AIR QUALITY TRENDS

CITY OF GREATER SUDBURY, ONTARIO

1953 – 2002

Summary Report Prepared By

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Key Findings

- Sulphur dioxide concentrations in the City of Greater Sudbury decreased by 50% immediately following the abatement measures undertaken in 1972. This was accompanied by a decrease of 66% and 80% in the frequency of exceedance of the 1-hour and 24-hour provincial criteria. Equally significant improvements were realized in the ensuing decades, such that by the mid-1990s, the occurrence of fumigations potentially injurious to vegetation had become an isolated event. Since 1999, the frequency of exceedance of the 1-hour criterion has fallen 85% from the early 1990s. The 24-hour and annual criteria have consistently been met for many years.

- For the period 1990 to 2002, Sudbury had the 3rd highest composite SO_2 mean from seven Ontario cities selected for comparison. It was also the only city to record exceedances of the 1-hour criterion.

- During that period, Sudbury had the highest composite annual ground-level ozone concentrations of the cities selected for comparison and ranked 4th highest for exceedances of the 1-hour criterion.

- The levels of suspended particulate matter were generally low and well within provincial criteria. Concentrations of TSP gradually decreased by about 36% from the early 1970s. The levels of inhalable particles were also low and fell by 33% from the early 1990s. Both contaminants had essentially identical levels at the industrial and downtown sites and no exceedances of the provincial criteria. Compared to other selected cities, Sudbury had the 3rd lowest composite mean for TSP and the lowest composite mean for inhalable particulate.

- During the period 1989 to 2001, good to very good Air Quality Index readings were reported more than 94% of the time. Compared to other cities, Sudbury recorded the 2nd highest frequency of air quality readings in the moderate to poor range, largely due to elevated ground-level ozone, and, to a much lesser extent, due to SO_2.

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1.0 OVERVIEW

Air quality in the City of Greater Sudbury, due to historical air emissions from one of the world's largest metal smelting complexes, is a well known topic that has brought much unwanted attention to the area. Pictures of industrial barrens, acid-damaged lakes and of the "Superstack", the world's tallest smokestack, have historically tainted the area with an undesirable image. However, from the evidence of environmental recovery following emission reductions from local smelters and much improved air quality, and from the United Nations' recognition of its very successful re-greening program, the City of Greater Sudbury has now assumed a more favorable international reputation.

Since the early 1980s, other air issues such as acid deposition, smog, global warming, urban air quality and their associated environmental and health effects have become household words not only for Sudbury area residents but for people around the globe. Hence we have come to understand and realize that air pollutants do not respect geographical boundaries, and that air emissions far removed from the Sudbury area can also affect its local air quality. Consequently, the air quality in the City of Greater Sudbury is not limited to the impact from local sources.

The purpose of this report is to provide a summary of the results of air quality monitoring programs undertaken by the Ontario Government in the Sudbury area since the mid-1950s. Although historical air quality is of significant interest and will be reviewed, the focus is on more recent trends and the current state of air quality in the City of Greater Sudbury. The results of this analysis are compared, depending on data availability, to those from other urban centers in Ontario, namely Toronto, Hamilton, Ottawa, Sault Ste Marie and Thunder Bay for the period 1990 to 2002.

The report provides information on: the air contaminants monitored; their sources, effects, emission trends and provincial limits; the link between air quality and meteorology; the evolution of the monitoring network in the Sudbury area and on overview of the actions taken to reduce smelter emissions.

This report documents the significant improvements in local air quality realized in the past three decades. It is also intended to provide a baseline of information to stakeholders and decision makers for discussions on possible future actions to further improve air quality in the City of Greater Sudbury.

2.0 AIR POLLUTANTS AND PROVINCIAL LIMITS

The characteristics, sources, effects and provincial limits for the air pollutants of interest in this report are presented in this chapter.

Air quality in the outdoors, i.e. in the ambient air, is universally determined from measurements of air pollutants present as gases and as particulate matter. The principal gaseous pollutants routinely measured are sulphur dioxide (SO_2), nitrogen oxides (nitric oxide (NO) but principally nitrogen dioxide (NO_2)), ground level ozone (O_3), carbon monoxide (CO), and total reduced sulphur (TRS). Ambient concentrations of particulate matter have historically been obtained from measurements of soiling index (also termed coefficient of haze or COH) and total suspended particulate (TSP). In the past decade, concerns about the health effects of fine particulate matter have lead to the determination of inhalable (PM_{10}) and respirable ($PM_{2.5}$) particulate concentrations. The sampling methods used to measure ambient concentrations of the pollutants listed above and the units of measurement are described in appendices A to H.

In Ontario, the responsibility for air quality management rests with the Ministry of the Environment (MOE), created in 1970. The MOE has established two types of concentration limits for a large number of air pollutants for acceptable air quality: air quality standards and ambient air quality criteria (AAQC). The standards are listed in Regulation 346 and are known as Point of Impingement (POI) standards. They apply over half-hour averaging periods and are used by MOE approvals engineers in their review of applications for the issuance of certificates of approval for new or existing facilities that emit air pollutants.

On the other hand, the AAQCs are desirable concentrations for acceptable air quality. They are defined in Regulation 337 and cover averaging periods in some cases as short as 10 minutes, but more commonly for periods of 1 hour, 24 hours and 1 year. Unlike the POI standards, they are not legally enforceable unless they are specified in a control document such as a certificate of approval or a control order issued by the MOE. Current Ontario ambient air quality criteria for the pollutants considered in this report are listed in Table 2.1, together with the basis for their limiting effects.

2.1 Sulphur Dioxide (SO_2)

Sulphur dioxide (SO_2) is a colorless gas caused by the combustion of sulphur-bearing substances and it smells like burnt matches. It can be transformed to sulphur trioxide (SO_3), which in the presence of water vapor readily becomes sulphuric acid (H_2SO_4) mist. Sulphur dioxide can also be oxidized to form acid aerosols. It is a precursor to sulphates, which are significant components of fine particulate matter in the atmosphere. According to emission estimates compiled by the MOE for a number of years, more than two thirds of the SO_2 annually emitted in Ontario come from smelters, utilities and petroleum refineries. Of these, smelter emissions typically comprise the largest fraction; in 2001, smelters accounted for 44% of provincial emissions (1). Other industrial sources

include steel mills and pulp and paper mills. Lesser sources include residential, commercial and industrial space heating.

Air Pollutant	Ambient Air Quality Criteria (AAQC)	Limiting Effect
Sulphur Dioxide	0.25 ppm (250 ppb) 1 hour	Vegetation protection
	0.10 ppm (100 ppb) 24 hours	Health protection
	0.02 ppm (20 ppb) 1 year	Vegetation protection
Nitrogen Dioxide	0.20 ppm (200ppb) 1 hour	Health protection
	0.10 ppm (100 ppb) 24 hours	Health protection
Ozone	0.08 ppm (80 ppb) 1 hour	Health and Vegetation protection
Carbon Monoxide	30 ppm (30000 ppb) 1 hour	Health Protection
	13 ppm (13000 ppb) 8 hours	Health Protection
Total Reduced Sulphur	0.027 ppm (27 ppb) 1 hour	Offensive Odours
Soiling Index	1.0 COH unit 24 hours	Health Protection (with SO_2)
	0.5 COH unit 1 year	Visibility
Total Suspended Particulate	120 $\mu g/m^3$ 24 hours	Visibility
	60 $\mu g/m^3$ (*) 1 year	Visibility
Inhalable Particulate	50 $\mu g/m^3$ (**) 24 hours	Health Protection

(*) Geometric mean
(**) Interim criterion

Table 2.1: Provincial Ambient Air Quality Criteria (AAQC)

In the City of Greater Sudbury, the principal sources of SO_2 emissions are the INCO Ltd. and Falconbridge Ltd. smelters. The Environment Canada Canadian Emissions Inventory

of Criteria Air Contaminants for1995 (2) estimated smelter contributions to be 99.3%. Transportation accounted for the rest.

There is growing scientific evidence that exposure to high levels of SO_2 can result in breathing problems, respiratory illness, changes in the lung's defenses and worsening respiratory and cardiovascular disease. People with asthma, chronic lung disease or heart disease are believed to be the most sensitive to SO_2. Under certain climatic conditions, sulphur dioxide can damage trees and crops. Sulphur dioxide and NO_2 are the main precursors of acidic deposition (mostly acid rain), which results in the acidification of sensitive lakes and streams, accelerates the corrosion of buildings and contributes to reduced visibility. Sulphur dioxide also causes the formation of microscopic acid aerosols which have health implications and are thought to contribute to global warming.

2.2 Nitrogen Oxides (NO_x)

Nitrogen oxides (NO_x) consist of nitric oxide (NO) and nitrogen dioxide (NO_2). NO is a colourless and odourless gas, while NO_2 is a reddish-brown gas with a pungent and irritating odour. Nitric oxide has no known adverse or environmental effects; however it can oxidize in the atmosphere to NO_2. Nitrogen dioxide transforms in the air to form gaseous nitric acid (HNO_3) and organic nitrates. It plays a major role in atmospheric reactions that produce ground-level ozone. Nitrogen dioxide is also a precursor to nitrates (NO_3) which contribute to levels of fine particulate matter in the atmosphere.

All combustion processes in air produce nitrogen oxides. Natural sources of NO_x include lightning and aerobic activity of soil bacteria. These are considered to be small compared to emissions from human activity, which are of greater concern. In Ontario, as in many jurisdictions, the transportation sector accounts for a significant fraction of NO_x emissions from human activity, followed by fossil fuel power generation. Approximately 63% of NO_x emissions in Ontario in 2001 were attributed to the transportation sector (1). A large fraction of the remaining 37% came from fossil fuel power generation (15%) and incineration processes (11%).

Based on 1995 Environment Canada estimates (2), the transportation sector in the City of Greater Sudbury accounts for over 89% of NO_x emissions, followed by the industrial sector (7.7%) and fuel combustion (3%).

Nitrogen dioxide is a lung irritant and can increase the chance of respiratory illness by lowering resistance to infection. People afflicted with asthma and bronchitis have increased sensitivity. Nitrogen dioxide chemically transforms into nitric acid which, when deposited, contributes to lake acidification. Nitric acid can corrode metals, fade fabrics, degrade rubber and damage trees and crops.

2.3 Carbon Monoxide (CO)

Carbon monoxide is a colourless, odourless, and tasteless gas which is poisonous at high concentrations. It enters the bloodstream and impedes oxygen delivery to the organs and tissues. People with heart disease are particularly sensitive. Carbon monoxide is produced primarily by the incomplete combustion of fossil fuels. The transportation sector is responsible for most of the CO emissions in Ontario. In 2001, this sector accounted for 85% of all province-wide CO emissions from human activity. The remainder was attributed to industrial processes, area fuel consumption and miscellaneous area sources (1).

The 1995 Environment Canada inventory (2) estimates that 99.6% of the carbon monoxide emissions in the City of Greater Sudbury can be attributed to transportation sources, and the rest to incineration (0.2%) and industrial processes (0.2%).

2.4 Total Reduced Sulphur (TRS)

Total reduced sulphur compounds are sulphur-containing gases, most of which is hydrogen sulphide (H_2S). The other components are mostly methyl mercaptan, dimethyl sulphide and dimethyl disulphide. These compounds have a very low odour threshold (concentrations of about 5 ppb) and produce an offensive odour similar to rotten eggs or cabbage.

Natural sources of TRS include swamps, bogs and marshes from decaying vegetation. Emissions from pulp and paper mills using the Kraft process, steel mills, petroleum refineries and sewage treatment plants under upset conditions are the principal industrial sources of TRS.

At concentrations normally found in ambient air, i.e. less than about 100 ppb, TRS compounds are not considered a health hazard. However at higher concentrations resulting from industrial process upsets or accidental releases, sensitive individuals may experience nausea and headaches. These compounds are a primary cause of odours and public odour complaints at some locations in the province.

With the exception of very localized and isolated emissions from sewage treatment plants during upset conditions, there are no significant sources of TRS in the City of Greater Sudbury. The closest industrial source is the Domtar pulp and paper mill located in the town of Espanola, approximately 70 kilometres west-southwest of the city.

2.5 Ground-Level Ozone (O_3)

Ozone (O_3) is a colourless gas naturally occurring in the upper atmosphere (stratosphere) which shields the earth from the sun's harmful ultra-violet radiation. Unlike stratospheric ozone, ground-level ozone is found at the earth's surface and is formed when nitrogen

oxides, principally NO_2, and volatile organic compounds (VOCs) react in the presence of sunlight (photochemical reaction). It is not emitted directly into the atmosphere (a primary pollutant), as are most other air pollutants. Its formation and transport are strongly dependent on meteorological conditions. Changing weather patterns contribute to short-term and year-to-year variability in ozone concentrations. In Ontario, elevated concentrations of ground-level ozone are typically recorded on hot sunny days from May to September, between noon and early evening.

It is estimated that more than half of the provincial ozone levels during widespread smog episodes are due to long range transport of ozone and its precursors, NO_x and VOCs, from neighbouring U.S. states (1). Every urban airshed that emits ozone precursors will produce its own 'background' ozone, an amount dependent on the levels of precursor emissions and meteorological conditions. In addition, since local emissions of nitrogen oxides are known to remove ozone, it has been demonstrated that ozone levels are higher in rural areas and downwind of urban centres (1). The amount of locally produced ground-level ozone in the Sudbury airshed has not been quantified and is thus unknown at this time. However, as in all urban centres in the province, a significant proportion of the ozone measured during smog episodes, or ozone episode days, is imported from long range transport sources.

Ozone irritates the respiratory tract and eyes. When exposed to O_3, sensitive individuals can experience chest tightness, coughing and wheezing. Children playing outdoors in the summer, when ground-level ozone levels are at their highest, are particularly at risk of experiencing such effects. Individuals with pre-existing respiratory disorders, such as asthma and chronic obstructive lung disease, are also at risk. Ground-level zone is now linked to increased hospital admissions and premature deaths. It also causes visible leaf damage in many crops, garden plants and trees and is responsible for agricultural crop losses each year, mostly in southwestern Ontario.

2.6 Particulate Matter

Particulate matter (PM) is the general term used to describe a mixture of solid particles in air. It is characterized according to size, ranging from less than 0.1 microns to over 100 microns, because of the different health effects associated with particles of different diameters. The full range of particle sizes, i.e. up to about 100 microns, is described as either Total Suspended Particulate (TSP) or Suspended Particulate (SP) according to the sampling method used. Historically, TSP and SP have been associated mostly with soiling and visibility effects. Health effects have been associated with finer particulate matter, i.e. particles 10 microns or less (PM_{10}), and especially with particles 2.5 microns or less ($PM_{2.5}$). These are also known as inhalable (PM_{10}) and respirable ($PM_{2.5}$) particles. They can penetrate the respiratory system further than can larger particles. Exposure to inhalable and especially respirable particles is reported to be associated with hospital admissions and several serious health effects, including premature mortality. People most at risk are those with asthma, cardiovascular or lung disease, as well as children and the elderly.

Particulate matter includes smoke, fumes, dust, aerosols, fly ash and pollen. Its composition varies with location, season, and atmospheric conditions and typically comprises soil particles, organic matter, sulphur and nitrogen compounds and metals. Particles originate from many different stationary and mobile sources, as well as from natural sources. Industrial sectors include iron and steel, pulp and paper, forestry, mining and smelting, aggregates, cement, and construction. In urban air sheds, motor vehicle exhaust, residential wood combustion and road dust are major sources. Natural sources include wind-blown soil, pollen, forest fires, ocean spray and volcanic activity.

The Ministry of the Environment's best available estimates for particulate emissions by sectors in Ontario indicate that emissions from transportation, area fuel consumption and miscellaneous area sources account for over 60% of emissions from human activity (3). These estimates do not include emissions from road dust, construction and agricultural activity which are not sufficiently known at this time. From recent studies undertaken by the MOE during periods of widespread elevated levels of $PM_{2.5}$, it is estimated that more than 50% of this contaminant in Ontario comes from the U.S. (1). The Ministry's estimates are revised with updated source/sector information or improved emission estimation methodologies as they become available.

The Environment Canada 1995 particulate emission contribution estimates for the Sudbury area are summarized in Table 2.2. Open sources, such as construction, paved/unpaved roads, forest fires, mine tailings, erosion from farmlands and landfill sites, were estimated to account for over 78% of Total Particulate Matter (TPM) emissions, followed by emissions from industrial sources (19.8%). The remainder was attributed mostly to transportation and fuel combustion sources.

Source category	**TPM**	**PM_{10}**	**$PM_{2.5}$**
Industrial	19.8	37.9	61.4
Fuel combustion	0.5	2.0	4.4
Transportation	1.3	4.8	8.7
Incineration	0.01	0.03	0.05
Miscellaneous	0.05	0.2	0.4
Open sources	78.3	55.1	25.0

Table 2.2: Estimated Percentage Contributions to Particulate Emissions Within a 25 km Radius of Sudbury – Environment Canada (1995)

For PM_{10}, open sources contributed 55.1% followed by industrial sources at 37.9%. Transportation (4.8%) and fuel combustion (2%) accounted for most of the remaining fraction. On the other hand, industrial emissions were estimated to contribute 61.4% of total fine particulate ($PM_{2.5}$) emissions followed by open sources (25%), transportation (8.7%), fuel combustion (4.4%) and miscellaneous sources (0.4%).

Measurements of ambient concentrations of respirable particulate ($PM_{2.5}$) in the City of Greater Sudbury air shed were only recently (2002) initiated as part of a special study, the Sudbury Soils Study, a comprehensive ecological and health risk study aimed at assessing the impact of and determining associated risks of elevated metals in soils. This study is also concurrently collecting samples of PM_{10} and TSP. The results of these measurements are not within the scope of this report and will be reported later as part of the overall special study results.

3.0 AIR POLLUTION INDEX, AIR QUALITY INDEX AND SMOG ALERTS

This chapter describes the provincial index systems used over the past three decades in the Sudbury area to provide the public with real-time air quality information and alerts to elevated air pollution levels. Two systems have been used, namely the Air Pollution Index and the Air Quality Index.

3.1 Air Pollution Index (API)

The Air Pollution Index (API) system was launched in Ontario in 1971. It is the basis of an alert and control system to warn of deteriorating air quality. The index is a number computed each hour from the most recent 24-hour running average concentrations of sulphur dioxide (SO_2) and suspended particulate measured as soiling index or coefficient of haze (COH). The combination of these pollutants has long been associated with adverse health effects, such as those experienced in the 1952 and 1956 London England disastrous air pollution episodes caused by elevated and persistent concentrations of SO_2 and particulates.

Regulation 346 under the Environmental Protection Act (1971), authorizes the Minister of the Environment to order any source not essential to public health or safety to decrease or cease operations that emit the above pollutants when air pollution levels may be injurious to health.

If the index reaches 32 and weather forecasts indicate a continuation of adverse atmospheric conditions for at least 6 hours, an air pollution advisory is issued. Managers of significant sources of pollution are advised to prepare for possible curtailment of operations. If the index reaches 50, and if at least 6 hours of adverse atmospheric conditions are forecast, owners of major sources may be ordered to curtail operations. This is a first level alert.

A second level alert is issued when the index reaches 75 and further curtailment may be ordered. The threshold level of an air pollution episode occurs at an API of 100. If atmospheric conditions are not expected to improve for at least 6 hours, owners of all selected sources not essential to public health or safety may be ordered to shut down.

3.2 Air Quality Index (AQI)

As scientific evidence mounted on health effects associated with air pollutants other than SO_2 and suspended particulate measured as soiling index, the need for an improved air quality reporting system became apparent. Hence in May 1988, the Ministry of the Environment launched its Air Quality Index (AQI) system, partly adopted from the Canadian Air Quality Index and the U.S. EPA Pollutant Standards Index.

The AQI provides the public with real-time air quality information across the province. In 2001, the AQI network included 35 continuous stations located in 22 urban centres and

7 rural areas (1). The index is based on hourly average readings for the following continuous air pollutants: sulphur dioxide (SO_2), ground-level ozone, nitrogen dioxide (NO_2), total reduced sulphur (TRS) compounds, carbon monoxide (CO), and suspended particles (SP) measured as soiling index (COH). Every hour, the concentration of each contaminant is converted into a number the ranges from zero upwards using a common scale or index. The calculated number for each pollutant is called a sub-index. The API, which is based on the combination of SO_2 and SP, continues to serve as a regulatory tool under the Environmental Protection Act (1971) and is incorporated in the AQI as a sub-index. At a given site, the highest sub-index for any given hour becomes the AQI. As the index increases, the air quality worsens. The index values, their corresponding air quality categories and potential health and environmental effects are shown in Table 3.1.

Index	Category	Carbon Monoxide (CO)	Nitrogen Dioxide (NO_2)	TRS Compounds	Sulphur Dioxide (SO_2)	Suspended Particles (SP)	API (SO_2 + SP)	Ozone (O_3)
0-15	Very Good	No known harmful effects	No known harmful effects	No known harmful effects	No known harmful effects	No known harmful effects	No known harmful effects	No known harmful effects
16-31	Good	No known harmful effects	Slight Odour	Slight Odour	Some vegetation injury with ozone	No known harmful effects	No known harmful effects	No known harmful effects
32-49	Moderate	No noticeable impairment	Odour	Odour	Damages some vegetation	Some decrease in visibility	Some vegetation damage due to SO_2	Respiratory irritation in sensitive people; some risk for people with heart & lung disorders; damages very sensitive plants
50-99	Poor	Increased symptoms for smokers with heart disease	Air smells and looks brown; some effect on asthmatics	Strong odour	Odourous; increasing vegetation damage	Decreased visibility; soiling evident	Increased symptoms for people with chronic lung disease	Sensitive people may experience irritation when breathing and possible lung damage; greater risk for people with heart/lung disorders; damages some plants
100-over	Very poor	Increased symptoms in non-smokers with heart disease; blurred vision	Increased sensitivity for people with bronchitis and asthma	Severe odour; some people may have nausea and headaches	Increased sensitivity for people with bronchitis and asthma; more vegetation damage	Increased sensitivity for people with bronchitis and asthma	Significant effects for people with asthma and bronchitis	Serious respiratory effects even during light activity; people with heart/lung disease at high risk; more vegetation damage

Table 3.1: Air Quality Index Pollutants and Their Effects

The computed AQI values are released daily to the public and news media at set intervals. The public can also access the AQI values by calling the MOE automatic telephone answering system or from its Web site: www.airqualityontario.com.

