AN URBAN VENTILATION MODEL APPLIED TO MONTREAL

by

Peter W. Summers

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

Department of Meteorology,
McGill University,
Montreal.

April 1964

Montreal from the Mount Royal Lookout

EXTREMELY POOR VENTILATION - 0935 EST 29 November 1962. Anticylonic Weather. Mixing Depth 350-400 ft. Soiling Index 10.7 Coh units.

EXCELLENT VENTILATION - 1400 EST 9 March 1963. Several hours after the passage of a cold front. Wind Speed 15 mph. Estimated Mixing Depth 3500 ft. Soiling Index 0.8 Coh units.

PREFACE

This study started as a result of data collected by Weather Engineering Corporation of Canada Ltd. in 1960. The author wishes to thank Mr. B.A. Power and Mr. P.J. Denison of this Company for, 1) their helpful ideas, discussions and encouragement in the initial stages of the project, 2) permission to use their data and 3) for allowing part-time attendance at McGill whilst still in their employ.

The co-operation of the Meteorological Branch in providing the punched cards and other data tabulations is gratefully acknowledged, as also is permission from the Provincial Health Dept. for use of the data from the Botanical Gardens meteorological tower.

The Canadian Broadcasting Commission co-operated by providing facilities for a smoke sampler in their building atop Mount Royal.

Help with computer programming was provided by Miss M. Macfarlane and Mrs. U. Manley.

Mr. P. Hamilton gave considerable assistance in maintaining the two McGill University smoke samplers and also helped with temperature and visual observations from Mount Royal.

The careful drafting of the diagrams was performed by Mrs. P. Forgacs and the final manuscript was typed by Miss B.J. Stevens.

Many useful ideas, helpful advice and personal observations were freely given by members of the staff and students of the Department of Meteorology. In particular the author is indebted to the supervisor of this project, Dr. J.S. Marshall, for his continued encouragement and stimulating ideas.

ABSTRACT

Time variations of soiling index at three locations in central Montreal are analysed. The average week end reduction in smoke is about 20 percent. Readings adjacent to Mount Royal Park are reduced by nearly one half, but no attempt is made to separate out the effects of the Park acting as a smokeless zone, and the mountain acting as an obstacle to the wind flow. Data from the elevated location, together with visual observations, suggests that at night the smoke over the city is usually confined to a layer several hundred feet deep. A simple model is developed to consider the modification of stable air as it moves across a city acting as a heat and smoke source. An adiabatic mixing layer of increasing depth builds up due to the accumulation of heat. Applying this model indicates that half of the smoke in mid-winter is due to heating of buildings.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 The Air Pollution Problem

Air pollution can be defined as "the presence of unwanted material in the air"; or more rigorously by the Engineers Joint Council of the U.S.A. as "the presence in the outdoor atmosphere of one or more contaminants, such as dust, fumes, gas, mist, odour, smoke or vapour, in quantities, of characteristics, and duration such as to be injurious to human, plant, or animal life or to property, or to interfere unreasonably with the comfortable enjoyment of life and property".

Since the discovery of fire, Man has been polluting the Earth's atmosphere at an ever increasing rate until today, when recent estimates (Rupp 1956) put the total annual emission of major contaminants over the United States alone in excess of 3×10^9 metric tons (see Table 1.1).

Table 1.1 Estimates of annual emission of major air contaminants in the U.S.A.

Pollutant	Million Tons (metric)
Carbon dioxide	3000
Carbon monoxide	50
Vapours and gas (hydrocarbons, oxides of nitrogen, flourides, etc.)	40
Sulphur oxides	20
Industrial dust	6
Smoke (Carbon)	5
Natural dust	30
Pollen	1

There are numerous references in the Bible to brimstone and sulphur as a form of punishment, and also Abraham "beheld the smoke of the country go up as the smoke of a furnace" (Genesis, XIX.28). However, for the first several thousand years of Man's life as a civilized being, atmospheric pollution was not a serious problem because of the low population density and the essentially rural life he led. By the 13th century A.D. concentrations of population were beginning to develop in a few strategically located cities, in particular London, England, where in 1273 the use of coal was prohibited as being "prejudicial to health". A Royal Proclamation issued in 1306 prohibited artificers from using sea-coal in their furnaces. Evidently the authorities in those days were much tougher because the execution of one such offender is on record! One year later a Commission of Inquiry was appointed to "inquire of all such who burnt sea-coal in the city or parts adjoining, and to punish them for the first offence with great fines and ransoms, and upon second offence to demolish their furnaces". In 1578 Queen Elizabeth I "findeth hersealfe greately greved and anoyed with the taste and smoke of the sea-cooles".

The first treatise on the problem of air pollution was submitted to King Charles II by John Evelyn (1661), one of the founding members of the Royal Society. He described it as the "hellish and dismal cloud of sea-coal which maketh the City of London resemble the suburbs of Hell". After discussing in detail the nuisance and medical effects of smoke and sulphur, Evelyn suggested a simple solution. Namely, all the industries, breweries, soap and salt boilers, lime-burners and the like should be banished from London to the other side of Greenwich. He was also in favour of planting trees, shrubs and flowers in planned open spaces. Unfortunately little heed was taken of this work and so with the advent of the Industrial Revolution in the 18th and 19th centuries many areas in Europe and later the U.S.A. began to suffer from severe air pollution problems.

The population began to move from the country to the rapidly growing industrial areas, leading to densely populated working class areas. Added to the burning of coal for home heating was the rapidly increasing consumption of fuel by the newly discovered manufacturing processes. In those days no attempt was made to limit the amount of effluent put into the atmosphere or to use any filtering or cleaning devices on chimneys or smoke stacks.

Although visitors from London raved about the clean air in North America in 1761 and 1775, a century later in 1873 the situation was very different and medical authorities were beginning to get concerned about the air in cities being thoroughly polluted with organic dust, thought to be spores and germs (Godey's Lady Book 1873). At about this time a rather novel solution to the problem was suggested on both sides of the Atlantic (Harpers 1872). The idea was to discharge smoke into the sewers instead of into the atmosphere.

During the early 19th century several committees were set up in England to look into the problems of smoke produced by the steam engine and furnaces. The second half of the 19th century saw many smoke abatement acts passed in parliament leading eventually to the formation of the Coal Smoke Abatement Society in 1899. It was one of the leaders of this society, Dr. Des Voeux, who coined the term smog to describe the thick pea-soup mixture of smoke and fog common to London and other industrial centres in Britain. The use of the term smog has been extended outside of its original context, and is now in common usage as a convenient abbreviation for air pollution, whether or not fog is present.

By the 20th century the problem had become world-wide and all large cities and urban areas were affected to some extent. During the first half of this century many committees studied the problem in England and further acts were passed, but the use of coal continued as the main fuel, particularly for domestic heating. The first smokeless zone was established in Coventry in 1951 almost 300 years after Evelyn had envisioned the idea!

Air pollution continued to be thought of as a necessary evil and the price to be paid for living in an industrial era, even though millions of dollars worth of damage was inflicted on property and vegetation and the smells were sometimes objectionable. The health dangers were not fully realized until it was definitely established that severe smog episodes had caused death. Among the more notable cases were in the Meuse Valley, Belgium, in December 1930 (Dehalu et al. 1931); Donora, Penn., U.S.A. in 1948 (U.S. Public Health Service 1949) and finally the now famous and catastrophic smog in London, England, in December 1952 (Absalom 1954, Wilkins 1954 and Martin 1959). It has been estimated that at least 4000 deaths could be directly attributed to this last episode, and that many tens of thousands more suffered acutely from all kinds of respiratory diseases and complaints. It is of course much harder to determine the medical effects of prolonged exposure to moderate levels of pollution, but studies indicate that the death rate due to bronchial diseases is much higher in urban and industrialized areas than in rural and underdeveloped areas (Manos 1957). This problem has now become of great concern to the World Health Organization (1961).

The growing concern of cities in the southern hemisphere is illustrated by Sullivan (1962) in a paper entitled "Sydney: Potential Los Angeles of the Southern Hemisphere".

In some areas of the world separate metropolitan areas have almost expanded to the point where they will be joining with adjacent areas to form huge urban areas or a conurbation descriptively called a Megalopolis by Landsberg (1962). Thus the problems of large-area pollution will soon expand to entities an order of magnitude larger. Examples of Megalopoles in the making are the region along the Atlantic Seaboard of the U.S. from Richmond, Virginia to Portland,Maine, the Midlands including the Black Country of England (so called with good reason) and the Ruhr region in Germany.

Since World War II there has been a rapid industrialization of this country due to the tremendous growth of the oil, mining and manufacturing industries to the point where Canada now ranks 6th in manufacturing output for the nations of the world but still only 27th in total population. This in turn has produced a remarkable growth in urban populations, with some of the medium-sized cities doubling their populations in the last decade. Large concentrations of industry have grown up in and around the two largest metropolitan areas of Montreal and Toronto having respective populations of just over and just under 2 million. Although Canada may have a long way to go before developing Megalopoles referred to above, there are early indications of such regions beginning to form, in particular along the Oshawa-Toronto-Hamilton-Niagara belt around the west end of Lake Ontario, and again in the St. Lawrence Valley between Montreal and Kingston (Katz 1961). Both these examples are in regions where the topography of a shore line or valley has important effects on the meteorological variables producing atmospheric dispersion of pollutants. A complete survey of Air Pollution problems in Canada and the work currently in progress has been published recently (Katz 1963).

1.2 Meteorological Aspects

The cycle of pollution in the atmosphere goes through three phases:

1) Emission of gases and particulates, produced as by-products of combustion and of chemical, nuclear and biological processes, from various sources ranging from a single stack to a whole urban area.

2) Transport and diffusion of this material by the atmosphere.

3) Deposition of this material causing damage to health and/or property when it comes into contact with humans, animals, vegetation and property.

A study of this complete cycle involves all the branches of science. Meteorological factors are important in all three stages.

The emission of pollution caused by the burning of fuel to heat buildings is directly related to the outside temperature and will be shown to be the major single source of urban smoke in the cold Canadian winter. Although not man-made, some allergy producing pollens are only released into the atmosphere under certain temperature and humidity ranges. After deposition particulate pollution and dust can be re-entrained into the air by strong winds. The effective stack height for a chimney source of pollution is very dependent on such factors as temperature, stability and wind speed.

Receptor effects are also sometimes dependent on the prevailing weather. Corrosion of metal and synthetic materials is humidity dependent. Photo-chemical reactions under bright sunlight produce secondary pollutants such as the famous Los Angeles type smog. Moisture in the air can also produce sulphuric acid from suphur dioxide -- a fairly common pollutant, (see Table 1.1).

The meteorologists main interest is in the transport phase of the pollution cycle and the basic question he is called on to answer is simply this -- Given a source emitting some contaminant at a known rate and at a known height above the ground, then how do meteorological parameters affect the concentration of this contaminent at some receptor downwind?

The first serious study of the diffusive capacity of the atmosphere was made by Taylor (1915). After 7 months aboard a ship measuring the temperature and humidity above the cold water over the Grand Banks off Newfoundland, Taylor accounted for the modification of the air masses as they moved out over the water by vertical transfer processes analogous to molecular conductivity. The eddy conductivity of turbulent transfer turned out to be ten thousand times greater than its molecular counterpart. Shortly after World War I,an extensive study of atmospheric diffusion was initiated at the British Army's Defence Research Establishment at Porton on the Salisbury Plains of southern England. This work was a direct outcome of the use of gas warfare for the first time in the war. Little was known at that time other than the empirical evidence that both light winds and stable lapse rates tended to inhibit rapid diffusion. During the next 20 years Taylor at Porton and Schmidt in Austria continued to study the vertical and horizontal diffusion of heat, water vapour and momentum. It became obvious gradually that the exchange coefficient (or as Schmidt called them Austausch koeffizienten) were not in fact constant and the analogy with molecular diffusion was eventually abandoned in favour of a statistical model. This new approach was first suggested by Taylor (1921) and further developed by Richardson (1926) and Sutton (1932) leading to the "Gaussian Plume" model. The last 30 years has seen many refinements in the theory and its application to experimental work in wind-tunnels, the many measurements of vertical wind and temperature profiles taken over various earth surfaces, evaporation and the transport of water vapour and pollution problems.

The study of diffusion of material from a point source received an urgent impetus with the development of nuclear reactors after World War II. Because of the possibility of the leakage of small, but still potentially dangerous, amounts of radio-active material from reactor sites, even more extensive studies of diffusion were initiated at such places as the Brookhaven National Laboratory in the U.S.A. All of this work has been brought together in three recent textbooks: Sutton (1953), Priestley (1959) and Pasquill (1962).

The currently accepted models of atmospheric diffusion are substantiated by a vast amount of experimental data (Pasquill 1962) and give good estimates of diffusion from point or line sources in all but extreme situations of weather and/or topography.

The underlying assumptions in these models are 1) uniform flow over a smooth surface; 2) lapse rates near the adiabatic and 3) distances of not more than ten miles. Unfortunately the problems of urban air pollution are concerned with diffusion of contaminants emitted from thousands of point sources distributed over large areas with distances involved often greater than ten miles. Furthermore, the worst air pollution situations usually occur in extremes of weather and/or topography when the diffusion models break down. The most recent example of this is from Denver, Colorado, U.S.A. An interesting phenomenon of a bank of smog oscillating back and forth across the city under the influence of valley winds has been described by Crow (1964). A new approach is, therefore, required in the study of large area pollution, and several have been attempted recently. Most of these are empirical prediction models based on observational data.

From 1920 on, a large amount of information had been collected about pollution at a few fixed points in each of several large towns in England. Whilst these data gave a useful measure of long term trends in pollution, they were of little use in comparing one town with another until much more was known about the spatial distribution within any given town. The first study of distribution of pollution over a large area was conducted in Leicester, England, during the three years 1937-39 (Dept. of Scientific and Industrial Research 1945). Pollution by smoke and sulphur dioxide was related to wind speed and Richardson's Number, and empirical prediction equations were obtained. The next intensive study was made in Los Angeles in the years following World War II, the results of which are contained in the reports of the Stanford Research Institute (1954). In these and other studies the roles of the semi-permanent inversion caused by subsidence in the Pacific high pressure cell was brought out as an important factor (Edinger 1958). Although meteorologists fully realize that horizontal ventilation by wind is just as important a factor, "the inversion" is often used in the popular literature as the scapegoat for all air pollution problems. During the last decade extensive studies have been made in many large cities in the U.S.A. and the spatial distribution of pollution in cities is well documented.

In January 1949 a special International Joint Commission was set up to study the problems of pollution in the Detroit-Windsor area (I.J.C. 1960). Using multiple correlation techniques, empirical prediction equations were obtained for predicting daily mean concentrations of suspended particulates in terms of wind speed, departure from mean temperature and rainfall. This work is described in more detail by Baynton (1956). Frenkiel (1956) applied the theoretical formulae of single-source diffusion to a simulated area source consisting of the integrated effect of many point sources.

Lucas (1958) using Sutton's (1947, 1950) formulae obtained an approximate formula for the concentration of SO_2 (and smoke) over a city due to the emission from an area source. By putting in a linear variation of emission from the edge to the centre of the city as a first approximation to the actual source density, Lucas arrived at a cross-city distribution that compares favourably with those observed in such places as Leicester.

Pooler (1961) applied an empirical diffusion model to SO_2 data obtained in Nashville, Tenn., U.S.A., to compute patterns of mean monthly relative concentrations from the standard climatological summaries of wind speed and direction obtained from the Nashville Weather Bureau Station. Munn (1959) has applied Sutton's diffusion equations to the phenomena of the morning fumigation in order to derive criteria as an aid to town planning. The electronic computer is currently being used to simulate various multiple source configurations (Hilst 1961, Pooler 1961) and evaluate their effects on downwind concentrations.

In this study the importance of the "urban heat island effect" will be discussed. Over a large urban area this effect modifies the temperature structure to a height of several hundred feet at night producing a layer in which the pollutants are strongly mixed in the vertical. Changes in the ground level concentration of pollution can then be related to the rate at which the pollution is being produced, the rate at which it is being removed by the horizontal wind flow and the height of the mixed layer.

1.3 Air Pollution Measurements in Montreal

For many years local residents have been aware that Montreal is a smoky city, a fact which is brought home forcibly in the winter months on returning from the Laurentian Mountains. As one approaches the city from the open countryside snow lying on the ground gradually changes from pure white to off-white and finally a dirty grey in the city proper. Many civic minded groups have complained about the smoke and frequent annoying odors which plague the city from time to time. Meteorologists working at the International Airport, eight miles west-southwest of the city centre, are quite familiar with the smoke that drifts in across the airfield in a northeast wind flow and frequently limits VFR flying.

Although dustfall data have long suggested that Montreal has the highest readings in Canada (see Table 1.2), and approaches some of the worst areas in the United States and United Kingdom, no other measurements of such pollutants as suspended particulates or gases were taken or at least published by 1960.

Table 1.2 Mean Monthly Dustfall in Various Cities (after Katz 1963)

CITY	YEAR	MEAN CORRECTED DUSTFALL (tons/sq.mile/month)
Canada		
Montreal	1960	60
Windsor	1955	55
Sydney	1958	53
Toronto	1956	50
Winnipeg	1958	49
Hamilton	1958	34
Ottawa	1956-57	31
Vancouver	1957	21
United States		
New York	1956	85
Detroit	1956	67
United Kingdom		
Glasgow	1954	73
Birmingham	1954	93
Manchester	1954	97
London	1954	112

In January 1960 measurements of the soiling index were commenced at the offices of Weather Engineering Corporation of Canada Ltd. in a residential-commercial district of central Montreal. Within a few weeks it became obvious, first that, readings were very high and on a par with those obtained in some of the smokiest cities in the U.S., and second, that the meteorological conditions producing the smokiest conditions were often very different from the classical anticyclonic pattern. Some preliminary findings were presented at the First National Congress of the Canadian Branch of the Royal Meteorological Society (Denison, Power and Summers 1960). This prompted the City of Montreal and the Public Health Authorities to step up their programs of air monitoring within the City. Also a group of Industrialists set up an association to measure the extent to which the East End Industries were contributing to the problem. Neither of these groups ~~have~~ has as yet published any reports. Early in 1961 the McGill Observatory installed smoke samplers on the campus and atop Mount Royal and data from these plus that from the WEC sampler are all that are currently available to the public or for analysis in this study. Some tentative comparisons between these stations were presented by Summers (1961).

The mean soiling index at the WEC location is 1.97 which will be compared to other locations in Canada and the U.S. in Section 3.1.

The Division of Building Research of the National Research Council of Canada has studied sulphur dioxide in many urban areas across Canada in connection with its corrosive effect on materials (Foran, Gibbons and Wellington 1958). Once more some of the highest monthly values have been recorded in Montreal. Thus all evidence to date points to the fact that Montreal has the most seriously polluted atmosphere of all cities in Canada and that only a few other cities in the United States and the United Kingdom are worse.

1.4 Bibliography

For a fuller introduction to the history and problems of air pollution a short bibliography follows. Much of the material presented in the previous three sections came from these sources.

A. C. Stern, ed. Air Pollution. Academic Press, New York, 1962.

O. G. Sutton. The Challenge of the Atmosphere. Harper and Bros., New York, 1961.

World Meteorological Organization. Turbulent Diffusion in the Atmosphere. Technical Note 24, Geneva, 1958.

U.S.Public Health Service. Air Over Cities. S.E.C. Technical Report A62-5, 1961.

National Society for Clean Air. Clean Air Year Book 1963-64. London, England, 1963.

Advances in Geophysics No. 6, International Symposium on Atmospheric Diffusion and Air Pollution, Academic Press, New York, 1959.

World Health Organization. Air Pollution. Geneva, 1961.

CHAPTER 2

INSTRUMENTATION AND DATA SOURCES

2.1 The A.I.S.I. Smoke Sampler

The equipment used is the Model E automatic spot sampler developed for the American Iron and Steel Institute by Hemeon (1953) and manufactured by the Research Appliance Company of Pittsburgh. This is illustrated in Figure 2.1.

