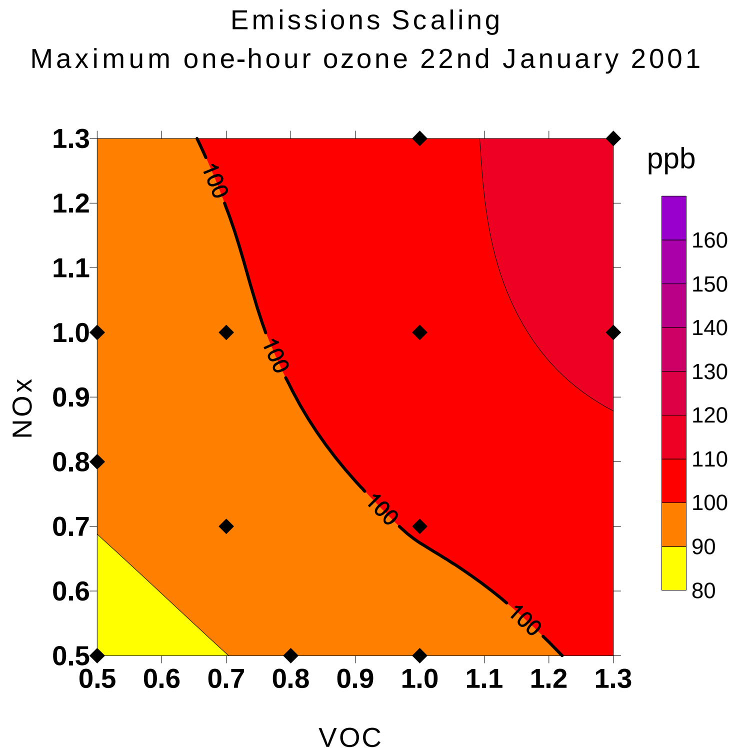


Figure 44: Ozone isopleths, 22 January 2001

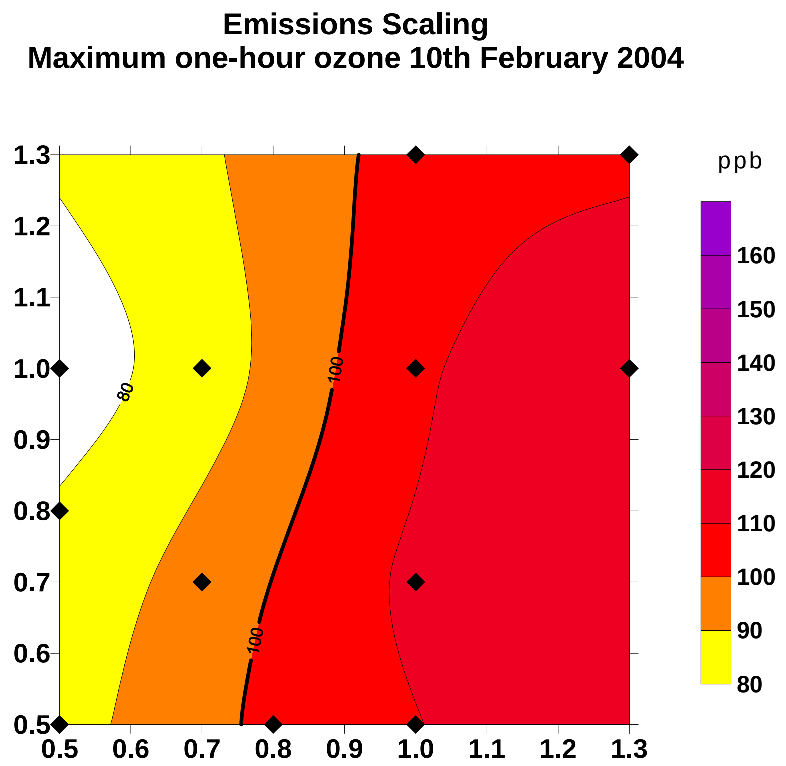
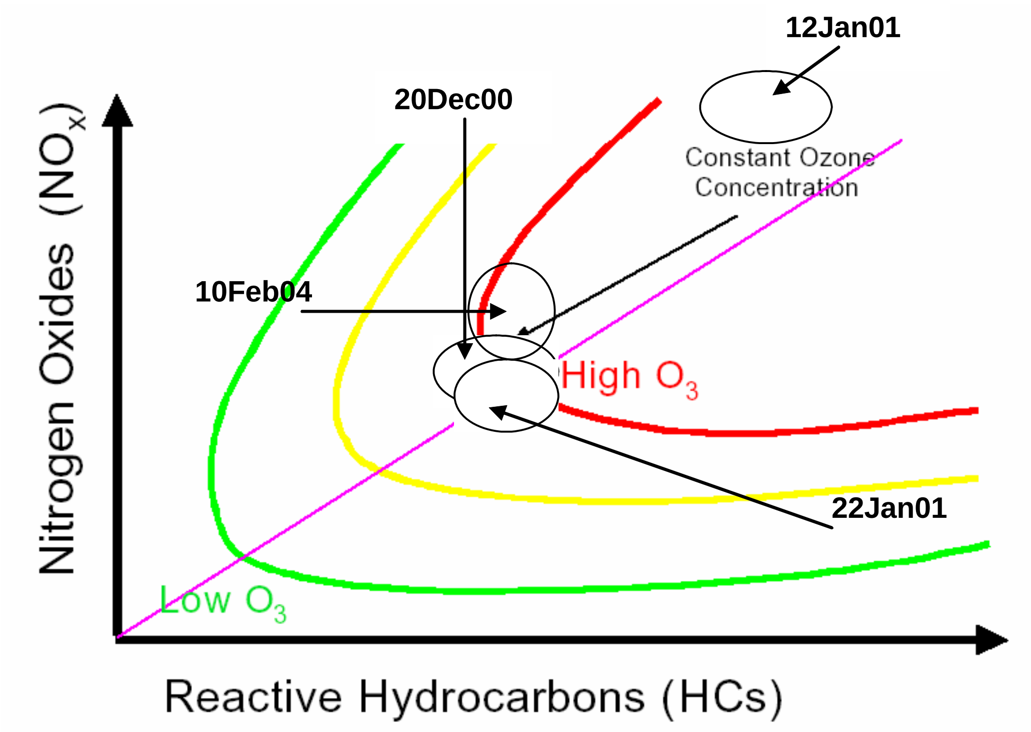


Figure 45: Ozone isopleths, 10 February 2004



Adapted from Lawson (2002)

Figure 46: EKMA diagram

The differences among the events are clear from the ozone isopleths, Figures 42–45. Two different day types appear to be represented. The 20 December 2000 and 22 January 2001 are examples of one type of event, while 12 January 2001 and 10 February 2004 show the other. These modelling results imply that NO_x-rich conditions in the morning are significant for 12 January 2001 and 10 February 2004 event days but not for the other two.

These simulations show that reducing VOCs is always beneficial, but is insufficient by itself to meet current AAQ NEPM standards, as emissions would need to be halved. Combining reductions in VOCs with reductions in NO_x is more effective for reducing ozone concentration for two days (20 December and 22 January) and moderately effective for 10 February. The remaining event, 12 January, is much more extreme and requires substantial reductions in precursors. Optimal strategy for this day is to reduce VOCs but maintain current NO_x emissions. However, this is a poor general strategy as it is less effective for two other days.

The EKMA diagrams show that, overall, a 25% reduction in both precursors is sufficient to meet the current AAQ NEPM one-hour standard for three of the four days. For the other day, 12 January, such an emissions reduction yields a modest reduction in maximum ozone concentration (7% in maximum one-hour and four-hour) with reductions of more than 35% in total grid-cell hours exceeding the AAQ NEPM standards.

Based on the VOC and NO_x concentrations described by the emissions inventory, the results of this stream can be summarised as follows:

- On three days, a reduction of approximately 25% in both NO_x and VOCs was necessary in order to reach compliance with the NEPM standards.
- While reduction in both precursors is important, the results show a greater sensitivity to VOCs than to NO_x.
- 12 January 2001 is an extreme event that behaves significantly differently from two days and slightly different from another. Current emission strategies may not be able to stop such an event from occurring.
- Two event days behave similarly with reduction in both NO_x and VOCs being the optimum strategy.
- 10 February 2004 behaves somewhere in between the two types but reduction in both precursors was still effective.

3.4 Stream 2: Sensitivity of the specific emission source reduction to maximum ozone concentration

In order to explore uncertainties in the emissions inventory, scenarios exploring the significance of two anthropogenic emission source categories – mobile sources and commercial-domestic emissions – to simulated ozone concentration have been constructed. These scenarios have been completed for four ozone event days: 20 December 2000; 12 January 2001; 22 January 2001; and 10 February 2004.

Motor vehicle emissions

The 2002 inventory has mobile sources as the greatest anthropogenic source in the Sydney region. This category contributes 74% of anthropogenic NO_x and 44% of anthropogenic VOCs of Sydney emissions. On a high oxidant day, over 95% of the emissions of ozone precursors in this category come from motor vehicles, the remainder being generated by non-electric trains, commercial shipping and recreational boating. Throughout this report, the terms ‘mobile sources’ and ‘motor vehicles’ will be used interchangeably.

In broad terms, motor vehicle emissions can be reduced in two ways: by reducing the emissions per kilometre travelled and by reducing the usage of motor vehicles. In the past decade, per capita motor vehicle usage in the Sydney region has been increasing. Combining this increase with the population increase of approximately 1.3% per year generated an increase in the estimated total vehicle kilometres travelled of approximately 2.3% per year over this period.

However, in that time, emissions per kilometre travelled for the fleet decreased significantly as tighter emissions limits were introduced and then met by an increasing portion of the fleet. Current national policies implement further tightening of emission limits and are expected to result in significant reductions in emissions from this sector, even though total usage is projected to continue to increase at current rates. Motor vehicle emission standards are shown in Table 35. Tiers 1 and 2 are currently mandated, with tier 3 yet to be mandated.

The significance of this category of emissions has been investigated by simulating the four ozone events using a series of variations to motor vehicle emissions. This included direct scaling of NO_x, application of currently mandated and proposed emission limits to the current fleet, and scaling motor vehicle usage as measured by vehicle kilometres travelled (VKT). The scenarios are summarised in Table 36. Tables 37–40 summarise the results of these simulations for four base-case days.

Table 35: Vehicle emission standards

	Year of implementation	Standards		
Tier 1	1978	ADR27 for light-duty petrol vehicles		Standards used for 2026 emissions projection
	1986	ADR37/00 for light-duty petrol vehicles		
	1996	ADR70 for diesel vehicles		
	1997–99	ADR37/01 for light-duty petrol vehicles		
Tier 2	2002–03	ADR80/01 as Euro 3 for heavy-duty vehicles with 500ppm diesel sulfur content		
	2003–04	ADR79/01 as Euro 2 for light-duty vehicles		
	2005–06	ADR79/01 as Euro 3 for light-duty vehicles		
	2006–07	ADR80/01 as Euro 4 for heavy-duty vehicles with 50 ppm diesel sulfur content		
Tier 3	2008–09	Proposed adoption of Euro 4 for light-duty vehicles		
	2009–10	Proposed adoption of Euro 5 for heavy-duty vehicles		

Table 36: Emissions for mobile source scenarios for a high oxidant day

Label	Scenario	VOCs			NO_x		
		kg/day Sydney	% anthro	% change total anthro from 2001	kg/day Sydney	% anthro	% change total anthro from 2001
	2001 base-case	150,431	44	–	156,777	74	–
A	Apply mandated controls	81,452	30	–20	100,183	64	–27
B	Apply proposed controls	66,888	26	–25	55,266	50	–48
C	Increase mv NO_x 40%	150,431	44	0	217,785	80	+29
D	Decrease mv NO_x 20%	150,431	44	0	124,450	69	–15
E	Increase VKT 50%	210,447	53	+18	218,182	64	+29
F	Decrease VKT 50%	77,009	29	–22	99,379	80	–27

Table 37: Simulated maximum ozone concentrations, 12 January 2001

	VOCs	NO_x	VOCs Sydney	NO_x Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
	1.00	1.00	1.00	1.00	136.7	96.6	136	81	161	164
A	0.81	0.87	0.80	0.73	135.4	94.6	112	64	134	135
B	0.78	0.77	0.75	0.52	131.7	94.5	107	71	129	165
C	1.00	1.14	1.00	1.29	105.8	83.0	18	7	18	10
D	1.00	0.93	1.00	0.85	156.1	105.1	186	122	241	310
E	1.21	1.13	1.18	1.29	129.9	94.0	114	71	129	136
F	0.82	0.88	0.78	0.73	140.8	97.0	133	82	162	184

Table 38: Simulated maximum ozone concentrations, 20 December 2000

	VOCs	NO_X	VOCs Sydney	NO_X Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
	1.00	1.00	1.00	1.00	109.9	94.2	186	371	213	667
A	0.81	0.87	0.80	0.73	97.2	85.4	0	77	0	99
B	0.78	0.77	0.75	0.52	88.7	78.8	0	0	0	0
C	1.00	1.14	1.00	1.29	114.3	96.3	261	413	323	785
D	1.00	0.93	1.00	0.85	109.5	92.1	92	308	97	517
E	1.21	1.13	1.18	1.29	120.7	101.4	473	590	651	1262
F	0.82	0.88	0.78	0.73	99.7	86.6	0	131	0	171

Table 39: Simulated maximum ozone concentrations, 22 January 2001

	VOCs	NO_X	VOCs Sydney	NO_X Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
	1.00	1.00	1.00	1.00	106.2	89.3	79	263	79	550
A	0.81	0.87	0.80	0.73	95.5	81.6	0	39	0	42
B	0.78	0.77	0.75	0.52	87.1	75.6	0	0	0	0
C	1.00	1.14	1.00	1.29	106.7	90.9	64	273	66	580
D	1.00	0.93	1.00	0.85	103.5	87.1	37	209	37	408
E	1.21	1.13	1.18	1.29	114.8	95.7	231	392	276	1003
F	0.82	0.88	0.78	0.73	97.1	82.5	0	83	0	101

Table 40: Simulated maximum ozone concentrations, 10 February 2004

	VOCs	NO_X	VOCs Sydney	NO_X Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
	1.00	1.00	1.00	1.00	108.2	85	54	108	54	173
A	0.81	0.87	0.80	0.73	99.4	76.4	0	0	0	0
B	0.78	0.77	0.75	0.52	96.4	77.6	0	0	0	0
C	1.00	1.14	1.00	1.29	111.6	84.2	47	18	47	22
D	1.00	0.93	1.00	0.85	100.5	81	2	3	2	3
E	1.21	1.13	1.18	1.29	113.8	87.6	65	94	65	146
F	0.82	0.88	0.78	0.73	102.5	78.6	6	0	6	0

Applied to 2001 emissions, currently mandated emission limits for motor vehicles significantly reduce emissions in the Sydney region – VOC by 20% and NO_x by 27%. This emission reduction is sufficient to achieve compliance with the AAQ NEPM one-hour goal for 20 December 2000, 22 January 2001 and 10 February 2004. Maximum ozone is reduced by more than 10% for these events. However, for the 12 January 2001 event, this reduction in emissions results in only small reductions in ozone concentration. The maximum reduces very little, while the other metrics show only modest improvements to air quality.

Proposed emission limits reduce emissions further, particularly for NO_x. These are estimated to generate a 25% reduction in VOCs and a 48% reduction in NO_x in the Sydney region. This very substantial reduction to emissions results in significant reductions to maximum ozone concentrations for 20 December 2000, 22 January 2001 and 10 February 2004 with compliance to both one- and four-hour goal. Yet for 12 January 2001, only a small reduction is found for maximum ozone and the associated metrics.

Increasing motor vehicle NO_x by 40% resulted in a substantial decrease in maximum ozone concentration for 12 January 2001 but an increase for the other three event days, notably 20 December 2000. The number of grid cell hours and grid area decreases for 10 February 2004 for both AAQ NEPM standards while there is a slight decrease in one-hour area and dose on 22 January 2001. Conversely, reducing motor vehicle NO_x by 20% generated small reductions for 20 December 2000 and 22 January 2001. Large reductions were generated for 10 February 2004 but there was a marked increase for 12 January 2001.

Increasing VKT by 50% results in increased emissions of both VOCs (18%) and NO_x (29%) within Sydney. As expected given the previous results, this increased maximum ozone concentrations for 20 December 2000, 22 January 2001 and 10 February 2004, but slightly decreased maximum ozone concentrations for 12 January 2001. Halving VKT achieves substantial reductions in emissions: VOCs by 22% and NO_x by 27%. This reduces ozone concentrations for 20 December 2000, 22 January 2001 and 10 February 2004. The reduction is sufficient on 20 December and 22 January to meet the current AAQ NEPM one-hour goal while there is a significant drop in four-hour dosage on 10 February 2004. Again, 12 January 2001 shows contrary behaviour, the reduction in emissions resulting in a slight increase in ozone concentrations.

The significance of motor vehicle emissions to ozone production can be assessed by comparing the maximum ozone concentration from these scenarios with that predicted by the results of the emission scaling simulations presented in Section 3.3. The predicted maximum one-hour ozone concentration for each scenario is derived from the scaling simulations by interpolating the results from the stream 1 experiment, using kriging at a resolution of 0.01 (scaling). This comparison explores the significance of the emission controls on each source category.

Table 41 shows that the Sydney airshed is sensitive to motor vehicle emissions. Scenario B is a significant reduction in emissions in the Sydney airshed. For all four base-case days, there was a greater reduction in maximum one-hour ozone concentrations than was predicted from the results of the emission scaling scenarios (stream 1). Scenario A also shows greater sensitivity, but to a lesser degree than scenario B and for only two of the four base-case days. The February 10 event shows maximum one-hour ozone concentration similar to the predicted value, while the extreme event – 12 January – shows a smaller reduction than predicted.

Scaling motor vehicle usage by reducing VKT (scenario F) does not show the greater sensitivity seen in the scenarios reducing tailpipe emissions. For this case there is contrary behaviour for the extreme event (12 January), slightly increased sensitivity for 20 December, no difference in sensitivity for 22 January and reduced sensitivity for 10 February. Similarly, a marked increase in emissions by increasing motor vehicle usage (scenario E) shows decreased sensitivity on 12 January,[3] similar sensitivity for 10 February and 22 January, and slightly increased sensitivity for 20 December.

[3] January 12 is expected to show a decrease in maximum one-hour ozone concentration in response to this increase in emissions. The decrease was less than predicted.

Table 41: Maximum one-hour ozone concentrations for emission perturbations compared with value predicted by scaling simulations (stream 1)

	A Mandated motor vehicle	B Proposed motor vehicle	C 40% increase in motor vehicle NO_x	D 20% reduction in motor vehicle NO_x	E 50% increase in VKT	F 50% reduction in VKT
Sydney VOCs (ratio)	0.80	0.75	1.00	1.00	1.18	0.78
Sydney NO_x (ratio)	0.73	0.52	1.29	0.85	1.29	0.73
12 Jan, 2001 base-case[1]	*136.7*	*136.7*	*136.7*	*136.7*	*136.7*	*136.7*
12 Jan 2001 predicted	132.0	136.5	105.4	144.2	127.0	130.0
12 Jan 2001 simulated	135.4	131.7	105.8	156.1	129.9	140.8
20 Dec 2000 base-case[1]	*109.9*	*109.9*	*109.9*	*109.9*	*109.9*	*109.9*
20 Dec 2000 predicted	101.0	96.0	114.5	109.0	119.0	100.8
20 Dec 2000 simulated	97.2	88.7	114.3	109.5	120.7	99.7
22 Jan 2001 base-case[1]	*106.2*	*106.2*	*106.2*	*106.2*	*106.2*	*106.2*
22 Jan 2001 predicted	97.0	93.0	107.2	103.8	115.0	97.0
22 Jan 2001 simulated	95.5	87.1	106.7	103.5	114.8	97.1
10 Feb 2004 base-case[1]	*108.2*	*108.2*	*108.2*	*108.2*	*108.2*	*108.2*
10 Feb 2004 predicted	99.0	98.8	104.2	110.0	102.5	99.0
10 Feb 2004 simulated	99.4	96.4	104.0	111.6	102.5	102.5

[1] Base case results provided for comparison – they have emission scalings of 1.00 for both VOCs and NO_x.