3.3 Smog Alerts

In the spring of 1993 as a joint effort with Environment Canada, the MOE initiated a smog advisory program. Smog advisories are issued to the public when widespread, elevated and persistent ground-level ozone concentrations (AQI in the poor category) are forecast to occur within the next 24 hours. In May 2000, the MOE modified this program with the following enhancements:

- a two-level air quality forecast that provides a three-day outlook, a smog watch, in addition to the current 24-hour smog advisory; a smog watch is called when there is a 50% chance of a smog day coming within the next three days

- the immediate issuance of a smog advisory with the occurrence of unexpected widespread and elevated smog levels forecast to continue for at least six hours

- increased frequency of AQI updates on week days and weekends; other public information dissemination improvements (1)

The City of Greater Sudbury is included in the smog advisory program which covers southern, eastern and central Ontario.

4.0 METEOROLOGY AND AIR QUALITY

Weather has a major influence on air quality. The dispersion and behaviour of air contaminants is directly affected by wind, temperature, precipitation, sunshine and the stability condition of the atmosphere. Once released in the atmosphere, air contaminants and precursor substances follow the air currents and undergo chemical transformations and removal/dispersion depending on prevailing meteorological conditions. These conditions also have a significant influence on the speed or the rate at which these processes occur.

Generally, the concentration of air pollutants will decrease with increasing wind speed and vice-versa. Air pollution episodes typically occur under light or stagnant winds since the atmosphere is unable to quickly flush out or disperse the pollutants, and these can build up leading to elevated ground-level concentrations. Wind direction determines which areas near or downwind of a source will be affected. Wind directions have seasonal patterns. For example in many areas of the province, including Sudbury, winds typically are from the south-southwest, the southwest and the west during the late spring and summer months. During the colder seasons, the winds in the Sudbury area generally blow from the northwest and the north. Knowledge of the frequency distribution of wind directions in an area, typically represented in a wind rose diagram (see Appendix I), is very important in identifying acceptable sites for new sources of air pollutants near populated areas and in determining the pollution controls or strategies required.

Ambient temperature plays an important role in the rate of transformation of certain air contaminants. Generally, chemical reactions in the atmosphere are enhanced by warmer temperatures. Hence the formation of secondary pollutants, such as ground-level ozone, is greater in warmer climates. A critical factor affecting the behaviour of air contaminants is the stability condition of the atmosphere. It is driven by the temperature of the air as a function of altitude. This 'temperature profile' dictates whether the air is stable, i.e. very little vertical movement, or unstable, i.e. with significant vertical movement which is the case with updrafts and downdrafts. Air pollutants released in unstable air can reach ground-level due to downdrafts, even if released from elevated stacks. The air temperature normally drops with increasing altitude. Under certain conditions, however, the opposite occurs over a short range of altitudes and for short time periods, leading to so-called 'temperature inversions.' These often trap air pollutants near ground level resulting in short-term air pollution episodes or fumigations.

Precipitation, in the form of rainfall and snowfall, effectively washes out air pollutants from the atmosphere. Typically, wet summers result in better air quality due to the dual beneficial effect of precipitation and lower temperatures. This cleansing of the air, however, leads to the wet deposition of contaminants to the ground and to area lakes and streams, some of which can become acidified.

The influence of meteorology on air quality in the Sudbury area is best exemplified with ground-level ozone and sulphur dioxide. Ground-level ozone is formed when its precursors (VOCs and NO_x) react in sunlight and high ambient temperatures.

Widespread elevated ozone episodes typically occur in late spring and summer under high pressure systems. On such days, air masses generally reach southern Ontario from the southwest, having crossed large industrial and urban areas of the eastern and mid-western U.S. These areas are potential sources of ozone and its precursors. From time to time, these ozone-laden air masses, pushed by westerly and southwesterly winds, reach central Ontario and cause elevated ground-level ozone concentrations along the Sudbury-North Bay corridor. Air quality advisories are often issued during this type of weather.

In the Sudbury area, SO_2 episodes or fumigations occur when SO_2 emitted at significant heights from smelter stacks impinges at ground level. This 'looping plume' phenomenon typically occurs under sunny conditions from late spring to early fall - from late morning to mid-afternoon - when the air is most unstable and mixes down to the ground entraining parcels of sulphur dioxide gas released from the stacks and also to a much lesser degree from smelter building roof vents. This phenomenon is aggravated under light winds or stagnant conditions. Short term fumigations can also occur when the SO_2 plume is released below a temperature inversion, effectively preventing its upward dispersion. This can result in an accumulation of sulphur dioxide gas which is forced to mix down to the ground at elevated concentrations under the light wind conditions. From the fall through to the spring, i.e. when the atmospheric dispersion conditions are most favorable, the incidence of sulphur dioxide fumigations in the City of Greater Sudbury is typically very low and average sulphur dioxide concentrations are at background levels.

5.0 AIR QUALITY TRENDS AND PROVINCIAL PERSPECTIVE

5.1 Sulphur Dioxide

Emissions and Abatement Efforts

Since the turn of the century, more than 100 million tonnes of SO_2 have been released from the Sudbury basin due to the mining and smelting of sulphur bearing copper/nickel ores (4). In the early 1960s, Sudbury's smelting complexes represented one of the largest point sources of SO_2 in the world (5). The history of sulphur dioxide abatement efforts and programs by the provincial government and industry is well documented (4, 6). Abatement efforts and strategies have focused on sulphur removal before smelting through rejection of the high sulphur iron minerals from the copper/nickel concentrates at the ore processing stage, the containment of sulphur through the production of sulphuric acid and liquid SO_2, and roasting/smelting process improvements to increase the efficiency of sulphur containment and production of these by-products.

Historical trends in emissions of SO_2, shown in Fig. 5.1, illustrate the magnitude of Sudbury area sources and the success of abatement efforts since the 1960s. In addition to legislated requirements for emission reductions imposed by the provincial government since the 1970s, labour disruptions and periods of reduced nickel production (1966, 1969, 1975, 1978, 1979, 1982, 1983, and 1994) contributed to the significant decline in SO_2 emissions. In comparing the first and last 5 years of the period 1960 to 2002 shown in Fig. 5.1, annual average emissions have decreased by about 88%.

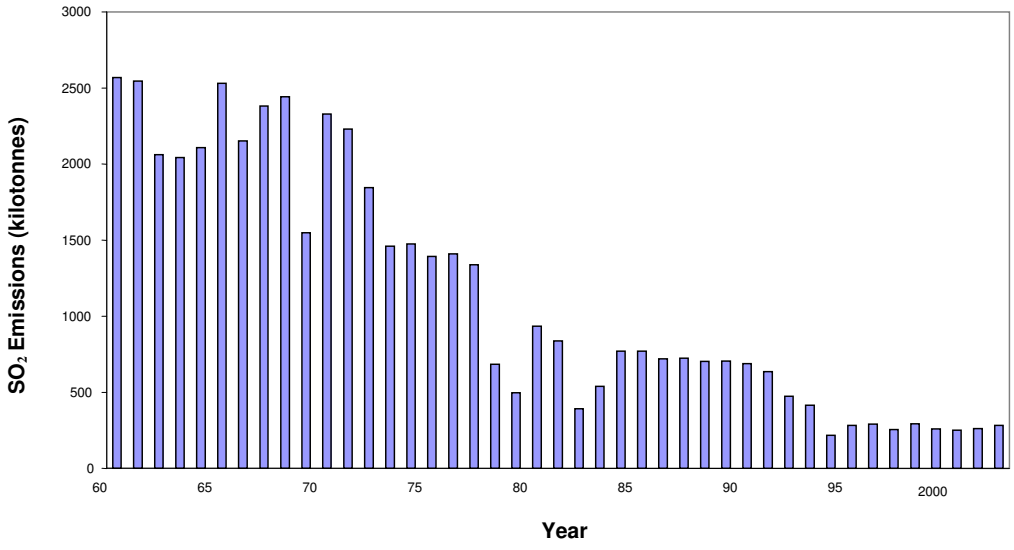


Figure 5.1: Sulphur Dioxide Emissions from Sudbury Area Smelters (1960-2002)

In February 2002, the MOE issued an Order imposing lower SO_2 emission limits on Sudbury area smelters. Starting in 2007, the current collective annual limit of 365 kilotonnes (kt), in effect since 1994, will be reduced by 34% to 241 kt.

Supplementary Control Program

In spite of very substantial reductions in annual emissions, with their current smelting process and associated emission levels, the Copper Cliff and Falconbridge smelters cannot meet, at all times, the provincial hourly SO_2 ambient air quality criterion (0.25 ppm) and the half-hour standard (0.30 ppm) specified in Ontario Regulations 337 and 346 respectively. This is due to the 'looping plume' phenomenon, described earlier in section 4.0, which often results in short-term fumigations at ground-level. From the experience gained by the Tennessee Valley Authority in the U.S. during the late1960s/early 1970s, and by INCO Ltd. after the commissioning of its tall stack in Copper Cliff in 1972, this strategy was deemed to be effective in reducing the intensity of fumigations. The strategy consists of the timely reduction of SO_2 stack emissions through production curtailments during periods of poor atmospheric dispersion conditions. Weather forecasting and dispersion modelling are critical components of this strategy in order to determine when and how much to reduce production.

On the basis of the knowledge and experience gained in the Sudbury area during the 1950s and 1960s on acute injury to vegetation from SO_2 exposure, a ground-level concentration of 0.50 ppm (500 ppb) for any
60-minute period was chosen as the control limit for stack emissions. This strategy became a Ministry Control Order requirement for INCO Ltd. in 1978 and for Falconbridge Ltd. in 1984. In February 2002, the Ministry issued a revised Order imposing a lower supplementary emissions control limit of 0.34 ppm (340 ppb) on both smelters, effective April 2002. This lower control limit is the hourly Environment Canada maximum acceptable level for SO_2 in ambient air. The Order also required both companies to complete a study by the year 2010 which identifies: the best available technologies and design, and their associated costs to meet the provincial sulphur dioxide half-hour standard of 0.30 ppm (300 ppb) and an implementation plan on how the standard would be achieved by the year 2015.

Monitoring Program

In the past five decades, the SO_2 monitoring program has seen significant changes which are detailed in published Ministry of the Environment reports (7, 8, 9). The following is an overview of these changes.

The original SO_2 monitoring network of stations operated by the province in the Sudbury basin was established in 1953 at the following locations: Burwash, Skead, Grassy Lake, Garson and Lake Penage. The location of these stations is shown in Fig. 5.2. With the exception of Burwash, most of the stations were aligned along a southwest-northeast axis

(Lake Penage to Grassy Lake) covering a distance of over 130 kilometres. At that time, ground-level concentrations of SO_2 were determined with Thomas autometers. These devices used a dilute sulphuric acid solution as the detection medium; the absorption of SO_2 in this solution changed its electrical conductivity which was then converted to a concentration of SO_2 in the air. Since, at that time, the damaging impact of SO_2 emissions on vegetation, such as forests, agricultural crops and gardens was the main concern, the stations were only operated during the growing season, i.e., from May to October. This measurement method was very labour intensive and the final results were only available the following fall or winter. By 1970, another six stations (St Charles, Morgan, Rayside, Callum, Happy Valley near Falconbridge, and Ash Street in the city of Sudbury) had been added to the network. Their locations are also shown in Fig. 5.2.

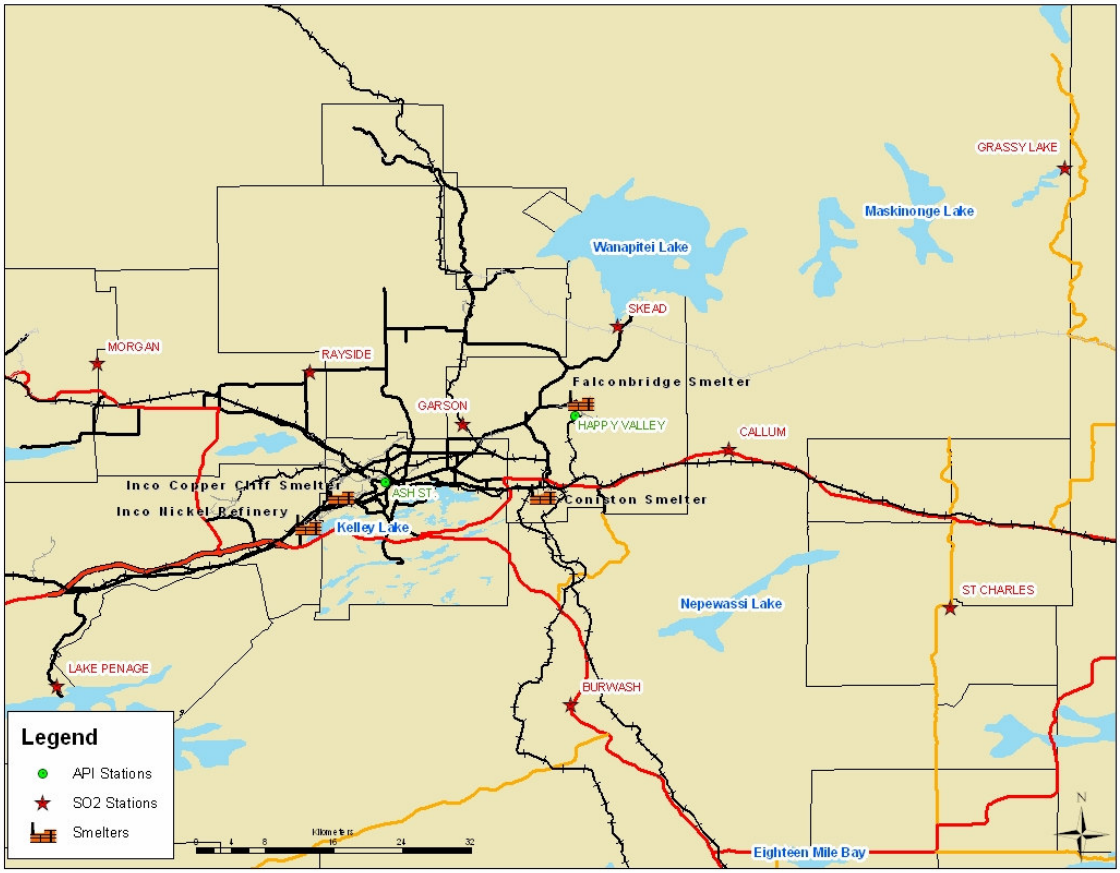


Figure 5.2: Air Quality Monitoring Network in the Sudbury Area (1953-1970)

During the 1970s, significant changes to the network occurred. These were in response to the following: the introduction of better monitoring and data transmission technology; growing concerns within and outside the Sudbury basin about air quality impacts of emissions at greater distances from the tall stack commissioned in 1972 at the INCO Ltd.

Copper Cliff smelter; and the emergence of new issues such as acid deposition and possible health effects of sulphur dioxide.

Firstly, the network had grown to 17 stations by 1980 as shown in Figures 5.3a and 5.3b, with sites as far away to the east and northeast as Verner and Lake Temagami (Fig. 5.3a). Most of the sites were converted to year-round operation in temperature-controlled shelters. The Sudbury (Ash Street), Coniston and New Sudbury stations were established as Air Pollution Index sites.

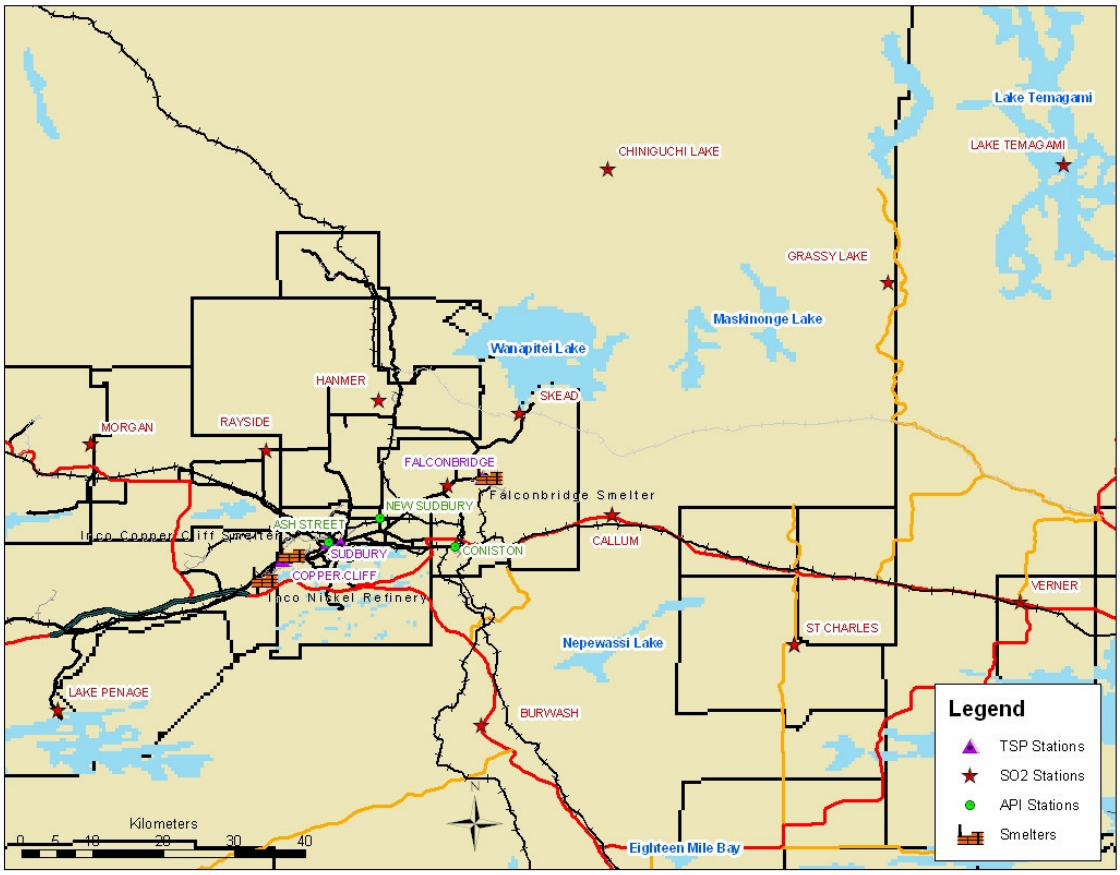


Figure 5.3a: Air Quality Monitoring Network in the Sudbury Area (1980). (Map shows distant stations and a few of the stations in/near Sudbury)

Secondly, by 1974 the Thomas autometers had been replaced by more automated, wet-chemical SO_2 analyzers (the Davis and the Beckman 906A analyzers). By the mid to late 1970s, solid-state monitors, using the pulsed fluorescence detection principle, described in Appendix A, began to replace these wet-chemical analyzers.

Lastly, in 1978 the network was upgraded with the installation of a data telemetry system. It improved the accuracy and quality of the data and provided the Ministry, using

telephone lines, with real-time 5-minute average readings from the SO_2 monitoring stations in the Sudbury area. Readings above a preset value triggered a telephone message to MOE staff for their notification and follow-up action with the responsible source as required. The data acquisition system stored the hourly average readings for transmittal to the Ministry's provincial database in Toronto.

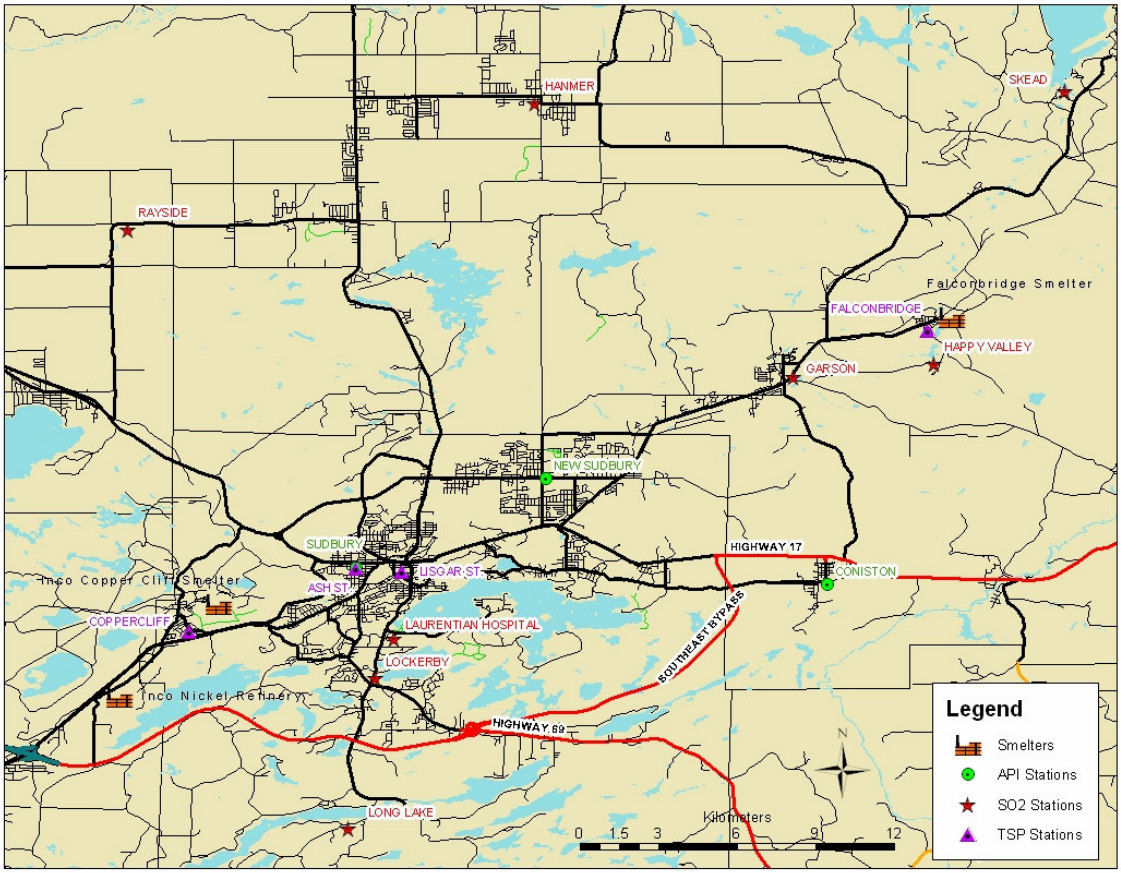


Figure 5.3b: Air Quality Monitoring Network in the Sudbury Area (1980). (The more distant stations are shown in Fig. 5.3a)

The 1980s and 1990s brought an additional number of significant changes to the network. In 1985, the data telemetry system was enhanced with greater data storage and communications capabilities. The INCO Ltd. and Falconbridge Ltd. facilities were provided access to the real-time 5-minute average readings for inclusion in their supplementary SO_2 control systems. It was then possible to transmit the hourly data electronically to the Ministry's Toronto computer for inclusion in the provincial Air Quality Information System (AQUIS) and for generating the hourly AQI values. Further enhancements to this system were made in the late 1990s with the substitution of data loggers with PCs and the use of a Windows-based operating system.

