NATIONAL ENVIRONMENTAL HEALTH FORUM

# *Sulphur dioxide*

**National Environmental Health Monographs**

**Air Series No. 4**

1999

# Sulfur dioxide

Len Ferrari and Janet Salisbury

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**Air Series No. 4**

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# Contents

# Preface

The National Environmental Health Forum has been established by the Directors of Environmental Health from each State and Territory and the Commonwealth with a secretariat provided by the Commonwealth Department of Health and Family Services.

The National Environmental Health Forum is publishing a range of monographs to give expert advice and guidance on a variety of important and topical environmental health matters. This publication is the fourth in the air series. A list of published monographs is provided on page vi.

The National Environmental Health Forum, in expediting publication of this document, have undertaken targeted consultation only.


## Acknowledgments

The air monitoring data for this report have required the assessment of large amounts of data provided by various organisations. The report examines the most recent air quality information available and analyses it in a uniform format. This has meant that the information was not always readily available and sometimes had to be generated by the supplier in the required format.

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**Please note:** Every care has been taken to ensure validity of data used and for the quality assurance on the analysis performed.

## Disclaimer

## Published Monographs

*Water Series*

1. Guidance for the control of Legionella (1996)
2. Guidance on water quality for heated spas (1996)
3. Guidance on the use of rainwater tanks (1998)

*Soil Series*

1. Health-based soil investigation levels, 2nd edition (1998)
2. Exposure scenarios and exposure settings, 2nd edition (1998)
3. Composite sampling (1996)

*Metal Series*

1. Aluminium, 2nd edition (1998)
2. Zinc (1997)
3. Copper (1997)

*Air Series*

1. Ozone (1997)
2. Benzene (1997)
3. Nitrogen Dioxide (1997)
4. Sulfur dioxide (1999)

*General Series*

1. Pesticide use in schools and school grounds (1997)
2. Paint film components (1998)
3. Guidelines for the control of public health pests – Lice, fleas, scabies, bird mites, bedbugs and ticks (1999)
4. National standard for licensing pest management technicians (1999)

*Indigenous Environmental Health Series*

1. Indigenous Environmental Health No. 1 (1999)

*Exposure Series*

1. Child activity patterns for environmental exposure assessment in the home (1999)

*Counter Disaster series*

1. Floods: An environmental health practitioner's emergency management guide (1999)

# 1. Introduction

Oxides of sulfur occur in several forms in the atmosphere: as gas; in liquid aerosols; and as major constituents of fine atmospheric particles. They are active constituents in atmospheric processes that have important and often poorly understood influences over urban air quality, weather patterns and global climate.

Sulfur dioxide ($SO_2$) is a colourless gas that forms an acidic solution in water, which is readily oxidised to sulfuric acid. It is released into the atmosphere in large quantities by natural processes. An important source is from the action of anaerobic bacteria in peat bogs and tidal marshes, forming hydrogen sulfide, which is oxidised to sulfur dioxide and sulfur trioxide ($SO_3$) in the atmosphere. Sulfur and sulfur gases are also emitted in large quantities as a result of volcanic activity.

Most of the sulfur dioxide that is of concern to public health results from human activities, principally the burning of fossil fuels. It is readily converted to sulfuric acid and sulfates in the atmosphere which is an important process in the formation of aerosols and particulate materials associated with smog over large urban areas of industrialised countries. Sulfur dioxide is also a major component of acid rain, which is devastating forests and freshwater ecosystems in many parts of the world.

Typically, sulfur dioxide in the atmosphere is oxidised to sulfur trioxide at a rate of 0.5% to 10% per hour. The sulfur trioxide then reacts with water to form sulfuric acid. Sulfur oxides are usually adsorbed onto atmospheric particles, particularly carbonaceous (eg soot) particles, on which these reactions occur.

Combustion of fossil fuels is a major source of sulfur oxides worldwide, where coal or oil with a high sulfur content is burned in power stations and boilers. Fossil fuels typically contain 0.1% to 3% sulfur, although fuels from some sources can contain considerably larger amounts. Australian fuels are low in sulfur and local coal typically contains less than 1% sulfur, oil has less than 0.5 % and natural gas is very low in sulfur. Roasting of metal sulfide ores during smelting processes and sulfuric acid manufacture can also be important sources in some areas.

Traditionally, high sulfur dioxide emissions from industrial plants have been controlled through the use of tall chimneys, some over 200 metres in height (involving high capital costs in construction and operation). These rely on atmospheric dispersion to dilute emissions to safe concentrations before they reach ground level. Dispersion from a stack is critically dependent on the meteorology and topography of surrounding areas. Because of these factors, a tall stack cannot always guarantee that concentrations at ground level will remain below levels of concern for public or environmental health. In Australia, stacks over 200 metres high have been constructed at a number of sites including Port Pirie, Mount Isa and Wollongong in order to alleviate problems of sulfur dioxide pollution.

Alternative techniques, collectively known as flue-gas desulfurisation technology, are being adopted in many countries. This technology involves scrubbing systems utilising lime or limestone to react with sulfur oxides, producing calcium sulfate as a by-product.

Sulfur dioxide is an irritant when it is inhaled because of its acidic nature, and high concentrations can cause breathing difficulties for people exposed to it. People suffering from asthma may be especially susceptible to these adverse effects. The associated health impacts of sulfur oxide gases have been recognised by the establishment of health guidelines.

## National Health and Medical Research Council air quality goals

In November 1995 the National Health and Medical Research Council (NHMRC) introduced revised ambient air quality goals for sulfur dioxide:

- a 10-minute average of 700 micrograms per cubic metre (µg/m3) expressed at 0°C and 101.35 kPa (equivalent to 0.25 ppm; see Box 1);
- a one-hour average of 570 µg/m3 (0.2 ppm) expressed at 0°C and 101.35 kPa; and
- an annual mean of 60 µg/$m^3$ (0.02 ppm) expressed at 0°C and 101.35 kPa (existing 1988 goal).

The NHMRC also issued the following statement to accompany these levels:

**'CAUTION: At these recommended levels, there still may be some people (for example, asthmatics and those suffering chronic lung disease) who will experience respiratory symptoms and may need further medical advice or medication.'**

In setting the goals the NHMRC emphasised that the revised levels are not mandatory standards but represent a technical framework for identifying acceptable air quality through community consultation, and that as such should be brought to the attention of environment and health agencies.

Over the period of assessment described in this monograph (1980–95), sulfur dioxide levels in Australia have seldom reached these levels in urban areas. Fuel containing high levels of sulfur has been eliminated from use in major cities in Australia. No exceedances of the guidelines have been reported in Canberra,[†] Melbourne or Brisbane and has been reported only once in Sydney(1980). Exceedances of the guidelines have occurred in Adelaide and Perth and in industrial regions outside of the capital cities. The elevated levels of sulfur dioxide that have been recorded have generally been the result of emissions from point sources related to ore smelting, oil refining, acid production and occasionally from very large coal combustion sources. Peak levels are a result of episodic releases or unusual meteorological conditions. The likelihood of extreme levels being detected is closely related to the siting of monitors, which is discussed in Section 5.

This monograph summarises recent findings on the health effects of sulfur dioxide and the exposure levels of the Australian population to sulfur dioxide, and will help health, education and environmental professionals gain a better understanding of the issues relating to the NHMRC air quality goals for sulfur dioxide and the options for meeting the goals.

*Box 1*

**UNITS**

The international unit for sulfur dioxide concentration is **micrograms per cubic metre (μg/m$^3$)**.

This unit is a mass of gas in a volume of air and must be expressed at a specified temperature and pressure. In Australia the standard temperature for expression of air pollution concentrations is 0°C at 101.35 kilopascals air pressure. In the United States it is generally 25°C and in Europe it varies.

As most instrumental readings of sulfur dioxide are expressed in **parts per million (ppm)** — a measurement of the airborne concentration of a substance by volume — most researchers use this unit of measure, which does not vary with temperature or atmospheric pressure. The latter unit is used throughout this report. The conversion of ppm to μg/m$^3$ varies with temperature and pressure but the following approximate conversion applies:

**1 ppm sulfur dioxide (by vol) = 2750 μg/m$^3$ (range: 2860–2620 μg/m$^3$) at 0–25°C and 101.35 kPa**

## 2. Sources of sulfur dioxide

On a global basis, natural emissions of sulfur compounds exceed those resulting from human activity and the formation and disposal of sulfur compounds in the natural system is termed the sulfur cycle. An important part of this cycle is the action of anaerobic bacteria in peat bogs and tidal marshes where hydrogen sulfide is produced as a by-product of decomposition of organic matter. In the atmosphere, hydrogen sulfide is oxidised to sulfur dioxide and sulfur trioxide. Volcanic activity is also a major component of natural emissions, accounting for up to 20% of the total. Sulfur oxides, both from natural sources and from human activity, are washed out of the atmosphere by rain water and returned to the soil and oceans where the process continues. Natural background concentrations of sulfur dioxide in remote

[†] In Canberra, because of the batch nature of the monitoring, only the mean goal can be assessed.

locations have been measured at between 0.1 ppb (parts per billion) and 1 ppb, with an average of approximately 0.3 ppb.

In urban and developed regional areas of Australia where sulfur dioxide is of concern, natural emissions are not a major source and sulfur dioxide pollution results from human activities involving the combustion or oxidation of materials containing sulfur. On a worldwide basis, combustion of fuels containing sulfur is a significant source of sulfur dioxide, but in Australia this is not the case. Fortunately, Australian coal, oil and gas are low in sulfur (all less than 1%) and imported fuels are seldom used. Results of the 1985 national airshed inventory of emissions and the 1992 inventory of the Sydney Region show that industry is by far the most important source of sulfur dioxide in urban areas except in Canberra (see Table 1, Figure 1 and Appendix A).

Roasting or smelting of sulfur-rich ores has the potential to produce substantial amounts of sulfur dioxide. Australian lead, copper and nickel ores, frequently contain a very large percentage of sulfur. In some cases the sulfur-rich emissions are used to manufacture sulfuric acid but at other sites they are discharged, virtually without control, from tall stacks.

Refining high sulfur crude oil has the potential for significant emissions of sulfur dioxide and hydrogen sulfide. Combustion of huge quantities of coal, even when the sulfur content is less than 1%, can give rise to episodic high concentrations of sulfur dioxide in the air. The manufacture of sulfuric acid, from the burning of sulfur, can give rise to high emissions of sulfur dioxide, especially if the catalytic conversion of sulfur dioxide to sulfur trioxide is deficient.

Episodes of increased sulfur dioxide concentrations can occur in the vicinity of industrial point sources. Atmospheric concentrations of sulfur dioxide are determined by source strengths and stack height of release, but they are also heavily influenced by the weather (eg wind speed). Impingement of a plume from a point source to ground level after atmospheric dispersion, is difficult to predict. Under some meteorological conditions high concentrations can occur near the point of emission but under other conditions a plume emitted from a tall stack can travel, with little dilution, for long distances and in extreme conditions up to hundreds of kilometres before it reaches the ground. Dispersion models are used to predict ground level concentrations at different emission rates, stack heights and meteorology. Variability in some factors accounts for the variability of ambient levels and the constant state of flux around point sources.