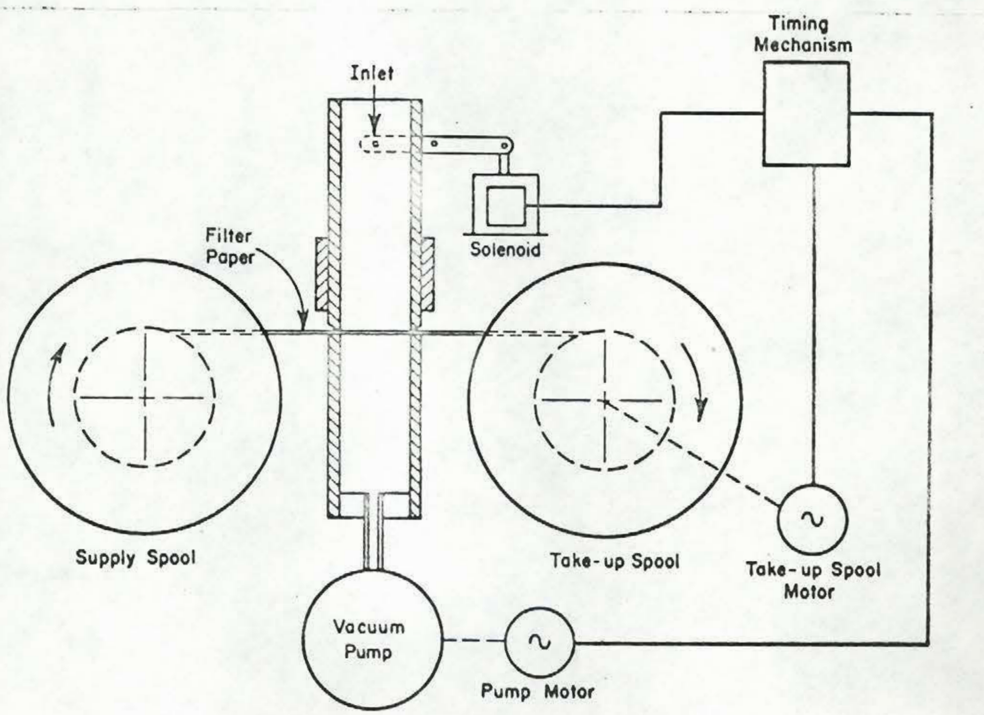


Figure 2.1 Schematic representation of the A.I.S.I. Automatic Smoke Sampler. (from American Society for Testing Materials Designation: D1704-61)

Outside air is drawn in through a given circular area of filter paper at a known flow rate by a reciprocating diaphragm pump. A roll of filter paper tape is held firmly by a clamp that can be released by a solenoid. After the required sampling time a timing mechanism activates the solenoid to release the clamp and a fresh area of filter paper is moved into the airflow. This method of testing for particulate matter in the atmosphere has been adopted as a standard by the American Society for Testing Materials and is described in full in ASTM Designation : D1704-61.

2.2 Evaluation and Units

The soiled spots on the filter paper tape are evaluated by measuring the optical density of the spot with a photometer using a monochromatic 400 mμ source of light. The photometer is adjusted to read 100% transmittance on a clear area of filter paper. A reading is then obtained on the soiled spot. The optical density (O.D.) is evaluated as follows:

$$\text{Optical Density} = \log \frac{I_o}{I}$$

where:

I_o = intensity of light transmitted through clean paper

I = intensity of light transmitted through soiled spot

For comparison with similar samples taken in other locations where the area of the spot or the flow rate of the pump may be different the optical density is converted to a concentration of haze unit (Hemeon, Haines & Ide 1953) called the Coh unit, defined as follows:

$$1 \text{ Coh unit} = 100 \times \text{O.D.}$$

The density of the filter paper stain is dependent on both the area of the spot and the total volume of air drawn through the filter in the sampling time. The size of air sample is, therefore, expressed in linear units of air, i.e., the volume of the air aspirated divided by the cross sectional area of the filter spot. For convenience the volume is expressed in thousands of linear feet. If L is the quantity of air sampled expressed in thousands of linear feet then:

$$L = \frac{\text{flow rate } (ft^3\ min^{-1}) \times \text{sampling time (min)}}{1000 \times \text{area of soiled spot } (ft^2)}$$

The final expression for the amount of smoke is expressed in:

$$\text{Coh units per 1000 linear feet of air} = \frac{\text{O.D.} \times 100}{L} \qquad (2.1)$$

This is now completely independent of the flow rate of the pump, the area of the stained spot and the sampling time. Throughout this study the smoke measurements taken by this method will be referred to as the soiling index and for brevity the units will either be omitted or expressed as Cohs/1000 ft.

2.3 Limitations

a) The artificial introduction of log $\frac{I_o}{I}$ produces a non-linear relation between the percent transmission and soiling index. However, for percent transmissions of less than 50% the relation is approximately linear and so the sampling time should be adjusted to ensure that the optical density seldom exceeds 0.3.

b) Variations in the thickness and quality of the filter paper affect both the flow rate of air through the paper (error 1) and the value of the percentage transmission of light through the paper (error 2). Extensive tests have been made by Stalker et al. (1960) using 11 samplers to determine the amount of both these variations. The flow rates through each of 2 clean areas on four rolls of filter paper selected at random were measured twice. Analysis of this data showed that there was a significant difference in flow rate between the rolls, but that the variations between spots on the same roll were not significant at the 95% confidence level. The range in flow rates was from 0.308 cfm to 0.385 cfm or 22% of the mean value. Similarly it was found that there was a statistically significant variation of the percentage light transmission between rolls and that the standard deviation of the transmission within a roll of clean paper was 2.4%. Tests made on the paper used in this project showed that percent transmission was accurate to within $\pm$ 3%. In terms of the soiling index this is equivalent to an accuracy of $\pm$ 0.3 Cohs/1000 ft. for a two hour sampling time and ± 0.5 Cohs/1000 ft. for a 1 hour sampling time. However, if the photometer was always reset on 100% transmission on the clean paper between each stained spot on the paper the errors were reduced to ± 0.1 Cohs/1000 ft. and ± 0.2 Cohs/1000 ft. respectively. This error is only important for low values of soiling index and is negligible compared to other sources for values in excess of 2.0.

c) A third source of error (error 3) is the decrease in flow rate during the sampling time caused by the deposit building up on the filter paper. Again Stalker et al (1960) has shown that there is linear relationship between flow rate and optical density of the form:

$$q = q_o - KD$$

where q = flow rate through paper having a stain of optical density O.D.

q_o = initial flow rate through clean paper

K = constant

Thus if $\bar{q}$ = mean flow rate for the sampling time

$$\bar{q} = \frac{q + q_o}{2} = q_o - \frac{KD}{2}$$

From tests with 10 samplers Stalker found $K = 0.158$

thus $\bar{q} = q_o - 0.08\ D$

This introduces negligible error for small values of soiling index, 4% error for values of 3.5 Cohs/1000 ft. and 8% error for values of 11.0 Cohs/1000 ft. This is not a random error, since the value of soiling index obtained by Eq.2.1 is always an underestimate.

Table 2.1 Summary of Errors for 1 hour Sampling Time

Soiling Index	Error 1	Error 2	Error 3	Maximum range of Combined Errors
1.0	± 11%	± 20%	- 1%	+ 30% - 32%
3.5	±11%	± 6%	- 4%	+ 13% - 21%
11.0	± 11%	± 2%	- 8%	+ 5% - 21%

Although any one single value of soiling index may be in error by as much as 30% the random errors 1 and 2 can be reduced by dealing with the mean value of a large number of soiling index measurements; and in fact if the errors are normally distributed the total error will be very close to zero for means of 30 or more measurements. The means will still be a slight underestimate (up to 5%) of the true value due to the bias introduced by error 3.

d) Several attempts have been made to correlate the density (D) of smoke stains obtained on filter paper with the mass concentration per unit volume (M) of particulates in the atmosphere. Probably the first was made by Clark (1916) who found a crude relationship between the Owens scale (a graduated grey scale to visually estimate the optical density of a stained spot) with the mass concentration (Owens 1918). The Owens shade has now been replaced by photoelectric reflectence measurements, but the original relationship is still used in the United Kingdom.

More recently Katz et al. (1958) derived a relationship of the form $M = aD^b$ using data obtained in the Windsor-Detroit area. The large particles were removed from the air by a trap containing glass marbles. A large variation of the values of the constants 'a' and 'b' was found among different series of tests.

The most recent work has been done by Sullivan (1962) who used various pre-filtering techniques to remove the coarser particulates. He found that the removal of particles as small as 1μ before obtaining the stain on filter paper made little difference to the optical density of the stain, and confirmed the relationship $M = aD^b$ derived by Katz. He also found that the values of 'a' and 'b', whilst easily reproducible for samples of similar volume, varied considerably from volume to volume. These results were finally combined in an empirical compromise formula

$$M = \frac{a\ (100D)^b}{V^{0.67}}$$

where V = total volume of air sampled (ranging from 22.5 to 45 $ft.^3$).

Thus soiling index measurements can be used to give a mass concentration of particulates less than 1μ size present in the atmosphere and which describe the smoke and haze content of the atmosphere. Particulates larger than 1μ and up to about 100μ, whilst accounting for by far the largest fraction (86%) of the mass concentration of all suspended particulates in the atmosphere, do not contribute to the soiling characteristics of the air.

2.4 Advantages

The mass concentration of all particulates in the atmosphere can be obtained using high volume samplers but under most circumstances these require a sampling time of several hours in order to obtain enough material to weigh accurately. This method is, therefore, unsuitable for correlation with short period meteorological changes.

Gases such as sulphur dioxide can be measured accurately but in an urban area the concentrations are strongly affected by a few large point sources, and are thus not suitable for general meteorological studies.

Soiling index measurements depend on the smoke emitted from thousands of point sources more or less uniformly distributed over the whole of the city area.

Fuel oil which is extensively used in Montreal for domestic heating produces particulates less than 1.0μ (Rossano 1959). Industrial processes produce also particulates greater than 1.0μ, but these will not affect soiling index measurements. Thus as a first approximation the city can be considered as a uniform area source. Smoke samplers are easy to use, can be left to run automatically for several days and produce a measurable stain in a one hour time interval. In spite of the limitations and errors discussed in the previous sections it is felt that smoke is an extremely useful tracer to use for correlating with the behavior of meteorological conditions over a city as a whole.

2.5 Location of Montreal

The St. Lawrence River flows northeast from the Great Lakes into the Atlantic Ocean. To the north lies the Laurentian Shield with an average height of between one and two thousand feet. To the south lie the Adirondacks and the northern end of the Appalachian Chain. The average height of this land is around two to three thousand feet with peaks rising up to between five and seven thousand feet. Near Montreal the flat land of the St. Lawrence Valley, between these two mountain masses, is up to 50 miles wide. Several outcrops of volcanic rock have formed small mounts with heights ranging between 500 and 1500 feet dotting this plain. One of these, Mount Royal, lies in the centre of Montreal rising to a height of 760 feet above sea level.

The river valley has a marked effect on the winds of the area, which are funneled into prevailing southwesterlies and northeasterlies (see Section 2.9). Mount Royal also has a local effect, providing an obstruction to the winds in the central Montreal area.

The City of Montreal is located on a large island situated in the St. Lawrence River at the confluence of the Ottawa River. The Greater Montreal area extends over two smaller adjacent islands and is now expanding rapidly on the south shore of the river. The latest population figures issued by the Dominion Bureau of Statistics in March 1964 put the total population of the Metropolitan Area at 2,205,000 as of June 1, 1963. The map in Fig. 2.2 shows the area that can be considered as being continuously built-up with only small breaks. The outer area consists of mainly single houses in sprawling housing developments and a considerable amount of intervening land. The inner area is more densely populated with multi-story buildings, large apartment complexes and commercial buildings. Most of the heavier industry in Montreal extends along the north shore of the St. Lawrence from the east-end oil refineries, along the dockyards to the Lachine Canal and the Ville St. Pierre area.

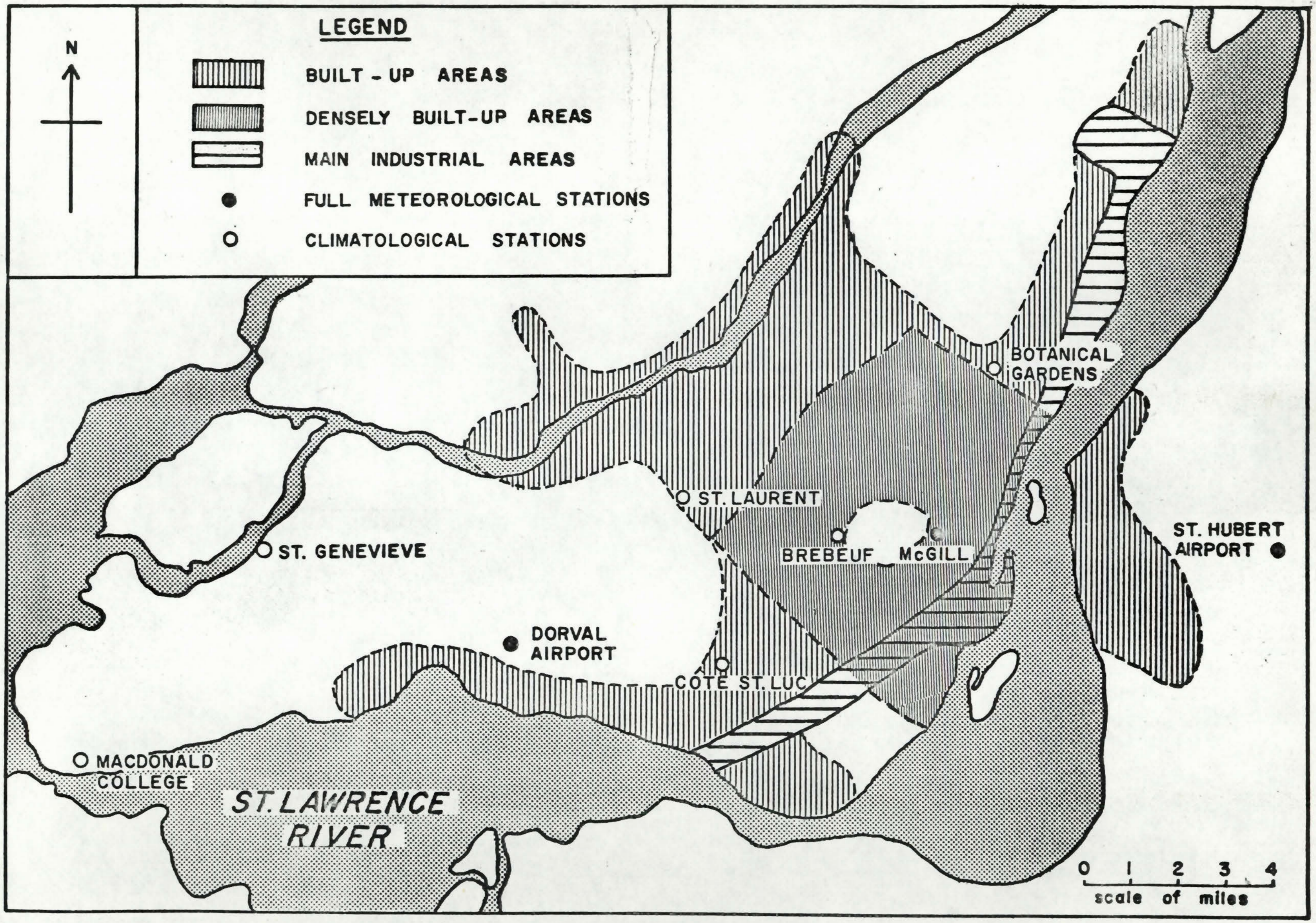


Figure 2.2 Map of Montreal Area showing Land Usage and location of Meteorological Stations

2.6 Location of Smoke Samplers

The location of the three samplers providing data for this study, with respect to Mount Royal and the downtown Montreal area is shown in Figure 2.3. This area in turn is indicated on Figure 2.2 in relation to the larger scale topographical features of the Montreal district.

The height of the air sampling intake is shown in feet above M.S.L. The McGill and Weather Engineering intakes are situated about 35 ft. above the ground, and the CBC intake is 10 ft. above the ground.

The following abbreviations for the samplers will be used throughout:

WEC - Weather Engineering Corporation of Canada Ltd. sampler at 2030 Crescent Street near corner of of Burnside Street.

McGill - McGill University sampler located on the 2nd floor of the MacDonald Physics Building on the Campus.

CBC - McGill University sampler located in the Canadian Broadcasting Commission building on top of Mount Royal.

The WEC sampler is in an old residential part of the City, with a few large apartment blocks and commercial buildings nearby. Many of the older houses have also been converted into small commercial establishments.

The McGill sampler is on the campus with no sources of smoke nearer than 400 ft. on University Street. The only source on the campus itself is the powerhouse stack which is 1000 ft. away to the northwest. This will only affect the sampling site with suitable wind direction and speed to cause a looping plume of the right wave-length. Very few such occurrences have been detected.

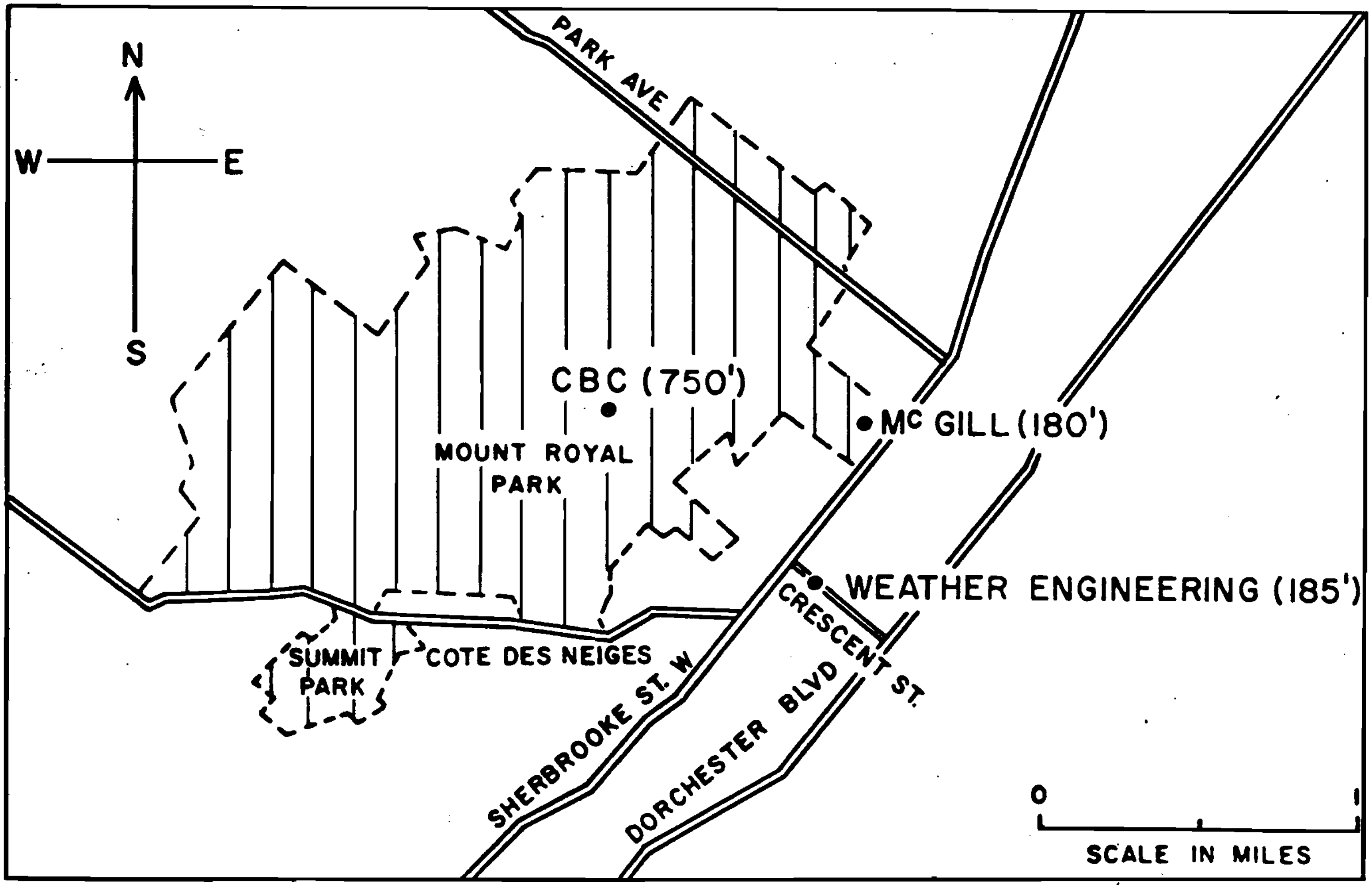


Figure 2.3 Map showing Location of the Three Smoke Samplers with respect to Mount Royal Park

2.7 Sampling Period

The definition of the soiling index introduces a non-linear relation between the optical density and percent transmission for values of the optical density greater than about 0.3 (see Section 2.3a). With the flow rates and soiled spot size available on the samplers used in this study, this value of optical density is frequently exceeded for two-hour samples in the winter months at the WEC and McGill locations. Error type 3 (see Section 2.3c) is also reduced by ensuring that the optical density does not get too high. Thus during the months October through May a one hour sampling time was used at all three locations. One hour samples have the advantage of convenient correlation with meteorological variables, since these are normally tabulated on an hourly basis in published summaries.

During most of the first year of operation the WEC sampler was operated on a two hourly cycle in general use elsewhere. This was however changed to a one hour cycle on occasions when very high soiling indices occured. Thus in any analyses involving one-hour data the period January 1960 to January 1961 has to be omitted.