The size and configuration of the network changed as well. Because of significant improvements in air quality outside the Sudbury basin due to decreasing emissions and

greater dispersion afar from the tall stack at the Copper Cliff smelter, the more distant stations such as Lake Temagami, Verner and Callum were decommissioned. In addition, decreasing SO_2 emissions from the tall stack at the Copper Cliff smelter resulted in lower stack gas volume and temperature with an accompanying negative impact on ground-level concentrations closer to the smelter due to reduced plume buoyancy/dispersion. Consequently, some of the more distant stations were relocated closer to the smelters and in populated areas within the City of Greater Sudbury. By the late 1990s, the network had been streamlined to 12 stations (see Fig. 5.4), which is the size of the 2002 network.

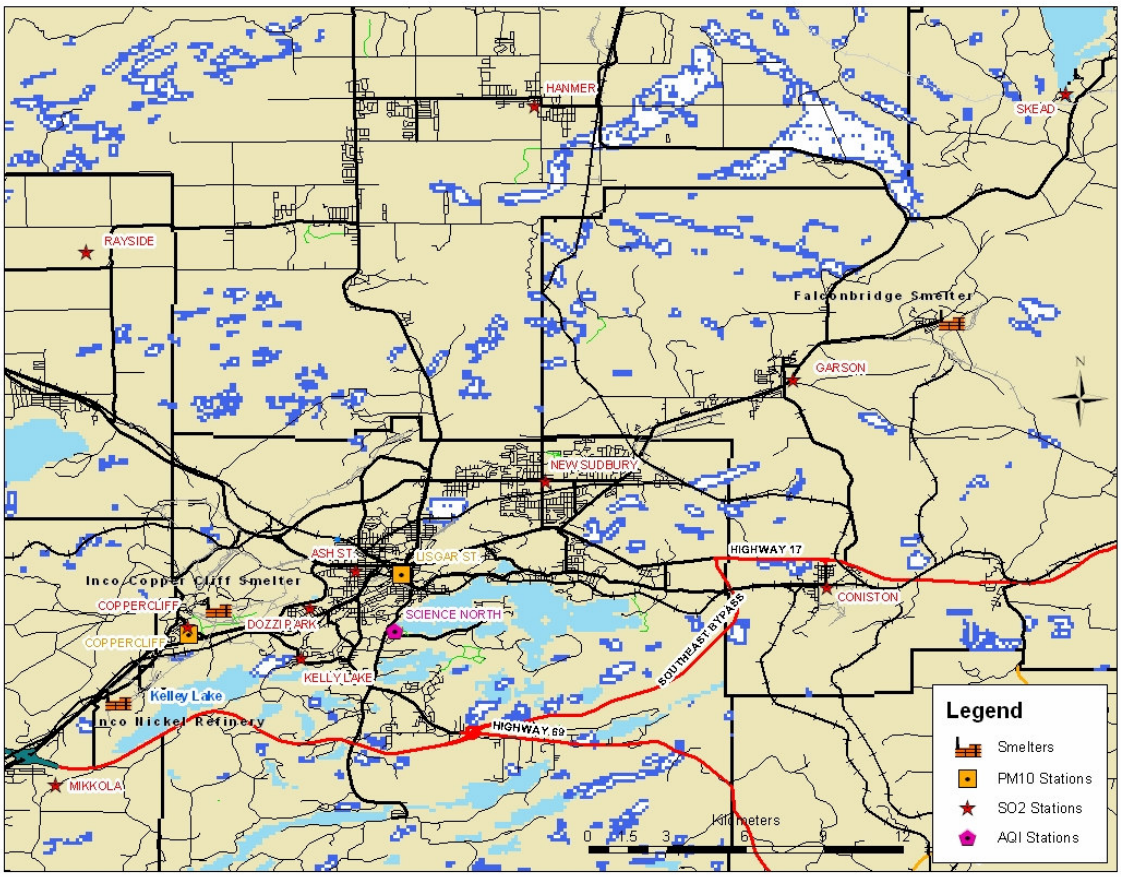


Figure 5.4: Air Quality Monitoring Network in the Sudbury Area (2002)

Results

The 1950s and 1960s

In the 1950s and 1960s, ground level concentrations of SO_2 were oftentimes elevated at all monitoring locations in the Sudbury basin, with many exceedances of the Ministry's ambient air quality criteria. During the growing seasons from 1953 to 1964, an elliptical area of about 540 miles^2 (over 1300 km^2) - stretching from New Sudbury to Lake

Wanapitei - was exposed to average SO_2 concentrations in excess of the annual criterion (10) of 0.02 ppm (20 ppb). The highest levels of SO_2 (see Table 5.1) were recorded at Skead, located in the northeastern sector of the basin and just south of Lake Wanapitei. In that area, maximum seasonal 1-hour readings would range from about 1 ppm (1000 ppb) to over 3.5 ppm (3500 ppb), well above the Ministry criterion of 0.25 ppm (250 ppb). In addition, this criterion would be exceeded during 100 to over 300 hours per season, whereas the 24-hour criterion of 0.10 ppm (100 ppb) would be exceeded for approximately 13 to 40 days per season.

During that period, many cases of vegetation injury associated with severe fumigations, sometimes as far as 80 km from the Sudbury smelters, were documented (11, 12). Extensive damage to area forests, and to a lesser degree to agricultural crops, was evident (13, 14). The size of area where sensitive species such as white pine were affected with severe-to-moderate injury covered more than 1800 km^2, with an additional 4000 km^2 of sporadic injury (15).

Location	**Maximum 1 hour (ppb)**	**# of Times Above Criteria**	
		1-hour	**24-hour**
Lake Penage	330 – 1330	4 –54	0 – 8
Burwash	390 – 1130	6 – 72	0 – 7
Skead	1110 – 3570	102 – 328	13 – 41
Garson	840 – 1940	50 – 219	4 – 26
Grassy Lake	190 – 1240	0 –31	0 – 2

Table 5.1: Range of Maximum 1-Hour Values and Exceedance Frequency of the 1-Hour and 24-Hour SO_2 Criteria From 1953 to 1969

Pre- and Post-1972

The combination of increased dispersal of pollutants, realized with the commissioning of the world's tallest (381 metres) smokestack at the INCO Ltd. Copper Cliff smelter in 1972, reduced emissions and the closure of obsolete plants led to dramatic improvements in local air quality after the early 1970s. A comparison of SO_2 ground-level concentration data collected from monitoring stations in operation during the growing seasons from 1967 to 1977, with 1972 as a transition year, demonstrates the extent of these improvements (8). The results of this analysis, using data for the growing seasons only for this group of stations, are shown in Figure 5.5. From over 181,000 hours of data collected in the period 1967 to 1971, 2423 hours exceeded the 1-hour criterion; the 24-hour criterion was exceeded on 189 days. For that period, the overall average

concentration was 13 ppb. The seasonal mean in 1972 was 8 ppb. During the 'post-1972' period (1973-1977) and from over 187,000 hours of recorded data, 750 hours exceeded the 1-hour criterion and the 24-hour criterion was exceeded on 32 days. The overall average concentration for that period was 7 ppb.

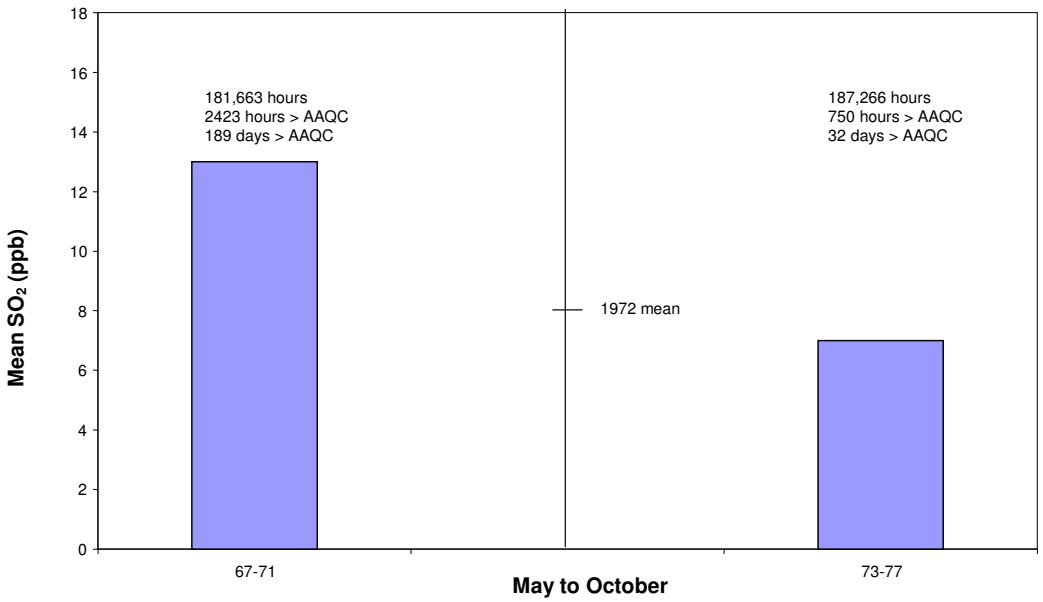


Figure 5.5: Mean SO_2 Concentrations in the Sudbury Area (1967-1971 and 1973-1977)

This analysis demonstrates that the measures undertaken in 1972 dramatically improved air quality in the Sudbury basin. The average concentration of SO_2 dropped very quickly by about 50% in the 'post-1972' period. Moreover, the frequency of excessive hourly values decreased by about 66%, and the frequency of 24-hour averages above the criterion fell by approximately 80%.

Long Term Trends

From the 2002 SO_2 monitoring network, the Skead, Garson (old and new) and Ash Street stations have the longest monitoring records, dating back to 1953 (Skead and Garson) and 1970 (Ash Street).

Historically, the Skead and Garson sites have been exposed to the highest measured concentrations of SO_2 in the Sudbury area (10). Since annual average concentration data only became available in the mid-1970s at these sites when they were converted to year-round operation, the best available trend indicator is the frequency of exceedance of the SO_2 1-hour and 24-hour criteria. The trend in the frequency of exceedance of these criteria for both sites combined, averaged per year for each decade, is illustrated in

Figure 5.6. The significant improvements realized in the 'post-1972' era have been surpassed over the past 23 years; the exceedance frequency of the 1-hour and 24-hour criteria in the 1990s was 90% and 97% lower, respectively, than in the 1970s.

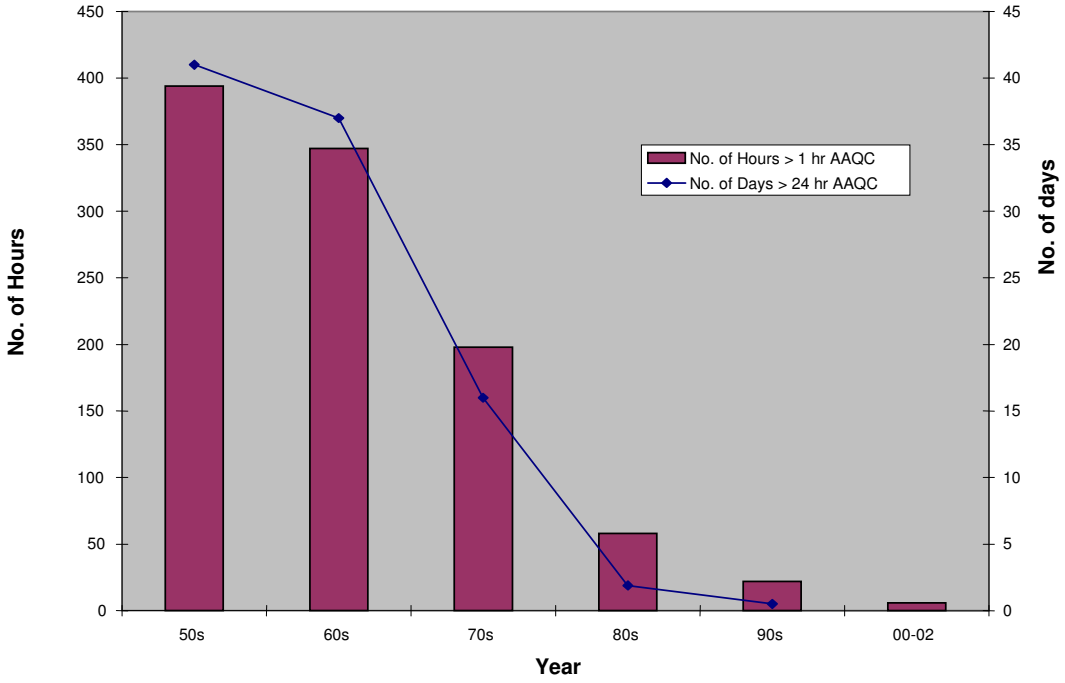


Figure 5.6: Exceedance Frequency of the SO_2 AAQCs at Skead and Garson

Annual average concentrations of SO_2 have also steadily decreased since the 'post 1972' era. A typical trend is shown in Figure 5.7 at the Ash Street site in Sudbury. The annual criterion was last exceeded at that location in 1975. Since then, the annual means have trended downwards and in the past decade, they have leveled off at about 6 ppb, roughly one half of the average values measured in the late 1970s.

Another measure of improved air quality conditions comes from the frequency of occurrence of potentially injurious fumigations (PIFs). From observations of vegetation injury in the Sudbury area during the 1950s and 1960s in relation to SO_2 fumigations of varying duration and intensity, researchers (12, 13, 16, 17) determined that under certain environmental conditions, injury to vegetation could result if it was exposed to the following levels of sulphur dioxide during daylight hours:

950 ppb for 1 hour
550 ppb for 2 hours
350 ppb for 4 hours
250 ppb for 8 hours

During the 'pre-1972' era, approximately 35 to over 80 PIFs per growing season were recorded with a network of 10 stations (16, 18). During the 1980s, the occurrence of PIF events had dropped to less than 5 per year with a network of 17 stations (19). That trend continued such that by the mid-1990s PIFs had become isolated events. Since 1993, only one PIF event has been recorded (in 1997). The combination of reduced emissions and the implementation of supplementary emission control programs markedly reduced the intensity and duration of SO_2 fumigations. These vastly improved conditions have enabled the successful re-greening of the Sudbury landscape with some of the most SO_2 sensitive tree species such as white pine.

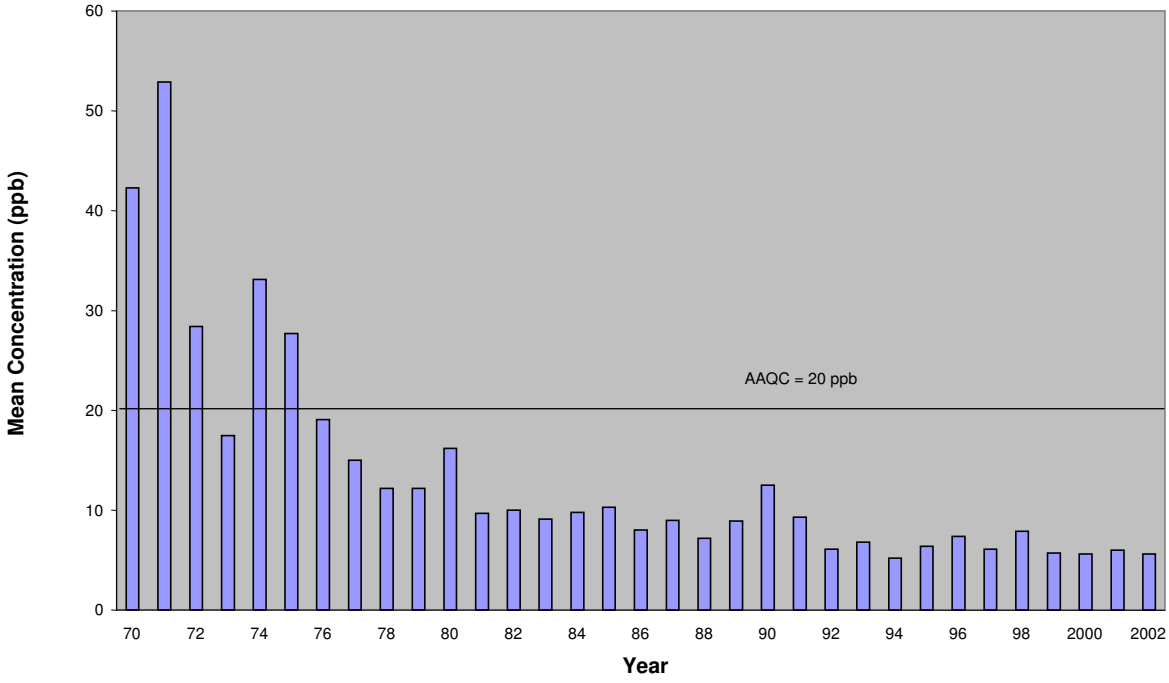


Figure 5.7: Mean SO_2 Concentrations at Ash Street in Sudbury (1970-2002)

Recent Trends (1990 – 2002)

The trend in the composite annual mean SO_2 concentrations for the 2002 monitoring network is shown in Figure 5.8 for the period 1990 to 2002. Since 1992, the composite mean has been rather constant, ranging from 3.7 ppb to 5.5 ppb. During that time, all sites recorded annual mean concentrations lower than the annual criterion of 20 ppb. The Copper Cliff station, shown separately in Figure 5.8, recorded the highest 13-year composite mean. It also realized the most significant improvements with the annual mean SO_2 concentrations falling from 20 ppb in 1990 to 5 ppb in 2002.

Figure 5.9 shows the trend in the frequency of hourly concentrations greater than the 1-hour and 24-hour provincial criterion for the 2002 network. From 1990 to 1993, the network recorded an annual average of 246 hours above the 1-hour criterion. The combination of reduced emissions required by the provincial acid rain regulations

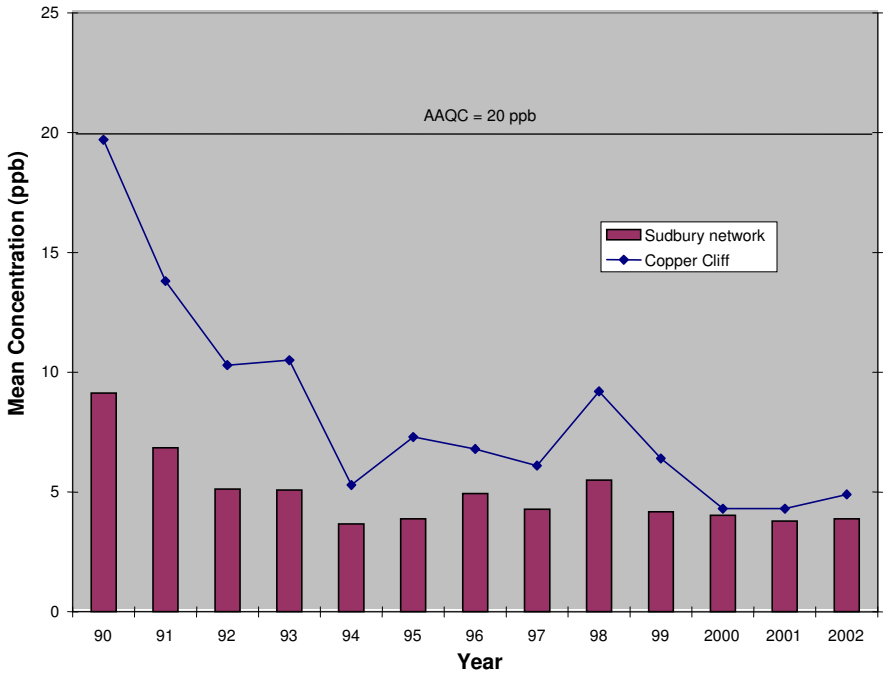


Figure 5.8: Mean SO_2 Concentrations in the Sudbury Network and in Copper Cliff

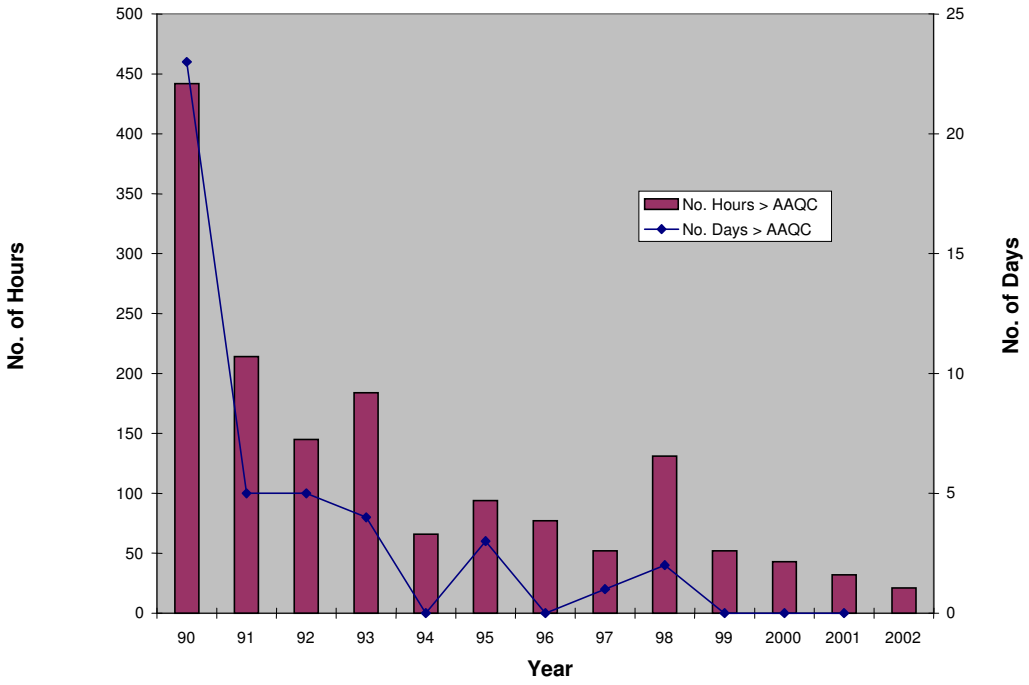


Figure 5.9: Frequency of Exceedance of the SO_2 AAQCs in Sudbury

imposed in 1994 and improved operating procedures in the smelters to reduce fugitive emissions, resulted in a significant reduction in the frequency of these events. In fact, since 1999 the network recorded an annual average of 37 hours above the 1-hour criterion, a drop of 85% from the period 1990-1993. These improvements are also reflected in the reduced occurrence of average concentrations above the 24-hourcriterion, the majority being recorded at the Copper Cliff site. Since 1998, this criterion has been met at all monitoring sites.