Ambient sulfur dioxide concentrations around point sources are strongly influenced by emission control requirements and regulations requiring stack heights to be sufficient to give ground level concentrations within the guidelines.

*Table 1: Percentages of sulfur dioxide emissions from various human activities, 1985.*

| *Source* | *Sydney* | *Melbourne* | *Brisbane* | *Adelaide* | *Perth* | *Canberra* |
|---|---|---|---|---|---|---|
| Motor vehicles | 18 | 17 | 4 | 4 | 5 | 71 |
| Other mobiles | 5 | 4 | 1 | 1 | 1 | 8 |
| Waste combustion | 1 | – | – | – | – | – |
| Non-mobile fuel combustion | 25 | 35 | 76 | 13 | 14 | 21 |
| Petroleum/solvent | 50 | 43 | 12 | 14 | 64 | – |
| Miscellaneous | – | – | 7 | 68 | 15 | – |
| **Total kilotonnes** | **16.4** | **7.2** | **20.9** | **12.4** | **20.0** | **0.5** |

– < 0.5% NB: due to rounding, not all columns will total 100%

Source: 1985 National Airshed Inventory (AEC 1988)

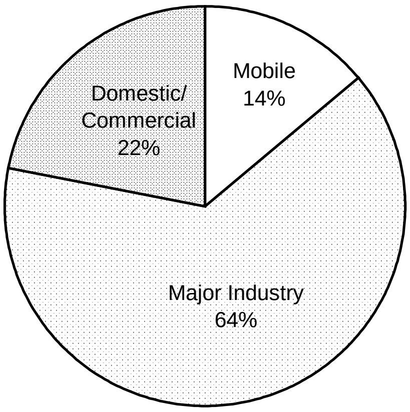



*Figure 1: Sulfur dioxide emissions, Sydney Region 1992*

Source:Carnovale et al 1995 (see also Appendix A)

### Indoor and occupational sources

Of the few direct 'indoor' sources of sulfur dioxide that result in elevated concentrations of sulfur dioxide, most occur in industrial environments.

Except for occupational exposures, indoor levels of sulfur dioxide are generally far lower than those outdoors. The infiltration of sulfur dioxide into the indoor environment is a source of indoor air pollution but chemical and physical reactions effectively reduce the indoor levels to the extent that they are always less than those outdoors.

Indoor sources and exposures will not be discussed further in this document.

## 3. The effects of sulfur dioxide on human health

Information on the effects of sulfur dioxide on human health was obtained from:

- Steer KH and Heiskanen LP. (1994) *Options for Australian Air Quality Goals for Oxides of Sulphur*. Report to the Environmental Health Standing Committee, National Health and Medical Research Council.
- UK Department of Environment (1995) *Sulphur Dioxide*. Expert Panel on Air Quality Standards, HMSO, London.

Information on the effects of sulfur dioxide on human health has been derived from studies of volunteers (*controlled exposure studies*) and from population studies on people living in polluted areas (*epidemiological studies*). Historically, health effects from exposure to sulfur dioxide have been linked with those of suspended particulate matter. This arose from their close association in terms of sources and environmental concentrations, notably where coal was generally used for domestic heating and industrial processes. This situation has now changed substantially but much of the available epidemiological evidence is still based on earlier studies carried out in localities highly polluted with sulfur dioxide and particulate matter (in the form of smoke) from the burning of coal. More recent studies have begun to present a clearer view of the separate effects of these pollutants and the World Health Organization (WHO) first considered them separately in their 1994 review.

Evidence from human and animal studies shows that exposure to sulfur dioxide can cause a reduction in lung function. Epidemiological, controlled exposure, and animal studies have all shown reduced forced expiratory volumes ($FEV_1$) and increased airway resistance (bronchoconstriction). In animals, interactions between sulfur dioxide, sulfuric acid with ozone or nitrogen dioxide have been demonstrated to cause further reductions in lung function.

Because of its high solubility in water, sulfur dioxide dissolves readily in epithelial fluids in the nasal area and upper respiratory system. Oxidation to sulfuric acid is followed by neutralisation and excretion as ammonium or other salts. Sulfuric acid aerosols can be deposited in the nose, throat, tracheal and bronchial regions or lung alveoli, according to their size. The deposition pattern in the lungs is affected by such factors as atmospheric loading and humidity. Conditions that generate highly acidic droplets, which can exceed the neutralising capacity of ammonia in the upper respiratory tract, lead to greater deposition of acidic aerosols into the lungs.

The irritant effect of sulfur dioxide occurs when nerves in the lining of the nose, throat and the airways of the lungs are stimulated by sulfuric acid. This causes a reflex cough, irritation and a feeling of chest tightness and may lead to narrowing of the airways. This latter effect is particularly evident in people suffering from asthma and chronic lung disease, whose airways are often inflamed and easily irritated. Such people often have already narrowed airways and further narrowing can affect their ability to breathe properly.

Although the asthma incidence in Australia and elsewhere has been increasing over the last few decades, there are no data that link this trend with air pollution levels. A study in Australia (Hunt and Hollman 1987) compared cases (hospital discharges recorded for asthma) and matched controls against ambient sulfur dioxide concentrations. These were stratified into specific exposure locations and asthma hospitalisation rates for children or adults. They found no significant correlations with mean annual sulfur dioxide levels. The highest annual mean concentration recorded in this study was 0.016 ppm, which is below the NHMRC annual goal of 0.02 ppm. Short-term peak concentrations of sulfur dioxide were not available (or used) to investigate a relationship under maximum exposure situations.

## Controlled exposure studies

Direct information on the acute effects of sulfur dioxide has come from controlled chamber experiments on volunteer subjects. Most of these studies have been for exposure periods ranging from a few minutes to 1 hour but the exact duration is not critical because responses occur very rapidly, within the first few minutes of starting inhalation. Continuing the exposure further does not increase the effects. The effects observed include reductions in $FEV_1$ or other indices of lung capacity, increases in specific airway resistance and symptoms such as wheezing and shortness of breath. Such effects are enhanced by exercise, when the volume of air inspired increases, allowing sulfur dioxide to penetrate further into the respiratory tract.

In normal healthy volunteers, measurable narrowing of the airways may occur after breathing the gas at concentrations of about 4–5 ppm. There is considerable variation between individuals and the exposure–response relationship is continuous, without any clearly defined threshold. Adverse lung function effects in healthy subjects are minimal at concentrations below 1 ppm, although some reversible irritation of the mucus-producing tissues of the lungs, and cellular changes indicative of inflammation have been observed at this level. In general, people with asthma are considerably more sensitive to sulfur dioxide than healthy individuals (see below).

### *Asthma*

Asthma is a major public health concern in Australia. It is characterised by intermittent respiratory symptoms (laboured breathing, chest tightness, wheezing and coughing), airway hyperresponsiveness (allergy) to a variety of nonspecific stimuli, and reversible or variable airways obstruction. Airway inflammation is a hallmark of this condition and asthma attacks are episodes of acute airflow obstruction.

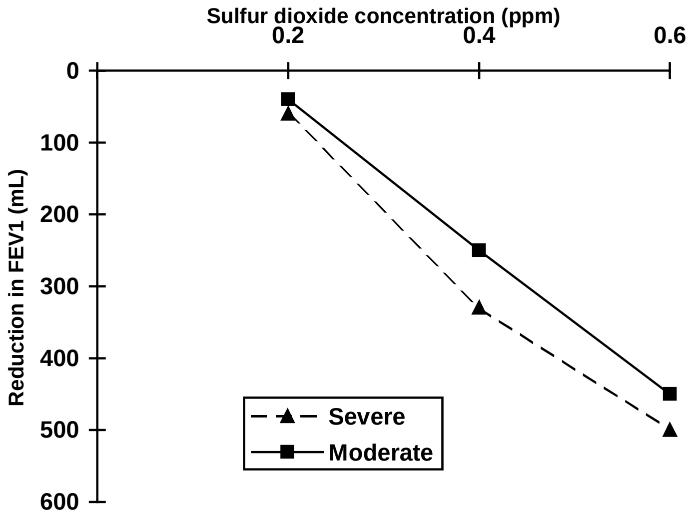



*Figure 2: Dose-response relationship of reduction in mean $FEV_1$ with increasing concentrations of sulfur dioxide with exercise (after subtracting the effect of exercise alone) in patients with moderate and severe asthma*

Source: Linn et al 1987/WHO 1994

Controlled exposure studies of exercising asthma patients have provided clear evidence that asthma sufferers show reductions in breathing capacity after short-term exposure to concentrations of about 0.3–0.4 ppm sulfur dioxide. Some individuals have developed bronchoconstriction at concentrations of 0.2 ppm or less. An example of the exposure–response relationship for such subjects is shown in Figure 2, expressed in terms of reductions in $FEV_1$ after a 15 minute exposure. In this study only small changes, not regarded as clinically significant, were seen at 0.2 ppm; reductions representing about 10% of baseline $FEV_1$ occurred at 0.4 ppm; and reductions of about 15 % occurred at about 0.6 ppm. A reduction of 10% of baseline $FEV_1$ has been defined by the US Environment Protection Agency as an adverse health effect for lung function. The response was not greatly influenced by the severity of the asthma. Most seriously affected asthmatic subjects do not take part in such experiments, and there may be a subgroup that would be affected at lower concentrations (occasional responses at lower concentrations have been recorded).

Administration of some types of asthma medication (such as beta-2 agonists or mast cell stabilising compounds) has been shown to decrease the responses of asthma sufferers to sulfur dioxide in a dose-dependent manner. Administration of anticholinergic medication, however, although improving $FEV_1$ before sulfur dioxide exposure, did not prevent bronchoconstriction after exposure to the gas, indicating that cholinergic mechanisms are not important for sulfur dioxide induced effects.

Exposure studies have also been carried out using sulfuric acid mist/aerosols. The results were variable but asthmatic subjects generally showed greater susceptibility than individuals with normal lung function.

## Epidemiological studies

The responses measured in epidemiological studies of sulfur dioxide are complicated by other air pollution components which also affect lung function (particles, nitrogen oxides, volatile organic compounds, ozone and other oxidising species) and, as the controlled exposure studies show, individual responses are variable.

### *Short-term exposure*

Investigations in the UK in the 1950s and 1960s showed that an increased number of deaths (compared to the number expected) was associated with pollution episodes in which sulfur dioxide concentrations of 0.17 ppm (24-hour average) were combined with comparable increases in airborne particle concentrations. There was also evidence of an increase in the number of people complaining of respiratory symptoms at sulfur dioxide concentrations down to a daily average of 0.085 ppm in association with particle increases. **It must be noted that daily averages can conceal short-term peaks significantly greater than these values.**

A number of epidemiological studies in different countries have shown associations between short-term peaks of sulfur dioxide concentration (with daily means above 0.04 ppm or hourly means above 0.2 ppm) and health effects, including respiratory symptoms, hospital admissions for pulmonary diseases and decreases in lung function. Such increased levels of sulfur dioxide were usually found in conjunction with increased particulate matter and nitrogen dioxide.

