INVESTIGATION REPORT ET/IR 570R

INTER-REGIONAL TRANSPORT OF AIR POLLUTANTS STUDY (IRTAPS)

Prepared for Pacific Power International on behalf of:

Eraring Energy, Delta Electricity & Macquarie Generation

by

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December 2002

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EXECUTIVE SUMMARY

The Inter-regional Transport of Air Pollutants Study (IRTAPS) has been performed by CSIRO and Macquarie University for Pacific Power International, on behalf of the NSW Electricity Generators, Eraring Energy, Delta Electricity and Macquarie Generation.

Project objectives of IRTAPS were to determine:

- The incidence of IRT (inter-regional transport), and an assessment of how often it occurs from each of the three power station regions into the Sydney airshed.
- The impact of IRT on air quality in the Sydney region, particularly photochemical smog production, and, if IRT is significant.
- The meteorological mechanisms that are responsible for IRT of power station emissions.

In this study, state-of-the-art air quality assessment and modelling techniques have been used to assess these questions. In addition, previous studies which have addressed air quality in Sydney and other locations, have been examined for evidence for a significant impact of IRT on Sydney's air quality. In each phase of the study, a conservative approach was taken in order to assess the maximum possible impacts of IRT on photochemical smog formation.

The review of previous studies identified a potential meteorological mechanism for IRT, and plume tracking measurements with instrumented aircraft provide observational evidence for inter-regional transport from the Central Coast power stations towards the northern edge of the Sydney Basin. In spite of this limited qualitative evidence for inter-regional transport, it was not possible before IRTAPS to determine the frequency of this process, nor to determine the magnitude of the potential effects on existing or future air quality in the Sydney region.

An observational and modelling approach was used to examine IRT of power station emissions. Air quality monitoring information obtained in the Sydney airshed for every hour of two summer periods (September – April) was reviewed. The data showed periods when the sulphur dioxide (SO_2) concentrations were correlated with the concentrations of oxides of nitrogen (NO_x). The conservative assumption was made that all such instances were due to IRT. In a further conservative assumption, all cases where SO_2 concentrations exceeded a baseline value and O_3 exceeded a background value, were considered to have resulted from IRT. On the balance of the evidence it is probable that IRT occurs but it is difficult to determine the precise frequency and impact based on the monitoring record. A major outcome of the examination of the air quality data was to identify suitable days for subsequent modelling. The air quality monitoring data were also broadly consistent with the

outputs of a prognostic air pollution model (TAPM) run in tracer mode. In general, plumes from the western region showed the lowest frequency of IRT to the Sydney region, while plumes from the Central Coast and the Hunter Valley areas had relatively similar frequencies.

The second objective of IRTAPS, an assessment of the impact of power station emissions on photochemical smog formation in the Sydney region, can only be adequately addressed using a numerical modelling approach, which accounts for all precursor emissions, meteorological processes and chemical reactions to predict concentrations of air pollutants. Two modelling approaches were devised to assess the magnitude of the impacts. The first used a simplified description of the chemistry, and was aimed at determining the effects of power station emissions on the annual frequency distribution of ozone (O_3) and nitrogen dioxide (NO_2) concentrations. The second used a detailed description of the chemistry to predict the impacts of power station NO_x emissions for 5 selected events when there was strong evidence for IRT. An inventory of precursor emissions had to be developed for this aspect of the study, based on information supplied by the New South Wales Environment Protection Authority (NSWEPA) and new estimates for industrial emissions. The report also describes the development of this updated inventory.

Using the simplified chemistry, two photochemical smog seasons were modelled. The results show that power station emissions make, at most, a small impact on smog impacts in Sydney. For days when the ambient air quality National Environment Protection Measure (NEPM) standard (1 hour averaging period) for ozone of 10 pphm (or 100 ppb) was exceeded in the Sydney airshed, the worst case contribution was between 1.0 and 1.5 pphm (ie a 10-15% contribution) for only one hour of the two smog seasons modelled. For the majority of the time power stations emissions were predicted to have no effect on smog occurrence in Sydney.

Results from the detailed chemical modelling were consistent with the simplified chemistry approach. Using a conservative approach, which would tend to over-predict the contribution of power station emissions, the model shows that power station emissions, at least during the early morning hours, tend to further slow photochemical production rates and lead to reduced concentrations of ozone. A positive contribution from power station plumes may occur on rare occasions if a) rural ozone generation raises the ozone background within the urban plume; b) the Sydney urban plume is sufficiently photochemically aged so as to become NO_x-limited. In either case, the maximum predicted O_3 increment, within the Sydney plume was less than 5 ppb (that is, less than 5% of the NEPM standard).

In summary, IRTAPS demonstrates that the contribution of power station emissions to ozone levels greater than air quality guidelines is, at most, small and infrequent. Hence, it is not likely that the magnitude and frequency of ozone events in the Sydney region would be significantly reduced by additional controls on power station NO_x emissions.

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1. INTRODUCTION AND BACKGROUND

1.1. General

Photochemical smog forms in urban airsheds as a consequence of photochemically initiated reactions of precursor pollutants which are principally comprised of volatile organic compounds (VOC, also known as ROC) and oxides of nitrogen (NO_x). The major product of these reactions is ozone (O_3), which has been demonstrated to have adverse effects on the airways of healthy children, adolescents and young adults. There is additional evidence for a range of health effects in the general population, including eye, throat and nose irritation, chest discomfort, coughs and headaches.

These health concerns have resulted in the formulation of air quality standards and goals for ozone and nitrogen dioxide concentrations in ambient atmospheres. In Australia, national standards have been adopted. The National Environmental Protection Measure standards and NSW EPA long-term reporting goals (EPA, 1998) for O_3 and nitrogen dioxide (NO_2) are shown in Table 1.1.

Table 1.1: NEPM Air Quality standards and NSW EPA long-term reporting goals for Ozone and Nitrogen Dioxide.

Pollutant	Authority	Averaging Period	Maximum Concentration (ppm)	Goal within 10 years maximum allowable exceedences
Photochemical oxidants (as ozone)	NEPM	1 hour	0.10	1 day a year
	NEPM	4 hour	0.08	1 day a year
	NSW EPA	1 hour	0.08	1 day a year
	NSW EPA	4 hour	0.06	1 day a year
Nitrogen dioxide	NEPM	1 hour	0.12	1 day a year
	NEPM	1 year	0.03	None
	NSW EPA	1 hour	0.105	1 day a year

Achievement of these goals has presented significant challenges to air pollution control authorities. An additional challenge is posed by the nature of photochemical smog as a secondary pollutant (i.e., a pollutant formed in the atmosphere from reactions of primary pollutants directly emitted from sources such as motor vehicles). The relationship between ozone formation and the primary pollutants (VOCs and NO_x) is complex, and the optimum control strategy (i.e., control of VOCs and/or NO_x) is not always easy to determine.

Achieving and maintaining good air quality in NSW is crucial to public health and to the economic vitality of NSW. The ever-expanding population of Sydney, especially into the western and south-western areas, has raised concerns about potential deterioration in Sydney's air quality as a result of urban changes. In 1992, the Metropolitan Air Quality Study (MAQS, 1996), conducted by the NSW government, outlined the interaction between meteorological conditions, emission of pollutants, and chemical processes within the atmosphere, and the overall effect of these factors on Sydney's regional air quality.

A number of meteorological features important for smog formation in Sydney have been identified in air quality studies extending back to the 1970s. These include accumulation of precursor pollutants in overnight and early morning cold air drainage flows as well as pollutant transport offshore and return, following the development of the sea breeze in the late morning and early afternoon.

MAQS also led to the conclusion that under certain meteorological conditions there could be inter-regional transport (IRT) of emissions between sub-regions of the Greater Metropolitan Region (GMR), resulting in the possible exacerbation of urban photochemical pollution.

In its 1998 air quality management plan "Action for Air", the NSW Government (EPA, 1998) proposed developing a framework to control nitrogen oxide (NO_x) emissions in the GMR. In particular, it proposed capping industrial emissions of NO_x and setting up a scheme for trading within the cap. The New South Wales EPA subsequently commenced developing the framework for a possible scheme.

The three state-owned electricity generators in NSW, Delta Electricity, Eraring Energy and Macquarie Generation operate seven coal-fired power stations within the GMR. The IRT phenomenon and the proposed cap and trade scheme are particularly relevant to the three generators whose major electricity generation is located in three sub-regions toward the boundaries of the GMR as shown on Figure 1.1 i.e. Hunter Valley, Central Coast and Western coalfields. The seven power stations, within these regions, account for more than 70 % of the industrial NO_x emissions within the GMR (Carnovale *et al*, 1996).

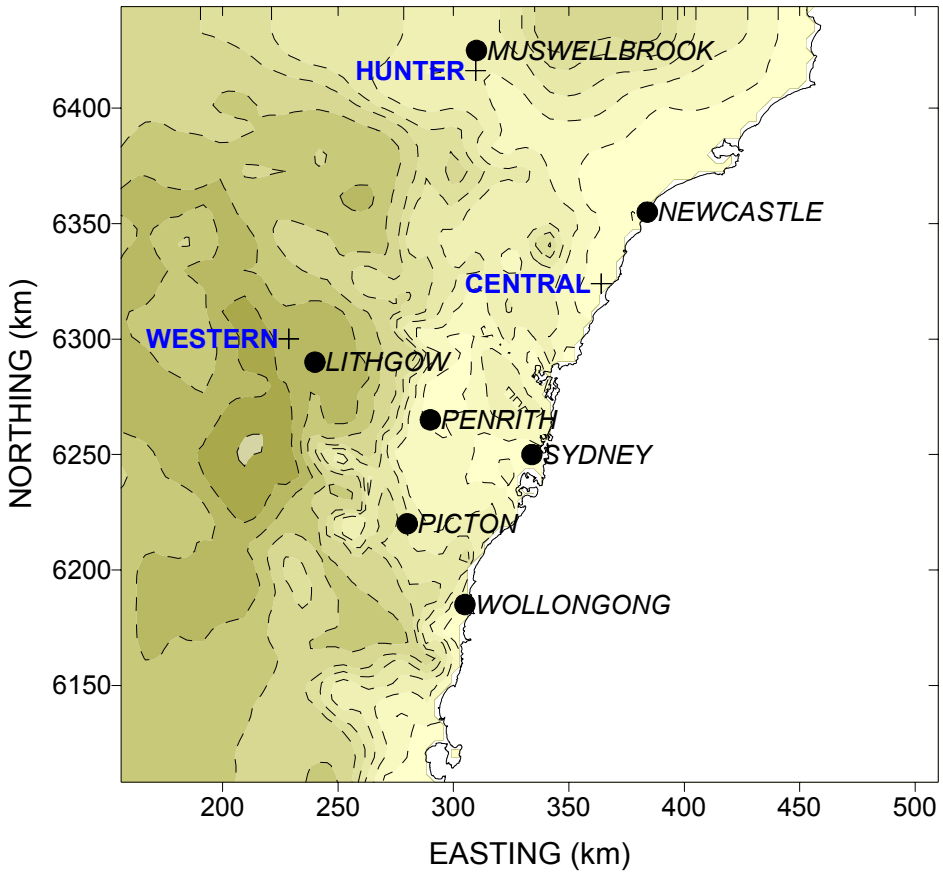

Figure 1.1. Map of modeling domain, showing topographic relief together with the location of the three power station groups.

MAQS was not able to examine key characteristics of IRT that would be necessary for the development of the proposed NO_x Policy, and in particular the frequency of occurrence of IRT from the various sub-regions within the GMR and the potential impact of IRT on levels of photochemical pollution in the urban areas of the GMR.

In 1998 Pacific Power International (PPI) on behalf of the three electricity generators in NSW commissioned CSIRO to address the above uncertainties regarding IRT to enable them to contribute relevant scientific information to the development of the NO_x policy.

The possibility of IRT and the impact of the emissions from the remotely located power stations on urban air quality in NSW were first explicitly raised in the early 1990s. In 1993, both Pacific Power and the Environment Protection Authority were briefed about the possibility of inter-regional transport following an investigation into the air quality issues associated with the Co-Generation Study (see Section 2.4.2) for Pacific Power (Johnson et al., 1993) carried out by CSIRO and Macquarie University. This briefing was considered necessary because the pattern of pre-sea breeze ozone occasionally observed at western Sydney air quality monitoring stations during photochemical smog episodes could not be satisfactorily explained on the basis of the existing chemical and meteorological knowledge.

The MAQS consultancy report (Hyde et al., 1997) postulated possible mechanisms for this process. EPA subsequently concluded that these events were the result of recirculation of Sydney air (EPA, 1996).

MAQS also provided data from the EPA Richmond air quality monitoring station which showed a coherent and long lived (several hours) SO_2 peak (up to ~10ppb) which was strongly correlated with ozone. Subsequent trajectory analyses by the Consultancy Team indicated that the air mass may have arisen from locations on the Central Coast (including the location of the Central Coast Power stations) and may have been carried into the north-west Sydney basin by north-easterly winds.

It has been suggested that NO_x generated by the growth of new industry over the next 25 years could substantially increase formation of smog or cause exceedences of the nitrogen dioxide goal (EPA, 1998), and that limitations on the production of NO_x by industry should be imposed (see Project Brief 'Study of Inter-Regional Transport of Air Pollutants'). This would have major implications for the Hunter, Central Coast and Western power generation regions of NSW.

1.2. Aims of the IRTAP Study

The two major aims of the project were to determine:

- The incidence of inter-regional transport from each of the three power station regions into the Sydney region.

- The impact of power station emissions on the air quality of the Sydney region, particularly with regard to photochemical smog production.

In this study, state-of-the-art air quality assessment and modelling techniques have been used to assess the above two questions. In addition, previous studies that have addressed air quality in Sydney and other locations have been examined for evidence for a significant impact of IRT on Sydney's air quality, particularly photochemical smog formation.

The results of the study are summarised in the current report.

Section 2 reviews previous studies relevant to this work.

Section 3 presents an assessment of the available air quality monitoring data for the Sydney region (for the periods 1st September 1996 to 30th April 1997, and 1st September 1997 to 30th April 1998) for evidence of inter-regional transport.

Section 4 reports the results of three modelling approaches devised to assess the magnitude and potential impacts of IRT. The first approach treated the NO_x in the power station plumes as a conserved tracer in order to examine the potential frequency of IRT; the second approach used a simplified description of the photochemistry and was aimed at determining the effect of power station emissions on the annual frequency distribution of ozone concentrations; the third approach used a detailed description of the photochemistry and predicted the impacts of NO_x emissions, on ozone formation in the Sydney region, for 5 events where the data suggested IRT might be occurring. It also includes an assessment of the sensitivity of the modelling outcomes to various assumptions about biogenic emission source strengths. An

inventory of precursor emissions had to be developed for the two chemical modelling approaches. Section 4 also describes the development of this inventory.

Section 5 presents a synthesis of all the results.

Section 6 highlights some of the assumptions inherent in the conclusions.

2. REVIEW OF PREVIOUS STUDIES

2.1. Preamble: Photochemical Smog Formation – Status of Current Understanding

Ozone, the key indicator of photochemical smog, is not emitted directly to the atmosphere, but, instead, is formed by a series of complex chemical reactions between oxides of nitrogen (NO_x = NO + NO_2) and volatile organic compounds (VOCs). Several factors influence the spatial distribution of ozone formation. These include:

- Proximity to fresh NO_x emissions: nitrogen oxide emissions are normally in the form of NO, which destroys ozone by chemical reaction. This can result in low ozone concentrations near combustion sources.
- Meteorology, which is the single most important determining factor.
- Distance from primary emission sources: The process of ozone formation takes several hours depending of the reactivity of the air. The maximum concentration normally forms tens of kilometres downwind of the primary sources.
- Distance and travel times to receptor areas: The direction and speed of winds will determine where ozone and ozone precursors are transported.

"Despite its seemingly minute concentration, atmospheric ozone (O_3) has an enormous environmental impact. **In the stratosphere**, where about 90% of the atmospheric O_3 resides, it protects life from harmful UV radiation**. In the troposphere**, O_3 is a key part of an oxidizing system that cleans the atmosphere of a wide range of pollutants. **At ground level**, however, O_3 can damage human health, agricultural yields, and other ecosystems."

From NARSTO (2000), State of the Science assessment

Photochemical smog, as first proposed correctly by Haagen-Smit in the 1950s in Los Angeles, forms as a result of photochemical reactions of NO_x and VOCs. Ozone and other oxidants, such as peroxyacetyl nitrate (PAN) and aldehydes, are the components of photochemical smog. Motor vehicle exhaust is a significant source of NOx and VOCs in cities. As there are several hundred different hydrocarbons in motor vehicle exhaust and other sources, the photochemistry is extremely complex.

Extensive research has shown (see summary of chemistry in Finlayson-Pitts and Pitts, 2000) that the following major reactions are responsible for the formation of ozone in the urban atmosphere:

$$OH + RH \rightarrow R + H_2O$$

$$R + O_2 + M \rightarrow RO_2 + M$$

$$RO_2 + NO \rightarrow RO + NO_2$$

$$RO + O_2 \rightarrow HO_2 + R'CHO$$

$$HO_2 + NO \rightarrow OH + NO_2$$

$2\ (NO_2 + h\nu \rightarrow NO + O)$

$2\ (O + O_2 + M \rightarrow O_3 + M)$

Overall: $RH + 4O_2 + 2h\nu \rightarrow R'CHO + H_2O + 2O_3$

Where:

RH = a reactive organic compound, variously described in the literature as a volatile organic compound (VOC), or a reactive organic compound (ROC), or a non-methane hydrocarbon (NMHC)

$R'CHO$ = a carbonyl product (aldehyde or ketone) where R' has one fewer carbon atom than RH

M is a non reactive, energy-absorbing third body (N_2, O_2) and hν represents energy from solar radiation.

The carbonyl compounds can undergo further reactions resulting in additional organic and hydroxyl radicals and, in turn, produce more ozone. VOC and NO_x are referred to as ozone precursors.

In the above scheme, the organics are consumed, while NO_x acts in a similar way to a catalyst. There are also reactions which remove NO_x from the atmosphere as HNO_3, or as other nitrates through deposition processes.

In remote regions and over the oceans, organic concentrations are relatively small, and ozone production may be dominated by oxidation of CO and methane (CH_4). Biogenic emissions from vegetation can also play a role in the background atmosphere.

In urban regions emissions from motor vehicles and other sources lead to much higher organic concentrations and the overall production of ozone is determined by both the absolute concentrations of the precursor species and their relative abundance. Early attempts to understand the relationship between precursor species and ozone produced, using isopleth diagrams, and to develop control strategies based on the relationship have been shown to have significant limitations. These approaches have now largely been replaced by three dimensional numerical modelling of airsheds because of the complexity of the interactions. In some locations within some airshed regions where the production of ozone is governed by available sunlight or NO_x concentrations, so-called light and NO_x limited regions can be experienced, but these depend on complex interactions between meteorology, emissions and chemistry which can only be adequately explored with modelling techniques.

2.2. Introduction

Air quality in Sydney and the Greater Sydney Region has been the subject of a number of coordinated studies and other research activities over the past 30 years. In addition the dispersion, transport and deposition of acid gases from the NSW power stations have also been extensively studied. Hence, an important component of the IRTAPS is a critical review of the publicly available information that may be relevant to inter-regional transport of air pollutants in the Greater Sydney or Greater Metropolitan Region (GMR).

Internationally, there have been long-standing concerns about emissions of SO_2 and NO_x from the combustion of coal. These have concerned the near field impacts of SO_2 and NO_2 concentration as well as the deposition of sulfur and nitrogen on land, water and vegetation as a result of wet and dry deposition processes. These issues have been previously recognised and well studied in NSW, and there is ongoing monitoring, assessment and reporting.

Recent evidence, including studies in a number of Australian cities, suggests that the concentrations of ozone produced may, on occasions, be NO_x limited. As a consequence there is an increasing trend for more stringent controls on emissions of oxides of nitrogen. Based on Australian inventories of pollutant emissions, motor vehicle emissions are the major source of NO_x in Australia, but coal combustion in power stations is the largest industrial source of emission. This comparison, however, ignores the potentially very different impacts of ground level NO_x emissions (motor vehicles) in urban areas and NO_x emitted from tall stacks in remote regions.

In this section, relevant previous studies in the Sydney area are reviewed. It is recognised that inter-regional transport of pollutants in the northern hemisphere has been extensively researched and characterised. Some examples of major studies include:

- Regional ozone formation in the Eastern United States (see summary in National Research Council, 1991, pp. 98-107) under the Eastern Regional Air Quality Study (ERAQS).

- More recent studies of regional ozone formation in the Eastern United States under the umbrella of the Ozone Transport and Assessment Group (OTAG, 1999).

- The Southern Oxidants Study (Chameides and Cowling, 1995).

- Studies in support of the Sofia Protocol to the international convention on Long Range Transboundary Air Pollution in Europe (see references in Derwent *et al*, 1998).

Similarly, photochemical smog formation in power plant plumes has been extensively studied (see, for example, Luria *et al*, 1999 and references therein). However, both the large-scale regional assessments, and the plume studies, are highly specific to the meteorological conditions, topography and emission characteristics (eg, VOC/NO_x ratios, VOC reactivities) of the locations considered and hence the results and conclusions are not readily applicable to other regions. For these reasons these studies are not addressed further in this report.

2.3. Early Studies of Air Pollutant Formation in the Sydney Region (circa 1975-1983)

2.3.1. Sydney Oxidant Study

Study of ozone formation in Sydney began in 1971, when significant levels of photochemical smog were first observed (SPCC, 1979). Extensive studies of the formation of smog were co-ordinated into the Sydney Oxidant Study (SOS), and involved a multi-disciplinary team from the NSW State Pollution Control Commission, CSIRO, the University of Sydney and Macquarie University.

In reviews of the study (SPCC, 1979; Mitchell, 1983), it was concluded that the worst smog occurs in the central, southern and western areas of Sydney. Smog "episodes" were

identified, and the weather conditions responsible were characterised by prolonged periods of sunny weather and low wind speeds which permitted accumulation of the precursors and their photochemical products. Detailed aspects of the meteorology during such episodes included westerly drainage flow down the Liverpool and Parramatta Valleys in the morning, and north-easterly sea breezes in the early afternoons. This combination resulted in the location of the highest concentrations of ozone in the central, southern and western parts of Sydney. The most significant source regions at the time of the studies (1976-1978) were the Parramatta River Valley, the central business district and the Botany Bay region.

No reference to inter-regional transport of NO_x was made in the reviews of the SOS (SPCC, 1979; Mitchell, 1983), although Hyde *et al* (1978) also recommended that air quality monitoring be undertaken on higher ground north of Sydney to examine possible IRT of ozone from the Newcastle area.

A number of the supporting studies provided more detail of the formation of smog in Sydney. Using an instrumented mobile laboratory, researchers from the Department of Mechanical Engineering at the University of Sydney determined regional emission source strengths (for the CBD and the industrial area centred around Silverwater), and ozone-precursor relationships for the Sydney region (Post and Bilger, 1977, 1978; Post, 1983). Inter-regional transport was not considered in this analysis. A simple ozone formation model was developed (Post, 1983), and provided a measure of potential downwind ozone concentrations for non-methane hydrocarbon (NMHC) and NO_x ratio limits of 5-20 (i.e., NMHC/NO_x = 5- 20 ppmC/ppm, volumetric mixing ratios i.e. v/v):

$$\text{Potential afternoon downwind ozone} = 0.39\ ([NO_x][NMHC])^{0.36}\ \text{ppm}$$

where [NO_x] and [NMHC] are upwind morning precursor concentrations (ppm and ppmC respectively). Excellent agreement was observed between the predictions and the SPCC monitoring network, suggesting that emissions derived from the source locations characterised by the University of Sydney team (CBD, and Parramatta River Industrial area) were largely responsible for the levels of smog experienced in Sydney at this time.

This simple model was also used to assess control options, and, as applied to Sydney precursor conditions, indicated that hydrocarbon control was the preferable route to oxidant control (Mitchell, 1983).

Macquarie University (Hyde *et al*, 1977, 1978) was responsible for producing surface air mass trajectories during the Sydney Oxidant Study, and detailed investigation of meteorological mechanisms for smog formation in the Sydney Basin. From an analysis of a subset of days when ozone exceeded 10 pphm, Hyde *et al* (1978) concluded that ozone formed predominately within the nocturnal / early morning westerly drainage flow, Botany Bay Breeze, and the regional seabreeze.

One observation of potential relevance to the issue of inter-regional transport of pollutants was the observation of high concentrations of ozone at Campbelltown in the morning between 0900 and 1100-1200. This ozone was responsible for 14% of the total dosage experienced at this site, and mainly occurred within light northerly winds (Hyde *et al*, 1978). This morning ozone invariably followed days with high concentrations of ozone within a seabreeze, and overnight south-westerly drainage flows, and Hyde *et al* concluded that "recirculation of polluted air overnight may be occurring in the southwest of the Sydney basin". The source of this recirculated air was not further commented on, and the authors do

not invoke inter-regional transport as a possible mechanism, but IRT cannot be excluded as a possible explanation.

2.3.2. Sydney Brown Haze Study

The composition and occurrence of particulate haze in the Sydney Basin formed the subject of the Sydney Brown Haze study (1978-1980), which was jointly performed by CSIRO (Williams, 1983; Williams *et al*, 1981, 1983; Roberts *et al*, 1983) and Macquarie University (Hyde *et al*, 1983a,b). Fine particulate pollution falls outside the scope of the IRTAPS Study; however, the observations concerning air movements and pollutant composition may have some relevance.

It was found (Williams *et al*, 1981) that, at this time:

- Haze was widespread in the Sydney region.
- There were three major emitting regions located at or near Matraville, Silverwater and the Balmain-CBD region.
- The major elements or species present at levels higher than 1% (w/w) were, in order of decreasing mass, total C, SO_4^{2-}, Na, NO_3^-, Cl, Si, Pb, K, Ca, Zn and Al.
- Composition was remarkably uniform, suggesting the importance of area-based sources.
- Eighty percent of the aerosol was in the fine particle mode (in this case less than 1.5 μm).
- contributions of the various sources were:
  - to aerosol mass: motor vehicles (17%), sea salt (17%), vegetative burning (10%), soil and cement dust (5%)
  - to visibility degradation (by the sources given above): motor vehicles (24%), sea salt (3%), vegetative burning (10%), soil and cement dust (< 1%)

Williams (1983) also provided some information on the spatial and temporal distribution of the haze. Significant concentrations of haze were observed in the Hawkesbury River Valley between Blacktown and Penrith, based on airborne surveys. However, it was also observed that little or no SO_2, was present in the haze suggesting that power station emissions and inter-regional transport was an unlikely source. In fact, the major sources of airborne sulphur compounds at this time were located at Botany and Silverwater (Williams, 1983).

The relevant meteorology conducive to the occurrence of Sydney brown haze was summarised by Hyde *et al* (1983b). Three features of the meteorology common to many occasions of elevated haze concentrations are described:

- Morning haze (typically between 0600-1200) when particles are trapped within well-defined local and regional drainage flows.
- Late afternoon and early evening haze, when trapping within sea breezes or on-shore gradient winds can lead to high concentrations.

- Overnight haze when previous particulate emissions are recirculated within local or regional drainage flows or spillover from the Hawkesbury Basin.

Also of possible relevance, because of the insight into meteorological mechanisms they provide, are the observations (collected during the Brown Haze Study, or the Western Basin Experiment) reported by Hyde *et al* (1983a) of drainage flows across the northern plateau of the Sydney basin. These flows, measured at Arcadia, were WSW to WNW in direction, and it was argued (Hyde *et al*, 1983a) that they could not be the result of locally induced down-slope flow, or of a spillover of air out of the Hawkesbury Basin given the location of the monitoring site on top of a ridge.

Hence, in summary, the consolidated results of the Sydney Brown Haze studies imply that local sources of particles (i.e. within the Sydney basin) predominated and that drainage flows and/or recirculation were implicated. There is little evidence, based on these studies, for inter-regional transport of pollutants, and IRT was not invoked as a possible mechanism for pollutant formation and transport.