The frequency of exceedance of the 1-hour criterion, by monitoring site, is shown in Figure 5.10 for the period 1990 to 2002. The Copper Cliff site recorded the highest number of exceedances (472) and Coniston the lowest (34). In general, the stations located closest to the smelters recorded more exceedances. Figure 5.10 also shows the maximum hourly concentration recorded at each site. This ranged from 1480 ppb at Dozzi Park to 560 ppb at the Rayside station. The former site was commissioned in late 1993.

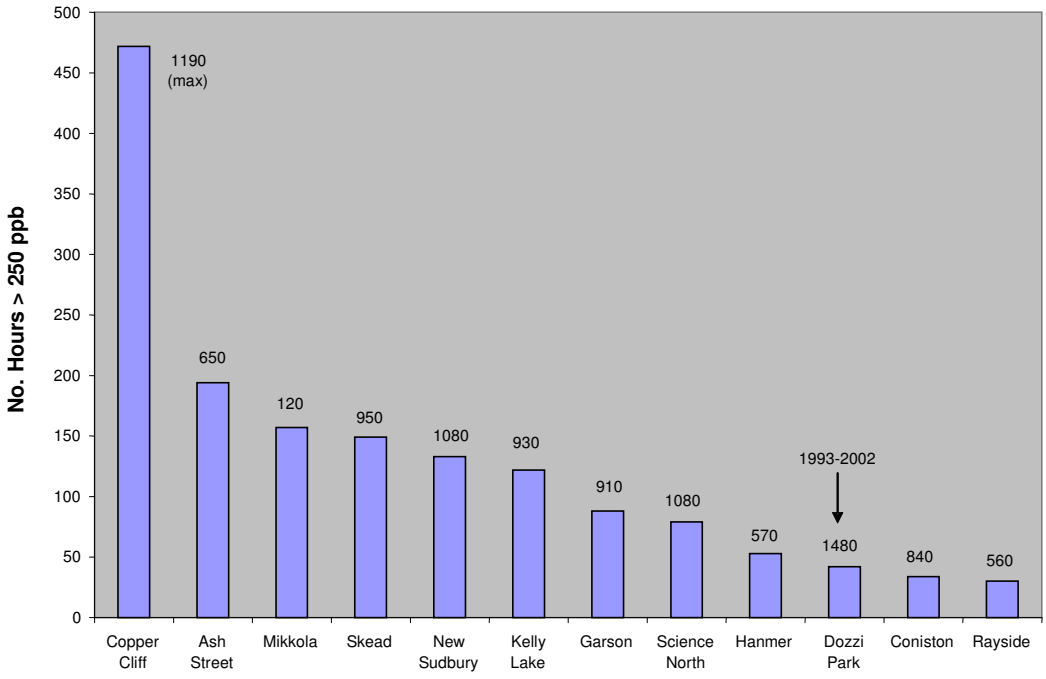


Figure 5.10: Frequency of Exceedance of the SO_2 AAQC, and the 1-Hour Max. in the Sudbury Area (1990-2002)

Comparisons with Other Cities in Ontario (1990 – 2002)

The composite annual mean SO_2 concentrations for the period 1990 to 2002 are shown in Figure 5.11 for the following cities: Windsor, Hamilton, Toronto, Ottawa,

Sault Ste. Marie, Thunder Bay and Sudbury. For each city, the data was taken from an AQI station preferably located in a downtown area; the Science North AQI site was selected for Sudbury. The highest 13-year means (over 6 ppb) were recorded in Windsor and Hamilton, while Thunder Bay recorded the lowest (0.4 ppb). Sudbury recorded a composite mean of 4.2 ppb and ranked 4th best out of the 7 cities compared, behind Thunder Bay, Sault Ste. Marie and Ottawa.

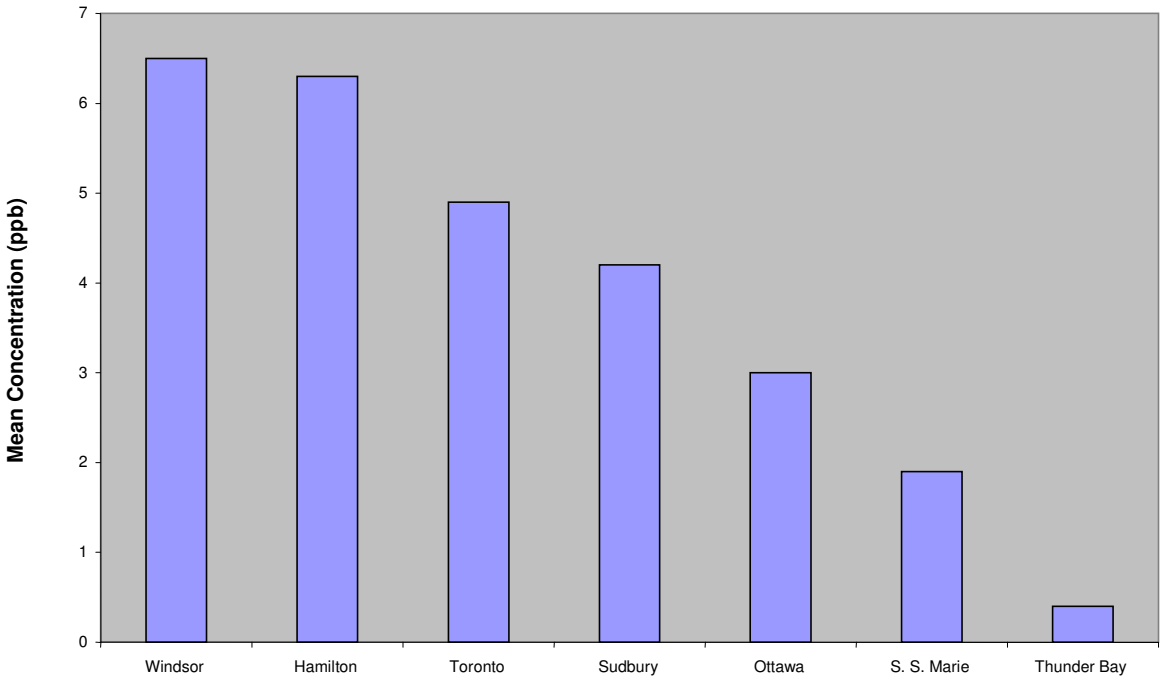


Figure 5.11: Mean SO_2 Concentrations in Selected Cities (1990-2002)

A comparison of the annual frequency of occurrence of the 1-hour AAQC (250 ppb) revealed that for the cities selected, Sudbury was the only city that recorded exceedances of the AAQC during this 13-year period. Most (67%) of the exceedances were recorded between 1990 and 1993, with an average of 13 exceedances per year (Figure 5.12). Since 1994, an average of 3 exceedances per year has been recorded at the Science North site.

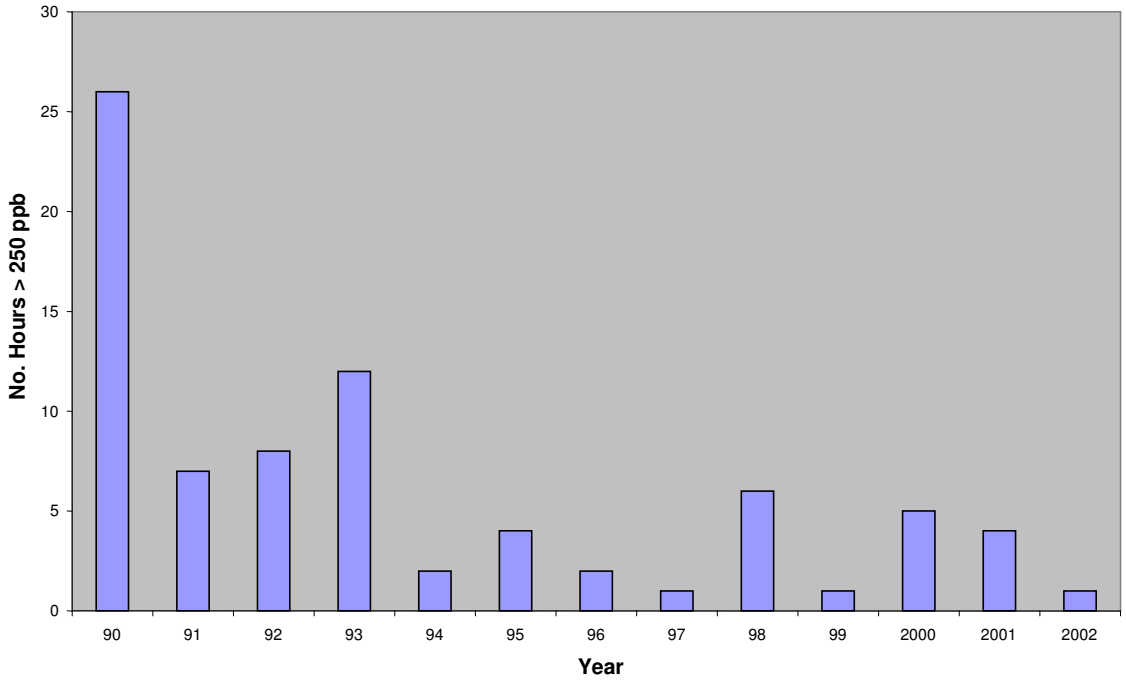


Figure 5.12: Frequency of Exceedance of the SO_2 1-Hour AAQC at Science North

5.2 Nitrogen Oxides (NO_x)

Monitoring Program

In the City of Greater Sudbury, monitoring for NO_x was performed at the Ash Street station from 1973 to 1984, and at Science North starting in 1985. Due to instrumentation problems, the first full year of valid data from the Ash Street station was 1976.

Results

Long Term Trends

The annual average concentrations of NO_x (NO + NO_2) varied considerably from year-to-year (see Figure 5.13), ranging from 10.6 ppb (1983) to 23.5 ppb (1977). Initially, the concentrations were somewhat higher at the Science North location for both NO and NO_2. Nitrogen dioxide comprised the largest fraction of NO_x.

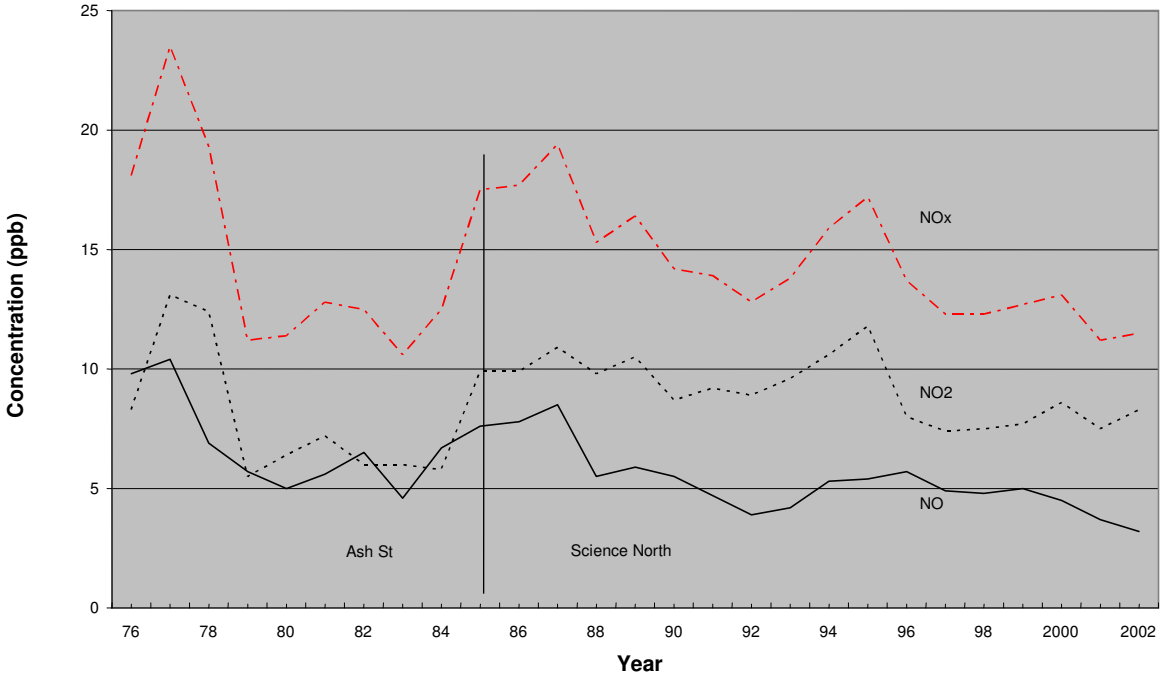


Figure 5.13: Trend of NO_x Concentrations in Sudbury (1976-2002)

Since the late 1980s, the levels of NO and NO_2 show an overall decreasing trend. Average concentrations in 2002 were 62% (NO) and 24% (NO_2) lower than the levels recorded in 1987. Except for an increase of about 25% during the early to mid-1990s, annual average daily traffic volumes near the Science North air monitoring station (Paris Street and Ramsey Lake Road) have remained fairly constant, ranging from 44,000 to 46,000 vehicles per day from the late 1980s to 2002 (20). Hence the reductions in the average concentrations of NO and NO_2 are attributed to reduced emissions from transportation sources due to stricter automotive emission controls. During the period 1976 to 2002, the 1-hour NO_2 criterion (200 ppb) was exceeded three times (1984), whereas the 24-hour criterion (100 ppb) was never exceeded.

Comparisons with Other Cities in Ontario (1990 – 2002)

Nitrogen dioxide composite annual means for the period 1990 to 2002 for selected cities in southern and northern Ontario are displayed in Figure 5.14. Downtown Toronto recorded the highest 13-year mean (28.5 ppb), while Sudbury recorded the lowest mean (8.9 ppb). The means for Sault Ste. Marie and Thunder Bay were 11.4 ppb and 12.4 ppb respectively. Typically, the highest values in Ontario are measured in larger urban centres, such as the Greater Toronto Area (GTA) and the Golden Horseshoe area.

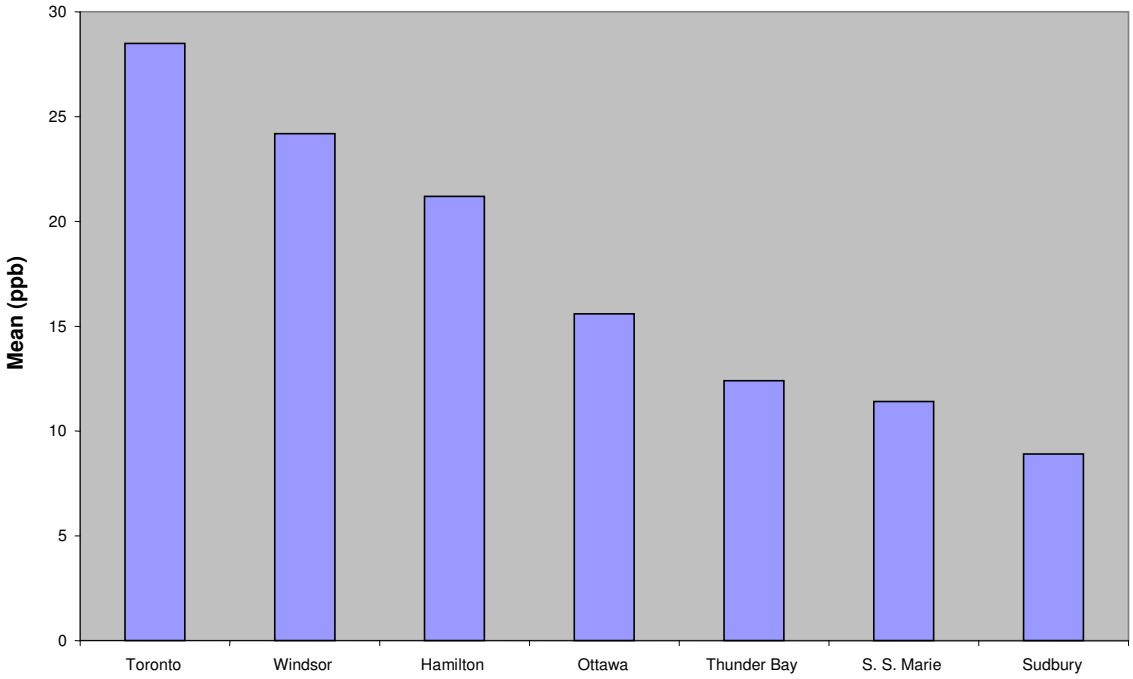


Figure 5.14: Mean NO_2 Concentrations in Selected Cities (1990-2002)

It should be noted that the measurement of traffic-related pollutants such as NO_x is strongly dependent on traffic patterns and atmospheric ventilation/dispersal rates in the vicinity of the monitoring station.

5.3 Carbon Monoxide (CO)

Monitoring Program and Results

Monitoring for CO began in 1969 at the Ash Street site. However because of on-going intermittent instrumentation problems, 1976 was the first year when sufficient valid data was available to determine an annual mean. Monitoring for CO was terminated at that location in 1987. Carbon monoxide was also monitored at the Science North location starting in 1984.

Long Term Trends

The average concentration of CO at the Ash Street site in 1976 was 0.95 ppm. The levels decreased over time such that by 1987 the annual concentration had dropped to 0.08 ppm. Due to the closer proximity to a major traffic artery and the greater impact of traffic emissions, in the mid-1980s the annual CO concentrations at the Science North location

were about 4 to 8 times higher than at the Ash Street site. Carbon monoxide concentrations have been rather steady in the Science North area. The annual means in 1990 and 1991 were 0.46 ppm and 0.34 ppm respectively, similar to the means recorded in 2001 (0.36 ppm) and in 2002 (0.56 ppm). There was no obvious correlation with traffic volumes near Science North.

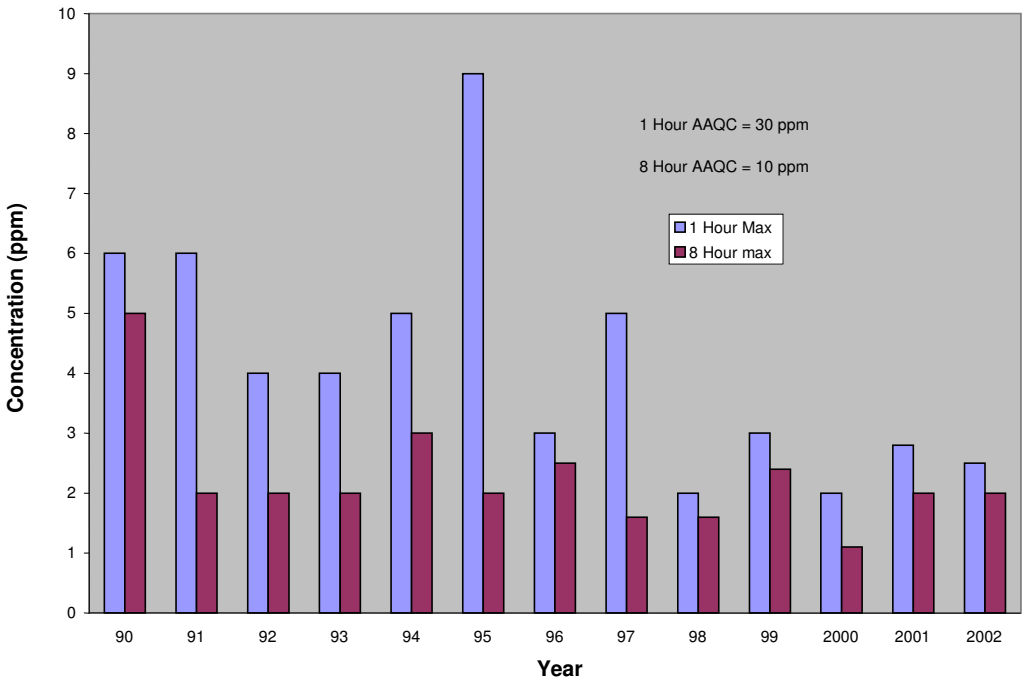


Figure 5.15: Carbon Monoxide 1-Hour and 8-Hour Maxima in Sudbury

As shown in Figure 5.15, the 1-hour maximum concentrations of CO were higher in the first half (1990 to 1997) of the 13-year monitoring period. Except for the higher value in 1990, the concentrations of the 8-hour maxima show no discernible trend over this period. The 1-hour (30 ppm) and 8-hour (13 ppm) provincial criteria were never exceeded at the Ash Street and Science North monitoring stations.

