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Air Quality – Local, Regional and Global Aspects

by R.E. Munn

October 1972

Air Quality – Local, Regional and Global Aspects

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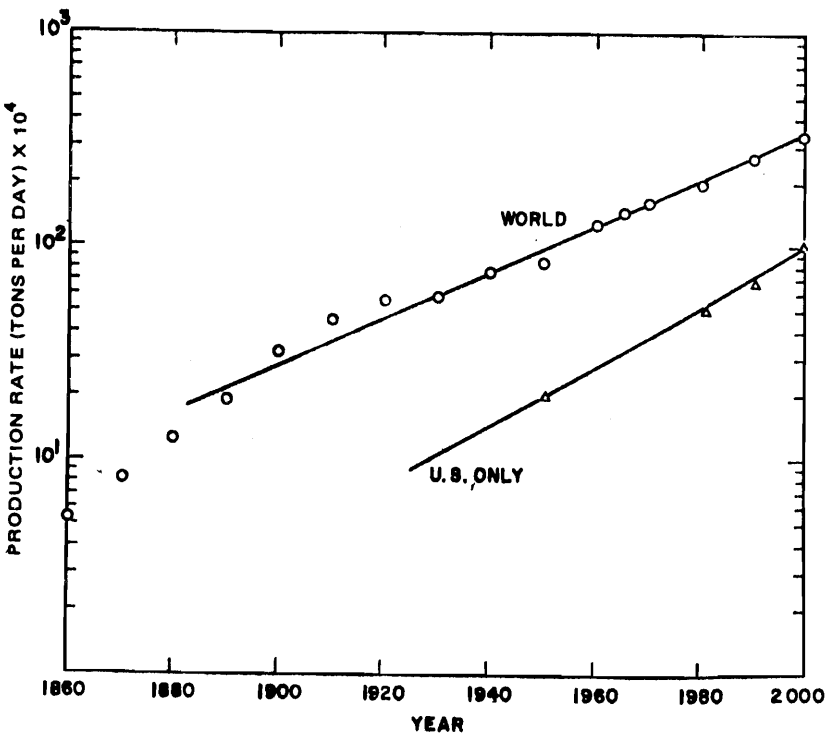
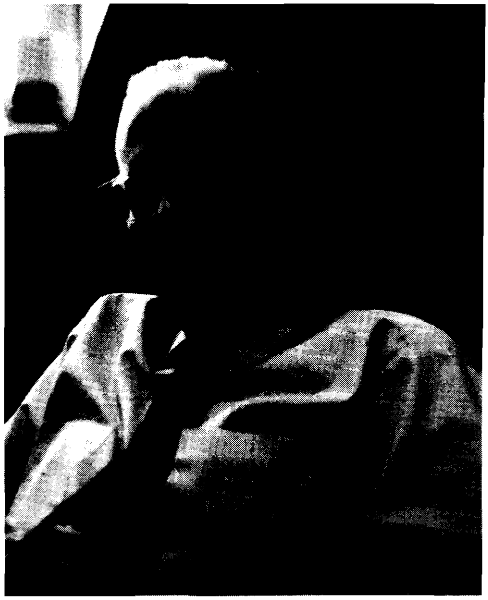
Figure 4 – Projected global emission of sulphur dioxide





R.E. Munn

The author, R.E. Munn, was born in Winnipeg in 1919. He received his B.A. in mathematics from McMaster University in 1941, his M.A. in Meteorology from the University of Toronto in 1945, and his Ph.D. in Air Pollution Meteorology from the University of Michigan in 1962. Dr. Munn is a research scientist with the Atmospheric Environment Service, a component of Environment Canada, and has been with the Government since 1941. He is also a lecturer at the University of Toronto and an Honorary Associate Professor at the University of Guelph. In 1970 he was Visiting Professor at the University of Stockholm. He is Editor-in-Chief of the *International Journal of Boundary-Layer Meteorology*. He has published about 75 papers and two books (*Descriptive Micrometeorology*, 1966, and *Biometeorological Methods*, 1970).

Dr. Munn is a member of many scientific committees. He is Chairman of the World Meteorological Organization's Working Group on Atmospheric Pollution and Atmospheric Chemistry. Within the International Council of Scientific Unions, he is a member of SCOPE (Scientific Committee on Problems of the Environment) and SCOR (Scientific Committee on Oceanic Research), as well as of the International Commission on Atmospheric Chemistry and Global Pollution, the Commission on Global Monitoring, and A Working Party on Mathematical Modelling of Ecosystems. He participated in the MIT Study of Man's Impact on Climate, held near Stockholm in the summer of 1971.

Foreword

This study was written in the spring of 1971 for the Science Council of Canada and was presented at a meeting of the Committee on Environmental Problems. The author subsequently edited the manuscript into a form suitable for publication.

The appearance of a survey paper on air pollution is timely. The UN Stockholm Conference on Problems of the Human Environment has focussed attention on pollution and on the need to achieve solutions, not only on the local, but also on the national and international levels. This brings to mind, of course, the wind transport of air pollution across jurisdictional boundaries. Canadian scientists have in fact been studying this problem for many years, beginning in the 1930s with an investigation, at the request of the International Joint Commission, of the flow of sulphur dioxide from Trail, B.C. along the Columbia River Valley into the United States.

Dr. Munn is well known for his research in air pollution. He approaches his topic from the point of view of a meteorologist, but he has a broad interdisciplinary understanding of the field. He also has first-hand knowledge of current European activities, having spent a recent winter at the University of Stockholm.

The Science Council believes that publication of this study, written for the non-specialist, will serve a useful purpose in providing an authoritative account of the state of the art and in promoting interdisciplinary dialogue.

P.D. McTaggart-Cowan,
Executive Director,
Science Council of Canada.

Preface

In this report I have tried to present a balanced view of present scientific knowledge and uncertainties concerning local, regional and global air pollution. My curiosity was first aroused in 1957, when I was assigned to the Windsor Laboratories of the Canadian Section of the International Joint Commission to undertake studies of air pollution meteorology in the Windsor-Detroit area. Since then, I have had a continuing involvement in the problems of air resource management.

In my view, the most pressing Canadian air pollution problems of the next few decades will be regional in nature. In the so-called Windsor to Quebec City corridor, for example, the pressures to accelerate urban growth rates are very real, and towns and cities are beginning to impinge on one another. The need for imaginative regional planning is becoming apparent, not merely to extrapolate population trends over the next ten years, but to plan for the next century. It would have been relatively easy 100 years ago to preserve as parkland the entire area between St. Clair and Eglinton Avenues in Toronto. It is not so easy now (but also not impossible) to establish green belts around new towns or beyond the outer perimeters of existing metropolitan areas. At the very least, new sites for heavy industry should be separated from new residential developments by at least a few miles, and adequate rapid transit systems should be provided.