2.4. More Recent Studies of Air Pollutant Formation in the Sydney Region (circa 1990 – 1994)

2.4.1. Pilot Study: Evaluation of Air Quality Studies for the Development of Macarthur South and South Creek Valley Regions of Sydney (1990)

CSIRO and Macquarie University evaluated the air quality of the Macarthur South and South Creek Valley region (Hyde and Johnson, 1990) for the Department of Planning. The authors claimed that data published previously by the State Pollution Control Commission of NSW (SPCC) had seriously underestimated the severity of photochemical smog in the Sydney region. While it was noted that there were gross deficiencies in the knowledge of the causes and distribution of photochemical smog in Sydney, simple modelling, based on the Integrated Empirical Rate (IER) approach developed by Johnson (1983, 1984) showed that urban growth during the years 1990-2010 would give increases of up to 50% in western Sydney ozone concentrations.

Extensive discussion of the meteorology of the Sydney airshed was included in the Pilot Study, including a discussion of cold air drainage flows and their duration, and recirculation of air within the Sydney Basin and trajectory assessments of photochemical smog. The most common pattern of wind flow for photochemical smog events in Sydney was identified as:

- Night-time drainage flow down the Parramatta River Valley.

- Returning air flow within a sea breeze, recrossing the coast at about 1100 hr and proceeding inland over the Parramatta River Valley and the Liverpool Basin.

- For the Hawkesbury Basin, night-time drainage flows from about midnight were found to regularly bring air northwards via Macarthur and South Creek Valley to arrive at areas around St Mary's, Penrith, Richmond, Windsor and Blacktown at about 0900 hr. Under conditions conducive to photochemical smog this air was then likely to stagnate in these districts until the arrival of the sea breeze the following afternoon.

The Pilot Study confirmed the previous mechanisms for ozone formation identified in the Sydney Oxidant Study and provided additional information about air movements in the western part of the Sydney basin.

2.4.2. Co-generation Study (1993)

An assessment of the air quality impacts of co-generation and standby power units was undertaken in 1993 for Pacific Power by CSIRO and Macquarie University (Johnson *et al*, 1993). The major findings of this study were that the Sydney region could be divided into four regions based on meteorological conditions and the characteristics of the air in each region. Briefly the characteristics of each of these regions were as follows:

- Eastern region; characterised by relatively fresh emissions, with the IER extent parameter (Johnson 1983, 1984) less than about 0.6. High ozone could occur under some meteorological conditions.

- South east coastal region; high ozone concentrations were recorded here more frequently than in the eastern region.

- Central region; IER extent parameter was frequently in the range 0.5 to < 1.0, indicating precursors had been exposed to significant sunlight, but with smog production not yet attaining the NO_x – limited regime.

- Inland region; extent could have a value of less than or equal to 1 regardless of the ozone concentration.

In addition, the authors (Johnson *et al*, 1993) found that there were typically two types of ozone events: "pre-seabreeze ozone" and "seabreeze ozone". The study reported no evidence for inter-regional transport. However, Hyde (personal communication, 1999) reported that some of the observations could not be reconciled with the then current understanding of photochemical smog events. The authors raised the possibility of IRT with the client at this time.

2.4.3. Metropolitan Air Quality Study (MAQS, 1992-1994)

2.4.3.1. Air Movements

MAQS was a three-year study, coordinated by the NSW EPA. Some specialist aspects of the study were performed by a team of consultants, led by Coffey Partners International Pty Ltd, and including CSIRO, Macquarie University, and the EPA of Victoria. The major findings are summarised in EPA (1996).

MAQS confirmed previous observations and findings dating back to the 1970s including the following meteorological conditions identified as important in the production of photochemical smog:

- A high pressure cell located in the central Tasman Sea and northerly sector gradient winds.

- Warm temperatures aloft.

- A temperature inversion at sunrise.

- Reduced mixing depths.

- More detailed air movements on days when ozone was observed included.

    - Light drainage flows moving across the Sydney region towards the coast and out to sea; precursor emissions of ROC and NO_x offshore in these flows.

    - North-easterly sea breezes, developing in the late morning and early afternoon, which transport reacting precursors across the Sydney basin to the south-westerly regions of the basin; however, the direction of sea breezes in Sydney could be influenced by the gradient winds, resulting in transport to different parts of the greater Sydney region, including the Illawarra.

These findings are largely consistent with those reached in the Sydney Oxidant Study and the Pilot Study (Section 2.3). MAQS, however, also suggested some additional processes for ozone formation. Modelling (Hyde *et al,1997)* using the CSIRO wind flow model, LADM, predicted vertically rotating wind flows, in which pollutants in the south-western areas of Sydney could be transported towards the north in a southerly drainage flow, and then forced upwards by the local topography. These pollutants could then be advected southwards by a northerly gradient wind, and could mix down to the surface the following morning.

MAQS also identified the potential for inter-regional transport of air pollutants in a southwards direction from the lower Hunter and Sydney regions, and, less frequently in a northwards direction from the Illawarra and Sydney regions (Hyde *et al*, 1997). MAQS also suggested that conditions leading to high ozone concentrations in Sydney were often the same as those potentially resulting in IRT from the north. A number of mechanisms for transporting pollutants towards Sydney, and for mixing them down to the surface were described (EPA, 1996).

There is however little evidence for the frequency and significance of these possible mechanisms, or of the contribution they make to determining ultimate ozone concentrations in the Sydney region. The exception is a detailed analysis of the concentrations of ozone and other pollutants on the 9^{th} – 10^{th} February 1994. It was found, from two-minute average concentrations of ozone and SO_2 at Richmond, that there were periods when the concentrations of these pollutants were highly correlated. Peak ozone concentrations of about 7 pphm were observed on this occasion (Note that this concentration is below the 1-hour average long-term reporting goal for ozone in New South Wales of 8 pphm at any monitoring station, as outlined in the NSW EPA's *Action for Air,* (EPA, 1998) where the latter value represents a level of long term concern from a health impact point of view.

While sulfur dioxide, SO_2, can be taken as an indicator of power station emissions, there are also significant emissions from other sources. The air emissions inventory for the Greater MAQS region (Carnovale *et al,* 1996) showed that power stations contributed 59% of the SO_2 with basic metal processing also contributing 29%.

On the 10^{th} February 1994, peak SO_2 concentrations of about 1.3 pphm were observed at Richmond. Observed winds for the 9-10^{th} February provide additional evidence that the observed pollutant concentrations could be strongly influenced by inter-regional transport of pollutants. For example, a back trajectory through Richmond at 1500 hours on the 10^{th} February showed air being brought to Richmond from the NE, and passing over major source regions on the Central Coast. It was concluded (Hyde *et al*, 1997) that "transport from a

combination of sources, including the Central Coast and Newcastle, could account for the afternoon peaks of ozone observed in northwest Sydney on the 10th February 1994". The authors further concluded that:

> "In view of the evidence supporting inter-regional transport of emissions from sources in the Upper Hunter Valley, Newcastle and Central Coast there is a need to examine the conditions conducive for such transport in more detail, and to consider the possible impact on ozone concentrations in Sydney…Other scenarios not discussed in this report are the inter-regional transport of northern MAQS emissions along the coast and into the Illawarra region, and the possible contribution to photochemical smog in Sydney of emissions from power stations to the west (Hyde *et al*, 1997, p. 13-20)."

2.4.3.2. MAQS Modelling Studies

Some of the airshed modelling studies undertaken by EPAV in MAQS are also relevant to the assessment of the contribution of power station emissions to photochemical smog in Sydney (Cope and Ischtwan, 1996). The MAQS modelling effort consisted of the application of the CIT airshed model to a number of generic days, which were taken as typical of ozone formation in the MAQS region. CIT models mathematically, the complex interactions between emissions, meteorology and air chemistry, according to the atmospheric diffusion equation (McRae *et al*, 1992 a,b).

The days selected for modelling and the overall outcomes of the modelling were (Cope and Ischtwan, 1996):

- 4-5th February 1991; a generic coastal event. Inter-regional transport, particularly from the Sydney region to the Illawarra, was an important contributor to photochemical smog throughout the region. Motor vehicles were found to have the dominant impact on smog concentrations.

- 18th January 1993; Newcastle generic event. Conditions were conducive to smog production (7-8 pphm) on the Central Coast and in Newcastle and the Hunter valley region.

- 9-10th February 1994; detailed inland event. This event was used to validate the airshed model with excellent agreement between observed and predicted ozone and NO_x. This event demonstrated the build-up of smog in western Sydney and its transport south. Motor vehicles were also the major contributors to smog production for this event. Some ozone formed from emissions from the Newcastle, Hunter valley and Central Coast area was transported inland into the Hunter Valley, and into the northern Hawkesbury basin in the afternoon. This ozone was attributed to the interaction of biogenic VOCs and motor vehicle and industrial NO_x emissions from the Hunter Valley and the Central Coast.

Sensitivity analyses formed an important component of the MAQS modelling studies (Cope and Ischtwan, 1996). Calculations performed by perturbing precursor emission fluxes are important in the context of this review. For each event listed above, effects on ozone

formation were investigated by reducing, for example, motor vehicle reactive hydrocarbon emissions by 50%. Of most relevance to the contribution from power station emissions are the effects of eliminating industrial NO_x. In the greater MAQS region, power generation contributes some 35% of total NO_x, and some 70% of industrial (or non-vehicular) NO_x. Hence elimination of all industrial NO_x will over-estimate the effects, but does provide an upper limit to the effects.

The effects of eliminating all industrial NO_x were as follows:

- For 4-5th February 1991; maximum ozone concentration in the airshed increased by 0.018 ppm, or 15% of the maximum base case ozone; there were some spatial differences in the increases with the Sydney-Wollongong plume having increases of less than 0.025 ppm, and the Newcastle-Gosford plume showing a maximum increase of 0.047 ppm. On this day it was considered that "NO_x control of the Newcastle-Gosford plume is estimated to be counter-productive" (Cope and Ischtwan, 1996, p. 3-81), since ozone formation is in the light-limited regime. The effects of eliminating power station NO_x alone were also calculated (Cope and Ischtwan, 1996, Fig. 3-35). It was found that the estimated maximum ground level ozone concentrations for the emissions scenario with power station NO_x eliminated were unchanged compared to the base case.

- 18th January 1993; this was a generic Newcastle event and less sensitivity modelling was performed. However, elimination of industrial NO_x again led to ozone increases (maximum of 0.032 ppm), and NO_x control was considered to be counter-productive.

- 9-10th February 1994; similar effects were found as for the 4-5th February 1991. Elimination of industrial NO_x led to increases in maximum ozone of 0.015 ppm, or 12% of the base case ozone. However there was some evidence for a NO_x limited regime in the plume downwind of the Hunter Valley and extending towards Richmond; maximum ozone decreases of 0.022-0.025 ppm were predicted, compared with measured peak concentrations of about 0.07 ppm. It should however be noted that ozone concentrations in this plume also exhibited significant sensitivities to changes in ROC emissions from motor vehicles, biogenic sources and area-based domestic sources. Hence, for example, elimination of biogenic sources in the Gosford-Newcastle-Hunter Valley region resulted in reductions of 40-60% in the maximum 1-hour ozone concentrations (Cope and Ischtwan, 1996, p. 4-167).

Air movement and airshed modelling results arising from MAQS, have been reviewed for their possible relevance to the IRT of power station emissions. The air movement studies (Hyde et al, 1997) identified a number of possible mechanisms for inter-regional transport, and suggested a need for further study of the issues. However, the modelling studies suggest, on the basis of the days studied in detail, which were explicitly chosen to include examples of events when there was evidence for inter-regional transport, that the airshed was generally not NO_x-limited. This is particularly the case downwind of urban emissions. In summary the MAQS modelling suggests that NO_x control in general, and industrial NO_x reductions in particular, are usually counter-productive to reducing maximum ozone concentrations, and population exposure to ozone and NO_2.

2.5. Other Studies of Relevance to Inter-Regional Transport of Pollutants into the Sydney Airshed

2.5.1. CSIRO Plume Tracking Studies

CSIRO studied the dispersion of plumes from the Hunter Valley, Central Coast and Wallerawang power stations during 1982/83 (Wallerawang) and 1988/89 (Hunter Valley and Central Coast). The studies were performed with instrumented aircraft, and were funded by the Electricity Commission of New South Wales (Carras *et al*, 1984, 1992a,b,c). The overall objectives of the work were:

- To determine the transport, dispersion and interaction of emissions from the power stations and other significant sources of emission.

- To develop computer based models of the air quality in the Hunter Valley to assist in future power station development.

Several aspects of these studies are of relevance to IRTAPS. One detailed objective of the Hunter Valley studies was to determine the paths and dispersion characteristics of the plumes from the five large power stations in the region for a variety of meteorological conditions, with particular attention to Eraring and Bayswater. For this purpose 33 individual research flights were carried out, and a large body of information obtained on the paths and dispersion characteristics of the power station plumes for convective, neutral and stable boundary layers.

The Bayswater and Liddell plumes were observed to travel either down the Valley toward the sea or back up the Valley in the opposite direction. They were measured as far as ~ 100 km from the source and out to sea from Newcastle.

Trajectories from the coastal power station plumes were more complex. They were observed to travel:

- Out to sea, where they were measured at distances up to 45 km from the source; the plumes were blown back inland as sea breezes developed.

- Toward Newcastle on one occasion.

- Toward Sydney on two occasions.

- Inland on one occasion passing ~ 20 km south of Singleton.

Plume directions were determined by the wind-field at plume height.

These studies also provided useful information on the in-plume oxidation of SO_2 to sulphate and NO to NO_2, which is of relevance to the use of SO_2 and NO_x as conservative tracers for power station emissions. It was found that oxidation of SO_2 to sulphate in the plumes was less than ~1% per hour. The data for NO oxidation was more difficult to interpret.

These studies provide observational evidence for inter-regional transport of power station emissions. Modelling using LADM of some cases of air movements that were consistent with the observations in MAQS (Hyde *et al*, 1997) showed that, under the right synoptic wind directions and with limited mixing or a stable atmosphere, plumes from the power stations could be carried toward the Sydney Basin. It was also observed (Carras *et al,* 1992a) that,

under sea breeze conditions, plumes carried offshore from the Central Coast during the morning could be carried back inland during the afternoon sea breeze. The strength and direction of the sea breeze, and the photochemistry, will determine the ultimate fate and impacts of these emissions.

2.5.2. Aerosol Sampling Project (ASP)

This study was conducted by ANSTO, Macquarie University and the University of New South Wales, with funding provided by ERDC (Cohen *et al*, 1995a), and the NSW Environmental Research Trusts (Cohen *et al*, 1995b). Sampling and analysis of fine aerosol particles (< 2.5μm in diameter) was conducted at 24 sites during 1992 and 1993, yielding a large database of information (5000 samples; 125,000 elemental analyses).

Using Chemical Mass Balance (CMB) and source reconciliation techniques, contributions of various sources to the particle loadings were determined. Source fingerprints used were for:

- Motor vehicles.
- Coal combustion.
- Industry on high sulphur days.
- Smoke from wood/vegetation burning.
- Soil.
- Seaspray.

It was claimed (Cohen *et al*, 1995b) that, at inland sites, the coal combustion fingerprint dominated the airborne particles in summer and continued to be widespread and relatively abundant throughout most of the year. In related work (Cohen *et al*, 1993), based on the same samples, fine particle sulphur concentrations were reported for the ASP network. This paper raised the possibility that fine particle S observed at a significant number of stations in the network on specific occasions (27 December 1992 was the example given) was derived, by implication, from Hunter Valley power stations.

However, the overall ASP study design, interpretation and factual detail has stimulated considerable discussion (Sligar *et al*, 1993). Attempts to identify source contributions on the basis of the data were seen to ignore a number of complexities associated with the nature of the data. It has also been claimed that the wealth of available information and understanding about meteorological processes which contribute to air quality problems in the Sydney region was not adequately considered. However, the ASP database has the potential to yield important information about the source of fine particles, and may provide valuable information on the contribution of inter-regional transport to their atmospheric concentrations.

2.5.3. Urban Air Pollution in Australia, an Inquiry by the Australian Academy of Technological Sciences and Engineering

An independent inquiry into Urban Air Pollution in Australia was commissioned by Federal Environment Minister Robert Hill and conducted by the Australian Academy of

Technological Sciences and Engineering (AATSE, 1997). One of the specialist supporting reports included in the inquiry was a study of "Anthropogenic influences in Australian Urban Airsheds" by Katestone Scientific (Katestone, 1997). This report concluded that, for Australian airsheds:

> "There is, as yet, little evidence of inter-shed transport of pollutants that is important in North American and European situations (Katestone, 1997, summary, p.2)"

In the main body of the report (Katestone, 1997, chapter 1, p.1), it is claimed that intra-airshed circulations are more likely to dominate in the future than the inter-airshed transport that dominates adverse European and North American situations.

General features, common to pollutant formation in all Australian airsheds are also identified (Katestone, 1997, chapter 14, p.1):

- Seabreeze-drainage flow circulations are important for all major cities.
- High ozone days usually occur when synoptic conditions delay the flushing of the airshed by the seabreeze front.
- Humidity and increased smoke levels may accelerate photochemical formation.
- High haze days are mainly a winter phenomenon, and require lower temperatures, poor flushing and probably intense radiation inversions (indicated by the temperature range for those days).

2.6. Conclusions

This review of previous air quality studies in the Sydney region has considered the mechanisms for smog and particle formation and transport in the following studies:

- The Sydney Oxidant Study.
- The Sydney Brown Haze Experiment.
- The NSW Department of Planning Pilot Study of air pollution issues in western Sydney.
- The Pacific Power Co-generation Study.
- The Metropolitan Air Quality Study.
- Urban Air Pollution in Australia (particularly Supporting Report No. 1: Anthropogenic Influences in Australian Urban Airsheds).
- The Aerosol Sampling Project (ASP).
- CSIRO aircraft measurements of the plume transport from five major power stations in the Hunter Valley region.

Some consideration was also given to overseas studies of this issue, but it is argued that the conclusions reached in, for example, the OTAG study are specific to that particular region and its emission characteristics.

In general there is significant consistency in the results and identified mechanisms from the various local studies. They show that the following features are important for smog formation in Sydney:

- Accumulation of precursor VOC and NO_x pollutants in overnight and early morning cold air drainage flows.

- Pollutant transport offshore, and return as sea breezes develop in the late morning and early afternoon.

- Highest ozone concentrations, and highest potential for growth in ozone exceedences, in the western parts of the Basin.

- Based on the most recent available airshed modelling (Cope and Ischtwan, 1996), overall higher sensitivity of ozone concentrations to VOC concentrations than to NO_x; in most cases, NO_x control was predicted to be counter-productive.

The review also examined the evidence for inter-regional transport of pollutants from the power stations to the Sydney region. Modelling using LADM (Hyde *et al*, 1997) identified a potential meteorological mechanisms for such transport, and the CSIRO plume tracking measurements (Carras *et al*, 1992a) provided observational evidence for inter-regional transport from the Central Coast power stations towards the northern edge of the Sydney Basin.

However, in spite of this limited qualitative evidence for inter-regional transport, it was not possible to determine the frequency of this process, nor to determine the magnitude of the effects on existing or future air quality in the Sydney region. The IRTAPS results presented in this report address these issues.

3. AIR QUALITY MONITORING DATA

In this component of the project, monitoring data for NO_x, SO_2, O_3 and wind speed and direction were used to identify periods when inter-regional transport of NO_x and some impact on photochemical formation of ozone in the Sydney region may have occurred. The data were provided by the NSWEPA from their network of air quality monitoring stations distributed throughout the Sydney metropolitan area, as well as in locations to the north and south of Sydney. Additional data were also provided by industry, including the power generation industry.

Full details of this assessment are given in the Appendix Volumes. The main features of the analysis are reported and discussed here.

Air quality monitoring data for the two summer periods 1st September 1996 to 30th April 1997, and 1st September 1997 to 30th April 1998 were assessed. Monitoring stations selected for analysis needed to meet the following criteria:

- Be equipped with SO_2 monitors as well as NO_x monitors.
- Be located in areas where local emissions of NO_x from motor vehicles and SO_2 emissions from industrial sources were lower than those in the Eastern part of the Sydney Basin.
- Most likely to be influenced by any inter-regional transport from the three power station regions, based on hypothesized mechanisms for IRT.

On this basis the following monitoring stations were selected:

- Bringelly
- Blacktown
- Richmond
- Vineyard
- Lindfield
- Arcadia

3.1. Analysis of the Monitoring Data

3.1.1. Data Quality

For each selected monitoring station, a time series for each pollutant and meteorological parameter was plotted and examined.

The data were checked and verified for the following:

- Unrealistic values that may have been flagged as valid in the original data. If the value was negative and was not associated with baseline drift (to be described below) it was assumed that the value was a missing value. A total of 101 hours of data were rejected on this basis from a total number of 59,215 possible monitoring site hours ie < 0.18% of the data.

- Zero offsets. A particular problem with the SO_2 data was in prolonged constant excursions from a very low or zero value even when the measurements of other pollutants indicated very low overall concentrations. For these periods the zero value was recalculated, and used to correct the concentrations measured for these periods.

For each selected monitoring station the number of recorded hours of available SO_2 concentration were determined for each selected month. In general, the percentage of hourly acceptable recorded data was greater than 80% although on occasions, particularly for Arcadia the value could be much lower. Indeed, the lowest percentage of hourly acceptable SO_2 data of 10% was recorded at Arcadia during February 97. (Note that complete details of the data availability, for each station, can be found in the Appendix Volume).

3.1.2. Assessment of the Monitoring Data

The following assumptions were used in the assessment of the monitoring data:

- All observed SO_2 was assumed to be derived from the power station emissions. It is recognised that other sources also emit SO_2, but power generation contributes around 60% of SO_2 in the Greater Metropolitan Air Quality Study Region (Carnovale et al, 1996). Therefore assuming all SO_2 derives from power stations is clearly a worst case assumption.

- SO_2 was assumed to be a conserved pollutant. This is not strictly accurate. However measurements of in-plume oxidation by Carras et al (1992a) show that the rate of oxidation of SO_2 to sulfate in the Hunter Valley and Central Coast plumes was less than ~1% per hour. Assuming that plumes from the major power generation regions are travelling at a speed of 5 m/s, then the total amount of SO_2 oxidation within the plume would be approximately 5% for plumes from the Central Coast and Western Region, and 9% for plumes from the Hunter Valley.

On this basis, SO_2 concentrations recorded at the selected monitoring stations were used as an initial filter to identify possible occasions when plumes from the power stations might be transported into the Sydney Basin. Due to the conservative assumption concerning the source of SO_2 the derived frequency of elevated concentrations of SO_2 should be regarded as an upper bound for possible occurrences of long-range transport of power station emissions into the Sydney airshed.

Initially the time series of hourly averaged concentrations of SO_2, NO_x, and O_3 were plotted and examined. In addition the values of SO_2/NO_x and $SO_2 \times NO_x$ were calculated and also plotted. As the ratios of SO_2/NO_x can be very different for different sources, the initial intention was to use the ratios to distinguish power station sources from other sources. Similarly the product of the two concentrations is a simple way of seeing whether the signals from two instruments are approximately correlated.

Examples of some of the data are shown in Figure 3.1. Figure 3.1a shows monitoring data for Blacktown on the 22 January 1997 for SO_2, NO_x and O_3. While there is some correlation between the SO_2 and the NO_x signals the NO_x peak occurred at 0600 hrs while the SO_2 peak occurred 1 hour later at 0700 hrs. The data for Richmond (Figure 3.1B) on 13 March 1998 suggest a correlation between the SO_2 peaks and the O_3 peaks, but no correlation between the NO_x and the SO_2.

As a result of some of the ambiguity in interpretation presented by the data analyses described above, a conservative approach was adopted to the estimation of days which might have been affected by inter-regional transport. This was as follows:

- As standard monitoring instruments for SO_2 have a baseline uncertainty of ~ 0.3 pphm, only those SO_2 concentrations greater than or equal to 0.3 pphm were considered to represent above baseline values.
- The days selected on the above basis were then further screened to reject those days for which ozone concentrations were less than 3 pphm (a value typical of background ozone concentrations). Ozone levels less than this value are unlikely to be of significance for air quality impacts.
- The remaining data were examined in closer detail, and it was assumed that events where ozone concentrations exceeded 8 pphm (80 ppb) anywhere in the Sydney monitoring network exhibited evidence for IRT and an impact on Sydney air quality. This assumption is conservative.

Table 3.1 shows the total number of hours that survived the first criterion above.

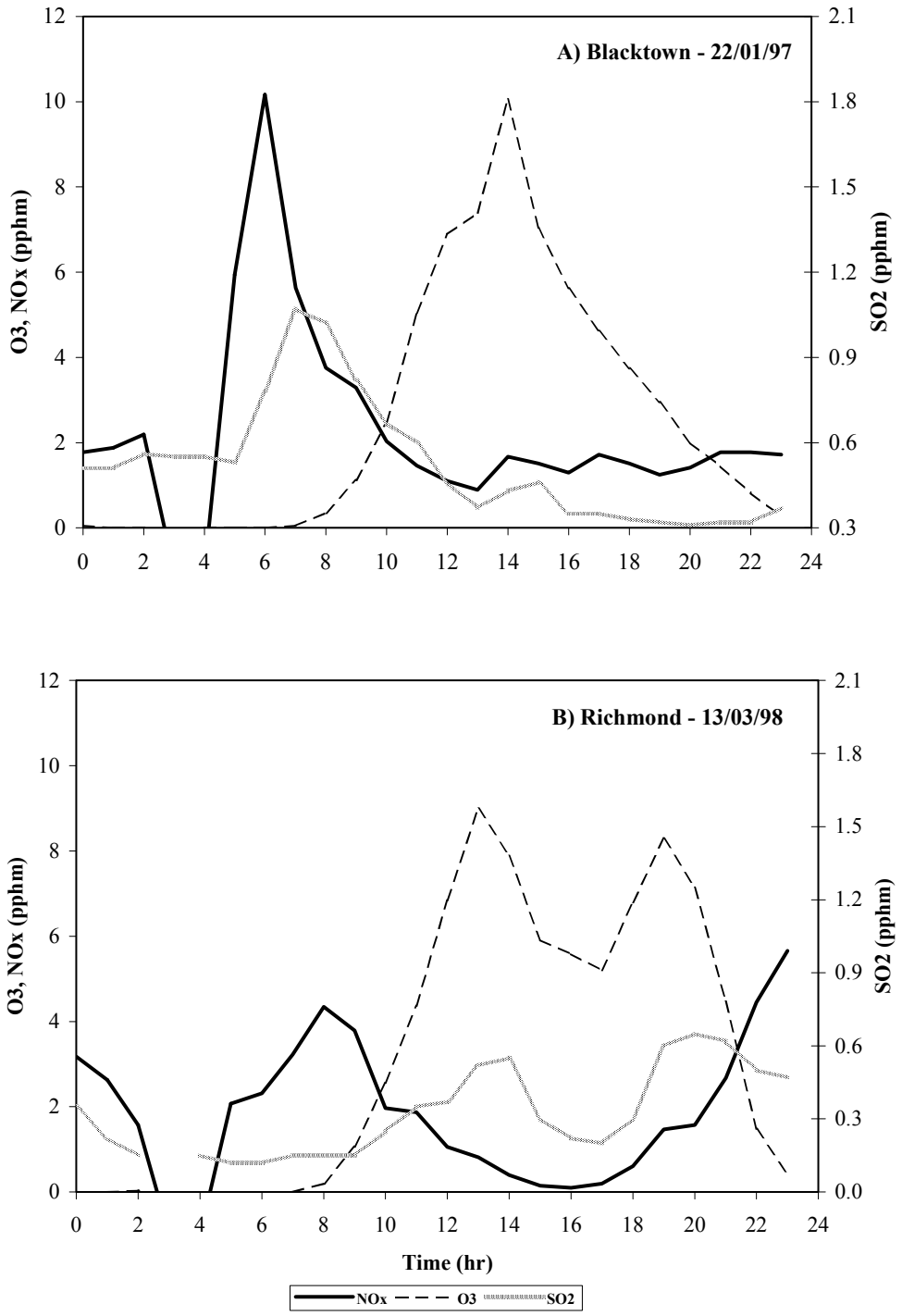

Figure 3.1. An example of data examined in the current assessment.