Comparisons with Other Cities in Ontario

Considering data availability, 2001 data was used as the basis for comparing annual means for the group of selected cities in Ontario. As illustrated in Figure 5.16, Toronto recorded the highest mean (0.93 ppm) and Windsor the lowest (0.26 ppm). Sudbury recorded the second lowest mean (0.36 ppm).

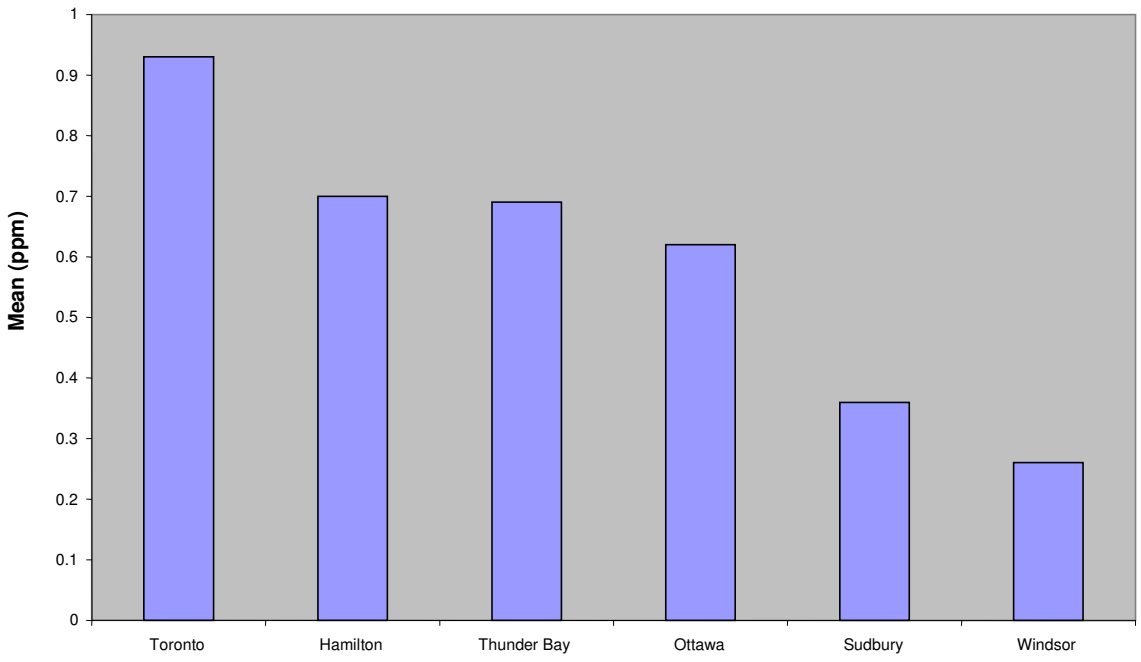


Figure 5.16: Carbon Monoxide Annual Means in Selected Cities (2001)

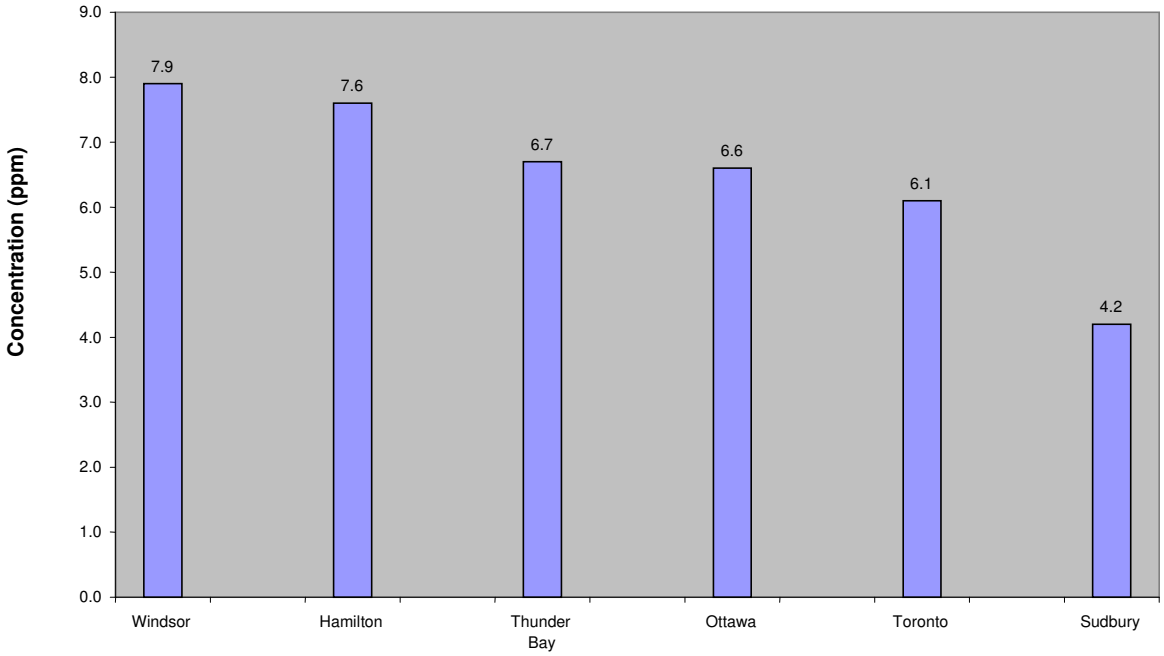


Figure 5.17: Mean 1-Hour Max. CO Concentrations in Selected Cities (1990-2002)

The larger urban centres are expected to have the highest levels due to the dominant contribution of the transportation sector to CO emissions. However, as noted earlier, concentrations of traffic-related pollutants are very site specific and are strongly dependent on the traffic patterns in the vicinity of the monitoring station.

The composite average maximum 1-hour concentrations for the selected cities for the period 1990 to 2002 are shown above in Figure 5.17. Windsor recorded the highest value at 7.9 ppm followed by Hamilton, Thunder Bay, Ottawa and Toronto. Sudbury recorded the lowest value at 4.2 ppm.

5.4 Total Reduced Sulphur (TRS)

Monitoring Program and Results

Monitoring for TRS compounds in Sudbury started in late 1984 at the Science North location.

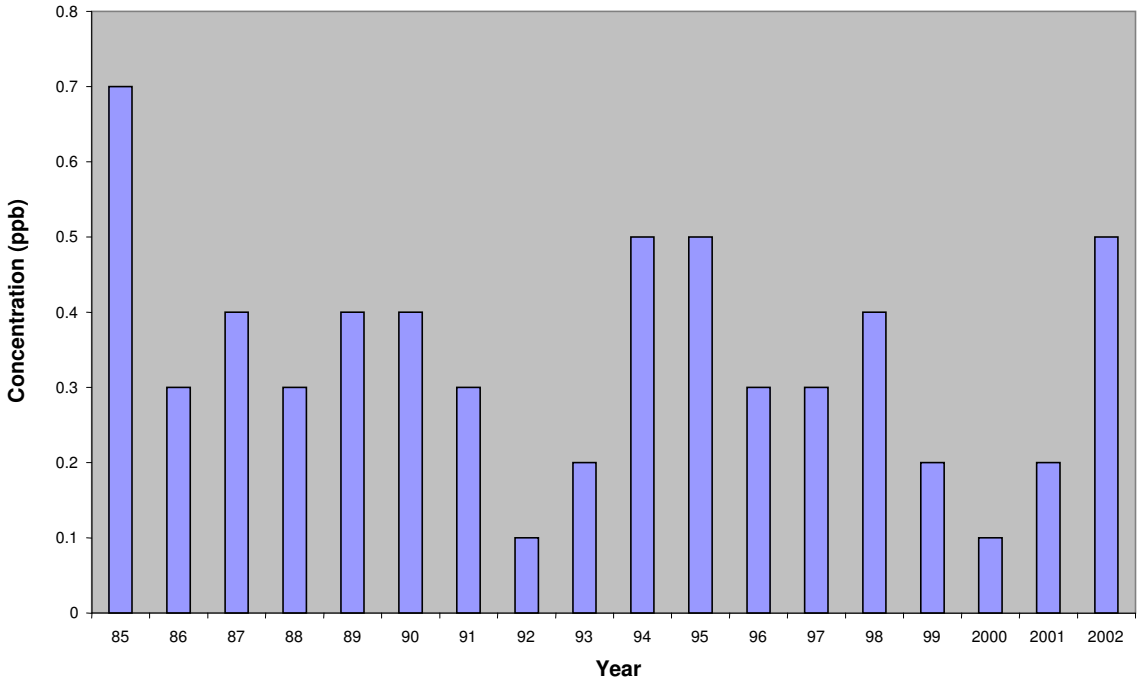


Figure 5.18: Mean TRS Concentrations in Sudbury (1985-2002)

Long Term Trend

Annual mean TRS concentrations for the period 1985 to 2002 were quite variable from year-to-year. They ranged from 0.1 ppb to 0.7 ppb with no discernible trend (Fig. 5.18). The 1-hour criterion of 27 ppb was never exceeded during this 18-year period; the maximum 1- hour concentration recorded was 18 ppb (1989). It is possible that from time to time, under certain meteorological conditions, TRS emissions from the Espanola Kraft pulp and paper mill contributed to the levels recorded at the monitoring station.

Comparison With Other Cities in Ontario

From the group of cities selected for comparison, TRS data was available for Thunder Bay, Sault Ste Marie, Windsor and Hamilton. For the period 1990 to 2001, the highest composite annual means were recorded in Windsor (1.0 ppb) and Hamilton (0.9 ppb). As illustrated in Figure 5.19, Sudbury recorded the 2nd lowest composite mean (0.3 ppb)

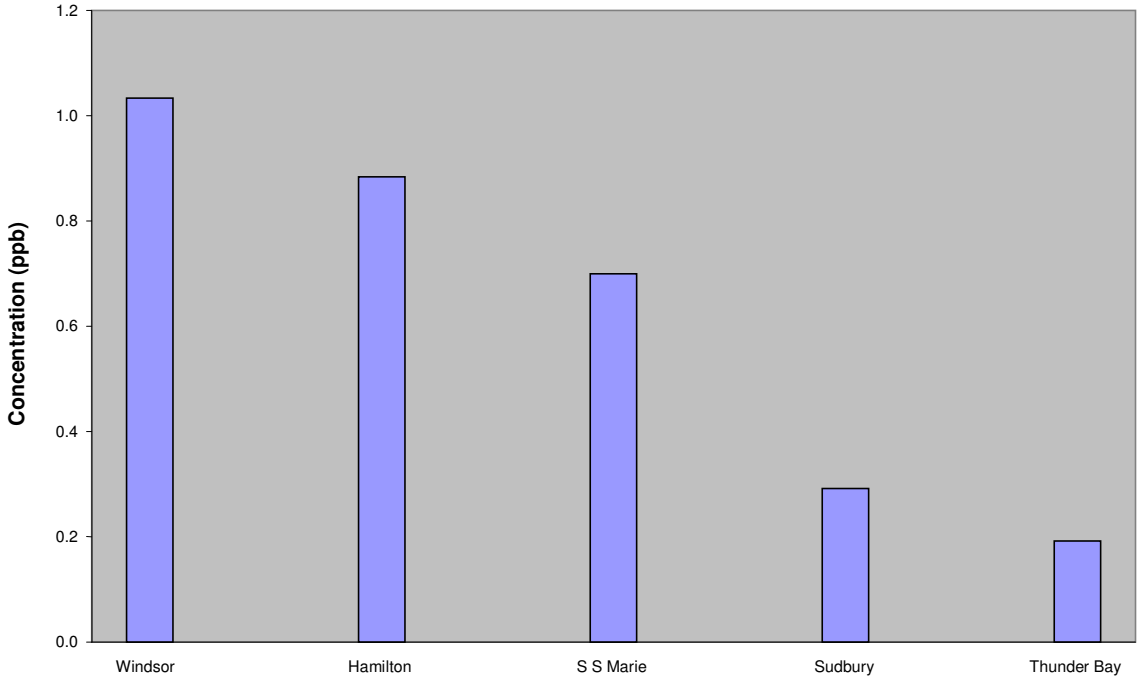


Figure 5.19: Mean TRS Concentrations in Selected Cities (1990-2001)

behind Thunder Bay (0.2 ppb). Windsor recorded the largest number (86) of exceedances of the 1-hour criterion, followed by Hamilton and Sault Ste Marie (12 each). Thunder Bay recorded 2 exceedances. As stated earlier, the criterion was never exceeded in Sudbury.

5.5 Ground-Level Ozone (O_3)

Monitoring Program

Monitoring of ground-level ozone in Sudbury was performed at the Ash Street site from 1975 to 1987, and at the Science North location starting in 1984. Due to instrumentation problems, Science North recorded its first full year of valid data in 1987.

Results

Long Term Trends

Annual mean concentrations at the Ash Street site ranged from 13.3 to 22.3 ppb with an overall composite mean of 16.8 ppb, and had no discernible trend (Figure 5.20). At the Science North location, the means ranged from 25.4 to 30.7 ppb with a composite mean of 27.9 ppb, and again revealing no discernible trend (Figure 5.20).

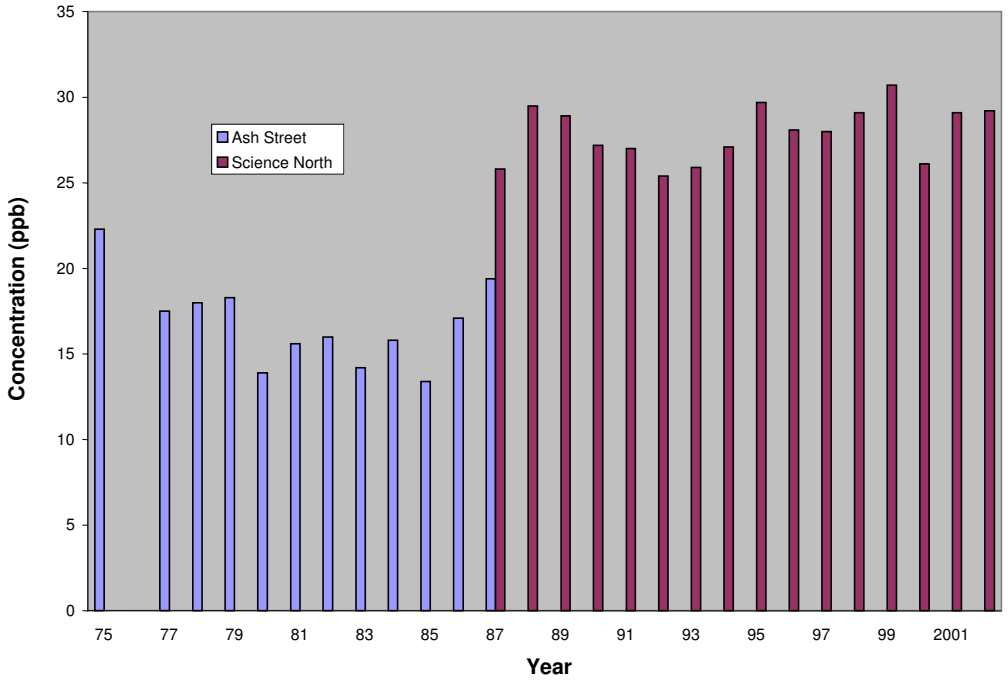


Figure 5.20: Mean Ozone Concentrations in Sudbury (1975-2002)

In 1987, the only common year of available data from both locations, the annual at the Science North site was 6.4 ppb higher. Variations in O_3 levels across an urban centre typically result from localized effects near the monitoring stations such as scavenging of O_3 by local NO_x emissions. The highest 1-hour value recorded at the Ash Street site was 118 ppb (1978), considerably higher than the 1-hour AAQC of 80 ppb. That year, the

AAQC was exceeded for 44 hours. At the Science North site, the highest 1-hour value was 117 ppb (1985) and 1988 was the worst year for AAQC exceedances with 91 hours greater than 80 ppb. As shown in Figure 5.21, the frequency of ozone concentrations above 80 ppb was quite variable from year-to-year as it is strongly dependent on weather conditions.

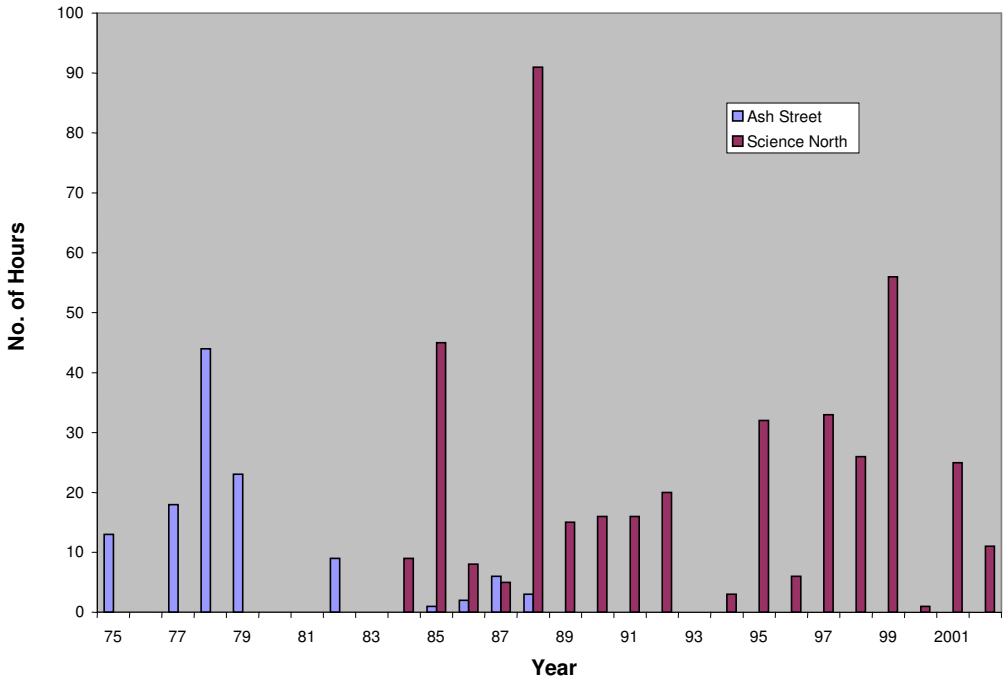


Figure 5.21: Frequency of Exceedance of the 1-Hour Ozone AAQC in Sudbury (1975-2002)

Comparison With Other Cities in Ontario

As shown in Figure 5.22, Sudbury recorded the highest composite mean (27.9 ppb) for the period 1990 to 2002 closely followed by North Bay (25.9 ppb) and Sault Ste Marie (23.7 ppb). Downtown Toronto recorded the lowest value (17.4 ppb). On a province-wide basis, annual mean ozone concentrations in many southern Ontario cities have been shown to be consistently lower than those in northern Ontario cities, specifically during the cooler seasons (1). During the summer, the ozone monthly means in most southern Ontario cities are equal to or greater than the monthly means in northern Ontario cities by about 5 ppb (1). In spite of the typically higher influx of ozone and its precursors into southern Ontario from U.S. sources, the greater destruction of ozone by nitrogen oxides, substantially present in the larger urban areas, explains the lower ozone concentrations in southern Ontario cities. On the other hand, the frequency of 1-hour ozone exceedances and the magnitude of the annual 1-hour maximum ozone concentrations are typically greater in the south, notably in rural areas.