A study in Athens from 1975 to 1982 showed that on days of 'high pollution' (daily average sulfur dioxide levels above 0.05 ppm) deaths from respiratory conditions exceeded the expected numbers. For the age group of 75 years and over, an association was evident for immediate cause of death. In a similar study for Lyons (monthly sulfur dioxide maximum 0.07 ppm) and Marseilles (monthly maximum of 0.06 ppm), a statistically significant association was found between daily sulfur dioxide levels and mortality from respiratory causes for people aged 65 years and over (75% of all deaths).

### *Long-term exposure*

The long-term effects of sulfur dioxide on humans, are not very clear at the present time because it is difficult to distinguish the effects of this gas from those of other air pollutants. Despite these shortcomings the epidemiological data appear to support the conclusion that associations exist between the long-term exposure to moderately increased levels of ambient pollution and an increased incidence of respiratory disease symptoms, and in some cases decreases in pulmonary function. These associations have been observed at quite low annual average levels of sulfur dioxide (0.008 ppm) and when particulate levels were below control values. Not all studies have demonstrated these effects. As mentioned above, the Australian study of Hunt and Holman (1987) found no association between asthma hospitalisation rates and annual average sulfur dioxide levels.

It must be stressed again that the significance of annual average sulfur dioxide concentrations to recorded health effects is unclear. Days of 'high' sulfur dioxide levels and peak hourly values may be more relevant indicators for observed health effects.

### *Sensitisation to allergens*

It has been suggested that exposure to sulfur dioxide may cause sensitisation to inhaled allergens (such as grass pollen) in animals and some studies have also suggested that people living in polluted areas may be more likely to become sensitised to certain allergens. Whether this effect is due to sulfur dioxide or to other components of polluted air is not clear.

## Summary of health effects

The scientific data indicate that for asthma sufferers in Australia, short-term reductions in lung function may occur when sulfur dioxide goals are exceeded (ie a 10-minute average of > 0.25 ppm or a 1-hour average of > 0.2 ppm). The reductions may be transient and small on average but an unknown number of people with greater sensitivity to sulfur dioxide may experience clinically significant reductions in lung function and some who already have impaired lung function may be severely affected. It is possible that reducing sulfur dioxide exposures in Australia could reduce the number and severity of asthma attacks.

Acute lung function effects become evident in experimental exposure studies with exercising asthmatics after about 10 minutes of exposure. This is why the 10-minute goal is necessary, especially around point sources, to indicate exposure of the sensitive population.

The long-term effects of sulfur dioxide are not well understood, particularly the question of whether sulfur dioxide actually causes lung disease rather than simply provoking attacks of asthma. Recent epidemiological evidence appears to indicate that moderately elevated ambient sulfur dioxide levels (annual means of above 0.008 ppm) are linked to an increased incidence of respiratory illness and symptoms and decreases in pulmonary function.  However, annual average figures can conceal many high short-term peaks, which may be more closely correlated with the health effects than the long-term average.

# 4. International standards, goals and guidelines

Air quality is assessed by comparing levels of contaminants against standards or goals. In Australia, since 1994, when the *National Environmental Protection Council Act 1994 (Cwlth)* was passed by parliament, it has been the responsibility of the NEPC to set standards for environmental protection including ambient air quality standards (known as National Environmental Protection Measure for Ambient Air Quality). The National Environmental Protection Council (NEPC) is a body established jointly by each State and Territory and the Commonwealth Government to work cooperatively at a national level to ensure that all Australians enjoy the benefits of equivalent protection from air, water, soil and noise pollution and that business decisions are not distorted nor markets fragmented by variations in major environment protection measures between member governments. Previously, national air quality goals had been set by the National Health and Medical Research Council and, in some cases, levels were set by State authorities to serve as guidelines for those who take responsibility for controlling emissions and developing strategies for reducing air pollution.

National standards for ambient air quality (the National Environmental Protection Measures for Ambient Air Quality) for sulfur dioxide, nitrogen dioxide, carbon monoxide, lead, photochemical oxidant (as ozone) and particles (as PM10) were set by NEPC in June 1998.

The 1997 WHO Air Quality Guidelines for Europe recommend a 10-minute goal of 500 $\mu g/m^3$ (0.18 ppm), a 24-hour goal of 125 $\mu g/m^3$ (0.045 ppm) and 50 $\mu g/m^3$ (0.018 ppm) over a one-year period. No goal was set for 1-hour.

The ambient air quality standard for Australia is a one-hour maximum concentration of 0.2 ppm, a 24-hour maximum of 0.08 ppm, and a yearly maximum concentration of 0.02 ppm [the NHMRC outdoor goal for sulfur dioxide is a 10-minute maximum of 0.25 ppm, a 1-hour maximum of 0.2 ppm (NHMRC 1995) and an annual average of 0.02 ppm (NHMRC 1988)]. A range of 1-hour averaged international air quality goals for sulfur dioxide are shown in Figure 3 and it shows a wide variation in goals around the world, reflecting the different approaches taken to the achievement of such goals.

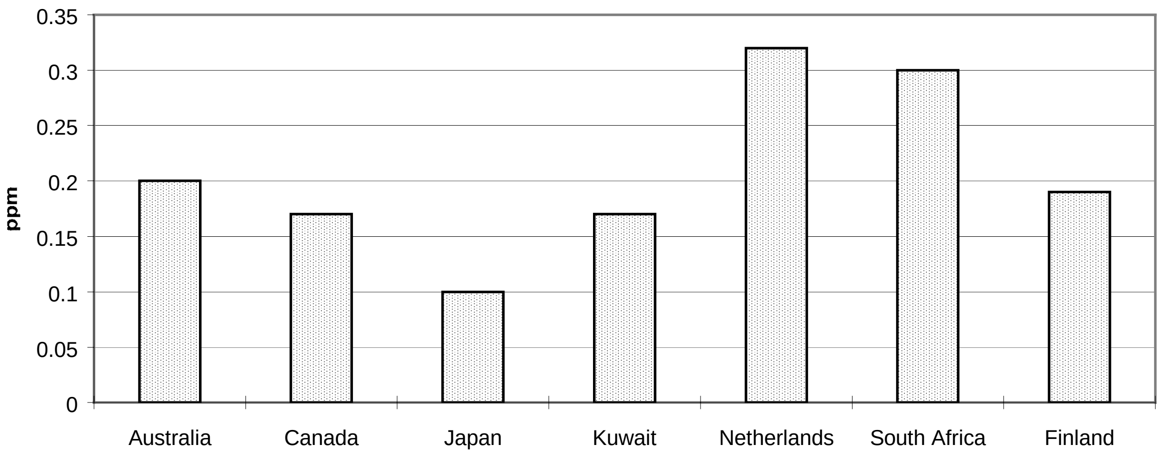



*Figure 3: International sulfur dioxide goals: 1-hour averages (ppm)*

Source: Cochran et al 1992 and elsewhere

# 5. Measurement and monitoring of sulfur dioxide

## Methods

The monitoring methods used by the organisations providing data, over the period of assessment, 1980–95, comply with the Australian Standard AS3580.4.l: Determination of Sulfur dioxide — Direct-reading instrument method.

Three techniques of measurement of sulfur dioxide are permitted under the Australian Standard — ultraviolet fluorescence, flame photometry and electrochemistry. The measurement method generally employed in Australia is UV fluorescence (sometimes pulsed). The performance standard requires the techniques to meet certain minimum specifications, including tolerance to interference by known concentrations of other gases likely to be in the atmosphere at the time of measurement, to provide a minimum detection limit of 0.01 ppm and to meet other performance criteria. Compliance with the Australian Standard ensures that the methods are reliable, sensitive and specific for sulfur dioxide. The UV fluorescence method is described briefly below.

### *Ultraviolet fluorescence*

The sample air is first drawn through a scrubber designed to remove poly-nuclear aromatics (which can interfere in the analysis). The air then passes into the reaction cell where it is irradiated by a beam of ultraviolet energy at a known wavelength. Sulfur dioxide molecules present in the sample air become excited to produce a metastable higher energy molecule. This high energy molecule, on returning to its ground state, releases energy in the 120 nm to 190 nm range.

The following equations show the reactions

$$SO_2 + \text{UV (190–230 nm)} \rightarrow SO_2^*$$

$$SO_2^* \rightarrow SO_2 + \text{Energy (120–190 nm)}$$

* represents a sulfur dioxide molecule in an excited (higher energy) state

The energy emitted passes through an optical filter to a photomultiplier tube (PMT). The radiation emitted is proportional to the concentration of sulfur dioxide in the sample air (Okabe and Schwarz 1974).

### *Calibration*

Sulfur dioxide calibration is carried out using certified gas mixtures. The calibration procedure is specified in AS3580.4.1.

### *Positions of measurement sites*

To obtain a measure of general population exposure, ambient air quality is usually measured at sites that represent residential exposure, typically along the guidelines in Australian Standard AS 2922 for Neighbourhood Stations. Since the sulfur content of fuels in Australia is low, the sulfur dioxide levels obtained in urban areas are generally low unless the measurement sites are around major industries that are producing the gas. Sulfur dioxide measurement is therefore more often carried out at Peak Stations in an effort to detect peak levels at points of estimated maximum ground level concentration (calculated by dispersion modelling). For this reason it is difficult to estimate population exposure (see Section 8).

## Monitoring

### *Rationale for monitoring*

As with other air pollutants, monitoring of sulfur dioxide concentrations in ambient air in Australia is carried out by State environmental authorities and major industries or utilities required to monitor sulfur dioxide. Monitoring is usually at fixed stations where a continuous record of sulfur dioxide levels is collected.

As already described, the fixed stations used for sulfur dioxide monitoring differ from those used for other pollutants in that they tend to be near major point sources rather than in residential areas. The relationship between such fixed station monitoring and population exposure is difficult to determine.

It should also be noted that, as with outdoor measurements for most other pollutants, the majority of people are indoors when peak outdoor pollutant readings are recorded and are thus not exposed to the outdoor concentrations. People living in industrial cities, including groups that could be particularly sensitive to the health effects of air pollution, such as young children and the elderly, may spend more than 90% of their time indoors. Studies in the United States have shown that although lower, indoor concentrations of reactive gases are frequently a significant fraction of the outdoor concentrations and track outdoor levels closely, as a result of infiltration of outside air. No data are available for indoor levels of sulfur dioxide in Australia.

The health goals for sulfur dioxide have been established using time-averaging periods from 10 minutes to one year to cover acute and chronic effects. In non-urban areas where sulfur dioxide pollution is mainly from point sources, short-term exposures are more likely, whereas in urban areas long-term exposures may be more important.