I acknowledge the support and helpful comments I have received from various colleagues in the Atmospheric Environment Service. I wish to make it clear, however, that I am writing as an individual scientist and that my views may not necessarily correspond with those of Environment Canada.

R.E. Munn,
Atmospheric Environment Service,
Toronto, Ontario.

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I. Introduction

Air pollution is defined as "a condition of the ambient air, arising wholly or partly from the presence therein of one or more air contaminants, that endangers the health, safety or welfare of persons, that interferes with normal enjoyment of life or property, that endangers the health of animal life or that causes damage to plant life or to property" (Canada. Bill C-224, 1971)*. In the broadest context, air pollutants include not only the conventional trace gases and particles monitored by control agencies, but also carbon dioxide, water vapour and heat because of their possible climatic effects. Pollution has also been defined as "a resource out of place", suggesting the positive value of abatement.

Air pollution in the first instance is a local problem. However, the boundless atmosphere quickly carries contaminants across provinces, over oceans and around the world. This transport is both a disadvantage and an advantage. On the one hand, pollution abatement cannot always be undertaken successfully by local levels of government, but requires regional and sometimes international cooperation – and this is often difficult to achieve. On the other hand, the pollution is diluted as it expands into larger and larger volumes of air, and a large fraction is removed from the atmosphere by precipitation scavenging, by absorption at the ground and by chemical reactions in the atmosphere itself. These self-cleansing processes are called *sink mechanisms*, and they may occur far from the point of emission.

The amount of air available to a city or region for "breathing" depends considerably on the strength of the wind and on the vertical extent of turbulent mixing. When flying over a large city, one frequently observes a sharp top to the urban haze layer; this lid separates well stirred surface air from the clean air aloft. The height of the lid, called the *mixing height*, varies from hour to hour and from day to day. During stormy weather, of course, the cap is disrupted and pollution may diffuse upward to great heights. There is, however, another lid, the *tropopause*. This barrier to upward ventilation exists around the world at a height of about 30 000 feet, separating the turbulent troposphere from the relatively quiet stratosphere. Aircraft observations confirm that there is a very sharp decrease in pollution concentrations at the tropopause.

Consider a volume of air with horizontal dimensions equal to those of a city or region, and vertical dimensions equal to that of the mixing height. Then the rise or fall of pollution concentrations within this open-ended box can be interpreted as an imbalance of pollution production to losses by the action of various pollution sink mechanisms and by net horizontal transport out of the box. Similarly, Northern Hemisphere budgets can be evaluated; in this case, however, the net transport term disappears, and the appropriate vertical dimension is the height of the tropopause.

The outline for this report is as follows. The next two sections of this chapter contain introductory discussions of atmospheric time and space variability, and of the nature of pollution. Chapters II to IV describe atmospheric processes and potential pollution problems on the local,

*All bibliographic detail is listed at the back of the book in the section titled "References" (page 34).

regional and global scales. Finally, Chapter V summarizes the action that has been taken or is contemplated to preserve or restore the quality of the atmosphere.

Time and Space Variability

Fortunately for Canada, there are still relatively large air spaces between major population centres. In addition, the Pacific Ocean, the Arctic and sub-Arctic, and the Atlantic Ocean provide giant reservoirs of clean air. This, of course, does not mean that air quality problems cannot arise locally or regionally if the production of pollution exceeds the sink strengths and transport terms, a condition that occurs particularly at times when the mixing height is low and horizontal ventilation is poor.

In other words, with certain local exceptions, the air quality over Canada is excellent on most days of the year. This makes it difficult for citizens' groups and the press to sustain interest in pollution abatement. Whereas the water pollution burden is relatively constant from day to day, air contaminant concentrations vary greatly at ground level, even from minute to minute sometimes. Only on rare occasions does air quality deteriorate seriously in our large cities, and then for only a few days at a time, when winds become light and vertical ventilation is restricted. An example of such an episode was the Grey Cup smog in early November, 1962, when the national championship football game had to be postponed in Toronto. The press and the public become alarmed at such times, but within a few days clean air from Canada's northland invariably sweeps into the region, dissipating awareness again.

Even over longer time periods, there is great year-to-year variability in the average ventilation of regions, making it difficult to determine pollution trends and evaluate the adequacy of control programs.

Schmidt and Velds (1969), for example, found that the observed decrease in average winter SO_2 (sulphur dioxide) levels over Rotterdam during the 1960s could be explained by a concurrent decrease in the frequency of weather patterns conducive to poor regional ventilation. Their data (Table 1) do not, however, support the thesis that the Rotterdam air pollution control program has necessarily been outstanding.

Similarly, the observed increase in sulphur content of precipitation falling over Sweden in the 1960s can be interpreted almost entirely in terms of the varying annual frequencies of various rain-bearing weather patterns. When precipitation is associated with northeasterly winds, for example, the air has come from the Siberian reservoir of clean air. Rains with south and southwest winds, on the other hand, are relatively polluted. It seems that year-to-year changes in the frequencies of European storm tracks must be included in any discussion of Swedish acid rains.

The question of space variability is also important. Most serious pollution problems occur when emissions are too great for the local ventilation capacity of the atmosphere. This condition is most likely when the air flow is constrained by a valley, or by tall buildings in a city. The Donora, Pennsylvania "disaster" of 1948 arose because of valley topography.

Table 1 – Trends in winter SO_2 concentrations and in the frequencies of weather patterns conducive to poor ventilation in Rotterdam

Winter	Mean SO_2 ($\mu g/m^3$)	Total number of days with poor ventilation
1962-63	261	55
1963-64	258	51
1964-65	229	22
1965-66	216	29
1966-67	203	11
1967-68	183	8

Source: F.H. Schmidt and C.A. Velds, "On the relation between changing meteorological circumstances and the decrease of the sulphur dioxide concentration around Rotterdam", *Atmospheric Environment 3*, 1969. Pages 455-460.

Another situation of concern occurs when there is an ebb and flow of regional pollution due to land-breezes and sea- or lake-breezes (Vancouver, Toronto) or to slope winds (Denver), with no significant net transport out of the region for several days. Canada is characterized by great differences in the ventilation capacity of the atmosphere. The Arctic in winter, for example, has long spells of light winds and poor vertical mixing.

For these reasons, the implementation of national or international emission standards cannot guarantee that ambient concentrations will never exceed any preassigned level. At best, they serve to distribute equitably the cost of reduction of regionally-averaged levels of contamination, and to eliminate pollution havens. The permissible rate of release of pollution into the atmosphere should preferably be a function of the numbers and heights of emitters and of local meteorological and topographical conditions. The controls to be placed on emissions from a chimney on a 2-story building need not be as stringent in open countryside as when the structure is surrounded by skyscrapers. National and international air quality criteria, on the other hand, make sense because they are related to effects.