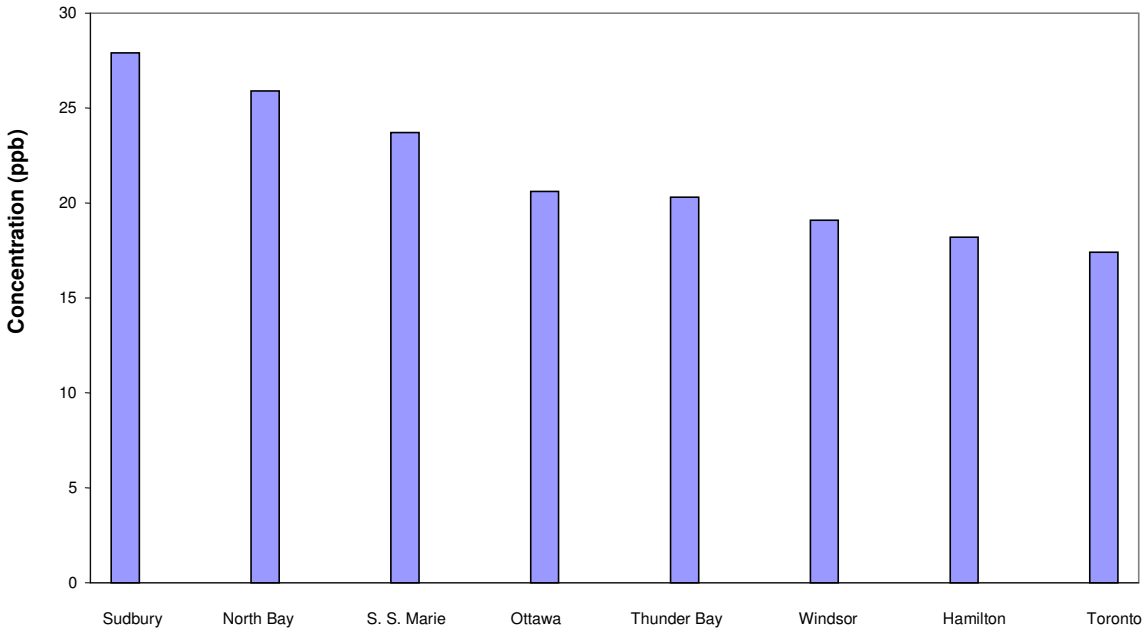


Figure 5.22: Mean Ozone Concentrations in Selected Cities (1990-2202)

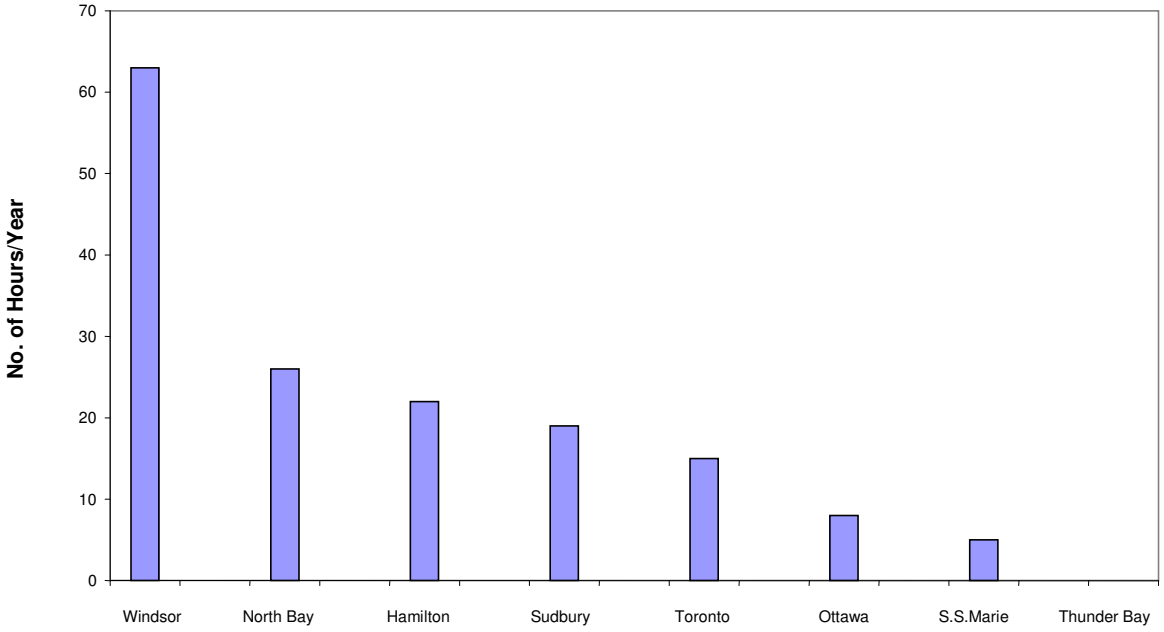


Figure 5.23: Frequency of Exceedance of the 1-Hour Ozone AAQC in Selected Cities (1990-2002)

Figure 5.23 shows that during the 13-year period covered, Windsor recorded an average of over 60 hours per year with ozone concentrations greater than 80 ppb. Thunder Bay did not record any hours over that value. Sudbury recorded an average of 19 hours per year above the 1-hour criterion, ahead of Toronto, Ottawa, Sault Ste Marie, and closely behind Hamilton. It should be noted that the city of North Bay recorded an average of 26 hours per year above the 1-hour ozone criterion. Although the specific reason for the relatively high frequency of exceedance of the criterion in Sudbury and North Bay has not been determined with certainty, ozone-laden air masses arriving from the U.S. on the eastern shores of Lake Huron, which travel south of Sault Ste Marie and north of Toronto, and the lower ozone destruction capabilities in Sudbury and North Bay by local NO_x emissions could explain this phenomenon.

Table 5.2 summarizes the range of ozone 1-hour maximum concentrations for selected cities in the province. Downtown Windsor recorded the highest averages followed by Hamilton, Sudbury and North Bay. Thunder Bay recorded the lowest.

Location	**Maximum 1 hr (ppb)**	**Average 1 hr (ppb)**	**Minimum 1 hr (ppb)**
Windsor	139	111	102
Hamilton	117	96	82
Sudbury	104	96	77
North Bay	108	95	67
Toronto	136	92	41
Ottawa	99	87	69
Sault Ste Marie	98	87	77
Thunder Bay	79	69	62

Table 5.2: Range of Maximum 1-Hour Ozone Concentrations in Selected Cities (1990 to 2002)

These results show that Sudbury and North Bay are, on average, exposed to some of the highest 1-hour ozone maximum concentrations recorded in the urban areas of the

province. Moderate to light vegetation injury symptoms, typical of those caused by exposure to ozone, have been observed in the Sudbury area in the late 1970s following elevated ozone episodes in the early part of growing seasons. The most severe injury symptoms were observed on sweet corn and grape and to a lesser degree on potato, tomato, onion, bean, and Manitoba maple (18). However, the extent of vegetation injury was substantially below that encountered in southern Ontario where injury to cash crops is typically much more significant (21).

5.6 Particulate Matter

5.6.1 Soiling Index

Monitoring Program

During the 1970s and 1980s soiling index, also known as coefficient of haze (COH), was measured at the following locations in the city of Greater Sudbury: Lisgar Street (1974-1980), New Sudbury (1976-1988), Ash Street (1970-1987), Coniston (1975-1988) and Science North (1984-2002). At all locations, with the exception of Lisgar Street, these measurements were part of the Air Pollution Index monitoring system. Since late 1989, soiling index measurements have been performed at the Science North location only, and were suspended there as well in 2002 as part of an initiative to modernize the provincial air quality monitoring network with state-of-the art fine particulate monitoring technology.

Results

Long Term Trends

Since the Ash Street and Science North sites collected the largest databases and the results are quite similar to those from the other sites, only the data collected at these two sites will be discussed here. Both sites recorded annual mean concentrations within the annual criterion of 0.5 COH unit, with values ranging from 0.1 to 0.3 COH unit. There was no discernible temporal trend. The 24-hour criterion (1.0 COH unit) was marginally exceeded only once (1971) at the Ash Street site and on five occasions in the 1980s at the Science North site.

Comparison With Other Cities In Ontario (1990-2002)

Hamilton and Toronto recorded the highest (~ 0.4 COH) 13-year composite mean soiling index values, well above those recorded in the other cities (Figure 5.24). Sudbury recorded the lowest mean (0.14 COH), slightly lower than the means for Thunder Bay and Ottawa. Downtown Hamilton recorded the most number of exceedances of the 24-

hour criterion with 121, followed by Toronto with 28. During this 13-year period, Sudbury was the only city to record no exceedances.

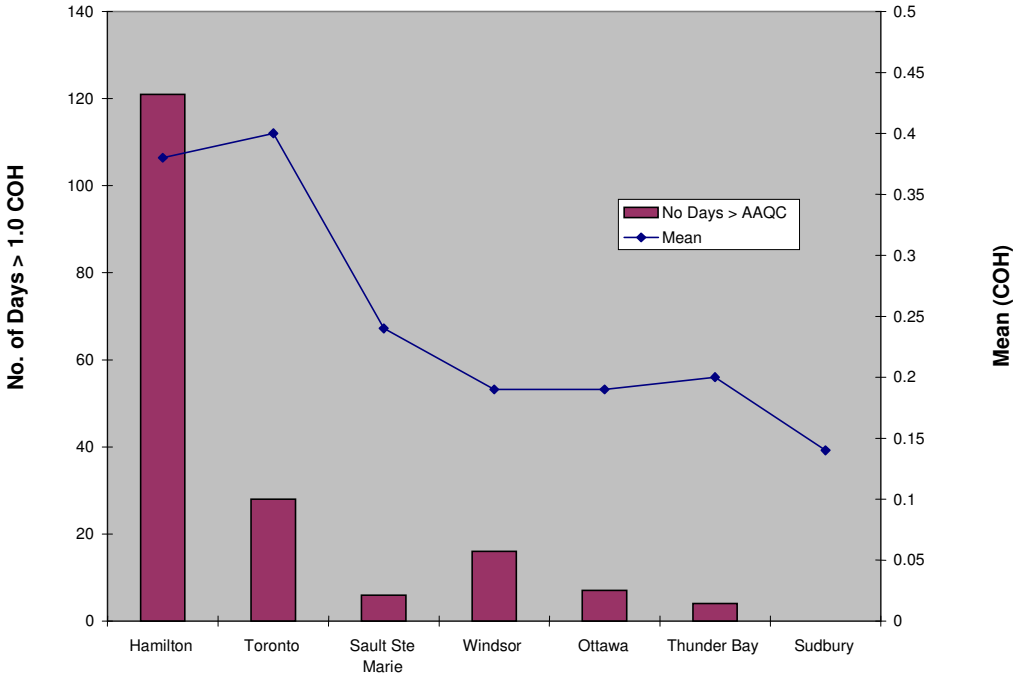


Figure 5.24: Mean Soiling Index and Frequency of Exceedance of the 24-Hour AAQC in Selected Cities (1990-2002)

5.6.2 Total Suspended Particulate (TSP)

Monitoring Program

Monitoring of TSP was performed in the Sudbury area at a number of locations, starting in 1970. The stations with the longest data record are Ash Street (1970 to 1990), Lisgar Street (1974 to 1995), Copper Cliff (1977 to 1995) and Falconbridge (1977 to 1983, 1985). A TSP sampler also operated in Coniston in 1975 and 1976. The Copper Cliff and Falconbridge surveys were established to determine the levels of TSP in these town sites located near the smelters. Summer surveys were also conducted from 1972 to 1975 at five rural sites (Burwash, Morgan, Lake Penage, Rayside, Skead) to assess possible impacts on the levels of total suspended particulate matter in these outlying areas with the commissioning of the tall stack at the Copper Cliff smelter.

Results

The summer surveys showed that TSP levels in the outlying areas of the Sudbury basin were usually well within the provincial criteria, and either remained essentially the same and/or decreased after 1972 (7). Very few exceedances of the 24-hour criterion (120 $\mu g/m^3$), were recorded and these were attributed to local sources such as road dust and agricultural activities. The brief survey undertaken at Coniston recorded annual means of 36 $\mu g/m^3$ and 40 $\mu g/m^3$ in 1975 and 1976 respectively, both well below the annual criterion of 60 $\mu g/m^3$ (geometric mean).

Long Term Trends

The annual mean TSP concentrations at both the Copper Cliff and Falconbridge town site sampling locations were below the annual provincial criterion for the entire survey period and decreased appreciably over time to about half the criterion (Figure 5.25). At the Falconbridge site, 5% of the TSP samples exceeded the 24-hour criterion, whereas at the Copper Cliff site only 2% of the samples were above the criterion. These exceedances were attributed to wind-blown soil and tailings dust under freeze-dry conditions in late fall or early spring.

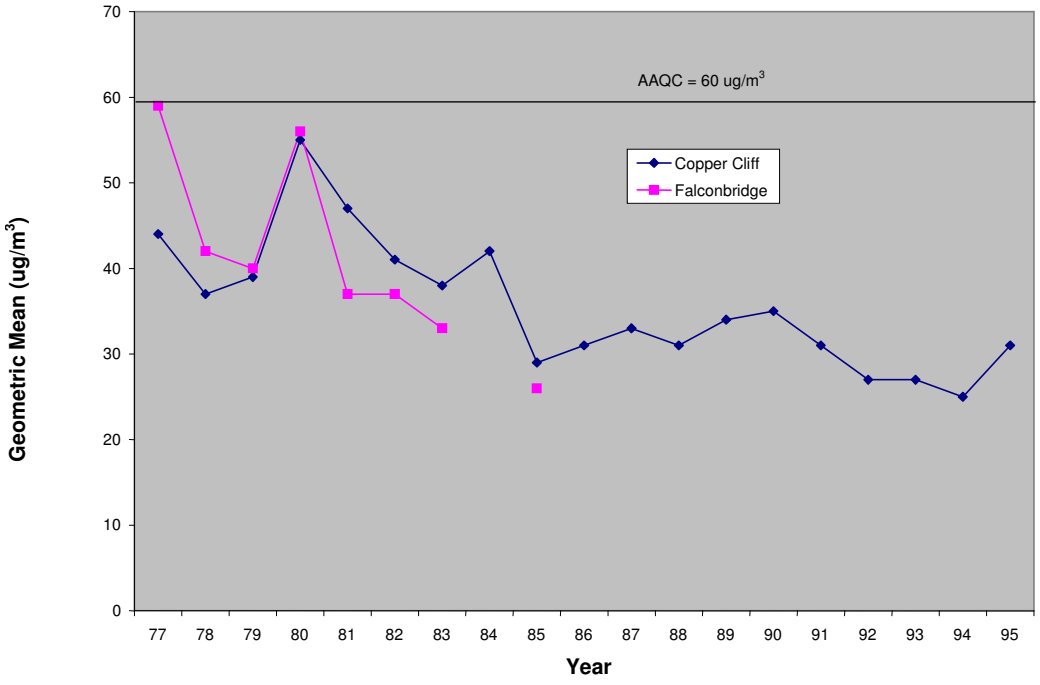


Figure 5.25: Mean TSP Concentrations in Copper Cliff and in Falconbridge (1977-1995)

Temporal trends and mean concentrations very similar to those observed at these industrial sites were recorded at the downtown Sudbury sites (Figure 5.26). Except for the marginal exceedance of the annual criterion at the Lisgar Street location in 1976, the annual means were always within the provincial criterion. The downward trend was essentially identical for both sites, such that by the early to mid-1980s, mean TSP concentrations had fallen in the range of 30 to 40 µg/m^3 from their 50 to 60 µg/m^3 level in the early 1970s. The composite means for the industrial and downtown sites were essentially the same, ranging from 36 to 41 µg/m^3.

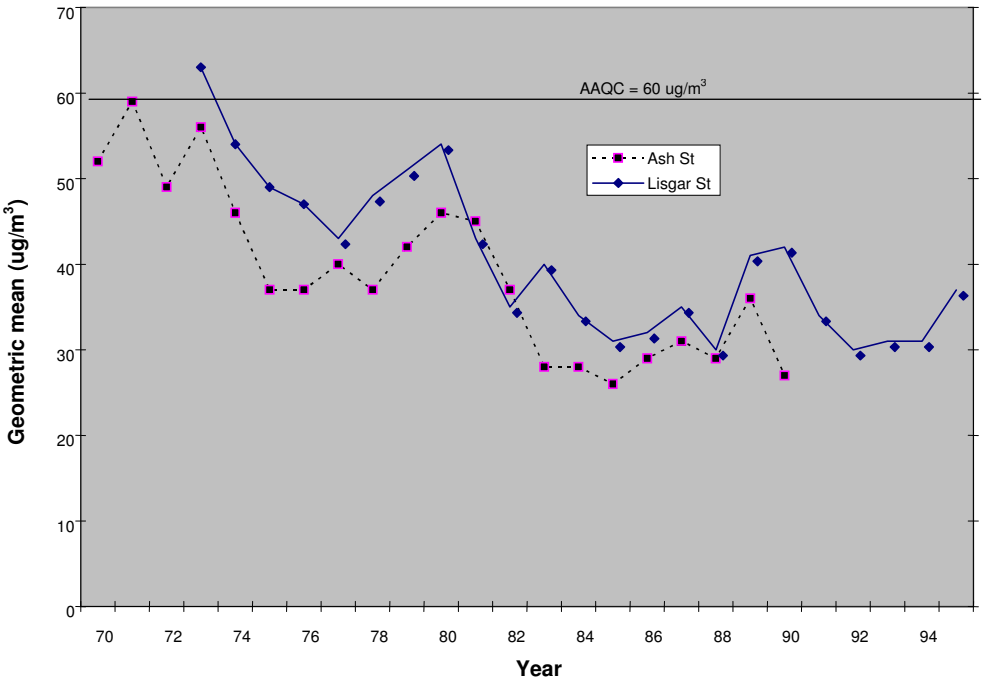


Figure 5.26: Mean TSP Concentrations at Ash Street and at Lisgar Street in Sudbury (1970-1995)

Reductions in particulate emissions from smelting operations and improved management of road dust (from municipal street cleaning operations) and of wind-blown soil and mine tailings (through successful revegetation efforts throughout the Sudbury area) are felt to be largely responsible for the observed downward trends in the levels of TSP.

Comparison With Other Cities In Ontario (1990-1995)

Composite annual mean TSP levels at selected cities in the province are shown in Figure 5.27 for the period 1990 to 1995 (since 1996 many of the TSP samplers were either terminated or replaced with PM_{10} and/or $PM_{2.5}$ samplers). The southern cities (Hamilton, Windsor and Toronto) recorded the highest means, ranging from 52 to 58 µg/m^3.

Sudbury (Lisgar Street), Sault Ste Marie and Thunder Bay recorded TSP composite means approximately 40% lower than the southern Ontario cities. The levels of TSP in the northern cities were essentially identical, varying from 32 to 34 µg/m^3.

Sudbury was the only city to not exceed the 24-hour AAQC for TSP. Hamilton had the most exceedances (8% of the samples), whereas Thunder Bay recorded the 2nd lowest (1%) after Sudbury.

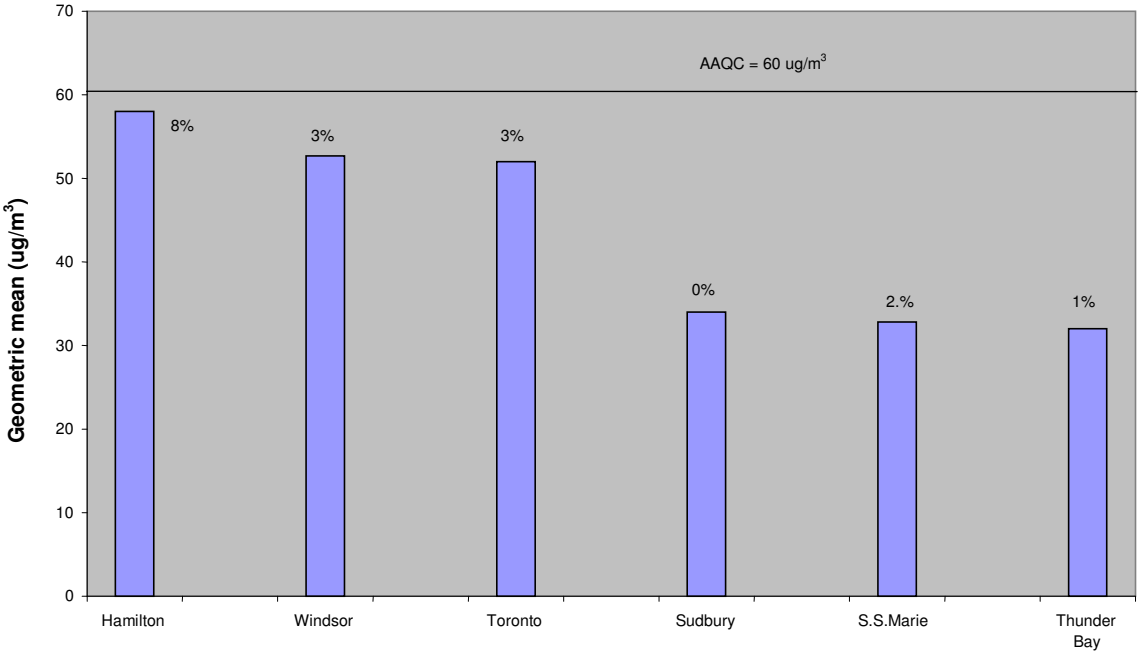


Figure 5.27: Mean TSP Concentrations and Exceedance Frequency of the 24-Hour AAQC in Selected Cities (1990-1995)

5.6.3 Inhalable Particulate (PM_{10})

Monitoring Program and Results

A PM_{10} sampler was first commissioned in Sudbury at the Federal building on Lisgar Street in late 1991. Sampling was suspended for much of 1998 and all of 1999 due to extensive building renovations. A second inhalable particulate sampler was installed in Copper Cliff in the summer of 1996.

Trends

From 1992 to 1995, the annual geometric mean PM_{10} concentrations at the Lisgar Street location varied from 14 to 21 µg/m^3 (Figure 5.28). Since 1996, the means decreased and have remained fairly steady in the range of 11 to 13 µg/m^3. In Copper Cliff, the annual means have also been steady and essentially identical to those recorded at the downtown Lisgar Street location, varying from 12 to 14 µg/m^3. The interim 24-hour AAQC for inhalable particulate (50 µg/m^3) was marginally exceeded for 2 of 476 samples collected at Lisgar Street and for 6 of 315 samples collected at Copper Cliff.