### *Monitoring sites in Australia*

Figure 4 shows the 62 monitoring sites in Australia where continuous 1-hour average ambient data are available for assessment. Although there is an NHMRC 10-minute goal, data in this format are not widely available. In the capital cities, these sites mainly represent government monitoring while in the regions near to major industries, eg in Latrobe Valley (Victoria) and Hunter Valley (New South Wales), monitoring is usually carried out by industry.

The data examined for this report were recorded during the period 1980–95 and include some sites that are now discontinued and some that have only recently started recording. As elevated sulfur dioxide concentrations generally come from point sources, the ambient sites are often less permanent than are commonly the case for sites monitoring area sources such as motor vehicle emissions. Although the sites where data are available represent a reasonable percentage of the population, they do not cover a large proportion of the geographical area. The combined data obtained for analysis amounts to over 300 years or approximately 2.5 million hourly averages.

Hourly average data for sulfur dioxide were available from the capital cities Sydney, Melbourne, Brisbane, Adelaide and Perth. The Melbourne data comes from the Port Phillip Control Region and includes Geelong. No continuous monitoring is carried out in Canberra, Hobart or Darwin. It is unlikely that very elevated levels will be experienced in these centres because of the absence of large sulfur dioxide emissions within the cities. In regional areas, where the siting is usually aimed at measuring peak values from industrial emissions, data are available from Newcastle, Wollongong and Hunter Valley (New South Wales), Latrobe Valley (Victoria), Gladstone and Mount Isa (Queensland) and Port Augusta (South Australia). Comprehensive monitoring data are available from all government sites but in some of the regional areas, where major industrial emissions occur, the ambient data are incomplete or were not available for this survey.

In the capital cities, the siting of the sulfur dioxide monitors is sometimes based on measuring a general population exposure and sometimes based on measuring local impacts from point sources. In Adelaide, the majority of sites were aimed at measuring peak levels around an acid plant and do not represent average population exposure. For this reason the levels reported do not necessarily provide a consistent measure of levels within a city and cannot easily be used for extrapolation between cities.

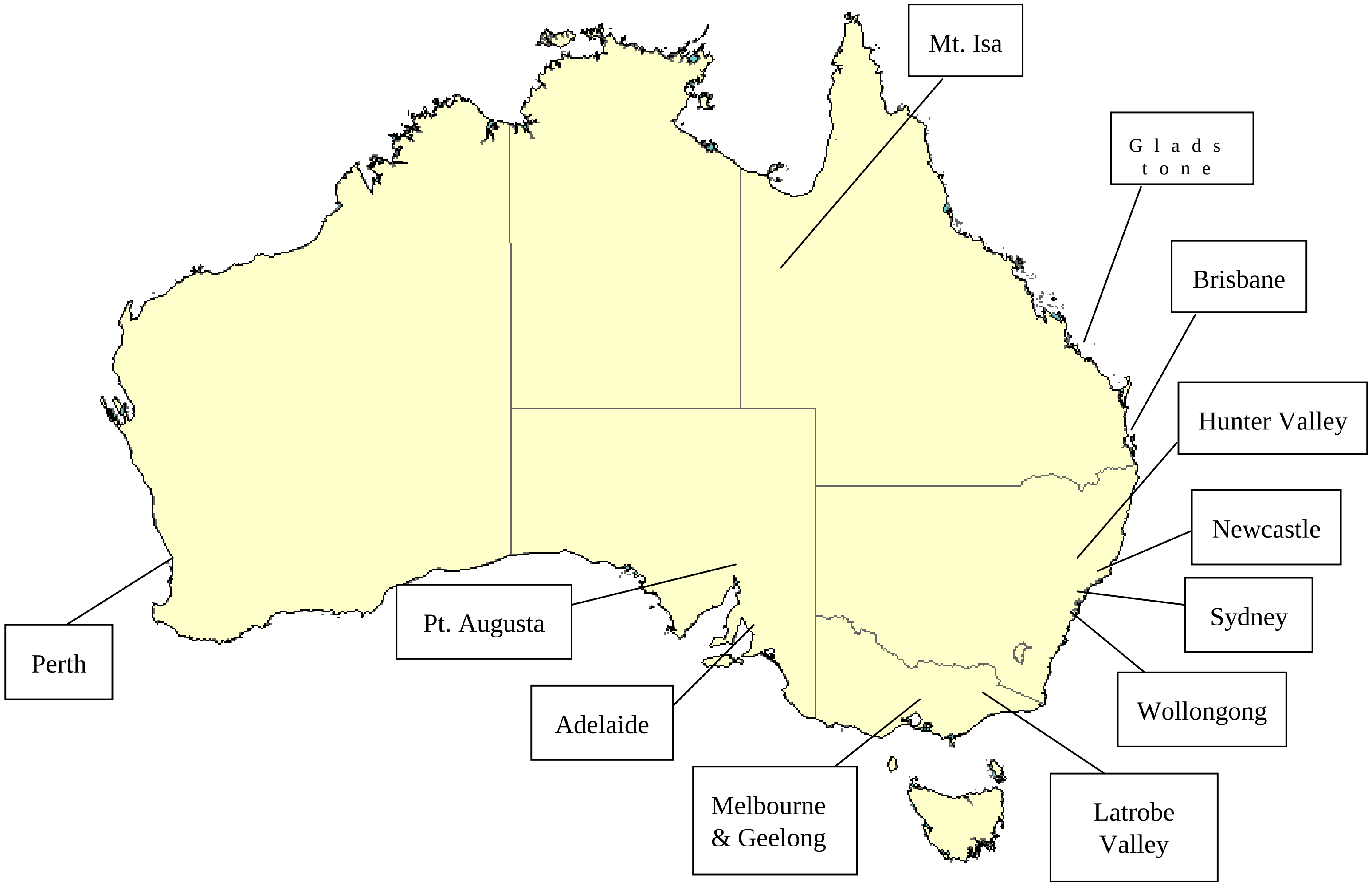



*Figure 4: Monitoring sites for sulfur dioxide in Australia, 1996 (62 sites)*

# 6. Sulfur dioxide levels in Australia

Sulfur dioxide pollution varies widely around Australia. Australian coal, oil and gas contain low levels of sulfur by world standards and in most large cities the sulfur content of fuel is regulated to limit emissions of sulfur dioxide. Sulfur content of petrol is very low, in diesel it is also low and in industrial fuel it is also relatively low. The major emissions in Australia therefore occur from point sources where very large quantities of fuel are used (eg. coal fired power stations), from sulfuric acid plants or where large quantities of sulfur-rich ores are smelted. In Australia most of these point sources are away from the capital cities but may be encircled by a town or city, often dependent on the industry for livelihood.

Large coal-fired power generators are located in the Latrobe Valley, Victoria, the Hunter Valley in New South Wales and Gladstone in Queensland. Major smelting operations are carried out in the regions of Port Kembla and Boolaroo near Newcastle in New South Wales, Mount Isa and Gladstone in Queensland and Kalgoorlie in Western Australia, which are all large emitters of sulfur dioxide. There are sulfuric acid plants in Australia, notably near Newcastle and Adelaide.

The assessment of Australian sulfur dioxide levels presented in this monograph is based on the data that were available for review. It should be noted that the data from Mount Isa are from one station only, the data from Gladstone are from one station only, the data from Newcastle, Hunter Valley and Wollongong are incomplete, and there are no data presented from stations around the Kalgoorlie smelters in Western Australia. For the assessment presented here, data on annual peak 1-hour levels are given. The frequency of exceedance of the NHMRC 0.2 ppm 1-hour goal is also presented for the State/Territory capitals and for regional centres. For further assessment of possible population exposure in Australia, the frequency of exceedance of a 1-hour average of 0.1 ppm (ie 50% of the NHMRC goal) is also presented. Data are not available for 10-minute average levels.

In the following figures trend lines have not been drawn on the plots because, in many of the cities and regions, the number and location of monitoring sites have varied and local emission sources have changed. The levels measured therefore represent a local sphere of influence and not general population exposure.

The available 1-hour data in capital cities shows that over the last 16 years, Sydney, Melbourne, Brisbane, Adelaide and Perth have recorded levels above 0.1 ppm, while the 0.2 ppm NHMRC goal has been exceeded with some frequency in Adelaide and Perth. No continuous monitoring for sulfur dioxide is carried out in Canberra, Hobart or Darwin.

## Peak levels

*Table 2: Highest 1-hour levels of $SO_2$ for each city and the year of occurrence.*

| | | |
|---|---|---|
| Sydney | 0.25 ppm | 1980 |
| Brisbane | 0.2 ppm | 1980 |
| Melbourne | 0.18 ppm | 1991 |
| Adelaide | 0.35 ppm | 1995 |
| Perth | 0.39 ppm | 1989 |

Figures 5–9 display the annual peak 1-hour levels measured in capital cities for the years 1980–95 and Table 2 shows the highest 1-hour level for each city and the year in which it occurred. Many of the Adelaide stations are sited to measure peak readings around an acid plant and thus do not represent average Adelaide exposure levels.

The variability of the yearly maximum figures indicates not only the variability in siting, emissions and number of measurement stations, but also the influence of weather on pollutant concentrations. In the urban environment long-term data provide only an impression of underlying trends for sulfur dioxide. The general trend in Sydney is down, in Melbourne and Adelaide it appears to be increasing, and in Brisbane it is steady. There does not appear to be a definable trend in Perth.

*Figure 5: Maximum 1-hour sulfur dioxide averages (ppm), Sydney*

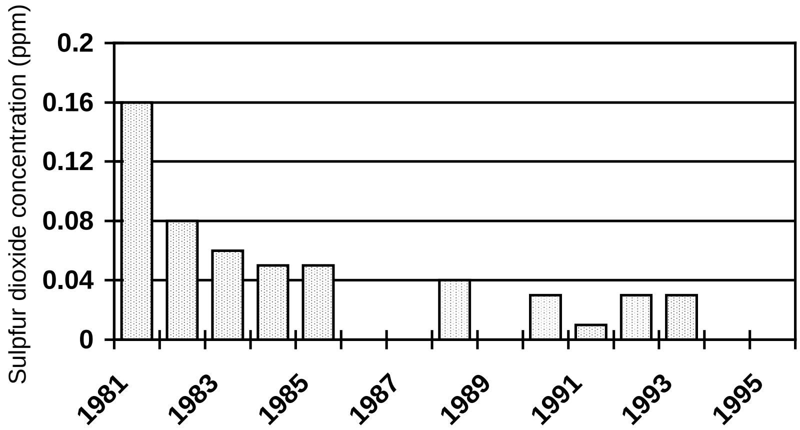
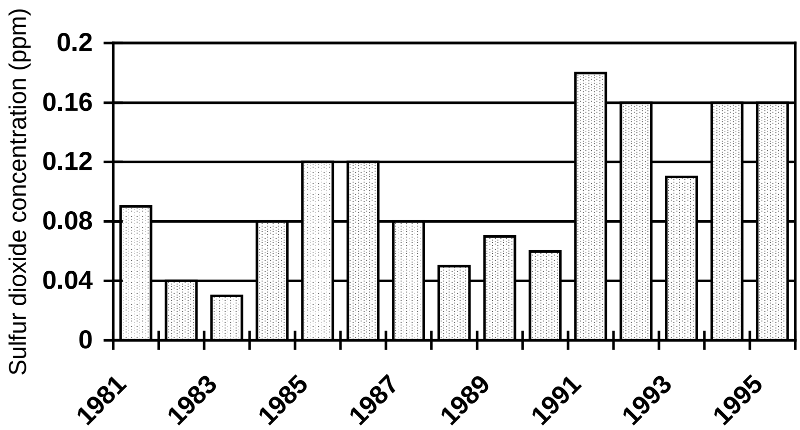



*Figure 6: Maximum 1-hour sulfur dioxide averages (ppm), Melbourne*




Appendix Figure B1 shows the maximum 1-hour levels available for the regional areas (Newcastle, the Hunter Valley and Wollongong in NSW, the Latrobe Valley in Victoria, Mount Isa and Gladstone in Queensland and at Port Augusta in South Australia). Maximum levels well in excess of the NHMRC 1-hour goal were recorded in some years in Newcastle, the Hunter Valley, Wollongong and Mount Isa.