The Principal Air Pollutants

Air pollutants are classified in many different ways, depending upon the purpose of the classification. One widely-used subdivision is as follows:

a) *Products of incomplete combustion* (soot, SO_2, hydrogen sulphide, etc.). This is the classical type of problem, common in Europe and in Canada in winter, and may be alleviated partially by achieving more efficient combustion of fuels and waste products.* Another approach is to remove most of the pollutants with filters or precipitators. This is completely successful in the case of large particles, and the fly-ash problem has disappeared in regions where control programs have been effective. Particles with diameters of less than 0.1 microns are difficult to trap, however. In addition, only about 96 per cent efficiency can be achieved in the removal of sulphur dioxide and other gases. The remaining 4 per cent may amount to more than 100 tons of sulphur a day released into the atmosphere from a single large smelter, gas-purifying plant or coal-fired power station.

*The Fuels Research Centre of the Canadian Department of Energy, Mines and Resources has a vigorous combustion research program that is recognized internationally.

b) Hazardous substances (such as lead, arsenic, mercury, cadmium and asbestos)
These pollutants *must* be controlled at source because frequently they are deposited on vegetation or lakes, and are subsequently concentrated in food chains.

c) The products of photochemical reactions (oxidants, PAN†, etc.)
In the presence of strong sunlight, hydrocarbons react with oxides of nitrogen to form a number of substances which create skin irritation, eye watering, crop injury and material damage, particularly to rubber and nylon. When photochemical smog first appeared in Los Angeles in the 1950s, its cause was not understood. Vigorous programs to reduce the SO_2 emissions simply made the situation worse, illustrating the fact that it is dangerous to treat symptoms without an understanding of causes. As another example, present programs designed to reduce automobile hydrocarbon emissions without parallel reductions in oxides of nitrogen will lead to a rise in concentrations of the latter gases, which are toxic in sufficiently high amounts. Photochemical smog has now been identified in many parts of the world, including Mexico, Chile and Australia. In southern Canada, the problem occurs in summer during spells of sunny weather. Injury to tobacco plants along the rural north shore of Lake Erie, for example, is caused by oxidants (Mukammal, 1965), which indicates the regional nature of the phenomenon. Whereas SO_2 is a problem primarily in cities and near large industries, oxidants are associated with whole air masses 500 miles or more in horizontal extent.

Another classification of pollution is based on residence, or turnover times in the atmosphere. These times range from an hour or so for oxidants in a city to a year or so for substances such as CO_2 (carbon dioxide) and CO (carbon monoxide). The residence time for SO_2 is several weeks in oceanic and rural areas, but less than an hour in a polluted atmosphere. This classification is useful in estimating atmospheric pollution budgets; substances with the same residence time can be studied in similar ways.

Still another subdivision of pollution is according to whether the source is natural or man-made. The sea, for example, is a major source for the sulphur in European rainfall. Locally, near towns, man-made emissions predominate. For global budgets, natural sources are often of equal importance (see Chapter IV).

Scientists tend to study substances and physical processes that can be monitored, not necessarily those of most importance. This is particularly true in the field of air pollution, where outdoor concentrations are in the ranges of ppm (parts per million) or ppb (parts per billion), and are often difficult to determine. As an example, odours from pulp and paper mills and from gas-purifying plants are caused mainly by mercaptans whose presence cannot be monitored by chemical methods, although they are readily detected by the nose. As another illustration, the determination of the acidity of rainwater turns out to be an exceedingly difficult task.

†peroxyacetyl nitrate.

A related problem is that we do not yet understand very well the responses of living organisms (plants, animals and people) to pollutants. Adaptation, as well as synergistic effects, is known to occur in some cases when several pollutants are present. The appropriate response times are also uncertain, ranging from a few seconds in the case of odour detection to a few years in the case of pollution-induced emphysema. However, many international societies and inter-governmental agencies now have active Working Groups on air pollution: the World Health Organisation (WHO), the World Meteorological Organisation (WMO), the Organisation for Economic Cooperation and Development (OECD), and the International Union of Pure and Applied Chemistry, etc.

A further problem is that, although very sensitive chemical methods are available in some cases, the equipment is costly and the analyst requires special skills and training. For pollution surveys and routine network operation, therefore, a lowest-common-denominator program is frequently undertaken, the sampling station being visited only once a week by a technician with only minimum training. The Ontario Air Management Branch has recognized this problem and has assigned a significant share of its operating budget to the provision of competent field staff.

International air quality monitoring programs are beset by the same difficulties. The collection of data that meet the needs of the scientific community is beyond the resources of many developing countries. In order to organize a global network, therefore, compromises must be made and nineteenth-century methods must sometimes be adopted.

II. Local Air Pollution

In early times, air pollution was an indoor problem. The Algonquin women, for example, frequently went blind by the age of 30 from the smoke and fumes in the cooking areas of their long houses. Even today, amongst the native population of the Highlands of New Guinea, there is a high prevalence of chronic non-tuberculous lung disease. Cleary and Blackburn (1968) have attributed this to the high concentrations of smoke, aldehydes and carbon monoxide in the native huts. No doubt, air quality is seriously impaired in our Canadian national and provincial parks on clear, windless August evenings, although many campers like the smell of wood smoke.

Indoor pollution may be alleviated by providing ventilation. For a small building, this is not a difficult or costly engineering problem. It should be noted, however, that a structure obstructs the air flow. In strong winds, puffs of chimney gases swirl down the lee side of the building (downwash), causing intermittent bursts of high concentrations. In one experiment in Denmark, for example, a tracer gas released through a fume hood on the windward side of a hospital re-entered the building through an upper-floor window on the leeward side (Lundquist 1970). Similarly, coal gases can be smelled on Barrington Street in Halifax when strong north-westerly winds are blowing: the pollution is sucked into the street cavity.

A chimney is often quite adequate for a single dwelling. As people congregate in towns and cities, however, the multiple sources of pollution eventually create problems. To improve air quality, several approaches may be taken:

a) a reduction of individual emissions through burning cleaner fuels, scrubbing the gases, etc.;

b) zoning, to separate residential, commercial and industrial areas in the city. In Europe, green belts and smokeless zones provide breathing spaces and permit dilution of the pollutants. In New York City, as another example, the air is cleaner in Central Park than in the surrounding built-up areas;

c) construction of taller chimneys to disperse the gases over larger volumes of air. This may, of course, replace a local problem with a regional one (see Chapter III).