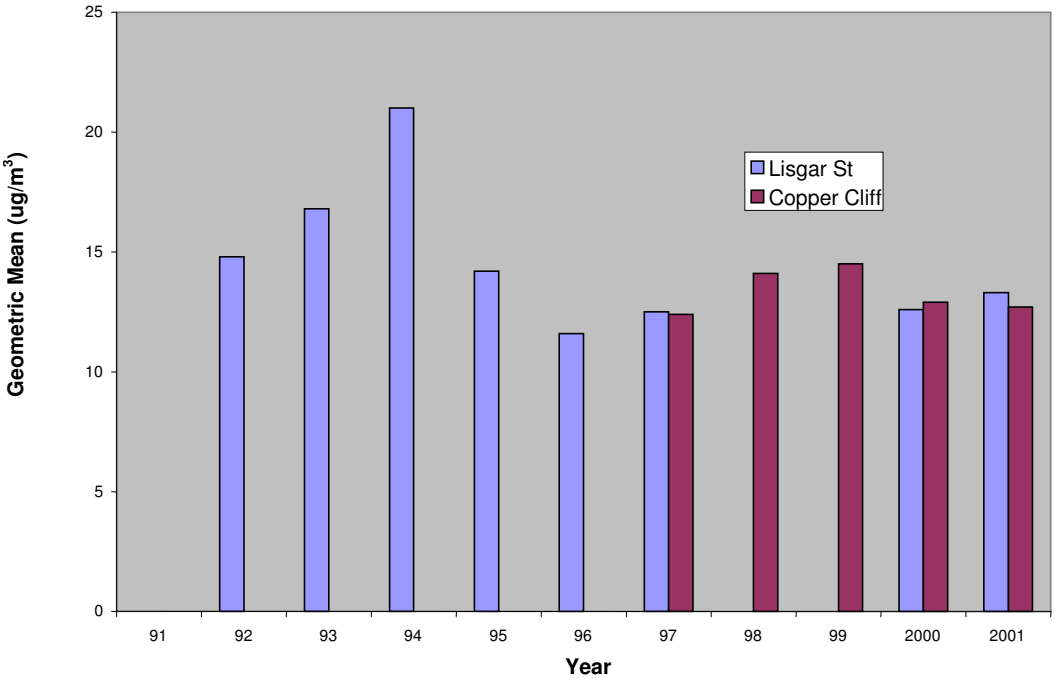


Figure 5.28: Mean Inhalable (PM_{10}) Concentrations at Lisgar Street and Copper Cliff (1992-2001)

Comparison With Other Cities In Ontario (1990-2001)

Of the cities compared, Windsor recorded the highest PM_{10} annual composite mean (24.5 µg/m^3), followed closely by Hamilton and Toronto (Figure 5.29). Sudbury recorded the lowest annual composite mean (14.5 µg/m^3), which was slightly lower than the means recorded in Thunder Bay (15.1µg/m^3) and in Sault Ste Marie (16.6 µg/m^3). Overall, the levels of inhalable particulate were approximately 35% lower in the northern cities. The exceedance rates of the interim 24-hour PM_{10} criterion for samples collected in Windsor, Hamilton and Toronto varied from 4.6% to 7.6%. The cities in northern Ontario recorded exceedance rates ranging from 1% to 3% of the samples collected.

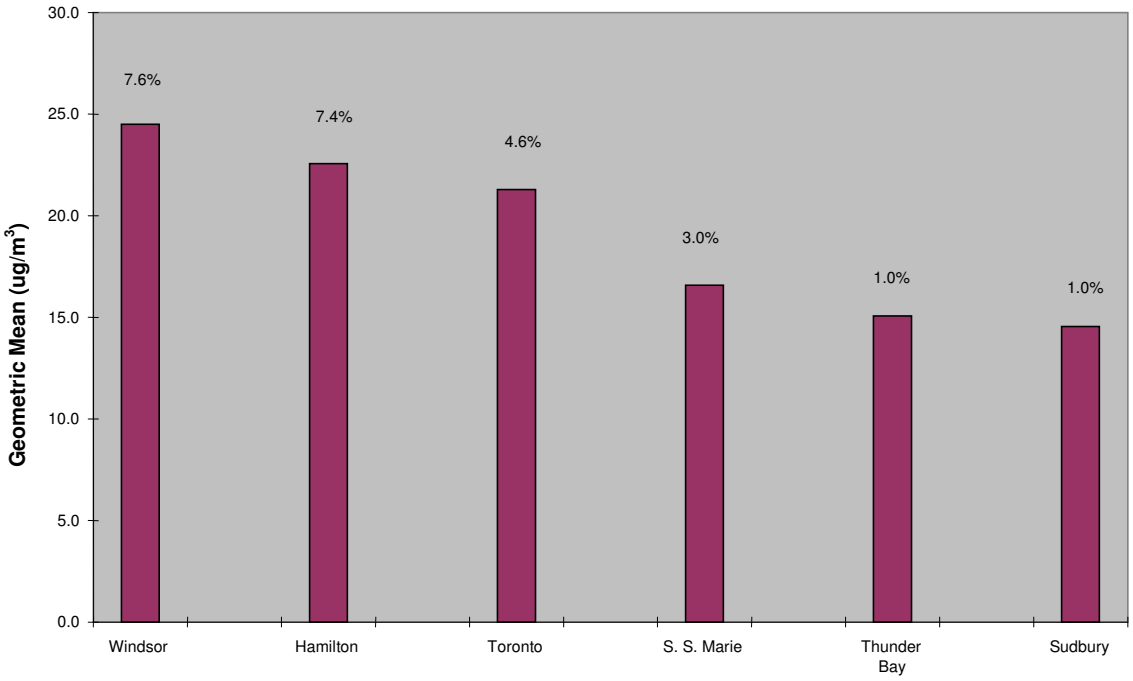


Figure 5.29: Mean Inhalable (PM_{10}) Concentrations and Exceedance Frequency of the 24-Hour AAQC (1990-2001)

5.7 Air Pollution Index (API)

Monitoring Program and Results

Air Pollution Index stations were first commissioned in the Sudbury area in 1971 at the Ash Street location and in a small settlement known as Happy Valley, located immediately south of the Falconbridge town site and smelter. API determinations were discontinued in 1987 at the Ash Street site. The Happy Valley API station was shut down in 1975 with the closure of the settlement, and relocated to Coniston. A third API monitoring station operated in the New Sudbury area of the City of Greater Sudbury from 1976 to 1988.

Trends

During the early 1970s, a number of API values in the moderate (API > 32) and in the poor (API > 50) to very poor (API > 100) categories were recorded in the Sudbury area, as shown in Table 5.3.

Year	Location	Number of Events > 32	> 50	Maximum Index
1971	Sudbury	26	3	87
	Happy Valley	20	7	64
1972	Sudbury	7	1	79
	Happy Valley	20	11	139
1973	Sudbury	Nil	Nil	26
	Happy Valley	19	10	94
1974	Sudbury	1	Nil	32
	Happy Valley	24	13	116

Table 5.3: API Events Recorded in the Sudbury Area from 1971 to 1974

Since the levels of suspended particulate in the Sudbury area were low, these API events resulted mainly from elevated 24-hour SO_2 concentrations. API events resulting in very poor air quality required curtailment of operations of the contributing source(s) until the atmospheric conditions were acceptable for proper dispersion of smelter emissions.

The commissioning of the tall stack at the Copper Cliff smelter in 1972 resulted in an immediate improvement in the frequency of API events recorded in Sudbury, as shown above. On the other hand, API events at Happy Valley continued to reflect poor to very poor air quality. This was the only location in the province which ever recorded API values greater than 100 (1972 and 1974).

Since the mid-1970s, the occurrence of API events in the Sudbury area have been very isolated due to reduced smelter emissions and the implementation of supplementary emission controls to curtail, on an hourly basis, smelter SO_2 emissions during periods with adverse atmospheric dispersion conditions. Since 1975, a total of 8 API events have been recorded, most of them marginally over the moderate index value of 32. The last event to be recorded in Sudbury occurred in 1983.

Comparison With Other Cities in Ontario

With the launching of the Air Quality Index system in 1988, which effectively superseded the Air Pollution Index system, the period 1975 to 1987 is an appropriate one for the comparison with other cities in Ontario. During that period, Hamilton, Toronto and Windsor recorded 101, 22 and 4 API events respectively. The majority of the events in these cities resulted from sustained elevated concentrations of suspended particulate in combination with moderate concentrations of SO_2. In the City of Greater Sudbury, 4 API

events were recorded over the same period, due to elevated concentrations of SO_2, while none were recorded in Thunder Bay and Sault Ste Marie.

5.8 Air Quality Index (AQI)

Monitoring Program

An AQI station was established in the City of Greater Sudbury at the Science North site in the fall of 1988. The station was equipped with analyzers to measure the concentrations of the full suite of AQI parameters, namely: ground-level O_3, SP (soiling index), TRS, NO_x, CO, and SO_2.

Results

From 1989 to 2001, the AQI described the air quality in the City of Greater Sudbury as being very good (AQI from 0 to 15) to good (AQI from 16 to 31) 94.3% of the time. It also indicated that the air quality was never in the very poor range (AQI > 99). The air quality was determined to be moderate to poor (AQI from 32 to 99) for 5.4% of the time, principally due to elevated ground-level ozone, and to a much lesser extent due to SO_2, and SP (soiling index), as shown in the Table 5.4. The air quality was determined to be poor (AQI from 50 to 99) for 292 hours (0.3% of the time), again principally due to ground-level ozone (85%) and sulphur dioxide (15%).

Trends

The temporal trend of recorded AQI values greater than 31 shows considerable year-to-year variability (Figure 5.30). The dominant influence of ground-level ozone, on a year-to-year basis, is obvious. The low years (1993 and 2000) coincide with 'low ozone years' (see Figure 5.20 and Figure 5.21).

AQI Contaminant	Parameter Responsible For Moderate to Poor Air Quality	Parameter Responsible For Poor Air Quality
O_3	97.5%	85%
SO_2	1.6%	15%
SP (soiling index)	0.3%	0%

Table 5.4: AQI Contaminants Responsible for Moderate to Poor Air Quality in Sudbury from 1989 to 2001

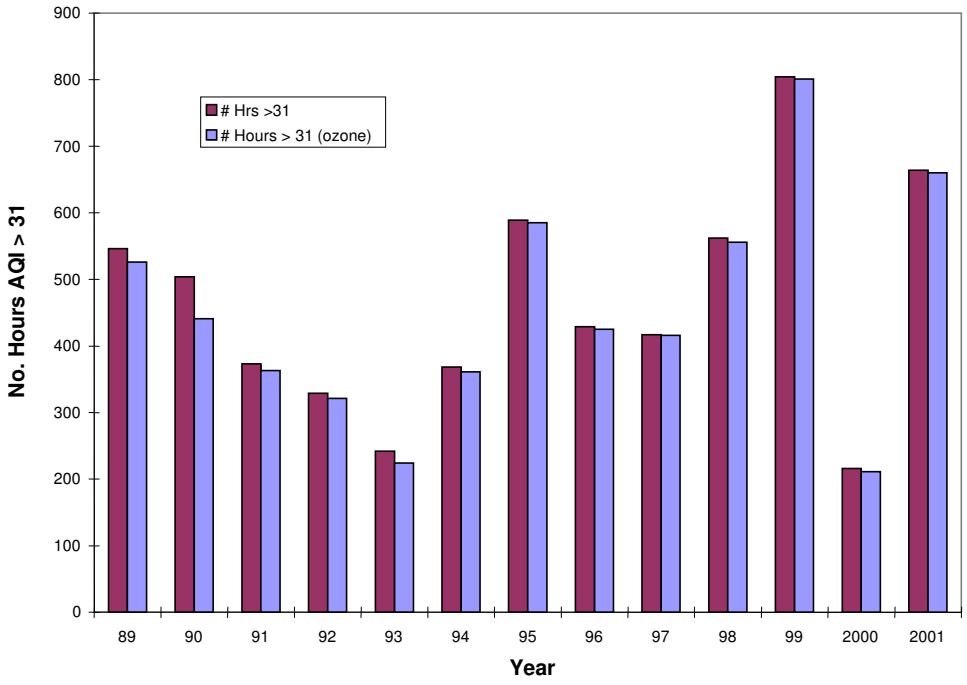


Figure 5.30: Number of Hours with AQI > 31 in Sudbury (1989-2001)

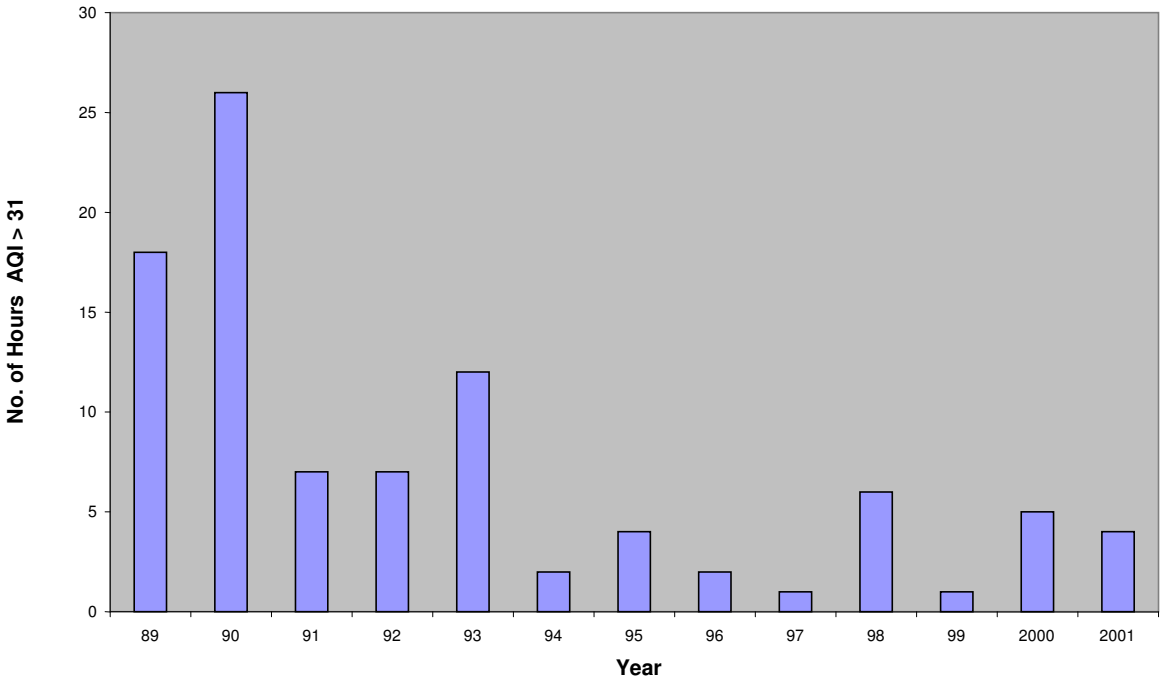


Figure 5.31: Number of Hours AQI > 31 in Sudbury Due to SO_2

The influence of SO_2 on the frequency of hours with AQI >31, corresponding to an hourly SO_2 concentration of 0.25 ppm (250 ppb) or greater, is shown above in Figure 5.31. Prior to 1994, this pollutant was responsible for an average of 14 hours/year of recorded AQI values > 31. Since 1994, this average has decreased to 3 hours/year. This trend is very similar to the trend shown earlier in Figure 5.11 for the frequency of exceedance of the 1-hour SO_2 criterion at the Science North site.

As indicated earlier, the influence of suspended particulate matter, determined from soiling index measurements, on air quality in the moderate to poor range has been minimal. From 1989 to 1994, suspended particulate matter accounted for an average of only 2 hours/year of air quality in that range, and for none since 1997.

Comparison With Other Cities in Ontario

As in Sudbury, in any given year the air quality in major urban centres of Ontario has historically been very good to good the majority of the time, i.e. in the low to mid-90% range. Hence moderate to poor air quality has typically occurred less than about 6% to 7% of the time. The composite mean frequency of occurrence of moderate to poor air quality in selected cities of Ontario, expressed as a percentage of the number of hours monitored at each location, is shown in Figure 5.32. Windsor recorded the highest frequency (6%), followed by Sudbury (5.4%) and Hamilton (5.2%).

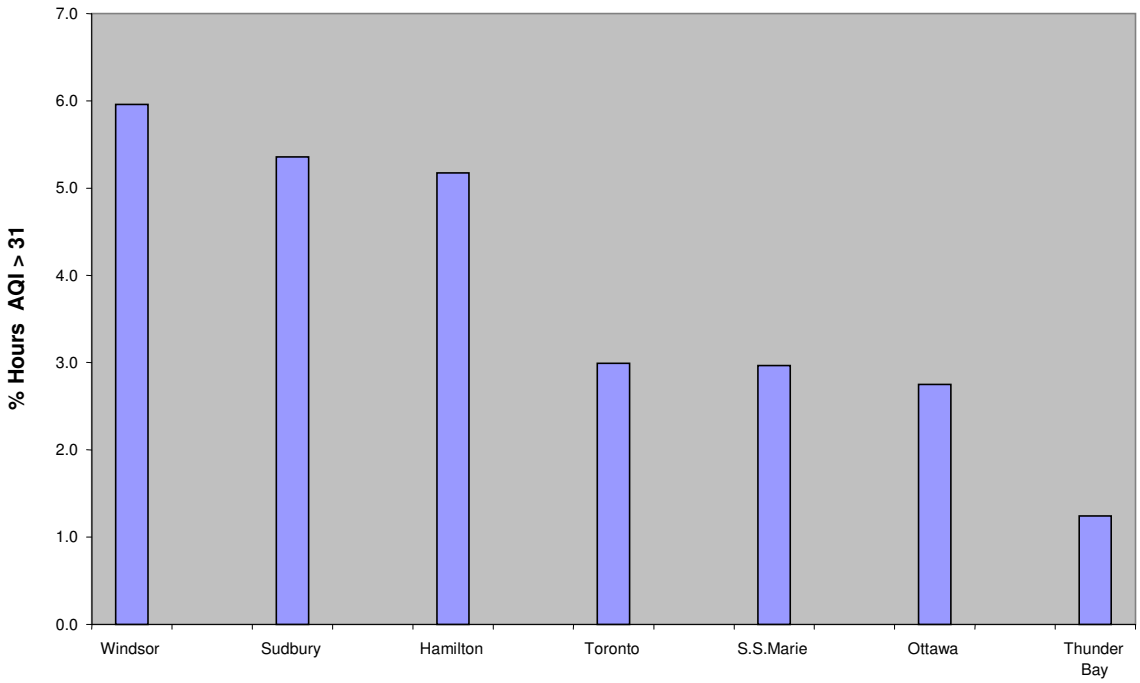


Figure 5.32: Percentage No. of Hours with AQI > 31 in Selected Cities (1989-2001)

The lower grouping was comprised of Toronto, Sault Ste Marie and Ottawa (all at about 3%), and Thunder Bay, the lowest at 1.2%. During the period 1989 to 2001, the air quality in the selected cities was never in the poor category.

At all locations, ground-level ozone was the pollutant largely responsible (upper 90% range) for AQI values >31. Suspended particulate matter, expressed as soiling index, contributed to AQI values >31 mostly in Hamilton, Sault Ste Marie, and Windsor, whereas the contribution from TRS was greatest in Hamilton, Sault Ste Marie and Thunder Bay. During this 13-year period, Sudbury was the only city to record moderate to poor air quality due to SO_2. Carbon monoxide was responsible for only 6 hours of moderate to poor air quality (Hamilton), while nitrogen dioxide was not responsible for AQI values >31 at any location during that period.

Summary

Almost fifty years after the establishment of the first network of sulphur dioxide monitoring stations, there has been not only significant but continued improvement in air quality in the Sudbury area.

The most notable improvements have been realized with sulphur dioxide. The combination of greatly reduced smelter emissions, improved dispersion and supplementary emission controls has been responsible for significant decreases in the annual concentration, in the intensity and duration of fumigation events and in the frequency of exceedance of the ambient air quality criteria for sulphur dioxide. The dramatic improvements have enabled the Sudbury area to be transformed from its infamous barren landscape to its 're-greened' environment where vegetation injury is an exception rather than the rule. In spite of these achievements, it should be noted that the occurrence of short-term fumigation events typically from April to September, although greatly reduced in number and intensity, remains an issue. Further improvements in this area are expected over time as government and industry work together to achieve further reductions.

The levels of carbon monoxide and oxides of nitrogen, typically associated with vehicle traffic emissions, were usually quite low and well within the provincial criteria for acceptable air quality. A slight downward temporal trend was evident for nitrogen dioxide.

With no industrial point source of emissions in the City of Greater Sudbury, the concentrations of total reduced sulphur compounds were very low throughout the study period and well below the criterion.

During the study period, the levels of ground-level ozone in the City of Greater Sudbury were observed to be generally elevated and variable from year-to-year, with no noticeable temporal trend. Hourly concentrations exceeded the provincial criterion in most years during smog events which from time to time imported ozone into central Ontario.

Measurements of suspended particulate (soiling index), total suspended particulate and inhalable particulate revealed that the City of Greater Sudbury had low levels of particulates with very few exceedances of the provincial criteria. Measurements of respirable particulate ($PM_{2.5}$) were not available for the study period.

Except for the early 1970s, when a number of air pollution index events resulted in poor and very poor air quality requiring curtailment of smelter emissions, API events since the mid-1970s have been very isolated and much lower in intensity. The last event on record dates back to 1983.

Based on results of the Air Quality Index, overall air quality in the City of Greater Sudbury during the study period was very good to good over 94% of the time. Instances of moderate to poor air quality resulted mostly from elevated ozone levels and, to a much

lesser extent, from elevated concentrations of sulphur dioxide. The contribution of suspended particulates was minimal.

Provincial Perspective

In comparison to other selected cities in Ontario, the City of Greater Sudbury ranked as one of the best for a number of air pollutants during the period of study, mostly from 1990 to 2002. The results of this analysis are summarized in Table 6.1.

Air Quality Parameter	**Sudbury Ranking From Selected Cities**
Sulphur Dioxide	3rd highest composite mean; the only city to record exceedances of the AAQCs
Nitrogen Dioxide	Lowest composite mean; AAQCs not exceeded
Carbon Monoxide	2nd lowest mean (2001); lowest composite 1-hour maxima; AAQCs not exceeded
Total Reduced Sulphur	2nd lowest composite mean; AAQC not exceeded
Ground-level ozone AAQC	Highest composite annual mean; 4th highest for exceedances
Suspended Particulate (soiling index)	Lowest composite mean; lowest number of AAQC exceedances
Total Suspended Particulate	3rd lowest composite mean; AAQCs not exceeded
Inhalable Particulate	Lowest composite mean; lowest number of AAQC exceedances
Air Pollution Index	3rd lowest frequency of API values in the moderate to poor range
Air Quality Index	2nd highest frequency of AQI values in the moderate to poor range

Table 6.1: Ranking of Sudbury's Air Quality from Selected Ontario Cities

For SO_2, the City of Greater Sudbury had the 3rd highest composite mean of the seven cities selected for comparison. It was the only city, however, to record exceedances of the AAQCs, specifically the 1-hour criterion. For NO_2 and CO, the City of Greater Sudbury recorded the lowest and 2nd lowest levels respectively and their AAQCs were not exceeded. Sudbury ranked 2nd lowest for the TRS composite mean and the 1-hour AAQC was not exceeded.