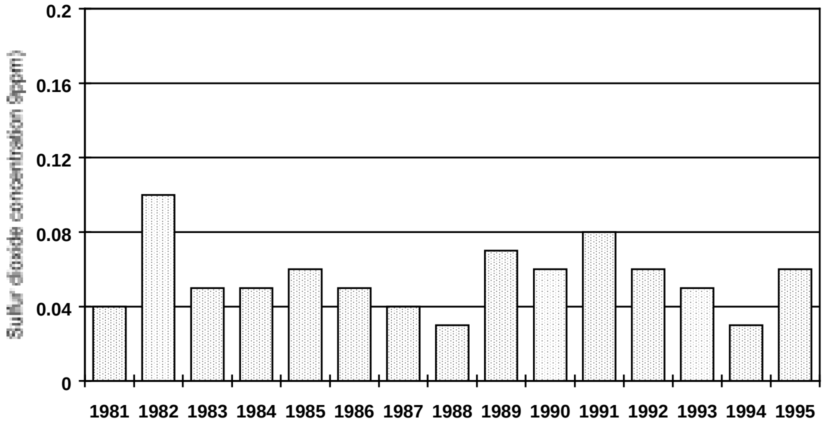



*Figure 7: Maximum 1-hour sulfur dioxide averages (ppm), Brisbane*

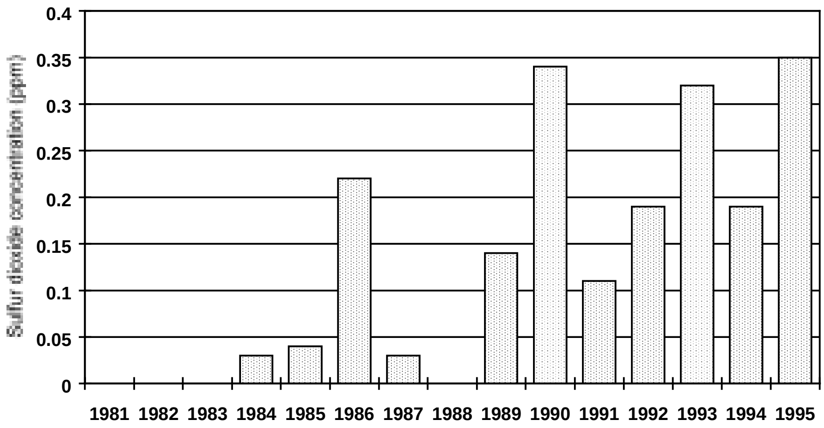



*Figure 8: Maximum 1-hour sulfur dioxide averages (ppm), Adelaide*

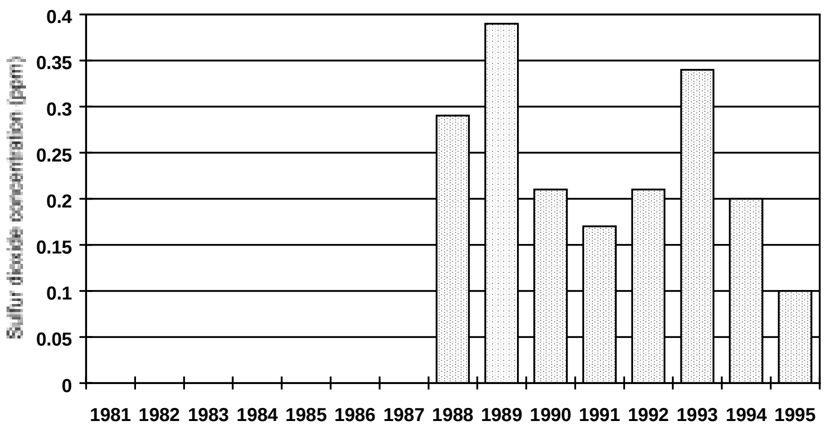



*Figure 9: Maximum 1-hour sulfur dioxide averages (ppm), Perth*

## Frequency distribution above 0.1 ppm and 0.2 ppm

Appendix Figure B2 shows the frequency of exceedances of a 1-hour level of 0.1 ppm (ie 50% of the NHMRC goal) in capital cities over the years 1980–95. Sydney exceeded the level on only three occasions, twice in 1981 and once in 1989. Melbourne exceeded the level frequently, especially in the 1990s. Brisbane has only exceeded 0.1 ppm on one occasion in 1980. Adelaide exceeded the level frequently, especially in the 1990s and in 1993 reached 217 exceedances. Over the last 8 years of assessment Perth, has frequently exceeded 0.1 ppm but the trend is definitely downwards.

Appendix Figure B3 shows the frequency of exceedances of a 1-hour level of 0.1 ppm in regional areas over the years 1980–95. Unfortunately, incomplete data are available for the exceedances in Newcastle, Hunter Valley and Wollongong in New South Wales and so no frequency distribution above 0.1 ppm can be provided for these sites. No definite trends can be established in any of the regions assessed. In the Latrobe Valley periodic exceedances of 0.1 ppm have occurred over the last eight years of the assessment period with a maximum of four exceedances occurring in 1988 and 1994. At Mount Isa the 0.1 ppm level was frequently exceeded, the maximum of 215 occasions occuring in 1987. At Gladstone the level was occasionally exceeded, with the maximum of six occasions occuring in 1986. At Port Augusta the level of 0.1 ppm has been exceeded on only one occasion, in 1984.

Appendix Figure B4 shows the frequency of exceedances of the 1-hour NHMRC goal of 0.2 ppm in capital cities over the years 1980–95. Sydney, Melbourne and Brisbane have not exceeded the goal since 1980. Adelaide exceeded the goal on nine occasions in 1995. Perth is the only other capital city to have exceeded the 0.2 ppm goal, with nine exceedances in 1989. In both cities the exceedances were episodic with no discernible trends over time.

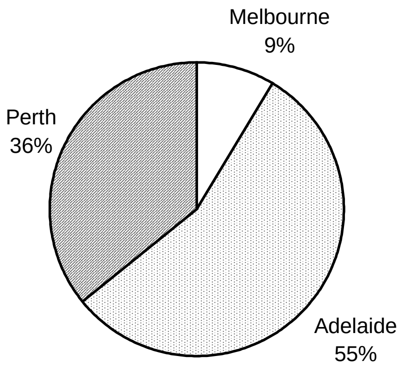



*Figure 10: Frequency distribution of average number of hours above 0.1 ppm sulfur dioxide per year for Australian capital cities, 1980–95*

Appendix Figure B5 shows the frequency of exceedances of a 1-hour goal of 0.2 ppm in regional areas over the years 1980–95. Again, incomplete data are available for the exceedances in Newcastle, Hunter Valley and Wollongong and no frequency distribution above 0.2 ppm can be provided for those sites. Of the other areas, Mount Isa was the only one where the 0.2 ppm goal was exceeded, and it occurred frequently, reaching 107 occasions in 1987 but with no definite trends over time.

Overall, the NHMRC 1-hour goal of 0.2 ppm has seldom been exceeded in Australian capital cities (only in Adelaide and Perth). Over the 16-year period, Sydney and Brisbane have only exceeded the level of 0.1 ppm on a total of three and one occasions, respectively, and the annual average of that exceedance, over the assessment period, is only a fraction of an hour. Figure 10 shows the annual average frequency during the assessment period, of 1-hour levels above 0.1 ppm for the three capital cities, Melbourne, Adelaide and Perth, where exceedances occurred with some regularity. Melbourne, with an average of 3.8 hours per year above 0.1 ppm, had 9 % of the exceedances; Adelaide, with an average of 25 hours exceedance had 55%; and Perth, with an average of 16 hours had 36 %.

# 7. Population exposure estimates

Population exposure refers to the dose received by individuals within an environment over the time of consideration. Population exposure to an exceedance of a particular level of pollution, say a 1-hour average of 0.2 ppm of sulfur dioxide, is an estimate of the number of persons actually breathing the air continuously for the full period of one hour. As discussed in Section 5, outdoor air measurements for sulfur dioxide assess peak levels and not average population exposure.

## Exposure to primary and secondary pollutants

Secondary pollutants or pollutants emitted mainly from area sources (eg ozone) are generally well mixed in the air. The levels of these pollutants measured at monitoring stations therefore represent air parcels of some magnitude and uniformity in concentration. It is therefore reasonable to assume that the level measured at a particular station will be experienced by several hundred thousand people as the air parcel spreads laterally and as it is carried along by the wind, without rapid changes in concentration. When considering population exposure to a primary pollutant such as sulfur dioxide, emitted by a point source however, the above scenario does not hold. In this situation, the pollutant is concentrated around the central axis  of a plume and the concentration decreases rapidly with distance from the centre of the plume. For a low stack height or fugitive emissions, the concentration of pollutants in the emission decreases rapidly and is in inverse proportion to the distance from the source. Emissions from tall stacks reach maximum ground level concentrations at distances from the stack depending on stack height, emission criteria and the meteorological conditions; elevated levels of the pollutant are only recorded when the wind blows the plume down to the monitoring station.

Figure 11 represents typical records of ambient ozone and sulfur dioxide levels measured at a monitoring station. Ozone, being a secondary pollutant resulting from area-wide emissions, provides a broad and relatively uniform trace with a clear daily cycle. Sulfur dioxide, coming from a point source, is much more erratic, only recording values when the plume comes down to ground level and impacts on the monitoring station.