All samplers were switched over to a two-hour sampling cycle in the summer months in order to keep error type 1 to a minimum (see Section 2.3b).

2.8 Period of Record

Soiling index data ~~is~~ are available from each of the locations as indicated below. Although readings are continuing, only data up to 30th April 1963 will be considered in this study.

	2 hourly samples	1 hourly samples
WEC	15 January 1960 - 31 January 1961	February - May 1961
	June - September 1961	October 1961 - May 1962
	June - September 1962	October 1962 - April 1963
McGill	June - September 1961	February - May 1961
	June - September 1962	October 1961 - May 1962
		October 1962 - April 1963
CBC		March - May 1961
	June - September 1961	October 1961 - May 1962
	June - September 1962	October 1962 - April 1963

For some purposes, such as comparing days of the week, it is necessary to group various months together in order to obtain a statistically large enough sample of data. The seasonal cycle of soiling index suggests the following three groupings:

Winter Months	-	December through March
Summer Months	-	June through September
Transition Months	-	April, May, October, November

2.9 Meteorological Data Sources in Montreal

Based on the records of the McGill Observatory dating back to 1874 a very detailed study of the climate of Montreal was made by Longley (1954). The Observatory is located at the foot of Mount Royal which acts as an obstruction to the general wind flow; as a result various other nearby city locations were tried out from time to time leading to a very erratic and incomplete series of wind observations. Direction frequency and mean speeds have been tabulated for the Observatory for the period 1922-1929 (Department of Transport 1948).

St. Hubert Airport (see Figure 2.2) is in a more exposed location and regular synoptic meteorological observations were commenced there in 1929. Wind tabulations for this station for the period 1929-1941 and the period 1949-1954 have been published (Department of Transport 1948, 1959).

The main meteorological office serving the Montreal area is now at the Montreal International Airport at Dorval (see Figure 2.2). This airport has been providing regular synoptic and hourly weather information since 1941. Again the exposure for wind observations here is unaffected by Mount Royal and the latest tabulations available are for the period 1941-1954 (Department of Transport 1959).

A comparison of the data from these three locations can be made from Tables 2.2, 2.3 and 2.4 which indicates that the main effect of Mount Royal is to increase the frequency of northwesterly winds at the McGill Observatory at the expense of northerly winds. The data ~~is~~ are not concurrent at all three stations, and, therefore, not strictly comparable, so the slight differences in wind speed, cannot be considered significant.

Table 2.2 Wind Direction Frequency and Mean Wind Speeds for DORVAL AIRPORT. (from Dept. of Transport 1959)

Station Montreal (Dorval) (A) Que. Height of Anemovane 76 ft.
Period 1941-1954

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Percentage Frequency													
N	14	11	11	11	10	10	8	10	10	11	11	11	11
NE	19	18	18	16	14	11	8	11	11	14	18	14	14
E	3	4	5	6	7	4	3	3	4	3	5	5	4
SE	5	6	8	8	11	9	8	7	10	8	9	6	8
S	7	6	6	8	12	13	13	10	14	12	8	7	10
SW	25	24	27	25	26	33	37	35	29	26	21	22	28
W	22	26	20	17	13	12	16	15	15	16	20	29	18
NW	4	4	5	9	6	7	6	8	6	9	7	5	6
Calm	1	1	*	*	1	1	1	1	1	1	1	1	1
Average Wind Speed in Miles per Hour													
N	9.4	8.9	9.6	10.0	10.1	8.4	7.4	7.3	7.4	8.3	8.9	8.5	
NE	14.6	14.8	15.6	13.3	12.7	10.7	8.7	10.1	10.4	11.9	13.7	14.1	
E	8.5	9.3	10.5	10.5	9.8	7.2	6.4	6.7	6.8	7.1	8.4	8.2	
SE	12.0	12.5	13.3	13.3	11.4	9.0	8.4	9.2	9.9	10.1	11.4	11.2	
S	10.5	10.1	9.1	9.0	8.7	7.5	8.1	7.1	8.1	8.5	10.3	9.3	
SW	13.8	13.1	12.8	12.3	11.7	10.8	10.2	10.0	10.8	11.7	12.7	13.8	
W	13.8	14.3	13.0	14.1	12.9	12.2	10.9	10.3	11.1	11.5	11.6	12.5	
NW	10.5	10.9	9.9	13.0	11.8	11.5	9.7	9.3	9.5	10.8	11.1	9.4	
All Directions	12.6	12.7	12.5	12.3	11.2	9.9	9.3	9.1	9.7	10.5	11.5	11.9	11.1

Station Information

Airport is located 8 mi. WSW of the centre of Montreal in quite flat open country. The St. Lawrence valley is oriented in an E-W direction in this area.

Table 2.3 Wind Direction Frequency and Mean Wind Speeds for McGILL OBSERVATORY. (from Dept. of Transport 1948)

Station MONTREAL (McGILL UNIVERSITY), QUE.
Period January 1922 - August 1929.

		Jan.	Feb.	Mar.	Apr	May	June	July	Aug.	Sept.	Oct	Nov.	Dec
Percentage Frequency (by directions)													
North	%	8	6	5	7	4	4	6	5	5	9	5	7
Northeast	"	14	20	19	20	20	11	8	11	15	12	14	12
East	"	3	4	5	5	5	4	4	5	7	3	2	3
Southeast	"	4	5	3	5	8	8	6	6	6	4	6	5
South	"	5	7	9	7	9	12	11	7	7	11	7	8
Southwest	"	29	23	21	22	21	26	33	30	29	27	35	28
West	"	20	20	21	15	15	19	17	18	17	14	13	18
Northwest	"	17	15	17	17	14	16	14	18	14	20	18	19
Calm	"	0	*	*	2	4	*	1	*	*	*	*	*
Average Wind Speed in Miles per Hour (by directions)													
North	%	7.6	7.9	10.8	10.8	9.9	6.4	9.1	8.4	9.3	10.8	6.9	11.0
Northeast	"	11.8	11.8	11.4	11.1	10.3	9.6	8.4	7.7	9.5	11.0	8.9	10.2
East	"	10.8	10.2	10.5	10.4	8.1	7.3	6.4	7.2	8.0	9.3	8.4	10.7
Southeast	"	9.6	8.6	9.5	10.5	10.1	8.5	6.2	8.2	9.4	8.4	8.7	9.4
South	"	10.1	11.7	11.8	12.2	9.4	8.3	8.7	7.6	9.9	9.9	10.9	10.0
Southwest	"	11.2	12.1	11.3	12.9	10.7	11.1	9.8	10.2	9.9	10.6	11.4	10.5
West	"	15.1	15.9	16.0	15.5	16.1	13.3	10.9	10.7	11.6	13.4	13.3	15.7
Northwest	"	16.0	14.9	14.4	13.3	14.2	11.7	11.8	10.5	12.8	12.0	12.1	13.9
Average Wind Speed in Miles per Hour		12.4	12.7	12.7	12.4	11.3	10.5	9.6	9.5	10.3	11.2	10.9	11.9

Table 2.4 Wind Direction Frequencies and Mean Wind Speeds for ST. HUBERT AIRPORT. (from Dept. of Transport 1959)

Station St. Hubert (A) Que. Height of Anemovane 58 ft.
Period 1949-1954

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Percentage Frequency													
N	25	24	21	24	11	9	9	17	9	12	16	16	16
NE	8	8	5	4	8	4	3	9	8	7	11	8	7
E	4	6	8	6	5	3	2	4	3	3	4	5	5
SE	4	3	7	6	10	7	4	5	7	7	6	6	6
S	18	14	16	16	20	22	23	21	26	26	23	20	20
SW	14	12	16	20	18	27	33	20	27	21	17	16	20
W	14	20	16	10	7	12	14	12	11	13	13	16	13
NW	9	8	9	13	16	14	10	9	7	9	8	11	10
Calm	4	5	2	1	5	2	2	3	2	2	2	2	3
Average Wind Speed in Miles per Hour													
N	9.9	9.2	11.1	10.4	8.2	6.7	7.6	8.2	8.0	8.3	9.5	8.9	
NE	12.4	13.0	13.0	11.1	10.3	6.9	4.7	10.0	10.8	9.6	13.2	10.9	
E	6.1	7.9	8.6	7.6	7.6	4.5	4.7	4.9	4.8	4.7	7.7	6.7	
SE	7.9	10.8	10.2	9.0	10.3	6.8	7.0	7.2	6.8	8.7	8.7	9.2	
S	15.8	12.3	11.0	11.3	10.1	9.0	8.8	8.9	10.9	10.4	12.6	13.3	
SW	14.1	14.4	13.4	13.3	10.4	10.4	10.5	10.6	11.1	11.7	11.4	13.6	
W	14.4	13.8	12.7	11.1	12.3	12.3	10.1	9.3	10.8	11.3	11.0	10.6	
NW	11.4	11.7	10.4	11.1	11.0	10.7	9.9	9.6	9.0	9.6	10.8	8.8	
All Directions	12.0	11.1	11.3	10.9	9.7	9.3	9.1	8.9	9.9	9.9	10.9	10.7	10.3

Station Information

Airport is located 7 mi. E of Montreal in quite flat country.

* Less than 0.5 percent.

Climatological data ~~has~~ have been obtained at Macdonald College since 1930, and the Botanical Gardens since 1939. Records of certain meteorological data are available from the Geophysical Observatory at Brebeuf College, and also co-operative climatological stations have been operated by the Meteorological Branch, Department of Transport in and around Montreal. Those currently in operation are shown in Figure 2.2

Soil temperatures have not been taken on a regular basis at McGill or any of the other main meteorological stations. Some early records are available from the McGill Campus for a few years at the end of the last century (McLeod 1896, 1902). Since the ground temperature has an important bearing on the stability of the atmosphere above it, the records from Macdonald College were analyzed to obtain the mean

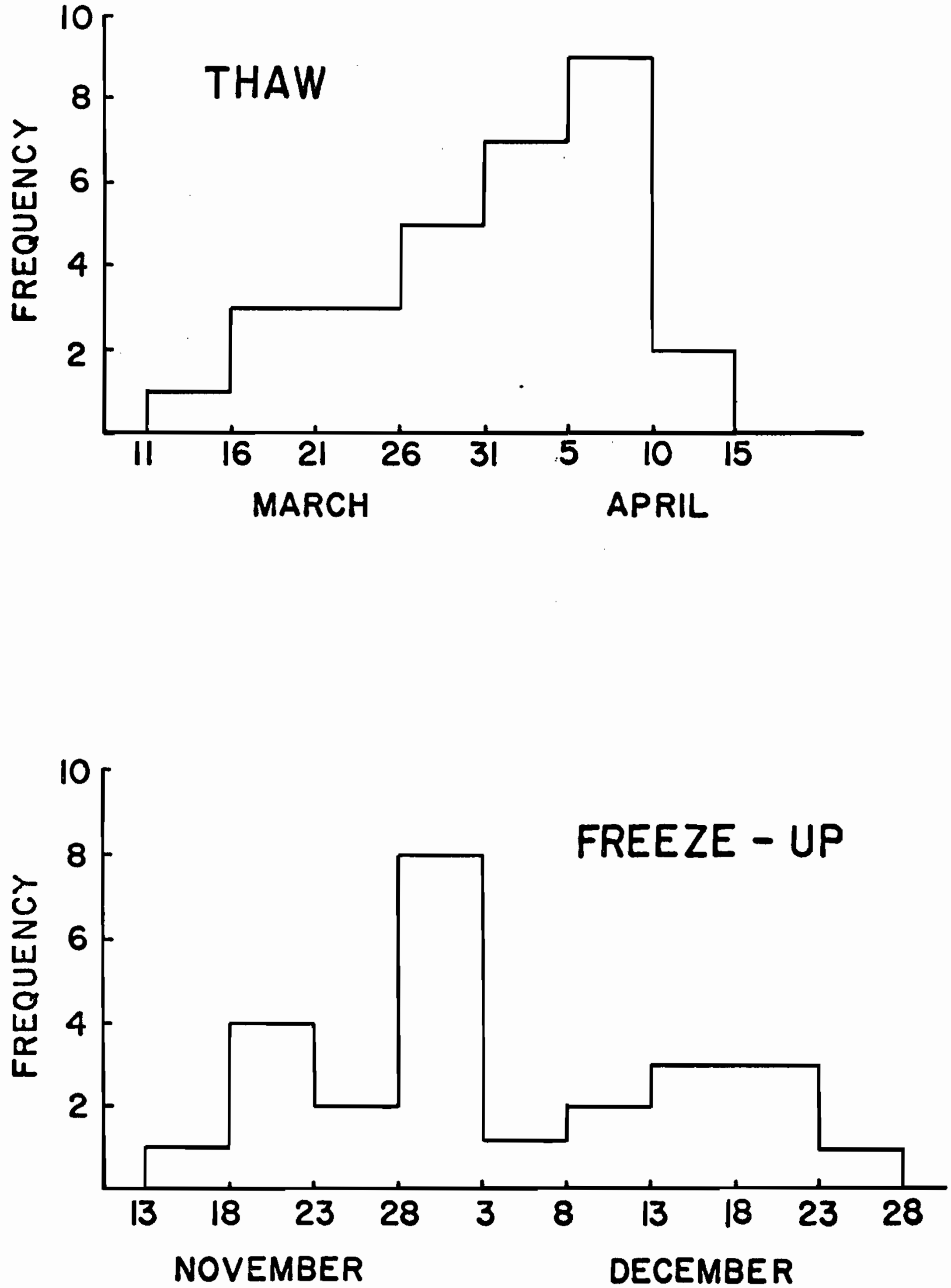


Figure 2.4 Date of Thaw and Freeze-up at Macdonald College 1930-63

date of freeze-up and thawing of the ground. Apart from a few short breaks a continuous record is available since 1930 of the temperatures at four and six inches below the surface obtained with a recording Negretti and Zambra mercury-in-steel thermometer.

During the latter part of October,and through November until freeze-up, there is little discernable diurnal variation in temperature at either level. Both temperatures fall very gradually until eventually the freezing mark is reached. Due to this very slow fall of temperature and scale errors in this recorder, the date of freeze-up so obtained may be in error by as much as one week.

The spring thaw occurs much more dramatically. Typically after several days with the mercury remaining near or just below 32°F the temperature suddenly jumps one afternoon to 35°F or 37°F. This is defined as the date of thaw. From this date on the temperature usually falls back to the freezing mark at night for a period of from two to ten days.

A frequency histogram of the date of freeze-up and thaw is shown in Figure 2.4 based on all the usable data since 1930. The mean date of freeze-up is 5th December, although it has occurred as early as 16th November and as late as 27th December. The date of thaw does not vary quite as widely. The earliest thaw was on 16th March but has been delayed as late as 15th April. The mean date over the 33 years is 1st April.

As part of an air pollution survey being conducted in Montreal by the Provincial Health Department, the ~~Meteorological Branch~~ Division of Industrial Hygiene installed a 200 ft. meteorological tower in the Botanical Gardens in March 1962. Temperature measurements are taken at elevations of 20 and 196 feet above the ground, and wind measurements at 35 feet and 200 feet. Tabulations of hourly temperature differences between the two levels have been made by the Meteorological Branch and for use in this study are available for the period March 1962 to April 1963.

The erection of a new television transmitting tower atop Mount Royal provided an opportunity for the McGill Observatory and the Meteorological Branch to co-operate in the installation of a temperature and wind measuring system. The base of this tower is 740 feet above mean sea-level. Thermometers have been placed at heights of 105 and 290 feet above the tower base, and an aerovane at 300 feet. Detailed tabulations of this data were not prepared in time for inclusion in this study although the observations are available for use in specific case studies.

2.10 Data Processing

Hourly data for Montreal International Airport were readily available on punched cards and so were used as the basic meteorological data in this study. When required, data from the other sources in and around Montreal were obtained from published material and hand tabulated as necessary.

All of the soiling index data for the periods indicated in Section 2.8 were placed on punched cards. Two types of cards were prepared:

1) Soiling Index data only: All 24(12) readings from one sampling station for one day were punched in one card using columns 9 to 80 (9 to 45). The first eight columns were reserved for station identifier, year, month, day and day of the week. An extra day of the week identifier eight was used for statutory and other Quebec holidays.

2) Meteorological and Soiling Index data: A complete set of hourly-observations cards for Montreal International Airport for the period January 1960 to April 1963 was supplied by the Meteorological Branch, with columns 61 to 80 left blank. These columns contain observations of the higher cloud layers which are of no value to this study. The corresponding day of the week identifier, and the soiling index readings for each of the three stations, were transferred from the type (1) card into columns 61 to 70 of these hourly cards. This set of 29,184 cards was used with the IBM 1410 computer at McGill Computing Centre for all tabulations requiring meteorological data. Tabulations requiring soiling index data only were performed with the small sets of type (1) cards.

2.11 Soiling Index Ratings

The New Jersey State Department of Health (N.J. Dept. Health 1958) carried out an extensive State-wide survey of air pollution in 1956 using the A.I.S.I. smoke sampler. Based on informed opinion in the field of air pollution, adjectival ratings were assigned to various ranges of soiling index as given in Table 2.4. These ratings have been used by several other agencies and will also be used from time to time in this report.

Table 2.4 Adjectival Ratings of Soiling Index

Soiling Index (Coh units/1000 feet)	Adjectival Rating
0.0 - 0.9	light
1.0 - 1.9	moderate
2.0 - 2.9	heavy
3.0 - 3.9	very heavy
4.0 plus	extremely heavy

The smoke sampler is in general use through North America and many cities have recorded maximum soiling indices in the range 8.0 to 12.0 for sampling periods of two hours. In Montreal on 14th April 1960 a two-hourly average of 12.8 was recorded between 1900 EST to 2100 EST, and during one half hour period from 1930 EST to 2000 EST a peak of 15.4 Coh units was reached. During a period of forest fires in the fall of 1952 a combination of fire and urban smoke produced a soiling index of 18.0 and a reading as high as 23.0 has been reported from Sydney, Australia.

CHAPTER 3

TIME VARIATIONS OF SOILING INDEX

3.1 The Mean Annual Soiling Index in Montreal

All available data were averaged to obtain the mean monthly values of the soiling index for each of the three sampling locations in Montreal. These 12 monthly means were then used to obtain the annual means shown in Table 3.1.

Table 3.1 The Mean Annual Soiling Index in Montreal

Location	WEC	McGill	CBC
Mean Annual Soiling Index	1.97	1.07	0.42

The most striking feature of these mean values is the large variation between the three sampling locations. Although only half a mile away from McGill, the WEC location is almost twice as smoky. However, the prevailing wind direction in Montreal is west-southwest to west and the map in Figure 2.3 shows that with such winds the air arriving at McGill has spent the last two miles of its trajectory passing over, or skirting around Mount Royal Park, and, therefore, picking up little in the way of smoke (Summers 1961).

The CBC location atop Mount Royal has only about 40% as much smoke as at McGill. This further reduction is due partly, to the effects of elevation, and partly, to the fact that with all wind directions no smoke will be added to the air arriving at this location during the last mile of its trajectory.

A comparison between Montreal and some other cities for which comparable data are available is shown in Table 3.2. It must be remembered though, that data from these other cities will also be a function of the location of the samplers within the city.

It can be seen that the smokiest location in Montreal (WEC) is only exceeded by one of the Ottawa stations, and has a mean soiling index greater than any other reported stations across Canada. This reinforces the suggestion made at the end of Section 1.3 that Montreal has a serious air pollution problem. Also there are very few areas in the United States that have a higher average soiling index than Montreal.

Table 3.2 Comparison of Mean Annual Soiling Index in Various Cities

City	District	Soiling Index	Reference Source
Canada			
Montreal (WEC)	Residential-Commercial	1.97	
" (McGill)	"	1.07	
" (CBC)	Elevated park	.42	
Ottawa (SVH)*	Commercial	1.7	Munn & Ross 1961
" (WRB)*	"	2.2	Munn & Ross 1961
Windsor		1.8	Katz 1963
Vancouver	Commercial	1.11	
Winnipeg	Central business	0.84	
"	Residential	0.38	
Harrow, Ontario		0.60	
United States			
Louisville		2.6	I.J.C. 1960
Pittsburgh		2.0	
Detroit	Urban	1.8	
Minneapolis		1.0	
Berkeley, Calif.		0.7	
Akron, Ohio		0.5	
Camden, N.J.		2.0	N.J. State Dept. Health 1958
Newark, N.J.		1.8	
Nashville, Tenn.	32 Stations	0.53	Stalker & Dickenson 1962

* SVH is St. Vincents Hospital and WRB is the War Records Building both in downtown Ottawa. For exact location see Munn & Ross (1961).

This soiling index has a marked seasonal, weekly and daily cycle and each of these will now be analyzed in some detail.