In summary, the technology exists to control most local pollution. The automobile is of course a special case, because of the multiplicity of sources, each of which contributes only a small fraction of the total burden. In some large United States cities, the concentration of carbon monoxide on urban expressways sometimes exceeds maximum permissible indoor levels. Brice and Roesler (1966), for example, collected 47 half-hour samples of air in moving vehicles in traffic in St. Louis and found a range of CO concentrations from 11 to 77 ppm.

III. Regional Air Pollution

The average height of a power plant chimney completed in the United States in 1960 was 73 metres, as compared with a 1969 average height of 183 metres (Tennessee Valley Authority, 1970). As a Canadian example of this trend, a 375-metre chimney has been built in Sudbury at a cost of approximately 10 million dollars. The tall-chimney approach is often successful in meeting local pollution abatement regulations. However, because the rise of a heated buoyant plume in a windy atmosphere is a complex scientific problem, because the weather varies so greatly from day to day, and because until recently there have been fewer experimental measurements than published formulae, the design of a chimney is difficult. Many engineering consulting firms have little competence in meteorology, and make the mistake of extrapolating textbook formulae out of context. In one recent case, this led to a plume-rise estimate of more than 60 kilometres!

Another frequently-made mistake is to design chimneys to meet only present-day air quality criteria, despite the trend over the last several decades toward more stringent regulations. In a discussion of the Cardinal steam-generating power plant on the Ohio river, Frankenberg *et al.* (1970) comment that:

"The two existing stacks have performed so well that it now appears feasible to increase the size of the third unit to 1300 MW [megawatts] if that should prove desirable. Such a development of the station might require that the third stack have a height of between 900 and 1,000 feet, although the final dimensions would be influenced by the ambient air standards in force at the design period."

For very tall chimneys, there are three meteorological situations of concern:

a) Strong winds

The building itself or the surrounding terrain may cause plume downwash. For very tall chimneys, this strong-wind phenomenon may occur 10 kilometres distant. In Indiana, for example, the height of a power plant's stack was increased to alleviate a local pollution problem. The net result, however, was that downwash still occurred, but at a distance of 5, rather than 1, kilometres from the plant. A satisfactory solution was eventually found by testing a scale model in a wind tunnel. This approach is successful provided that a tall building is not subsequently constructed nearby, significantly changing the local wind and turbulence patterns.

b) Light winds

The heat released from a tall chimney is so great that when winds are light a local thermal circulation cell may develop, causing the plume to loop to ground level a few kilometres distant. This behaviour may be either amplified or suppressed by other regional thermal circulations, such as lake-breezes or valley flows.

c) Fumigation conditions

When the atmosphere is turbulent and well mixed near the ground, with a capping stable layer near the height of the plume, the pollutants cannot escape aloft, but may instead fumigate to ground level. This phenomenon was first described by Hewson (1945) in the International Joint Commission study of SO_2 vegetation damage in the Columbia River Valley. Subsequently, there have been other investigations and it seems that local terrain is of great importance. Hirt *et al.* (1971) have recently described a case of afternoon fumigation at distances of from 6 to 10 kilometres inland from a thermal generating station on the shore of Lake Ontario. Three 155-metre chimneys were operating, emitting heat and SO_2 at the rates of 3.3×10^7 calories per second and 5.6 kilograms per second, respectively. Ground-level concentrations as high as 0.9 ppm were measured on a May day when there was a capping stable atmospheric layer.

Provided that these meteorological problems are recognized in the design stage, a satisfactory solution to the chimney-height problem can usually be found, ensuring that air quality regulations are met. Frequently, zoning is helpful. It is senseless to locate a residential area near a smelter, although historically towns and cities have grown up around single industries. Not much can be done about past mistakes, but for new communities a buffer zone should separate industry from homes, and transit systems should be provided. The merit in this approach was recognized many years ago by the atomic energy industry (e.g., Chalk River and Deep River). As another example, Kitimat, B.C. was subjected to meteorological analysis at the planning stage by Professor H.E. Landsberg, and his recommendations have stood the test of time. Today, whenever a large industry plans to locate in rugged terrain, the town site should be chosen only after a detailed meteorological survey of local wind flows has been undertaken. Air pollution is, of course, only one of a number of factors that must be considered by the planner, but the consequences of various land-use options should be explored.

Up to this point, the discussion has been limited to the single-industry town. When a number of tall chimneys are built in the same area, there is a possibility of degradation of regional air quality, particularly because the replacement of an existing chimney by a taller one usually implies an increase in production and emission of pollution. In Sweden, for example, there has been a public debate about the effects of the tall chimneys being built in Britain and the Rhine Valley. This is a difficult question to answer however, because at these distances diffusion and sink mechanisms become important.

Another problem facing regional planners is that on most days the atmosphere is a very efficient sewer, and strict controls are not then necessary to meet air quality criteria. During the 1966 Cleaner Air Week in Toronto, for example, helium-filled tagged balloons were released by school children at about noon each day. Many of the balloons were subsequently found, and the tags mailed back to the Cleaner Air Week

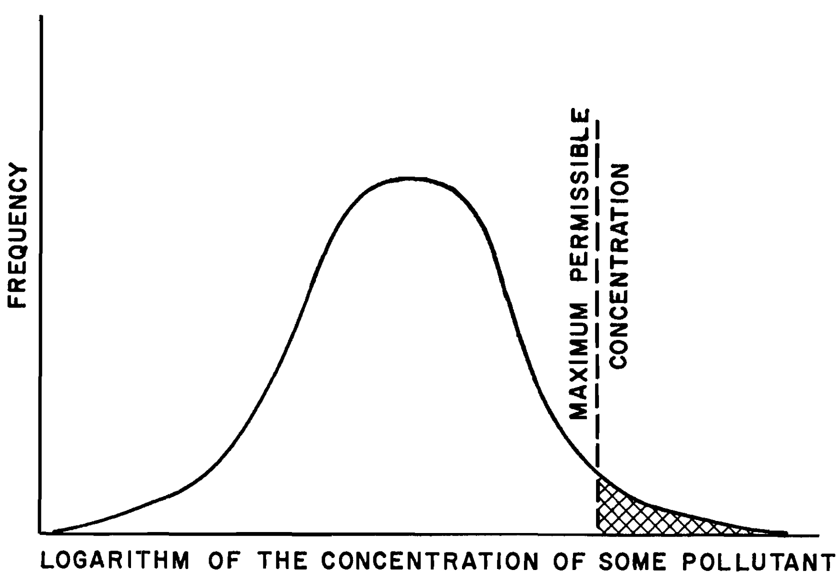
Table 2 – Extreme locations of balloon tags returned to Toronto, October 17 to 21, 1966

Date	Place where balloon found	Travel distance of balloon	Wind in Toronto area		
			Surface	2000′	4000′
Oct. 17	Megantic, Que.	450 miles	SW9	W19	W17
Oct. 18	Uxbridge, Ont.	90 miles	SE9	S9	NW5
Oct. 19	Barry's Bay, Ont.	135 miles	NW13	E6	S9
Oct. 20	Wilmington, Dela.	350 miles	NW16	NW11	NW19
Oct. 21	Springfield, Vt.	350 miles	S15	SW13	SW30

Committee. Some results are given in Table 2, which shows the maximum reported distances of balloon finds on each day. These data are reminders that air pollution is no respecter of jurisdictional boundaries.