Table 3.1: Number of hours and percentage of total hours when SO_2 concentration exceeded 0.3 pphm.

Sep 96-Apr 97	Arcadia	Blacktown	Bringelly	Lindfield	Richmond	Vineyard
Hours satisfying filter	296	561	148	2804	388	412
Total possible no. of hours of data	2833	5064	5752	5040	5745	5415
(%)	10.4	11.1	2.6	55.6	6.8	7.6
Sep 97-Apr 98	Arcadia	Blacktown	Bringelly	Lindfield	Richmond	Vineyard
Hours satisfying filter	558	1487	189	679	577	641
Total possible no. of hours of data	4394	4476	5501	4872	4799	5324
(%)	12.7	33.2	3.4	13.9	12.0	12.0

The number of hours and percentage of time for which SO_2 was greater than 0.3 pphm for the first summer period ranged from 148 hours (2.6%) at Bringelly to 561 hours (11%) at Blacktown and 2804 hours (56%) at Lindfield. Note that the monitoring record includes periods with some missing data, so that the frequency of occurrence of concentrations greater than the detection limit could be affected somewhat by periods of missing data. However, the result of this initial filtering of the data showed that detectable concentrations of SO_2 were frequently observed at the monitoring stations. At the Lindfield and Blacktown monitoring stations during the period September 1996 to April 1997, for example, the number of *days* satisfying this criterion was greater than 50%; the frequency at Bringelly was somewhat lower at 26%.

Table 3.2 shows the data that survived the second criterion above ie $SO_2 > 0.3$ pphm and $O_3 > 3$ pphm.

Table 3.2: Number of hours and percentage of total hours when SO_2 concentration exceeded 0.3 pphm and O_3 exceeded 3 pphm.

Sep 96-Apr 97	Arcadia	Blacktown	Bringelly	Lindfield	Richmond	Vineyard
Hours satisfying filter	2	59	50	353	106	47
Total possible no. of hours of data	2833	5064	5752	5040	5745	5415
(%)	0.1	1.2	0.9	7.0	1.8	0.9
Sep 97-Apr 98	Arcadia	Blacktown	Bringelly	Lindfield	Richmond	Vineyard
Hours satisfying filter	45	208	93	189	201	194
Total possible no. of hours of data	4394	4476	5501	4872	4799	5324
(%)	1.0	4.6	1.7	3.9	4.2	3.6

Notice that the number of hours has now fallen significantly. For instance the 2804 hours at Lindfield during 1996/97 (Table 3.2) has now fallen to 353 hours satisfying the stricter criterion.

Table 3.3 shows the result of the final process where the data have been screened for ozone concentrations greater than 8pphm.

Table 3.3: Number of hours and percentage of total hours when SO_2 concentration exceeded 0.3 pphm and O_3 exceeded 8 pphm.

	Arcadia	Blacktown	Bringelly	Lindfield	Richmond	Vineyard
Sep-96	0	0	0	0	0	0
Oct-96	0	0	0	0	0	0
Nov-96	0	0	0	0	0	0
Dec-96	0	0	1	0	0	0
Jan-97	0	0	1	0	0	0
Feb-97	0	2	1	0	0	1
Mar-97	0	0	0	0	0	1
Apr-97	0	0	0	0	0	0
Total	0	2	3	0	0	2
Total no. of hours	2833	5064	5752	5040	5745	5415
(%)	0	0.04	0.05	0	0	0.04
	Arcadia	Blacktown	Bringelly	Lindfield	Richmond	Vineyard
Sep-97	0	0	0	0	0	0
Oct-97	0	0	0	2	0	0
Nov-97	0	7	1	10	3	2
Dec-97	0	2	0	2	5	3
Jan-98	0	3	1	0	2	4
Feb-98	0	5	6	5	0	0
Mar-98	0	0	2	5	2	0
Apr-98	0	0	0	0	0	0
Total	0	17	10	24	12	9
Total no. of hours	4394	4476	5501	4872	4799	5324
(%)	0	0.4	0.2	0.5	0.3	0.17

The data in Table 3.3 show that for the 96/97 summer 7 station-hours satisfied the strictest criterion imposed, distributed as follows: 2 hours at each of Blacktown and Vineyard, and 3 hours at Bringelly. For the 97/98 summer the number of hours that met the strictest criterion was observed to increase substantially. Lindfield recorded 24 hours that satisfied this criterion, representing 0.5% of the total number of recorded hours, but Arcadia did not show any hours that complied with the selected criterion. Hence, there is evidence for both spatial and temporal variability in those observations which satisfied the strictest criterion.

The data in Table 3.3 can also be expressed in terms of the number of *days* when ozone concentrations exceeded 8 pphm at any monitoring location in the Sydney region. In total 38 days were found to pass this filter.

In addition to the 38 days from the filtered data set, 10 additional days were identified during the selected time periods, where ozone exceeded 8 pphm, but which did not satisfy the filtering criteria. In order to ensure that all days on which significant ozone was observed in the Sydney region were considered these ten days were also included in the data set for further detailed analysis. On this basis a total number of 48 days were selected for further detailed analysis. A subset of 5 events was subsequently chosen for detailed chemical modelling, as described in Section 4.

3.2. Summary of Data Analysis

All days when the SO_2 data from the monitoring stations exceeded the baseline value of 0.3 pphm and when the ozone concentration at any site in the Sydney domain was greater than 80 ppb were considered to have potentially resulted from inter-regional transport of power station plumes. This resulted in 38 separate days. In addition 10 further days when the ozone exceeded 8 pphm, but which did not satisfy the SO_2 filtering criterion were also included giving an upper bound of 48 days where the 80 ppb was exceeded. These days were further examined to provide a base set for detailed chemical modelling as described in section 4.

4. AIR QUALITY MODELLING OF INTER-REGIONAL TRANSPORT AND ASSOCIATED IMPACTS

Three approaches were used to model the frequency and impacts of power station NO_x transport to the Sydney region. These were:

1. Modelling of the power station plumes with NO_x treated as a conserved tracer. Maximum NO_x emissions were assumed for each power station with the objective of assessing the frequency of inter-regional NO_x transport.

2. Modelling two summers with actual power station NO_x emissions and simplified photochemistry. The Generic Reaction Set (GRS) simplified photochemical mechanism (Azzi, M. et al 1992) was used to model photochemical smog production, with the objective of assessing the frequency of photochemical ozone production due to the inter-regional transport of power station NO_x emissions.

3. Modelling of selected event days with actual NO_x emissions and detailed photochemistry included. The event days were based on evidence of IRT and smog production in the Sydney region. Detailed chemistry was used for photochemical smog production with the objective of assessing the occurrence of photochemical ozone during specific events including the impacts of power station NO_x transported to the study region.

These three approaches are described in sections 4.1 to 4.3 below.

4.1 Modelling the Power Station NO_x as a Conserved Tracer

Evidence for the frequency of IRT was assessed using The CSIRO Air Pollution Model (TAPM). TAPM is a non-hydrostatic three-dimensional prognostic model able to simulate every hour of a year at fine resolution (*e.g.* 3 km grid) in a manageable time. TAPM is described in detail in Hurley (1998).

TAPM was used to model all hours of the periods 1st September 1996 to 30th April 1997, and 1st September 1997 to 30th April 1998. TAPM directly uses the analyses of the Bureau of Meteorology and responds to the effects of local terrain, cloud cover, surface roughness and other surface properties and land-sea contrasts.

The model was used to simulate the emission of tracers from each of the power stations using stack parameters and operating conditions provided by the power stations. In order to assess the worst-case impacts, the modelling was carried out using the maximum possible emission rates of NO_x from the power stations.

Concentrations of NO_x for the entire modelling domain were generated for each hour of the modelling period.

The hour-by-hour data sets produced by TAPM have been used in several ways:

- The data sets have been filtered to identify occasions for potential IRT for emissions from each of the three power-generating regions (Hunter Valley, Central Coast and Western).

- The modelled ground level tracer concentrations (upper limits because of the assumption that the power station emissions were the maximum possible) at monitoring stations in

the Sydney region have been used to calculate frequency distributions of ground level NO_x concentrations, as contributed by the power stations. These have then been compared with observed NO_x distributions.

Using the TAPM post processing facility, the output data from TAPM were examined visually to identify those days where plumes from the power generation sources impacted on the Sydney Region. Two threshold criteria were adopted to indicate plume impact. These were NO_x concentrations of 5 $\mu g\ m^{-3}$ and 10 $\mu g\ m^{-3}$. The lower value (5 $\mu g\ m^{-3}$) chosen for the NO_x cut off is a value that is close to the threshold of detection of a monitoring instrument. In all, and based on the 5 $\mu g\ m^{-3}$ concentration threshold analysis, 49 days out of 484 days showed some evidence for transport of NO_x emissions from power stations into the Sydney Basin.

The data for 10 $\mu g\ m^{-3}$ (a value slightly above baseline concentrations) are presented in Figure 4.1 and show that the impact of plumes from the Central Coast and the Hunter Valley areas had relatively similar impacts on the Sydney region but impacts from the Western region power plants were clearly smaller. Comparisons between TAPM modelling and observations (see Appendix Volumes) also showed that, on average, concentrations due to contributions from power station emissions were significantly less than total NO_x concentrations (see also Section 4.2).

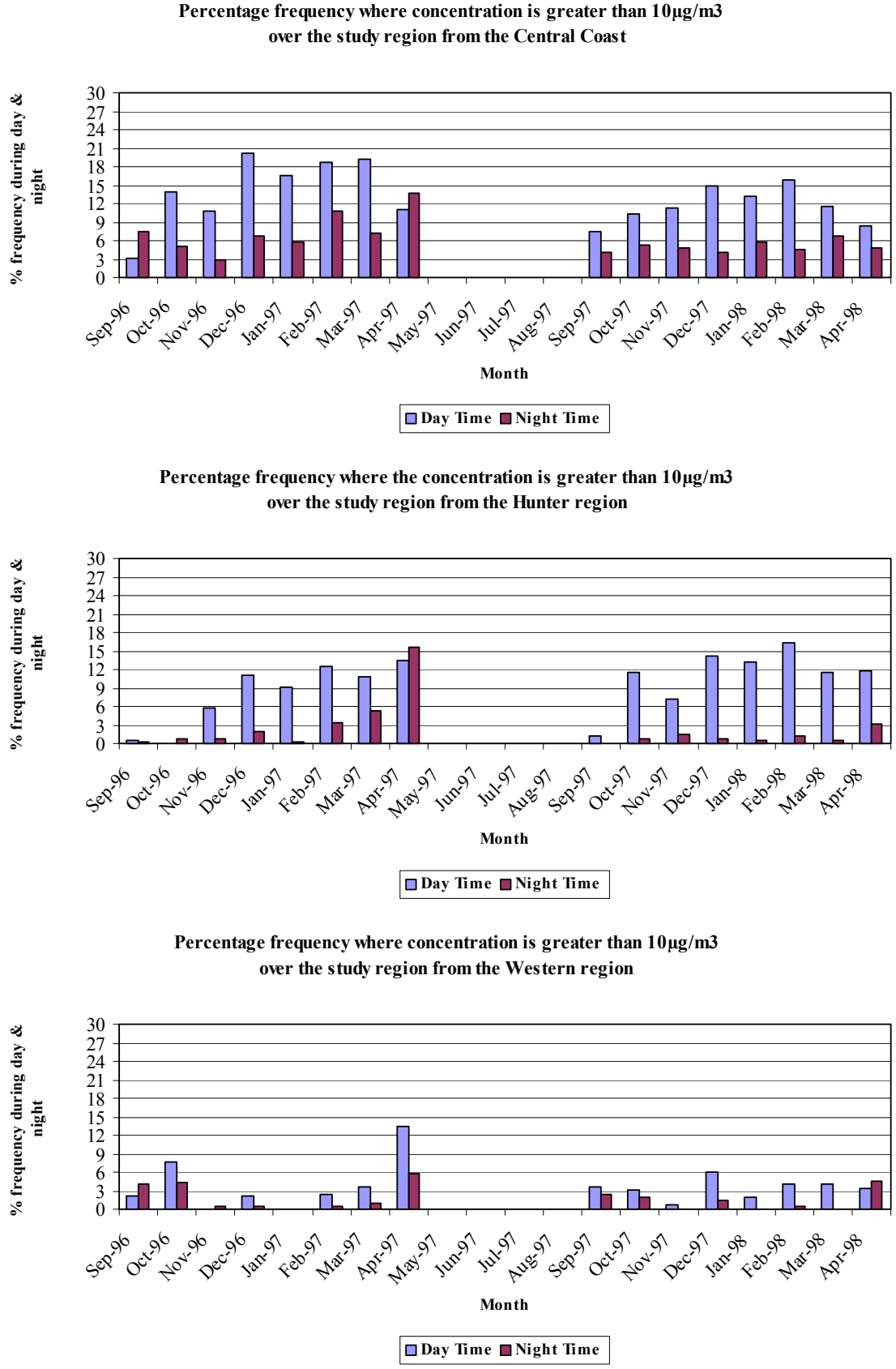

Figure 4.1. Percentage frequency of hours when concentration was greater than 10 µg m^3.

4.2. Modelling Power Station NO_x with Simplified Photochemistry

4.2.1 Modelling Approach

The effects of power station emissions on smog formation in the Sydney region can be best assessed using a modelling approach. In this section results obtained using TAPM to model seven months are reported. (Note more detailed modelling of individual days with high ozone concentrations are discussed in Section 4.3). The advantage of TAPM is its ability to generate predictions for long time periods. However this must be done with a simplified description of the smog formation chemistry, and without careful optimisation of model performance, as is possible for detailed modelling of individual days. Because of this the best use of the TAPM output is to look at overall impacts, and not to examine the prediction of pollutant concentrations as a function of space and time.

The modelling approach described in this section is as follows:

1. TAPM was used to simulate the meteorological and air quality fields (NO_x, NO_2 and O_3) for the Greater-MAQS region for two summer periods.

2. The model performance for these base-case simulations was analysed by comparison of observed and modelled 1-hour frequency distributions of the species listed above, where available.

3. One of the summer periods was selected on the basis of model performance and the frequency of IRT, and used to conduct three test-case simulations. These were:

    a) Removal of emissions from the Central Coast power stations.

    b) Removal of emissions from the Hunter Valley power stations.

    c) Removal of emissions from the Western power stations.

4. The differences between the base-case and test-case simulations described above were analysed. Consideration was also given to the differences in frequency and magnitude of the observed and modelled 1-hour concentrations of O_3, and the differences in the frequency and magnitude of the observed and modelled 1-hour concentrations of NO_2.

The test case simulations were performed for a seven-month period (January-April 1997, and January-March 1998) in order to provide more confidence in the predicted impacts. April 1998 was not included in the analysis because there was no evidence for IRT in this period (as determined by the examination of the monitoring record and the plume modelling).

While it is not unusual for Air NEPM standards for ozone to be exceeded in the Sydney region, it is difficult to detect any clear trends in the number of exceedences (NSWEPA, 2001). In 1998, the 1-hour standard (10 pphm) was exceeded on 13 days in the Sydney region, compared with 14 days in 1997 (NSWEPA, 2001). There is, however, significant annual variability in the 1-hour average concentrations, and the maximum concentrations observed (NSWEPA, 2001). In the period 1988–93 the Air NEPM standard was exceeded on fewer than 10 days annually, whereas in 1994 the standard was exceeded on 13 days, and in 1995 and 1996 there were very few days when the standard was exceeded. Consequently, the choice of time periods for modelling in this work corresponds to periods when the annual exceedence frequency was toward the higher end of the frequency distribution.

4.2.2. Emission Inventory Development

4.2.2.1. Background

Modelling of the impacts of the power station plumes on photochemical smog formation in the Sydney region requires:

- Meteorological information.
- An emissions inventory for the Sydney region, and the surrounding areas including the power stations.
- A description of the photochemistry.
- A suitable model which uses the above information as input to produce predictions of concentrations of pollutants as a function of space and time.

Previous inventories have been calculated for the greater Sydney region and used as the basis for predictions of air quality for the MAQS study (Carnovale *et al*, 1996; Cope and Ischtwan, 1996). There were a number of problems with the use of this inventory. The MAQS inventory was developed for the base year of 1992, and there have been significant changes in population and other factors, which influence the emissions, since that time and the time period modelled in the present study (1996-1998). In addition, the commercial components of the MAQS inventory are not publicly available, and permission for their use in the present study could not be obtained from the NSW EPA.

Hence, an inventory, which reproduces the major features of the 1992 MAQS inventory, was developed specifically for this study. This was done as follows:

- The population dependent components of the inventory were updated.
- Inventory data bases in TAPM-ready format were prepared.
- The inventory was validated through comparison (where appropriate) with inventory emission estimates provided in the MAQS- Inventory Report.

Emissions of volatile organic compounds (VOCs) and NO_x were also estimated for each individual grid cell in the MAQS region.

4.2.2.2. Study Area

The Metropolitan Air Quality Study Region (MAQSR) measures 150 km (east-west) by 201 km (north-south). The region was subdivided into a network of 3 km × 3 km grid cells to provide acceptable spatial resolution.

A number of major sources located to the north and north-west outside the MAQS region were also considered.

4.2.2.3. Population

Census data from 1996 (Australian Bureau of Statistics, ABS) at the Collection District (CD) level was used to calculate the population per grid cell. These data were used to determine the population for each 3 km × 3 km grid cell in the MAQS region.

The population in the MAQSR in 1996 was estimated to be 4.310 million with the highest population in any grid cell being approximately 66,000. A three-dimensional plot of population per grid cell in MAQSR for the year 1996 is given in Figure 4.2.

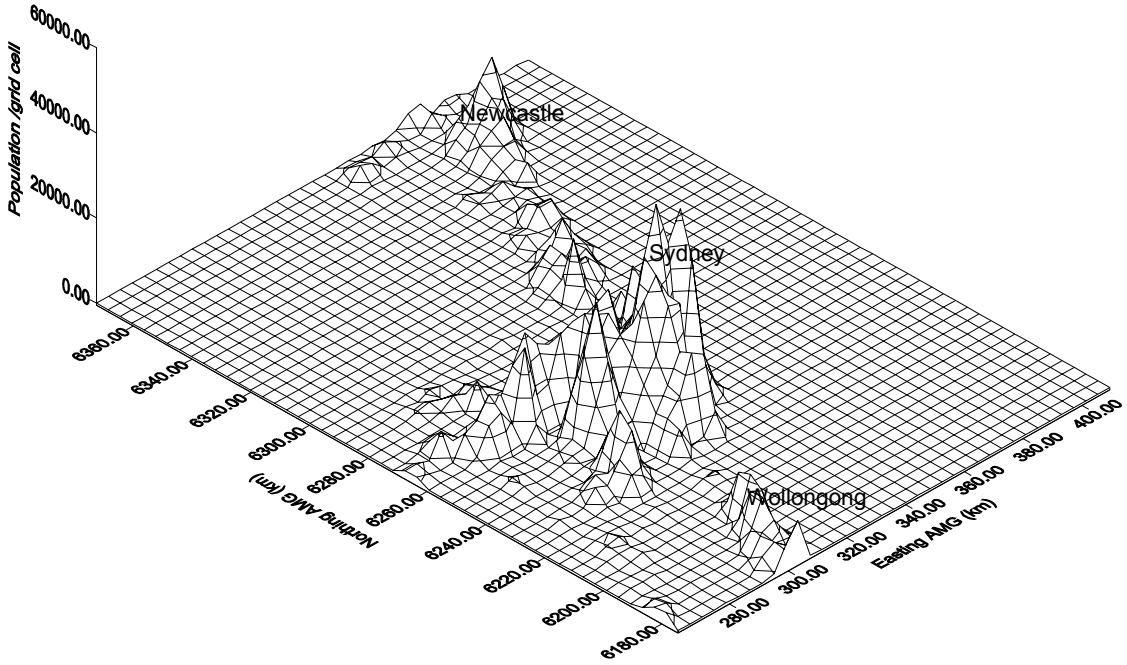

Figure 4.2. Three-dimensional plot of the estimated population per grid cell, 1996.

4.2.2.4. Area Based Sources

Area based sources considered in this study were identified by MAQS and include the domestic/commercial application of surface coatings, service station and petrol refuelling losses, lawn mowing, domestic/commercial aerosol used and the combustion of gas, liquid and solid fuels.

For any given grid cell, the emission from a population dependent emission source was calculated as the product of total regional emission (for a given source category) and the ratio of grid cell population to regional population. Using the population of 1996, source strengths of NO_x and VOC emissions have been calculated and are illustrated in Figure 4.3 and Figure 4.4.

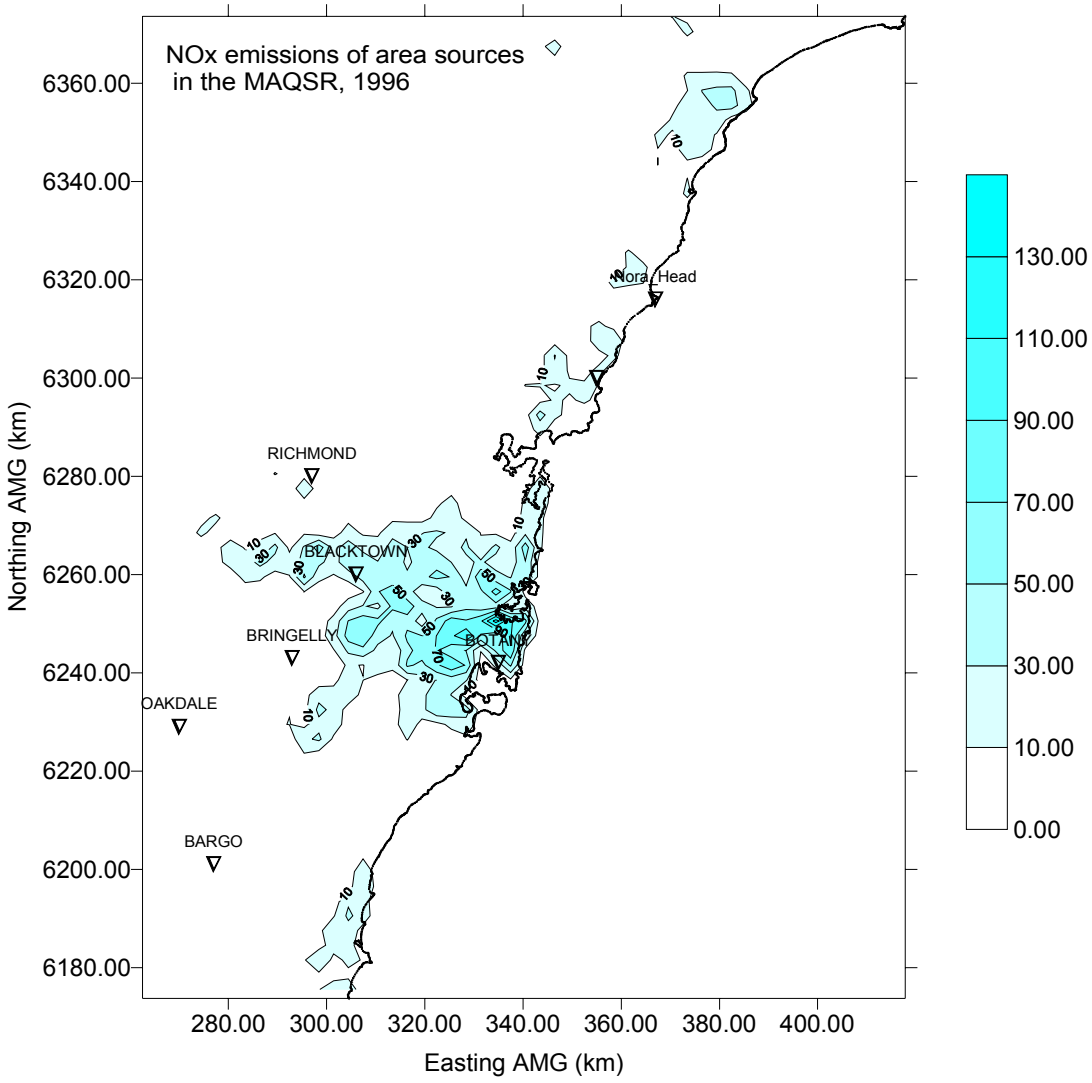

Figure 4.3. NO_x emissions (kg/grid cell/day) from area sources for MAQSR, 1996.

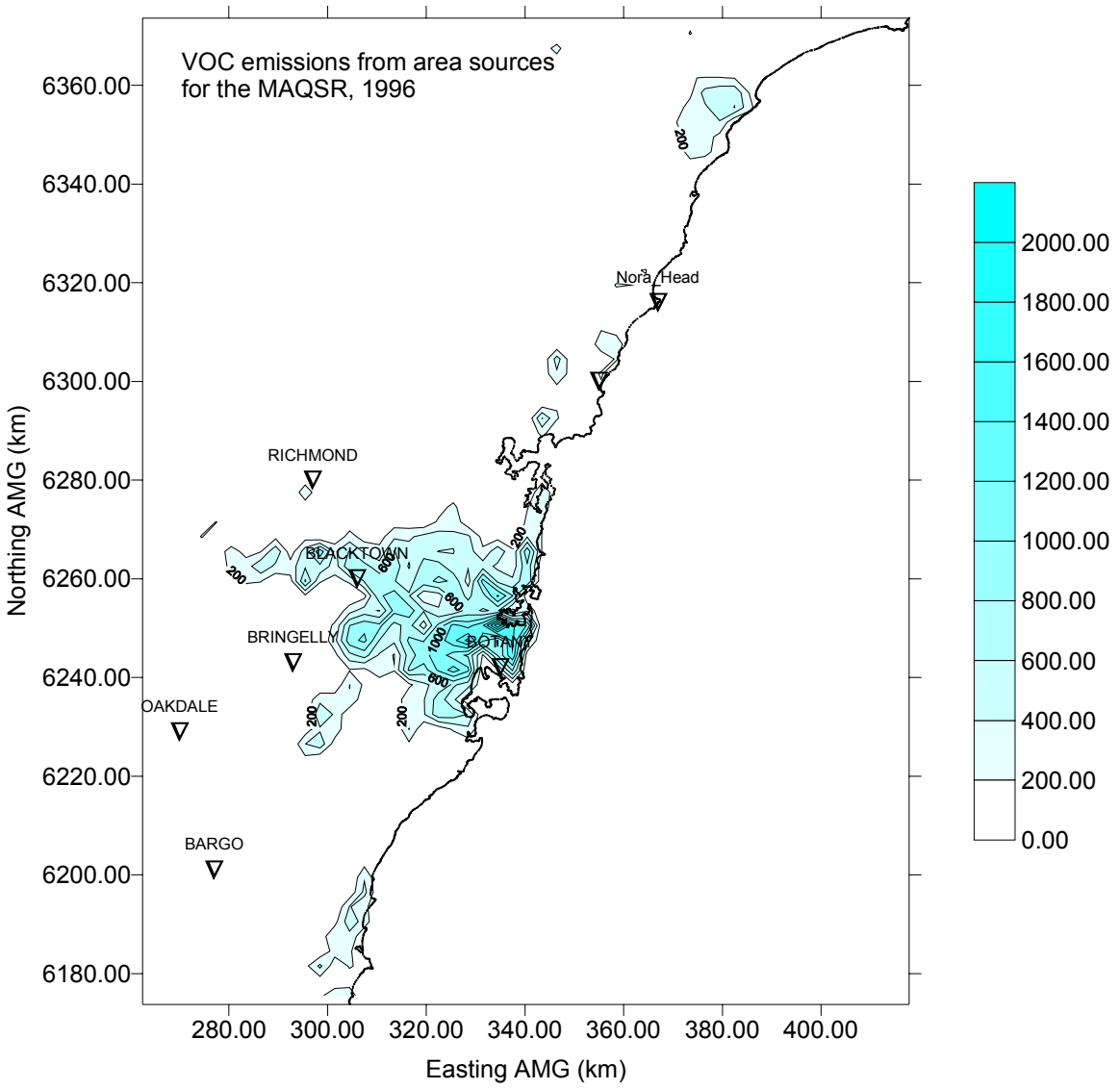

Figure 4.4. VOC emissions (kg/grid cell/day) from area sources for MAQSR, 1996.