3.2 Seasonal Cycle of Soiling Index

Figure 3.1 shows the seasonal cycle of Soiling Index at each of the three central Montreal sampling locations with the monthly averages computed from all the available data as listed in Section 2.8. Each point is thus an average of two to four years data. The vertical lines through each point give the absolute range of the monthly averages. The bottom horizontal bar gives the lowest monthly average recorded and the upper bar the highest monthly average.

All three stations have a similar seasonal trend. The lowest soiling index occurs in the summer months and the highest readings in the winter months. Both the Spring and Fall are considered as transition zones when the index is changing rapidly between the two main regimes. The smokiest month occurs in February and the cleanest in July. The transition through the year is quite regular and smooth except for a discontinuity in all three curves in December. At WEC and McGill this shows up as a slowing down in the rate of increase of the Soiling Index and at CBC there is a secondary minimum in December leading to a secondary maximum in November.

As will be shown later the soiling index is related to wind speed in such a way that all other conditions being equal increasing winds cause a decrease in soiling index. During the period considered the mean daily wind speed shows a very sharp increase from 8.0 mph in November to 12.0 mph in December, and this increase in ventilation almost offsets the increase in production of smoke.

The selection of a monthly average for study is quite arbitrary, but is a convenient time unit for tabulation of data. However, any

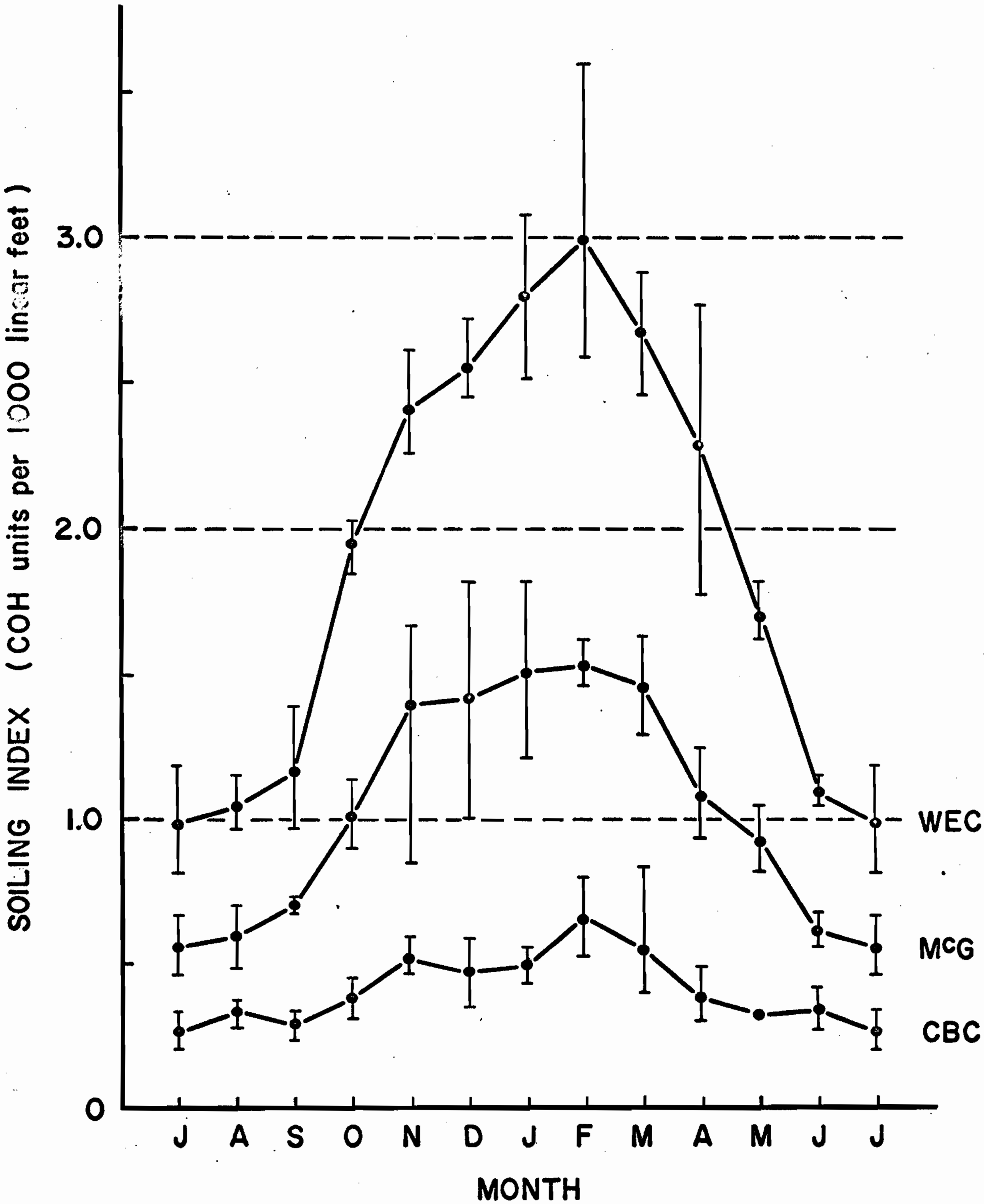


Figure 3.1 Seasonal Cycle of Soiling Index in Central Montreal

significant changes occurring in the middle of the month will be masked. One such change is the marked change in the daytime stability of the atmosphere once the snow cover has disappeared in the Spring.

The amount of smoke in the atmosphere over the City at any given time is dependent on two factors:

a) the rate at which smoke is being emitted into the atmosphere - rate of production

b) the rate at which this is being dispersed and diffused by the atmosphere - the ventilation rate

Both of these factors vary through the year, but a study of the variations in ventilation enables use of the data in Figure 3.1 to provide some information on how the rate of production varies.

3.3 The Weekly Cycle of Soiling Index

There is no detectable weekly cycle of meteorological parameters in the earth's atmosphere. Over a time interval of the order of a few months it is quite possible that a cycle in such elements as wind speed, temperature, cloudiness and precipitation may show up, having a period of between three and seven days. This would be due to the persistence of a certain circulation pattern in the atmosphere,and the period would correspond to the frequency of short wave disturbances passing through the area. However, these patterns seldom persist for more than a few months and so if a long enough sampling time were taken any meteorological cycles with a period of the order of two to seven days should be eliminated. Thus any weekly cycle remaining in the pollution content of the atmosphere will be due to a weekly cycle in production.

In Leicester, England, the ratio of both the smoke content and SO_2 content of the atmosphere on Sundays and Bank Holidays compared to other days averaged between 0.55 and 0.87, and was significantly less than 1.0 at all times of the year (D.S.I.R. 1945).

Munn and Ross (1961) by analyzing smoke observations from Ottawa, Ontario, found a year round reduction in smoke on both Saturday and Sunday as compared to all other days combined together. In Vancouver, B.C., Munn (1961) obtained similar results. No significance tests were made on these results and no information was given on variations among the days Monday-Friday, if any.

Grisollet and Pelletier (1957) carried out a very detailed study of the effects of meteorological elements on smoke, CO_2 and SO_2 in the centre of Paris. The smoke data ~~is~~ are expressed in mg/m^3, and although no significant variation was found in smoke on weekdays, a significant reduction occurred on Saturday, and a further reduction on Sunday. It was concluded that the closing down of many industrial activities accounted for Saturday's reduction, whilst the additional lessening of traffic on Sunday produced a further decrease in smoke.

Twenty years of incoming solar radiation measurements taken at Toronto have been analyzed by Mateer (1961). The readings were taken at the Meteorological Office in the downtown area; in order to detect the existence of a weekly cycle in pollution, the radiation on Sundays was compared to weekdays. The average radiation on weekdays was 305.2 langleys and on Sundays 313.8 langleys, an increase of 2.8% which was found by a χ^2 test to be significant at the 99.5% level.

In order to study the weekly cycle in Montreal, the daily average soiling index was computed for every day when no more than one quarter of the observations were missing. The data ~~was~~ were then stratified according to the day of the week, with statutory and other local holidays omitted. A mean value of soiling index and its standard error ~~was~~ were thus calculated for each day of the week. The results are shown in Tables 3.3, 3.4 and 3.5.

A comparison of the three Montreal locations with Paris, Vancouver and Ottawa is shown Figure 3.2. A logarithmic scale is used for the soiling index and it can be seen immediately that all five

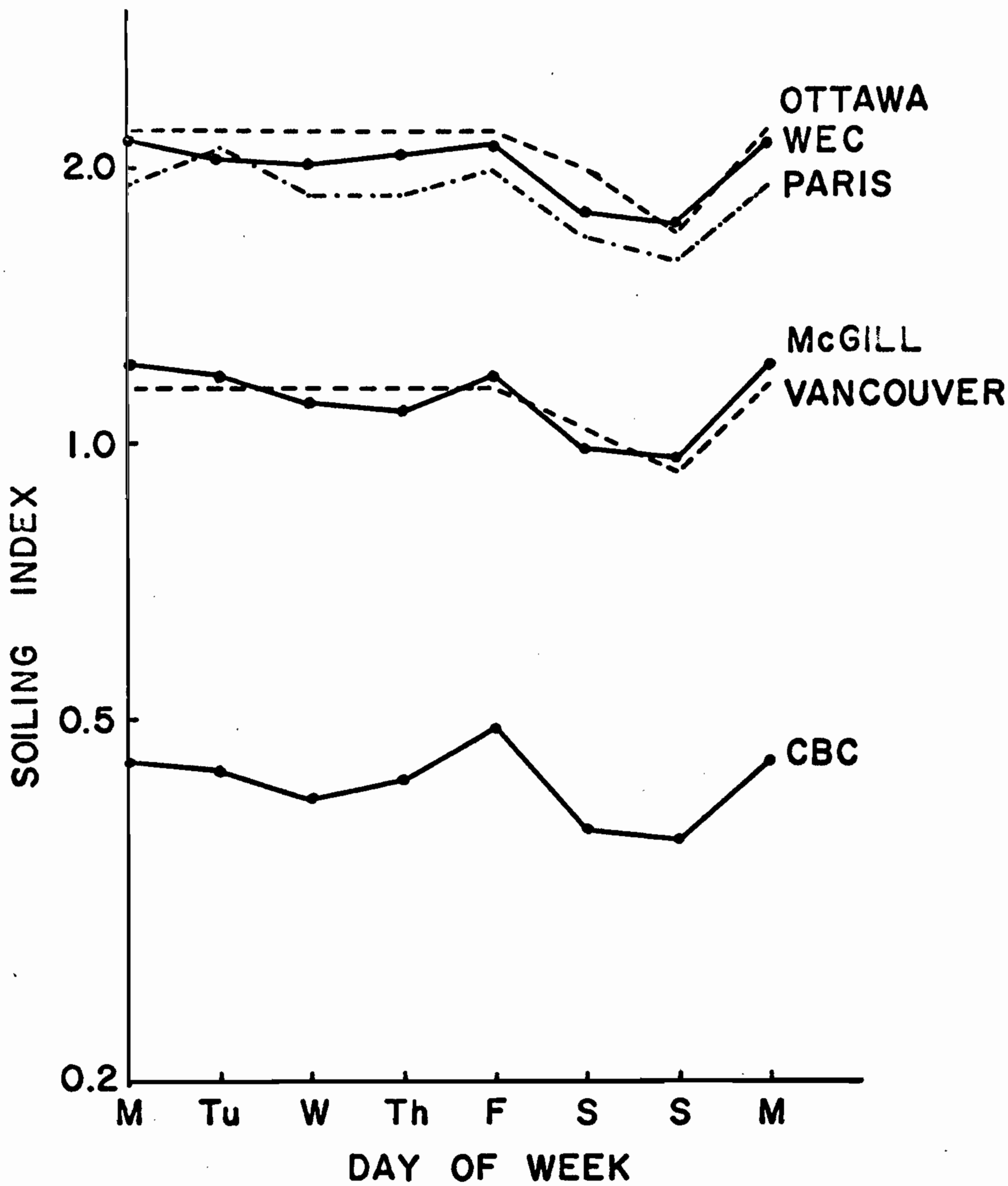


Figure 3.2 Weekly Cycle of Soiling Index in Montreal Compared to Three Other Cities

curves have a very similar shape. There is some variation among the weekdays with a tendency for higher readings at the beginning of the week; i.e., on Monday or Tuesday, and another peak on Friday. All cities show just about the same reduction on Sunday (17 to 23% of the mean weekday value), and a slightly smaller reduction on Saturday.

Table 3.3 Weekly Variation at WEC of Mean Daily Average Soiling Index ($\bar{c}$) and Standard Error of this Mean (s).

Day of Week	No. of Days	$\bar{c}$	s
Monday	103	2.15	1.13
Tuesday	114	2.06	1.13
Wednesday	120	2.02	0.99
Thursday	120	2.08	0.96
Friday	116	2.12	1.14
Saturday	116	1.79	1.00
Sunday	117	1.75	0.97
All Weekdays	573	2.09	1.07

For WEC consider first the weekdays Monday through Friday. Table 3.3 shows a slight day-to-day variation of $\bar{c}$. The maximum difference between weekdays occurs between Monday and Wednesday. Applying the "Students" t-test for comparing the means of two independent samples (Brooks and Carruthers 1953, pp. 66), then t = 0.93, with 221 degrees of freedom, giving a probability of the difference between Monday and Wednesday occuring by chance as 0.16. Thus there is no significant difference between these two days. Since the difference between any other two days will be even less, then it can be concluded that there is no significant variation of soiling index on weekdays. Further, we are now justified in combining all weekdays together into one homogeneous sample as in the last row of Table 3.3

Comparing Saturday with the combined weekday mean, then t = 2.76 with 687 degrees of freedom giving a probability of the reduction on Saturday occurring by chance as less than 0.005. For Sunday the probability of chance occurrence is even less. Thus for WEC the reduction of soiling index on both Saturday and Sunday compared to the mean weekday value is very highly significant.

The difference between Saturday and Sunday is less than between Monday and Wednesday and is non-significant.

Exactly the same analysis can be applied to the data from McGill and CBC shown in Tables 3.4 and 3.5 respectively. Again a non-significant variation is found among weekdays at McGill, with the probability of the difference between the smokiest (Monday) and the cleanest (Thursday) days occurring by chance equal to 0.10. Thus all weekdays are combined as shown in the last row of Table 3.4. The probability of the data for Saturday coming from the same population as the weekday data is 0.03 and for Sunday is only 0.005. Thus the weekend soiling index at McGill is significantly less than on weekdays.

Table 3.4 Weekly Variation at McGill of Mean Daily Average Soiling Index

Day of Week	No. of Days	$\bar{c}$	s
Monday	98	1.22	0.78
Tuesday	111	1.19	0.89
Wednesday	114	1.11	0.74
Thursday	115	1.08	0.73
Friday	110	1.18	0.89
Saturday	112	0.99	0.75
Sunday	111	0.96	0.65
All Weekdays	548	1.15	0.83

Table 3.5 Weekly Variation at CBC of Mean Daily Average Soiling Index

Day of Week	No. of Days	$\bar{c}$	s
Monday	91	0.45	0.30
Tuesday	102	0.44	0.32
Wednesday	108	0.41	0.26
Thursday	107	0.43	0.30
Friday	101	0.49	0.41
Saturday	105	0.38	0.28
Sunday	106	0.37	0.26
All Weekdays	509	0.45	0.32

Similar tests on the CBC data show that the difference between Friday and Wednesday is just significant at the 5% probability level, but that all other differences amongst the days Monday through Friday are non-significant. Again all weekdays are combined and the probability of the observed reduction in soiling index on Saturday occurring by chance is 0.02 and on Sunday is only 0.005. It thus appears that the smoke at a height of 600 feet above the city also has a significant reduction on the weekend. The apparent greater variability during the week may be due to the less accurate measurements of soiling index at the very low values generally obtained on top of Mount Royal (see Section 2.5).

3.4 Daily Cycle of Soiling Index

Since there is a significant reduction in the soiling index over the weekend, the daily cycle will be considered for three separate groups of data. For weekdays a sufficiently large sample of data can be obtained on a month-by-month basis and will be used to study the seasonal change in the daily cycle. Saturday and Sunday data will have to be grouped on a seasonal basis.

Figures 3.3 to 3.14 show the weekday diurnal variations of soiling index for the three locations in Montreal on a month-by-month basis. On each diagram the upper histogram is for the WEC sampler, the middle histogram for the McGill sampler and the lower one for the CBC sampler. The number in parenthesis at the right hand end of the histogram indicates the number of days averaged to form the monthly mean values at each hour.

The bottom two curves show the diurnal variation of temperature and wind speed. The range of time of sunrise and sunset for the month is indicated by the horizontal bar on the abscissa, and the vertical line gives the mean time for the month.

Both the WEC and McGill locations have the same basic well-defined daily cycle throughout the year, but with important changes in amplitude and times of the maxima from month to month. This basic cycle consists of:

a) Two main maxima -- one shortly after sunrise and another near or just after sunset.

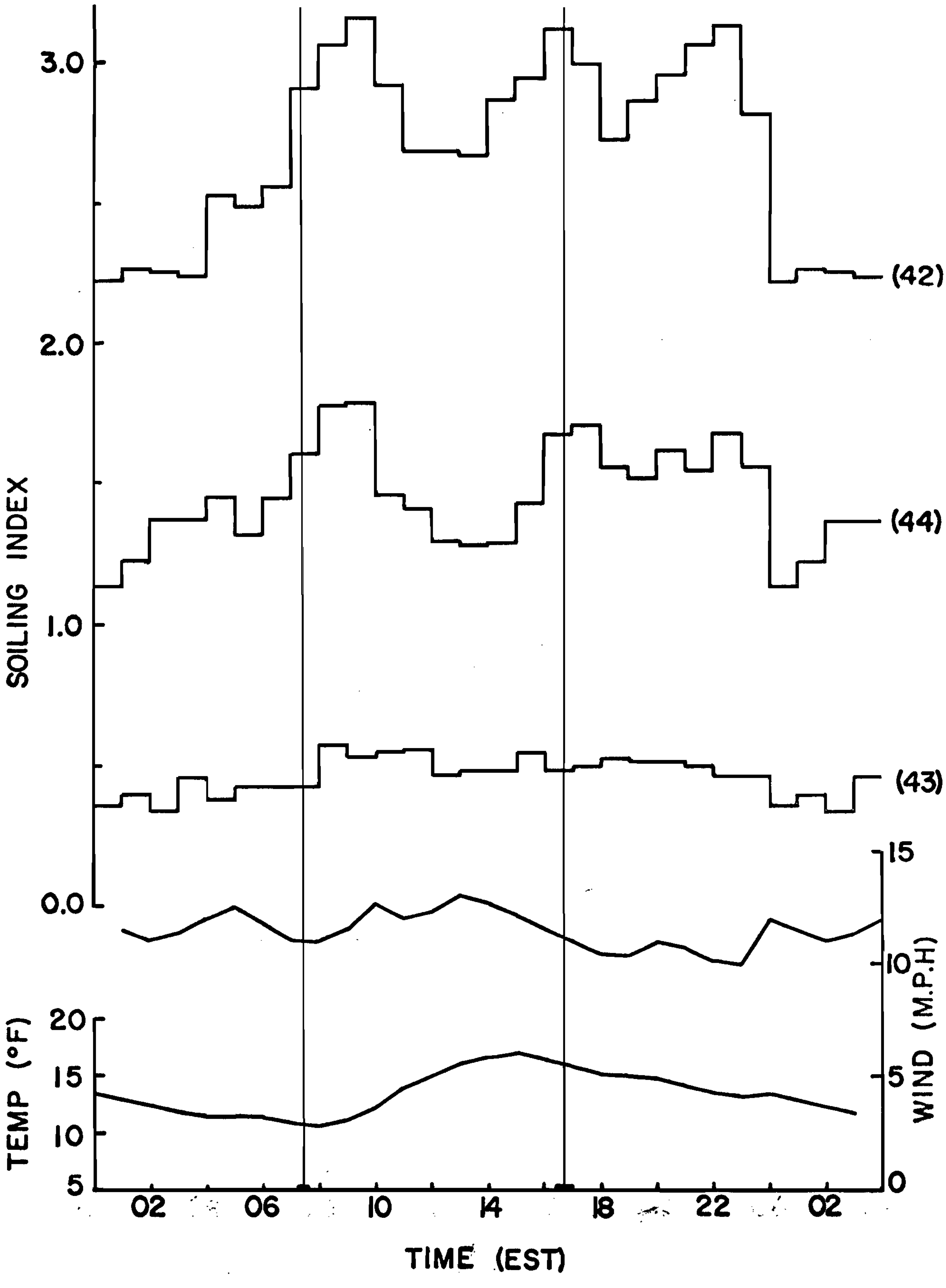
b) Two main minima occuring during the early morning hours and again in the early afternoon.

c) A secondary maximum between 2100 and 0000 EST during the months October through May.

<u>Figures 3.3 to 3.14</u>: The Diurnal Variation of Soiling Index, Wind Speed and Temperature on Weekdays only for the months January to December.