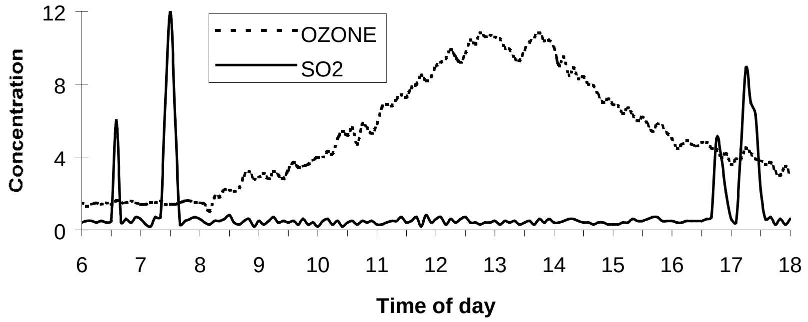



*Figure 11: Typical traces of ozone and sulfur dioxide concentrations*

Tall stacks are designed to disperse emissions under most meteorological conditions such that ground level concentrations will not result in exceedances of the NHMRC goal. Under abnormal conditions, however, ground level concentrations will exceed these levels. It is also important to note that the goals for short-term peaks have been reduced and the last review in 1995 resulted in a substantial reduction of the goals from 0.5 ppm for 10 minutes and 0.25 ppm for 1 hour to 0.25 ppm for 10 minutes and 0.2 ppm for 1 hour [NEPC, 1998 1-hour goal is 0.2ppm]. Therefore some stacks and controls applied to point sources before the curent goals were established, may not be adequate to maintain air quality at acceptable levels.

### Population affected

Large point sources of sulfur dioxide are not often located in capital cities but in the regions and it is not unusual to find that a residential population has developed around an industry or group of industries. In spite of this, when an exceedance is recorded by a monitoring station, population exposure around the point source will be substantially less than for area sources. The population potentially exposed to exceedances for ozone and nitrogen dioxide in capital cities is estimated at several hundred thousand for each exceedance. For sulfur dioxide the population exposure would be considerably less. Levels measured at sites in the vicinity of point sources may represent short-term and scattered peaks and do not usually represent large air parcels. Of course, peaks will occur in areas where no monitoring stations are sited. Unlike pollutants from area-wide sources or for secondary pollutants, there is little information that can be used to estimate population exposure to sulfur dioxide from point sources.

If an estimate of the total population likely to be exposed could be made, it would be necessary to consider only people who are outdoors at the time of measurement. A reasonable estimate is that possibly one person in 10 would be out of doors for a full hour of a sulfur dioxide episode exceeding the NHMRC 1-hour goal. This percentage may also apply to exposures to the 10-minute goal.

The potential population exposed in Sydney for each ozone exceedance has been estimated at around 310 000 persons (see the Ozone monograph in this series). Using a 10% factor for people actually outside at the time of exceedance, the estimate of population exposed to an exceedance is around 30 000. For a sulfur dioxide exceedance, the population exposure is estimated to be considerably less.

It is important to note that some levels measured at monitoring stations in some capital cities and in the regions are well above the NHMRC goals (in some areas the levels reported are many times the goals and there is a relatively high frequency of exceedance). In some areas, a sizeable number of people would therefore be exposed to levels that might result in health effects.

In summary, sulfur dioxide exceedances are likely to affect fewer people than would be the case with an area-wide pollutant such as ozone or nitrogen dioxide. However, for sulfur dioxide, the margin of exceedance and therefore the health risk, can often be far greater. This scenario is reflected in the number of complaints of symptoms experienced by residents living near major sources of sulfur dioxide.

## 8. Population exposure reduction options

Sources of sulfur dioxide include the smelting of sulfur-rich ores, oil refineries, acid plants and the combustion of large quantities of fossil fuel, especially in coal-fired power stations. The options for reducing population exposure to sulfur dioxide include reduction of emissions by process changes, pollution control devices and the secondary use of emissions such as conversion to sulfuric acid. An alternative technique used to reduce ground level concentrations, is tall stack dispersion. These control options are discussed below and summarised in Table 3, which includes their effectiveness, cost and time for implementation.

## Control options

### *Process change*

Changes in fuel characteristics can substantially modify emissions and the most effective method to control sulfur dioxide emissions caused by high sulfur fuel is to use fuel having a lower sulfur content. The emissions are reduced by the same proportion as the sulfur in fuel is reduced. Hence, a reduction from 1% to 0.5% sulfur will halve ground level concentrations. Such measures can usually be introduced at moderate cost and can be implemented immediately.

The introduction of a totally new process to reduce sulfur dioxide emissions is a major undertaking. Small changes may be implemented that significantly reduce emissions but the introduction of a major process change, especially changing to a new process, has a high capital cost. Such a change can provide substantial operating cost savings, and improve production efficiency. Minor changes in process can be achieved in a short time but major process changes may require long lead and implementation times.

### *Improved housekeeping*

A program to reduce the escape of fumes from a process can reduce the opportunity for emissions to affect the local area. Such programs aim to improve the capture of fugitive emissions by improved hooding, increased airflow in ductwork and reducing leaks from ducting and flanges. These actions result in more emissions passing to the stack for dispersion before reaching the ground. Such changes can usually be carried out at moderate cost and implemented quickly.

### *Pollution control devices*

Scrubbers can be used to remove sulfur dioxide from emission sources. Scrubbers are usually ‘wet’ using water, salt or caustic solution or they can be ‘dry’ using an absorbent or alkali such as lime. Where there are large volumes emitted, such as in power stations, scrubbing is only moderately effective. Scrubbing results in a moderate reduction of the sulfur dioxide content and a sulfur rich scrubbing material that requires disposal. The cost can be high and a considerable time may be required for installation.

### *Table 3: Sulfur dioxide control options*

| *Options* | *Effectiveness* | *Cost* | *Time for installation* |
|---|---|---|---|
| **Process change** | | | |
| Fuel change | directly proportionately to sulfur reduction in fuel | low to moderate | short |
| New process | new processes can often result in substantial reductions in emissions | high capital cost but can result in improved running costs | long |
| **Improved housekeeping** | | | |
| Fugitive emission reduction program | improved capture of fumes, sealing of ducting and flanges can be very effective | low to moderate | short |
| **Pollution control device** | | | |
| Scrubber | scrubbing of large scale emissions such as power station emissions can be moderately effective | medium to high when large volumes of emissions have to be treated | medium |
| Add-on acid plant | using the waste sulfur dioxide can lead to an effective reduction in emissions | substantial capital cost but can be cost effective as it supplies the raw materials for the acid plant. | long |
| Tall stack dispersion | will not reduce emissions, but very tall stacks can disperse the emissions to reduce ground level concentrations to satisfactory levels | expensive | medium |

### *Add-on acid plant*

Sulfuric acid plants require a supply of sulfur dioxide for subsequent oxidation to sulfuric acid. If sulfur dioxide emissions from a plant have few interfering components and are of uniform concentration, they can be utilised to supply a sulfuric acid plant. There are several plants in Australia which utilise sulfur dioxide-rich emissions from the roasting of sulfur-rich metallic ores.

Construction of an acid plant involves a substantial capital cost but this is balanced by the provision of ‘free’ raw material to manufacture the sulfuric acid. A considerable length of time would be required for construction of an acid plant.

### *Tall stack dispersion*

Tall stack dispersion does not reduce the sulfur content of emissions but allows the concentration of sulfur dioxide to become diluted before it reaches ground level. Tall stack dispersion is not effective if the ambient air is already contaminated with high levels of sulfur dioxide. In situations where ambient levels are low, and stack emmissions will not add to high level concentrations elsewhere at ground level, it can be effective, especially when used in combination with other control techniques.

The capital cost of tall stacks can be high but they have moderate running costs which helps to reduce the overall cost. Very tall stacks take some time to build.

## Environmental benefits of reduced sulfur dioxide pollution

The environment can be a more sensitive indicator of some air pollutants than human health, and the effects of sulfur dioxide on vegetation, lichens, freshwater (acidification) and buildings are well documented. Measures designed to achieve primary health outcomes may not provide adequate protection against losses in agriculture, forestry or natural ecosystems.

Responses of individual plant species vary enormously and ambient conditions may strongly influence the level at which damage occurs. For example, adaptations that prevent water loss from some native Australian plants in arid regions appear to protect them from sulfur dioxide injury at levels that would devastate species from more humid regions. Low levels of sulfur dioxide can enhance the growth of some species of plants, especially where soils have a low sulfur content. The transition between enhancement and reduction of yields is quite abrupt and cereal crops have shown reductions in all growth parameters after sustained exposure at 0.12 ppm or less. Australian native trees show a wide variety of responses to sulfur dioxide exposure, some being extremely sensitive. The implication of these results is that stringent goals may be required to adequately protect sensitive plant species.

The 1994 WHO Air Quality Guidelines for Europe Working Group for Ecotoxic Effects, after consideration of the European situation, recommended the following goals:

- 0.010 ppm for major agricultural corps (winter and annual mean)
- 0.007 ppm for forests and natural vegetation (winter and annual mean)
- 0.003 ppm for lichens (annual mean).

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# Appendix A ~ Sydney emissions data, 1992

*Table A1: Emissions inventory for 1992 for sulfur dioxide in the Sydney Region*

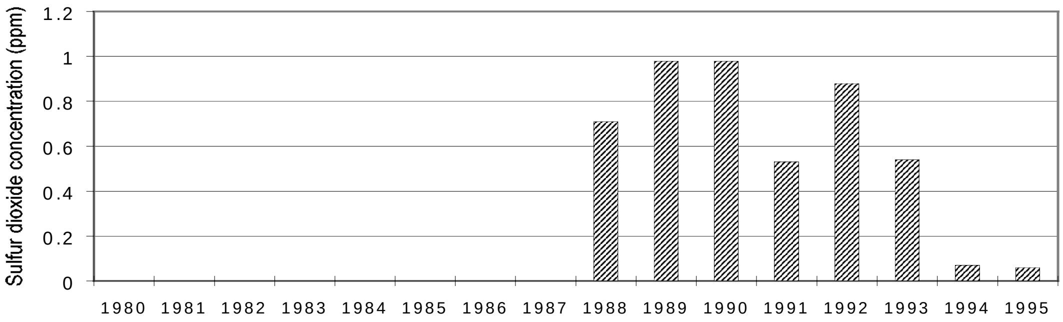
| *Category* | *Tonnes per year* | *Percentage* |
|---|---|---|
| **Mobile sources** | | |
| Motor vehicles | 1 900 | 9.6 |
| Marine pleasure craft | 10 | <0.1 |
| Aviation | 220 | 1.1 |
| Commercial shipping | 630 | 3.2 |
| Rail transport | 20 | 0.1 |
| **Subtotal: mobile sources** | **2 780** | **14.0** |
| **Domestic/commercial activity** | | |
| Domestic solid/liquid fuel combustion | 250 | 1.26 |
| Domestic lawn mowing | 10 | <0.1 |
| Other industrial/commercial emissions | 4 040 | 20.4 |
| Domestic natural gas combustion | 10 | <0.1 |
| Domestic waste combustion | – | – |
| **Subtotal: domestic/commercial activity** | **4 310** | **22** |
| **Major industrial/commercial – stationary** | | |
| Petroleum refining | 7 910 | 40.0 |
| Commercial manufacturing | 2 980 | 15.1 |
| Printing | – | – |
| Fabricated metals | – | – |
| Basic metal processing | 180 | 0.9 |
| Fuel storage | – | – |
| Other manufacturing | – | – |
| Food manufacturing | 40 | 0.2 |
| Non-metallic mineral processing | 1 020 | 5.2 |
| Hospitals, incinerators and harbour tunnel | 530 | 2.7 |
| Paper products | 10 | <0.1 |
| Quarrying | 20 | 0.1 |
| Textiles | – | – |
| Coal mining | 10 | <0.1 |
| **Subtotal: major stationary sources** | **12 700** | **64** |
| **Total: anthropogenic** | 19 790 | 100.0 |
| **Total: biogenic** | – | – |
| **Grand total** | **19 790** | |