4.2.2.5. Mobile Sources

In order to establish an inventory of emissions from motor vehicles for the MAQS region an estimate of vehicle kilometres travelled (VKT) was required at a resolution of 3 km × 3 km. The existing 1992 VKT data at the grid cell level for the entire MAQSR was updated to the year 1996 using a constant factor of 7.2% as reported in the "NSW State of the Environment" report 1997 (NSWEPA, 1997). The updated VKT data file was then used to estimate the amount of motor vehicle exhaust emissions of NO_x and VOC per day per grid cell in the greater MAQS region on a high oxidant day.

A summary of daily cell emissions from the MAQSR for the motor vehicle fleet is presented in Figures 4.5 and 4.6.

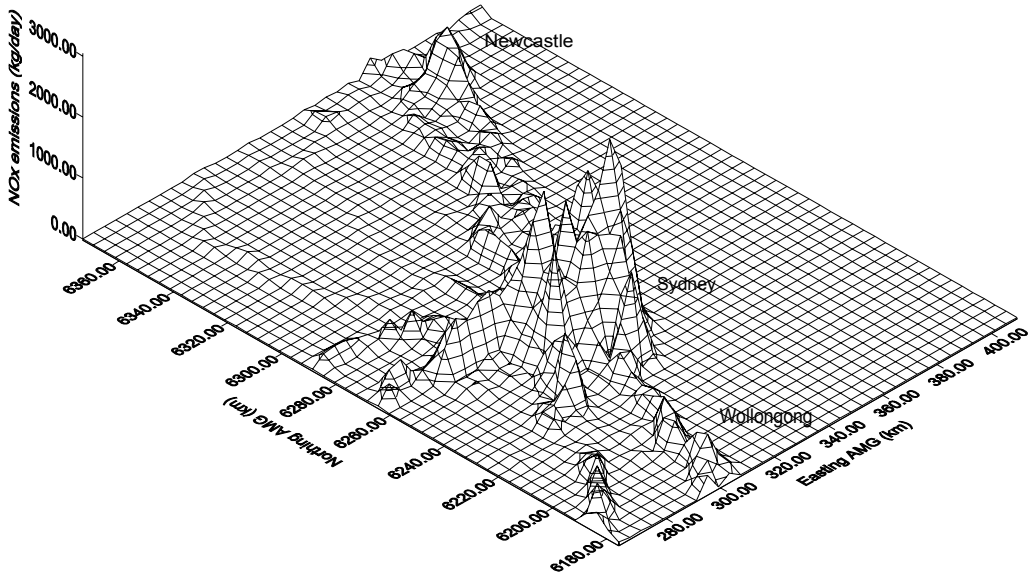

Figure 4.5. NO_x emissions (kg/grid cell/day) from motor vehicles for a high oxidant day in MAQSR, 1996.

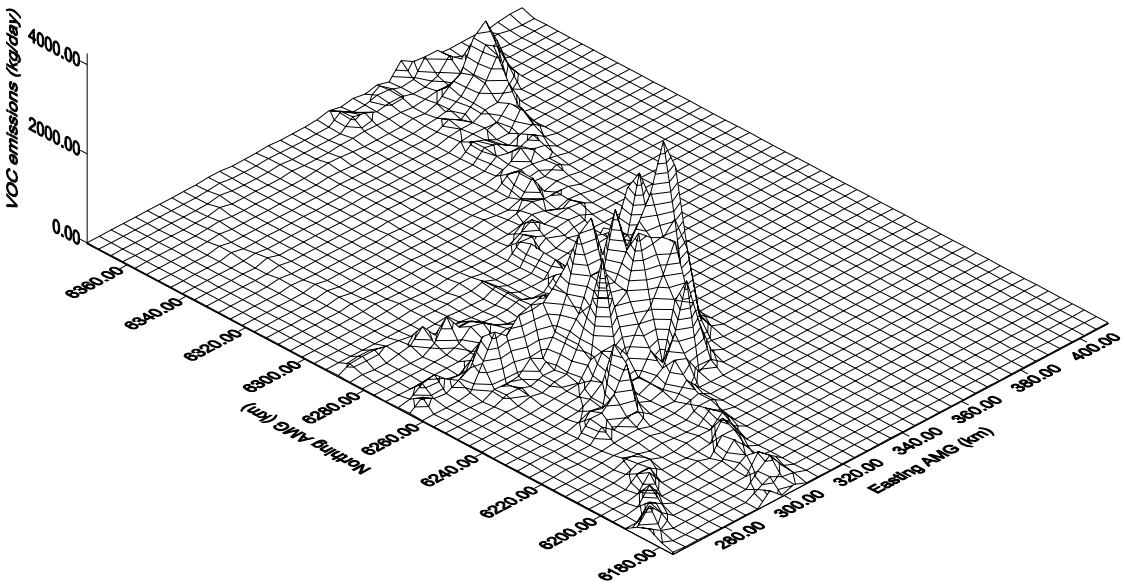

Figure 4.6. VOC emissions (kg/grid cell/day) from motor vehicles for a high oxidant day in MAQSR, 1996.

4.2.2.6. Biogenic Emissions

Natural emissions of volatile compounds are an important determining influence on the trace composition of the atmosphere, and the global carbon cycle. On a global scale, natural emissions of nitric oxide (NO), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOC) are substantial in comparison to man-made or anthropogenic emissions, although in urban locations, anthropogenic sources usually dominate ambient concentrations of these species.

Vegetation has been known to be a significant source of NMVOC since the pioneering studies of Went (1960), and Zimmerman (1979). However, the role of natural emissions of NMVOCs in photochemical smog formation was neglected until modelling studies of Chameides *et al* (1988), amongst others. They showed that these species could act as a sink for ozone or contribute to photochemical smog formation in urban and rural areas, depending on the availability of NO_x.

Emissions of NMVOCs from trees and other forms of vegetation, include:

- Isoprene, or 2-methyl-1,3-butadiene (C_5H_8).
- Monoterpenes, such as α- and β-pinene ($C_{10}H_{16}$), and oxygenated monoterpenes such as 1,8-cineole ($C_{10}H_{18}O$, also known as eucalyptol)
- Oxygenated hydrocarbons, for example aldehydes, ketones, alcohols etc.

The influence of species type, leaf temperature and photosynthetic photon flux density is known to affect emission rates of these species, and as a consequence the influence of these factors has been extensively studied.

Biogenic emissions can make a substantial contribution to the background ozone-forming potential of the troposphere. Hence estimation of biogenic emissions for the modelled region is an important component of the emissions inventory.

For this project biogenic emissions of isoprene and monoterpenes were estimated according to a model developed for the 1992 MAQS inventory (Carnovale *et al*, 1996). The model uses species emission rates, scaled for effects of sunlight and temperature, and spatially resolved biomass information. Biogenic emissions are estimated on an hourly basis for every land-based grid point using a gridded database of landuse category, and forecasts of leaf-temperature and sunlight. The emissions inventory of ROC was also modified to incorporate the results of a recent Sydney-based study into biogenic emission rates from trees and grasses (Nelson et al., 2000).

4.2.2.7. Industrial and Commercial Point Source Inventory

As noted above, the MAQS emission inventory for industrial and commercial point sources was not available for the current study. Hence, for the current assessment, VOC and NO_x emissions have been estimated from most of the most significant industrial premises in the MAQSR using the following procedures.

Identification of Sources

A list of pollution sources within the Greater MAQS region outlined in the MAQS Report (1996) was extracted from the National Pollutant Inventory (NPI) by searching the database of "Substance Information" i.e. seeking out emitters of NO_x and VOCs. This initial list was augmented by manually searching the NPI database and identifying any industries which could be possible NO_x or VOC emitters, but were not reported as such in the NPI.

It was found that in some cases data from the NPI was incomplete for the requirements of the inventory. The World Wide Web was one tool used to identify sources not registered on the NPI. Industrial and governmental web sites provided information on different industries. Sites used included the Australian Institute of Petroleum at http://www.aip.com.au/, the Australian Aluminium Council at http://www.aluminium.org.au/ and the Department of Industry, Science and Resources at http://www.isr.gov.au/.

For some industries there were a large number of point sources emitting low levels of NO_x and VOCs. Most of these industries are distributed across the region, and consequently documenting each and every source was not possible. A survey of relevant literature such as industrial databases and business registers was performed to determine an approximate geographical distribution of these industries within the region being modelled. The knowledge and experience of the CSIRO staff was also used to identify potential sources and distribute emissions accordingly.

Once a final list of emitters was established, the individual sources were divided into appropriate groupings corresponding to those sectors of the MAQS report. On the basis of the methods described above, it was found that the emissions calculated using these approaches accounted for 90% of the emissions reported in the MAQS inventory (Carnovale *et al*, 1996). The additional emissions were distributed on a population basis.

Inventory Requirements

The inventory required the following data from each discrete source:

Location – AMG coordinates;

The location of a source was provided by the NPI in the form of AMG coordinates, but for any sources not identified in the NPI, topographic maps and information from the Australian Surveying & Land Information web site were used to determine exact positions.

NO_x & VOC Emissions;

Emission data in the NPI are presented in kg/year. These data were converted into kg/weekday assuming that there are 201 weekdays per year[1]. In some cases the NPI did not present NO_x and VOC emission data, therefore their emissions had to be estimated by other means. The methodology for estimating these emissions varied according to the characteristics of the sector in question. The different methodologies, and the sectors they were used with, are described below:

[1] This conversion is based on industry surveys across a range of industries (N. Wong, EPAV, private communication)

1. *USEPA Emission Factors* - "Compilation of Air Pollutant Emission Factors AP-42, Fifth Edition, Volume I : Stationary Point and Area Sources" from the U. S. Environmental Protection Agency was used to estimate emissions in the "Non-Metallic Mineral Processing" sector. Production figures for the three major cement manufacturing plants in the region were obtained from the companies themselves, then, using the emission factors provided, daily emissions were estimated.

2. *Industry Survey by Area* - For sectors such as "Printing" and "Fabricated Metals" contributing point sources are spread over different areas within the region. In order to quantify the geographical distribution of these sources, surveys of different commercial and industrial databases were carried out to identify significant areas. One particularly useful database was the "Yellow Pages On-line". This provided a search within a particular industry from which it was possible to determine the number of potential emitters in an area. The "Total Weekday Emissions" presented in the MAQS report were then proportioned to different areas of the region according to the number of potential emitters in the area.

3. *MAQS Distribution* - The MAQS report presented spatial distributions of emissions for certain sectors e.g. "Commercial Shipping", "Marine Pleasure Craft" and "Rail Transport". Combining the "Total Weekday Emissions" with the spatial distribution enabled the identification of the major emission areas and the proportioning of the emissions accordingly.

4. *Production Distribution* - In the case of "Basic Metal Processing" the steelworks located in the region make up the majority of the NO_x emissions for that sector. Assuming comparable production methods, fuel usage and consequently NO_x generation rates, production figures for the different locations were used to assign total emissions from the sector.

Data Verification

The "Evaluation of air quality issues for the development of Macarthur South and South Creek Valley regions of Sydney: Pilot Study" Hyde, R. and Johnson, G.H. (1990) and the MAQS inventory (Carnovale *et al* 1996) were used to compare the new inventory with the geographical distribution of NO_x emissions in the Sydney basin. Broad agreement was observed.

The inventory used in the current project was based on, and hence, in good agreement with the MAQS inventory, but was updated as described to 1996 using population data. In some important respects the inventory approach used here represents an advance on the MAQS inventory. For example, power station emissions of NO_x (which account for about 70% of industrial NO_x) were based on hour-by-hour load information and relationships provided by the generators. This is the best possible source of accurate power station emissions data. The best available information on industrial (non-power station) sources of NO_x and VOCs was used to estimate industrial emissions.

The US EPA emission factors were used to check emission data for industries where relevant production data was available. Figure 4.7 and Figure 4.8 show the spatial distribution and source strengths of NO_x and VOC sources from industrial and commercial sources calculated using the above procedures. These figures do not include power station emissions, which were estimated as described in the following section.

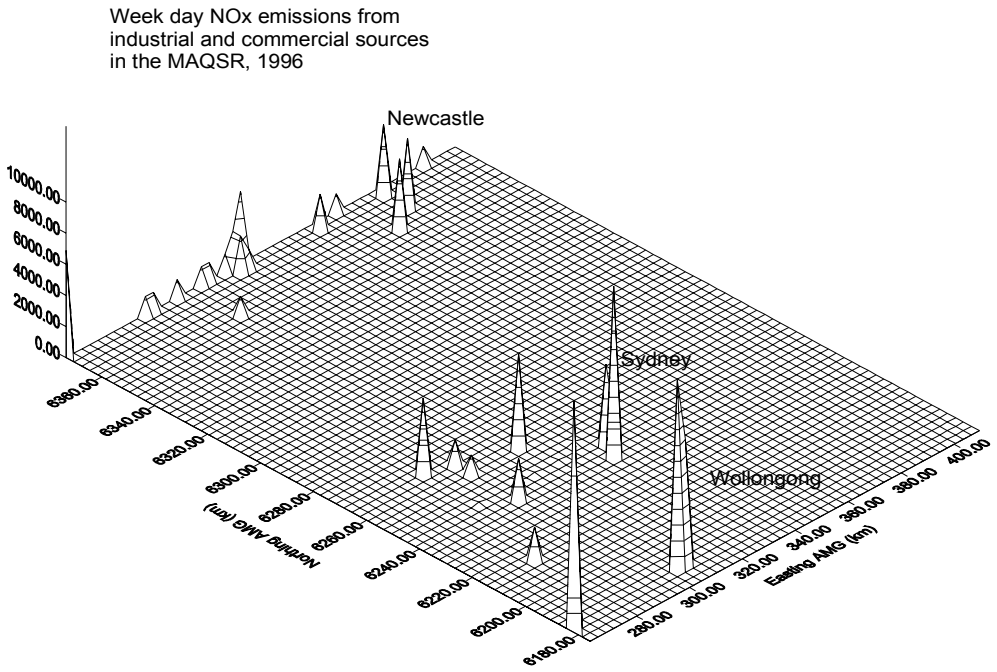

Figure 4.7. NO_x emissions (kg/grid cell/day) from industrial and commercial sources for MAQSR 1996.

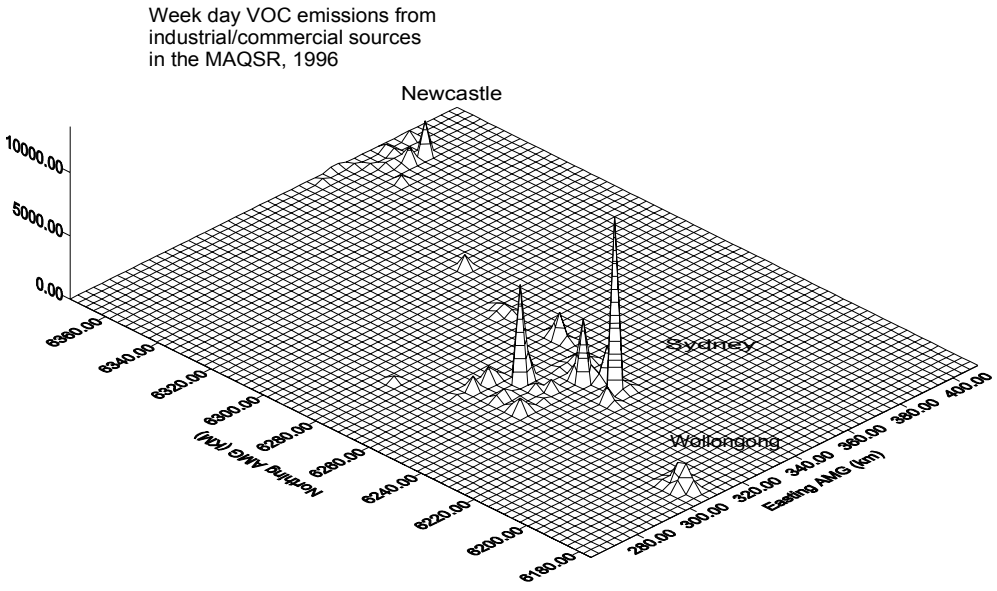

Figure 4.8. VOC emissions (kg/grid cell/day) from industrial and commercial sources for MAQSR 1996.

Power Station NO_x Emissions

Power station NO_x emissions are related to furnace load. For the purposes of this study data on the relationship between load and NO_x emission were provided by the power generators for each of the power stations in the study region. Load data for each hour of the study period were also provided, and using the load-NO_x relationship, hourly emission rates of NO_x were determined. This approach provides a more accurate estimate of these emissions than one based on generic average emission rates.

4.2.3. Results

A complete description of the setup of TAPM for this modelling task is given in the Appendix Volume. In brief, the power stations were classed into three geographical groups designated as Central Coast (Eraring, Vales Point and Munmorah power stations), Hunter Valley (Bayswater and Liddell) and Western Coalfields (Mount Piper and Wallerawang). Figure 4.9 shows the domains used in the calculations.

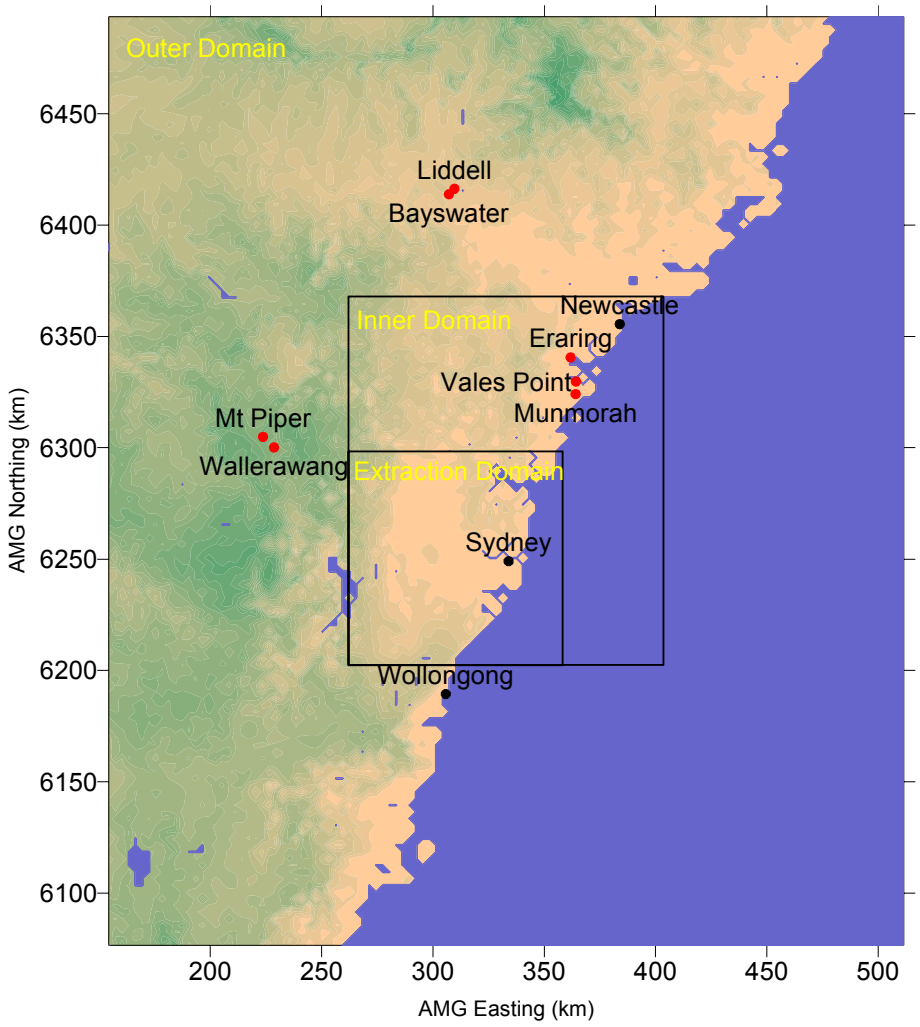

Figure 4.9. Modelling domains for use with TAPM.

Time series data for wind speed, wind direction, temperature, NO_x, NO_2, SO_2 and O_3 were extracted for all grid cells in both the inner and outer domains. All comparisons with observed data were provided by comparing model results from the inner domain with unmodified data provided by the NSWEPA. Supplementary data analyses were performed for an extraction domain as depicted in Figure 4.9, which is equivalent to the Sydney Region domain of the MAQS report.

4.2.3.1. Pollutant Frequency Distributions

Performance of TAPM with respect to meteorological parameters such as temperature, wind speed and direction are discussed in detail in the Appendix Volume. Figure 4.10 shows some of the meteorological data compared with the TAPM predictions for Lindfield. In general, the meteorological parameters predicted using TAPM were in reasonable agreement with the observations keeping in mind that the comparisons are being made for data paired both in space and time. For wind speed greater than ~1.5 m/s TAPM performed well relative to observed parameters. For low wind speeds the differences were greater. As the purpose of the current study is to identify long-range transport where the winds are usually greater than 3 m/s, it is concluded that TAPM outputs can be used with a relatively high degree of confidence.

Results for TAPM predictions and observations for NO_x for the seven months considered and for seven monitoring stations in the NSW EPA network are given in the Appendix Volumes. Figure 4.11(a) shows the cumulative frequency distributions (for January 1997) for the measurements and predictions for the monitoring stations at Blacktown, Bringelly, Lindfield, Liverpool, Oakdale, Richmond and Woolooware. As illustrated in Figure 4.11(a), the frequency distribution of concentrations of NO_x were predicted reasonably well for Bringelly and for Oakdale, but it is clear that at the remaining sites, particularly Blacktown, Lindfield, and Liverpool, TAPM predictions consistently exceeded the observed frequency distributions.

The reasons for this discrepancy between observed and predicted NO_x concentrations were exhaustively examined. Inventory inputs were carefully checked for consistency (for example, by calculating the ratio of VOC/NO_x), and shown to be accurate. Uncertainties in the emission inventory for NO_x could be responsible for some of the difference, as could uncertainties in the timing of emissions and the fact that emissions are held constant for each hour. Although these uncertainties undoubtedly contribute, a close examination of the time series of predicted and observed NO_x concentrations suggest an alternative explanation which may be responsible for the major part of the disagreement. The largest differences occurred under stable conditions, usually in the early morning when there are high emission rates of NO_x from motor vehicles. Under these conditions, TAPM tends to under-predict wind speed. It is also likely that the effective mixed layer height is under-predicted, although in that case there is no direct data comparison. These two factors together result in over-prediction of NO_x at specific times and particularly at monitoring sites located in regions of high motor vehicle emissions. This result does not significantly impact on the ability of TAPM to predict inter-regional transport because the latter is not dominated by conditions at the surface.

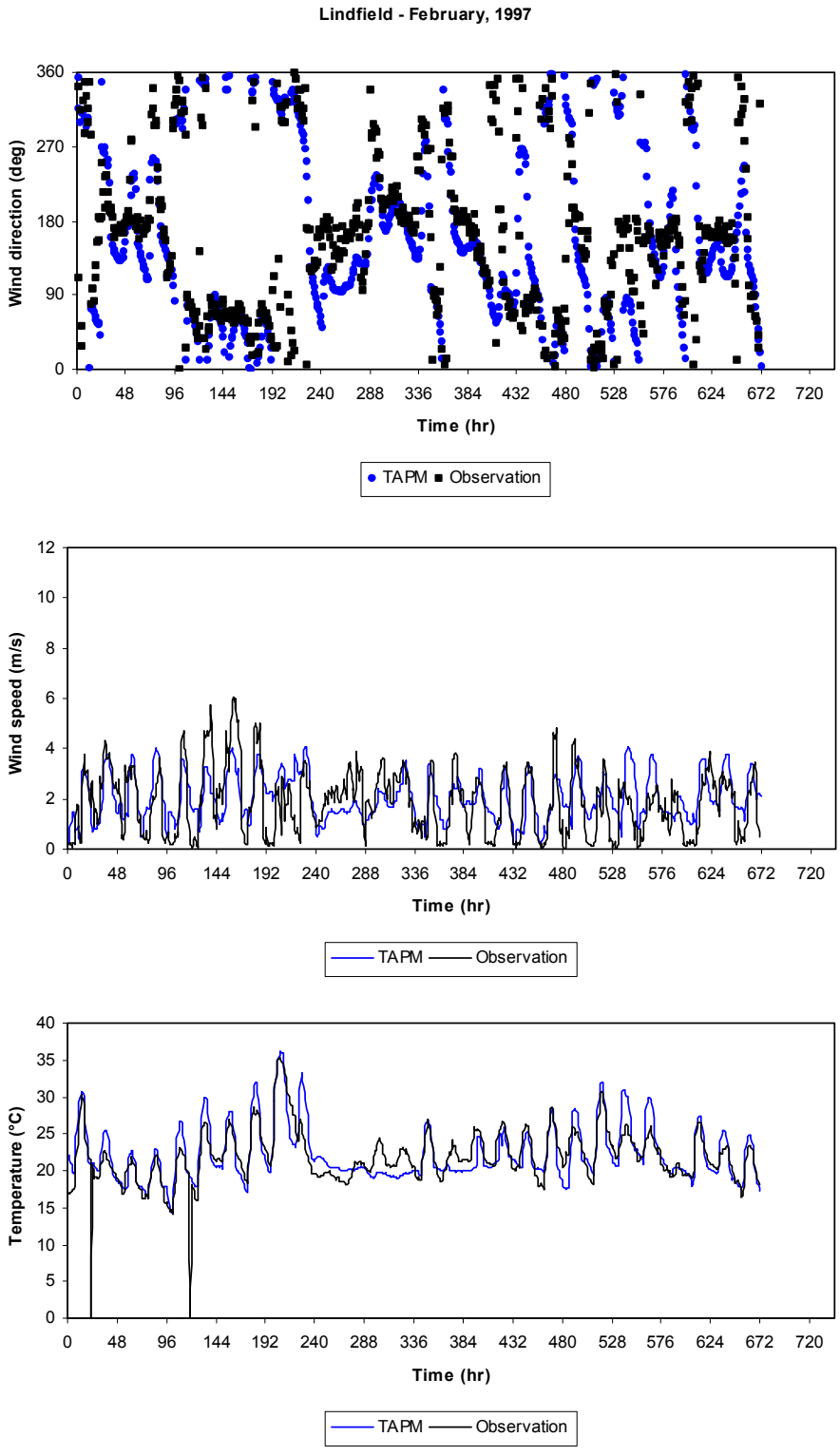

Figure 4.10. Time series of meteorological parameters predicted and observed (where available) at Lindfield on February 1997.