Figure 1 shows another approach to this problem; in it, the frequency distribution of pollution concentrations at any given sampling station is shown schematically. The shape depicted in the diagram occurs almost universally, whether the averaging time for individual values is a few seconds or a few hours.

Figure 1 – Schematic representation of the frequency distribution of pollution concentrations observed at an air sampling station. The hatched area represents occurrences which exceed designated maximum permissible concentration.



If a maximum permissible concentration is designated, then an optimizing strategy is to reduce only the values within the shaded area. To lower the other concentrations, on the other hand, would be costly and presumably unnecessary. This is the philosophy behind the pollution index of the Ontario Air Management Branch. When the index exceeds a specified value, the major emitters of pollution are asked to reduce their emissions, thus transferring some of the air quality values in Figure 1 from the shaded area to the unshaded area.

The Air Management Branch recognizes that this is a qualitative approach to a multiple-source problem. In order to apportion controls fairly amongst the various emitters, there is a requirement for an appraisal of the effects of emission strengths and heights, recognizing that the resulting ground-level concentrations, rather than the production rates, are important. For quantitative estimates, therefore, there is a need for urban and regional integrated models of dispersion. Initial attempts to produce such models were begun in the 1950s in the Los Angeles basin. Since then, increased computer capabilities have permitted much more flexibility in programming and model testing. The first step in this exercise is to undertake a detailed emission inventory, city block by city block. Next, the atmospheric diffusion equations are solved numerically for each source and the results are combined to yield detailed patterns of regional pollution. The Ontario Air Management Branch is in the final stages of testing a computer model of Toronto (Bowne *et al.* 1971), and similar work is in progress in Europe and in many United States cities. Hopefully, these models can be used to predict day-to-day air quality, as well as to simulate the long-term effects of proposed changes in land use, fuel type, or chimney heights. With increasing population pressures in southern Canada, this type of planning is essential.

The difficulty in computer modelling is that the atmospheric flow patterns are not sufficiently well monitored. A city, for example, is warmer than the surrounding countryside; this generates a thermal circulation and distorts the regional stream-lines. In many cases, a very complex computer program is being applied to very meagre meteorological data.

One must also recognize that the sink strengths are often not well defined. In a numerical model of SO_2 dispersion in Connecticut, Bowne (1969) found it necessary to use a residence time of only an hour in order to match predictions with observations of gound-level SO_2 concentrations. As another example, Miller and Ahrens (1970) have found that the destruction rate of oxidants in cities varies inversely as the square of the thickness of the surface mixed layer. Air concentrations depend on the imbalance of production over destruction rates; it follows that, as a city becomes larger over decades, the surface mixed layer becomes deeper and the oxidant destruction rate becomes less, at the same time as the production rate is increasing. This study illustrates the fact that there is a real need for three-dimensional investigations of the urban envelope, as have been undertaken recently in Montreal by Oke and East (1971).

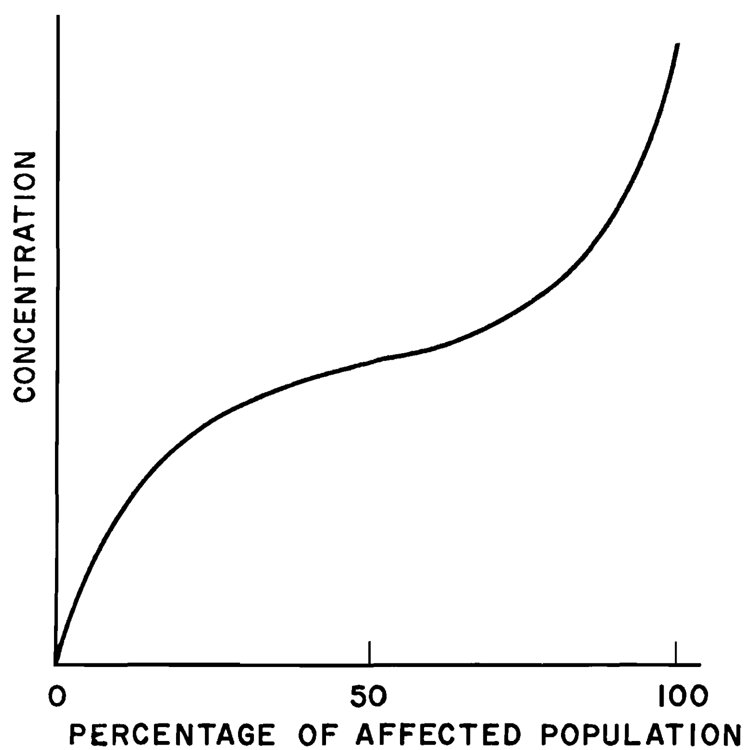
Incidentally, Figure 1 illustrates another important principle in pollution abatement, namely that unacceptably high concentrations do indeed occur from time to time. Although the frequency can be reduced to perhaps once in 50 years by emission controls, it is not practical (or in many cases, possible) to specify a maximum concentration that shall never be exceeded. Instead, an excedence risk of 1 per cent, 0.1 per cent or some other arbitrarily selected percentage must be accepted.

A further complexity is the response of a population of people or trees to environmental stress, as shown in Figure 2. The diagram illustrates the fact that one cannot specify a threshold concentration (except the zero value) below which no member of a population will be affected.

To supplement forecasts of actual pollution levels in the United States, daily predictions are made of *pollution potential* – i.e., predictions of those regional meteorological conditions which would cause poor air quality if multiple sources were present. A similar program in Canada is presently under consideration. Fortunately, our most serious "polution potential" occurs in remote areas far from sources (e.g., in the Arctic in winter), but this implies that industrial expansion into the North should be planned carefully.* Fairbanks, Alaska already has a serious winter problem due to the long spells of poor ventilation. Furthermore, vegetation and wildlife are in critical equilibrium with their harsh environment in the Arctic, and threshold concentrations causing ecological damage may be lower there than in more southerly latitudes.

*Chimney-height design formulae developed from temperate zone data cannot be applied indiscriminately to Arctic locations.