For ground-level ozone, Sudbury had the highest composite annual mean and ranked 4th highest for exceedances of the 1-hour criterion. Long range transport of ozone into central Ontario from U. S. source regions, in combination with the low ozone destruction capacity in the Sudbury area from local NO_x emissions, is felt to be responsible for this phenomenon.

With respect to particulate matter, the City of Greater Sudbury recorded the lowest composite means for suspended particulate (soiling index) and inhalable particulate. It also recorded the lowest number of exceedances of the soiling index and inhalable particulate criteria. The city had the 3rd lowest composite mean for TSP and the TSP 24-hour and annual criteria were not exceeded.

For the Air Pollution Index, which is based on the combination of SO_2 with suspended particulate, Sudbury ranked 3rd lowest for moderate to poor air quality. With respect to the Air Quality Index, which is a better measure of overall air quality, the city recorded the 2nd highest frequency of air quality in the moderate to poor range. This result is largely due to ground-level ozone and, to a much lesser extent, due to SO_2.

Glossary

Acid aerosol	Dispersion of fine particles (smoke) or fine droplets (fog) in air which are acidic. Examples include fine particulate sulphate compounds and sulphuric acid mists.
Acidic deposition	Refers to deposition of a variety of acidic pollutants (acids or acid-forming substances such as sulphates and nitrates) on biota or land or in waters of the Earth's surface. Deposition occurs in the dry form (fine particulate) or in the wet form (rain/snow).
Air Quality Index	Real-time information system that provides the public with an indication of air quality in cities and towns across Ontario.
AQI station	Continuous monitoring station used to inform the public of air quality levels on a real-time basis; station reports on criteria pollutants.
Air Pollution Index	Basis of Ontario's alert and control system to warn of deteriorating air quality; derived from 24-hour running averages of sulphur dioxide and suspended particles. Since 1988, it is a sub-index of the more comprehensive Air Quality Index.
Air Pollution Advisory	Public is advised when elevated pollution levels are forecast due to sulphur dioxide in combination with suspended particulates.
Airshed	A geographical region of influence, or spatial extent of the air pollution burden.
Ambient air	Outdoor or open air.
Continuous pollutant	Pollutant for which a continuous record exists; effectively, pollutants that have hourly data (maximum 8,760 values per year except leap year – i.e. 2000 where maximum values for the year are 8,784).
Continuous station	Where pollutants are measured on a real-time basis and data determined hourly (for example ozone, sulphur dioxide).

Criterion	Maximum concentration or level (based on potential effects) of contaminant that is desirable or considered acceptable in ambient air.
Daily pollutant	Pollutant with a 24-hour or daily value (maximum 365 values per year), such as Total Suspended Particulate.
Data telemetry system	An automated data collection and transmission system which sends environmental (or other) data to a central computer for storage, analysis and reporting. The data transfer can be done within minutes (real-time) after its detection by the analyzer at the monitoring station.
Detection limit	Minimum concentration of a contaminant that can be determined.
Exceedance	Violation of the pollutant levels permitted by environmental protection criteria.
Fine Particulate Matter	Particles smaller than about 2.5 microns in diameter, which arise mainly from condensation of hot vapors and chemically driven gas-to-particle conversion processes; also referred to as $PM_{2.5}$. These are fine enough to penetrate deep into the lungs and have the greatest effects on health. Also known as respirable particulate matter.
Fossil fuels	Natural gas, petroleum, coal and any form of solid, liquid or gaseous fuel derived from such materials for the purpose of generating heat.
Geometric mean	Statistic of a data set calculated by taking the n^{th} root of the product of all (n) values in a data set. Provides a better indication than the arithmetic mean of the central tendency for a small data set with extreme values. Typically used when data set is log normally distributed.
Global warming	Long-term rise in the average temperature of the Earth; principally due to an increase in the buildup of carbon dioxide and other green house gases.
Ground-level ozone	Colorless gas formed from chemical reactions between nitrogen oxides and hydrocarbons in the presence of sunlight near the Earth's surface.

Inhalable particles — Represent up to 60 per cent of the total suspended particulate matter; composed of both coarse (diameter 2.6 to 10.0 microns) and fine (diameter < 2.5 microns) particles; also referred to as PM_{10}.

Looping plume — Plume released from an elevated stack which is alternately brought down to ground and lifted up due to downdrafts and updrafts in an unstable atmosphere.

Micron — A millionth (10^{-6}) of a meter.

Non-continuous station — Station that measures pollutant concentration on a daily, six-day frequency or monthly cycle (as for total suspended particulate matter).

Nitrates — Compounds containing the radical $(NO_3)^-$. Most are soluble in water and when converted to nitric acid (HNO_3) can acidify sensitive aquatic ecosystems.

Ozone episode day — A day on which widespread (hundreds of kilometers) elevated ozone levels (greater than 80 ppb maximum hourly concentration) occur simultaneously.

Particulate matter — Refers to all airborne finely divided solid or liquid material with an aerodynamic diameter smaller than 100 microns.

Photochemical oxidant — Air pollutants (e.g. ozone) formed by action of sunlight on oxides of nitrogen and VOCs.

Photochemical reaction — Chemical reaction influenced or initiated by light, particularly ultraviolet light.

Photochemical smog — See smog.

Potentially injurious fumigation (SO_2) — A sulphur dioxide fumigation event which, on the basis of its intensity and duration, is sufficient to cause injury to vegetation during the growing season and daylight hours. From many years of field observations in the Sudbury area, injury can occur upon exposure to the following doses of SO_2:

950 ppb for 1 hour
550 ppb for 2 hours
350 ppb for 4 hours
250 ppb for 4 hours

	These events do not always result in injury since other factors such as species sensitivity and environmental conditions (air temperature and humidity, soil/plant moisture, etc…) also influence susceptibility to injury.
Precursor pollutant	Usually a primary pollutant which can be transformed (or enable the transformation) into secondary pollutants.
Primary pollutant	Pollutant emitted directly to the atmosphere.
Respirable particles	Particles smaller than about 2.5 microns in diameter, which arise mainly from condensation of hot vapours and chemically driven gas to particle conversion processes; also referred to as $PM_{2.5}$. These are fine enough to penetrate deeply into the lungs and have the greatest effects on health.
Secondary pollutant	Pollutant formed from other pollutants in the atmosphere.
Smog	A concentration of smoke and fog; colloquial term used for photochemical fog, which includes ozone and other contaminants; tends to be a brownish haze.
Smog advisory	Public is advised when elevated pollution levels are forecast due to ground-level ozone.
Stratosphere	Atmosphere 10 to 40 kilometers above the Earth's surface.
Stratospheric ozone	Ozone formed in the stratosphere from the conversion of oxygen molecules by solar radiation; ozone found there absorbs much ultraviolet radiation and prevents it from reaching the Earth.
Sulphate	A compound containing the sulphate radical $(SO_4)^{-2}$. It is formed from the gradual oxidation of sulphur. When combined with moisture in the air, it is transformed to sulphuric acid (H_2SO_4) which can acidify sensitive aquatic ecosystems when deposited to ground.
Supplementary emission control	A strategy to reduce air emissions on a short-term basis by curtailing production. The strategy relies on weather forecasting to anticipate periods of poor atmospheric dispersion conditions.
Suspended particles	Suspended particulate matter most likely to reach the lungs (diameter less than 25 microns).

Temperature inversion A rise in the air temperature with increasing altitude, usually over a short range of altitudes. Pollutants released under this inversion layer can effectively become trapped and unable to dissipate upwards, resulting in a build-up at ground level.

Wind rose A pictorial representation of surface wind data (direction and speed) collected from a meteorological tower over a number of years which displays the frequency distribution of wind speed classes, usually over sixteen or thirty six compass directions. A seasonal wind rose is very useful for identifying wind patterns during different times of the year. A 10-year (1987 to 1996) wind rose for wind data collected at the 115 metre level on the Frood Road tower in Sudbury is shown in Appendix I.

Abbreviations

AAQC - Ambient Air Quality Criteria (Ontario)

API - Air Pollution Index

AQI - Air Quality Index

AQUIS - Air Quality Information System (Ontario)

CO - Carbon monoxide

COH - Coefficient of haze reported as SP

HNO_3 - Nitric acid

H_2SO_4 - Sulphuric acid

H_2S - Hydrogen sulphide

MOE - Ministry of Environment

NO - Nitric oxide

NO_2 - Nitrogen dioxide

NO_x - Oxides of nitrogen

NPRI - National Pollutant Release Inventory (Canada)

O_3 - Ozone

PIF - Potentially Injurious Fumigation (vegetation exposure to SO_2)

PM_{10} - Inhalable particulate matter (< 10 microns)

$PM_{2.5}$ - Respirable particulate (< 2.5 microns)

POI - Point of Impingement Standard

SO_2 - Sulphur dioxide

SO_3 - Sulphur trioxide

SO_4 - Sulphate

SP - Suspended particles

TPM - Total particulate matter

TRS - Total reduced sulphur

TSP - Total suspended particulate

VOCs - Volatile organic compounds

kt - kilotonnes

nm - nanometres

$\mu g/m^3$ - micrograms (of pollutant) per cubic metre (of air)

ppb - parts (of pollutant) per billion (parts of air)

ppm - parts (of pollutant) per million (parts of air)

APPENDIX A

Method for Measuring Sulphur Dioxide (SO_2) in Ambient Air Using a Pulsed Fluorescent Monitor

The pulsed fluorescent sulphur dioxide (SO_2) monitor operates on the principle that SO_2 molecules excited by ultraviolet light give off radiation.

Pulsating ultraviolet light is focused through a narrow filter into the fluorescent chamber. Here it excites SO_2 molecules which give off their characteristic decay radiation. A second filter allows only this radiation to fall on a photomultiplier tube. Electronic signal processing transfers the light energy impinging on the photomultiplier into a voltage which is in direct proportion to the concentration of SO_2 in the sample stream being analyzed.

More specifically, light in the 230 nanometre (nm) to 190 nanometre (nm) region is used because it exhibits minimal interference by air and most other molecules that are found in ambient air. The pulsed light source emits ultraviolet radiation which acts on the SO_2 in the sample gas producing electronically excited SO_2. The electronically excited SO_2 can then decay back to the ground state by fluorescence. The following equation outlines the overall reaction where SO_2 is excited SO_2*, k_f is a rate constant and hv refers to the energy released by the reaction.

$$SO_2^* \xrightarrow{k_f} SO_2 + hv_2$$

The fluorescent radiation impinging upon a detector is directly proportional to the concentration of SO_2, thus forming the basis for this measurement technique.

APPENDIX B

Method for Measuring Nitrogen Dioxide and Nitric Oxide in Ambient Air Using a Chemiluminescence Monitor

The chemiluminescent method is based on the principle that nitric oxide (NO) and ozone (O_3) react to produce electronically excited nitrogen dioxide (NO_2) which emits light between 600 nm and 2500 nm.

A sample of ambient air is mixed with ozone in a reaction chamber and any NO in the sample reacts with the O_3 instantaneously to produce light. Under conditions of excess ozone, the light produced is proportional to the concentration of nitric oxide and is detected by a photomultiplier tube. The resulting current is amplified, and displayed in terms of the nitric oxide concentration.

For the measurement of nitrogen dioxide, the sample stream is diverted through a catalytic converter where nitrogen dioxide is reduced to nitric oxide. The latter subsequently undergoes the reaction described above together with the nitric oxide originally present in the sample. Concentrations of nitrogen dioxide are determined from the differences between signals obtained when the sample is passed through the reaction chamber directly and when the sample is diverted through the catalytic converter.

The normal working range for field instruments is 0-1 parts per million (ppm) by volume, or 0-1300 ug/m^3 for NO and 0-2000 ug/m^3 for NO_2, at 25°C and 101.3 kiloPascals (kPa).

The detection limit for both NO and NO_2 by this method is 0.002 ppm or about 2.5 ug/m^3 for NO and 4.0 ug/m^3 for NO_2 at 25°C and 101.3 kPa.

APPENDIX C

Method for Measuring Carbon Monoxide in Ambient Air Using a Non-Dispersive Infrared Spectrometry Monitor

Energy, from a source emitting radiation in the infrared region, is split into two parallel beams, one passing through a reference compartment and the other passing through a sample compartment. The two beams finally pass the detector which consists of two matched cells each containing carbon monoxide (CO). These two cells are separated by a diaphragm. The carbon monoxide in the detector cells absorbs infrared radiation corresponding to its characteristic frequencies. With a non-absorbing gas in the reference cell, and with no carbon monoxide in the sample cell, the signals from both detectors are balanced electronically. Any carbon monoxide introduced into the sample cell will absorb radiation, which reduces the temperature and pressure in the detector cell and displaces a diaphragm separating the two cells. This displacement is detected electronically and amplified to provide an output signal proportional to the CO concentration.

A range of 0-50 ppm, parts per million by volume (0-58mg/m^3), is suitable for most conditions.

The detection limit is 0.6 mg/m^3 (0.5 ppm).

APPENDIX D

Method for Measuring Total Reduced Sulphur Compounds (TRS) in Ambient Air Using a Pulsed Fluorescent Monitor and High Temperature Oxidizer

Ambient air is drawn through a scrubber where any sulphur dioxide (SO_2) is removed. The sample then enters an oxidizer where reduced sulphur compounds are oxidized to SO_2. The oxidizer temperature needs to be in the range of 800°C to 950° C.

The sample is then passed through a beam of ultra violet (UV) radiation of 190 to 230 nm wavelength. The SO_2 molecules will absorb this radiation and re-emit fluorescent radiation of characteristic frequencies.

The fluorescent light is separated from the UV light by narrow bandpass filters and detected by a photomultiplier tube whose output current is proportional to the concentration of sulphur dioxide in the sample. The output signal is processed and displayed on a recorder. The instrument is spanned with hydrogen sulphide H_2S. TRS concentrations are read directly from the recorder's chart as H_2S.

Normal working ranges for field instruments are 0 - 0.5, 0 – 0.1 parts per million (ppm) by volume, or 0 – 700 ug/m^3 as H_2S at 25°C and 101.3 kPa.

APPENDIX E

Method for Measuring Ground-Level Ozone in Ambient Air Using a Chemiluminescence Monitor

A continuous sample of ambient air is mixed with an excess of ethylene in a reaction chamber. Any ozone in the sample reacts instantaneously with the ethylene emitting visible light (chemiluminescence), with peak emission at 440 nanometers (nm). The light intensity, directly proportional to the ozone concentration, is measured with a photomultiplier tube whose output signal is fed to a recorder. The signal is calibrated so that ozone concentrations are read directly on the recorder.

A suitable working range fro field instruments is 0 – 0.5 ppm (0 – 1000 ug/m^3).

The detection limit (sensitivity) for the measurement of ozone by this method is 0.001 ppm (2 ug/m^3).

Interferences and Limitations

Particulate matter in the sample will scatter the emitted light, and also accumulate in the intake line and on optical surfaces. Particulate matter in the sample is removed with a suitable filter.

The reaction of ozone with ethylene is not subject to interference from any of the common gaseous air pollutants.

Moisture may be a potential interferent and can be removed with a suitable drying system.

APPENDIX F

Method for Measuring Suspended Particulate (SP) as Soiling Index in Ambient Air Using a Paper Tape Sampler

Ambient air is drawn through a circular area of filter paper at a known sampling rate for a one-hour sampling period. This operation is repeated automatically on fresh areas of paper at equal time periods. The absorbance of the circular spots or stains is measured in comparison with that of the clean paper with a photometer using white light of wavelength from 500 – 800 nm. For comparison purposes, the absorbance readings are reported in coefficient of haze (COH) units per 1000 linear feet of air sampled.

The soiling index, in terms of coefficient of haze (COH) units, is related to the effect of the sampled atmosphere when it is drawn through a clean white filter paper. One COH unit is defined as that quantity of light scattering by particulate matter, which produces an absorbance equivalent of 0.01:

Absorbance = $\log_{10} I_O/I$
I_O = intensity of light passing through the clean filter paper
I = intensity of light passing through the soiled paper

For comparison purposes with similar samples in other areas, COH units are normalized by dividing the absorbance by the volume of sample air expressed in multiples of 1000 linear feet.

Ambient air quality criteria for coefficient of haze outlined in Ontario Regulation 296 are 1.0 COH units per 1000 feet for a 24-hour period and 0.5 COH units per 1000 feet of air for one year.

APPENDIX G

Method for Measuring Total Suspended Particulate (TSP) in Ambient Air Using a High Volume Sampler

The high volume (hi-vol) sampling technique determines the mass concentration of suspended airborne particulate (<100 microns) by drawing a known volume of air through a pre-weighted filter medium. Standard operation of the sampler involves an airflow rate of 1.14 m^3/minute (40 cfm) using a flow controller and the use of Gelman AE glass fibre filters. The sample is collected over a 24-hour period, midnight to midnight, every one, three or six days. The six-day operating schedule is pre-determined and is consistent throughout Canada and the United-States. This six-day sampling is considered to be representative of the average air quality over a year.

High-volume samples may also be analyzed for trace metals and a variety of compounds.

APPENDIX H

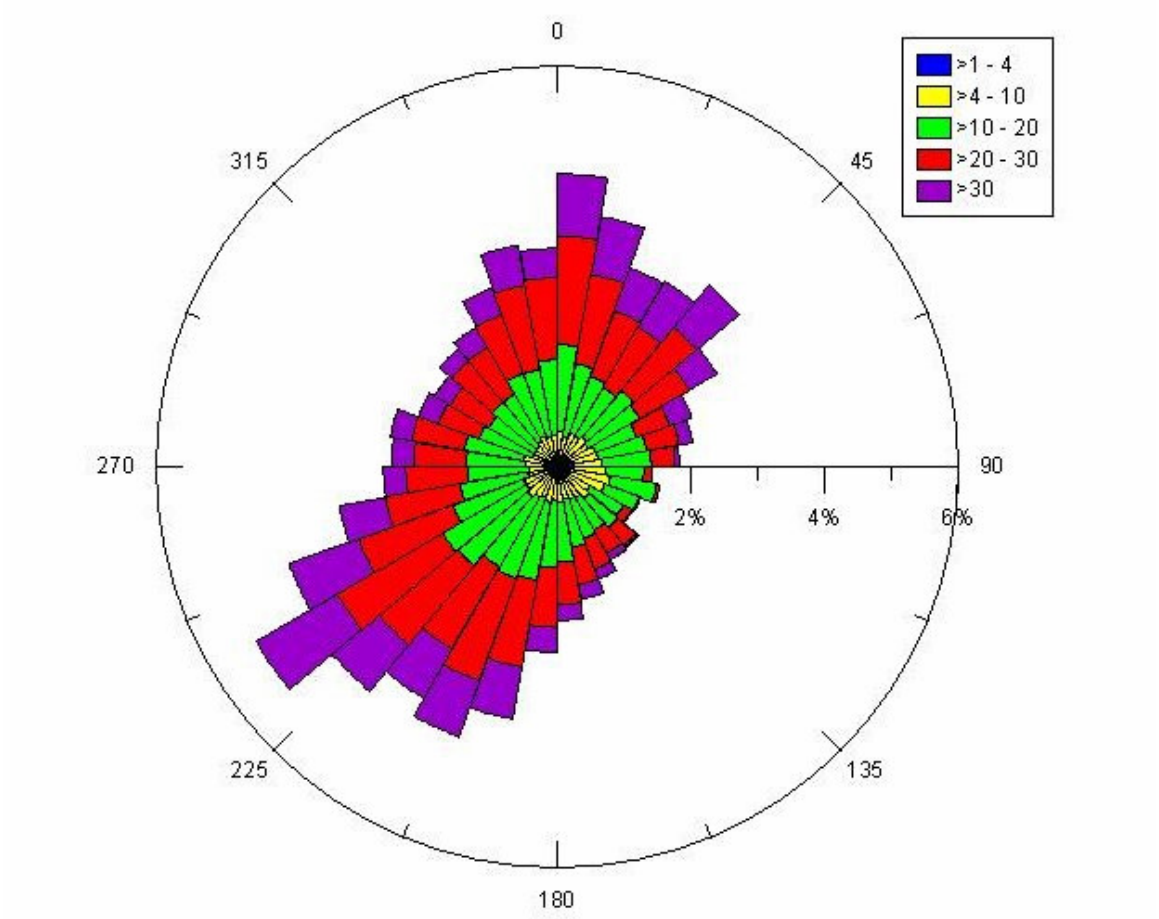
Method for Measuring Inhalable Particulate (PM_{10}) in Ambient Air Using a High Volume Sampler

The high volume (hi-vol) sampling technique determines the mass concentration of airborne particulate by drawing a known volume of air through a pre-weighted filter medium. When equipped with a size-selective inlet head for PM_{10}, the hi-vol sampler can be used to determine the mass concentration of inhalable particulate matter. Standard operation of the sampler requires an airflow rate of 1.14 m^3/min. (40cfm) using a flow controller and the use of quartz fibre filters 8 in. by 10 in. in size. The sample is collected over a 24-hour period, midnight to midnight, every one, three or six days. The six-day operating schedule is pre-determined and is consistent throughout Canada and the United-States. This six-day sampling is considered to be representative of the average air quality over a year.

The quartz filters may also be analyzed for trace metals and a variety of compounds.

APPENDIX I

**Wind Rose Diagram for Wind Speed (km/hr) and Direction (degrees)
Collected at the 115 Metre Level on the Frood Road Tower
in Sudbury for the Period Jan. 1987 to Dec. 1996**



Note: The wind sensor on this tower is operated and maintained by the Ontario Ministry of the Environment who provided the wind rose diagram

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