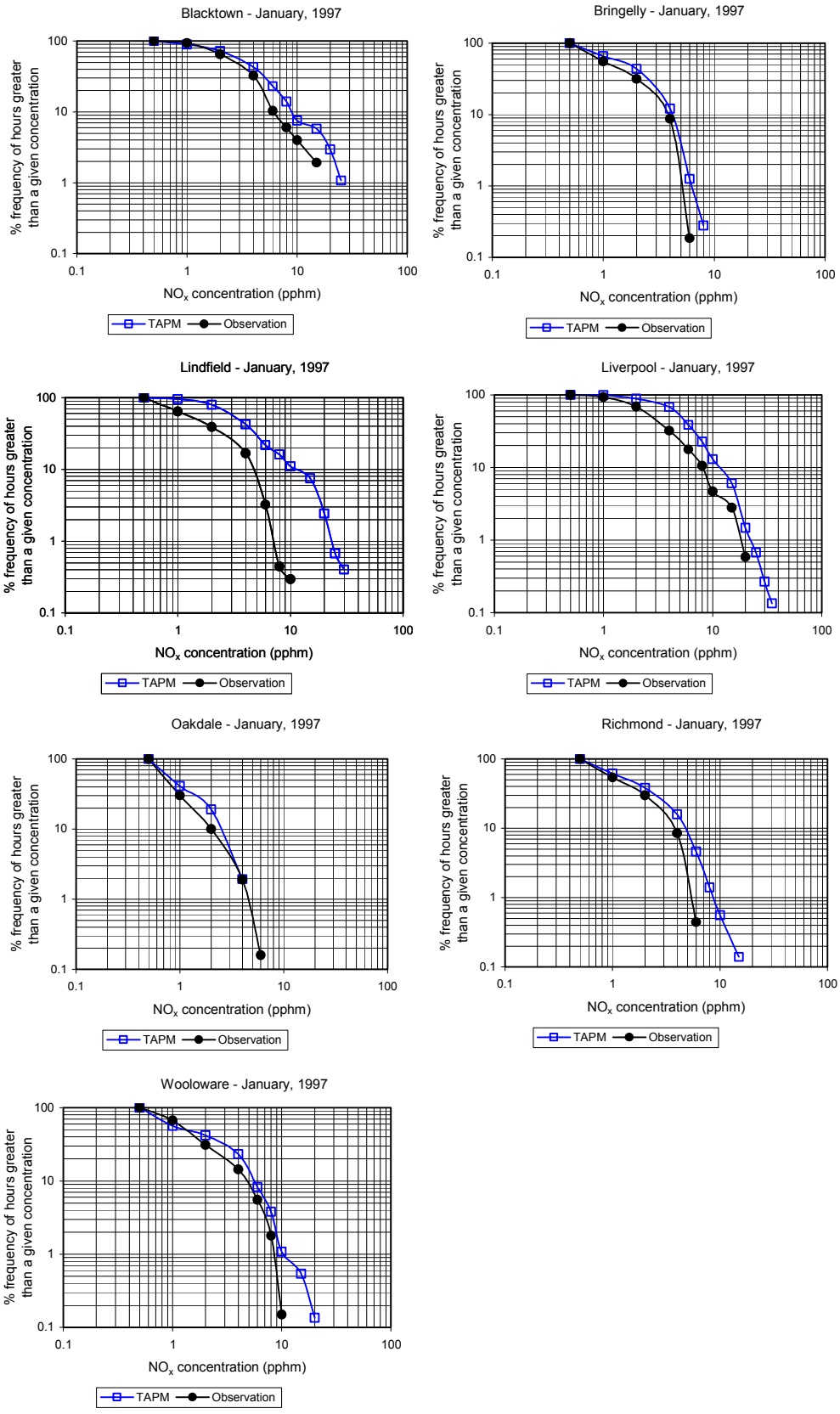

Figure 4.11(a). Frequency distributions of observed and TAPM predicted NO_x for selected monitoring stations for January 1997.

A comparison of TAPM predictions and observations for O_3 for the seven months considered and for the seven monitoring stations is also given in the Appendix Volumes. Figure 4.11(b) shows a comparison of the cumulative frequency distributions of the measurements and predictions for 7 sites for January 1997. There is good agreement between the predicted and observed concentrations at all sites and for, in general, each month. This is partly due to the fact that O_3 is a secondary pollutant formed from reactions of VOC and NO_x precursors, rather than being emitted directly. The low wind speed issue clearly does not affect predictions in this case, as it almost invariably occurs in the early morning when little ozone is observed or predicted.

This general agreement in the observed and predicted frequency distribution as illustrated in Figure 4.11(b), provides confidence for using TAPM to investigate the impact of power station emissions on ozone formation.

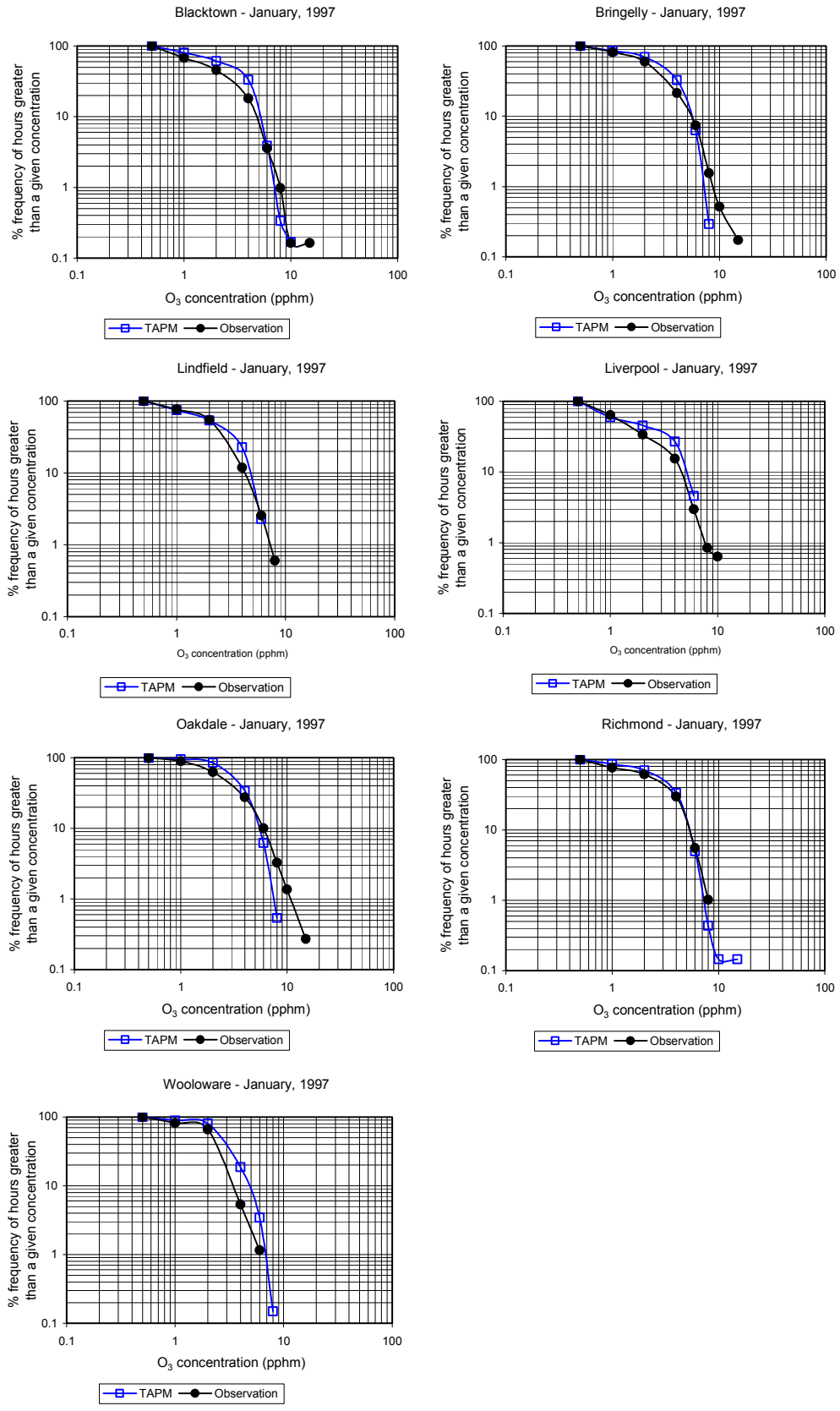

Figure 4.11(b). Frequency distributions of observed and TAPM predicted ozone for selected monitoring stations for January 1997.

4.2.3.2. Power Station Impacts – Ozone Formation

In order to examine the power station impacts, predicted concentrations of ozone with all power stations emitting NO_x at actual load (the base case) were compared with predicted concentrations with emissions from one group of power stations set to zero. In this report the comparisons are performed at the monitoring stations used to assess model performance. However, comparisons are in principle possible anywhere in the modelled domain, and graphical techniques have been developed to display these comparisons.

The comparisons were made for three sets of data:

- For all data (i.e. at every hour) in the 7 month period irrespective of the modelled ozone concentration for the base case.

- For data for the base case for which ozone exceeds 5 pphm; this concentration was selected because it exceeds the background surface ozone concentrations of 2-3 pphm observed in many studies (Warneck, 1988), and approaches the most stringent air quality guideline for O_3, that of the WHO (WHO, 2000) of 6 pphm for an 8 hour averaging time.

- For data for the base case for which ozone exceeds 8 pphm; this concentration was selected because it approaches the NEPM goal of 10 pphm (averaged over one hour, and with maximum allowable exceedances of 1 day per year), and is equivalent to the NSW EPA's long reporting term goal.

The results are discussed in detail in the Appendix Volumes. In summary the results show:

- In the case of all the data, there are a substantial number of hours (up to about 60 per month) where the power station emissions are predicted to result in positive contributions of 0.5 pphm in predicted ozone concentrations. (Note that negative differences were also predicted). At times the contributions could be larger, although the frequency was much smaller. Hence enhancements of up to 3-3.5 pphm were observed, but never for more than 1-2 hours per month. In general enhancements were more frequently observed than suppressions. It should be emphasised that these results are for all hours of the seven month period, for which there will be many hours where negligible ozone was observed and predicted. For that reason it is important to look at the subset of results demonstrating higher ozone concentrations.

- For those results with predicted O_3 greater than 5 pphm, there were up to 20 hours per month that showed positive contributions of 0.5 pphm. Likewise the frequency of the larger differences also decreased but a small number of hours each month still showed differences of 3-3.5 pphm.

- Finally, for those results with predicted O_3 greater than 8 pphm, the number of hours where the power stations resulted in a positive contribution is very small; most of the differences were of order 0.5 pphm, and the differences of 3-3.5 pphm were not contained in this subset of the results. The maximum difference was 1.5 pphm for one hour of one month at one monitoring station (Richmond in February 1998).

There is clearly a large amount of information in these results, and they present some challenges in effectively summarising the outcomes of this modelling approach. One possible approach is to tabulate the observed differences for all grid cells in the domain, in order to

extract the overall differences in predicted ozone with the power station emissions perturbed as described. The results for ozone are given in Table 4.1 for all the data and for events where the ozone concentration was predicted to be greater than 5, 8 or 10 pphm. In Table 4.1 the percentage of time is defined as follows:

$$\text{Percentage of time} = \{(\text{total hours contributing to a given concentration range difference})/(\text{number of grid cells} \times \text{total hours})\} \times 100$$

Ozone levels are often expressed in terms of the number of days when certain air quality goals or standards are exceeded. The present data can also be used in this way. Table 4.2 includes modelled results for the number of days in the study period when concentrations of ozone exceeded 8 and 10 pphm at some point in the Sydney region (as defined as the extraction domain in Figure 4.9). It also shows the number of days when power station contributions to ozone fell within a range of percentages (5-10%, 10-15%, etc). A day is apportioned to the category containing the maximum perturbation within the extraction domain per model day. The total number of days modelled for the seven month period is 210, the total number of hours is 5040 and the nodes are 33x33=1089 ie a total of 5040x1089=5,488,560 node hours.

Based on this modelling approach, over the seven months modelled, an exceedence of the NEPM ozone standard (10 pphm) was predicted to occur on 28 days. (Note that this may be compared with the 10 days on which exceedences actually occurred for the same period as recorded by the monitoring network). On about 80% of these days power station emissions were predicted to make less than a 5% contribution to the maximum ozone concentration. The maximum power station contribution to these events was between 10 -15% occurring on a single day. On a further 5 days power station emissions contributed between 5 - 10% to the ozone event.

For the 55 events exceeding the more stringent long term reporting goal of 8 pphm, there was one day when power station emissions contributed between 20-25% of the total concentration. For most of the events greater than 8 pphm, power stations were predicted to make less than 5% contribution to the maximum predicted ozone concentrations.

The data in Table 4.1 can be further simplified by summing the contributions due to different power station regions, and expressing the results in the form of a figure of the total percentage of time that power station emissions contribute to the given range of positive contribution to ozone. The comparison is between the base case ozone predictions, with all emissions included, and ozone predictions with the stated power station emissions set to zero. Figure 4.12 shows the result.

Table 4.1: Percentage of time that power station emissions contribute to changes in modelled ozone concentrations in the specified range; period modelled is January to April 1997, and January to March 1998.

		Power Station Contribution (pphm)[a]						
Data	Power Station Region	>0.1 – 0.5	>0.5 – 1.0	>1.0 – 1.5	>1.5 – 2.0	>2.0 – 2.5	>2.5 – 3.0	>3.0 – 3.5
All Data	Western	2.527	0.895	0.477	0.243	0.073	0.020	0.008
	Central	3.625	0.815	0.223	0.052	0.008	0.001	0.000
	Hunter	3.133	0.535	0.130	0.037	0.014	0.005	0.002
Events ≥ 5 pphm	Western	0.413	0.105	0.041	0.028	0.015	0.014	0.008
	Central	0.586	0.198	0.088	0.027	0.006	0.001	0.000
	Hunter	0.457	0.087	0.029	0.013	0.009	0.005	0.002
Events ≥ 8 pphm	Western	0.026	0.005	0.000	0.000	0.000	0.000	0.000
	Central	0.022	0.003	0.002	0.001	0.000	0.000	0.000
	Hunter	0.029	0.000	0.000	0.000	0.000	0.000	0.000
Events ≥ 10 pphm	Western	0.003	0.000	0.000	0.000	0.000	0.000	0.000
	Central	0.003	0.000	0.000	0.000	0.000	0.000	0.000
	Hunter	0.012	0.000	0.000	0.000	0.000	0.000	0.000

[a] ranges are differences between base case ozone predictions (all emissions included) and ozone predictions with power station emissions set to zero in stated group

Table 4.2: Days when modelled power station contributions to ozone concentrations (on days when stated ozone concentrations were exceeded) fell within stated percentage ranges; modelled period January-April 1997, and January-March 1998; modelled domain Sydney region (see Figure 4.9).

Events	No. of days[a]	Power Station Region	>5– 10%	>10– 15%	>15–20%	>20–25%	>25– 30%
Ozone ≥ 8 pphm	55	Western	8	4	0	0	0
		Central	7	0	0	1	0
		Hunter	2	0	0	0	0
Ozone ≥ 10 pphm	28	Western	3	0	0	0	0
		Central	2	1	0	0	0
		Hunter	0	0	0	0	0

[a] Days when modelled ozone concentrations exceeded stated concentrations with all power station contributions included

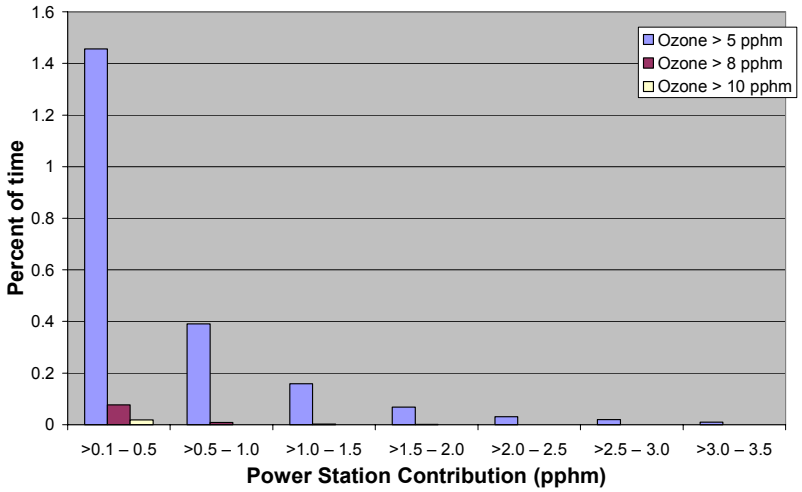

Figure 4.12. Percentage of time that power stations contribute positively to ozone at stated ranges; based on TAPM modelling of January-April 1997, and January-March 1998. The ranges are ozone differences (between base case ozone predictions (all emissions included) and ozone predictions with power station emissions set to zero).

The results in Table 4.1 and Table 4.2, and those in Figure 4.12 provide a measure of the overall impact of power station NO_x impacts on O_3 formation in the Sydney region. Hence, on the basis of this modelling approach, it would be concluded that power station emissions make a relatively small contribution to observed ozone concentrations in the Sydney region overall, and particularly for those occasions when O_3 exceeds the most stringent goal (the NSW EPA's long term reporting goal of 8 pphm, one hour average). Thus it can be seen that the magnitude of the positive power station impacts, decreases with increasing base-case O_3 concentration.

4.2.3.3. Power Station Impacts – NO_2 Formation

Impacts of power station emissions on NO_2 formation also need to be considered, but can be summarised here in less detail than for the ozone impacts given above. The over-prediction of NO_x noted above is largely related to night or early morning vehicular emissions. The NO_x in this case will be largely NO, since these are fresh emissions which have undergone little photochemical reaction. Nitrogen dioxide (NO_2), like O_3, is predominantly a secondary pollutant, photochemically generated, and is explicitly calculated using the scheme from Generic Reaction Set (GRS), (Azzi, M. et al 1992).

Table 4.3 and Table 4.4 present analogous information for NO_2 to that given in Table 4.1 and Table 4.2 for O_3. In this case the data are presented in the following ways:

- All data are considered.
- Events for which the predicted NO_2 concentration exceeds the long term reporting goal of 10.5 pphm and the NEPM standard of 12 pphm are considered.

Table 4.3: Percentage of time that power station emissions contribute to changes in modelled NO_2 concentrations in the specified range; period modelled is January to April 1997, and January to March 1998.

		Power Station Contribution (pphm)[a]						
Data	Power Station Region	>0.1 – 0.5	>0.5 – 1.0	>1.0 – 1.5	>1.5 – 2.0	>2.0 – 2.5	>2.5 – 3.0	>3.0 – 3.5
All Data	Western	1.288	0.056	0.007	0.001	0.000	0.000	0.000
	Central	5.142	0.566	0.063	0.012	0.003	0.001	0.001
	Hunter	1.176	0.077	0.008	0.003	0.000	0.000	0.000
Events ≥ 10.5 pphm	Western	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
	Central	0.0010	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
	Hunter	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Events ≥ 12.0 pphm	Western	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
	Central	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Hunter	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000

[a] ranges are differences between base case NO_2 predictions (all emissions included) and NO_2 predictions with power station emissions set to zero in stated group

Table 4.4: Days when modelled power station contributions to NO_2 concentrations (on days when stated NO_2 concentrations were exceeded) fell within stated percentage ranges; modelled period January-April 1997, and January-March 1998; modelled domain Sydney region (see Figure 4.9).

Events	Number of days[a]	Power Station Region	>5 – 10%	>10 – 15%	>15 – 20%	>20 – 25%	>25 – 30%
Events ≥ 10.5 pphm	29	Western	2	0	1	0	0
		Central	2	0	1	0	0
		Hunter	0	0	0	0	0
Events ≥ 12 pphm	20	Western	2	0	1	0	0
		Central	2	0	1	0	0
		Hunter	0	0	0	0	0

[a] Days when modelled NO_2 concentrations exceeded stated concentrations with all power station contributions included

Table 4.3 and Table 4.4, also suggest that power station emissions make a relatively small contribution to observed NO_2 concentrations in the Sydney region overall. This is particularly the case for that subset of the data where the long term reporting and NEPM goals are predicted to be exceeded.

4.2.4. Conclusions - Simplified Modelling Approach

Impacts of power station emissions on air quality in the Greater Sydney Region were examined using TAPM. In this case the GRS simplified photochemistry module was employed in order to model a long time period, and to determine overall impacts on O_3 and NO_2 formation.

TAPM was run over two smog seasons, first with all emission sources included, and secondly with the power station NO_x emissions set to zero. Before the model could be run the development of an emissions inventory for area, mobile, commercial, industrial and biogenic sources was required. This inventory was in part based on, and hence, in good agreement with the MAQS inventory, but was updated to 1996 using population data. Information on non-power station, industrial sources of NO_x and VOCs was used to estimate industrial emissions.

The modelled results show:

- For the majority of the time power station emissions have no effect on ozone occurrence in Sydney, even when ozone concentrations are elevated above naturally occurring concentrations.

- For ozone events predicted to reach the long term reporting target of 8 pphm, power stations typically made little contribution. The maximum power station contribution during these elevated ozone events was less than 2 pphm, which occurred for one hour, at one monitoring site.

Impacts on NO_2 concentrations were similarly minor, particularly at the long term reporting goal of 10.5 pphm.

4.3. Modelling Using Urban Airshed Model and Full Chemistry

4.3.1. Introduction to the Detailed Modelling

The modelling approach described in Section 4.2 was designed to examine the impacts of power station emissions of NO_x on smog formation in the Sydney region at the "macro" level. It is a relatively simplified approach using the GRS chemistry to describe O_3 formation, and with no attempt to tune the model for particular episodes of ozone formation. It also addresses the issue of the frequency distribution of pollutant formation, which is not possible with detailed modelling of "events". Nonetheless, it was considered important that this modelling effort be supported by detailed airshed modelling which considered specific days for which:

1. Significant ozone formation was observed

2. There was evidence either from the SO_2 monitoring data, and/or from TAPM calculated trajectories for transport of power station plumes to the Sydney region

This detailed modelling also covers the range of meteorological conditions that pertain to significant ozone formation in the Sydney region. The following approach was taken:

- Sydney ozone episodes were selected for which IRT of the NO_x emissions from the three power station groups (Central Coast; Hunter Valley; Western) into the Sydney basis was implicated.

- The meteorological fields for each event using TAPM and DARLAM were modelled.

- The air pollution fields were modelled using a comprehensive photochemical airshed model.

- Model performance was analysed for the base-case simulations through comparison of observed and modelled 1-hour time series of NO_x, NO_2 and O_3.

- Test-case simulations to identify the contribution made by the power station groups to photochemical smog development in the Sydney basin were performed.

- The differences between the base-case and test-case simulations described above were analysed.

In addition to the above, consideration was to be given to differences in the spatial and temporal distributions of peak observed and modelled 1 hour concentrations of O_3, and the differences in the spatial and temporal distributions of the peak observed and modelled 1-hour concentrations of NO_2.

This section describes the outcomes of this modelling approach.

4.3.2. Modelled Events

Detailed airshed modelling was performed for specific event days. Event days were selected from a 250-day data set using a comprehensive multi-stage filtering process as described in the Appendix Volume.

The filtering process cut the initial data set down to a 30-day sub-set from which five ozone episodes were selected. The episodes were selected on the basis of having high ozone concentrations and meteorological conditions that are suitable for inter-regional transport between the power stations and the Sydney region. The periods selected for detailed study were as follows.

7–8 February 1997

The 8th February 1997 was a significant ozone event in Sydney with six monitoring sites measuring maximum ozone concentrations of at least 8 pphm and for three of these sites maximum concentrations were greater than 10 pphm with a maximum of 12.5 pphm recorded at Bargo. In addition both days had similar meteorology with alongshore flow in the early hours of the morning at the coast and north-east flow across the northern plateau.

20–22 January 1997

The period 20th to 22nd January 1997 was selected for analysis and modelling on the basis that it was a significant ozone event in Sydney and there was evidence on all three days for inter-regional transport of ozone, oxides of nitrogen and sulfur dioxide from sources north of the Sydney Basin. Ozone concentrations up to 11.7 pphm (Oakdale) were recorded in the south and south western part of the Sydney Basin.

25–27 October 1997

The period 25 to 27 October contained a significant ozone event in the Sydney airshed (10.7 pphm Bargo, 27 October) and there was evidence on all three days for inter-regional transport of ozone, oxides of nitrogen and sulfur dioxide from sources north of the Sydney Basin.

11–13 March 1998

The 13th March 1998 was a significant ozone event in Sydney because moderate to high concentrations of ozone were measured throughout the region with two peaks of ozone concentrations being measured at many locations in the basin. Nine locations recorded maximum hourly concentrations of ozone of at least 8 pphm; three sites recorded maximum concentrations greater than 10 pphm and one site recorded a concentration greater than 12 pphm. Wind direction was generally from the north.

21–23 January 2001

The period 21st to 23rd January 2001 was selected for analysis and modelling as it formed a signicant ozone event in Sydney with particularly high concentrations of ozone on the 23rd January (17.5pphm at Brigelly), and some evidence of possible inter-regional transport into the Sydney Basin. The most significant day of this episode was the 23rd January when very high concentrations were measured with fourteen stations over 8 pphm with nine recording concentrations greater than 12 pphm. This episode is also important as high concentrations were measured in the east and at coastal locations. In addition at many locations two peaks of ozone were observed, one in the morning that was followed by a decrease in ozone concentrations for several hours, and another peak in concentrations following the arrival of the sea breeze.

4.3.3. Modelling Methodology

The use of numerical modelling to assess power station impacts comprises a four-stage process.

1. Development of an emissions inventory characterising all significant sources of oxides of nitrogen (NO_x) and reactive organic carbon (ROC). These pollutants comprise the principal precursors for the production of ozone (O_3) and other photochemical smog pollutants. (The emissions inventory was described in Section 4.2.2 and some additional details are given below).

2. Application of a numerical weather prediction system (NWP), to generate meteorological fields (wind, turbulence, temperature, humidity and radiation) for each case study period. In this stage of the study, prognostic meteorological fields were generated with two alternative NWPs- TAPM (version 1.5 and 1.8), and DARLAM (Katzfey 1995). The predictions of each NWP were assessed through comparison with observations and the most realistic transport fields selected for use.

3. Application of a chemical/transport model (CTM), driven by the inventory developed in 1) and the meteorological fields developed in 2) to generate a base-case (business-as-usual) set of pollutant fields. Model performance was assessed through comparison with air pollutant observations. For this stage of the study, photochemical transport–transformation was simulated using a modified version of the Carnegie/Mellon, California Institute of Technology Model (CIT; Harley et al., 1993). This model incorporates the Lurmann/Carter/Coyner mechanism (Lurmann et al., 1987), a

comprehensive chemical transformation mechanism, which enables the dynamics of photochemical smog development in MAQSR to be simulated in considerably greater detail than is possible using GRS (a simplified mechanism which was used during Stage 2 of the study). Note that an earlier version of CIT was used during the MAQS study (Cope and Ischtwan 1996). The current version includes an updated (numerical) plume rise algorithm and improvements to the vertical advection and mass conservation algorithms.

4. Development of a set of test-case emission scenarios which, when compared to the base-case, will enable net power station impacts to be assessed.

4.3.4. Emission Scenarios

Daily emission totals (surface sources) for NO_x and ROC for the modelling domain (Australian Map Grid system; Zone 56; 153-510 km easting, 6105-6462 km northing) are presented in Figure 4.13.

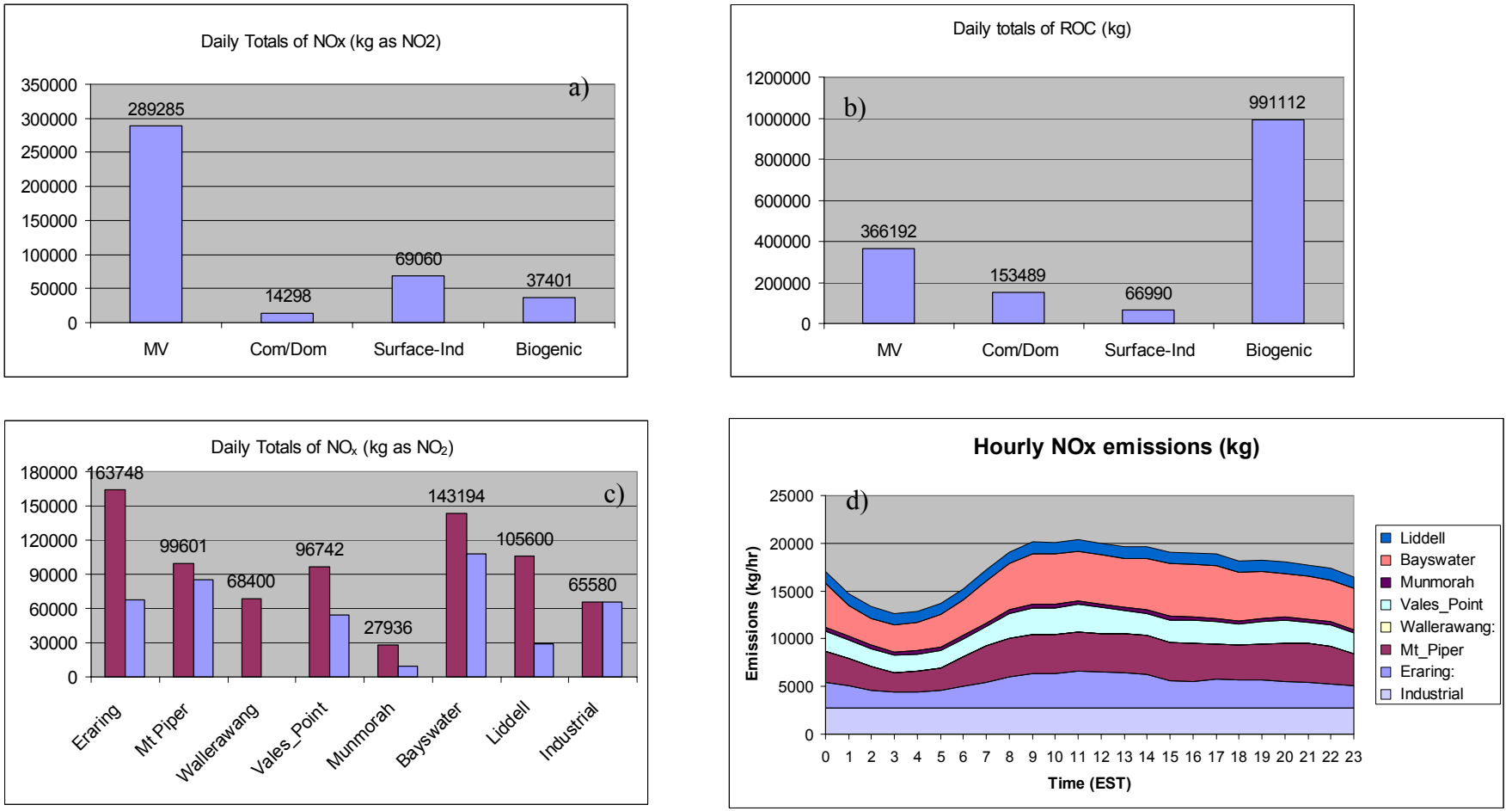

Figure 4.13. Daily emissions (kg) of NO_x (a) and reactive organic carbon (ROC, (b) for major source groups in the Metropolitan Air Quality Study Region (MV- motor vehicles; Com/Dom- commercial/domestic; Surface-Ind- surface level emissions from industrial sources; biogenic-emissions from vegetation and soils; for 7 February 1997). Also, emissions of NO_x from power stations and elevated industrial sources (c) daily totals for peak load and for 7 February 1997; (d) hourly totals for 7 February 1997).