Scenarios C and D explore the sensitivity of the photochemical plume to motor vehicle NO_x emissions. The 12 January and 10 February events showed increased sensitivity to a reduction in motor vehicle NO_x; the 22 January event showed similar sensitivity (to global scaling) while the 20 December event showed little response to this emissions change. Increasing motor vehicle NO_x resulted in maximum ozone concentrations close to those predicted from the scaling scenarios, a response similar to that of scaling all emissions.

This analysis highlights the complexity of the photochemical plume in Sydney. Reductions in motor vehicle emissions are particularly effective, but only for significant overall reductions. For moderate emission changes, there was no increased response to changes to emissions from motor vehicles.

Commercial-domestic emissions

Existing airshed modelling work indicates that the commercial-domestic category is the second most significant for production of ozone in the Sydney region. This category contributes little to total anthropogenic NO_x in the region (8%) but significantly to total anthropogenic VOCs (41%). Furthermore, these emissions have a similar geographic distribution to that of the most significant category, motor vehicles. The significance of this category has been explored using simulations where it has been halved and doubled. The resulting emissions are shown in Table 42.

These emissions scenarios have been run for four event days. The results are summarised in Tables 43–46.

In contrast to the findings of perturbations of motor vehicle emissions, the four days show the same response to commercial-domestic emissions. For all days, decreasing emissions decreased maximum ozone concentration while increasing emissions increased them. As this category is significant for VOCs but not NO_x, these results are showing the sensitivity of the simulated plume to changes to VOC emissions for a particular geographic distribution. The response is similar to that expected based on the event day EKMA diagrams (Figures 42–45), with that of 12 January 2001 a little stronger, indicating this category may contribute more to ozone concentration than is suggested by its contribution to total emissions.

Table 42: Emissions for commercial-domestic variation scenarios

Scenario	VOCs (Sydney)			NO_x (Sydney)		
	kg/day	% anthro.	% change total anthro from 2001	kg/day	% anthro.	% change total anthro. from 2001
2001 base-case	139,200	41	–	16,346	8	–
Half commercial-domestic	69,599	26	–20	8,173	4	–4
Double commercial-domestic	278,396	58	+41	32,691	14	+8

'anthro.' is an abbreviation for anthropogenic emissions

Table 43: Simulated maximum ozone concentrations, 12 January 2001

VOCs GMR	NO_x GMR	VOCs Sydney	NO_x Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
1.00	1.00	1.00	1.00	136.7	96.6	136	81	161	164
0.81	0.98	0.80	0.96	110.7	83.3	40	15	40	25
1.46	1.04	1.41	1.08	183.7	121.9	236	193	348	554

Table 44: Simulated maximum ozone concentrations, 20 December 2000

VOCs	NO_x	VOCs Sydney	NO_x Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
1.00	1.00	1.00	1.00	109.9	94.2	186	371	213	667
0.81	0.98	0.80	0.96	105.4	90.6	57	243	59	368
1.46	1.04	1.41	1.08	122.9	101.0	467	604	638	1347

Table 45: Simulated maximum ozone concentrations, 22 January 2001

VOCs	NO_x	VOCs Sydney	NO_x Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
1.00	1.00	1.00	1.00	106.2	89.3	79	263	79	550
0.81	0.98	0.80	0.96	101.2	86.0	4	160	4	274
1.46	1.04	1.41	1.08	115.6	95.6	254	426	307	1164

Table 46: Simulated maximum ozone concentrations, 10 February 2004

VOCs	NO_x	VOCs Sydney	NO_x Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
1.00	1.00	1.00	1.00	108.2	85	54	108	54	173
0.81	0.98	0.80	0.96	98.5	77.8	0	0	0	0
1.46	1.04	1.41	1.08	128.4	94.6	160	199	184	388

Based on the VOC and NO_x emissions described by the emissions inventory, the results of the stream 2 emissions sensitivity can be summarised as follows:

- Increasing VOC emissions increases maximum ozone concentration while decreasing VOC emissions reduces ozone concentration.
- Targeting commercial-domestic emissions has a significant impact due to its significant contribution to total VOC emissions.
- Sydney is more sensitive to motor vehicle control strategies. If the introduction of proposed and mandated vehicle emission controls was brought forward to 2002, the maximum ozone concentrations would fall below the NEPM standard on three of the four days.
- There is not one control strategy which will reduce maximum ozone concentrations on all days.

3.5 Stream 3: Future projections – what is the impact of increasing population on ozone concentrations?

Emissions projections for the year 2026 have been constructed using three scenarios for population and associated motor vehicle usage (as VKT) provided by the then Department of Infrastructure, Planning and Natural Resources (DIPNR). A description of the scenarios is presented in Appendix F. One of these projections has been used as a starting point for a series of emission variations exploring the sensitivity of simulated ozone concentration to assumptions inherent in the projections. The projections for the year 2026 estimate population growth of 1.45 million within the modelling domain, 1.1 million of this within the Sydney urban area. The above study ran three scenarios for this increase in population with different landfill/greenfield ratios.

They were:

- 85% landfill, 15% greenfield
- 70% landfill, 30% greenfield
- 55% landfill, 45% greenfield.

The results showed little to no difference in maximum ozone between the scenarios; therefore, the standard 2026 scenario used in this study will be the 70:30 ratio.

NO_x emissions for the Sydney region in the standard 2026 scenario are nearly 40% lower than those of 2002, despite an increase in population of nearly 30%. VOC emissions are 8% lower than those in 2002. Much of the significant reduction in emissions arises from reductions in emissions from the motor vehicle fleet, due to the introduction of emission controls even though usage as measured by VKT rises. The decrease in VOC emissions is smaller than that for NO_x emissions because the commercial-domestic emissions will increase proportionately to population increases.

The emissions in the Sydney region for the standard 2026 scenario can be expressed as a ratio of 2002 emissions. The results of stream 1 can then be used to predict the maximum one-hour ozone concentration for the standard 2026 scenario. Based on the EKMA diagrams presented in section 3.3 (Figures 42–45), Table 47 shows the emission scaling and maximum one-hour ozone concentrations for the 2002 base-case, the 2026 standard scenario, and predicted from stream 1 for the four base-case days.

Table 47: Maximum one-hour ozone concentrations for 2026 standard scenario compared with value predicted by scaling simulations (stream 1)

	Sydney VOCs (ratio)	Sydney NO_x (ratio)	2002 base-case	2026 predicted from stream 1	2026 standard scenario
20 December 2000	0.92	0.61	109.9	102.2	95.5
12 January 2001	0.92	0.61	136.7	151.2	142.4
22 January 2001	0.92	0.61	106.2	96.4	94.4
10 February 2004	0.92	0.61	108.2	108.7	104.0

Given that much of the emission reductions in the 2026 standard scenario come from reducing mobile emissions, the results of stream 2 predict that the maximum ozone concentrations simulated for the 2026 standard scenario will show a greater reduction in ozone from the 2002 base-case than is predicted by the results of stream 1. This is the case for the three events expected to show a reduction in maximum one-hour ozone concentration. Using the results of stream 1, the extreme event – 12 January 2001 – is expected to show an increase in maximum one-hour ozone concentration. The increase is less than predicted.

Description of emission projection scenarios

Seven scenarios for 2026 have been developed. Two of these explore motor vehicle emissions and complement the work presented in Section 3.4: two explore the significance of the commercial-domestic emissions category in the projected inventory to 2026; two explore options for electricity generation to meet potential demand from the significant population increase; and the remaining scenario explores the impact of drastic measures to restrict population growth within the Sydney metropolitan area. The scenarios are summarised in Table 48.

The two motor vehicle emission scenarios explore the impact of the increased population under reduced emission controls. The first of these implements no new controls at all, while the other implements only currently mandated controls. The standard 2026 projection assumes that:

- both currently mandated vehicle emission standards and proposed standards from Euro-IV and Euro-V are fully implemented (Table 35)
- all major proposed freeways and other arterials will be built.

The projected inventory for 2026 assumes that emission rates in the commercial-domestic category will continue at current rates. Two emission scenarios were constructed to test sensitivity of simulated ozone concentration to this assumption. The increase in emissions from 2001 was doubled for one and halved for the other.

The two electricity generation scenarios represent two approaches to meeting expected electricity demand for the substantially increased population. The first of these includes emissions from three 350 MW co-generation plants located in the Sydney urban area. The second includes geographically dispersed emissions from small-scale local generators producing the same electricity as one co-generation plant. These emissions have been geographically located using the population distribution.

The remaining scenario considers locating a substantial part of the population growth in the lower Hunter. In this scenario, the lower Hunter contains one million people, the growth being about 600,000 more than in the standard 2026 scenario. By increasing population growth in this region, the growth in the Sydney region is less (around 720 000 rather than the 1.1 million in the standard 2026 scenario). The results for these scenarios are shown in Tables 49–52.

Table 48: Emissions for future projection scenarios

	Scenario	VOCs (Sydney)			NO_x (Sydney)		
		kg/day	% change total anthro. from 2001	% change total anthro. from 2026	kg/day	% change total anthro from 2001	% change total anthro from 2026
	2001 base-case	339,631	–	–	212,123	–	–
A	2026 standard scenario*	313,948	–8	–	130,394	–39	–
B	2026 with current (2001) mv controls	420,275	+24	+34	259,120	+22	+99
C	2026 with mandated mv controls+	332,517	–2	+6	187,515	–12	+44
D	2026 with double commercial-domestic increase	356,342	+5	+13	135,286	–36	+4
E	2026 with half commercial-domestic increase	292,752	–14	–7	128,018	–40	–2
F	2026 with three large co-generation plants	313,948	–8	–	189,242	–11	+45
G	2026 with distributed electricity generation	313,948	–8	–	150,225	–29	+15
H	2026 with population growth in the lower Hunter	297,345	–12	–5	125,124	–41	–4

* Assumes the introduction of all proposed emission controls (Table 35)

+ Tier 2 Table 35

'anthro.' is an abbreviation for anthropogenic emissions

Table 49: Simulated maximum ozone concentrations, 12 January 2001

	VOCs	NO_x	VOCs Sydney	NO_x Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
	1.00	1.00	1.00	1.00	136.7	96.6	136	81	161	164
A	0.99	0.82	0.92	0.61	142.4	100.3	151	109	194	293
B	1.3	1.11	1.24	1.22	139.6	101.1	162	98	200	220
C	1.06	0.95	0.98	0.88	140.2	98.6	147	91	183	213
D	1.12	0.83	1.05	0.64	149.2	105.2	178	133	245	374
E	0.92	0.81	0.86	0.60	138.7	97.7	141	96	179	244
F	0.99	0.91	0.92	0.89	141.0	94.4	140	90	174	208
G	0.99	0.86	0.92	0.71	144.3	100.0	158	102	203	268
H	0.98	0.81	0.88	0.59	140.0	99.0	143	100	180	254

Table 50: Simulated maximum ozone concentrations, 20 December 2000

	VOCs	NO_x	VOCs Sydney	NO_x Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
	1.00	1.00	1.00	1.00	109.9	94.2	186	371	213	667
A	0.99	0.82	0.92	0.61	95.5	84.0	0	59	0	67
B	1.3	1.11	1.24	1.22	119.5	101.8	459	602	638	1294
C	1.06	0.95	0.98	0.88	105.5	91.9	63	287	65	461
D	1.12	0.83	1.05	0.64	97.8	86.0	0	115	0	154
E	0.92	0.81	0.86	0.60	94.5	83.0	0	36	0	39
F	0.99	0.91	0.92	0.89	98.1	87.5	0	196	0	260
G	0.99	0.86	0.92	0.71	98.2	86.3	0	112	0	144
H	0.98	0.81	0.88	0.59	91.2	82.7	0	36	0	38

Table 51: Simulated maximum ozone concentrations, 22 January 2001

	VOCs	NO_x	VOCs Sydney	NO_x Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
	1.00	1.00	1.00	1.00	106.2	89.3	79	263	79	550
A	0.99	0.82	0.92	0.61	94.4	80.6	0	4	0	4
B	1.3	1.11	1.24	1.22	116.3	96.6	239	402	294	1062
C	1.06	0.95	0.98	0.88	104.5	87.9	33	198	33	393
D	1.12	0.83	1.05	0.64	96.7	82.2	0	61	0	71
E	0.92	0.81	0.86	0.60	93.1	79.8	0	0	0	0
F	0.99	0.91	0.92	0.89	98.8	87.9	0	157	0	274
G	0.99	0.86	0.92	0.71	97.3	82.6	0	71	0	84
H	0.98	0.81	0.88	0.59	92.5	79.3	0	0	0	0

Table 52: Simulated maximum ozone concentrations, 10 February 2004

	VOCs	NO_x	VOCs Sydney	NO_x Sydney	Maximum one-hour ozone (ppb)	Maximum four-hour ozone (ppb)	Area exceeding one-hour standard (grid cells)	Area exceeding four-hour standard (grid cells)	Dosage one-hour standard (grid cell hours)	Dosage four-hour standard (grid cell hours)
	1.00	1.00	1.00	1.00	108.2	85.0	54	108	54	173
A	0.99	0.82	0.92	0.61	104.0	82.0	8	5	8	5
B	1.3	1.11	1.24	1.22	115.2	88.9	89	132	91	215
C	1.06	0.95	0.98	0.88	106.5	80.5	22	1	22	1
D	1.12	0.83	1.05	0.64	108.4	85.7	24	18	25	24
E	0.92	0.81	0.86	0.60	101.7	79.9	2	0	2	0
F	0.99	0.91	0.92	0.89	104.0	79.6	16	0	16	0
G	0.99	0.86	0.92	0.71	105.2	81.1	12	5	12	5
H	0.98	0.81	0.88	0.59	102.1	80.9	2	2	2	2

Impact of scenarios

Motor vehicles

The motor vehicle emission projections to 2026 assume that motor vehicle usage continues to grow at current rates. The absence of the currently mandated controls leads to significant increase in emissions in the Sydney region for the year 2026. Given the forecast growth in motor vehicle use, currently mandated limits achieve only modest reductions in emissions from this sector.

Failing to implement currently mandated controls (scenario B) will result in air quality poorer than both the base-case and the 2026 standard scenario for three days: 20 December 2000, 22 January 2001 and 10 February 2004. On these three days, implementing currently mandated controls (C) reduces maximum ozone concentration to less than the base-case, but still greater than the 2026 standard scenario, and not sufficiently to meet the current AAQ NEPM one-hour goal.

The 12 January 2001 event shows contrary behaviour, the 2026 standard scenario having a maximum one-hour ozone concentration greater than that of the base-case. For this event, failing to implement currently mandated controls (scenario B) resulted in a smaller increase in one-hour maximum ozone concentration than that for the 2026 standard scenario. Implementing only currently mandated controls results in marginally greater concentrations than the base-case.

As motor vehicles are the predominant anthropogenic source and contribute significantly to ozone production, it is expected changing emissions in this category will change resulting ozone concentrations. These results show that, should current growth rates continue, currently mandated emission limits are needed to avoid exacerbating air quality. Proposed motor vehicle emission strategies (scenario A) result in significant emission reduction, sufficient to achieve the current AAQ NEPM goal for two of the four days.

Commercial-domestic

The emissions projections to the year 2026 assumed that the current rates of emissions in this category would continue to grow with population. As there is significant population growth, this results in significant increases in emissions from this category. For the standard 2026 scenario, this category becomes the largest anthropogenic source of VOCs.

The changes to emissions result in small changes to maximum ozone concentration (less than 5%). For all four days, increasing this category increased maximum ozone concentration, while decreasing it decreased maximum ozone concentration. The modest changes to emissions produced even smaller changes to maximum ozone concentration.

Electricity generation

At current usage, the significant increase in population for the year 2026 requires additional electricity generation. Two scenarios have been constructed. One includes emissions from three 350 MW co-generation plants located within the Sydney Basin. This is estimated to meet the increased demand for electricity. The second scenario includes emissions from neighbourhood power stations equivalent to one 350 MW co-generation plant. This is not sufficient to meet the increased power needs; however, current emission estimates show that emissions are larger per unit of electricity for these neighbourhood plants. These two scenarios have differing total emissions, those of the co-generation case increasing NO_x emissions by 45% in 2026. They also differ in the location of the additional emissions.

Compared with the standard 2026 scenario, there are significantly greater emissions to the Sydney region. This results in increased ozone dosage for 20 December 2000 and 22 January 2001, although both still meet the current AAQ NEPM one-hour standard. For 12 January 2001, there is little change to one-hour ozone concentration, and a small decrease to four-hour ozone concentration. For 10 February 2004, this scenario results in a slight increase in the number of one-hour grid cells exceeding the standard, but a decrease in the number of grid cells exceeding the four-hour standard. The only difference between the two scenarios is with the four-hour dosage being slightly higher for 20 December 2000 and 22 January 2001 for the co-generation, and the distributed generation higher on the other two days.

Lower Hunter city

This scenario explores the impact on air quality resulting from the action to move population increase from the Sydney region to the lower Hunter. It results in a major urban conurbation joining Maitland, Cessnock and Newcastle containing one million people. Even so, compared with the standard 2026 scenario, emissions to the Sydney region are only 6% lower (VOCs) and 4% lower (NO_x).

This modest reduction in emissions reduces maximum ozone concentration for all days, particularly 20 December 2000, where a 5% reduction in maximum one-hour ozone concentration is found.

The results of stream 3 can be summarised as follows:

- If the current level of emission controls is maintained, the impact of the predicted increase in population out to 2026 has the potential to increase maximum ozone concentrations in the Sydney Basin.
- Modest reductions in total emissions from current levels will see decreased ozone on three days despite the increase in population if the right source is targeted.
- The most significant source to control is motor vehicles, i.e. both VOC and NO_x controls.
- The impact of the decrease in motor vehicle emissions will be reduced due to the increase in VOC emissions from population-related emissions (commercial-domestic).
- By 2026, control of NO_x emissions will become vital.
- Co-generation or distributed electricity plants (an increase in NO_x emissions) did not significantly impact on maximum ozone. However there was an increase in 4-hour dosage for two days.

3.6 Discussion of results

The process employed to analyse the model results was a three-step procedure. Stream 1 generated event day EKMA plots of the relationship of region total precursor emissions and maximum one-hour ozone concentration. These diagrams provided a basis for exploring the difference in significance of the source categories and the future projection assumptions. Each scenario resulted in a particular scaling of the region total precursors. The event day EKMA diagram provided an expected resulting maximum one-hour ozone concentration. The diagrams then try to describe what general emission controls are needed in order to implement effective air management strategies. This approach is the most simple and led to further steps in order to gain a better understanding of the ozone distribution from modelling.

Stream 2 explored the individual sources and the results of scaling those sources. The results were compared to the equivalent scaling of all emissions, based on the interpolations presented in the event day EKMA diagrams.

Once the emission inventory and model sensitivity had been explored, stream 3 looked at future projections for an increase in population, and the future changes to motor vehicle emissions and usage.

Stream 1 results showed that reducing VOC emissions reduced ozone concentrations in all cases, but that this was an insufficient strategy of itself as the reduction would have to be substantial in order to achieve compliance with AAQ NEPM standards. Rather, a strategy combining reduction in VOCs and NO_x is preferable, even though this is less effective for 12 January 2001. Analysis of the simulations showed that two of the four event days had NO_x-rich conditions in the morning in the eastern half of the Sydney Basin. This is consistent with analysis of observations, for while the highest concentrations in the network were NO_x-limited, other elevated concentrations occurred with extents less than 0.9 and hence there was potential to generate greater ozone concentrations.

Stream 1 highlighted that 12 January 2001 was an extreme event for which substantial reductions in emissions are needed to reduce ozone concentration. Within the range of scenarios for the other two streams, this event showed contrary behaviour.

Stream 2 results showed the importance of motor vehicle emissions and the significant potential of this category to contribute to reductions in ozone concentration. While significant gains can be obtained by reducing emissions per kilometre travelled (reduction in both VOC and NO_x emissions), usage is also of significance.

With regard to commercial-domestic emissions, results showed the response for VOCs was the same for all days. Reducing VOC emissions reduced maximum ozone concentrations and increasing VOC emissions increased maximum ozone concentrations. Results for 12 January 2001 suggested that this category contributes more to ozone concentration than its contribution to total emissions implies.