On each of the following figures the upper histogram is the soiling index at WEC, the middle one for McGill and the lower one for CBC. The number in parenthesis at the right-hand end is the number of days of data used. The bottom two curves show the diurnal variation of wind and temperature, each curve being attached to its appropriate scale.

FIG. 3.3 JANUARY



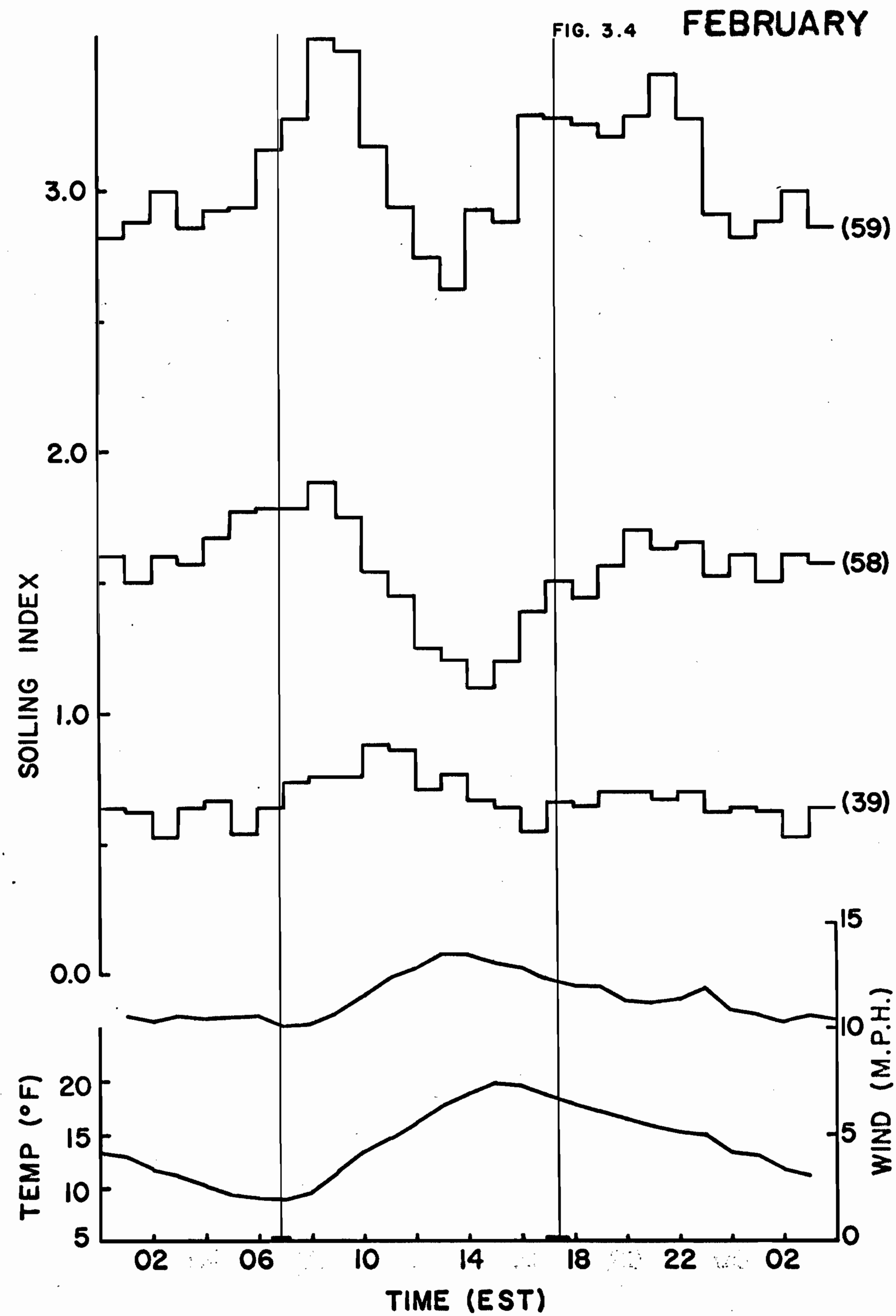


FIG. 3.4
FEBRUARY
SOILING INDEX
3.0
2.0
1.0
0.0
(59)
(58)
(39)
TEMP (°F)
20
15
10
5
WIND (M.P.H.)
15
10
5
0
02
06
10
14
18
22
02
TIME (EST)

FIG. 3.5 MARCH

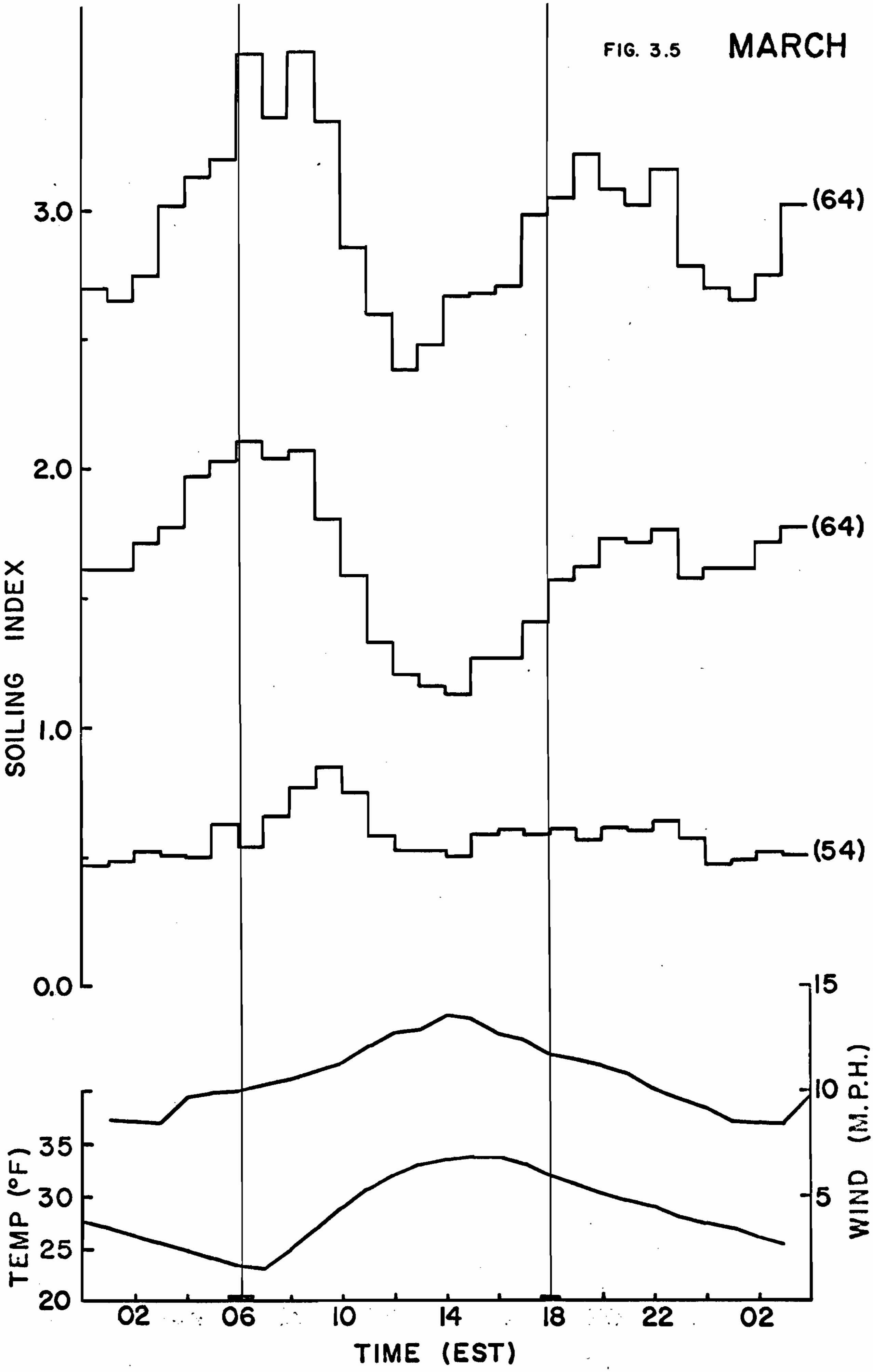
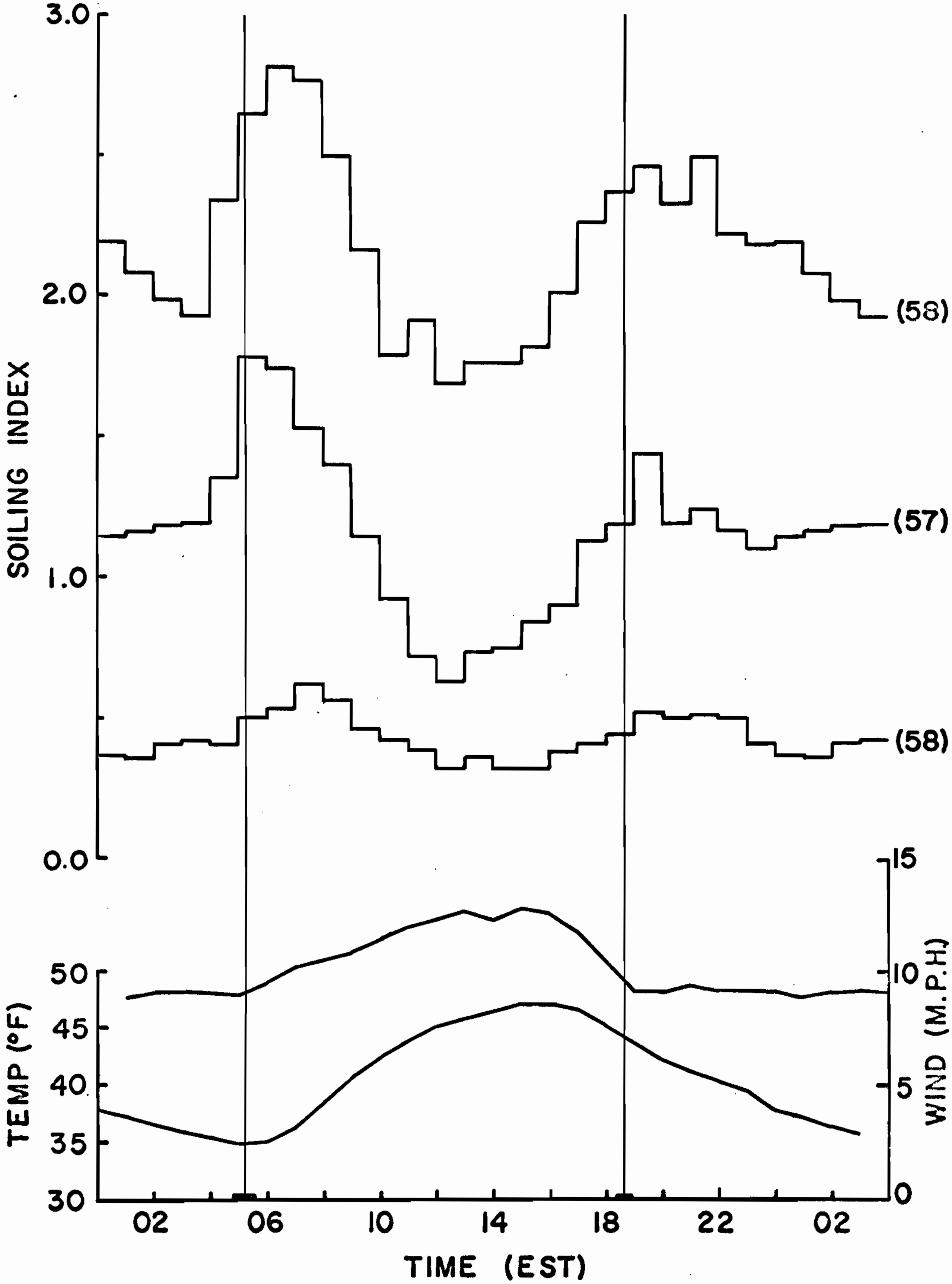

3.0
2.0
1.0
0.0
SOILING INDEX
(64)
(64)
(54)
15
10
5
WIND (M.P.H.)
35
30
25
20
TEMP (°F)
02
06
10
14
18
22
02
TIME (EST)

FIG. 3.6 APRIL



3.0
2.0
1.0
0.0
SOILING INDEX
(58)
(57)
(58)
15
10
5
0
50
45
40
35
30
TEMP (°F)
WIND (M.P.H.)
02
06
10
14
18
22
02
TIME (EST)

FIG. 3.7 MAY

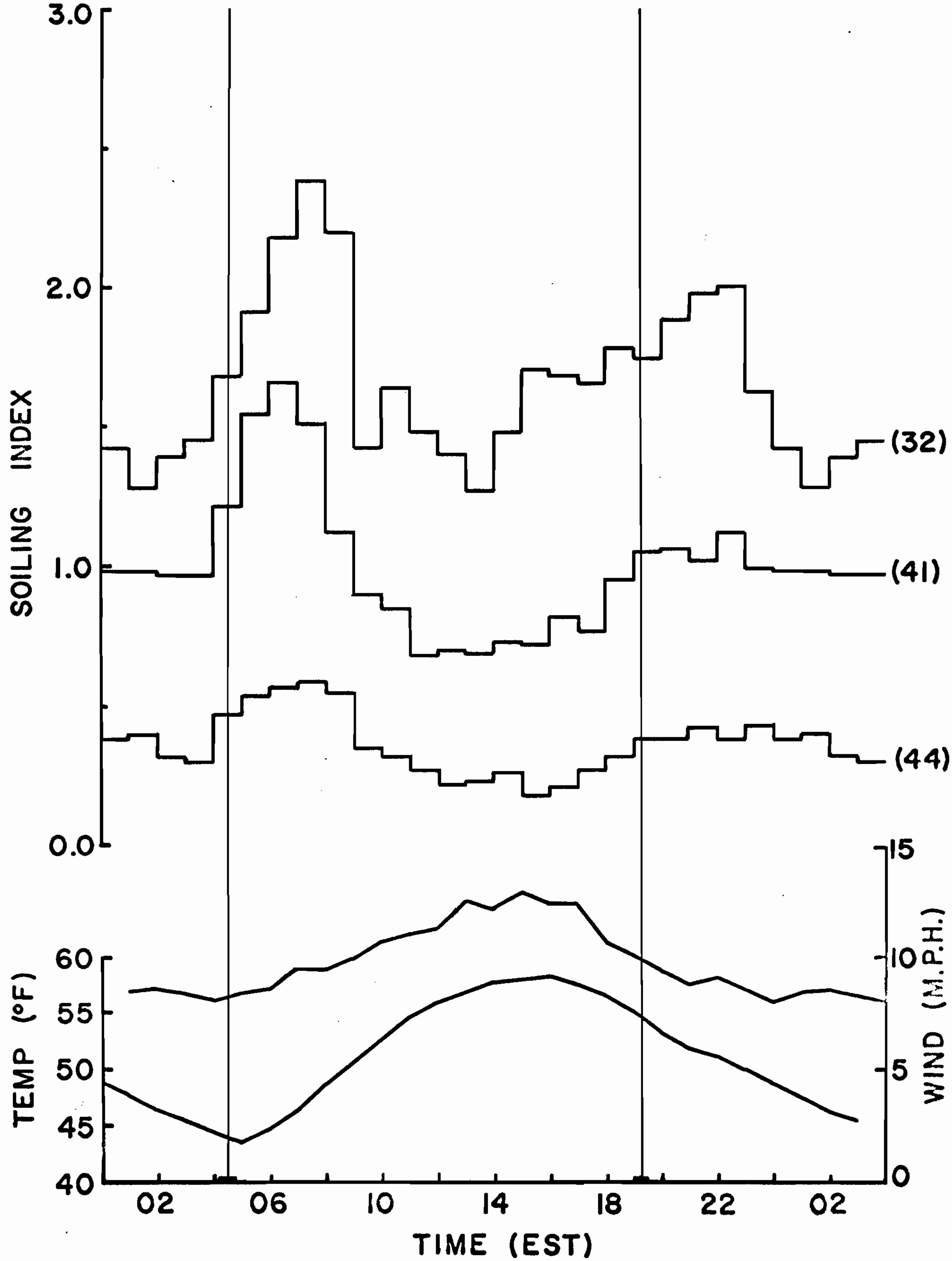

3.0
2.0
1.0
0.0
SOILING INDEX
(32)
(41)
(44)
15
10
5
0
WIND (M.P.H.)
60
55
50
45
40
TEMP (°F)
02
06
10
14
18
22
02
TIME (EST)

FIG. 3.8 JUNE

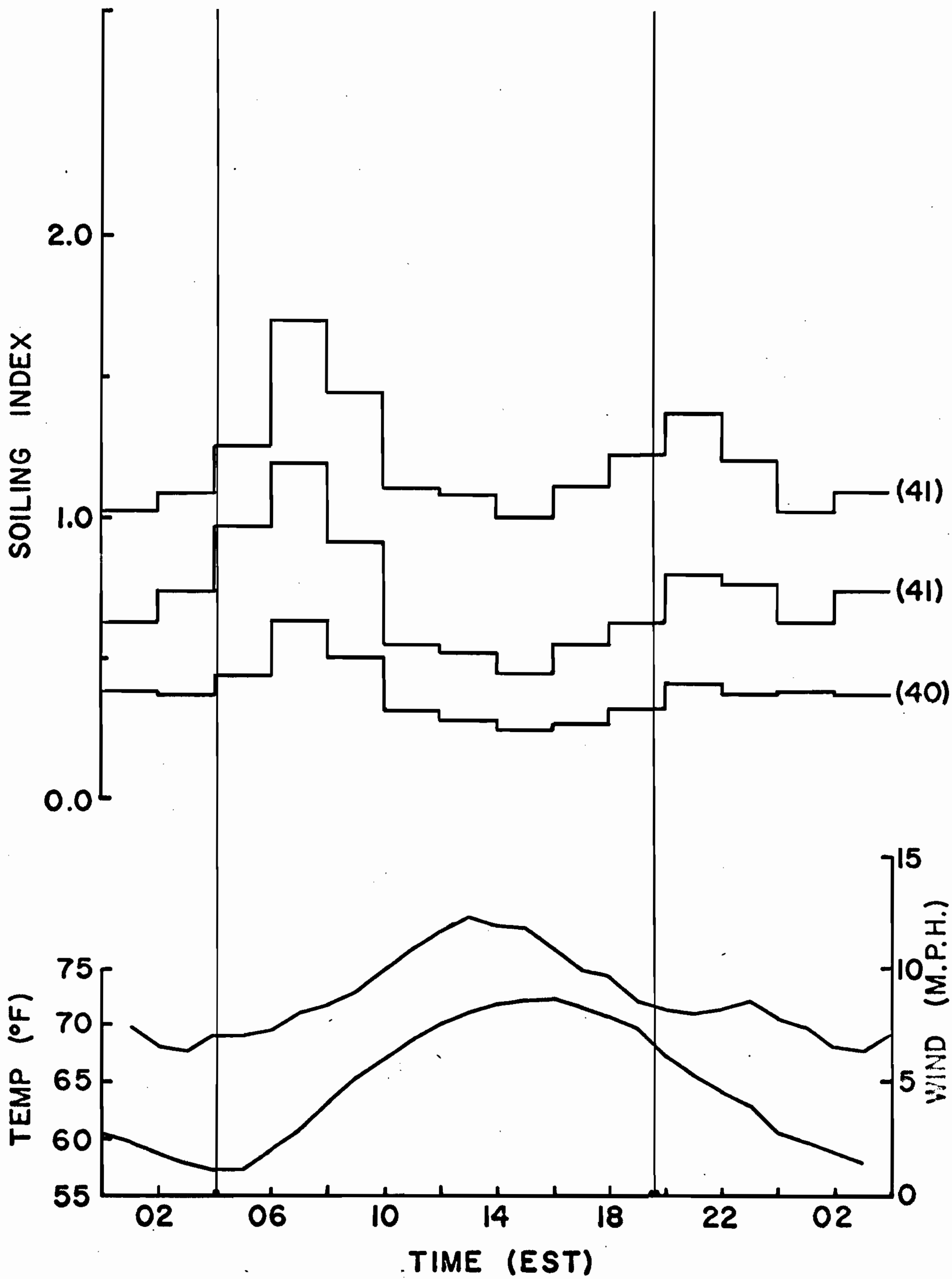
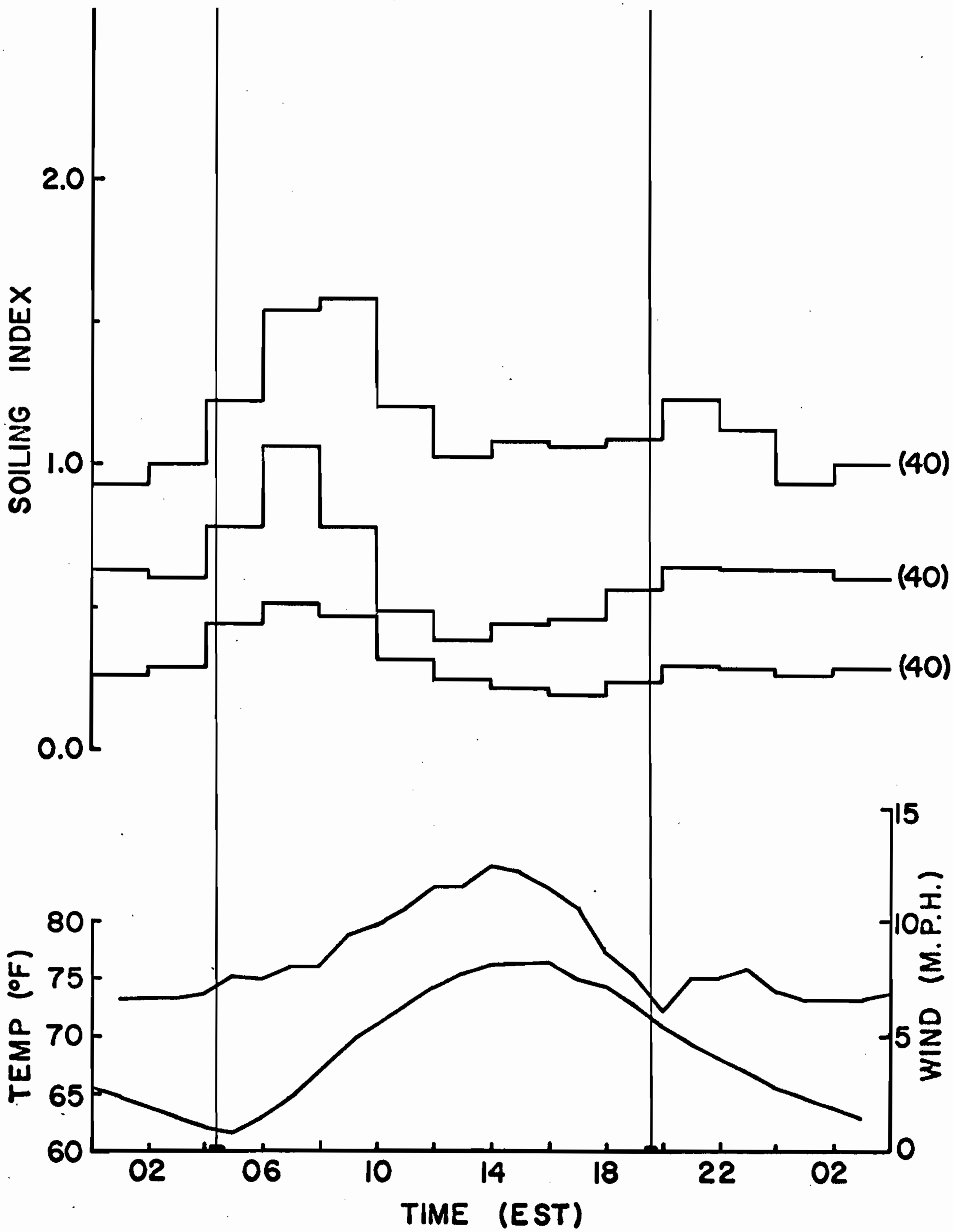