Figure 2 – Schematic representation of the percentage of a population which is adversely affected by given concentration values



IV. Global Air Pollution

The quality of the air far from cities is gradually changing over the decades, although the evidence is still fragmentary. The average concentration of CO_2 in the troposphere in the Northern Hemisphere has been increasing at the rate of 0.7 ± 0.1 ppm per year over the last decade (Bolin and Bischof, 1970). We should note, however, that this is much less than would be expected in consideration of the increase in man-made emissions of CO_2 over the same time period. About 20 per cent of the increase is being assimilated by vegetation and about 40 per cent is being absorbed by the oceans. Using OECD estimates of fossil-fuel combustion rates over the next 40 years, Bolin and Bischof have made the predictions given in Table 3 for the average tropospheric CO_2 concentrations up to the year 2010.

Several years ago, there was some anxiety that the world's oxygen supply was being threatened by the release of pesticides into the oceans. However, this is now considered to be a non-problem (Study of Critical Environment Problems, MIT, 1970). Ryther (1970) has reasoned that if all photosynthesis in the oceans were to cease, at least a million years would elapse before the atmospheric concentration of oxygen decreased by 10 per cent.

Table 3 – Predicted atmospheric CO_2 concentration (ppm) based on an emission increase of 4 per cent per year. For comparison, estimates obtained on the basis of a 5 per cent emission increase after 1980 are also shown.

Assumed Annual Growth Rate	Year	Predicted atmospheric CO_2 concentration	
		Assuming 35% of emission remains in atmosphere	Assuming 45% of emission remains in atmosphere
	1970	321 ppm	321 ppm
	1980	332 ppm	335 ppm
4% Annual Emission Increase	1990	348 ppm	355 ppm
	2000	371 ppm	388 ppm
	2010	403 ppm	430 ppm
5% Annual Emission Increase	1990	349 ppm	356 ppm
	2000	378 ppm	395 ppm
	2010	418 ppm	450 ppm

Source: B. Bolin and W. Bischof, "Variation of the carbon dioxide content of the atmosphere in the Northern Hemisphere", *Tellus 22*, 1970. pp. 431-442.

Some ecologists and climatologists are alarmed about the increase in particulate matter in the atmosphere. The evidence is again fragmentary, consisting mostly of data obtained in glacier cores. A short note by McCormick and Ludwig (1967) on atmospheric turbidity trends at Washington, D.C. and Davos, Switzerland is, however, widely cited. The essential results, given in Table 4, indicate that the atmosphere is becoming more turbid. Such limited data do run the risk of being non-representative, and many scientists would consider, for example, that the Washington data for 1962-1966 reflect primarily the global and persistent effects of the Mount Agung volcanic eruption.

During settled anticyclonic weather conditions, industrial haze can be detected on satellite photographs. Clodman and Taggart (1969) followed a large area of haze as it moved slowly from the Eastern United States to the mid-Atlantic. However, forest fires and dust storms, too, have been

Table 4 – Mean values of turbidity

Location	Years	Mean Turbidity
Washington, D.C.	1903-1907	0.098
	1962-1966	0.154
Davos, Switzerland	1914-1926	0.024
	1957-1959	0.043

Source: R.A. McCormick and J.H. Ludwig, "Climatic modification by atmospheric aerosols", *Science 156*, 1967. pages 1358-1359.

important sources of particulates over the centuries, while volcanic eruptions into the stratosphere may have reduced the intensity and quality of solar radiation for long periods.

There have been some attempts to develop global budgets of particular elements based on physical models of source, reservoir-storage and sink strengths. Verification of these models permits one to obtain projections of trends by simulating source-strength changes. For example, this approach has been used by Bolin and Bischof (1970) for CO_2 (yielding the predictions in Table 3), and by Robinson and Robbins (1968) for sulphur.

The estimated annual budget, in units of 10^6 tons of sulphur per year, is shown in Figure 3, the net annual uptake by the oceans being about 95 x 10^6 tons. Projected increases in the production of SO_2 are shown in Figure 4, from which the trends in atmospheric sulphur could be inferred by inclusion in an appropriate simulation model.

A principal uncertainty in such calculations is the determination of sink strengths. Some of the problems are as follows:

a) Atmospheric chemical reactions

The rates are not well known, often being functions of space and time. For this reason, the budgets of elemental substances such as sulphur are often chosen for study, rather than those of compounds such as SO_2.

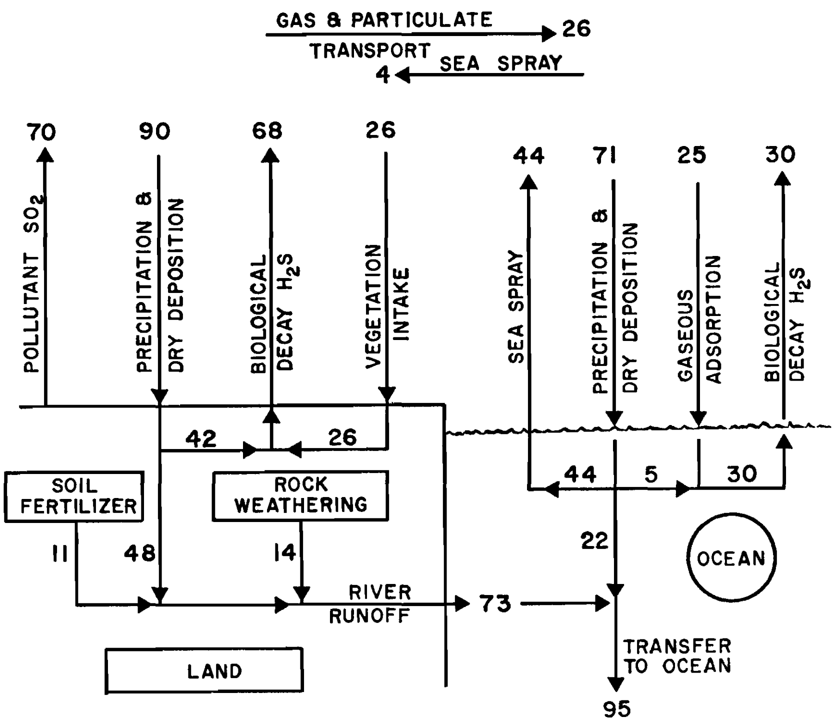
b) Precipitation scavenging

Although the physical processes causing scavenging are understood reasonably well, there are few observational data on the vertical distribution of pollution, the heights of the rain-producing clouds and the size distributions of the water droplets and of particulate matter.

c) Ground absorption

Large particles are deposited by the action of gravity. Very small particles and gases, however, are removed from the atmosphere in a multiplicity of ways – during dry weather, through the stomates of leaves and by absorption on buildings, for example. Meetham (1950) has estimated that in the 1940s 5.0 million tons of SO_2 per annum were emitted into the atmosphere over Britain. Of this total, 0.7 million tons returned in rain, 3.2 million tons were absorbed by vegetation and other surfaces, and the remainder, 1.1 million tons, was transported to the oceans and other regions. The uptake rate of 3.2 million tons by vegetation and other surfaces is substantial, but Spedding (1969) is not greatly in disagreement with this estimate.