Stream 3 explored future projections, in particular some assumptions contained within them. Mandated controls on motor vehicle emissions are necessary to offset the significant increase in motor vehicle usage. Proposed controls produce significant decreases in ozone concentrations and are therefore an important component of an overall strategy to improve air quality. The future projections were relatively insensitive to the assumed growth in emissions in the commercial-domestic category even though this becomes the largest source of VOCs. Modest changes to emissions in this category resulted in only small changes to ozone concentration.

The standard 2026 scenario assumes that electricity generation remains outside the Sydney region. Two alternative approaches were tested: co-generation plants and distributed generation. Current estimates show that of these two, emissions per unit of electricity generated are significantly higher for distributed generation. This potentially significant source of NO_x did not result in higher ozone concentrations compared with the distributed electricity ozone concentrations, although both scenarios had a greater dosage of four-hour ozone than the standard 2026 scenario.

The final scenario explored the impact of concerted population growth outside the Sydney region. This achieved only modest reductions in emissions, with associated reductions in ozone concentrations largest on 20 December 2000.

Emission estimates show that growth in both population and per capita motor vehicle usage are significant threats to air quality in Sydney. Without imposing additional limits on motor vehicle emissions, air quality deteriorates markedly due to the increase in both population and motor vehicle use. Conversely, implementing currently proposed motor vehicle standards for the 2001 population of the Sydney region is particularly effective at reducing ozone concentrations for three of the four days.

4. Air quality planning for the Sydney region

4.1 Background information

Four base-case days have been developed which reproduce the ambient conditions giving rise to the ozone concentrations on that day. These days have been used to investigate the impact of different management strategies on ozone formation in the Sydney Basin for the years 2002, 2016 and 2026. Isopleth diagrams have been constructed which provide information on the size of the decrease in source emissions necessary for attainment of the ozone standard.

Table 53 summarises the peak one-hour ozone concentrations monitored and modelled out to 2026 for each of the four modelled days. It can be seen that although the maximum ozone concentration generally decreases due to proposed strategies out to 2026, the ozone standard is still exceeded on two of the four days.

Table 53: Peak ozone concentrations – monitored and modelled

	20 December 2000 1-hour (ppb)	12 January 2001 1-hour (ppb)	22 January 2001 1-hour (ppb)	10 February 2004 1-hour (ppb)
Monitored 2002	115	126	103	107
Modelled 2002	110	137	106	108
2016 (modelled)	103	139	101	104
2026 (modelled)	96	142	94	104

The control strategies for 2016 and 2026 took into account proposed and mandated motor vehicle controls, and increasing emissions from area-based sources associated with an increase in population of 1 million people within the Sydney Basin (DEC 2004).

In order to investigate control strategy options, isopleth diagrams have been produced which evaluate the impact of control of both VOCs and NO_x on the formation of ozone. These isopleth diagrams demonstrate that meeting the ozone standard in 2002 requires an overall reduction in both VOCs and NO_x of roughly 25%.

Table 54 summarises the baseline emissions for 2002 and the change to the baseline emissions estimated for the years 2016 and 2026.

Table 54: Baseline emissions for the Sydney region for 2002, 2016 and 2026 used for modelling

	Baseline emissions		Required 25% emission reduction in VOCs and NO_X in 2002		Emission reduction by 2016 and 2026	
	VOCs kg/day	NO_x kg/day	VOCs kg/day	NO_x kg/day	VOCs kg/day	NO_x kg/day
2002	339,631	212,123	84,907	53,030	–	–
2016	308,317	176,160	–	–	31,314	35,963
2026	313,948	130,394	–	–	25,683	81,729

Table 54 demonstrates that, although by 2026 the emissions of VOCs have been reduced by 8% and NO_x by 39%, compliance with the ozone standard has not been achieved. This could be due to:

- not achieving the required reduction in VOCs
- the scenario strategies not delivering the impact on ozone formation which would be expected from associated change in VOC and NO_x emissions from the source control
- motor vehicle emissions being the only source reduction
- area-based source emissions increasing
- industrial emissions remaining at 2002 levels.

Further work on the sensitivity of source emission control showed that reduction in ozone formation is sensitive to the control strategy selected.

This makes the design of a control program particularly challenging and highlights that the impact of control strategies must be continually reviewed.

4.2 Attainment strategies

This section outlines a procedure for evaluating the level of emission reductions required to meet the ozone standard and identifying preferred sources for control programs. The modelling presented in this report is based on 2002 emission estimates derived from the 1992 MAQs emissions inventory (Carnovale et al. 1997). A substantial program to generate a comprehensive emissions inventory for the 2004 base year and projections to future years has begun. The new inventory will allow further investigation of the relationship of emissions to photochemical pollution and hence refinement of the advice regarding preferred sources for emission reduction programs.

Table 55 summarises the emission inventory for 2002, 2016 and 2026. The information contained in these inventories identifies control strategies (CARB 2004).

Table 55: Emissions inventory for 2002, 2016 and 2026

Sydney Region	2002		2016		2026	
	VOCs	NO_x	VOCs	NO_x	VOCs	NO_x
Anthropogenic						
Commercial-domestic						
Surface coatings	17,237					
Natural gas leakage						
Domestic fuel combustion	7,384	642				
Commercial-domestic solvent	10,027					
Service stations	5,949					
Cutback bitumen	5,198					
Commercial-domestic aerosols	5,144					
Domestic lawn mowing	4,916	76				
Domestic waste combustion	33	11				
Dry cleaning	663					
Other unaccountable	207	4,122				
Domestic natural gas combustion	33	381				
Total commercial-domestic	**56,789**	**5,231**	**59,883**	**7083**	**65,478**	**7,665**
% of 2002 emissions			**105%**	**135%**	**115%**	**146%**
Industrial						
Petroleum refining	8,908	7,157				
Chemical manufacturing	3,144	2,610				
Printing	2,273	12				
Fabricated metals	1,079	23				
Basic metal processing	1,055	348				
Fuel storage	1,021	12				
Paint manufacturing	742					
Other manufacturing	464	23				
Food manufacturing	429	302				
Non-metallic minerals	162	3,608				
Hospitals, incinerators, harbour tunnel	116	661				
Paper products	46	406				
Quarrying	36	232				
Textiles	24	68				
Coal mining	12	128				
Total Industrial	**19,511**	**15,590**	**19,511**	**15590**	**19,511**	**15,590**
Mobile						
Motor vehicles	52,908	64,707	34,402	42980	30,862	25,693
% of 2002			**55%**	**65%**	**58%**	**40%**
Marine pleasure craft	4,513	98				
Commercial shipping	720	710				
Aviation	1,270	1,680				
Rail transport	160	600				
Total mobile	**59,571**	**67,795**				
Total anthropogenic	**135,872**	**88,616**	**113,798**	**65653**	**115,853**	**48,998**
% of 2002			**84%**	**74%**	**85%**	**55%**
Biogenic	**46,500**	**1,050**	**46,500**	**1050**	**46,500**	**1,050**
TOTAL EMISSIONS	**182,372**	**89,666**	**160,298**	**66705**	**162,353**	**49,998**

As stated previously, the isopleth diagrams indicated that a reduction of 25% in both VOCs and NO_x was required to meet the AAQ NEPM standard in 2002. The modelling results also demonstrate that control of motor vehicle emissions alone will not ensure compliance with the ozone standard by 2016 and 2026.

If the information in Table 55 is used as a basis, a 25% reduction is for VOC emissions a reduction of 33,968 tonnes/annum and for NO_x emissions a reduction of 22,154 tonnes/annum. The emission projections for 2026 have a reduction from the 2001 emissions in VOCs and NO_x of 20,019 and 39,678 tonnes per annum respectively.

The detailed breakdown of the emissions inventory highlights that the only reductions included in the emission projections to 2026 are those from vehicle emissions. Area-based sources increase and industrial emissions remain constant. This provides options for emission control; for example, sensitivity studies have shown that targeting area-based emissions has a significant impact on ozone formation due to the large contribution this source makes to total VOCs.

The emissions update will provide more detailed information on the sources and their emissions and on source characteristics. This will enable emission reduction strategies to be identified.

5. Implications for future work program

The conclusions from the study highlight several areas where further work is required. The modelling results are all internally consistent and, at this stage, the development of further base-case days will not add any more information on ozone formation in the Sydney Basin. The chemistry of the model has highlighted that NO_x quenching can occur in the mornings and this impacts on the maximum ozone concentration reached during the day.

Validation of the emissions inventory is extremely important. National Pollutant Inventory (NPI) and load-based licensing (LBL) information can contribute to the validation of the NO_x and VOC emissions from the larger industries. Emissions from the area-based sources cannot be validated without ambient monitoring, particularly for VOCs.

While the model is internally consistent, we as yet cannot tie in the conclusions with the ambient observations. The routine ambient air quality measurements do not have the detailed information needed to validate the model results, particularly the evaluation of the model outputs that the ambient air is NO_x-rich in the mornings. This type of ambient measurement requires a specific targeted program as it is difficult and expensive to carry out.

Ambient measurements of hydrocarbons would serve several purposes: inventory validation; provide information for input into the model; provide information for smog chamber runs to validate the assumptions built into the model; and provide further information to confirm, or otherwise, the NO_x quenching effect in the mornings highlighted by the model runs.

Understanding the role of the meteorology, in ozone formation, in the Sydney Basin is becoming critical. Currently a Radio-Acoustic Sounding System (RASS) is installed at Shanes Park in western Sydney, and it is proposed that data from this instrument is analysed under contract as Atmospheric Science does not have the resources.

The only way to identify potential future air quality issues is to rely on modelling. Programs developed to answer the questions identified above would provide an increased level of confidence in the model results and the policy directions needed out to the future.

Appendix A: Detailed description of ozone formation

Ozone (O_3) is a colourless, strongly oxidising gas. It occurs in both the stratosphere (10-50 km above the ground) and in the troposphere (ground up to 10 km or so). Production of ozone differs in the troposphere and the stratosphere. In the stratosphere, and especially the ozone layer, ozone is produced from the interaction of ultraviolet light and molecular oxygen. The steady-state concentration of ozone in the stratosphere is described by the Chapman cycle and additional reactions involving halogens, Finlayson-Pitts and Pitts (2000) and references therein. In the troposphere, photochemical processes involving reactive organic compounds (also known as VOCs) and NO_x are the predominant system for producing ozone. These are the processes described here.

A1 Photochemical production of ozone

Photochemical production of ozone near the ground is complex and involves a large number of chemical species. Ozone concentration is the result of the balance between production and destruction.

Photochemical production of ozone can be described as the oxidation of nitrous oxide (NO) firstly to nitrogen dioxide (NO_2) and then to ozone (O_3), the energy for the oxidation provided by ultraviolet light. However, an important ozone destruction pathway is reaction with NO to form NO_2.

A1.1 Ozone formation

There are several means by which NO can be oxidised to NO_2. The pathway promoting ozone production does not involve ozone itself; rather the NO is oxidised by a peroxyl radical itself formed by the reaction of a hydroxyl radical with a reactive organic compound (hydrocarbon). The remaining organic radical can regenerate the hydroxyl radical, oxidising another molecule of NO to NO_2 and becoming a ketone. Denoting the reactive organic compound by RH, the equations are:

$$RH + OH\bullet \xrightarrow{O_2} RO_2\bullet + H_2O \qquad (1)$$

$$RO_2\bullet + NO \rightarrow NO_2 + RO\bullet \qquad (2)$$

$$RO\bullet + O_2 \rightarrow HO_2 + RO \qquad (3)$$

$$HO_2 + NO \rightarrow NO_2 + OH\bullet \qquad (4)$$

Formation of ozone occurs when nitrogen dioxide (NO_2) is photo-dissociated to release an oxygen atom which then forms ozone by reacting with an oxygen molecule. The equations are:

$$NO_2 + hv(\lambda < 430\,nm) \rightarrow NO + O \qquad (5)$$

$$O + O_2 \xrightarrow{M} O_3 \qquad (6)$$

Where M is another species which absorbs energy

A1.2 Ozone destruction

Ozone is a reactive oxidant. Important reactions destroying ozone are:

$$O_3 + NO \rightarrow NO_2 + O_2 \qquad (7)$$

$$O_3 + hv(\lambda < 336nm) \rightarrow O + O_2 \qquad (8)$$

$$O + H_2O \rightarrow 2\,OH \qquad (9)$$

$$NO_2 + O_3 \rightarrow NO_3 + O_2 \qquad (10)$$

A1.3 The hydroxyl radical

As noted above, current descriptions of urban photochemistry stress the importance of the hydroxyl radical (OH) in initiating the photochemical processes resulting in ozone, PAN and other pollutants. The hydroxyl radical has several sources, most of which require radiation.

$$O_3 + h\nu\,(\lambda < 336nm) \rightarrow O(^1D) + O_2 \qquad (11)$$

$$O(^1D) + H_2O \rightarrow 2\ OH \qquad (12)$$

$$HONO + h\nu(\lambda < 370nm) \rightarrow OH + NO \qquad (13)$$

$$HOOH + h\nu(\lambda < 370nm) \rightarrow 2\ OH \qquad (14)$$

$$HO_2 + NO \rightarrow OH + NO_2 \qquad (15)$$

As noted in section A1.1, hydrogen peroxide (H_2O_2 and denoted HOOH in equation 14) is produced not only by the reaction of molecular oxygen with free hydrogen atoms, but also from reactions of molecular oxygen with formyl radicals.

As well as reacting with VOCs (equation 1), the hydroxyl radical also reacts with NO and NO_2.

$$OH + NO + M \rightarrow HONO + M \qquad (16)$$

$$OH + NO_2 + M \rightarrow HNO_3 + M \qquad (17)$$

A2 Simplified descriptions and analysis tools

Health research has shown that ozone is a respiratory irritant. This has resulted in health-based standards and goals for ozone concentration, and routine measurement of ozone concentration in many urban areas of the world. Observations show that ozone concentrations exceed health-based standards in many of these urban areas. This prompts actions to reduce emissions of VOCs and NO_x as a way of reducing the ozone concentration. Theoretical descriptions of photochemical processes are used to generate specific descriptions of the photochemistry of a particular location. This informs actions to reduce emissions and assists analysis of observations assessing the effectiveness of emission reduction programs.

The photochemical system represented by equations 1–17 is a very simplified summary of the main features of the photochemistry occurring in the troposphere. There are a very large number of reactive organic species and hence a large number of intermediates. Furthermore, many of these equations are competing. Given that the reaction rates for some of the key reactions are a function of the concentration of one or more species taking part in the reaction, the overall photochemical system is very complex.

Given the complexity of photochemistry, simplified descriptions have been constructed to provide a framework for exploring the processes generating elevated concentrations of ozone. Associated with these descriptions are various approaches to analysis of both observations and simulations.

Most simply, the photochemical production of photochemical smog, including ozone, is described by the indicative reaction (Finlayson-Pitts and Pitts 2000, p.5):

$$\begin{aligned} & VOC + NO_x + h\nu \rightarrow \\ & \qquad O_3 + PAN + HNO_3 + \ldots + particles \end{aligned}$$

Here VOC denotes all volatile organic compounds and includes RH and intermediates (RO•; RO_2•) in the above equations. Given the same weather conditions (invariant hv), this description of photochemistry implies a relationship between ozone concentration and that of the two precursors VOCs and NO_x.

Using smog chamber experiments or computer simulations of the photochemistry, the relationship between ozone and its two precursors can be found. This is represented by two-dimensional isopleths of maximum ozone concentration plotted using concentration of each precursor as the two axes. As noted in Finlayson-Pitts and Pitts (2000), an early example of the results of investigating this relationship is presented in Dodge (1977). This used the EKMA model to generate such a presentation of the relationship. As this is an early example, this presentation form is often referred to as either a 'Dodge plot' or an 'EKMA diagram'. The figure below is an example of such a plot taken from Lawson (2002).

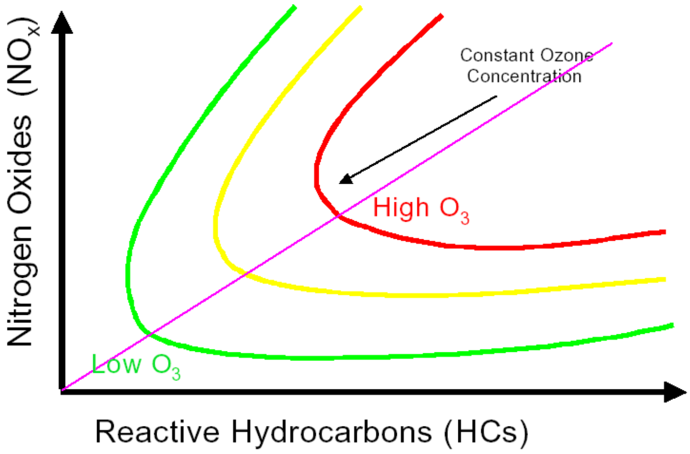


Figure A1: EKMA diagram (Dodge plot)

The diagram clearly shows that not only is ozone dependent on each precursor, but also on their ratio. Asymmetry in the plot shows that the two precursors differ in their contribution to maximum ozone concentration.

At high VOCs: NO_x (bottom right of the diagram), there is a relative excess of VOCs, so changes in its concentration have little impact on ozone concentration. Changes to NO_x concentration are important and result in marked changes to ozone concentration. Conversely, at low VOCs: NO_x (top left), the maximum ozone concentration responds more to changes in VOC concentration than to changes in NO_x.

The Dodge plot is a powerful way of describing photochemical production of ozone and it provides a framework for describing the photochemistry of an airshed. Combined with observations and modelling, it aids presentation of the results of investigations into the effectiveness of emission control strategies intended to reduce ozone concentration.

For particular concentrations of VOCs and NO_x, the Dodge plot shows the maximum ozone concentration that will develop given sufficient radiation. The available radiation for photochemistry on any particular day depends on location and weather conditions. Elevated concentrations of ozone usually occur on warm, sunny days. Sunlight is required for the photochemistry and, as temperature increases, photochemical processes speed up. Thus for given weather conditions and initial concentrations of precursors, the maximum ozone concentration that will develop can be calculated.

However, emissions occur throughout the day, and are moved by the wind. Thus for any particular ozone event, the observed ozone concentrations arise from photochemical processes occurring within a plume of air into which precursors are emitted and which is moved and distorted by meteorology. This additional complexity has prompted interest in developing airshed modelling systems – computer representations coupling emissions, meteorology, and photochemistry.

Because the photochemistry resulting in ozone requires radiation, this process can only increase ozone concentrations during daylight. Observations show that in general, ozone concentration tends to increase in daylight hours to a maximum in mid to late afternoon. The diurnal ozone concentration profile for a particular location will therefore result from the diurnal profile of sunlight, the diurnal profile of the emissions into the air that passes over that site, and the diurnal profile of the temperature of that air.

It is useful to describe photochemical production of ozone as having three stages. The first stage is oxidation of NO to NO_2. For this to lead to ozone production, it needs to occur by the pathway involving reactive organic species (equations 1 and 2 above). The hydroxyl radical controls this process, so the stage is referred to as ‘radical-limited’. The second stage is the production of ozone from NO_2. The concentration of ozone is governed by how much of the available NO_2 has reacted to form ozone. This is dependent on the radiation available for dissociating NO_2 – the cumulative light flux. This stage is referred to as ‘light-limited’. The third stage is the completion of photochemical production and exhaustion of the available NO_2. Ozone concentration tends to be static or fall in this stage. The maximum concentration of ozone is determined by the available NO_x, and if more becomes available photochemical production can resume. This stage is called ‘NO_x-limited’.

In a simple sense, the concentration of NO_x determines the maximum ozone concentration that can be generated given sufficient sunlight and VOCs. The VOC concentration controls the speed of photochemical production and thus how much of the NO_x will be used to form ozone within the available daylight (Johnson 1984).

This description of photochemical production provides a framework for describing the photochemical state of the airshed. In turn, this frames discussion of ozone production and the likely impact of emission control strategies intended to reduce ozone concentration. Thus observations can be assessed to characterise the urban plume throughout the day as radical-limited, light-limited, or NO_x-limited. This description of the photochemistry of an ozone event leads to assessment of the efficacy of possible emission reduction strategies. In any urban airshed, a variety of such events may occur and analysis over the range informs both desirable emission reduction strategies and helps analyse the effectiveness of past strategies.