Source: Carnovale et al 1995

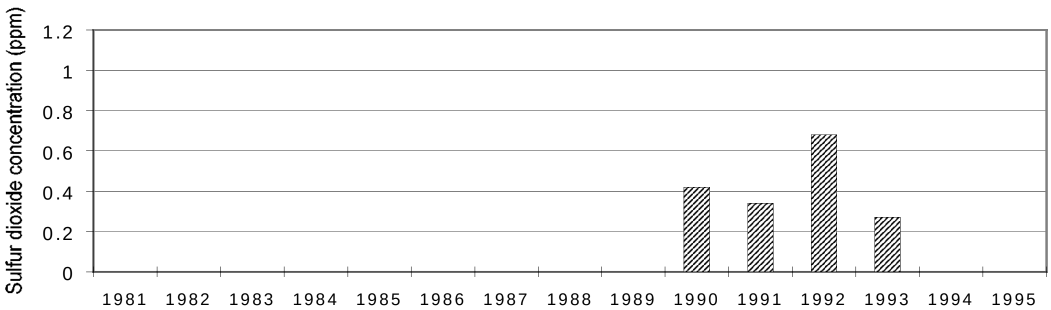
# Appendix B ~ Sulfur dioxide levels in Australian cities and regional centres

*Figure B1: Maximum 1-hour sulfur dioxide averages (ppm) for regional areas*

### Newcastle:




### Hunter Valley:




### Wollongong:

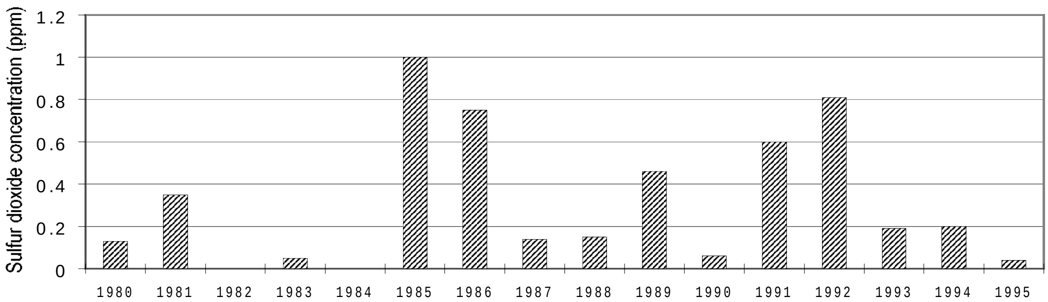
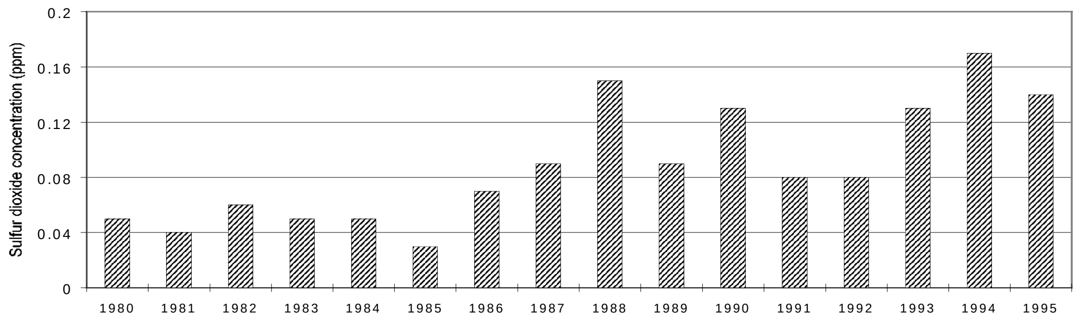
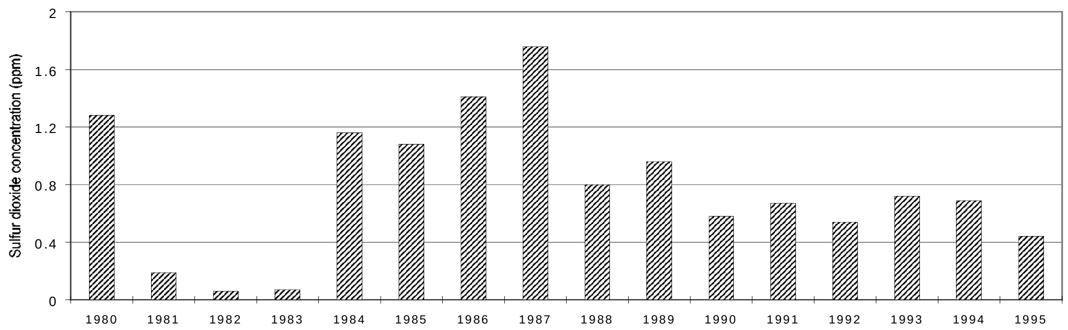


*Figure B1: Maximum 1-hour averages (continued)*

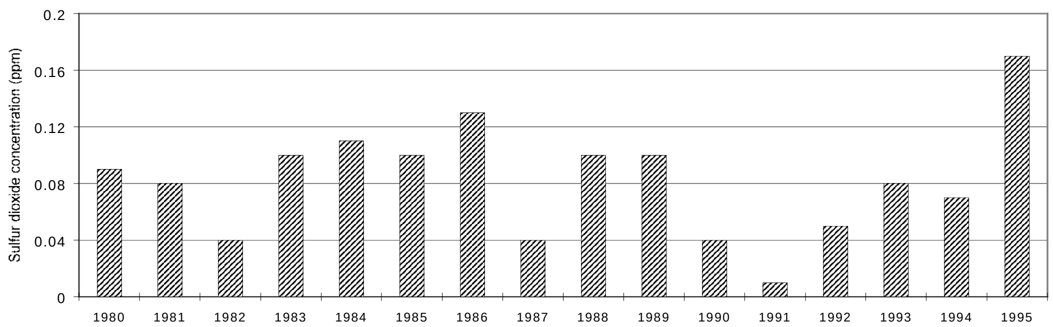
## LaTrobe Valley:



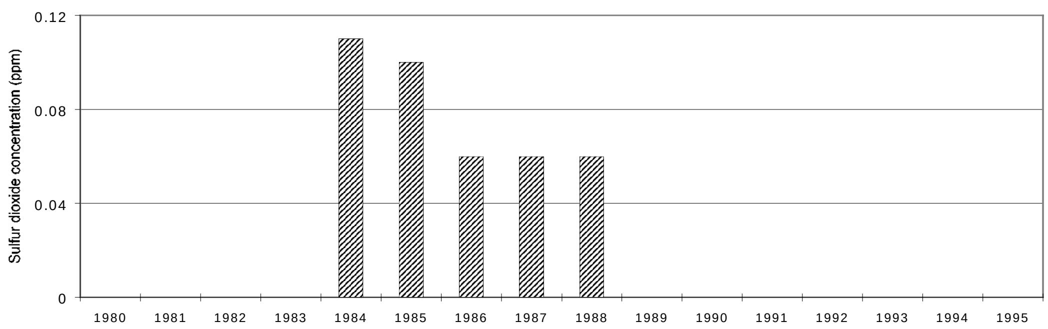

## Mount Isa:




## Gladstone:



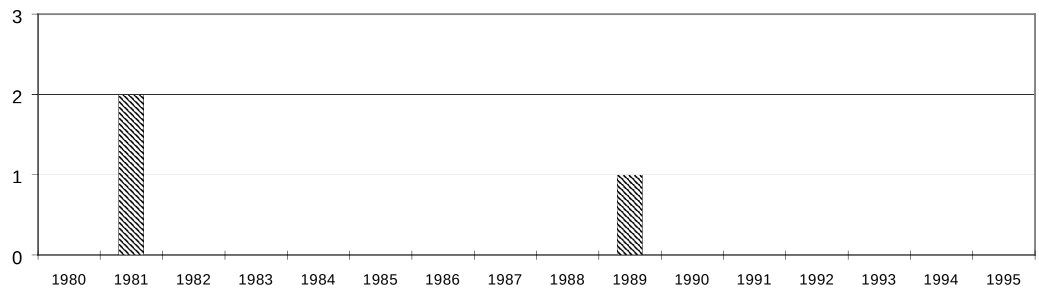

## Port Augusta:



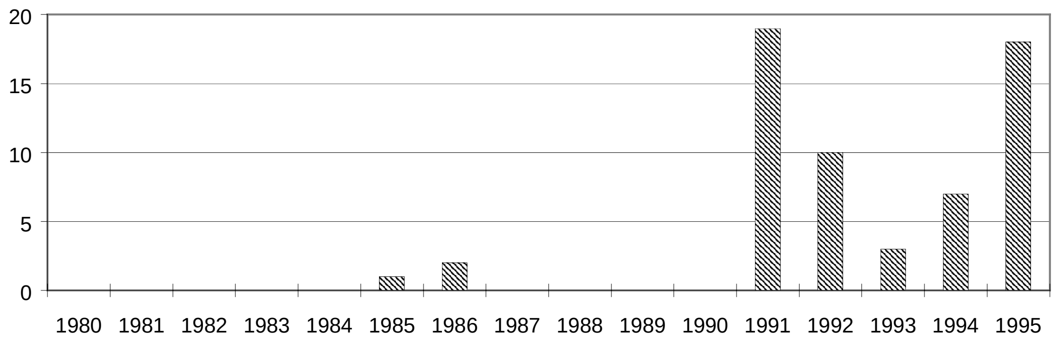

Note: Data from Mount Isa and Gladstone are from one station only.