Figure 3 – The annual global sulphur budget



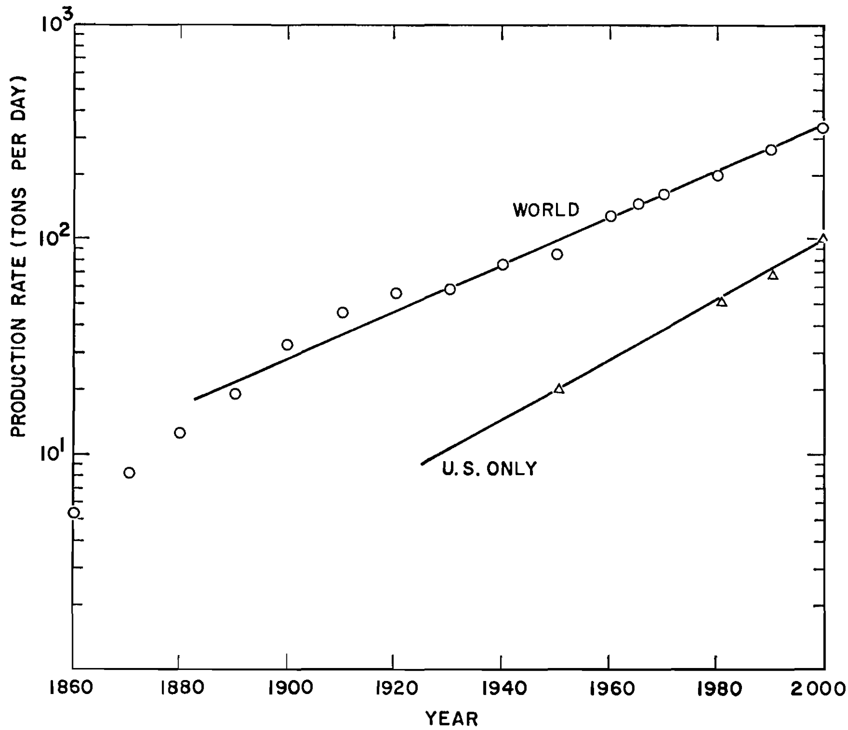
Source: E. Robinson and R.C. Robbins, *Sources, abundance and fate of gaseous atmospheric pollutants*, Final Report SR1 Project PR-6755, Stanford Research Institute, California, 1968. 123 pages.

Surface absorption is a strong function of the physical properties of the surface and of micrometeorological factors such as the turbulence regime near the ground. In a recent study of the removal of atmospheric SO_2 by building stones, Braun and Wilson (1970) found uptake rates of about 50 per cent in laboratory experiments lasting about 2 hours. Outdoors, however, the rates were much less, suggesting that the flux was limited by the rate at which the SO_2 was delivered to the surface by turbulence. There is an urgent need for further research on this problem, particularly over the oceans, which act as sources rather than sinks for some substances. The tropical Atlantic, for example, is a strong source region for CO (Seiler and Junge 1970).

Hidy and Brock (1970) have assessed the tropospheric aerosol budget, assuming a residence time of about 4 days in their calculations. The inventory is summarized in Table 5, which shows that man-made sources contribute about 9 per cent to the total loading. Assuming that controls continue at their mid-1960 level, the projected trends for the next 30 years are given in Table 6.

The direct ecological effects of upward trends in CO_2, SO_2 or particulates at background locations are not likely to be significant. A slight increase in photosynthetic activity (due to an increase in CO_2) would be

Figure 4 – Projected increases in the global production of sulphur



Sources:
World – E. Robinson and R.C. Robbins, "Gaseous atmospheric pollutants from urban and natural sources", *Global Effects on Environmental Pollution* (S.F. Singer, Ed.), Reidel Publishing Company, 1969. pages 50-64.
U.S. – J.H. Ludwig, G.B. Morgan and T.B. McMullen, "Trends in urban air quality", *Transactions of the American Geophysical Union 57*, 1970. pages 468-475.

Table 5 – Speculated global inventory of major sources after adjustment to known composition of aerosols

Source	Total Production, tons per day	% by Weight
1. Primary		
Dust Rise by Wind	10^6	21
Sea Spray	2×10^6	42
Extraterrestrial	550	0.01
Volcanic Dust	10^4	0.2
Forest Fires	4×10^5	8.8
Combustion and Industrial	3×10^5	6
2. Secondary		
Vegetation	2×10^5	4
Man-made Hydrocarbons	10^4	0.2
Sulphur Cycle	6×10^5	13
Nitrogen Cycle Ammonia	10^5	2
Nitrogen Oxides, Nitrate	2×10^5	4
Volcano (Volatiles)	10^3	0.02
Adjusted Total	**4.7×10^6**	**100**
Man-made	*4.3×10^5*	*9*

Source: G.M. Hidy and J.R. Brock, "An assessment of the global sources of tropospheric aerosols", Preprint, 2nd International Clean Air Conference, Washington, D.C., 1970.

Table 6 – Projected increased production of major contributors to anthropogenic aerosol through the year 2000, in tons per year

Source	1970	1980	1990	2000
Primary (Combustion and Industrial)	3.0×10^5	5.3×10^5	8.7×10^5	1.3×10^6
Sulphate	3.0×10^5	3.2×10^5	3.7×10^6	4.6×10^5
Nitrate	6.0×10^4	8×10^4	10×10^4	1.3×10^5
Reactive Volatile Hydrocarbons	7×10^3	$.7 \times 10^4$	1.1×10^4	1.7×10^5
	6.6×10^5	9.4×10^5	13.5×10^5	19.1×10^5

Source: Hidy and Brock, *op. cit.*

difficult to detect, as would any changes due to decreases in the intensity of solar radiation. Of greater concern is the distant transport of hazardous substances such as DDT and mercury, which are injurious to wildlife, vegetation and fish. Lead concentrations in Greenland snow have increased tenfold since 1850 (Murozami *et al.* 1967), while DDT has been found in Antarctica. There is some speculation, particularly in Sweden, that the mercury in northern lakes has been carried there by the atmosphere from other regions and has been scavenged by precipitation. Unfortunately, we know little about the world distribution of source strengths of some of these hazardous substances, and even less about the ways in which they cycle through the geophysical and ecological systems.