This approach complements the Dodge plot and helps to explain its shape. At high VOCs: NO_x, the available NO_x would be quickly exhausted and so the photochemical plume is NO_x-limited. Changes to NO_x concentration have a large impact on ozone concentration. Conversely, at low VOCs: NO_x the lack of VOCs suggests retardation of photochemical processes so that NO_x is not exhausted and ozone concentrations are lower. Furthermore, excess NO_x inhibits photochemical production as NO_2 competes with VOCs for the hydroxyl radical by forming HNO_3 (equation 17). Thus at high relative concentrations of NO_x, both the first and second stage take longer, limiting production to light-limited and therefore ozone concentrations below the maximum possible for the given NO_x concentration.

Johnson and co-workers at CSIRO developed the IER set as a highly simplified description of photochemistry: Johnson (1984), Johnson and Quigley (1989), Johnson and Azzi (1992). A simple, empirical model using this concept and developed by Johnson and co-workers is an excellent tool with which to interpret both observed and computer-simulated photochemical pollution. Full descriptions of the model can be found in Johnson (1983), Johnson (1984), Johnson and Quigley (1989) and Johnson and Azzi (1992).

This IER model describes the rate of formation of total smog products (Smog Produced, SP) as a function of concentrations of precursor NO_x and ROC, and the cumulative light flux. Within this description, Smog Produced (SP) is defined as the sum of NO oxidised to NO_2 and nitrates, together with O_3 produced.

The functionality of using SP occurs because it removes the confounding nature of the photostationary O_3 cycle from the photochemical smog production process (equations 6 and 7). For example, if a plume rich in O_3 moves over a source of NO, there is a rapid reduction of O_3 as titration to NO_2 occurs (equation 7). However, by definition, concentrations of SP will remain unchanged.

The use of SP fits neatly with the NO_x-limited–light-limited description. According to the IER model, the light-limited regime has readily available NO_x and the rate of smog production is a function of the ROC concentrations, the temperature, and the cumulative light flux only,

$$SP = [ROC\} * \int k \bullet f(T) \qquad (18)$$

where k is the rate coefficient for photolysis of nitrogen dioxide, and $f(T)$ is a function of ambient temperature.

In the NO_x-limited regime, nitrogen dioxide has been converted to stable nitrate products and the process of photochemical smog production has ceased. Empirical evidence suggests that the NO_x-limited regime occurs when,

$$SP = SP_{max} = 4.1 \times [NO_x]_0 \qquad (19)$$

where $[NO_x]_0$ is the initial NO_x concentration of the air mass.

Airsheds which have reached NO_x-limited conditions will exhibit reduced sensitivity to ROC emission controls. Moreover, an increase in NO_x emissions may lead to a re-establishment of the light-limited regime and a further increase in smog levels. Consideration of equations 18 and 19 leads to an additional useful IER parameter,

$$EXTENT = {}^{SP} / {}_{SP_{max}} \qquad (20)$$

EXTENT is the photochemical extent parameter and provides a quantitative measure of the degree to which the photochemistry within an air parcel has advanced towards NO_x-limited conditions.

These IER parameters have been used extensively to interpret both observed and simulated pollutant concentrations. For example, a photochemical extent close to zero indicates a fresh urban plume with abundant NO_x. In this case, the rate of photochemical production is likely to be primarily determined by the concentration and reactivity of the ROC mixture, the ambient temperature, and the solar actinic flux.

A photochemical extent in the range 0.4–0.6 is likely to indicate an urban plume in which photochemical processes are well developed. In this case it is likely that the plume would be characterised by high NO_2 to NO ratios and low to moderate concentrations of ozone. Again, the rate of photochemical smog production is determined mainly by the concentration and reactivity of ROC precursors.

On the other hand, a photochemical extent close to one indicates pristine background air, or a photochemical plume in which the initial mass of NO_x has been converted to stable nitrate products. Without the presence of NO_2 as a reaction pathway, ozone production effectively stops. Such a plume will not develop further unless additional NO_x becomes available. Thus the EXTENT parameter is a very useful indicator of the controlling precursor class.

A3 Photochemical modules for airshed modelling systems

A3.1 Basis of photochemical modules

As noted in the previous section, the complexity of the photochemistry has led to considerable scientific effort to develop simplified descriptions for use in computer models. These are usually components of an airshed modelling system. Jimenez et al. (2003) provide an overview of several chemical mechanisms in current use. In addition to these schemes, additional simplified descriptions have been developed to assist interpretation of observations, e.g. IER Johnson & Azzi (1992); Blanchard (2000).

Finlayson-Pitts and Pitts (2000) note that ‘oxidation of just one organic in air includes hundreds of reactions’. This has led to lumped mechanisms, where ‘the chemistry of the organics is treated by grouping or ‘lumping’ together a number of reactions and/or chemical species’ (ibid). Finlayson-Pitts and Pitts (2000) describe two broad classes of lumped chemical mechanisms.

The first group of mechanisms lumps organics by their traditional classification, e.g., alkanes, alkenes and aromatics. Examples of such schemes are LCC (Lurmann et al. 1987a and 1987b); RADM (Stockwell 1986) and its updates RADM2 (Stockwell et al. 1990) and RACM (Stockwell et al. 1997); and SAPRC, the latest of which is SAPRC99 (Carter 2000).

The second group of mechanisms groups organics in terms of bonding. These mechanisms are called carbon bond mechanisms and denoted CB(X) where X gives the version number. CB(IV) (Gery et al. 1989) is a widely used scheme, e.g. Models3/CMAQ (Byun and Ching 1999).

These chemical mechanisms are designed to be used as the photochemistry component of a modelling system. The utility of these systems arises from both the accuracy of their simulations, and the time it takes for a simulation to run. Operational predictive models need to be able to complete a simulation for the following day within a few hours; this places limits on the complexity of the chemical mechanism that can be solved within this time. There is a lesser time constraint on models used for research purposes and these can have greater complexity. Clearly, as computing power increases it allows greater complexity in the chemical mechanisms. For example, the early versions of LCC contained 65 species and 169 reactions (McRae et al. 1992c). Contrast this with more recent mechanisms such as CACM (Griffin et al. 2002) which is the first to include explicit description of the formation of semi-volatile products. It has 191 species and 361 reactions.

In all of these chemical mechanisms, rate reactions are required for the lumped species. This is non-trivial as among the species lumped together, the rate of any one reaction may vary by several factors of 10. Finlayson-Pitts and Pitts (2000) note ‘there is a great deal of flexibility and judgment involved in choosing kinetics and products that are representative of a whole group of organics’. Rates for these reactions are tested using data from smog chamber experiments.

As well as these systems arising from theoretical descriptions of the volatile organic compounds, it is also possible to derive purely empirical schemes directly from smog chamber experiments. Such schemes are highly simplified and do not relate to theoretical chemistry. Their simplicity is both a strength and weakness, as it results in trivial computation, but is limited to representing the photochemistry of the smog chamber experiments from which it was derived.

An example of such a scheme is the Generic Reaction Set (Johnson 1984, Johnson and Azzi 1992), hereafter GRS. This is a highly simplified scheme based on smog chamber studies conducted in Sydney, Australia, as represented by IER (see previous section).

Modelling systems have been designed for the urban scale, the regional scale, and more recently taking advantage of increased computational power and grid nesting, both scales. Urban scale is characterised by domains of up to several hundred kilometres and grid sizes of 1–10 km. Regional scale is characterised by domains of several thousand kilometres and grid sizes of tens of kilometres. It is common now for the photochemical module of a modelling system to allow a choice of photochemical mechanism.

A3.2 Modules used in NSW

The airshed modelling system used by DECCW NSW is the CIT model (McRae et al. 1992a, 1992b and 1992c) using the LCC chemical mechanism. This is used to both expand on observational information on days when elevated concentrations of ozone are observed, and to assess possible future air quality including the efficacy of proposed emission reduction strategies.

Australian Air Quality Forecasting System is a real-time air quality forecast system jointly developed by the Bureau of Meteorology and CSIRO (Cope et al. 1998 and 2005;). It uses a version of GRS embedded in a meteorological model such that the chemistry is integrated simultaneously with the meteorology. This computational approach reduces the time required for the overall task, and provides benefits for accuracy by eliminating the time averaging of meteorology parameters when the modules are run sequentially.

Appendix B: Measurement sites and current AAQ NEPM sites

Region	Site	Current AAQ NEPM sites for ozone
Sydney	Randwick	
	Kensington	
	Earlwood	
	Rozelle	✓
	Lindfield	
	Lidcombe/Chullora	✓
	Woolooware*	
	Liverpool	✓
	Bringelly	✓
	Oakdale	✓
	Bargo	
	Macarthur	✓
	St Marys	✓
	Richmond	✓
	Blacktown*	
	Vineyard	
	Westmead*	
	Kurrajong Heights	
	Wentworth Falls	
	Douglas Park	
	Appin	
Illawarra	Wollongong	✓
	Warrawong	
	Kembla Grange	✓
	Albion Park	✓
Lower Hunter	Newcastle	✓
	Wallsend	✓
	Beresfield	
Urban centre	Bathurst	✓

* Ceased operation in 2004

Appendix C: Observations – data availability (per cent valid hours)

Site name	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Sydney											
Appin		80.6	38.0	65.8	4.2						
Bargo			79.2	95.5	90.1	94.5	81.7	90.4	91.7	89.4	92.6
Blacktown	94.7	95.6	85.9	93.9	84.1	95.4	91.7	93.9	92.0	90.6	39.6*
Bringelly	96.5	94.9	94.5	94.0	74.7	92.4	95.2	91.8	93.2	91.5	91.4
Chullora										80.8	87.5
Douglas Park	30.7										
Earlwood	97.4	93.5	61.7	88.8	89.3	91.9	89.0	92.2	93.4	91.9	91.3
Kensington	74.9	23.4									
Kurrajong Heights							86.9	82.4	86.1	17.6	
Lidcombe	80.5	91.8	82.3	95.4	89.7	89.7	95.0	94.7	31.1		
Lindfield	57.8	94.1	94.7	95.9	88.5	90.0	87.8	94.4	93.3	85.7	85.3
Liverpool	97.2	95.9	95.4	88.8	93.3	83.8	93.6	95.0	93.8	93.5	92.5
Macarthur											16.3
Oakdale			60.8	89.8	54.6	89.8	90.4	34.9	18.6	91.3	85.8
Randwick	20.3	79.8	89.1	78.2	90.3	95.3	93.8	93.5	87.6	89.4	91.4
Richmond	94.8	86.4	91.8	79.6	91.3	92.3	90.0	91.0	92.7	86.3	89.8
Rozelle	90.8	83.8			72.7	90.1	88.0	93.7	88.3	91.4	89.1

St Marys	95.7	88.4	94.9	82.0	85.2	88.5	91.8	90.5	95.6	93.0	93.8
Vineyard	70.8	93.7	73.5	85.8	91.5	91.9	94.8	90.9	89.0	91.7	90.5
Wentworth Falls					60.8	52.0					
Westmead	96.4	89.9	88.8	89.6	91.1	84.2	79.4	78.5	82.8	85.7	56.9*
Woolooware	92.2	88.9	95.5	92.8	82.1	74.0	88.6	93.0	92.5	91.2	60.3*
Hunter											
Beresfield	87.4	94.3	72.6	86.3	81.9	95.1	92.6	90.8	91.4	86.4	87.5
Newcastle	92.9	68.9	88.6	92.3	94.9	92.3	88.6	93.6	94.3	92.6	92.6
Wallsend	96.5	84.6	92.1	77.0	86.8	83.5	90.7	88.2	82.2	91.8	88.4
Illawarra											
Albion Park	95.4	94.2	83.6	45.3							
Albion Park				41.1	90.2	90.7	90.2	93.9	57.7	93.1	93.8
Kembla Grange	96.7	93.0	95.3	89.9	87.4	91.3	94.2	82.5	92.0	93.6	91.6
Warrawong	93.5	94.9	91.3	90.2	90.5	89.0	94.6	95.7	94.4	93.2	91.9
Wollongong	93.0	59.9	94.6	90.9	87.2	88.0	94.3	94.3	90.9	93.0	92.8
Urban centre NSW											
Bathurst								50.6	34.8	76.6	90.2

* Ceased operation in 2004

Appendix D: Statistics definitions

Within this study, the following statistical measures have been used. The definitions are those of Tesche et al. (1990). In comparing observed concentrations with simulated concentrations, it has been standard practice to relax the conditions for matching in space and time. This is done to account for the significant sensitivity of the simulated photochemistry to meteorology fields. In this work the time relaxation is plus or minus one hour, and the spatial relaxation allows comparison to the four grid cells nearest the observation. Statistics are calculated using the relaxed criteria unless denoted otherwise.

In the definitions that follow, the following nomenclature is used: c is used to denote concentration, c_e being the estimated (simulated) concentration and c_o being the observed concentration; x denotes space; x_i being the location of the i^{th} monitoring station, x^m denotes matched in space; t denotes time, t^m denotes matched in time. Thus $c_e(x^m,t^m)$ denotes the simulated concentration matched to a particular place and time. A subscript *max* denotes maximum concentration.

The following statistics have been used:

Peak unpaired accuracy compares the maximum simulated concentration to the maximum observed concentration.

$$A_u = \frac{c_e(x,t)_{\max} - c_o(x_i,t)_{\max}}{c_o(x_i,t)_{\max}} \times 100$$

Overall bias indicates the average signed difference between the simulation and the observations at the N monitoring stations. It is normalised by the observed concentrations.

$$D^* = \frac{1}{N}\sum_{i=1}^{N}\frac{(c_e(x_i,t) - c_o(x_i,t))}{c_o(x_i,t)}$$

Gross error (normalised) measures the average difference between the simulated concentrations and all observations from the N monitoring stations where the concentration was greater than the chosen threshold value (60 ppb).

$$E_d^* = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|c_e(x_i,t) - c_o(x_i,t)\right|}{c_o(x_i,t)}$$

Average station peak estimation accuracy (per cent) describes how well the overall monitoring station maximum concentrations have been reproduced. This comparison is relaxed in time but matched in space.

$$\overline{A} = 100 \times \frac{1}{N}\sum_{i=1}^{N}\frac{\left|c_e(x_i^m,t) - c_o(x_i,t)\right|}{c_o(x_i,t)}$$

Gross error paired in time (normalised) measures the average difference between the simulated concentrations and the observed concentrations, where the simulated concentrations are constrained to match exactly in time.

$$E_d^{*m} = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|c_e(x_i,t^m) - c_o(x_i,t)\right|}{c_o(x_i,t)}$$

Appendix E: Emissions estimation – 2001 and 2026

Note that the emissions inventory presented here is that used to generate the emissions for the modelling work presented. This inventory was made in 2003 for base year 2001. Since then a new emissions inventory has been made (base year 2003) with a significant upgrade (base year 2008) due in 2010.

E1 Introduction

Emission inventories were developed for base year 2001 and projected year 2026 for the modelling domain shown in Figure E1. Extending from the Hunter Valley in the north to south of Goulburn, the modelling domain includes the major industrial and population centres of NSW. The Sydney sub-domain shown in Figure E1 is used for displaying results.

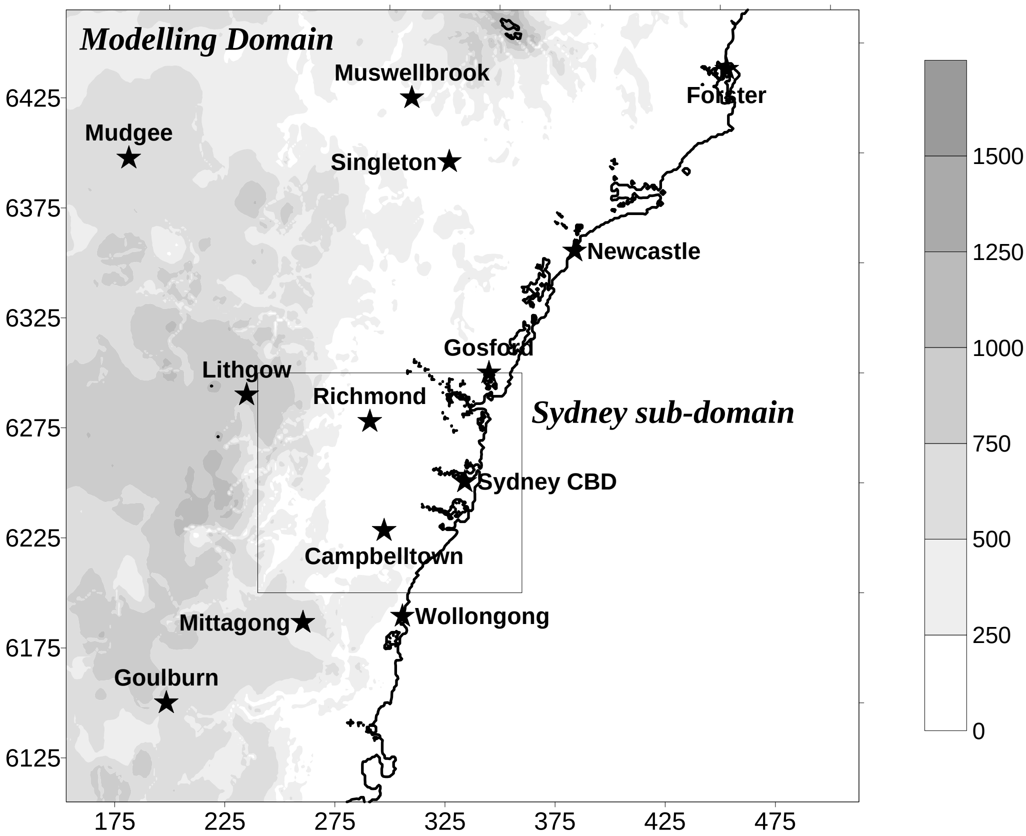


Figure E1: Modelling domain

Emission estimates were made using data provided by the Department of Infrastructure, Planning and Natural Resources (DIPNR).

To test the sensitivity of variation in land-use settings, three emission scenarios were incorporated into the 2026 inventories based on the different spatial distributions of forecast population growth (relative to 2001) over the modelling domain.

The three scenarios are:

Scenario A: 15% of the extra population will be distributed in the new fringe lands and 85% will be in infill areas, denoted (85/15)

Scenario B: 30% of the extra population will be distributed in the new fringe lands and 70% will be in infill areas, denoted (70/30)

Scenario C: 45% of the extra population will be distributed in the new fringe lands and 65% will be in infill areas, denoted (55/45).

However, the results of the simulations were so similar that only the 70/30 was used in this study. The distribution of the additional population for 2026 features two broad growing areas:

- new lands that have been proposed for release in south-west fringe areas (near Bringelly) and north-west fringe areas (near Box Hill)
- central urban infill niches.

DIPNR provided population and associated VKT forecasts for the two scenarios as data on a 1km * 1km grid system within the modelling domain. This data was used by the department's Atmospheric Science Section to generate estimates of emissions for two emissions categories based on these data: motor vehicles and commercial-domestic.

E1.1 Population growth scenarios

Total population numbers in the modelling domain and Sydney sub-domain are given in Table E1.

Table E1: DIPNR-forecast total population in the modelling domain and Sydney sub-domain

	Modelling domain		**Sydney sub-domain**	
	Population	**% growth cf 2001**	**Population**	**% growth cf 2001**
2001	4,845,345		3,890,248	
2026 (70/30)	6,294,225	*30*	5,000,791	*29*

As a reference point, the population spatial distribution pattern of 2001 for the Sydney sub-domain is shown in Figure E2. Figure E3 shows the differences in population between scenarios for 2026 and the base-case (2001).