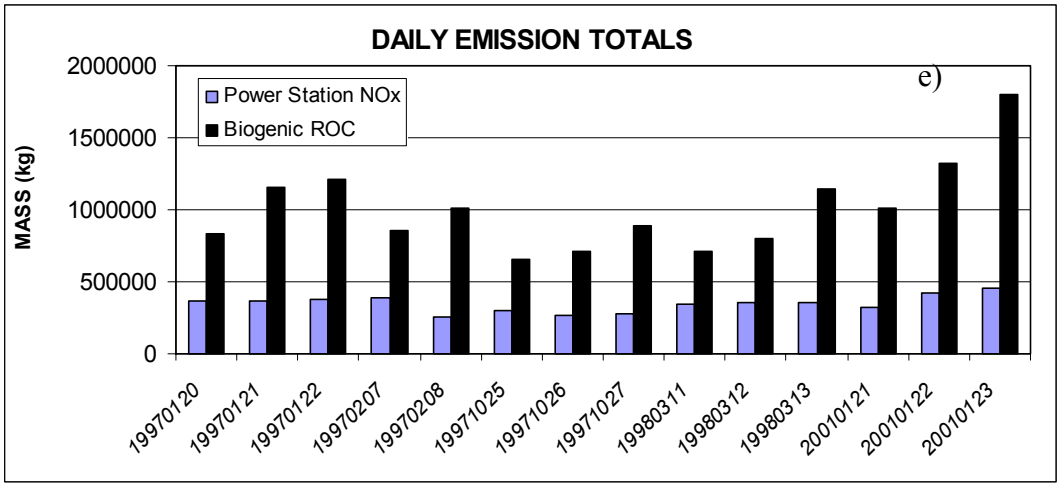

Figure 4.13. (cont) Emission totals (kg) of NO_x for power stations and reactive organic carbon from biogenic sources for each of the study days.

Note that both power station and biogenic emissions are day specific. Power station emissions vary on an hourly basis according to the generator load. Biogenic emissions vary with temperature and (for isoprene) radiation. As an example the grid-total emissions are given for 7 February 1997. Note that account has not been taken of the continued rollover of the passenger vehicle fleet to cars conforming to ADR-37, nor the on-going replacement of oil-based paints by water-based alternatives. Assuming that the emissions of ROC from anthropogenic sources for the MAQS inventory were estimated with little bias, then the anthropogenic ROC emissions used in the current study are likely to be overestimated. Furthermore, it should be noted that a weekday emissions profile has been used for all case study days. Thus for days lying on the weekend (i.e. 8 February 1997 is a Saturday), emissions of both NO_x and ROC will be overstated between the hours of 6 to 10 a.m. This will increase the concentration of the precursor pollutants during this period, leading to more rapid photochemical transformation.

The net effect of overestimating the emission rate of ROC will be to force the urban photochemistry to reach NO_x-limited conditions earlier in the model than in reality. Because incremental increases in NO_x (i.e. resulting from a power station plume mixing into the urban plume) will only lead to net increases in ozone when NO_x-limited conditions would otherwise be present, it may be concluded that any over estimate of ROC emission rates may cause the power station impact analysis to be conservative.

The biogenic emission fluxes were estimated using the procedures recommended in the MAQS inventory report (Carnovale et al., 1996). In considering Figure 4.13, it is noteworthy that the biogenic emissions of ROC exceed those from all anthropogenic source groups. The large biogenic ROC component is a consequence of the large modelling domain (360 x 360 km^2), of which a significant fraction of the surface area (relative to the urban areas) is covered in vegetation. Being a function of model domain size, the biogenic emission total should not be compared in an absolute sense with the anthropogenic totals.

The emissions inventory of ROC has also been modified to incorporate the results of a recent Sydney-based study into biogenic emission rates from trees and grasses (Nelson et al., 2000). Taking a limited set of per-leaf-area isoprene emission rates measured by Nelson et al (2000), it is estimated that isoprene emissions from a eucalypt canopy may be 2–5 times greater than those recommended by Carnovale et al (1996). As a consequence, we have developed an alternative biogenic test case in which biogenic ROC emissions are scaled up by a factor of three (3xbiogenic). Note that this is likely to provide a conservative upper bound estimate of the isoprene flux, as radiation attenuation and leaf temperature reduction due to canopy shading is not taken into account. Additionally, the simple vegetation-fraction scheme used by Carnovale et al (1996) to scale biogenic emission does not take into account vegetation type. Furthermore, it should be noted that the model uses isoprene as a surrogate for α-pinene. Isoprene is approximately three times more photochemically reactive than the latter (Carter 1996). Finally, it should also be noted that the isoprene chemical transformation scheme used in the CIT airshed model is the same as that used in the SAPRC-90 mechanism (Carter 1990). Carter has now released a revised isoprene mechanism, which is based on more resent smog chamber data (Carter 1996). Comparison of results from the SAPRC-90 mechanism and the revised mechanism suggests that the SAPRC-90 mechanism is between 10- and 20 % too reactive (thus produces ozone at a rate with is 10-20 % too fast). The net result of this and the other assumptions discussed in this section is that the system may over-estimate the rate of ozone production when a power station plume is advected over heavily vegetated regions of the airshed.

Daily and hourly emissions of NO_x (for 7 February 1997) from the power station sources are presented in Figure 4.13 (c), (d), and (e). Peak load emission rates are also shown. Emissions have been estimated from half-hourly load data using empirical functions that relate boiler load to mass of NO_x emitted **(**personal communication- Hugh Malfroy, Pacific Power International**).** In the case of peak load conditions, emissions have been estimated from the empirical functions by assuming that all boilers are operating at maximum capacity. From Figure 4.13 (c) and (d) it can be seen that Eraring is the largest source of NO_x under peak load conditions. On 7 February it was operating at about one third of capacity. It can also be seen that Wallerawang was not operating on this day, and that Bayswater was the largest emitter of NO_x for the 24-hour period (108 tonnes). The hourly emissions profile displays a weak diurnal variation, with a minimum occurring between 3 and 4 a.m. and a maximum load/emission rate occurring between 9 and 11 a.m.

Figure 4.13e shows the emissions totals for NO_x for each of the study days along with the estimate of reactive organic carbon. Note that the average daily (across all study days) power station NO_x emissions total 346 tonnes (386 tonnes for 7 February), which is substantially greater than that tabulated in the MAQS inventory report (Carnovale et al., 1996).

Table 4.5 lists the emission scenarios that have been undertaken to analyse power station impacts for the case study days.

Table 4.5: Emission scenarios developed to investigate the relative contribution made by the major power station groups (grouped by locality) to photochemical smog development in the Metropolitan Air Quality Study Region.

Power Station Emission Scenario	Surface Source Emission Scenario	Purpose
Base case	Base case	Control run
Full load	Base case	Control run for power stations operating under peak load conditions.
All power station emissions omitted	Base case	Identify combined impact regions and combined AQ perturbations due to power stations under normal or peak load operating conditions.
All power station emissions omitted	3xbiogenics	Identify combined impact regions and combined AQ perturbations due to power stations under enhanced biogenics scenario.
Base case	Motor vehicle NO_x emissions x 0.5	Provide context for the above.
Base case	3xbiogenics	Identify contribution of biogenic emissions to ozone production.

Test case emission scenarios have been included in which all power station emissions are omitted, and in which peak load emissions are used. Also included are the 3xbiogenic test case scenario, and a scenario in which NO_x emissions from the motor vehicle fleet are reduced by 50%. Results from the latter will provide additional insight into the photochemical state of the Sydney urban plume.

4.3.5. System Performance

As noted in the previous section, the power station impact assessment has been undertaken using a four-stage process. Verification of system performance is an integral and critical stage of the overall process. Verification has been undertaken for both the meteorological predictions and the chemical transport predictions. A preliminary verification of the emissions inventory is discussed in Carnovale et al. (1996). A detailed discussion of the verification procedures may be found in Hurley (1998) and in Cope and Ischtwan (1996). A review of the system performance for each of the case-study periods may be found in the Appendix Volume.

Indicative, quantitative measures of the CTM performance is given by the normalised gross error,

$$G_n = 1/n \sum |p - o| / o \times 100\% \qquad (1),$$

and the normalised bias,

$$B_n = 1/n \sum (p - o)/o \times 100\% \qquad (2).$$

Here p is the predicted 1-hour pollutant concentration, o is the observed 1-hour pollutant concentration and the average is taken over all monitoring stations and a given 24-hour period.

The daily mean normalised gross error and normalized bias and for 1-hour ozone (for $O_3 > 40$ ppb) are shown in Figure 4.14 for each of the case-study days.

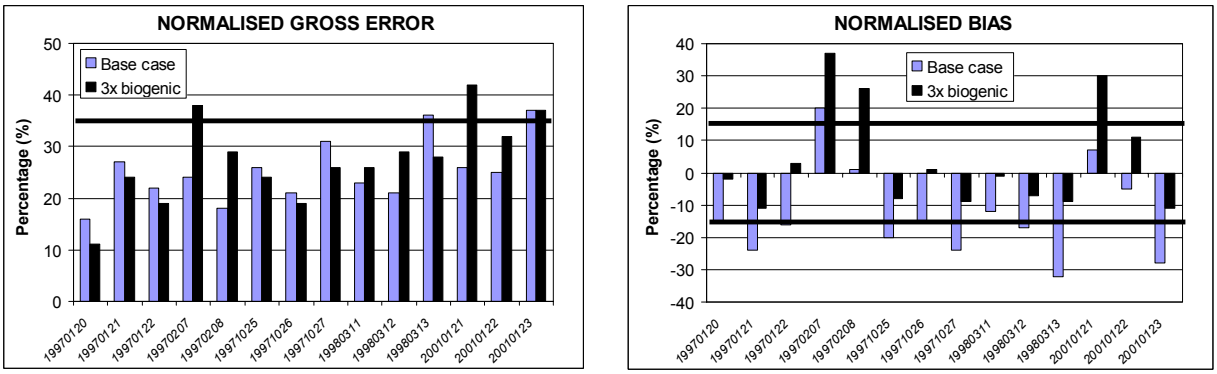

Figure 4.14. Daily mean normalised gross error and normalised bias for 1-hour O_3 > 40 ppb. Thick black lines indicate U.S EPA guidelines (USEPA 1991) for model acceptance.

Results are given for the base-case and 3xbiogenic test case (and day-specific power station emission rates). Also shown in Figure 4.14 are USEPA guidelines (USEPA 1991), which comprises (together with time series plots) a minimum set of criteria for acceptable model performance. It can be seen from Figure 4.14 that 1-hour O_3 has been predicted with a mean gross error that falls within the USEPA guideline for the majority of case study days. However, it can also be seen that system has a tendency to under-predict for the base-case emission scenario, with the bias falling below the US-EPA guideline for 7 of the 14 case study days. Use of the 3xbiogenic emissions test-case results in all of these days falling within the guideline, although at the expense of over prediction for 3 of the 14 case-study days.

In a critical review of photochemical smog models, Russell and Dennis (2000), presented gross error and bias estimates for 11 modelling studies (cut-off values ranged between 40 ppb and 60 ppb). The gross error varied between 15 % and 36 %, with the majority of cases lying below 27 %. The bias ranged between 24 % under prediction and 7 % over prediction. Thus it can be seen that the gross error and bias from the current study are consistent with those generated from other state-of-the-art modelling systems.

A more searching measure of performance is a comparison of observed and modelled 1-hour pollutant time series plots. For simulations in MAQSR, O_3 time series plots are of particular interest because the temporal profiles generally conform to a set of well-characterised shapes that may be related to the controlling meteorological conditions (Hyde et al., 2000).

As an example, a set of observed and modelled ozone time series are shown for Oakdale, Liverpool, Bargo and Camden monitoring stations for the period 20-22 January 1997 (Figure 4.15). Time series plots for other pollutants, and for the other episodes are given in the appendix. From Figure 4.15 it can be seen that the modelling system has been able to reproduce the characteristic shape of the observed ozone with some success on 20 and 22 January. Peak ozone concentrations are under-predicted for the base case but matched to within 10 % of the observed for the 3xbiogenic test case. On the other hand, when considering 21 January, both the base case and the 3xbiogenic simulations strongly under predict the observed ozone concentrations. The primary cause of the under-prediction on this day was an error in the simulated onset time and inland penetration of the sea breeze.

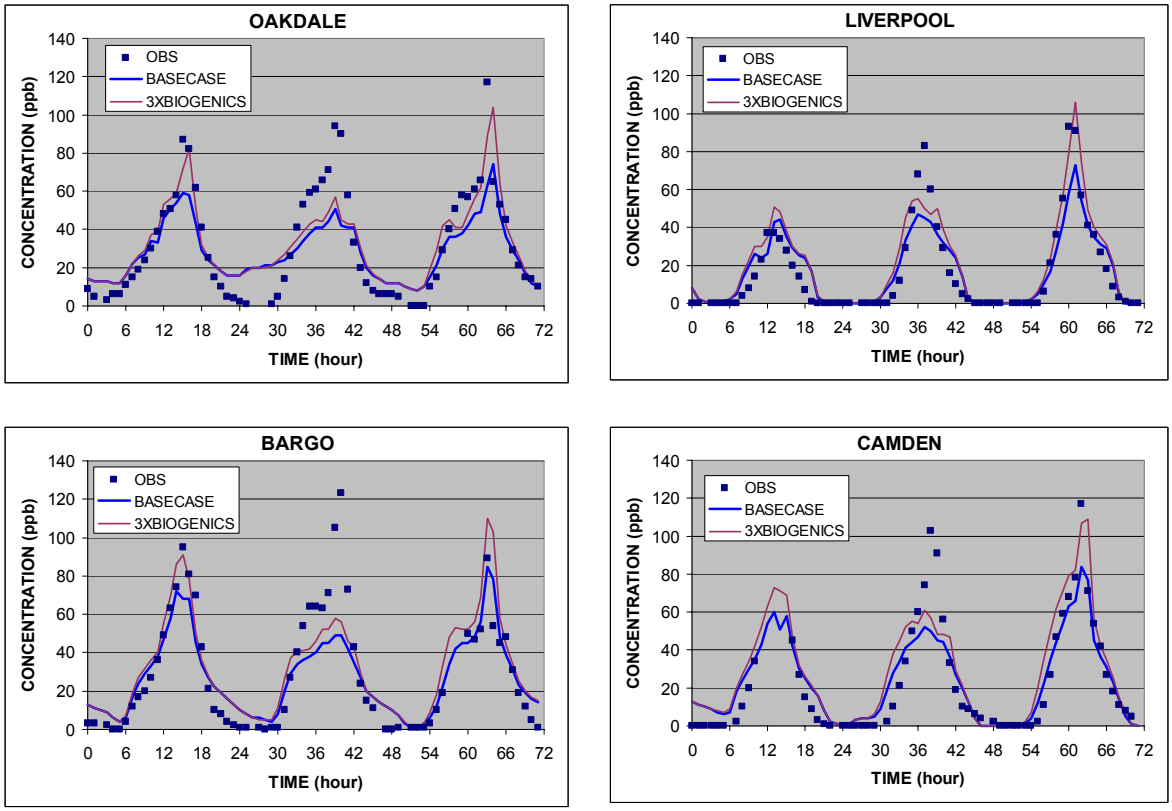

Figure 4.15. Observed (OBS) and modelled (BASECASE, 3xBIOGENICS) 1-hour ozone time series for 20-22 January 1997 (hours 0-71) for selected monitoring stations in the Sydney region. BASECASE- business as usual inventory; 3xBIOGENIC- biogenic emissions of isoprene scaled by a factor of 3.

Although the performance statistics defined in (1) and (2) above provide an indicative guideline with respect to CTM performance, conformance of predicted ozone fields with observed time series profiles, and the ability of the NWP to reproduce key features in the observed meteorological fields serves as our primary basis for acceptable system performance. On this basis, 21 January 1997 was omitted from the power station emission sensitivity analysis, because the NWP was unable to correctly predict the observed sea breeze characteristics for this day.

A similar methodology has been used to assess the system performance for the other case study periods. Days that have been omitted from the source sensitivity analysis are 21

January 1997, 27 October 1997, 13 March 1998 and 23 January 2001. Further details are given in the appendix volumes.

4.3.6. Source Sensitivity Analysis

The sensitivity of the base-case ozone concentration fields to power station emissions of NO_x has been assessed through comparison with a test case in which all power station emissions have been omitted. This has been undertaken for eleven case study days for the base-case with day specific power station emissions, for the 3xbiogenic test case with day specific power station emissions and for the base-case with peak load power station emissions.

4.3.6.1. NO_x Plume Behaviour in a Photochemical Environment

Before considering outcomes from the source sensitivity analysis, it is worth reviewing the stages of photochemical evolution of a NO_x plume in rural and urban environments.

Rural Environment

Within a rural NO_x-limited environment, three stages of plume behaviour can generally be identified (see Figure 4.16 use SO_2 as a surrogate for NO_x).

Immediately downwind of a NO_x emitter, where plume centreline concentrations of NO_x are high, O_3 concentrations are rapidly converted to NO_2 through the process of titration, radicals are scavenged through the formation of nitric acid and the whole photochemical process slows (Figure 4.16 left). At this point, the emitter is a net negative contributor to ozone concentration.

Further downwind, diffusion has mixed NO_x at the edge of the plume with ROC in the background air mass (in rural areas, this ROC may be a result of biogenic emissions). Because NO_x concentrations at the plume edge are reduced relative to the plume core, and because the rural air mass was initially NO_x-limited, efficient chemical transformation on the plume periphery will lead to net ozone production, resulting in growing ozone 'wings' (Figure 4.16 centre).

Following further diffusion, plume centreline NO_x concentrations are reduced and mixed with background ROC, and the region of net ozone production extends to cover the entire crosswind expanse of the plume. Net ozone production will continue until the air mass again becomes NO_x-limited, or until nightfall (Figure 4.16 right).

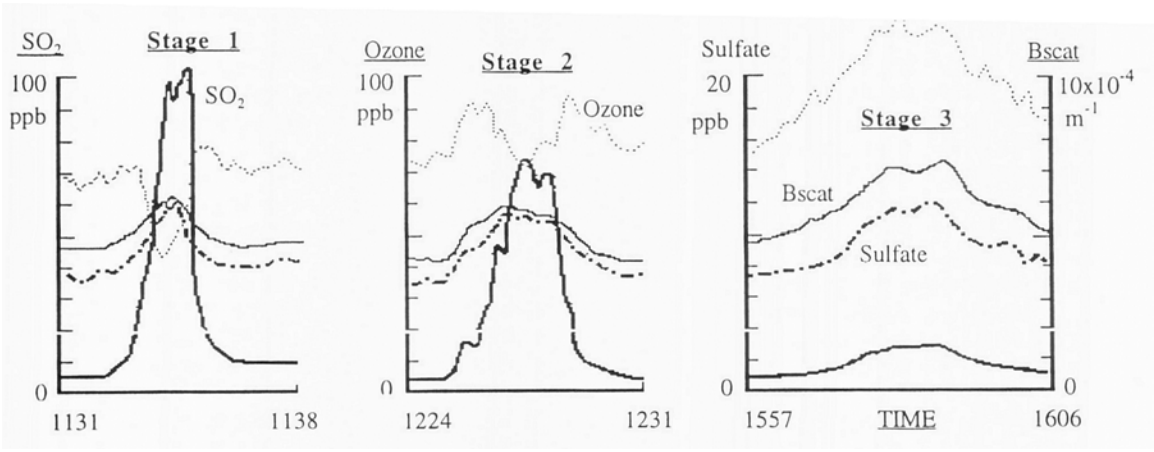

Figure 4.16. Example of the three stages of plume chemical development a large power station plume in Tennessee U.S. Data collected from aircraft traverses corresponding to travel times of approximately 4 hr, 5.5 hr and 8 hr. (Figure taken from Gillani et al., 1981).

Urban Environment

Within an urban photochemical plume, NO_x from a large emitter may lead to either a positive or negative change in the urban ozone concentration. The sign of the contribution will depend upon whether photochemical smog production within the urban plume would, in the absence of the NO_x emitter, reach NO_x-limited conditions. This in turn is dependent on the total NO_x and ROC concentrations, the ROC:NO_x ratio and the ROC reactivity within the urban precursor plume and exposure to sunlight.

Additionally, it should be noted that the direct transport of ozone into an urban area, from a 'Stage-3' mature plume will, of course, result in higher background ozone concentrations and more efficient photochemical production, leading to net ozone increases within the urban plume.

4.3.6.2. Spatial Differences

Power station impacts have been evaluated through consideration of spatial differences for selected hours (represented as contour plots and scatter plots), and through consideration of a cumulative difference metric.

Use of spatial differences to assess power station impacts is demonstrated in Figure 4.17 where model results are presented for hour 15 (EST) for 11 March 1998.

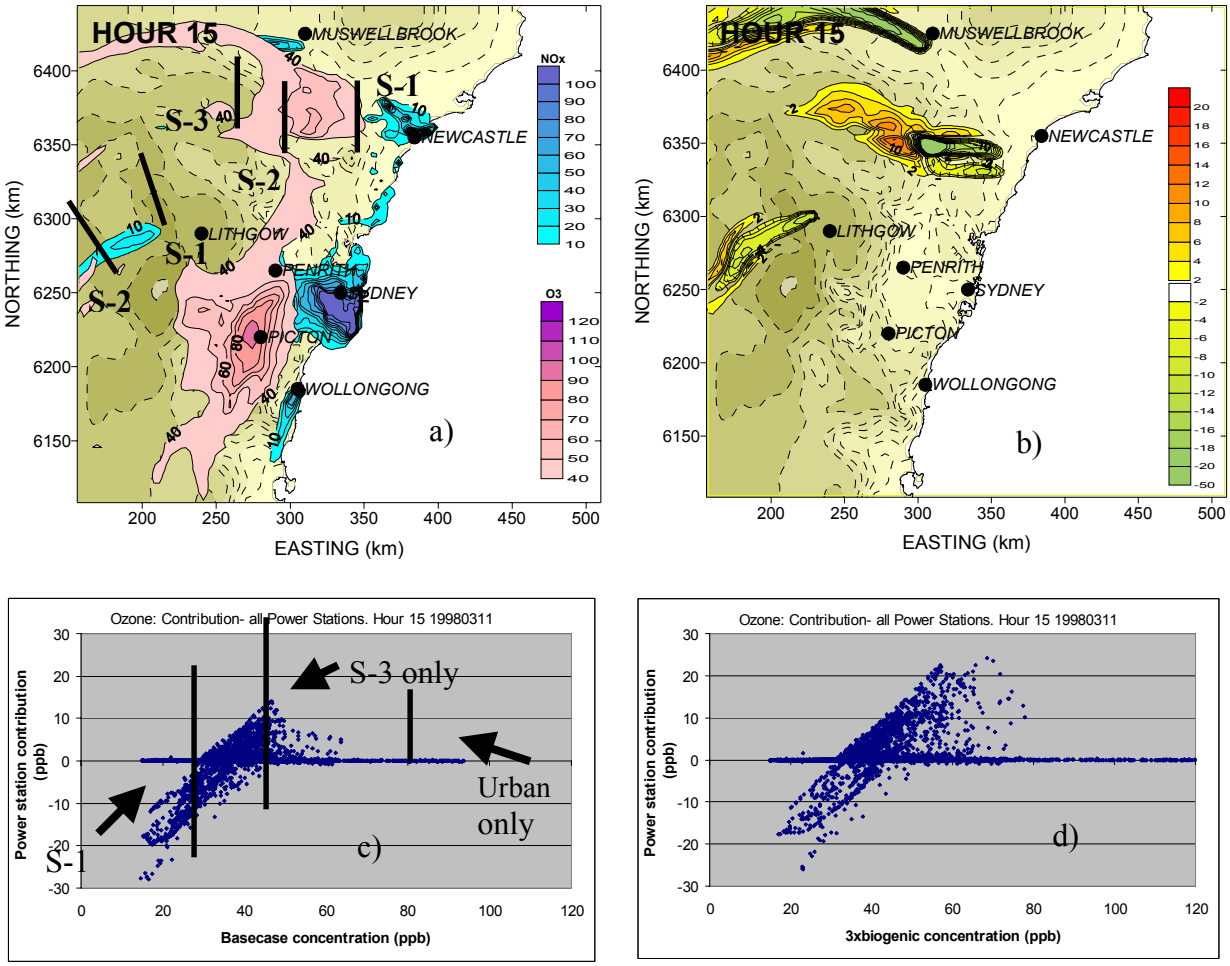

Figure 4.17. ***No urban interaction*****. a) Modelled near-surface base-case concentrations of NO_x (ppb) and O_3 (ppb) for 11th March 1998, hour 15. b) Contribution of power station NO_x emissions to the base-case ozone field. c) Scatter plot showing power station contribution as a function of base-case O_3 contribution. d) Scatter plot showing power station contribution as a function of 3xbiogenic O_3 contribution. Stage-1 (S-1), Stage-2 (S-2) and Stage-3 (S-3) zones of plume chemical development are also shown.**

The predicted near-surface, base-case concentration fields of O_3 and NO_x are shown in Figure 4.17a. The Sydney urban plume has been advected to the southwest within a sea breeze. Ozone concentrations of 80–100 ppb are predicted over a region centred on Picton, and an O_3 plume of up to 60 ppb is predicted inland of the Newcastle–Central Coast region. The difference between the base-case and zero power station emission test-case ozone fields are shown in Figure 4.17b. Note that the difference is defined as follows,

$$\Delta O_3 = O_3 \text{ (base-case)} - O_3 \text{ (zero power station emissions)} \quad (3),$$

in order to maintain the correct sign for a positive (ozone increase) impact from the power station emissions. For clarity, only concentration differences with a magnitude of 2 ppb or greater are plotted.

The third and fourth diagrams shown in Figure 4.17 (c, d) are scatter plots of,

$$O_3\text{(base case)} - O_3\text{(zero power station emissions) vs. } O_3\text{(base case)} \quad (4),$$

and scatter plots for the 3xbiogenic test-case.

$$O_3\text{(power station\&3xbiogenics)} - O_3\text{(zero power station emissions+3xbiogenics) vs. } O_3\text{(power station\&3xbiogenics)} \quad (5).$$

Differences have been plotted for every grid point in the near-surface layer. The scatter plots may be used to examine the contribution made by the combined power station groups to base-case (or 3xbiogenic) ozone concentrations for selected concentration ranges in the base-case (or 3xbiogenic) ozone field.