We turn now to a discussion of climatic change, one of the great environmental anxieties of this decade. In the first place, there is concern about the possibility that supersonic aircraft will disrupt the ozone layer in the stratosphere, thus increasing the ultraviolet solar radiation at the ground and increasing the incidence of skin cancer. Most scientists agree that this is a question that should be studied, and that a program of stratospheric monitoring should be started immediately. However, few scientists would be prepared to comment on the validity of the theory. A related uncertainty concerns the possibility that aircraft vapour contrails are increasing the incidence of high cloudiness. Some investigators claim to have found a trend over the last several decades, but the evidence is not very convincing. One observational problem is that some clouds that were classified as Cirrus in the 1940s may now be recorded as Altostratus or Altocumulus. Principal difficulties in the study of stratospheric effects related to ozone and water vapour are due to:

a) the fact that the chemical reaction rates have not yet been established in some cases (the continuing laboratory work by Prof. H. Schiff and colleagues at York University is of fundamental importance); and

b) the fact that current stratospheric models neglect the dynamic effects of man-made changes (Study of Man's Impact on Climate, MIT, 1971). Ozone destruction might be over-compensated for by an increase in the downward transfer of ozone from higher levels, for example.

As for the climatic effects of upward trends in CO_2 and particulates, an increase in atmospheric CO_2 should, acting alone, cause an increase in world temperatures, due to the so-called "greenhouse effect". An increase in suspended particulate matter, on the other hand, should cause surface temperatures to fall. Furthermore, there are interactions with various atmospheric processes, resulting in changes in cloudiness, in average trajectories of storms, in snow cover, etc. The net result is difficult to predict, and the scientific community is not yet prepared to speculate on the future trends in climate. In this connection, one must not overlook the year-to-year variability in stratospheric particulate loading. Lamb (1970) has produced a careful chronology of volcanic activity since the year 1500, and he finds a weak statistical relation between the presence of stratospheric dust veils and below-normal surface temperatures. For example, the three coldest summers between 1780 and 1960 at New Haven, Connecticut were all notable dust-veil years, and this effect was found also in Japan in the years 1695, 1755, 1783, and 1838. However, Lamb was also able to cite a number of exceptions.

The observational data indicated that there was a rise in world surface temperatures in the early part of this century, but a fall after about 1940; this pattern is not necessarily true for individual locations, though, because of changes in cloudiness, etc. Some unpublished Canadian results (M.K. Thomas, personal communication) are given in Table 7. The Toronto mean temperature has certainly decreased, but there has been little change at Victoria, and a rise at Edmonton. Whether these trends are due to pollution effects or to natural climatic variability is uncertain. In addition, Lamb (1970) notes that the first half of the twentieth century was remarkably free of stratospheric dust.

The solution to this great environmental riddle will be to sponsor Canadian research (e.g., into methods of controlling automobile emissions). This situation is gradually changing, and some industries are either undertaking or sponsoring applied research – through provincial research councils and foundations, for example.

Table 7 – Temperature means (°F) at a number of Canadian locations (airport data in most instances)

Location	1931-1960	1960-1969
Victoria	50.2	50.1
Vancouver	50.4	49.8
Prince George	38.0	38.5
Calgary	38.4	38.5
Edmonton	36.9	37.5
Regina	35.9	36.1
Winnipeg	36.5	35.8
Moosonee	30.1	29.8
Windsor	48.8	47.8
Toronto	46.0	44.8
Ottawa	42.2	42.1
Montreal	43.8	43.2
Quebec	41.2	39.3
Inoucdjouac	19.5	19.8
Fredericton	41.7	41.5
Yarmouth	44.9	43.8
Charlottetown	42.0	41.4
Gander	39.7	39.7
Goose	32.4	32.6
Dawson	23.6	23.0
Coppermine	11.5	11.0
Chesterfield	11.2	10.9
Frobisher	15.9	15.8
Resolute	2.8	2.3

V. Action to Preserve or Restore Air Quality

These are exciting times for the air pollution control and research communities. Some recent developments include the following:

a) In 1971, Canada established a new federal department, Environment Canada, and passed a Federal Clean Air Act.

b) An Environmental Secretariat and an Associate Committee on Scientific Criteria for Environmental Quality have been established within the National Research Council of Canada.

c) Interdisciplinary groups are being formed in the universities and at all levels of government in this country.

d) Citizens' groups such as Pollution Probe and SPEC have emerged as forces in shaping public opinion.

e) International agencies have become responsive to global environment problems. The United Nations' 1972 Stockholm Conference on Problems of the Human Environment was a major event. Mr. Maurice Strong, former president of CIDA, was Secretary-General of the Conference. He had a difficult task blending the differing aspirations of the developed and developing countries for a clean environment and for economic growth. However, the Conference did finally result in a Declaration on Environmental Human Rights, approval in principle for an integrated global monitoring network, and an increased public awareness of the complexity of environmental problems.

The UN Conference has provided the impetus for many international activities. A major workshop sponsored by MIT on the effects of pollution on climate was held near Stockholm in July 1971; the workshop produced a book, *Inadvertent Climate Modification*, which was published by MIT in 1971. As another illustration, the International Council of Scientific Unions has recently formed a Scientific Committee on Problems of the Environment. SCOPE held its first General Assembly in September 1971 in Australia, and is expected to play a major advisory role in international environmental activities. A Canadian National Committee for SCOPE has been formed.

Inter-governmental agencies, too, have taken new initiatives in the last two years. UNESCO has launched the MAB program (Man and the Biosphere), while FAO, OECD, WHO, WMO, NATO and other agencies have developed relevant activities. In particular, the World Meteorological Organization is in the process of organizing a network of baseline pollution stations. Environment Canada has agreed to participate in this monitoring program, and ten stations are being established at such isolated locations as Sable Island and Weather Ship Papa.

Countries such as Canada and Sweden still have time to examine dispassionately the various pollution source-sink and stress-response relationships, without the sense of urgency that characterizes much of the work in the United States. In this connection, we must remember above all else that ecological systems must be examined in total. Quick engineering solutions suitable for application to small components of an ecosystem may treat the symptoms without curing the causes of environmental degradation.

Explanation of acronyms used in this chapter:
CIDA – Canadian International Development Agency
FAO – Food and Agriculture Organisation (UN)
MAB – Man and the Biosphere
MIT – Massachusetts Institute of Technology
NATO – North Atlantic Treaty Organization
OECD – Organisation for Economic Cooperation and Development
SCOPE – Scientific Committee on Problems of the Environment
SPEC – Society for Pollution and Environmental Control (Vancouver)
UNESCO – United Nations Educational, Scientific and Cultural Organisation
WHO – World Health Organisation (UN)
WMO – World Meteorological Organization

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