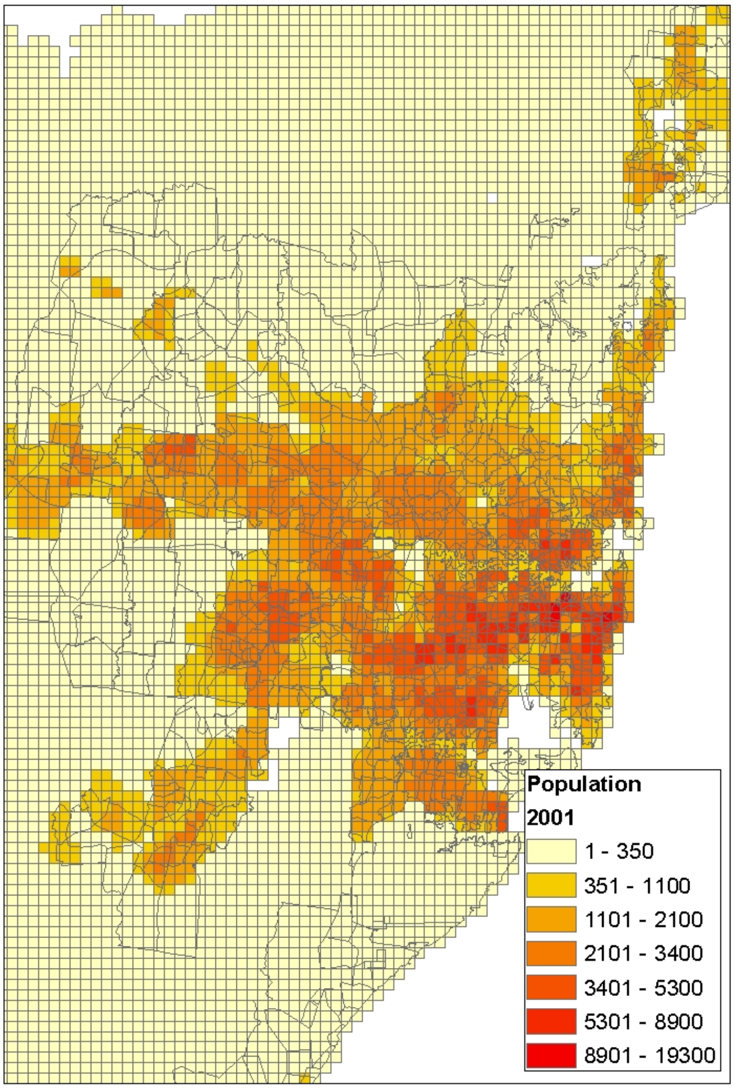


Figure E2: Population distribution in 2001, Sydney sub-domain

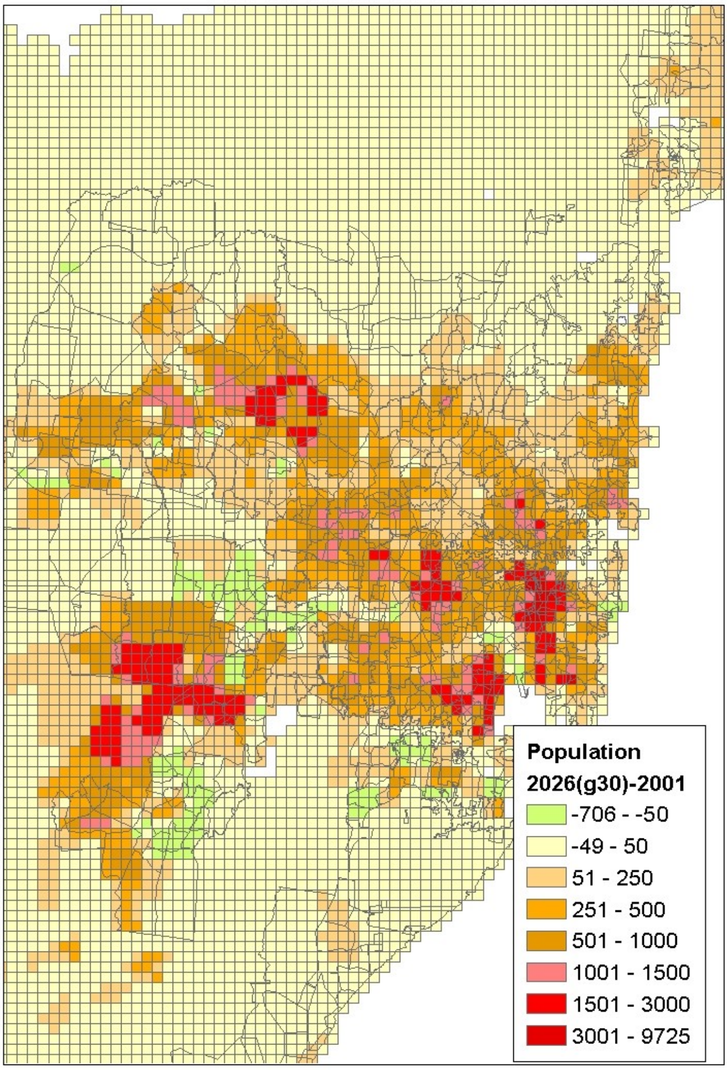


Figure E3: Difference in population from 2001 for scenario 2026 (70/30), Sydney sub-domain

E1.2 VKT data

DIPNR developed VKT (vehicle kilometres travelled) forecasts based on the population scenarios. The VKT data is broken down into five road types and nine vehicle types (Table E2) and developed hourly for a typical weekday.

To facilitate the DECCW modelling of the impact of congestion on emissions, DIPNR also produced a congestion indicator which is basically the VKT-weighted average speed of passenger cars for each grid cell. If the value of the indicator for a cell falls below a pre-determined threshold speed (currently 35 km/h), that cell is deemed to be congested. It has to be noted that while DIPNR modelling generated VKT forecasts for each hour of the day, the modelling of traffic speed was based on an aggregated time scheme, including only four daily periods, namely am (06:00–8:59) and pm peaks (16:00–17:59); mid-day business period (09:00–15:59); and off-business period (the remaining hours of day). Therefore, the congestion indicator that is derived from the traffic speed has to be based on the aggregated four daily periods. This aggregation artificially reduces the temporal variability of congestion and would probably impact on the sensitivity of emission modelling.

Table E2: Breakdowns of road and vehicle types

Road types: Arterial roads Highways/freeways Commercial arterial roads Commercial highways Local/resident roads
Vehicle types: Passenger cars in non-diesel fuels Passenger cars in diesel Light duty commercial vehicles in non-diesel fuels Light duty commercial vehicles in diesel Heavy duty commercial vehicles in non-diesel fuels Rigid trucks in diesel Articulated trucks in diesel Buses in diesel Motor cycles

The hourly profile of total VKT (combining all vehicle types) is shown in Figure E4. This profile, featuring a tall but narrow morning peak and a low but spreading afternoon peak, is common to the scenarios. Tables E3 and E4 provide the proportions of total daily VKT and its relative congestions for the different years.

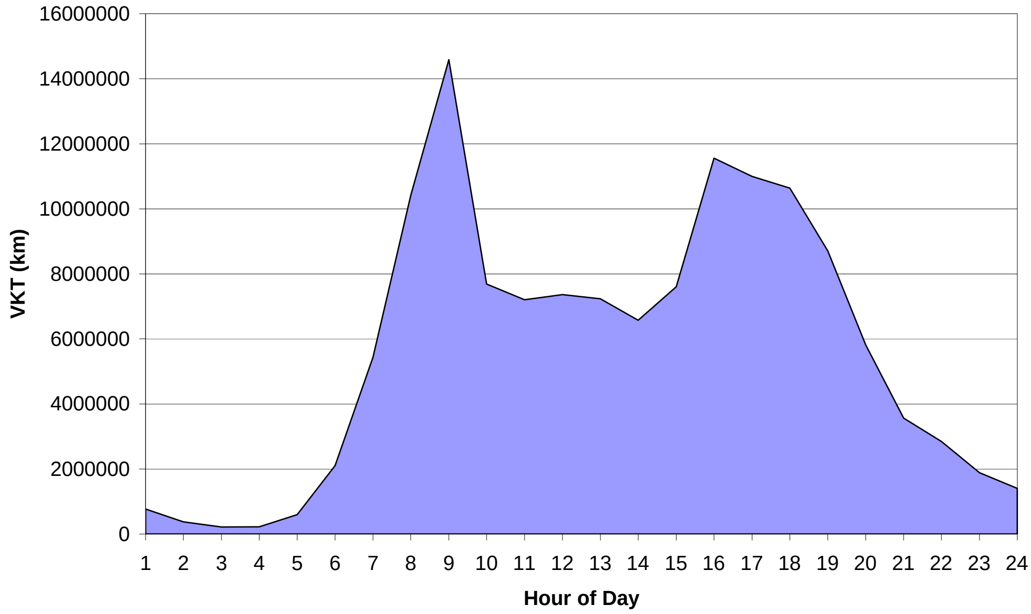


Figure E4: An example of hourly variation of VKT

Table E3: Total daily VKT in the modelling domain

	Scenario (70/30)
2001 ('000 km)	113,734
2026 ('000 km) **(% growth cf 2001)**	146,980 (29)

In general, daily VKT is predicted to increase by 29% in 2026, relative to 2001. However, the proportion of VKT in congestion does not appear to have any significant change over the 25-year period. The reason for the lack of sensitivity of congested VKT to the change of total VKT should be investigated and established, as this could be a source of uncertainty for emission modelling.

Table E4: Congested VKT as percentage of total VKT

Year	**Scenario (30% green field)**
2001	17.1%
2026	19.2%

E1.3 Spatial patterns of VKT

The VKT spatial distribution pattern for 2001 is shown in Figure E5. Figure E6 shows the difference in VKT between the 2026 scenario and 2001 base-case.

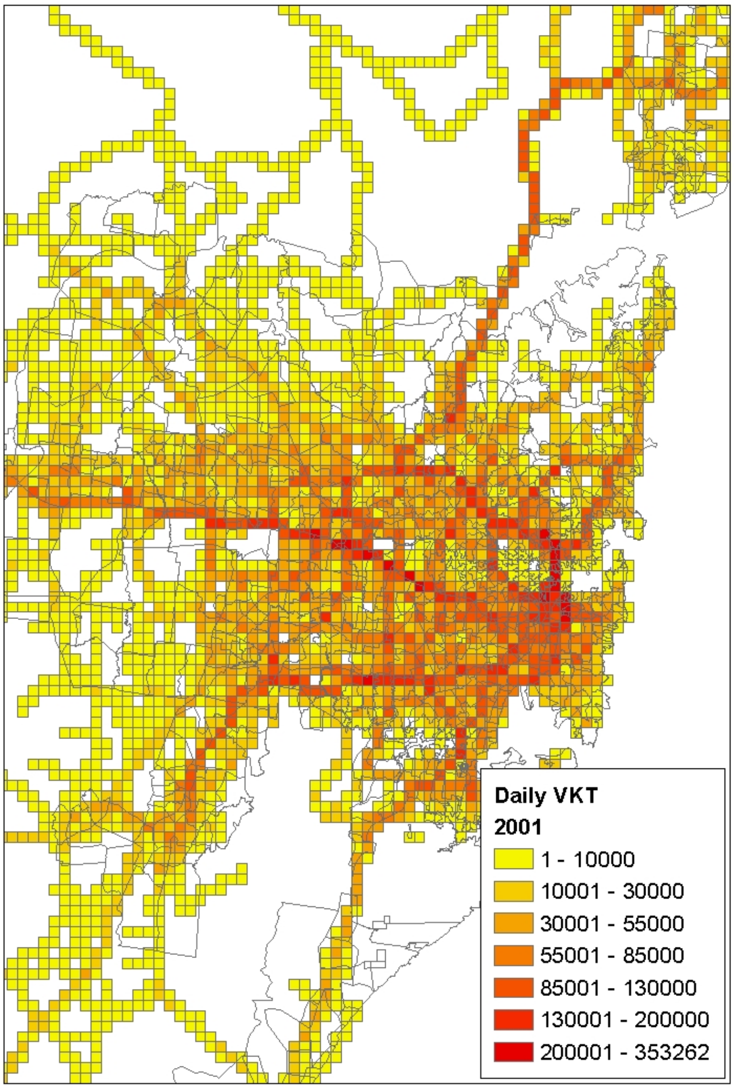


Figure E5: Spatial distribution of VKT in 2001, Sydney sub-domain

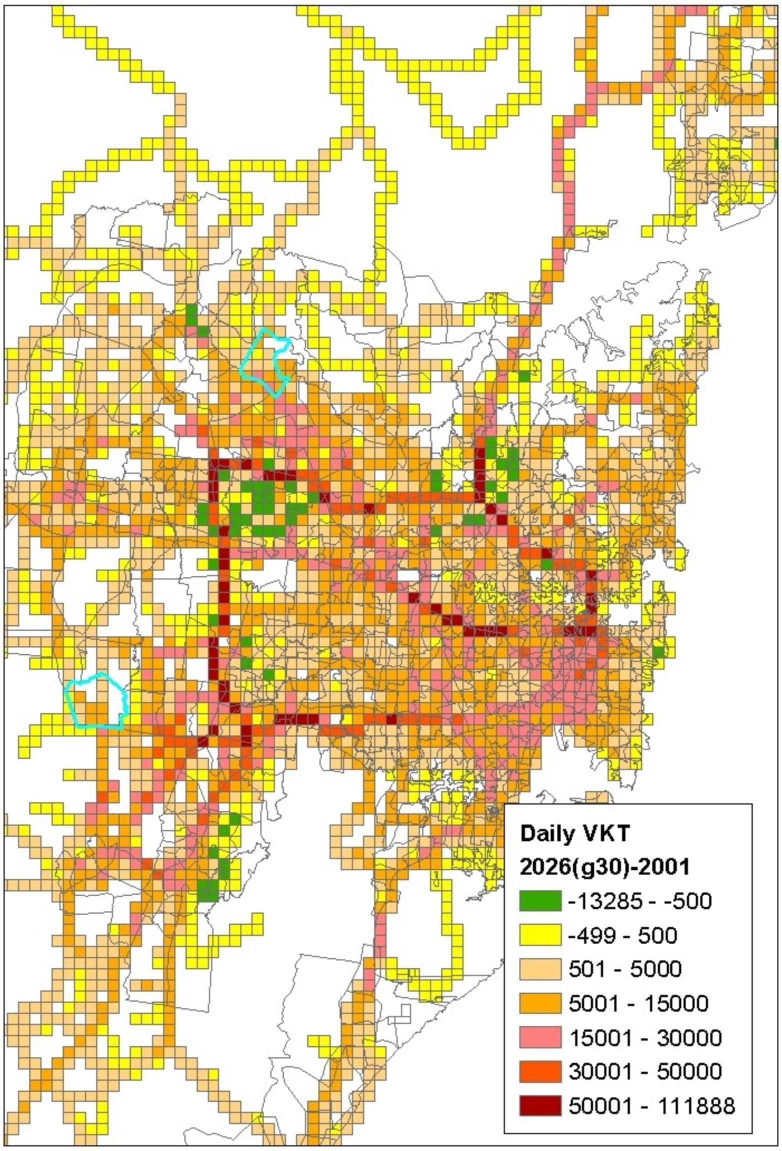


Figure E6: Change in VKT from 2001 for scenario 2026 (70/30), Sydney sub-domain

E2 Emissions modelling: motor vehicles

Emissions modelling was performed using VKT forecasts and congestion indicators provided by DIPNR, and composite emission factors developed by DECCW. The composite emission factors were generated from the motor vehicle emission projection system (MVEPS) and are a way of representing the motor vehicle fleet by a representative value. Emission factors are generated for each pollutant and is the quantity of emission for each vehicle kilometre travelled.

E2.1 General modelling approach

The general approach is illustrated in Figure E7.

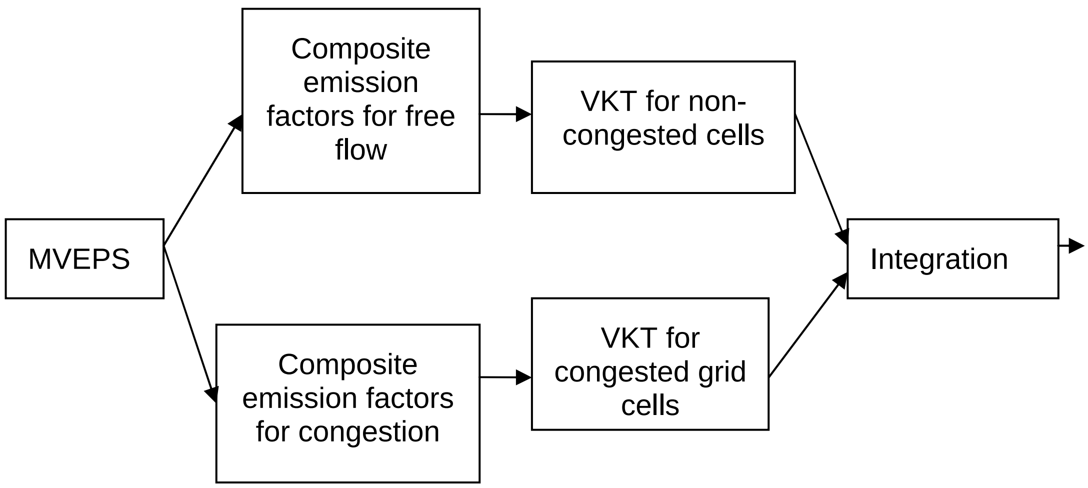


Figure E7: General modelling approach

Composite emission factors combine vehicles of different ages based on fleet age profiles, taking into account emission deterioration and reduction in average distance travelled as vehicles age. In producing the composite emission factors, MVEPS takes into account new emission and fuel standards which will be discussed in detail below. For a particular calendar year of interest, base emission factors are integrated using fleet composition profiles to generate composite emission factors. Adjusting processes are then applied to produce emission factors representing specific driving condition and fuel quality.

Two sets of composite emission factors were produced by MVEPS, one for free-flow and one for congested conditions. Each set contains composite emission factors for the nine types of vehicles in the five road categories. Pollutants involved are exhaust VOCs (from exhaust pipes), NO_X, CO, evaporative VOC (from fuelling systems), TSP and SO_2. The total emissions from a grid cell at a given hour are thus the sum of the products of hourly VKT and matching composite emission factors for each vehicle and road type pairing, for congestion and free flow conditions.

Evaporative emissions were adjusted against the diurnal changes in ambient temperature.

E2.2 Emissions test data

The development of MVEPS emission factors were partly based on emission test data collected under Australian conditions, including:

- historical data developed by the NSW EPA and Victorian EPA motor vehicle laboratories, which were used for MAQS inventory development
- National In-Service Emission Study (NISE) data
- datasets developed by NSW EPA lab for dynamometer calibration

- Cycle Comparative Study data developed by Ford Australia lab under the sponsorship of the Australian Government
- Diesel NEPM Preparatory Project 2 data developed by Parsons Australia
- Diesel NEPM Preparatory Project 7 data developed by Parsons Australia.

E2.3 Emissions modelling assumptions

Major modelling assumptions were made in relation to existing and future motor vehicle emission standards proclaimed as Australian Design Rules (ADRs). Table E5 provides a brief summary of the relevant emission ADRs used in this projection to 2026.

Table E5: A brief summary of Australian motor vehicle emission standards

Standard	Main date in place[1]	Main vehicles applied[2]	Emission limits[3]				Main test cycles
			HC	NO_x	CO	PM	
ADR27C	1982	Petrol cars	1.91 g/km	1.73 g/km	22 g/km	NA	US FTP72
ADR37/00	1986	Petrol cars	0.93 g/km	1.93 g/km	9.3 g/km	NA	US FTP75
ADR70	1996	Diesel heavy duty	1.1 g/kWh	8.0 g/kWh	4.5 g/kWh	0.61 g/kWh	ECE R-49 / US13-mode
ADR37/01	1999	Petrol cars	0.26 g/km	0.63 g/km	2.1 g/km	NA	US FTP75
ADR80/00 (Euro III)	2003	Heavy duty	0.78 g/kWh[5]	5.0 g/kWh	5.45 g/kWh[5]	0.16 g/kWh	ESC+ETC
ADR79/00 (Euro II)	2004	Petrol cars	0.25 g/km[6]		2.2 g/km	NA	ECE+EUDC
ADR79/00 (Euro II)	2004	Diesel cars	0.7 g/km[6]		1.0 g/km	0.08 g/km	ECE+EUDC
ADR79/00 (Euro II)	2004	Petrol light commercial[7]	0.5 g/km[6]		4.0 g/km	NA	ECE+EUDC
ADR79/00 (Euro II)	2004	Diesel light commercial[7]	1.0 g/km[6]		1.25 g/km	0.12 g/km	ECE+EUDC
ADR79/01 (Euro III)	2006	Petrol cars	0.2 g/km	0.15 g/km	2.3 g/km	NA	ECE+EUDC[4]
ADR79/01 (Euro III)	2006	Diesel cars	0.06 g/km[8]	0.5 g/km	0.64 g/km	0.05 g/km	ECE+EUDC[4]
ADR79/01 (Euro III)	2006	Petrol light commercial[7]	0.25 g/km	0.18 g/km	4.17 g/km	NA	ECE+EUDC[4]
ADR79/01 (Euro III)	2006	Diesel light commercial[7]	0.07 g/km[8]	0.65 g/km	0.8 g/km	0.07 g/km	ECE+EUDC[4]
ADR80/01 (Euro IV)	2007	Heavy duty	0.55 g/kWh[5]	3.5 g/kWh[5]	4.0 g/kWh[5]	0.03 g/kWh[5]	ESC+ETC
Euro IV	2009?	Petrol cars	0.1 g/km	0.08 g/km	1.0 g/km	NA	ECE+EUDC

Standard	Main date in place[1]	Main vehicles applied[2]	Emission limits[3]				Main test cycles
			HC	NO_x	CO	PM	
Euro IV	2009?	Diesel cars	0.05 g/km[8]	0.25 g/km	0.5 g/km	0.025 g/km	ECE+EUDC
Euro IV	2009?	Petrol light commercial	0.1 g/km	0.08 g/km	1.0 g/km	NA	ECE+EUDC
Euro IV	2009?	Diesel light commercial	0.06 g/km[8]	0.33 g/km	0.63 g/km	0.04 g/km	ECE+EUDC
Euro V	2010?	Heavy duty	0.55 g/kWh[5]	2.0 g/kWh[5]	4.0 g/kWh[5]	0.03 g/kWh[5]	ESC+ETC

1 The date is mainly for all types of vehicles. For new type approval, the date is usually one year in advance.

2 Only general vehicle groups are stated. There are detailed categorisations in the ADRs.

3 The units of emission limits are g/km for cars and g/bhp or g/kWh for heavy duty vehicles. They are not directly comparable.