SOILING INDEX
2.0
1.0
0.0
(41)
(41)
(40)
TEMP (°F)
75
70
65
60
55
WIND (M.P.H.)
15
10
5
0
02
06
10
14
18
22
02
TIME (EST)

FIG. 3.9 JULY


2.0
1.0
0.0
SOILING INDEX
(40)
(40)
(40)
80
75
70
65
60
TEMP (°F)
15
10
5
0
WIND (M.P.H.)
02
06
10
14
18
22
02
TIME (EST)

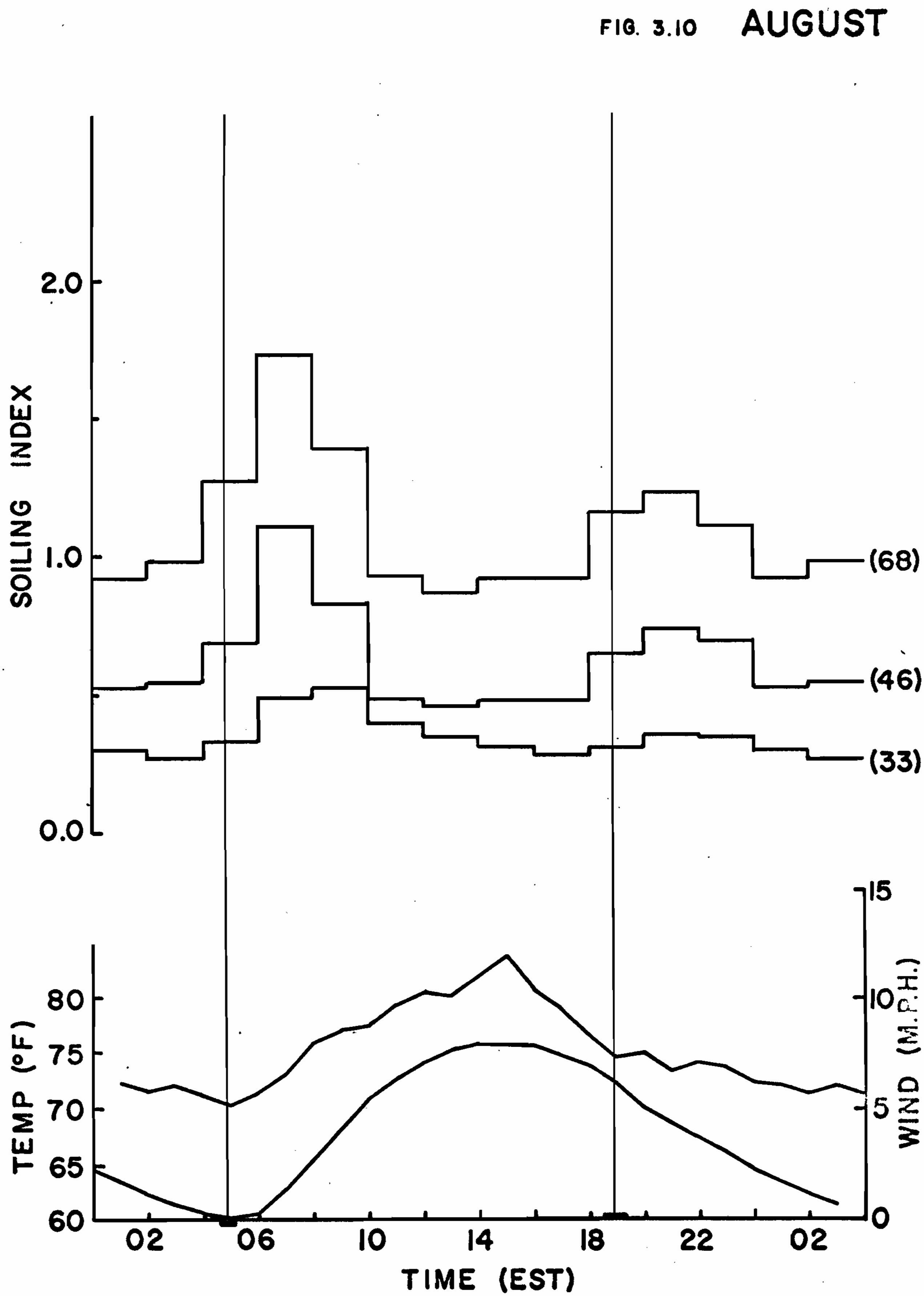
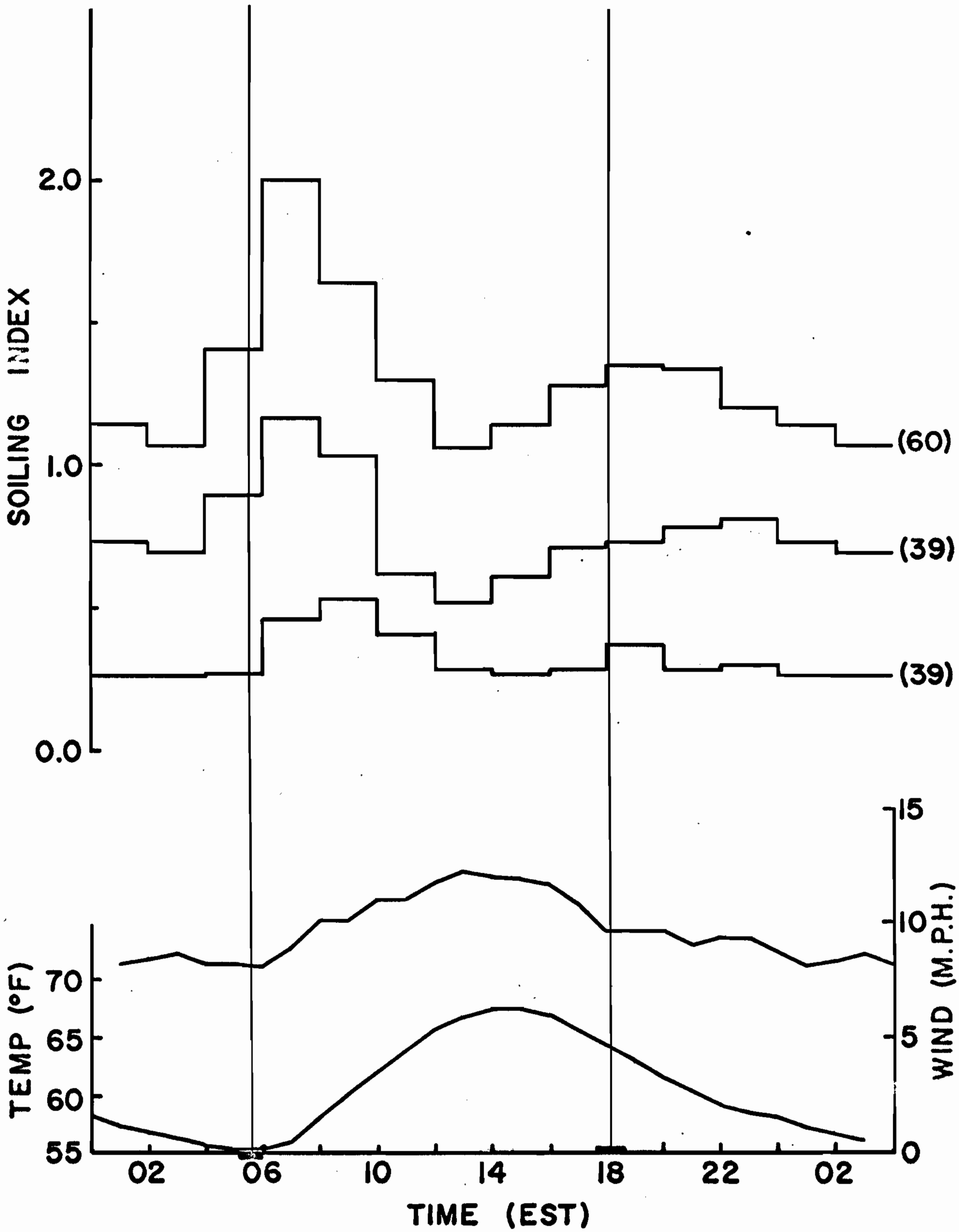


FIG. 3.10 AUGUST
SOILING INDEX
2.0
1.0
0.0
(68)
(46)
(33)
TEMP (°F)
80
75
70
65
60
WIND (M.P.H.)
15
10
5
0
02
06
10
14
18
22
02
TIME (EST)

FIG. 3.11 SEPTEMBER



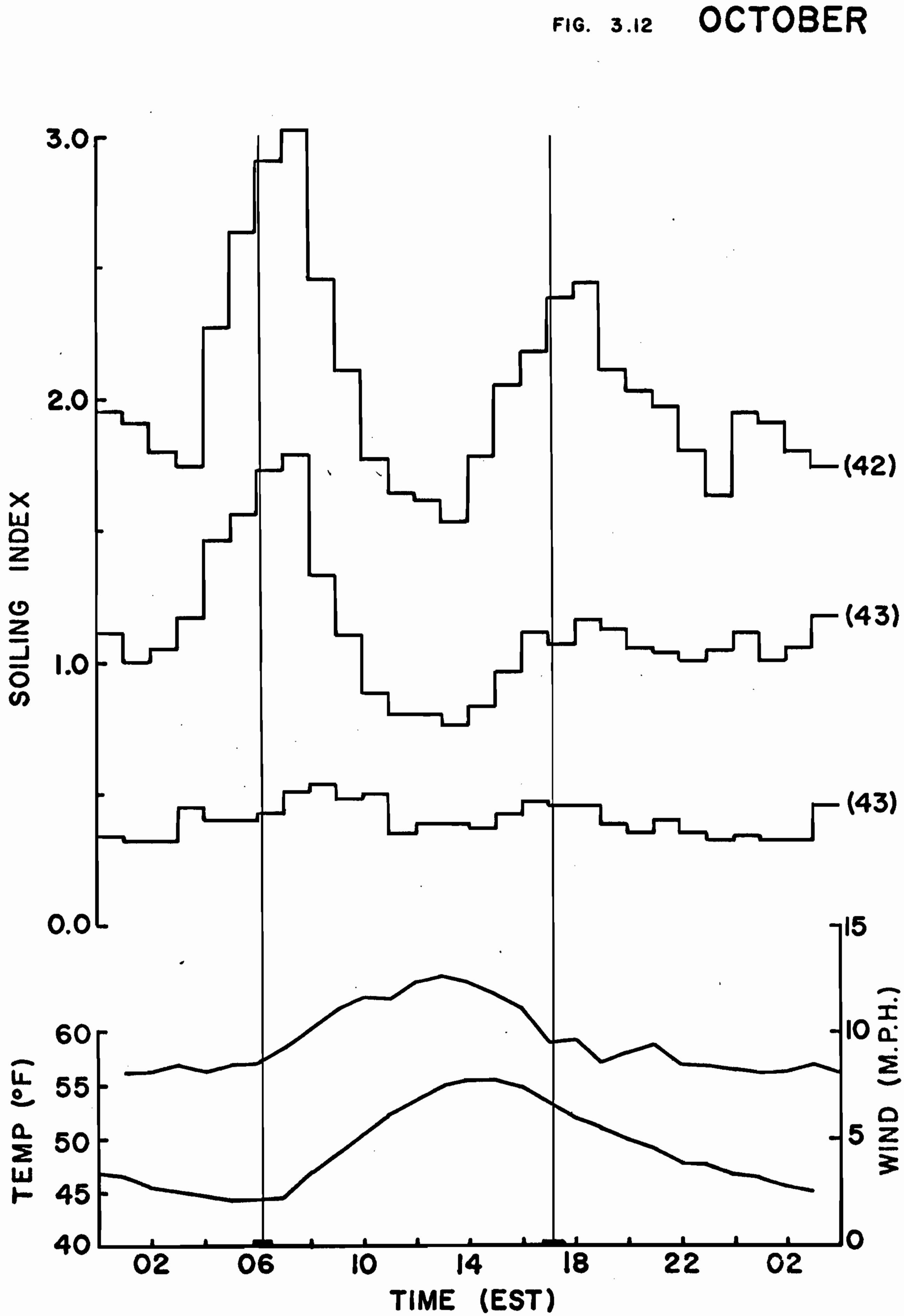
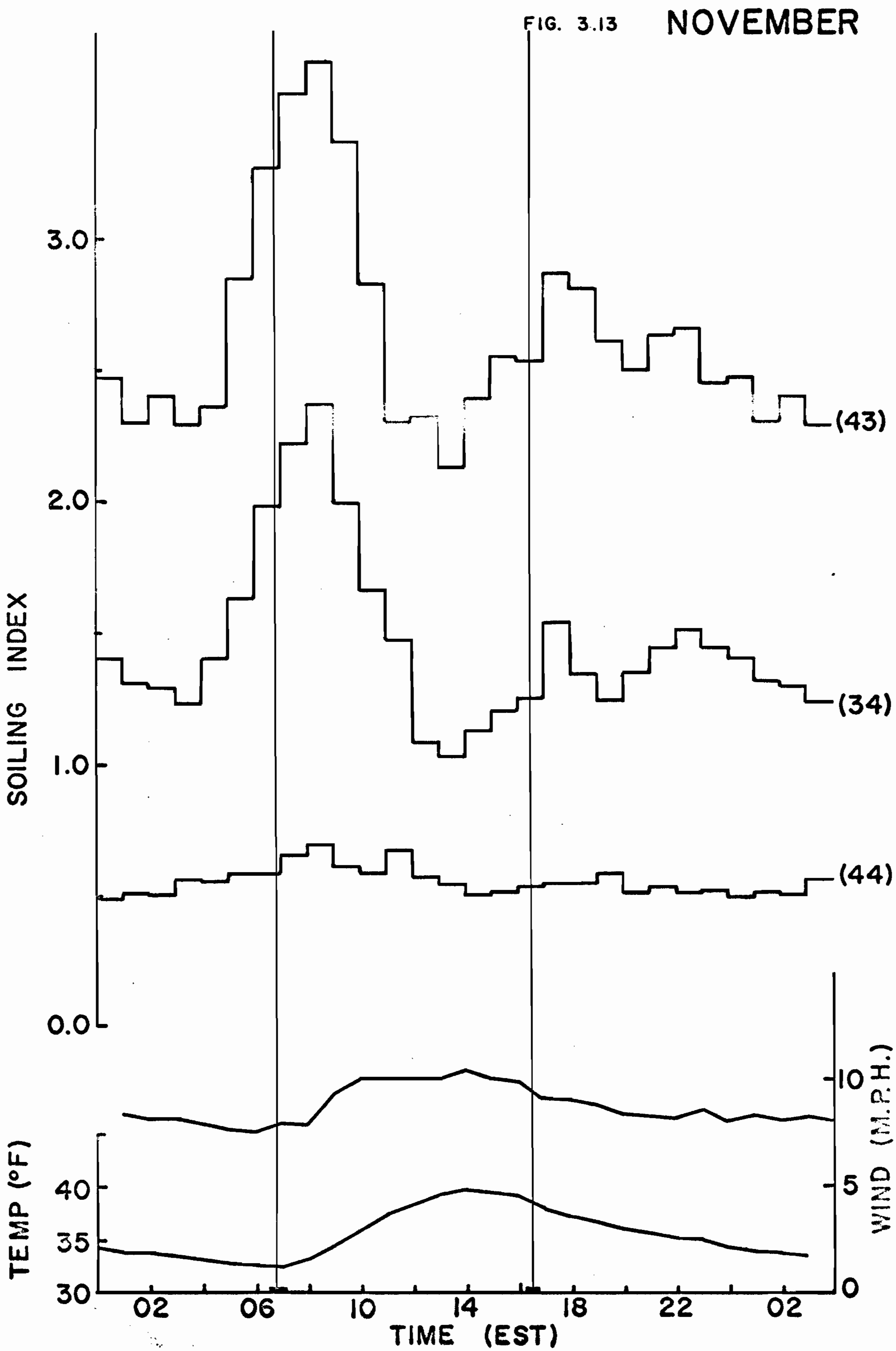


FIG. 3.12 OCTOBER
3.0
2.0
1.0
0.0
SOILING INDEX
(42)
(43)
(43)
60
55
50
45
40
TEMP (°F)
15
10
5
0
WIND (M.P.H.)
02
06
10
14
18
22
02
TIME (EST)

FIG. 3.13


NOVEMBER
3.0
2.0
1.0
0.0
SOILING INDEX
(43)
(34)
(44)
10
5
0
WIND (M.P.H.)
40
35
30
TEMP (°F)
02
06
10
14
18
22
02
TIME (EST)