*Figure B2:  Number of exceedances of 1-hour average level of 0.1 ppm sulfur dioxide - capital cities*

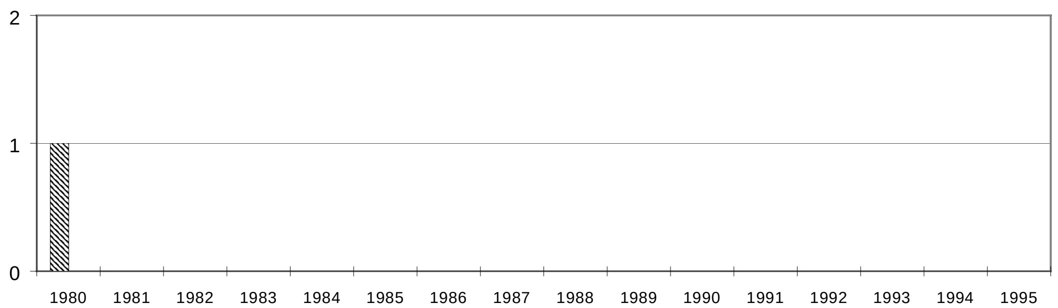
**Sydney:**




**Melbourne:**




**Brisbane:**




**Adelaide:**

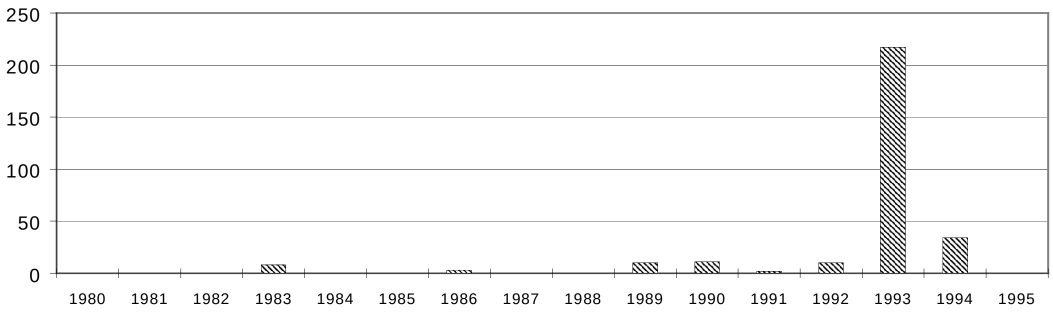


*Figure B2: Number of exceedances of 0.1 ppm 1-hour average in capital cities (continued)*

**Perth:**

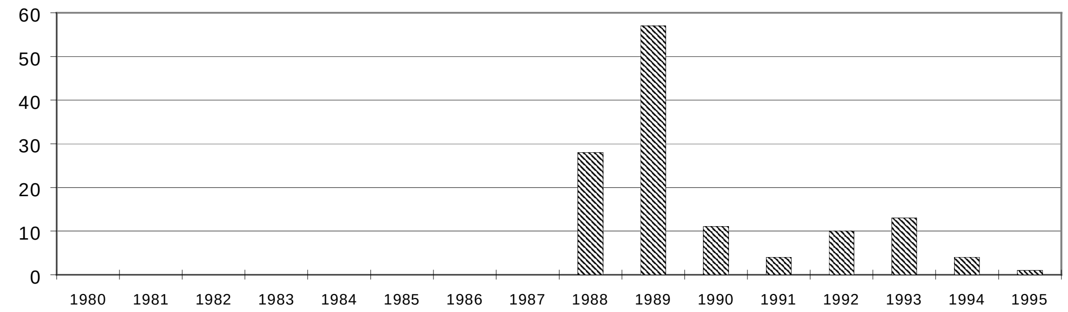
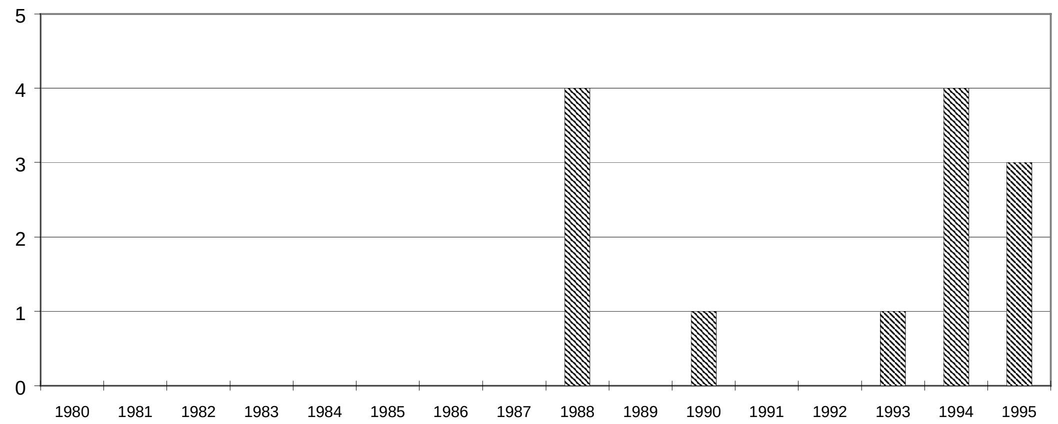



*Figure B3: Number of exceedances of 1-hour average level of 0.1 ppm sulfur dioxide - regional areas*

**LaTrobe Valley:**




**Mount Isa:**

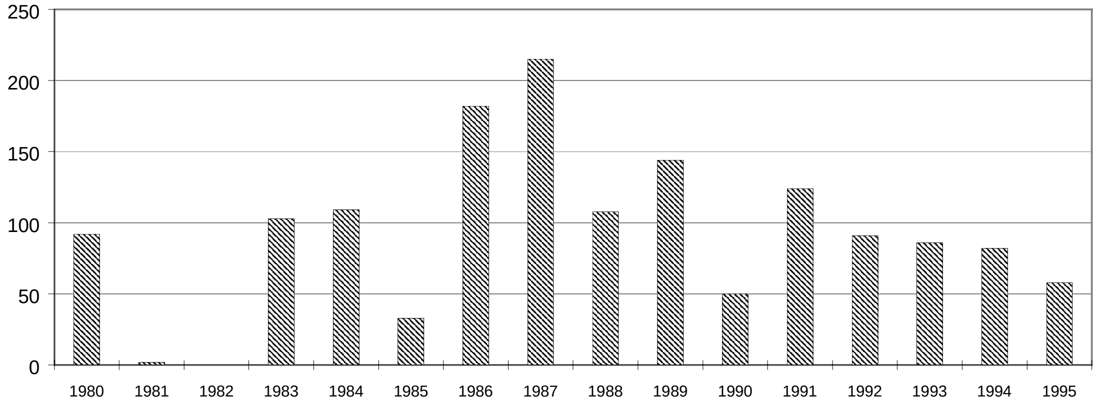
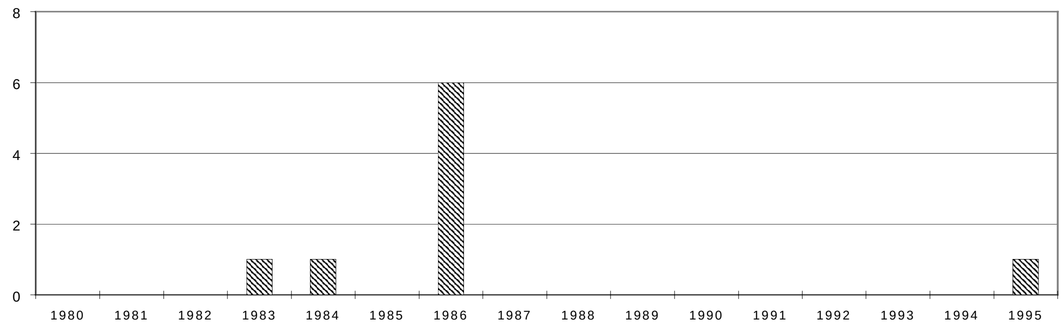


*Figure B3:  Number of exceedances of 0.1 ppm 1-hour average in regions (continued)*

## Gladstone:




## Port Augusta:

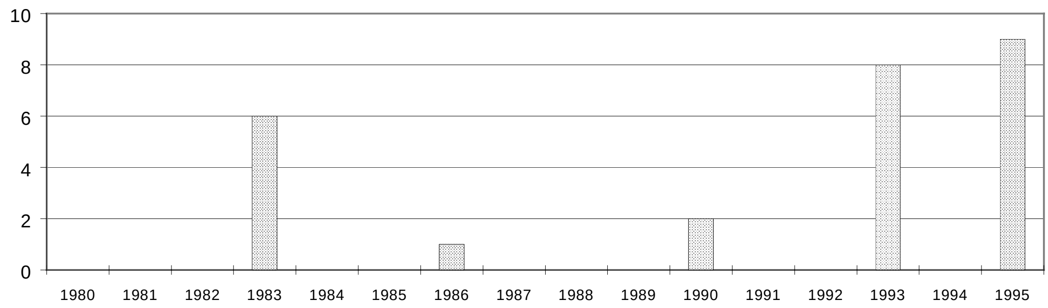

Notes:

1. Incomplete data were available for Newcastle, the Hunter Valley and Wollongong and are not shown.

2. Data from Mount Isa and Gladstone is from one station only.

*Figure B4: Number of exceedances of 1-hour average level of 0.2 ppm sulfur dioxide - capital cities*

**Adelaide:**




**Perth:**

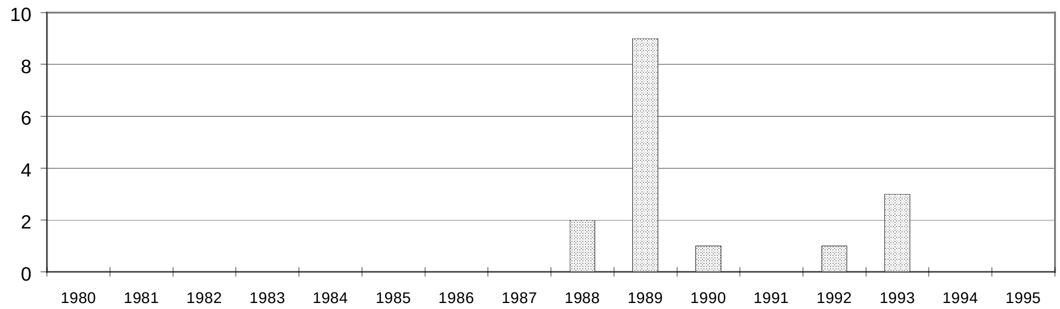
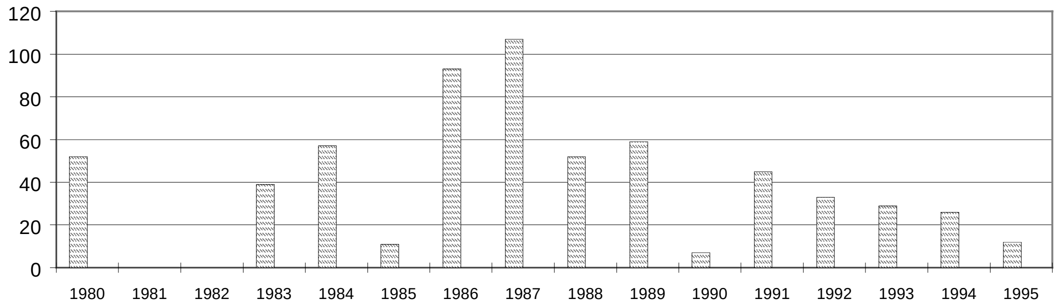


*Figure B5: Number of exceedances of 1-hour average level of 0.2 ppm sulfur dioxide - regional areas*

## Mount Isa:




Notes:

1. Incomplete data were available for Newcastle, the Hunter Valley and Wollongong and are not shown.

2. Data from Mount Isa is from one station only.

3. The goal was not exceeded at Latrobe Valley, Gladstone or Port