4 Modified by deleting 40 secs idle before testing

5 Based on ETC

6 Only specified as VOCs and NO_x combined

7 Only limits for middle range LCVs (1250–1700 kg RM) are listed in the table.

8 Due to the lack of individually specified HC limit, the limit in the table is calculated as the combined NO+HC limit minus the specified NO_x limit.

Emissions projection to 2026 assumed that Euro IV (light duty vehicles) and Euro V (heavy duty vehicles) would be in place from 2009 and 2010, respectively.

For the other emission standards, it was assumed that:

- Euro II and III for light duty vehicles would be in place from 2004 and 2006, respectively.
- Euro III and IV for heavy duty vehicles would be in place from 2003 and 2007, respectively.
- Diesel sulfur content (affecting diesel vehicle particulate emissions and SO_2 emissions) would be reduced from the 2001 value of 1500 ppm to 50 ppm in 2006.
- Summer petrol volatility (mainly affecting evaporative VOC emissions) would remain unchanged (relative to the base-case) at 62 kPa.

To support and supplement these major assumptions, more specific assumptions were used as follows.

For passenger cars:

- Changes in emission testing procedures from current standards to Euro II, and from Euro II to Euro III, would affect emission estimates. This effect was quantified by modification factors derived from available emission data.
- The emission levels of CO, VOCs and NO_x for a new car are initially about 50% of the relevant emission limits under Euro II and III standards.
- Emission data shows newer vehicles have less deterioration in CO emissions as they age. This trend of reduced deterioration was continued for Euro II (2004) and Euro III (2006).
- The increase in NO_x emissions with age was the same for Euro II as for pre-Euro. A slightly slower increase with age was used for Euro III.
- Alternative fuels (LPG and CNG) were assumed to be insignificant in market share and were not taken into account.
- Emission reduction for Euro IV was proportional to the reduction in the emission limit.

Emission test data was not available for petrol light duty commercial vehicles. However, most of them were unregulated for emissions, which led to the assumption that the then emission levels of these vehicles were very high – close to the uncontrolled level of passenger cars. The adoption of Euro II (2004) brought them under regulation for the first time. A significant reduction was therefore expected after Euro II came into force.

It was assumed that:

- under Euro II, new vehicle emission levels of NO_x were about 90% of the emission limit while keeping deterioration unchanged (note that even under this assumption a huge reduction was achieved relative to the high pre-Euro level) – Under Euro III, it was assumed that the new vehicle level would be 50% of the limit, and deterioration half of Euro II.
- new vehicle emission rates for CO and VOCs under Euro II and Euro III were estimated as a proportion of the limit using the same proportion as for NO_x
- emission reduction for Euro IV was proportional to the reduction in the emission limit.

For diesel vehicles:

- Emission deterioration is insignificant and was ignored.
- Emissions factors for light duty diesel vehicles in the current fleet were developed from in-service emission data presented in preparatory reports to the diesel NEPM (EPHC 1999, available at www.ephc.gov.au/taxonomy/term/70). No deterioration was assumed due to limitation of the data.

- Emission performance of the heavy diesel fleet was somewhat better than legally required due to vehicles meeting limits in their country of origin. Specifically, 50% of heavy-duty diesel vehicles met Euro II in 1997 and 20% of vehicles met Euro III in 2001.
- SO_2 emissions were proportional to fuel sulfur content and were otherwise not affected by changes in emission and fuel standards.
- Only the NO_x emission limit was tightened in Euro V relative to Euro IV. It was therefore assumed that only NO_x emissions would further reduce under Euro V and the magnitude of the reduction was proportional to the reduction in emission limits.

E2.4 Emissions output

MVEPS produces hourly emissions each day for each grid cell within the domain. Estimates for total emissions for a high oxidant day for the modelling domain and the Sydney region are presented in Tables E6 and E7, respectively. VOC emissions are the sum of exhaust and evaporative emissions in the table.

For 2026, VOC, NO_x, CO and TSP emissions for the modelling domain will have been reduced roughly by 43%, 54%, 84% and 57%, respectively, relative to 2001. For the Sydney region, the reductions are 44% for VOCs, 55% for NO_x, 85% for CO and 56% for TSP.

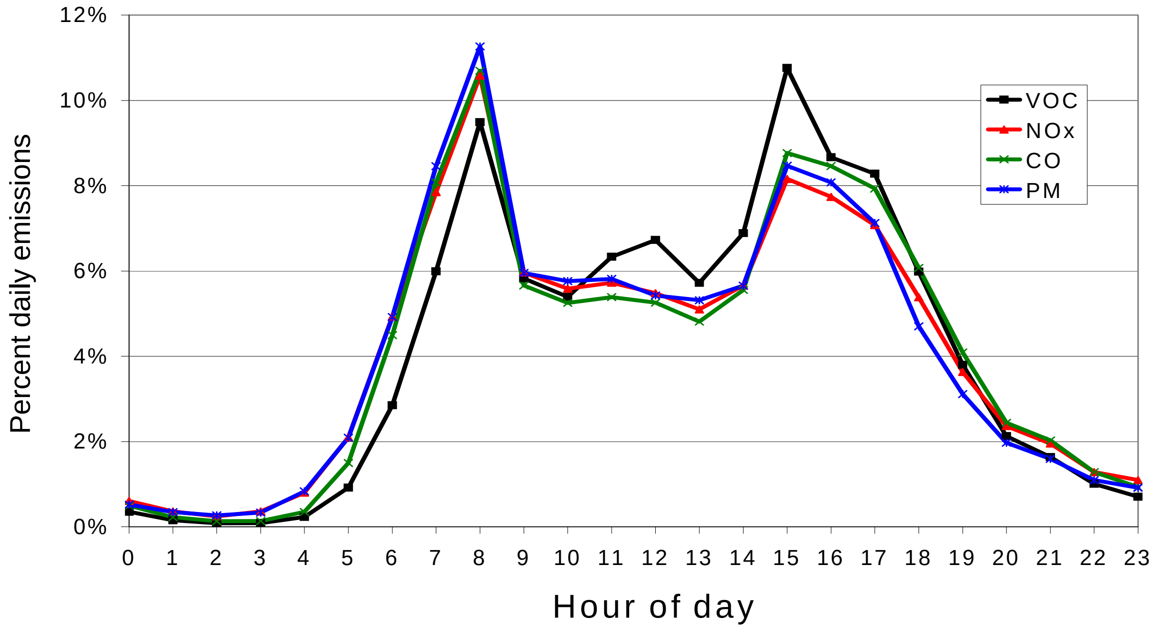
Table E6: Total emissions from motor vehicles in the modelling domain for a high oxidant weekday (tonnes/day)

		Scenario (70/30)
VOCs	2001	199.0
	2026	114.3
NO_x	2001	216.0
	2026	98.7
CO	2001	1137.2
	2026	178.4
TSP	2001	10.2
	2026	4.4
SO_2	2001	7.4
	2026	3.2

Table E7: Total emissions from motor vehicles in the Sydney region for a high oxidant weekday (tonnes/day)

		Scenario (30% green field)
VOCs	2001	150.4
	2026	84.6
NO_x	2001	156.8
	2026	70.4
CO	2001	852.0
	2026	129.1
TSP	2001	7.5
	2026	3.3
SO_2	2001	5.2
	2026	2.4

These daily totals are assigned to the hours of the day using a diurnal profile for each pollutant. Diurnal variations of VOCs, NO_x, CO and TSP for 2001 (base-case) are shown in Figure E8. The 2026 scenario has a very similar temporal pattern to that of 2001 and is not separately presented.



Depicted as percentages of total daily emissions

Figure E8: Diurnal variations of emissions, 2001 base-case

Figure E8 shows that the diurnal profile of NO_x, CO and TSP roughly follows that of VKT, featuring a sharp morning peak and a flatter afternoon peak. However, the VOC profile is different: the afternoon peak is higher than the morning peak as a result of combining the temporal profiles of exhaust and evaporative VOC emissions. Evaporative emissions in the afternoon are much higher than in the morning as they strongly depend on temperature, which is considerably higher in the afternoon.

Table E6 shows that the effect of the land-use scenarios on emissions is significantly reflected in the spatial patterns of emissions. The spatial pattern of differences in daily VOC emissions between 2026 land use and 2001 base-case are presented in Figure E9. Figure E10 shows these plots for NO_x.

It can be seen from Figures E9 and E10 that:

- While the regional total emissions of VOCs and NO_x have reduced dramatically in 2026 relative to 2001 (as reflected by the green dominance in the map), there are restricted areas in the region still experiencing increase in emissions relative to 2001 (represented by the orange areas on the map).
- All the areas of emission increase are within, or adjacent to, the north-west and south-west development zones.
- In general, there are more extensive areas showing emission increase relative to 2001 for VOCs than for NO_x.

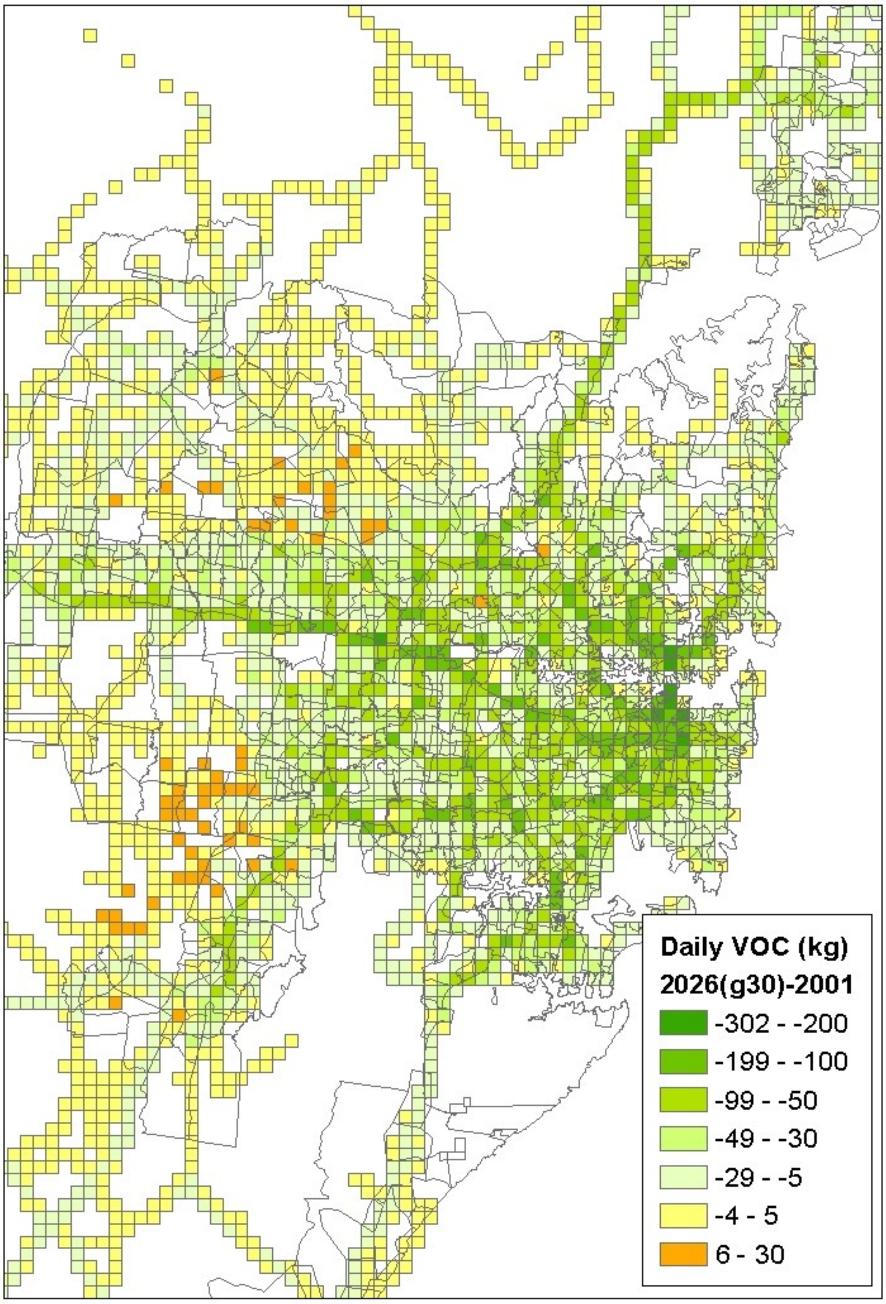


Figure E9: Difference in VOC emissions between 2026 scenario and the 2001 base-case

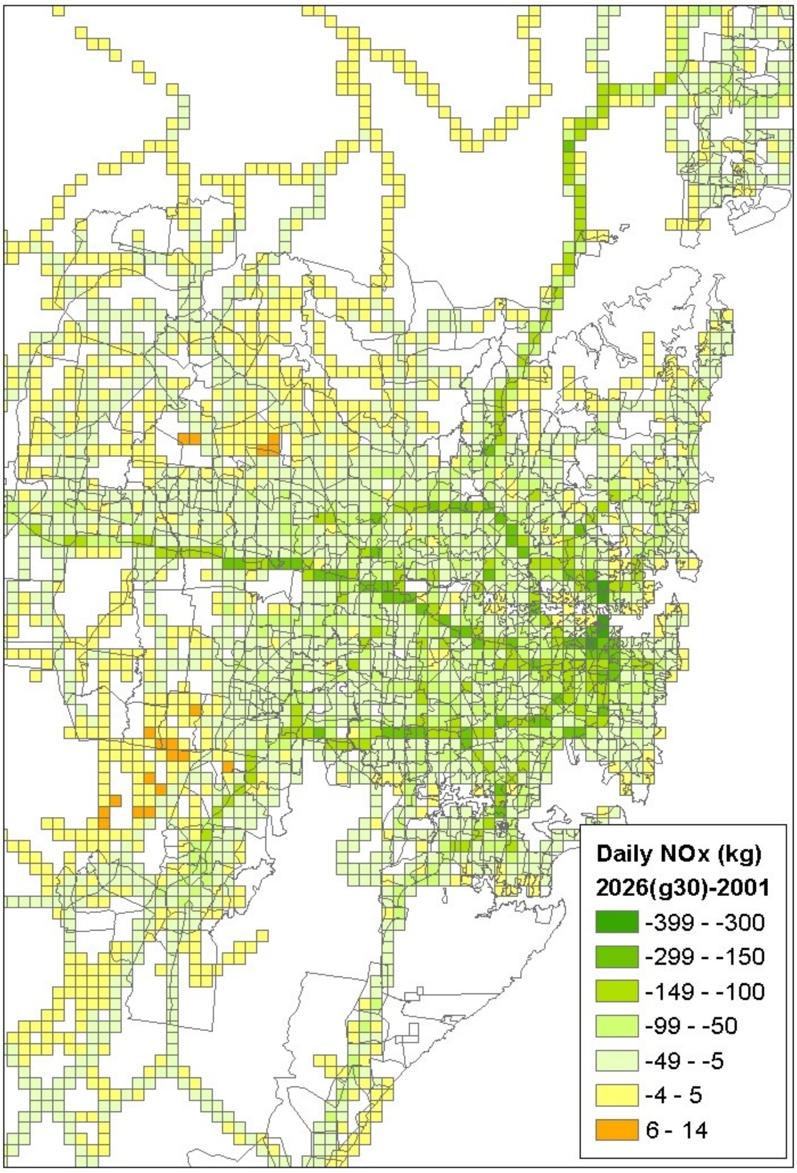


Figure E10: Difference in NO_x emissions between 2026 scenario and the 2001 base-case

E3 Emission estimates for other source categories

In addition to the estimates of motor vehicle emissions, estimates were also needed for commercial-domestic sources, industry sources and biogenic sources. The project primarily focuses on the impact of the proposed increase in population and possible variations in the distribution of the population. In order to evaluate differences between 2026 and the 2001 base-case, industrial and biogenic sources are kept the same for the base-case and 2026.

Eleven categories of commercial-domestic sources were defined in the inventory: aerosol usage; bitumen; dry cleaning; gas combustion; lawn mowing; gas leakage; petrol station losses; surface coatings; wood burning; miscellaneous; and unaccounted. The miscellaneous category captures non-aerosol products and domestic waste combustion, while the unaccounted category captures commercial emissions not included in other categories. Emissions for these sources are estimated based on population, thus the total population determines the total emissions within the domain.

These domain-total emissions were assigned to each grid-cell hour using the population distribution and specific diurnal profiles. Further details on the emissions inventory can be found in Carnovale et al. (1997).

The change in population, represented by the urban development scenario, generated a commensurate change in commercial-domestic sources. Table E8 shows emissions for the base-case and the 2026 scenario.

Table E8: Sydney region commercial-domestic emissions for 2001 and 2026 scenario

	Population	Commercial-domestic NO_x (kg)	Commercial-domestic VOC (kg)
2001 (base-case)	3,866,808	16,346	139,198
2026 (70/30) % change from 2001	4,974,085 +29	21,000 +29	179,393 +29

The inventory used industrial emissions for the year 1992 as developed within MAQS (Carnovale et al. 1997). Biogenic emissions for 2001 were used for the base-case and the 2026 urban development scenario (CSIRO Energy Technology 2002).

Appendix F: Future projections – significance of population distribution assumption

F1 Scenario development

Three emission scenarios for the year 2026 were developed using data provided by DIPNR. Three datasets were provided, reflecting three assumptions for accommodating population growth. Each dataset contained spatially resolved population and associated VKT. These datasets were used only for the commercial-domestic and vehicle emission source categories. Industrial and biogenic emissions are the same as the base-case for these scenarios.

The proposed development of western Sydney is described for the year 2026. The population of the modelling domain in 2001 is 4.84 million. This is projected to rise to 6.29 million by 2026, an increase of 30% (DIPNR, pers. comm.). On the defined Sydney sub-region, the population is 3.87 million in 2001 and 4.97 million in 2026, an increase of 29% from 2001.

The increase in population is spread between existing developed areas (infill) and proposed new developments (greenfield). Three scenarios were developed: 70% infill, 30% greenfield denoted (70/30); 55% infill, 45% greenfield denoted (55/45); and 85% infill; 15% greenfield denoted (85/15).

Population for the three scenarios is summarised in Table F1.

Table F1: Population for the six scenarios

	Modelling domain	**Sydney sub-domain**	
			Diff from 2001
2001	4,845,345	3,890,248	
2026 (70/30)	6,294,225	5,000,791	1,110,543
2026 (55/45)	6,294,115	4,989,269	1,099,021
2026 (85/15)	6,294,245	5,000,129	1,109,881

Minor rounding artefacts result in slightly differing total populations among the three scenarios for the modelling domain. On the Sydney sub-domain, however, there are greater differences in population between the scenarios as it excludes some greenfield areas.

Figure F1 shows the population distribution for 2001 (top-left), and the change in population for each of the scenarios 2026 (70/30) (top-right); scenario 2026 (55/45) (bottom-left); and scenario 2026 (85/15) (bottom-right) as a difference from the 2001 base-case.