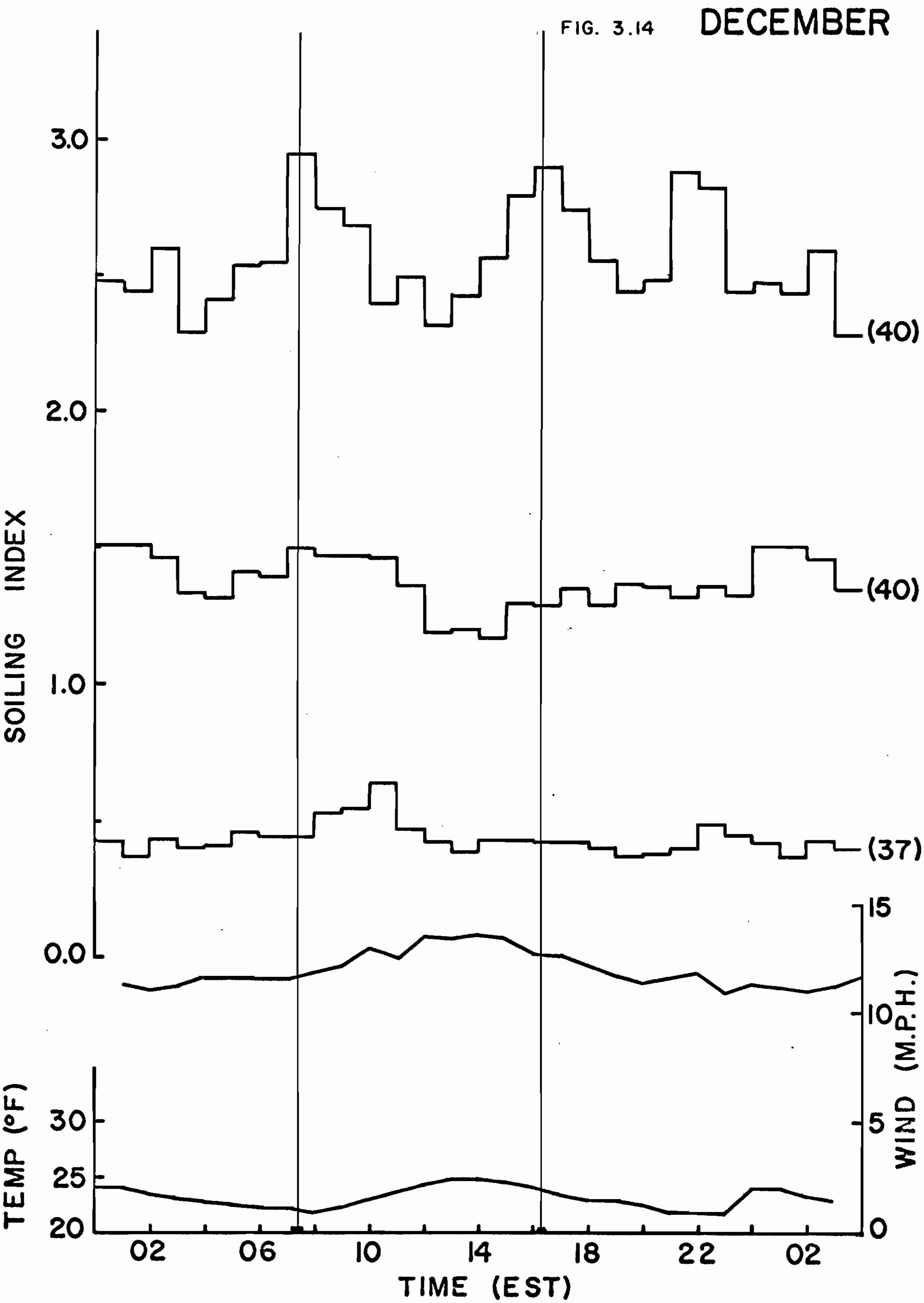

DECEMBER
SOILING INDEX
3.0
2.0
1.0
0.0
(40)
(40)
(37)
15
10
5
0
WIND (M.P.H.)
TEMP (°F)
30
25
20
02
06
10
14
18
22
02
TIME (EST)

FIG. 3.14

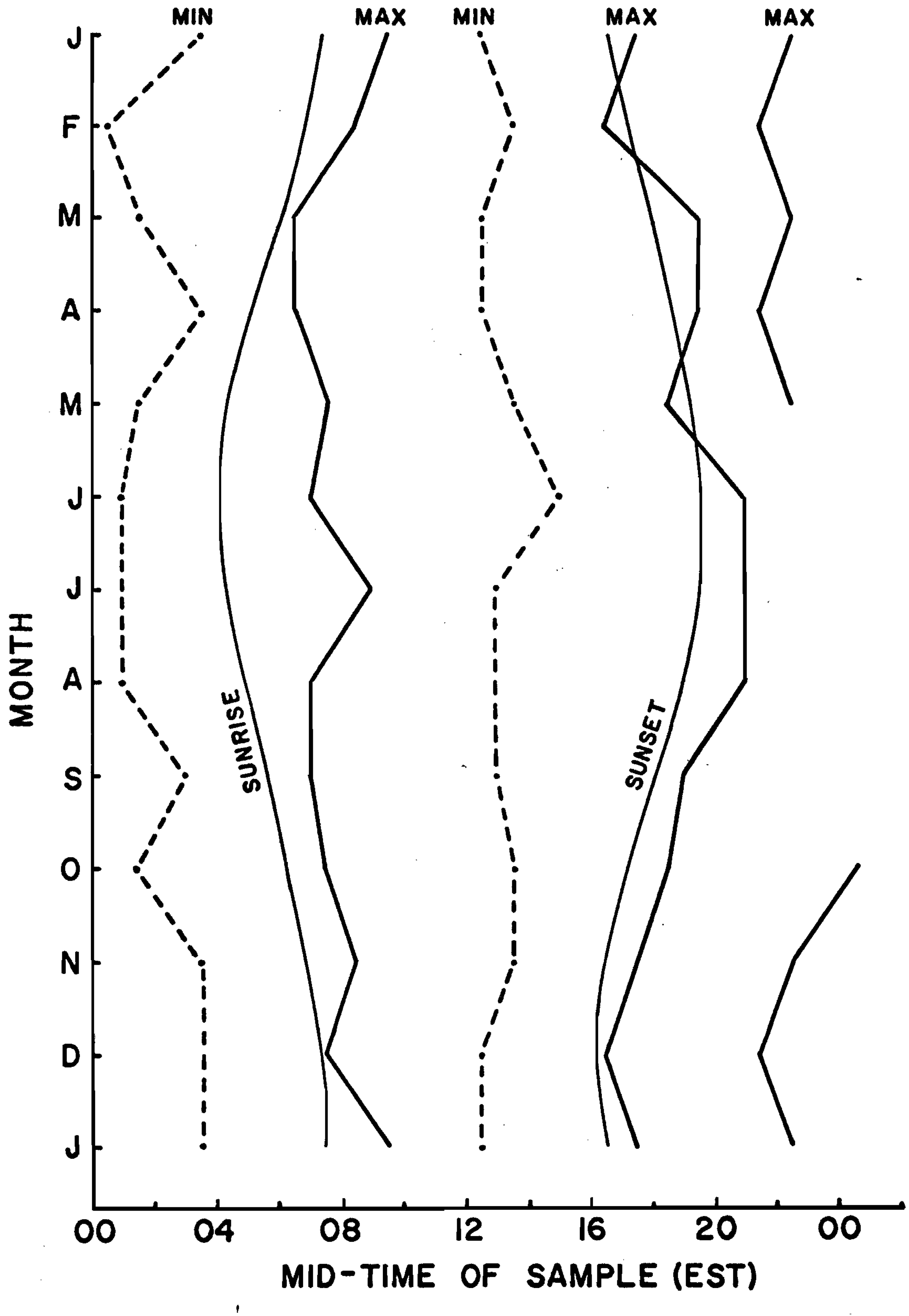


Figure 3.15 Seasonal Change in Time of Maxima and Minima at WEC

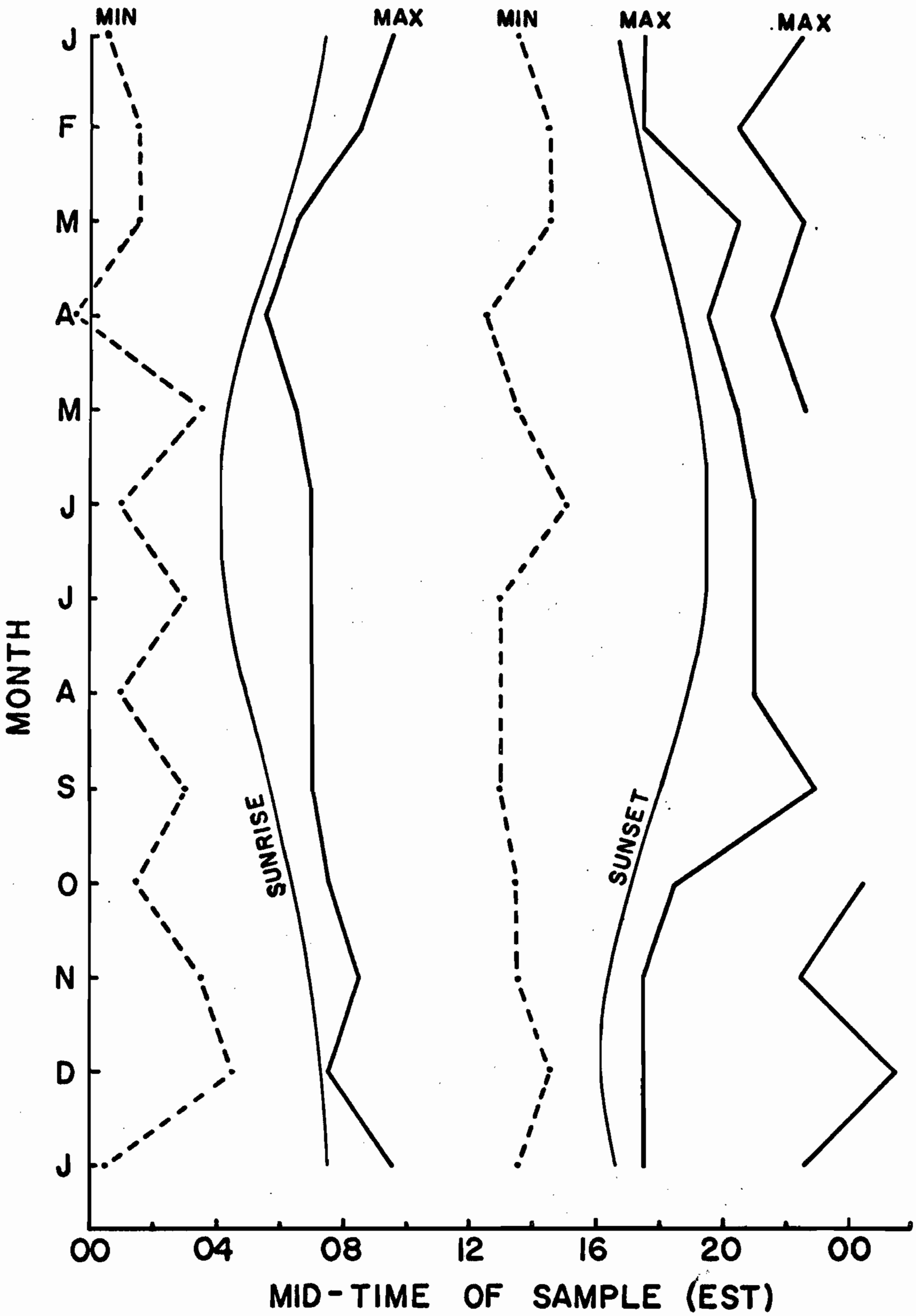


Figure 3.16 Seasonal Change in Time of Maxima and Minima at McGill

The late evening peak may also exist during the summer months but is not detected with a two hourly sampling period, and because the main maximum occurs during the late evening also.

The yearly cycle of the times of these significant points for WEC and McGill is shown in Figures 3.15 and 3.16 along with the times of sunrise and sunset.

The daily cycle of soiling index at the CBC location is not nearly so well defined. Of all the significant points only the morning maximum shows up in all months of the year. An interesting feature of the morning peak at the CBC is that it lags behind the time of the maximum at the lower elevations by up to three hours. This time lag can be evaluated readily from Figures 3.3 to 3.14 but for convenience is tabulated in Table 3.6. There appears to be a greater time lag in the winter months compared to the summer months.

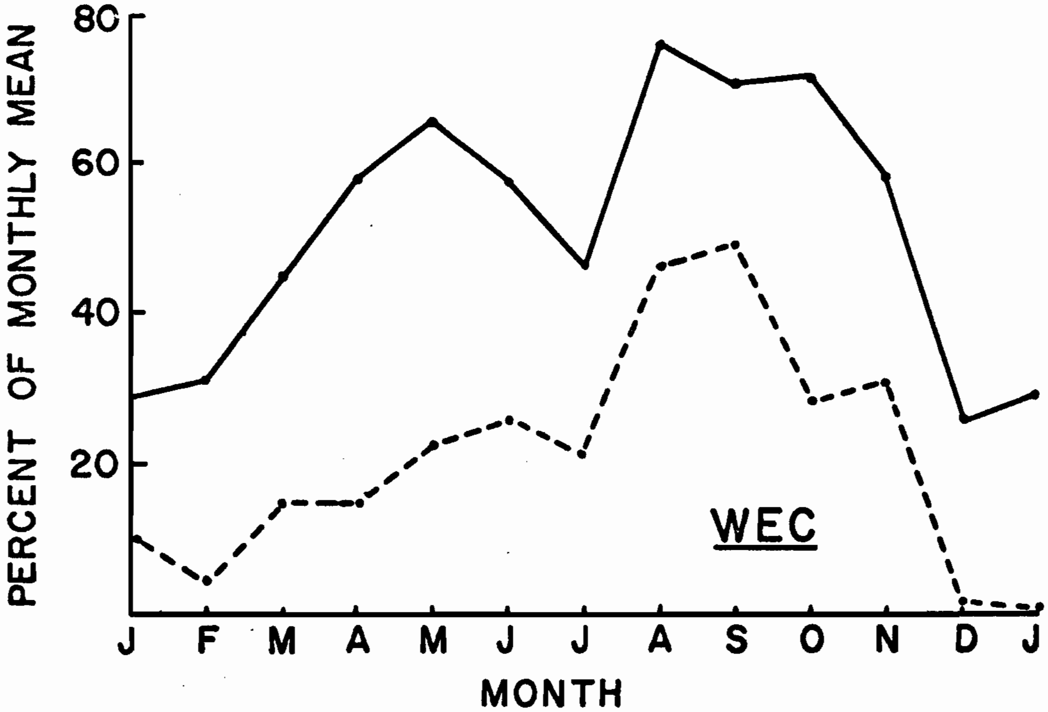
Table 3.6 Time Lag of Morning Soiling Index Maximum at CBC

Month	Lag of Morning Peak at CBC	
	Behind McGill (hrs.)	Behind WEC (hrs.)
January	2	2
February	2	2
March	3	1
April	2	1
May	1	0
June	0	0
July	0	-2
August	2	2
September	2	2
October	1	1
November	3	3
December	3	3
Mean	1.75	1.25

There is some slight evidence for two evening peaks in most of the winter months, but in view of the errors inherent in measuring the low values of soiling index (see Section 2.3) little confidence can be placed in such evidence.

Further inspection of the WEC and McGill daily cycles shows that the daily range has a marked yearly cycle. The daily range, defined as the difference between the daily maximum and the daily minimum was evaluated from Figures 3.3 to 3.14 for each month of the year. This was then expressed as a percentage of the mean soiling index for the month. The results are shown in Figure 3.17. Due to the use of a two-hourly sampling time in the summer months, the maxima and minima tend to the flattened out and thus the daily range is underestimated. Thus the values of the daily range shown in Figure 3.17 are an underestimate of the true range by a larger amount in the summer months than at other times during the year.

Again from Figures 3.3 to 3.14 it can be seen that the values of the morning and evening peaks are nearly the same in the winter months, but in the summer months the morning peak is much higher. The difference between the morning and evening maximum was evaluated for each month and again expressed as a percentage of the mean monthly soiling index. This is shown in Figure 3.17 as the dotted curve, and it indicates a very similar yearly cycle to the daily range. It, therefore, appears that the months with a small daily range correspond to months with a small difference between the magnitudes of the morning and evening peaks, i.e. the winter months of December through March.



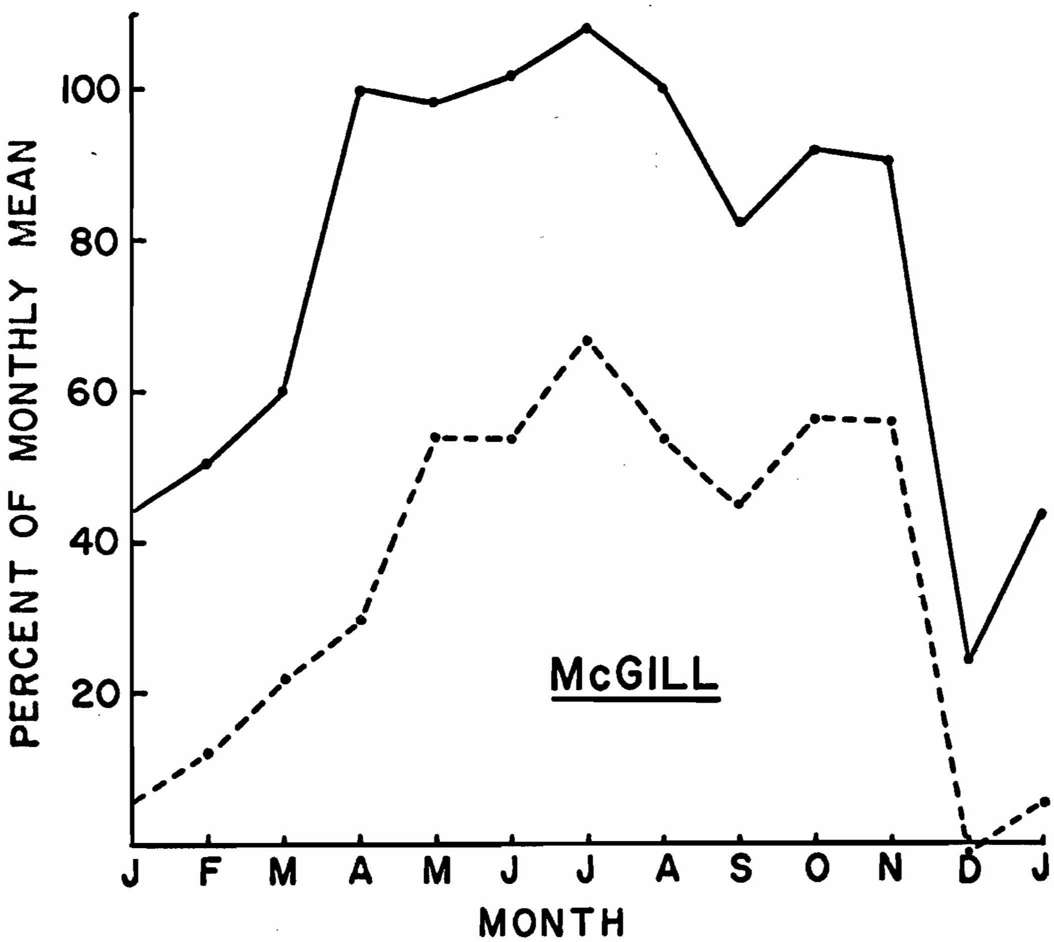


Figure 3.17 Diurnal Range (solid curve), and Morning Maximum minus Evening Maximum (broken curve), as percent of Monthly Mean Soiling Index.

Both the diurnal range and the difference between the morning and evening peaks are at a maximum in the summer and fall months. This then suggests two basic types of daily pollution cycle:

Type A	Small daily range (amplitude at WEC $<$ 45%, at McGill $<$ 60%). Small difference in magnitude of morning and evening peak.
Type B	Large daily range (amplitude at WEC $>$ 45%, at McGill $>$ 80%). Morning peak considerably greater than evening peak (by $>$ 20% at WEC and by $>$ 25% at McGill).

Type A occurs during the winter months December through March and Type B during the remainder of the year. The transition from Type B to Type A is very sudden in the late fall. In the spring the transition from Type A to Type B is more gradual and in fact the limits of the two types could be changed such that March and April would have to be considered as a transition state. More data or a study of individual years could possibly improve the limits. This daily cycle will be discussed in more detail after urban ventilation has been considered, and an attempt will be made to explain, at least subjectively, the reasons for the two types.

CHAPTER 4

ATMOSPHERIC VENTILATION

4.1 Introduction

The ability of the atmosphere to dilute any pollutants emitted into it varies over a wide range on a diurnal, day to day and seasonal basis. It also varies with the distance scale under consideration.

As pointed out in the introduction the dispersion of material from discrete sources is now well documented but only under a fairly restricted range of conditions which are not always present over an urban area in serious air pollution situations. Some ideas of horizontal and vertical mixing will now be discussed with a view to combining them with the urban heat island effect to obtain a model of nighttime urban ventilation.

4.2 Vertical Mixing and Mixing Depth

The atmosphere is normally stably stratified during the night. Daytime heating of the ground by solar radiation establishes a lapse rate near or slightly greater than the dry adiabatic in a layer close to the ground. Any pollutants emitted into this layer will be strongly mixed producing an almost uniform distribution of concentration with height.

In anticyclonic weather the lowest several thousand feet of the atmosphere are stable due to subsidence. Also a strong surface-based inversion of temperature builds up overnight in the lowest few hundred feet of the atmosphere. Daytime solar heating destroys at least the lowest part of this inversion and strong vertical mixing takes place through a layer which can be estimated from the tephigram by following the dry adiabat through the surface temperature up to the point where it intersects the upper air sounding. The estimated maximum depth through which mixing takes place corresponds to dry adiabat through the maximum surface temperature and is illustrated schematically in Figure 4.1.