It can be seen from Figure 4.17b that there are three broad regions of ozone perturbation, corresponding to emissions from the power station groups located at Central Coast, Upper Hunter and Western Region. It can also be seen that NO_x from the power stations contributed both positively and negatively to the unperturbed ozone field. In addition, by comparing the position of the Sydney urban photochemical plume in Figure 4.17a with the positions of the ozone perturbations in Figure 4.17b, it can be seen that the power station emissions haven't interacted with the Sydney plume on this day.

Considering the Central Coast power station plumes, it can be seen that the three stages of rural plume development discussed earlier are broadly evident, with high concentrations of NO_x immediately downwind of the source region leading to Stage-1 chemical development and a negative ozone impact. Further downwind, net ozone production has occurred on the northern side of the plume, indicating a Stage-2 level of development. Stage-3 plume development is indicated further inland with net ozone production occurring across the entire horizontal extent of the plume.

This information is also contained in the ozone difference scatter plots shown in Figure 4.17 (c) and (d) although it is complicated by the differences which also arise because of the data for the Western and Upper Hunter power stations. Nevertheless, the following regions can be identified.

Stage-1 only. Large negative ozone differences occurring below base-case ozone concentrations of 30 ppb correspond to near-source ozone titration within the core of a power station plume.

Stage-3 only. Positive ozone differences only, occurring at base-case ozone concentrations of 45-60 ppb, result from net ozone production within a mature power station plume. Considering Figure 4.17c, it can be seen that ozone production within the power station plumes has contributed up to a maximum of 15 ppb of ozone for base-case ozone concentrations in the range 45-60 ppb. In the case of the more conservative 3xbiogenic emissions scenario Figure 4.17d, it can be seen that power stations emissions are predicted to contribute up to 25 ppb to base-case ozone concentrations in the range 50-70 ppb.

For base-case concentrations in the range 30-45 ppb, net ozone production with the power station plumes included is both positive and negative. Thus ozone differences in this range could result from a combination of Stage-1, Stage-2 and Stage-3 states of plume chemical evolution.

Urban Impact Only.

Base case ozone concentrations of 80 ppb and above occur only within the core of the urban photochemical plume for the ozone episodes considered in this study. Ozone differences at and above base-case ozone concentrations of 80 ppb are not significant because power station plumes were not predicted to interact with the Sydney plume on 11 March 1998.

An important point of consideration is the impact of model resolution on the rate at which the plume chemistry will pass through the three stages of chemical evolution. In the CIT model, point source emissions are treated as volume sources, with the emissions being instantaneously diluted into the volume of the grid cell at the effective height of the point source plume.

In the current study, the CIT model has been configured with a 3 km horizontal grid spacing, and variable vertical layer thickness (layers below 1000 m are about 100 m thick). Given the relatively high resolution of the layer thickness in the vertical, the greatest concern is the impact of the horizontal grid spacing on plume dispersion and chemistry. Table 4.4.6 shows the estimated downwind distance and travel time required for a point source plume to reach a crosswind dimension of 3 km (horizontal grid spacing of the model) and 6 km (horizontal grid spacing plus initial plume spread following numerical advection).

Table 4.6. Downwind distance and travel time required for a boundary-layer plume to reach a width of 3 km and 6 km.

		$2\sigma_y$ = 3 km		$2\sigma_y$ = 6 km	
Stability	Wind speed[1] ($m\ s^{-1}$)	Distance[2] (km)	Travel time (hr)	Distance[2] (km)	Travel time (hr)
A	2	10	1.3	26	3.6
B	4	15	1.0	43	3.0
C	6	26	1.2	83	3.9

[1]Characteristic wind speeds for stabilities A-C taken from EPAV (1985).

[2] Calculated using Briggs (1973) rural dispersion coefficients.

For the convective conditions considered in this study it can be seen that a plume must disperse for 1-4 hours before the horizontal width of the plume is comparable to the grid spacing of the model. Thus the overall effect of the volume source approximation is to dilute the in-plume NO_x concentrations more rapidly than may occur in reality, accelerating the transition of the plume chemical evolution from Stage-1 through to the later stages. Again, this will lead to a conservative estimate of the impact of power station NO_x on ozone production, particularly within rural areas.

An example of power station plume interaction with the Sydney urban plume is given in Figure 4.18.

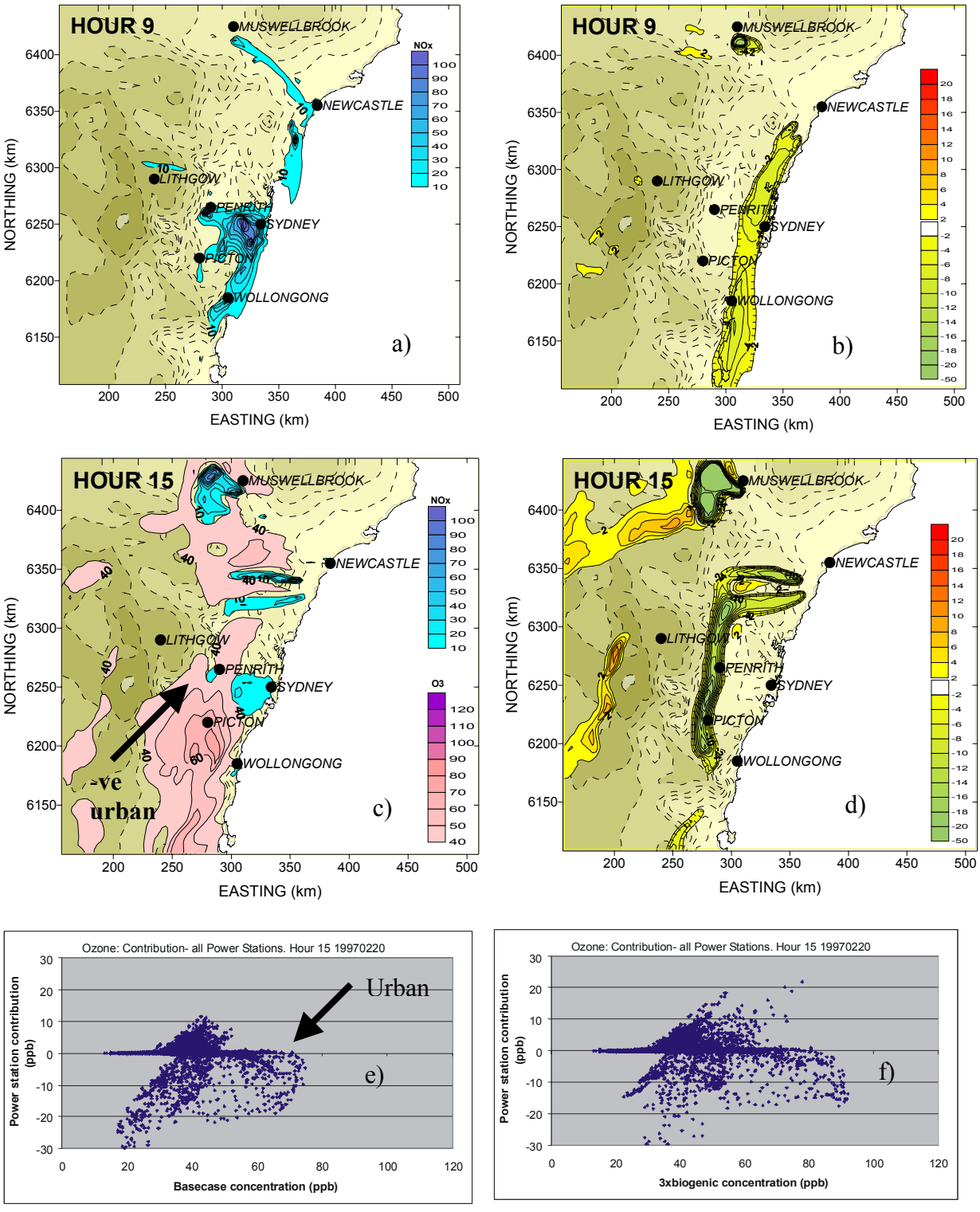

Figure 4.18. ***Sydney urban interaction*****. a) Modelled near-surface base-case concentrations of NO_x (ppb) on 20 January 1997, hour 9. b) Contribution of power station NO_x emissions to the base-case ozone field at hour 9. c) Near-surface base-case concentrations of NO_x (ppb) and O_3 (ppb) for hour 15. d) Contribution of power station emissions to the base-case ozone field at hour 15. e) Scatter plot showing power station contribution as a function of base-case O_3 contribution. f) Scatter plot showing power station contribution as a function of 3xbiogenic O_3 contribution.**

This example is taken from a numerical simulation of 20 January 1997. From the spatial plots of near-surface NO_x and ozone difference for hour 9 (Figure 4.18 (a), (b)), it can be seen that the system has predicted the transport of NO_x emissions from the Central Coast power station group into the Sydney urban basin. This plume then interacts with the Sydney urban plume as it is advected inland by sea breeze action during the afternoon (Figure 4.18 c, d). It can be seen that within the urban ozone plume, the effect of NO_x from the power station group has been to reduce ozone concentrations. This is also apparent from the scatter plots in Figure 4.18 (e) and (f) where the zone of urban impact is characterised by ozone reductions for base-case concentrations in the range 50-80 ppb (60-90 ppb for 3xbiogenic).

A final example of power station plume impact is given in Figure 4.19, where we have presented spatial and scatter plots for the 22 January 2001 simulations.

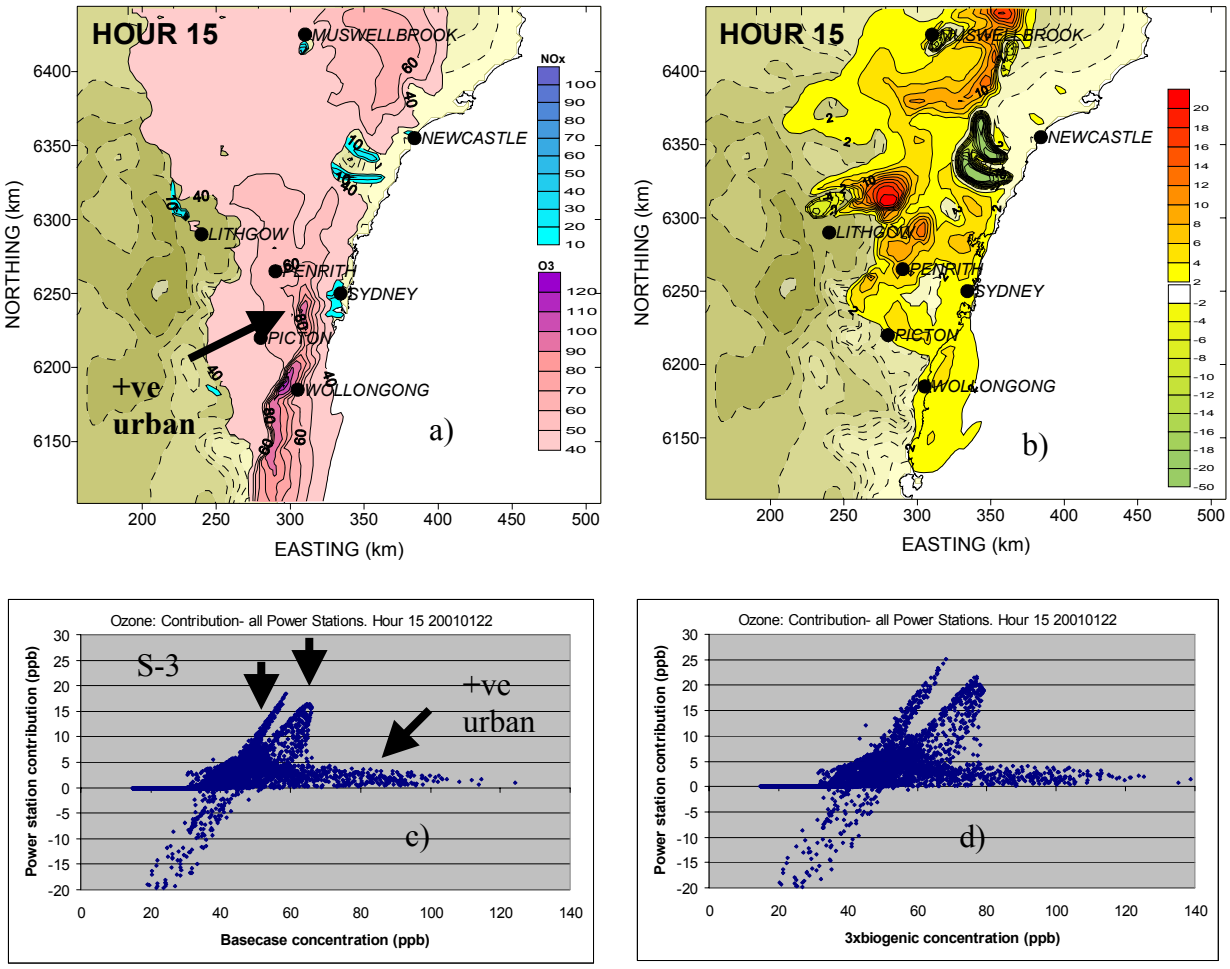

Figure 4.19. *Multiple interactions*. a) Modelled near-surface base-case concentrations of NO_x (ppb) and O_3 (ppb) for 22 January 2001, hour 15. b) Contribution of power station NO_x emissions to the base-case ozone field. c) Scatter plot showing power station contribution as a function of base-case O_3 contribution. d) Scatter plot showing power station contribution as a function of 3xbiogenic O_3 contribution.

In this example, power station emissions have combined with Sydney urban emissions to generate a zone of positive urban impact. Figure 4.19 (c) and (d) shows that the inter-regional transport of NO_x from the Central Coast power station group has contributed 2-5 ppb of ozone to the urban plume at a base-case concentration of 100 ppb. Zones of Stage-3 ozone production are also evident in the scatter plots, with the power stations contributing about 15 ppb to the net ozone concentration of 60 ppb (base-case) and about 20 ppb to a net ozone concentration of nearly 80 ppb (3xbiogenic). The ozone perturbations in these zones are the highest seen throughout the studied days and are due to an overlap of the Central Coast and Upper Hunter power station plumes, biogenic ROC and precursor emissions from the Newcastle region.

As discussed earlier, the zone of urban ozone impact may be positive or negative. Direct transport of Stage-3 plume ozone into the urban plume will result in higher background ozone concentrations and a zone of positive urban impact. Transport of power station NO_x only (i.e. early-mid morning fumigation of an elevated power station plume, still in Stage-1) may generate a zone of positive or a negative urban ozone impact. The sign of the contribution will depend upon whether photochemical smog production within the urban plume is NO_x–rich or NO_x-limited.

Of the 11 days selected for source sensitivity analysis, 10 contained urban ozone perturbations in the modelled fields due to inter-regional transport from power stations. For the base-case emissions scenario, power stations were predicted to have a zero or negative impact on urban ozone concentrations (for ozone concentrations above a threshold of 80 ppb) in 70 % and 50 % of the cases (considering impacts at hour 13 and hour 19 respectively). Of the other 30 % and 50 % of cases peak ozone increases of 2–4 ppb (< 5 %) were predicted at an ozone threshold concentration of 80 ppb. For the conservative 3xbiogenic emissions scenario, positive urban ozone impacts were predicted on 100 % and 80 % (hour 13 and hour 19 respectively) of the source analysis days. In all cases, power stations were predicted to increase urban O_3 concentrations by 5 ppb or less (< 6 %) at an 80 ppb threshold.

Considering zones of Stage-3 O_3 development (outside of the Sydney urban plume), power station plumes were predicted to contribute 15-20 ppb of O_3 to base-case concentrations in the range 40–60 ppb. For the more conservative 3xbiogenic case, contributions of up to 20 ppb were predicted for net O_3 concentrations in the range 60–80 ppb.

4.3.6.3. A Cumulative Net Impact Metric

Because power station emissions are predicted to produce both positive and negative changes to peak O_3 concentrations, we have also calculated a cumulative daily net ozone impact due to power station emissions. This metric is generated by calculating the cumulative number of grid-cell-hours that a prescribed ozone concentration threshold is exceeded. The cumulative number of grid-cell-hours is equivalent to the sum, across all hours, of the area enclosed by the contour line of the prescribed threshold concentration,

$$\int_t \int_{xy} H(O_3 - O_3^T) ds\, dt \qquad (6),$$

where $H(x)$ is the Heaviside function that has value zero for x<0 and value 1 for x≥0 and O_3^T is the threshold concentration.

Consideration is given here to ozone threshold concentrations of 60 and 80 ppb (1-hour average). Recall from the previous section that ozone perturbations above a threshold concentration of 80 ppb are primarily due to zones of urban ozone impact. On the other hand, perturbations at the 60 ppb threshold include (and are dominated by) zones of Stage-2 and Stage-3 ozone development directly downwind of the power stations. Thus the selection of 60 and 80 ppb thresholds provide a useful discrimination between the non-urban and urban plume impacts of power station emissions. Other thresholds are considered in the appendix.

4.3.6.4. Base-Case and 3xBiogenic Test-Case

Shown in Figure 4.20 (a) for all source sensitivity days, for a 60 ppb ozone threshold, is the number of cell-hours for the no-power station test case and the number of cell-hours contributed by power station NO_x emissions.

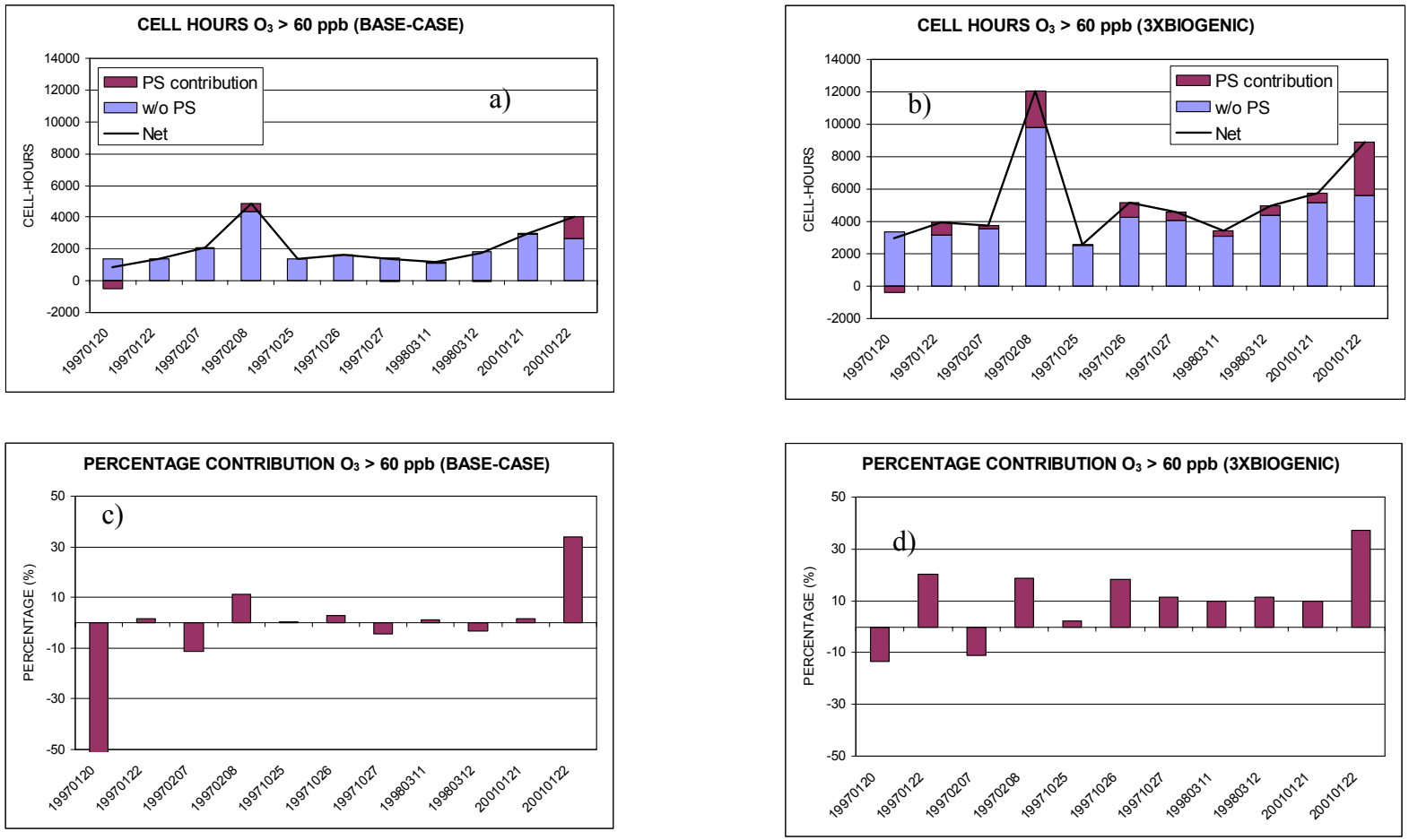

Figure 4.20. Modelled power station impacts for the 11 analysis days. *a)* Number of cell-hours for which an ozone threshold concentration of *60 ppb* is exceeded (*w/o PS*- power station NO_x emissions omitted; *PS contribution*- the change in cell-hours when day-specific power station emissions are included). *b)* As for *a)* but with biogenic ROC emissions scaled by a factor of three. *c)* The percentage contribution of day-specific power station emissions to the *base-case*. *d)* As for *c)* but for the *3xbiogenic* test-case.

Thus, in the case of 20 January 1997, 1372 cell-hours are predicted in the absence of power station emissions. Including the power station emissions reduces this total by 531 cell hours, resulting in a net of 841 cell-hours for which base-case ozone concentrations exceeded 60 ppb. Considering Figure 4.20 c), it can be seen that power station emissions of NO_x are predicted to reduce the potential number of base-case cell-hours by more than 50 % of the base-case total for this study day. On the other hand, power stations are predicted to increase the number of O_3> 60 ppb cell-hours by more than 30 % of the base-case total for the 22 January 2001 study day. The magnitude of variation for the remaining days is of order ± 10 %. Of the 11 study days considered in this source sensitivity analysis, power station emissions are predicted to reduce the number of cell-hours on four occasions, and to increase the number of cell-hours on seven occasions. The net relative change in cell-hours, summed across all study days is negative.

When consideration is given to the cell-hour exceedences of the 60 ppb threshold for the more conservative 3xbiogenic test case it can be seen that a negative contribution is predicted for two of the study days and a positive contribution is predicted for the other nine days. The majority of these impacts correspond to net ozone generation within a Stage-3 photochemical plume over the rural areas. As expected, the net relative change summed across all days is positive for the 3xbiogenic test-case emissions scenario.

Ozone cell-hour contributions for an 80 ppb concentration threshold are shown in Figure 4.21.

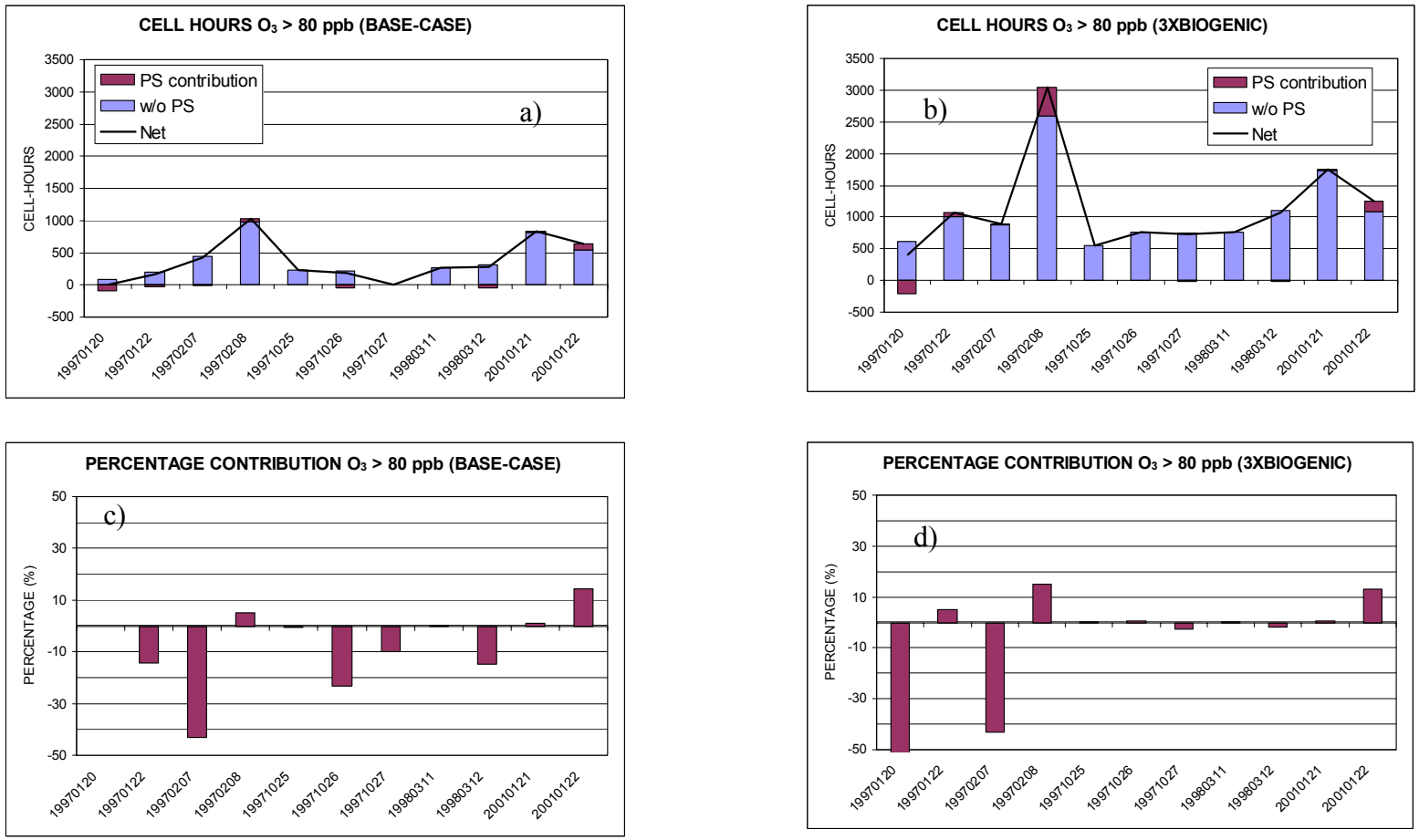

Figure 4.21. Modelled power station impacts for the 11 analysis days. *a)* Number of cell-hours for which an ozone threshold concentration of *80 ppb* is exceeded (*w/o PS*- power station NO_x emissions omitted; *PS contribution*- the change in cell-hours when day-specific power station emissions are included). *b)* As for *a)* but with biogenic ROC emissions scaled by a factor of three. *c)* The percentage contribution of day-specific power station emissions to the base-case. *d)* As for *c)* but for the 3xbiogenic test-case.

Recall that power station impacts at concentrations above 80 ppb correspond almost entirely to zones of urban ozone perturbation. Considering Figure 4.21(a) and Figure 4.21(c), it can be seen that the system predicts a negative power station contribution for seven of the 11 study days (note that the effect of power station emissions on 20 January 1997 is to collapse the region of > 80 ppb to zero in the base-case, thus the percentage change relative to the base-case is undefined). The net relative change in cell-hours, summed across all study days is negative. When the 3xbiogenic test case is considered, the number of negative impacts decreases to four (giving six positive impacts and one zero impact- 11 March 1998). A maximum increase in cell-hours of 15 % is predicted for 8 February 1997. A maximum decrease of 52 % is predicted for 20 January 1997. The net relative change in cell-hours, summed across all days, remains negative for the 3xbiogenic scenario.

4.3.6.5. Full Load

Plotted in Figure 4.22 for O_3 thresholds of 60 ppb and 80 ppb is the relative contribution to all source cell-hours for the base-case, 3xbiogenic and full load test cases.