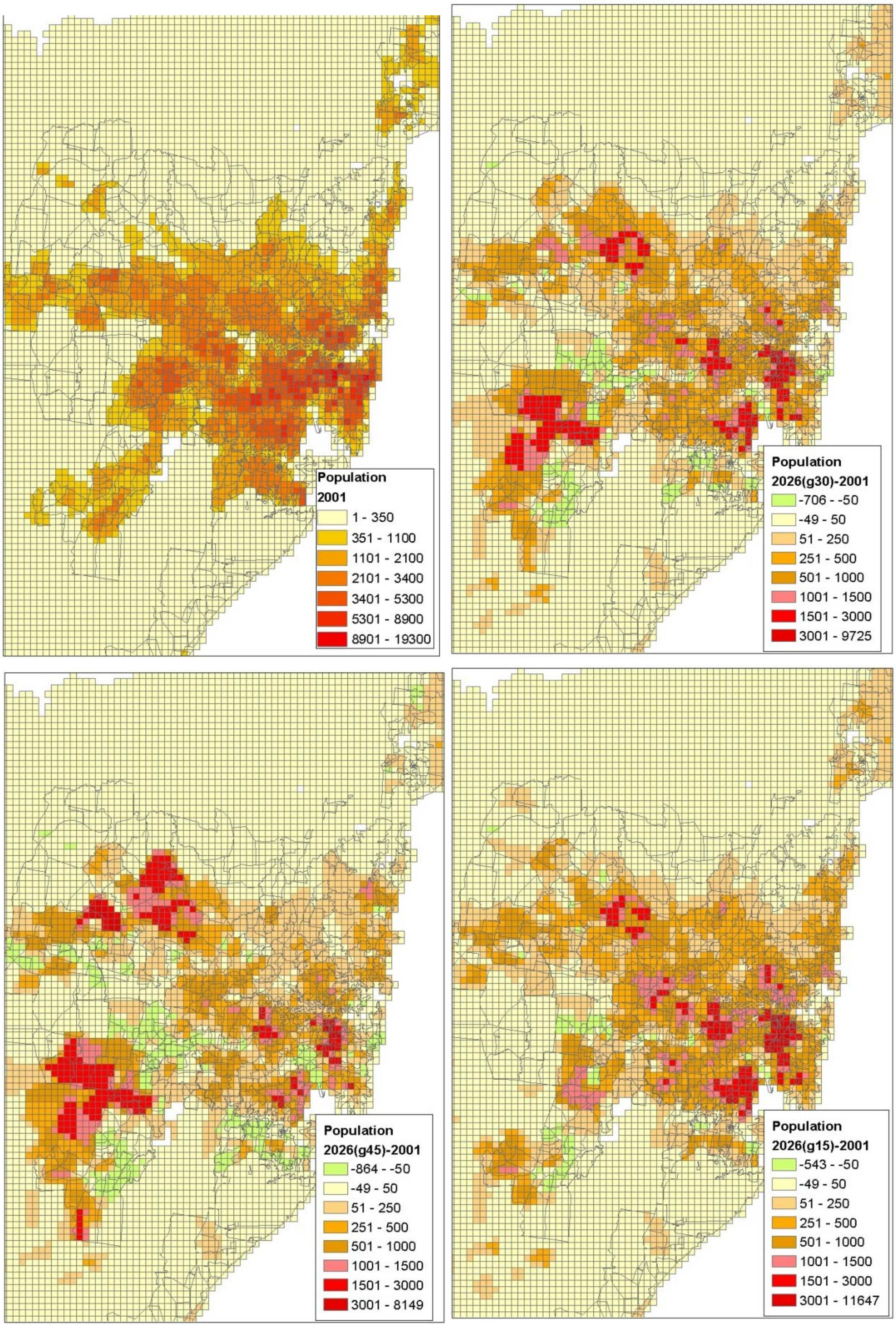


Figure F1: Population for the base-case and three 2026 scenarios

Emissions in the Sydney region for the three scenarios are shown in Tables F2 and F3, for NO_x and VOCs, respectively. Note that as the scenarios have differing spatial distributions of population increase, they will also have differing spatial distributions of emissions.

Mobile sources and commercial-domestic emissions predominate in the Sydney region. Combined, these two categories contributed 82% of anthropogenic NO_x and 85% of VOCs in 2001.

In broad terms, the assumptions used to derive these estimates were:

- motor vehicle emissions include both currently mandated vehicle emission standards and proposed standards from Euro IV and Euro V
- commercial-domestic sources increase in proportion to population increase
- industrial emissions are held constant
- biogenic emissions are held constant.

Table F2: Sydney region anthropogenic NO_x emissions on a high oxidant day for three growth scenarios

	Population	Motor vehicles		Commercial-domestic		Industrial	Total	
		kg/day	% change	kg/day	% change	kg/day	kg/day	% change from 2001
2001 (% of total)	3,890,248	156,777 (74)		16,346 (8)		39,000 (18)	21,2123	
2026 (70/30) (% of total)	5,000,791	70,394 (54)	–55	21,000 (16)	+29	39,000 (30)	130,394	**–39**
2026 (55/45) (% of total)	4,989,569	71,954 (55)	–54	20,949 (16)	+28	39,000 (30)	131,903	**–38**
2026 (85/15) (% of total)	5,000,129	69,472 (54)	–56	20,997 (16)	+28	39,000 (30)	129,469	**–39**

Table F3: Sydney region anthropogenic VOC emissions on a high oxidant day for six growth scenarios

	Population	Motor vehicles		Commercial-domestic		Industrial	Total	
		kg/day	% change	kg/day	% change	kg/day	kg/day	% change from 2001
2001 (% of total)	3,866,808	150,431 (44)		139,200 (41)		50,000 (16)	339,631	
2026 (70/30) (% of total)	4,974,086	84,555 (27)	–44	179,393 (57)	+29	50,000 (16)	313,948	**–8**
2026 (55/45) (% of total)	4,963,706	87,148 (28)	–42	178,977 (57)	+29	50,000 (16)	316,125	**–7**
2026 (85/15) (% of total)	4,972,188	82,989 (27)	–45	179,380 (57)	+29	50,000 (16)	312,369	**–8**

Implementation of mandated and proposed motor vehicle emission controls significantly reduces the emissions for this source. NO_x emissions fall 54–56%, about 40% of total anthropogenic emissions. This is offset a little by an increase from commercial-domestic (2% of total) resulting in an overall decrease of 38–39%. For VOCs, the 42–45% reduction in the mobile source category (about 19% of total) is offset by the 29% increase from the commercial-domestic sector (about 12% of total), resulting in an overall reduction of 7–8%.

Table F4 summarises Sydney Basin emissions for the base-case and the three scenarios.

Table F4: Sydney region emissions for three growth scenarios for a high oxidant day

		Anthropogenic NO_x	Anthropogenic VOCs
	Population	kg/day	kg/day
2001 (base-case)	389,0248	212,123	339,631
2016 (70/30) % change from base	4,614,951 +19	176,160 –17	308,317 –9
2016 (55/45) % change from base	4,590,587 +18	176,316 –17	307,779 –9
2016 (85/15) % change from base	4,633,154 +19	175,768 –17	308,441 –9
2026 (70/30) % change from base	5,000,791 +29	130,394 –39	313,948 –8
2026 (55/45) % change from base	4,989,269 +28	131,903 –38	316,125 –7
2026 (85/15) % change from base	5,000,129 +29	129,469 –39	312,369 –8

For each ozone event, the three scenario simulations for 2026 are compared to the base-case for the day and the other scenario simulations for that year.

F2 Results

Three emission scenarios have been run for three ozone events: 20 December 2000; 12 January 2001; and 22 January 2001.

F2.1 20 December 2000

Model simulation of the maximum one-hour ozone concentration for the base-case is presented in Figure F2a. Figures F2b–d present, in order, Scenario 2026 (70/30); Scenario 2026 (55/45) and Scenario 2026 (85/15). Table F5 summarises maximum ozone concentration and the area where maximum concentration exceeded the goals.

The figures and table show that for this event the differences among the scenarios are small. The differences in maximum ozone concentration among the scenarios are less than two per cent while the number of grid cells exceeding a standard varies by less than 20%.

Table F5: Simulated maximum ozone concentrations and number of grid cells exceeding the AAQ NEPM standards, 20 December 2000

	One-hour max ozone (ppb)	One-hour area (# grid cells)	Four-hour max ozone (ppb)	Four-hour area (# grid cells)
Base-case	110	186	94	371
Scenario 2026 (70/30) % change from base	96 –13	0 –100	84 –11	59 –84
Scenario 2026 (55/45) % change from base	97 –12	0 –100	84 –11	67 –82
Scenario 2026 (85/15) % change from base	95 –13	0 –100	84 –11	54 –85

Differences between scenarios and the base-case are larger. One-hour maximum ozone differs by up to 13% and the number of grid cells exceeding the standard differs markedly between the base-case and the scenarios. The large reduction in ozone concentration in the 2026 scenarios generates a very marked reduction, with no scenario showing an exceedence of the one-hour standard, and the number of grid cells exceeding the four-hour standard reduced to about 15% of that in the base-case. This very marked response to modest changes in concentration arises from the relatively large area simulated to have maximum ozone concentrations just greater than the standard. For these areas, only small reductions in ozone concentration are needed to reduce concentrations below the standard.

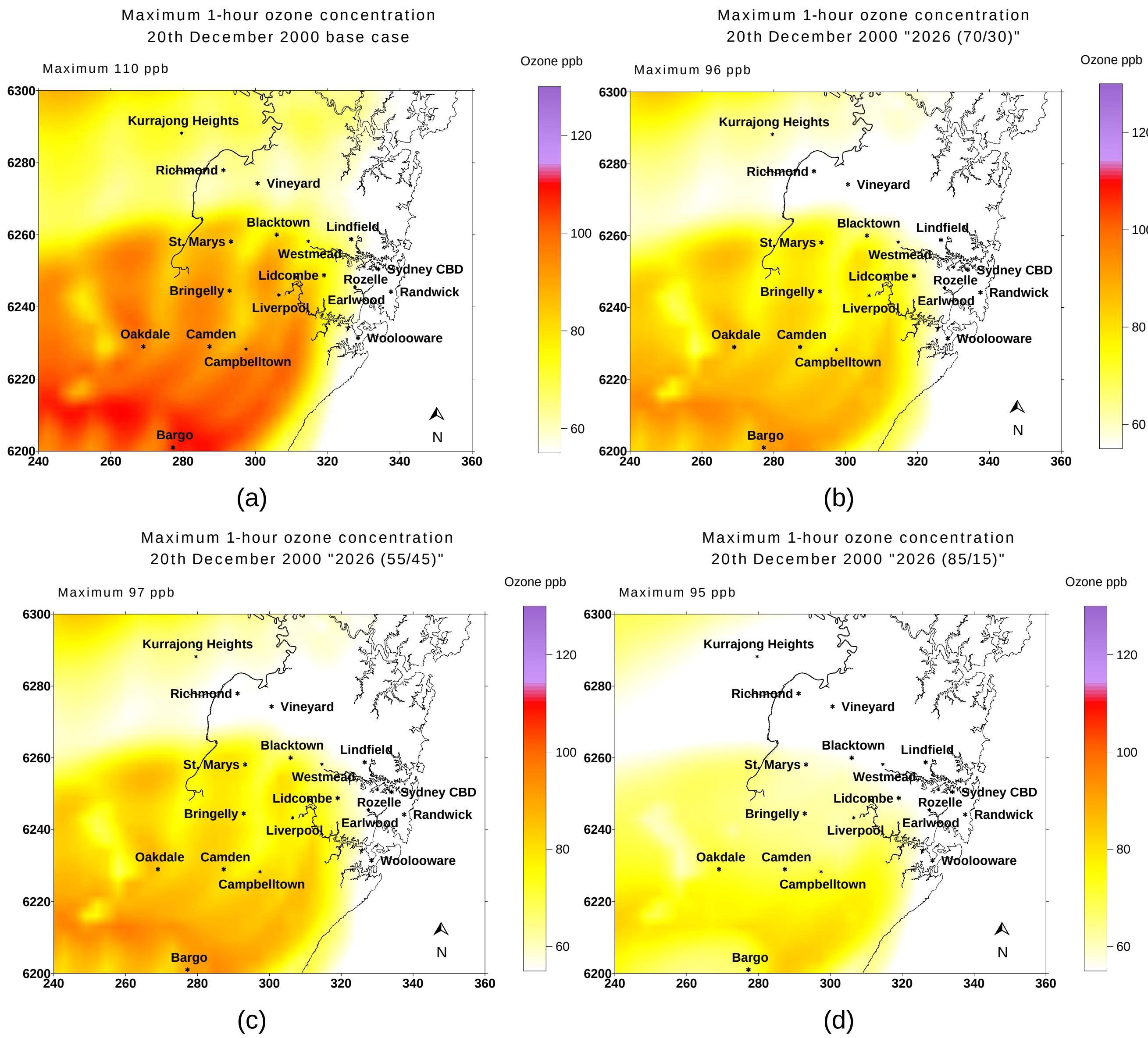


Figure F2: Simulated maximum one-hour ozone concentrations, 20 December 2000

(a) Base-case (b) Scenario 2026 (70/30) (c) Scenario 2026 (55/45) (d) Scenario 2026 (85/15)

The differences between scenarios are explored further in Figure F3, which shows the percentage change in maximum one-hour ozone concentration from the base-case for the Sydney sub-domain for each scenario. All three 2026 scenarios have very similar plots with a very large area of the domain showing moderate reductions in ozone concentration, and a small area showing an increase. Note that this area of increase occurs where ozone concentrations are simulated to be well below the standard.

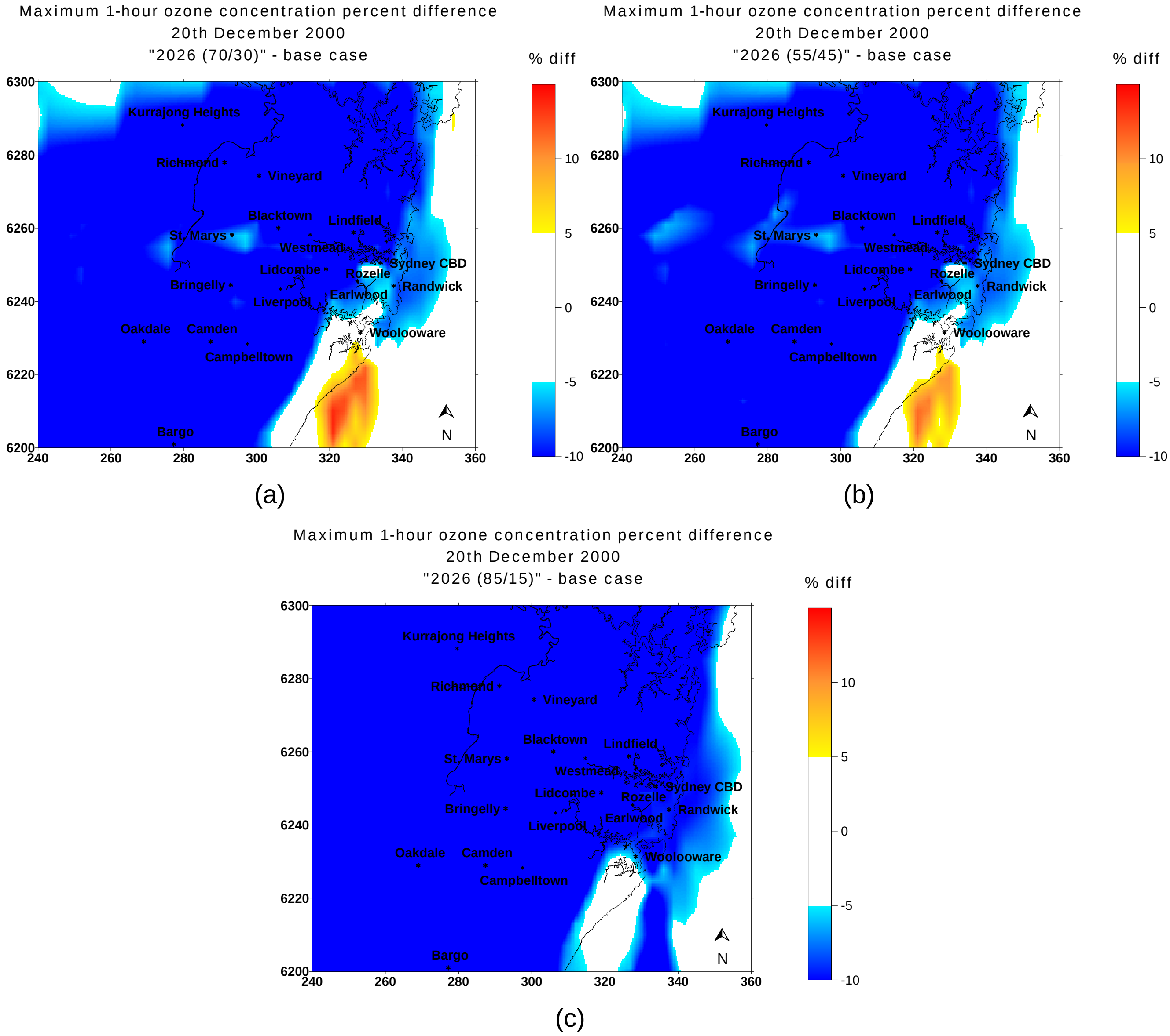


Figure F3: Percentage difference in simulated maximum one-hour ozone concentrations, 20 December 2000[1]

(a) Scenario 2026 (70/30) – base-case (b) Scenario 2026 (55/45) – base-case (c) Scenario 2026 (85/15) – base-case

1 Note that plotting differences may show artefacts due to the time resolution in the model output.

F2.2 12 January 2001

Model simulation of the maximum one-hour ozone concentration for the base-case is presented in Figure F4a. This shows a maximum ozone concentration of 137 ppb, with the elevated plume spread across the central and south-western areas of the Sydney Basin. About 16% of the basin had maximum ozone concentrations greater than the AAQ NEPM one-hour standard.

Figure F4a–d presents, in order, base-case, Scenario 2026 (70/30), Scenario 2026 (55/45) and Scenario 2026 (85/15). Table F6 summarises maximum ozone concentration and the area for which maximum concentration exceeded the goals.

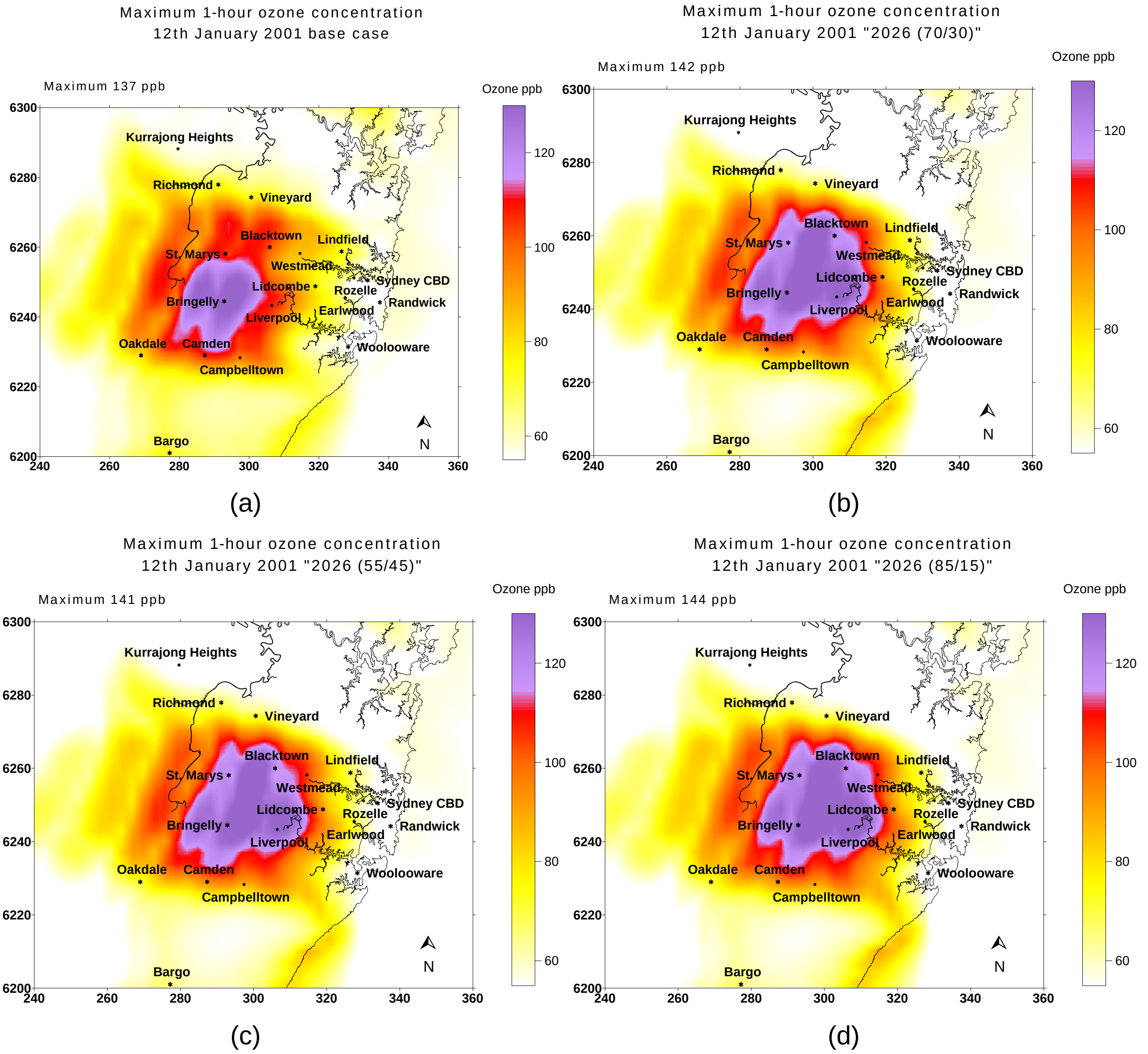


Figure F4: Simulated maximum one-hour ozone concentrations, 12 January 2001

(a) Base-case (b) Scenario 2026 (70/30) (c) Scenario 2026 (55/45) (d) Scenario 2026 (85/15)

Table F6: Simulated maximum ozone concentrations and number of grid cells exceeding the AAQ NEPM standards, 12 January 2001

	One-hour max ozone	One-hour area (# grid cells)	Four-hour max ozone	Four-hour area (# grid cells)
Base-case	137	136	97	81
Scenario 2026 (70/30) % change from base	142 +4	151 +11	100 +3	109 +35
Scenario 2026 (55/45) % change from base	141 +3	149 +10	100 +3	107 +32
Scenario 2026 (85/15) % change from base	144 +5	151 +11	101 +4	103 +27

Table F6 shows that despite the reduced emissions, ozone concentrations in the scenarios remained high, exceeding both the one-hour and four-hour AAQ NEPM standards in all cases. Of the six scenarios, all resulted in increased maximum one-hour ozone concentration, and all except scenario 2016 (55/45) produced an increase in maximum four-hour ozone concentration.

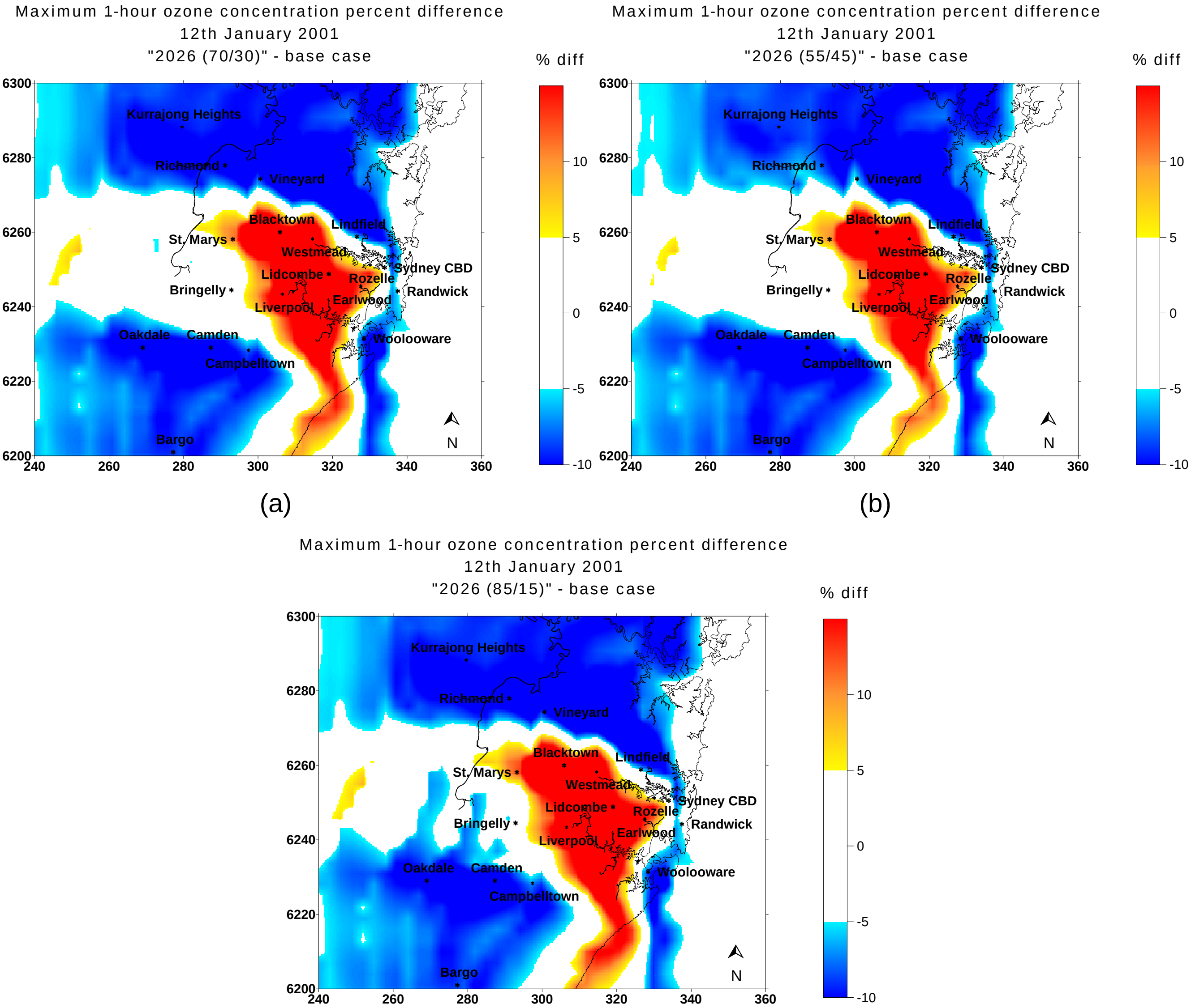
The figures and table show that the differences in maximum ozone concentrations between scenarios are small and vary by less than two per cent. The number of grid cells exceeding an AAQ NEPM standard varies by less than seven per cent in all cases.

Differences in maximum ozone concentration between each scenario and the base-case are also small, but larger than the differences among the scenarios. The largest change was an increase of five per cent. The number of grid cells exceeding the standards differs from the base-case by up to seven per cent for 35 per cent for 2026.

Figure F5 shows that the area of greatest concentration in the three 2026 scenarios is larger than that of the base-case and is located further east.

To further explore the change to the urban plume in the scenarios, Figure F5 shows contours of the percentage change in maximum ozone concentration from the base-case for the Sydney sub-domain for the three 2026 scenarios.

Figure F5 shows maximum ozone concentrations increasing by more than 10% over a substantial part of the metropolitan area for all three 2026 scenarios, although as noted from Table F6 maximum ozone concentration changed less than this. Moderate decreases occur to the north and south.



(a) (b) (c)

Figure F5: Percentage difference in simulated maximum one-hour ozone concentrations, 12 January 2001[1]

(a) Scenario 2026 (70/30) – base-case; (b) Scenario 2026 (55/45) – base-case (c) Scenario 2026 (85/15) – base-case

[1] Note that plotting differences may show artefacts due to the time resolution in the model output.

F2.3 22 January 2001

Model simulation of the maximum one-hour ozone concentration for the base-case is presented in Figure F6a. This shows a maximum ozone concentration of 106 ppb in the south-west of the basin. Elevated ozone concentrations occur in the central west and south-west. About 10% of the Sydney Basin is simulated to have concentrations greater than the NEPM one-hour standard.

Figure F6 shows the simulated maximum one-hour ozone concentration for the base-case (a), scenario 2026 (70/30) (b), scenario 2026 (55/45) (c), and scenario 2026 (85/15) (d). Table F7 summarises maximum ozone concentration and the area for which maximum concentration exceeded the goals.

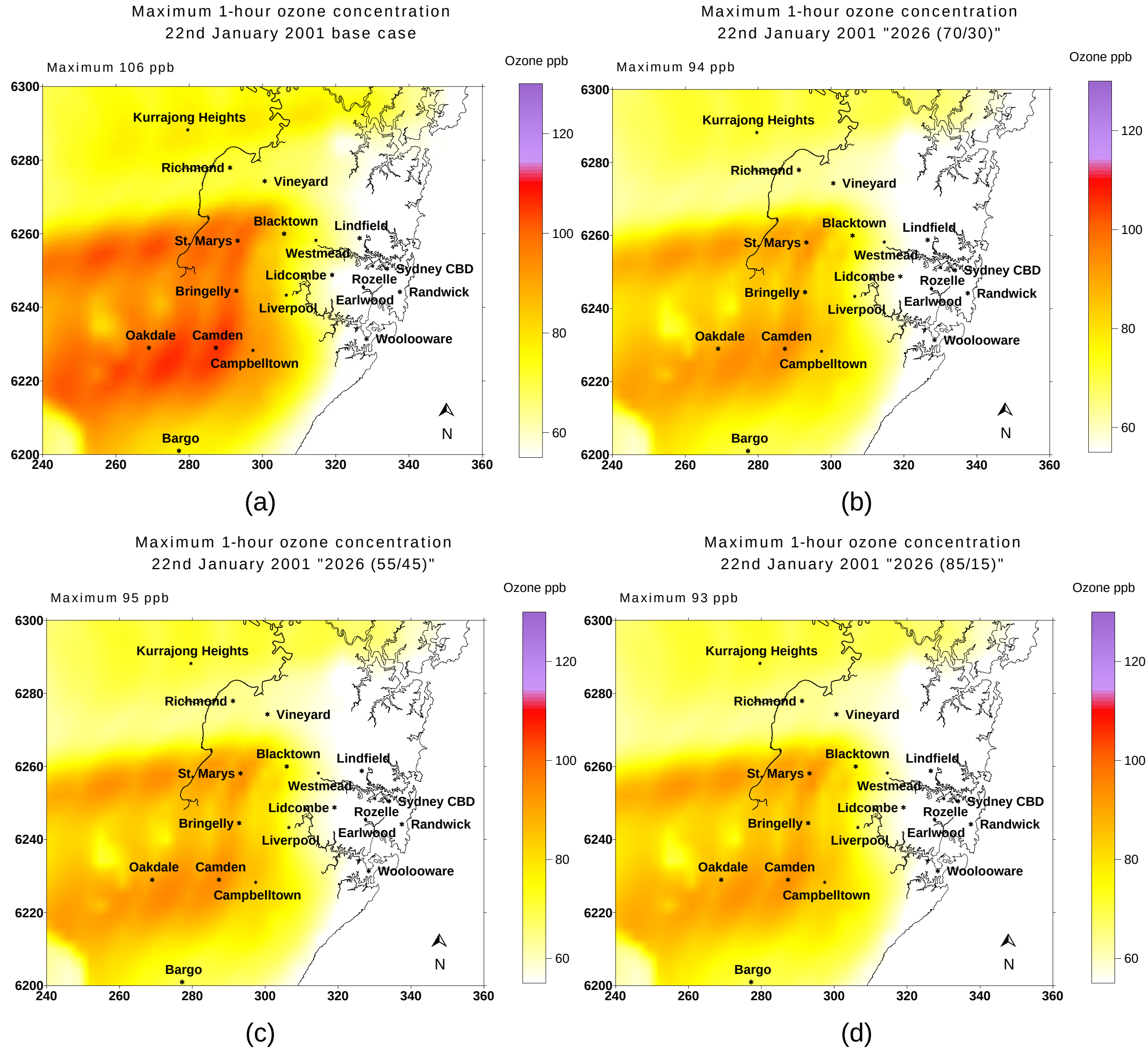


Figure F6: Simulated maximum one-hour ozone concentration, 22 January 2001

(a) Base-case (b) Scenario 2026 (70/30) (c) Scenario 2026 (55/45) (d) Scenario 2026 (85/15)

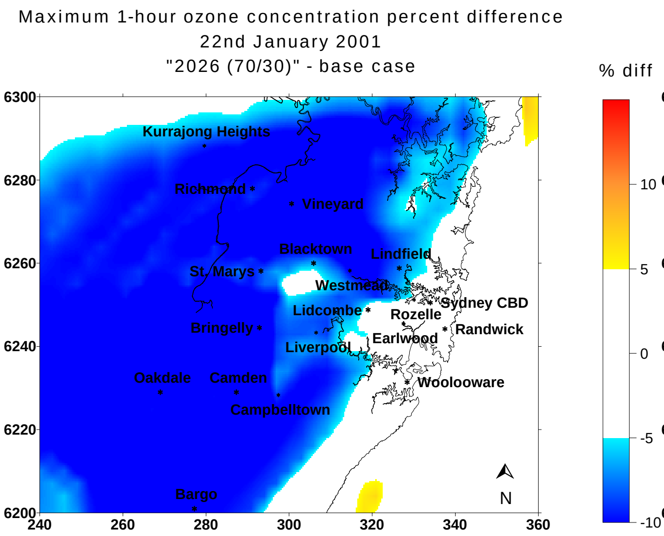
Table F7: Maximum ozone concentrations and number of grid cells greater than the AAQ NEPM standards, 22 January 2001

	One-hour max ozone	One-hour area (# grid cells)	Four-hour max ozone	Four-hour area (# grid cells)
Base-case	106	79	89	263
Scenario 2026 (70/30) % change from base	94 –11	0 –100	81 –10	4 –98
Scenario 2026 (55/45) % change from base	95 –10	0 –100	81 –9	24 –91
Scenario 2026 (85/15) % change from base	93 –12	0 –100	80 –11	0 –100

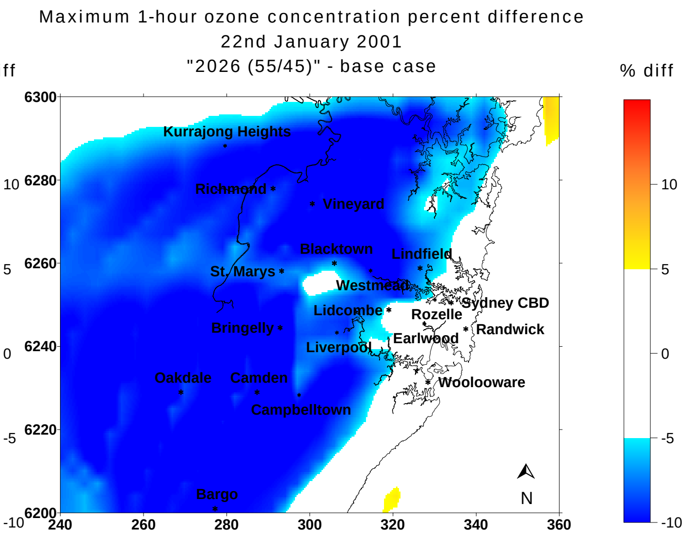
The figures and table show that for this event there is a greater difference between the base-case and any one scenario than between any two 2026 scenarios. Differences among the scenarios are small, both one-hour maximum ozone concentration and four-hour maximum ozone concentration differing by less than two per cent.

Larger differences occurred between each scenario and the base-case than between each scenario. Maximum one-hour ozone concentration differed from the base-case by up to 12% for the three 2026 scenarios. The reduction in emissions in the 2026 scenarios was sufficient for all to meet the one-hour standard and for scenario 2026(85/15) to also meet the four-hour standard. The number of grid cells exceeding the standard were reduced substantially for both one-hour and four-hour ozone concentration.

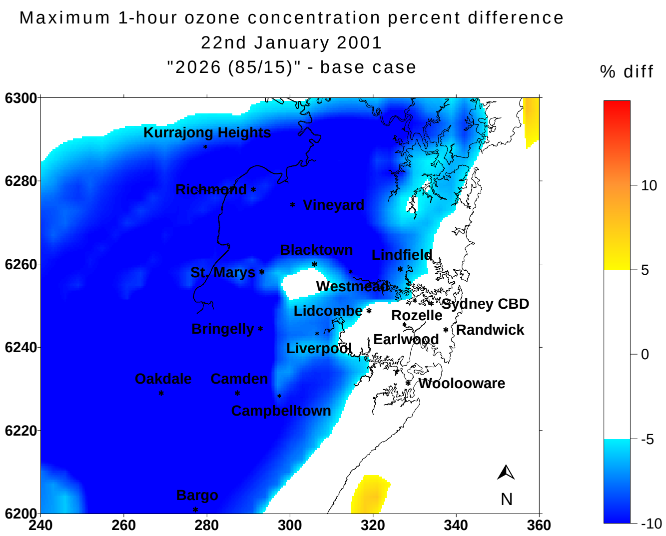
To further explore the change in ozone concentration for these scenarios, Figure F7 presents contour plots of the percentage change in maximum one-hour ozone concentration from the base-case for the Sydney sub-domain for the 2026 scenarios.



(a)



(b)



(c)

Figure F7: Percentage difference in simulated maximum one-hour ozone concentrations, 22 January 2001[1]

(a) Scenario 2026 (70/30) – base-case (b) Scenario 2026 (55/45) – base-case (c) Scenario 2026 (85/15) – base-case

1 Note that plotting differences may show artefacts due to the time resolution in the model output.

F2.4 Results by scenario

Tables F8–F10 re-present these results by scenario. The 12 January 2001 event responded differently to the emissions scenarios than the other two days, and is placed at the end of the tables.

Table F8: Results for 70% infill – percentage change from base-case

	cember 2000		22 January 2001		12 January 2001	
	2016	**2026**	**2016**	**2026**	**2016**	**2026**
One-hour max ozone	**–7**	**–13**	**–5**	**–11**	**+2**	**+4**
One-hour area (# grid cells)	**–88**	**–100**	**–95**	**–100**	**–3**	**+11**
Four-hour max ozone	**–4**	**–11**	**–5**	**–10**	**0**	**+3**
Four-hour area (# grid cells)	**–42**	**–84**	**–42**	**–98**	**–3**	**+35**

Table F9: Results for 55% infill – percentage change from base-case

	cember 2000		22 January 2001		12 January 2001	
	2016	**2026**	**2016**	**2026**	**2016**	**2026**
One-hour max ozone	**–6**	**–12**	**–5**	**–10**	**–1**	**+3**
One-hour area (# grid cells)	**–87**	**–100**	**–94**	**–100**	**–7**	**+10**
Four-hour max ozone	**–4**	**–11**	**–4**	**–9**	**–1**	**+3**
Four-hour area (# grid cells)	**–40**	**–82**	**–41**	**–91**	**–3**	**+32**

Table F10: Results for 85% infill – percentage change from base-case

	cember 2000		22 January 2001		12 January 2001	
	2016	**2026**	**2016**	**2026**	**2016**	**2026**
One-hour max ozone	**–7**	**–13**	**–6**	**–12**	**+4**	**+5**
One-hour area (# grid cells)	**–88**	**–100**	**–99**	**–100**	**0**	**+11**
Four-hour max ozone	**–4**	**–11**	**–5**	**–11**	**+1**	**+4**
Four-hour area (# grid cells)	**–43**	**–85**	**–46**	**–100**	**0**	**+27**

These results highlight several points:

- The overall increase in population is more significant than its spatial distribution, as the difference between any two scenarios for a given year is insignificant for all three modelled days.

- The impact on simulated ozone of reducing emissions varies from event to event. In particular, the lower emissions in the 2026 scenarios reduced ozone concentrations for 20 December 2000 and 22 January 2001 but increased ozone concentration for 12 January.
- The overall reduction in VOC emissions by 2026 of approximately eight per cent and NO_x emissions of 38% has not resulted in a commensurate decrease in ozone concentration.

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