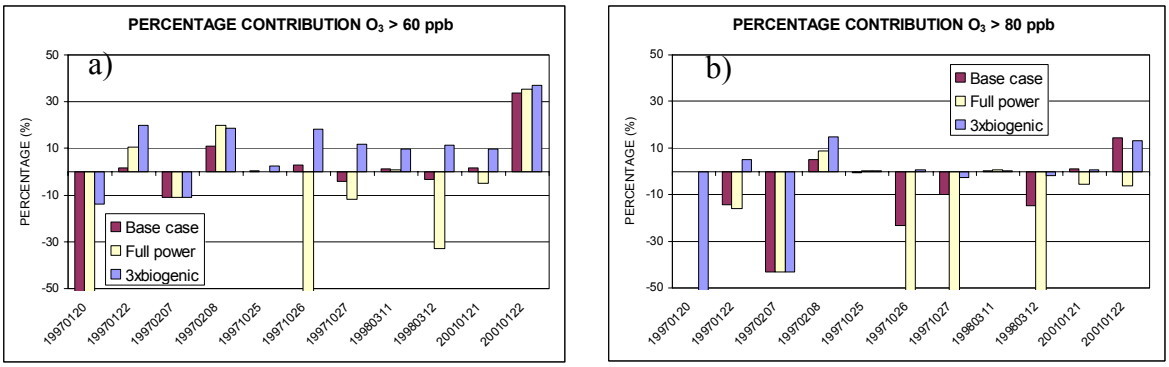

Figure 4.22. Percentage contribution to O_3 exceedance cell-hours [a) 60 ppb and b) 80 ppb thresholds] of base-case (day specific power station emissions), power station emissions under full load conditions and 3xbiogenic (day specific power station emissions).

Recall that the full load test case corresponds to all power stations operating at maximum generation capacity. The base-case biogenic emission fluxes have been used for this test case. At a 60 ppb threshold (Figure 4.22 a), the predicted impact of adding additional NO_x to the airshed is to increase the number of negative impacts from four to seven, with a corresponding decrease in the number of positive impacts. However, an increased number of cell-hours are predicted for 8 February 1997 and 22 January 2002.

Considering an 80 ppb threshold, Figure 4.22 b), the full load test case is predicted to result in an additional day of negative impact (seven days for the base-case, eight days for the full load test case).

4.3.6.6. Motor Vehicle Perturbation.

The final test case scenario presented in this section is one in which the motor vehicle emissions of NO_x are reduced by 50 %. Motor vehicle emissions of ROC remain unchanged relative to the base case. Note that a 50 % reduction in motor vehicle NO_x emissions is equivalent to a 42 % reduction in the total daily mean power station emissions. The relative

change in base-case cell-hours for ozone thresholds of 60 ppb and 80 ppb is shown in Figure 4.23.

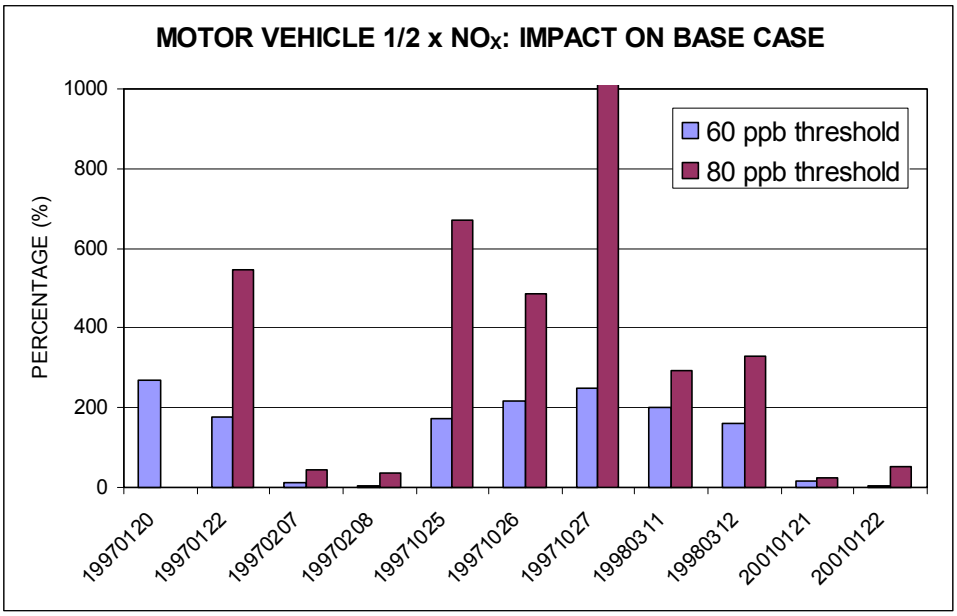

Figure 4.23. Percentage change to O_3 exceedance cell-hours for halved motor vehicle NO_x test case scenario.

It can be seen that the system predicts a strong sensitivity to the emissions of NO_x from motor vehicles for a majority of the study days, with relative increases in base-case cumulative cell-hour of more than 100 % (and more than 1000 % for 27 October 1997) being predicted. This is far more significant that the range predicted for the power stations (where NO_x emission changes are double those modelled for the motor vehicle test scenario), and is a direct consequence of the motor vehicle emissions comprising the major source of precursor emissions within the core of the Sydney urban plume.

The ozone cell-hours increase significantly as the motor vehicle NO_x is decreased because photochemistry in the Sydney urban plume as modelled is NO_x-rich. This follows directly from the relative proportions of NO_x and ROC, and the reactivity of ROC as defined by the emissions inventory. Under NO_x-rich conditions, radicals are scavenged by the NO_x to produce nitrate compounds rather than O_3. This results in a large negative feedback on photochemical production rates because O_3 is itself a significant source of radicals. Under NO_x-rich conditions O_3 is rapidly titrated to NO_2, radical production rates are reduced and the whole process of photochemical smog production becomes more inefficient. To some degree, the existence of NO_x-rich conditions within the Sydney urban plume is a direct and positive consequence of the introduction of the ADR-37 design rule for motor vehicles in the mid-1980's.

4.3.7. Discussion and Conclusions of Detailed Modelling

A comprehensive air quality modelling system has been used to assess the impact of NO_x emissions from power stations in the MAQS region on photochemical smog production downwind of Sydney for five photochemical smog events.

The system has been run for a base-case and a scaled biogenic surface emissions inventory in which isoprene fluxes have been increased by a factor of three (3xbiogenic). We believe that the latter may constitute a conservative upper bound estimate of the biogenic emission fluxes. Day-specific and full load power station emission scenarios have been considered. In addition, we have simulated a case in which NO_x emissions from the motor vehicle fleet have been halved.

We have undertaken a preliminary verification of system performance and have found that the system generally under predicts peak ozone concentrations for the base-case. The level of agreement between modelled and observed ozone concentrations is comparable with that achieved by other state-of-the-art systems.

Power station impacts have been assessed by comparing the differences between the unperturbed and perturbed power station emission test cases. Impacts have been reviewed through the consideration of spatial difference plots, through the use of scatter plots of cell-level differences and through a comparison of cumulative ozone exceedence areas for selected threshold concentrations.

Power station impacts fall into two general patterns.

a) Stage-1, Stage-2 and Stage-3 (see Section 4) chemical evolution of the power station plume within a rural environment. Close to the source (Stage-1), the effect of the power station NO_x is to reduce ozone concentrations by 20-30 ppb through the process of titration. Further downwind and on the edges of the plume (Stage-2), and across the entire horizontal extent in the far field (Stage-3), NO_x in the power station plume may interact with the background ROC field to generate excess ozone.

In rural areas, the background ROC field is dominated by biogenic emissions (surrogated by isoprene and its reaction products in the model). Under these conditions, the system predicts that base-case rural ozone concentrations may reach 60 ppb within a power station plume, with power station NO_x contributing up to 20 ppb through NO_x-biogenic ROC reactions. For the more conservative 3xbiogenic scenario, power stations are predicted to contribute a maximum of 20-25 ppb to maximum rural ozone concentrations of 70-80 ppb.

The largest predicted non-urban Sydney ozone impact occurred for a case where power station plumes from Upper Hunter and Central Coast interacted with biogenic ROC and the Newcastle photochemical plume. On this occasion, and using the conservative 3xbiogenic emission scenario, power stations were predicted to contribute 20 ppb to a predicted maximum of 75-80 ppb.

b) Sydney urban plume interactions occur when power station NO_x and/or Stage-3 ozone are transported into the Sydney basin in time to participate in the photochemical generation cycle. Under these conditions the system either predicted negative ozone impacts of up to 20 ppb, or positive impacts of up to 5 ppb. The largest negative impact was predicted for a scenario in which the Central Coast plume was advected directly over the eastern suburbs of Sydney during the early morning hours.

The positive impacts occurred for conditions in which the power station plumes were more dilute. We have not established whether the positive impacts resulted from the addition of small amounts of NO_x to areas of the Sydney urban plume which would otherwise have reached NO_x-limited conditions, or whether the impacts were caused by the advection of

dilute Stage-3 ozone generated within the rural areas upwind of the Sydney basin.

Note that the system generally predicted a monotonic decrease in power station impact with increasing urban ozone concentration. A hypothesis for this behaviour is that the highest urban ozone concentrations are associated with regions of the Sydney urban plume that have undergone the least amount of dilution. By definition, interaction between this component of the urban plume and other external air masses will be limited and a reduced level of impact from external sources will result.

The region-wide sum of the cell-hours for which O_3 exceeded 60 ppb, indicated that, when integrated over a day, net power station impacts might be either positive or negative. For the base-case, the largest positive increase was more than 30 % and the largest negative decrease was more than 50 %. The remainder of the study days had changes of less than 10 % in magnitude. In the case of the more conservative 3xbiogenic emissions scenario, net power station impacts at the 60 ppb threshold were generally positive, contributing 10-20 % to the number of cell-hours.

When considering the 80 ppb ozone threshold, power station impacts were generally negative, for both the base case and 3xbiogenic emission scenarios. Ozone concentrations of 80 ppb and above primarily occur within the Sydney urban plume.

Note that the rural power station impacts are likely to be over-stated for the following reasons.

- Conservative assumptions in the biogenic emissions inventory.
- The chemical mechanism for isoprene used in CIT is currently considered to be 10-20 % too reactive.
- The treatment of point source emissions as volume sources leads to more rapid onset of Stage-2 and Stage-3 chemical development, both of which are characterised by the generation of excess ozone.

In conclusion, the modelling suggests that photochemical behaviour in MAQSR may be divided into two regimes.

- Rural NO_x-limited. Biogenic emissions of ROC species such as isoprene are available to generate moderate concentrations of photochemical smog, but are limited by the availability of NO_x. Power station plumes (which generally originate from rural or semi-rural sites) can provide the NO_x 'fuel' for generating excess rural ozone. The model predicts that peak ozone concentrations of 60-70 ppb may be generated within a power station plume. Under a conservative worst case scenario, peak concentrations were predicted to reach 80 ppb with power station NO_x contributing 20 ppb.
- Urban NO_x-rich (ROC-limited). Rates of photochemical smog production within the Sydney urban plume are less than optimal because of radical scavenging and ozone titration in the urban NO_x-rich atmosphere. Under these conditions, the injection of additional NO_x mass, at least during the early morning hours, will further slow photochemical production rates and lead to reduced concentrations of ozone. A positive contribution from power station plumes may occur if a) rural ozone generation

raises the ozone background within the urban plume; b) the Sydney urban plume is sufficiently photochemically aged as to become NO_x-limited. In either case, the maximum predicted O_3 increment was less than 5 ppb.

5. SYNTHESIS

5.1. Project Overview and Implications

5.1.1. Project Objectives

The project objectives of IRTAPS were to determine the incidence of IRT (Inter-regional transport), and an assessment of how often it occurs from each of the three power station regions into the Sydney air shed; and the impact of IRT on air quality in the Sydney region, particularly smog production.

The study has significantly increased the scientific understanding of the occurrence of photochemical pollution in the Sydney region, particularly in relation to the significance of IRT. In terms of the frequency of the phenomenon, the results of the assessment of air quality data, supported by modelling of plume transport using TAPM, clearly show that there are occasions when IRT of power station emissions to the Sydney region can be identified.

Using the monitoring data (SO_2, NOx and O_3), it was found that there is evidence for both spatial and seasonal variability in observations that provide some evidence for IRT of power station emissions. The frequency of occurrence of IRT is estimated to be generally much less than 5% of the time on days of elevated O_3.

The CSIRO TAPM model was also used to predict the frequency of IRT of power station emissions for the monitoring periods examined. The analysis revealed that, assuming continuous *maximum* NO_x emissions from the power stations, concentrations greater than 10 $\mu g\ m^3$ (marginally above "baseline" levels) were predicted to occur in the Sydney region between approximately 5% and 15% of hours, but with substantial variability. The results from this part of the assessment provided an identification of a number of days in the selected period for which there is evidence, based on monitoring records and/or TAPM modelling, for IRT of power station emissions. The conservative nature of the methodology and assumptions employed suggests that the results represent an upper limit for the estimated frequency of occurrence of IRT of power station emissions into the Sydney airshed. Comparisons between TAPM modelling and observations also showed that, on average, concentrations due to contributions from power station emissions were significantly less than total NO_x concentrations.

The second objective of the project, a determination of the significance of IRT on air quality in the Sydney region, was assessed by a comprehensive modelling approach. One modelling exercise involved a determination of the effect of reducing power station emissions to zero on the observed frequency of ozone formation at all points in the modelled domain. Results showed that, for the majority of the time, power station emissions of NO_x have no detectable effect on ozone occurrence in Sydney, even when ozone concentrations are elevated above naturally occurring concentrations. Perhaps of more significance is the impact of power station emissions on ozone formation during ozone "events"; i.e. when ozone concentrations approach or exceed air quality guidelines, including the NSW EPA long term reporting target of 8 pphm. During these events, power stations typically made little contribution. The maximum power station contribution during these elevated ozone events was less than 2 pphm, which occurred for one hour, at one monitoring site.

The air quality modelling also considered the effects of power station NO_x on observed concentrations of NO_2 in the Sydney region. Nitrogen dioxide (NO_2) is largely a secondary

pollutant in the atmosphere, formed from the oxidation of NO. Impacts on NO_2 concentrations were also small, particularly at the long term reporting goal of 10.5 pphm.

The second modelling effort used a more complete description of the chemical processes, and was used to assess impacts on ozone events on specific days. Model performance was assessed and verified by a number of rigorous methods of comparison of predicted and observed concentrations. Verification of system performance is an integral and critical stage of the overall process. Verification was undertaken for both the meteorological predictions and the chemical transport predictions. In general, the model reproduces the observations in a way comparable with other state of the art air quality models.

Based on the modelling of 5 multi-day events when elevated concentrations of ozone were observed in the Sydney region, power station impacts were found to fall into two general patterns: a rural effect under NO_x limited conditions, and interactions with the Sydney urban plume. Impacts can both increase and decrease the predicted ozone concentration. A positive contribution from power station plumes may occur on rare occasions if rural ozone generation raises the ozone background within the urban plume, or if the Sydney urban plume is sufficiently photochemically aged as to become NO_x-limited. In either case, the maximum predicted O_3 increment, was less than 5 ppb.

Outcomes of the two modelling approaches are very consistent. They demonstrate that the contribution of power station emissions to ozone levels of concern is small. The results are also consistent with the outcomes of a previous project undertaken by the CSIRO team for the State Energy Research and Development Fund (SERDF). In that study (Azzi *et al*, 2000), the impacts on air quality of a generic NO_x source, with emission characteristics similar to that of some proposed industrial developments, were determined. These developments included the installation of gas turbines for combined heat and power production (co-generation), and the utilisation of landfill gas or of drained gas (largely methane) from coal mines to produce power. The effects of the new NO_x sources varied depending on location in the Sydney basin. In the eastern part of the basin there was no impact on downwind ozone concentrations, but some increases were observed in the western part of the basin. However, the increases were small and spatially constrained to the narrow area intersected by the plume.

5.1.2. Meteorological Conditions/Processes Relevant to Different Regions

There are clearly differences in the contribution of different power station regions to the frequency of IRT but a detailed identification of meteorological conditions responsible has not been made. Given the relative infrequency of the contributions of power station emissions to air pollutant levels of concern, the development of a robust metric does not appear to be justified at this time.

5.1.3. Broader Airshed Issues – NO_x vs ROC Control

The issue of the comparative merits of hydrocarbon and/or NO_x control in the Sydney region has been vigorously debated since at least the mid 1970s (CASANZ, 1976). It is not appropriate in this report to re-visit the detailed history of this dialogue, but some comments on recent developments are informative.

As described in Section 4, MAQS modelling showed that, in general, the Sydney basin and region has overall higher sensitivity of ozone concentrations to VOC concentrations than to NO_x; in some cases, NO_x control is predicted to be counter-productive.

Results obtained in this study, and elsewhere (Azzi *et al*, 2000) support this conclusion. Based on the two modelling approaches reported here, which use a number of conservative assumptions likely to overestimate the impacts of power station NO_x, the contribution of power station emissions to ozone levels of concern is small.

5.2. Assessment of Control Options

The NSWEPA's *Action for Air* proposes, in addition to initiatives aimed at reducing vehicular emissions, a framework for controlling industrial NO_x, and foreshadows a cap and trade scheme. This scheme has yet to be introduced.

The results of IRTAPS suggest that even very significant reductions in or elimination of all power station NO_x emissions would not have a major beneficial effect on the extent or severity of ozone events in Sydney. By implication, more modest reductions of 20-50% would be similarly ineffectual, and hence the need to manage this particular issue using tools such as pollutant forecasting or cap and trade schemes does not appear to be justified at this time.

This conclusion is in contrast to that reached in other locations. For example, it has been claimed that a NO_x emissions trading scheme covering the north-eastern United States has been a success in reducing NO_x emissions to more than 60% below 1990 levels (OTC, 2002). The scheme was implemented in 12 Northeast and Mid-Atlantic states, and in the District of Columbia.

However, as Figure 5.1 shows (prepared by G Deans, Delta Electricity) the density of power stations and, hence, of NO_x emissions in the NE USA is much greater than in the greater Sydney region. The resultant higher sensitivity of ozone concentrations to regional NOx might be expected in the American location.

Effects of power station emissions on rural and background ozone predicted in Section 4 could be further investigated, in the first instance using existing and new monitoring data, since the major effects are only predicted to occur under the 3X biogenics emission scenario.

There are also possible impacts of power station NO_x on secondary particle formation; these are difficult to address using current modelling approaches, but some conservative estimates of the contribution to fine particles may be possible.

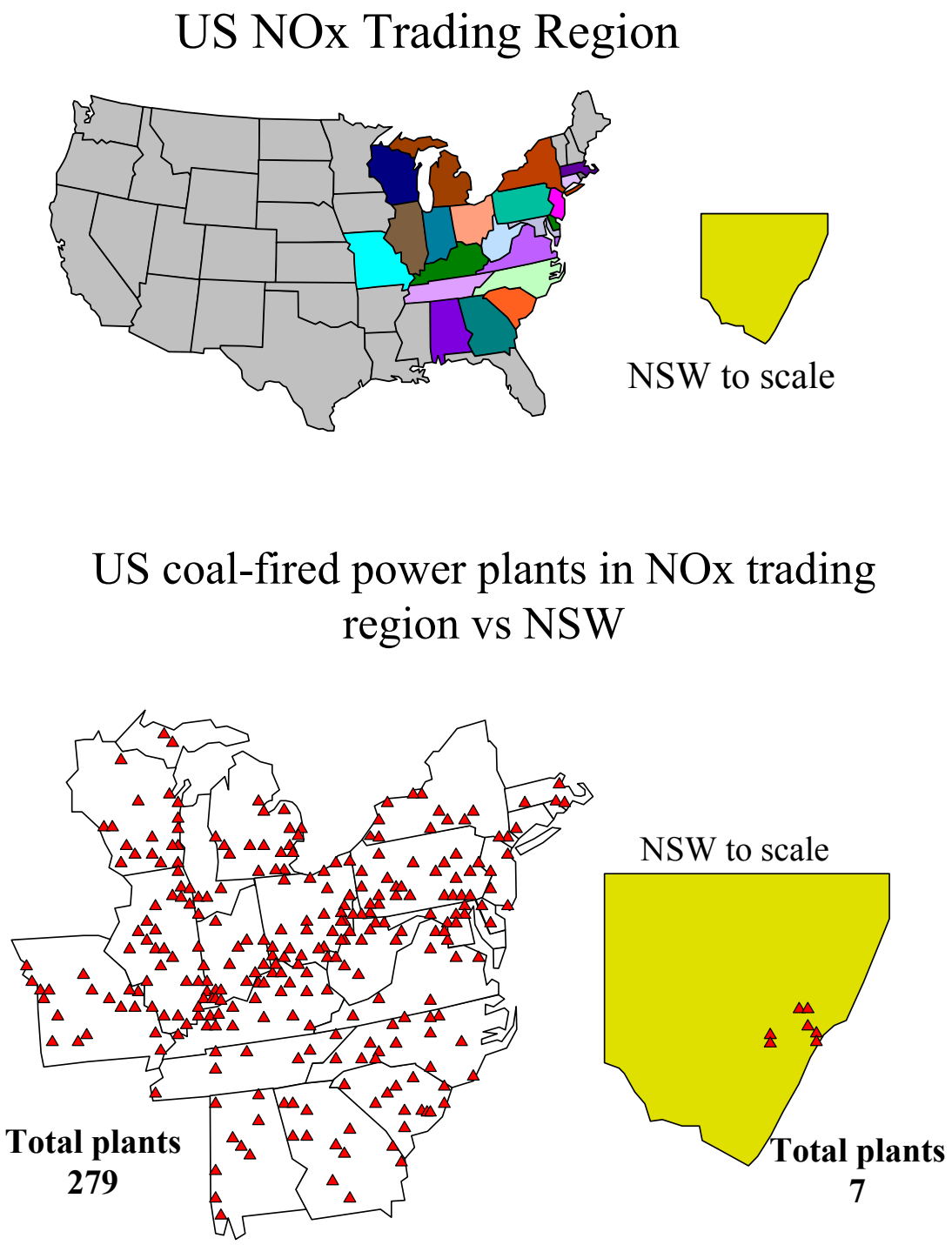

Figure 5.1. United States of America NO_x trading region with NSW shown to scale (kindly provided by Mr G Deans, Delta Electricity).

5.3. Uncertainties – Limitations – Conservatism

The conservative assumptions used in the course of this study should be emphasised since they result in over-estimation and over-prediction of the impacts.

In the assessment of air quality, it is assumed that

- the SO_2 emitted by the power stations can be used as a conservative tracer,
- all observed SO_2 was due to power station emissions.

In addition, in the consideration of the monitoring data, all days where ozone exceeded 8 pphm, but which did not show evidence for IRT were included in the analysis to ensure that all days on which significant ozone was observed in the Sydney region were considered.

In the modelling approaches it is assumed:

- for the initial plume modelling, that all stations are operating at full load with maximum NOx emissions for the whole of the period,
- for the modelling of impacts of power station NOx on the frequency of ozone concentrations, GRS chemistry is used; this chemical scheme is known to produce results which are over-sensitive to the impacts of NOx on predicted ozone.

For the detailed modelling of ozone events, power station impacts are likely to be over-stated for the following reasons:

- Conservative assumptions are used in the biogenic emissions inventory.
- The chemical mechanism for isoprene used in CIT is currently considered to be 10-20 % too reactive
- The treatment of point source emissions as volume sources leads to more rapid onset of Stage-2 and Stage-3 chemical development, both of which are characterised by the generation of excess ozone.

This approach, together with the extensive tests of model performance described elsewhere in the report, ensure that the conclusions of the study are well founded.

6. CONCLUSIONS

The Inter-regional Transport of Air Pollutants Study (IRTAPS) used a combination of methods to assess the frequency of air pollutant transport of power station emissions to the Sydney region, and impact of those transported emissions on smog formation. The methods included a review of previous studies of air quality, an assessment of air quality monitoring data and numerical modelling. The conclusions are listed below.

6.1. Review of Previous Studies

Previous studies which have addressed air quality in Sydney and other locations, were reviewed to examine the evidence for a significant impact of IRT on Sydney's air quality. The review identified potential meteorological mechanisms for such transport, and plume tracking measurements with instrumented aircraft provide observational evidence for transport from the Central Coast power stations towards the northern edge of the Sydney Basin. In spite of this qualitative evidence for inter-regional transport, it was not possible before IRTAPS to determine the frequency of this process, or to determine the magnitude of the effects on existing or future air quality in the Sydney region.

6.2. Air Quality Assessment

Monitoring data for the periods September 1996 to April 1997, and September 1997 to April 1998 were examined, and SO_2 concentrations at selected sites were used as a tracer for power station emissions. The results show that a number of days can be identified when detectable concentrations of SO_2 were measured at the monitoring sites, and ozone concentrations exceeded the guideline somewhere in the Sydney basin. It should be emphasised that this approach leads to an upper limit on the frequency for inter-regional transport because of the conservative assumptions used (eg, all SO_2 is attributed to power station emissions).

There is evidence for both spatial and seasonal variability in those observations which are indicative of inter-regional transport of power station emissions.

6.3. Modelling

Three approaches were taken to the modelling of the frequency and impacts of power station NO_x transport to the Sydney region.

6.3.1. Plume Modelling

The CSIRO model TAPM was used to predict the frequency of inter-regional transport of power station emissions for the periods September 1996 to April 1997, and September 1997 to April 1998. This analysis revealed that, assuming *maximum* NO_x emissions from the power stations, concentrations greater than 10 $\mu g\, m^{-3}$ were predicted to occur between approximately 5% and 15% of hours, but with substantial variability. Comparisons between TAPM modelling and observations also showed that, on average, concentrations due to contributions from power station emissions were significantly less than total NO_x concentrations.

6.3.2. Modelling of the Frequency of Ozone Formation

Impacts of power station emissions on air quality in the Greater Sydney Region were examined using the CSIRO Air Pollution Model (TAPM). In this case a simplified photochemistry module was employed in order to model a long time period, and to determine overall impacts on O_3 and NO_2 formation. TAPM was run over two smog seasons, first with all emission sources included, and secondly with the power station NO_x emissions set to zero.

The modelled results show:

- For the majority of the time power station emissions have no effect on ozone occurrence in Sydney, even when ozone concentrations are elevated above naturally occurring concentrations.

- For ozone events predicted to reach the long term reporting target of 8 pphm, power stations typically made no contribution. The maximum power station contribution during these elevated ozone events was less than 2 pphm, which occurred for one hour, at one monitoring site.

- Impacts on NO_2 concentrations were similarly minor, particularly at the long term reporting goal of 10.5 pphm.

6.3.3. Modelling of Specific Ozone Events

A comprehensive air quality modelling system has been used to assess the impact of NO_x emissions from power stations in the MAQS region on photochemical smog production downwind of Sydney for five photochemical smog events.

Using a conservative approach, which would tend to over-predict the contribution of power station emissions, the model shows that power station emissions, at least during the early morning hours, tend to further slow photochemical production rates and lead to reduced concentrations of ozone. Power station impacts were found to fall into two general patterns: a rural effect under NO_x limited conditions, and interactions with the Sydney urban plume. A positive contribution from power station plumes may occur on rare occasions if a) rural ozone generation raises the ozone background within the urban plume; b) the Sydney urban plume is sufficiently photochemically aged as to become NO_x-limited. In either case, the maximum predicted O_3 increment, was less than 5 ppb.

In summary, IRTAPS demonstrates that the contribution of power station emissions to ozone levels of concern is, at most, small and infrequent. Hence, it is likely that the magnitude and frequency of ozone events in the Sydney region would not be significantly reduced by additional controls on power station NO_x emissions.

7. ACKNOWLEDGEMENTS

The authors thank the NSW EPA for assistance in this project through the provision of air pollution monitoring data, and the MAQS inventory of emissions. The project benefited greatly from discussions with representatives of the electricity generators in particular G Deans, G Sharrock and S Wheeler from Delta Electricity, R Shirtley and M Cooper from Eraring Energy, S Ireland and P McDonald from Macquarie Generation.

The authors also wish to acknowledge the significant contribution of the project manager, Hugh Malfroy of Pacific Power International. The authors wish to express their gratitude for many detailed discussions, probing questions and his careful reading of the draft report.

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