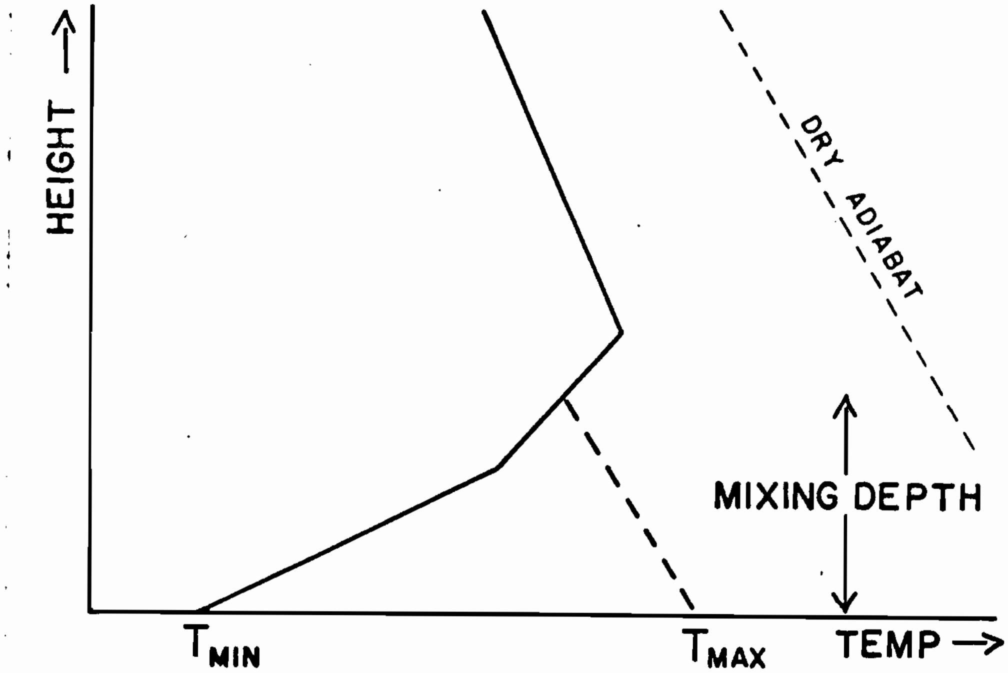


Figure 4.1 Calculation of Maximum Mixing Depth

This idea was first used in studies made in Los Angeles where a semi-permanent inversion persists aloft due to subsidence in the Pacific high-pressure cell. The mixing depth below this inversion varies from time to time, according to the intensity of the high and the surface temperature, and such variation has a critical effect on smog concentrations. This idea was also used in pollution studies by Pack and Hosler (1958) during a prolonged anticyclonic spell over the eastern United States in October 1956. Holzworth (1962) extended the idea to a climatological study of mean monthly mixing depths simply by using the mean monthly radiosonde data and the mean monthly maximum temperature. In this way a first approximation to the ability of the atmosphere to mix vertically can be obtained for various seasons and localities. Holzworth compares various cities in Texas with the California coast. Two of his curves are reproduced in Figure 4.2, and a similar analysis performed on eight years of radiosonde and surface temperature data from Maniwaki, Quebec, (about 130 miles northwest of Montreal) is added for comparison.

San Antonio, Texas, shows a striking seasonal variation with the mixing depth at a minimum in mid-winter when even during the daytime strong mixing is only limited to the lowest 1500-2000 feet of the atmosphere. In mid-summer the mean mixing depth is over 5000 feet.

On the Southern California Coast the trend is almost the reverse although the range of mixing depth is much less, varying from a maximum of nearly 5000 feet in March lowering steadily through the summer months to only about 2500 feet in the late summer and fall. It is during the months July through October that the subsidence inversion due to the "Pacific High" is at its maximum intensity and pollution problems in Los Angeles are at their worst.

If Maniwaki can be taken as typical of southern Quebec and in particular Montreal then again there is a very marked seasonal variation. In the winter months November through March when the ground is snow covered the maximum mixing depth remains near 2000 feet. In the summer

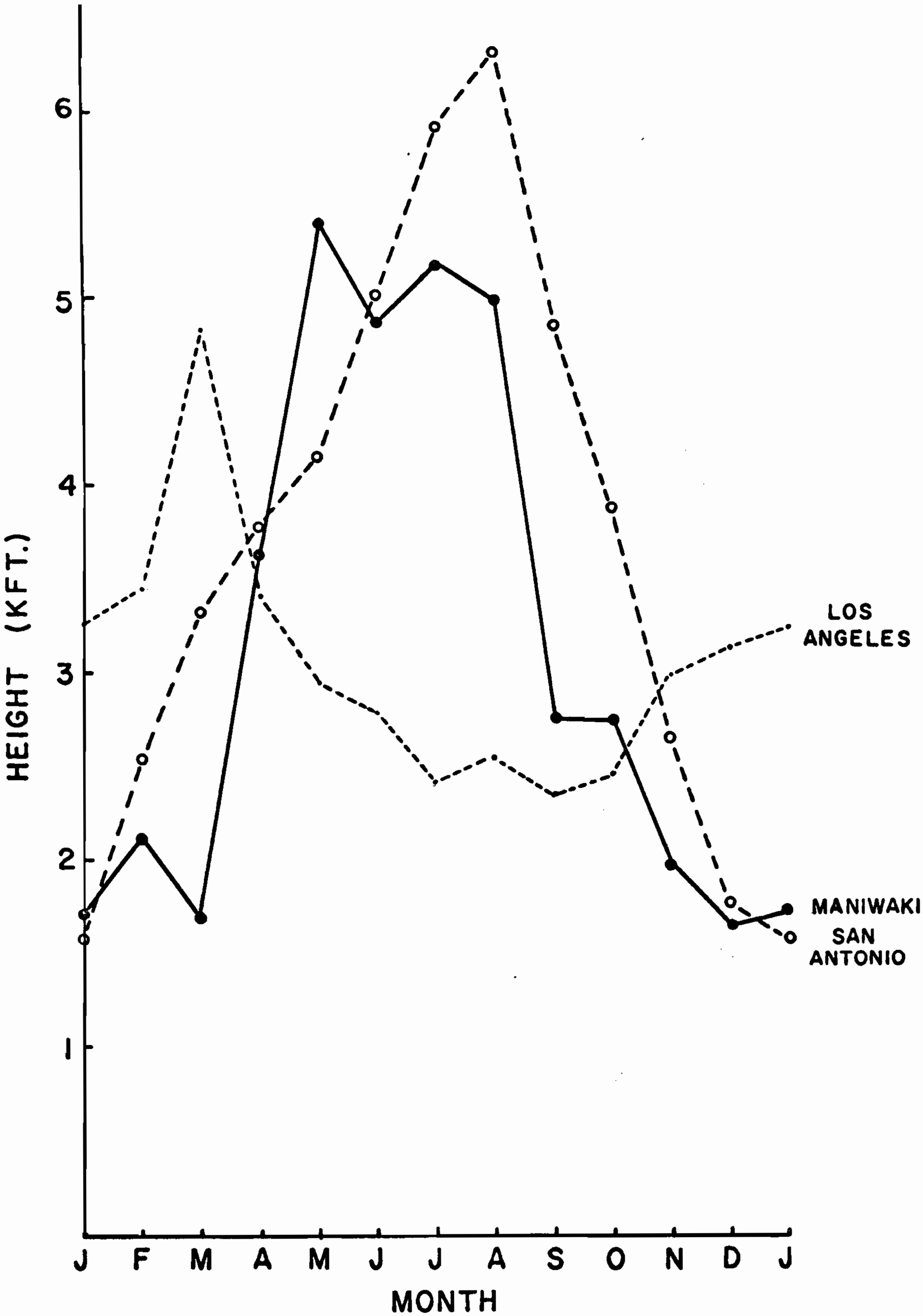


Figure 4.2 Mean Monthly Maximum Mixing Depth at Maniwaki Compared to Los Angeles and San Antonio

months May through August the depth increases to about 5000 feet with a transition between the two regimes is Spring (April) and Fall (September, October). It is interesting to note that the mean maximum mixing depth at Maniwaki during the winter months ~~if~~ is lower than at any time of the year in Los Angeles.

4.3 Nighttime Vertical Mixing

Vertical mixing is usually at a minimum during the night. The ground cools due to a net loss of infrared radiation. The layer of air in contact with the ground cools by conduction and this cooling gradually spreads upwards through the lowest layers of the atmosphere. Since this cooling is greatest near the ground a temperature inversion forms. Water vapour and clouds easily absorb and re-emit in certain bands of the infrared spectrum and so under cloudy skies radiation from the ground is partly absorbed and returned back to the ground. Thus clouds tend to inhibit the formation of noctural ground inversions and the lapse rate from the ground to cloud base approaches the dry adiabatic. Strong winds cause mechanical turbulence which mixes heat downwards rapidly enough to prevent an inversion forming.

A very extensive study has been made by Hosler (1961) of inversion frequency over the United States. Using all available radiosonde and meteorological tower data, the frequency of inversions during various seasons is tabulated along with other relevant parameters such as percentage of time wind less than eight mph and cloud cover less than 4/10.

During the last few years several meteorological towers have been set up in southern Ontario. At the present time eight of these, plus two in Montreal, are providing continuous measurements of temperature differences in the lowest few hundred feet of the atmosphere. A preliminary analysis of some of the data from these towers has been published recently (Munn 1963). Some of the more relevant findings will now be discussed.

The percentage frequency of days with an inversion at some time during the 24 hours (usually at night) is shown in Table 4.1.

Table 4.1 Percentage Frequency of Days with an Inversion at Some Time During the 24 Hours

Station	Winter	Spring	Summer	Fall
Detroit	68	77	95	85
Montreal	55	75	80	83
Ottawa	65	79	95	88
Chalk River	87	74	89	88
Rolphton	97	--	99	97

It is quite clear from Table 4.1 that a day without an inversion is the exception, particularly at the stations in the open country such as Chalk River and Rolphton. As Munn points out the Ottawa tower is in an area more rural than urban in character but is sometimes affected by the urban heat island. The Montreal tower is just inside the northern limits of the built up area and with the prevailing southwesterly winds is often within the area affected by the urban heat island. This accounts for the somewhat lower inversion frequency at Montreal. Also the mean inversion intensity is much less at Montreal compared to that at Ottawa, Sarnia and Detroit. This again can be accounted for by the heat island. A full discussion of the implications of this heat island effect will be held over for the next Chapter. For now it will be assumed that the increase in surface temperature over a city has a similar effect to that shown in Figure 4.1 and that strong vertical mixing occurs at night through the lowest few hundred feet.

4.4 Horizontal Ventilation

The stronger the horizontal wind speed the faster clean air is brought in at the upwind of the city and the more rapidly the pollutants are transported out downwind.

In Figure 4.4 the seasonal variation of the mean monthly wind speed for Los Angeles and San Antonio (after Holzworth 1962) are shown together with data from Montreal.

In Los Angeles the strongest average winds occur at the same time as the deepest maximum mixing depth. Winds are lightest in the late summer and fall and so reinforce the lack of dilution caused by shallow daytime mixing depths.

The seasonal variation of wind at San Antonio follows a similar pattern, but with winds on the whole three to four miles per hour stronger.

In Montreal the strongest winds occur in winter at a time when the mixing depth is at a minimum and so helps to offset the low vertical dilution. In the summer when winds are lightest the daytime mixing depth is high. The effects of horizontal ventilation and vertical mixing will now be considered to give a single ventilation coefficient.

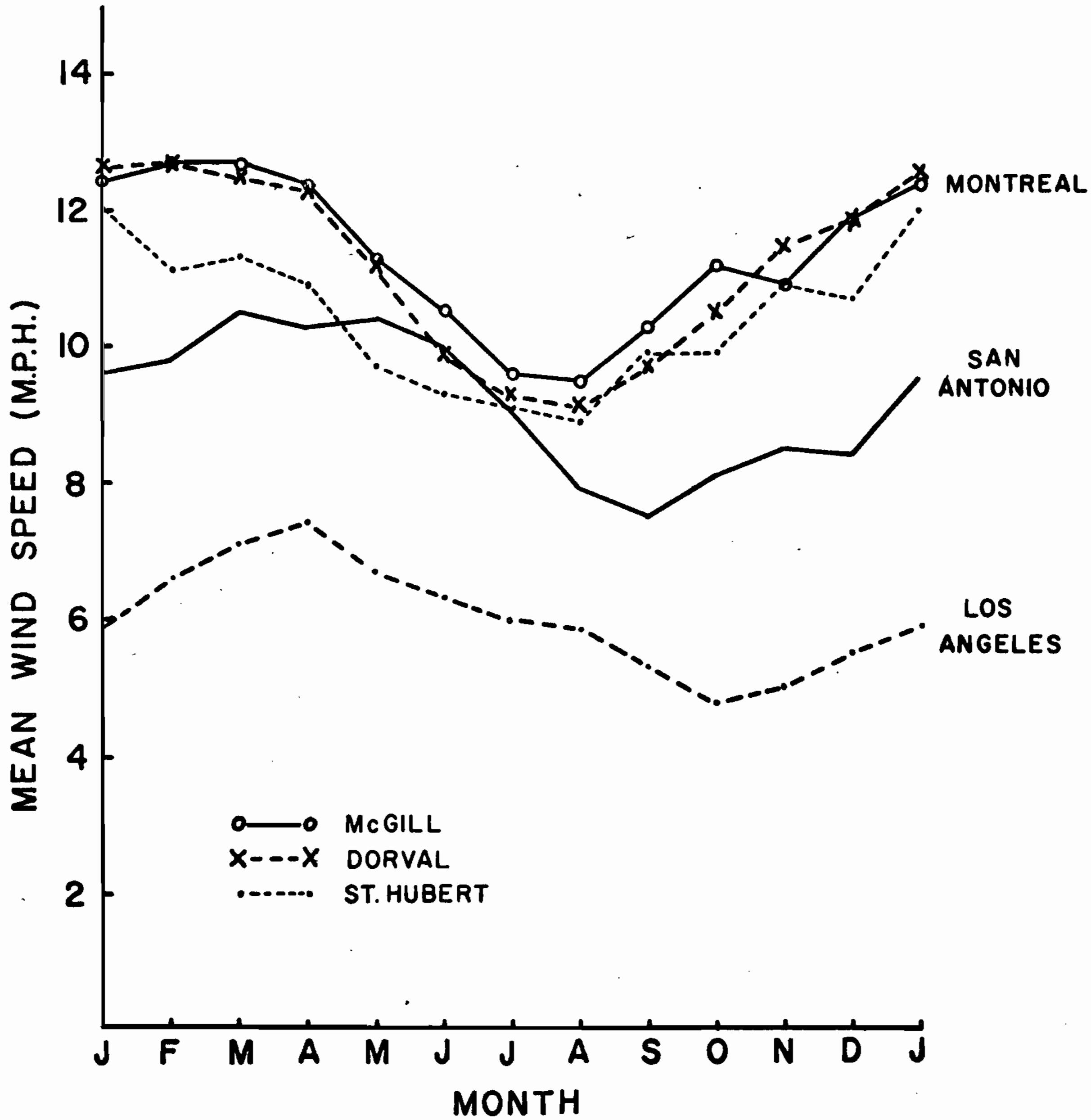


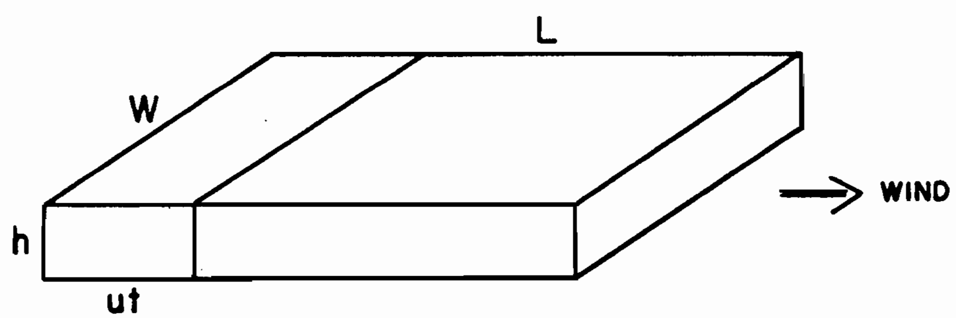
Figure 4.3 Mean Monthly Wind Speed in Montreal

4.5 A Simple Model and the Ventilation Coefficient

The ideas of the preceding sections will now be combined to give one simple measure of atmospheric ventilation.

In considering diffusion from a large area source of pollution the simplest model which suggests itself is that of a reservoir of air above the area. The top of this reservoir is defined by the upper limit of vertical mixing which is assumed to be at the same height h everywhere over the city. This height will be changing with time but during certain periods of the day will be nearly constant for up to several hours. One such period will be the early afternoon when h will be steady at the maximum mixing height (see Section 4.2). Another and probably more prolonged period will be in the early morning hours before sunrise when meteorological conditions over a large urban area will be in a quasi-steady state.

Consider a rectangular city having a mixing depth h, length L and width W.



Then if A is the area of the city

$$A = LW \tag{4.1}$$

Let the rate of production of smoke per unit area equal Q and be constant over the whole city. The smoke is assumed to be uniformly mixed over the whole city through the mixing depth h. Then the volume of air containing the smoke is

$$V = Ah \tag{4.2}$$

If M is the total mass of smoke in this volume, then if C is the concentration

$$C = \frac{M}{V} \tag{4.3}$$

Now consider ventilation as the replacement of a fraction of V containing a corresponding fraction of M by an equal amount of clean air. If the rate of ventilation is D, then the amount of smoke lost from the volume per unit time is DC. The rate of change of M with time will, therefore, be equal to the difference between the rate at which smoke is being produced and the rate at which it is being removed by ventilation, that is

$$\frac{dM}{dt} = QA - DC \tag{4.4}$$

If removal of smoke by diffusion through the lid, and by fall-out, wash-out, impaction are all neglected as being small compared to the mass transport by the wind, then

$$D = \bar{u}Wh \tag{4.5}$$

where $\bar{u}$ is the mean wind blowing parallel to the side L of the city.

Substituting from Eq. 4.5 in Eq. 4.4 then

$$\frac{dM}{dt} = QA - \bar{u}WhC \tag{4.6}$$

But for constant h, implying constant V, from Eq. 4.3

$$\frac{dM}{dt} = \frac{VdC}{dt} \tag{4.7}$$

Substituting from Eq. 4.7 in 4.6 and using 4.2 then

$$\frac{dC}{dt} = \frac{Q}{h} - \frac{\bar{u}C}{L} \tag{4.7}$$

This then is the basic ventilation equation which describes the time variation of smoke concentration in the volume over an area source of pollution,

In the steady state, or equilibrium, conditions $\frac{dC}{dt}$ is zero and the equilibrium concentration C_e is given from Eq. 4.7 by

$$C_e = \frac{QL}{h\bar{u}} \tag{4.8}$$

This simple relation has been derived also by Smith (1961), and Davis (1961) has applied Eq. 4.7 to the city of Philadelphia with some success.

It can be seen that the equilibrium concentration depends on four factors, all of which are related either directly or indirectly to meteorological parameters. Each will now be discussed in turn.

Q is the rate of production of smoke, which is related to the consumption of fuel. A large amount of fuel is consumed in the winter months to heat buildings; since the amount of heating required is dependent on the ambient air temperature, Q will also depend on temperature.

L is the effective cross-city dimension parallel to the wind direction. This will vary widely from day to day in a non-symetrical city such as Montreal, but Tables 2.2, 2.3 and 2.4 show no marked seasonal shift in wind direction frequency and so mean monthly L will not vary appreciably.

h is the mixing depth over the city and its variation with time was discussed briefly in Sections 4.2 and 4.3.

$\bar{u}$ is the mean wind speed, the most variable of all the quantities affecting C_e, and its seasonal variation was considered in Section 4.4. Although there is a strong diurnal variation of the wind speed at the surface (see Figures 3.3 to 3.14), the mean wind speed through the whole mixing depth is more dependent on the pressure gradient wind speed; this has a strong variation cycle of the order of two to seven days associated with synoptic-scale disturbances.

For any given city h and $\bar{u}$ are the direct meteorological factors which determine the equilibrium concentration. It is, therefore, useful to combine them into a single ventilation coefficient defined as the product of h and $\bar{u}$. It follows from Eq. 4.8 that the equilibrium concentration is inversely proportional to the ventilation coefficient.

One time of day when conditions approach a steady state is the early afternoon (see Figures 3.3 to 3.14). The mixing depth, which has been increasing rapidly during the morning due to the rise in surface temperature, steadies off near its maximum value. At this time of day Q will be essentially constant. Thus it is possible to

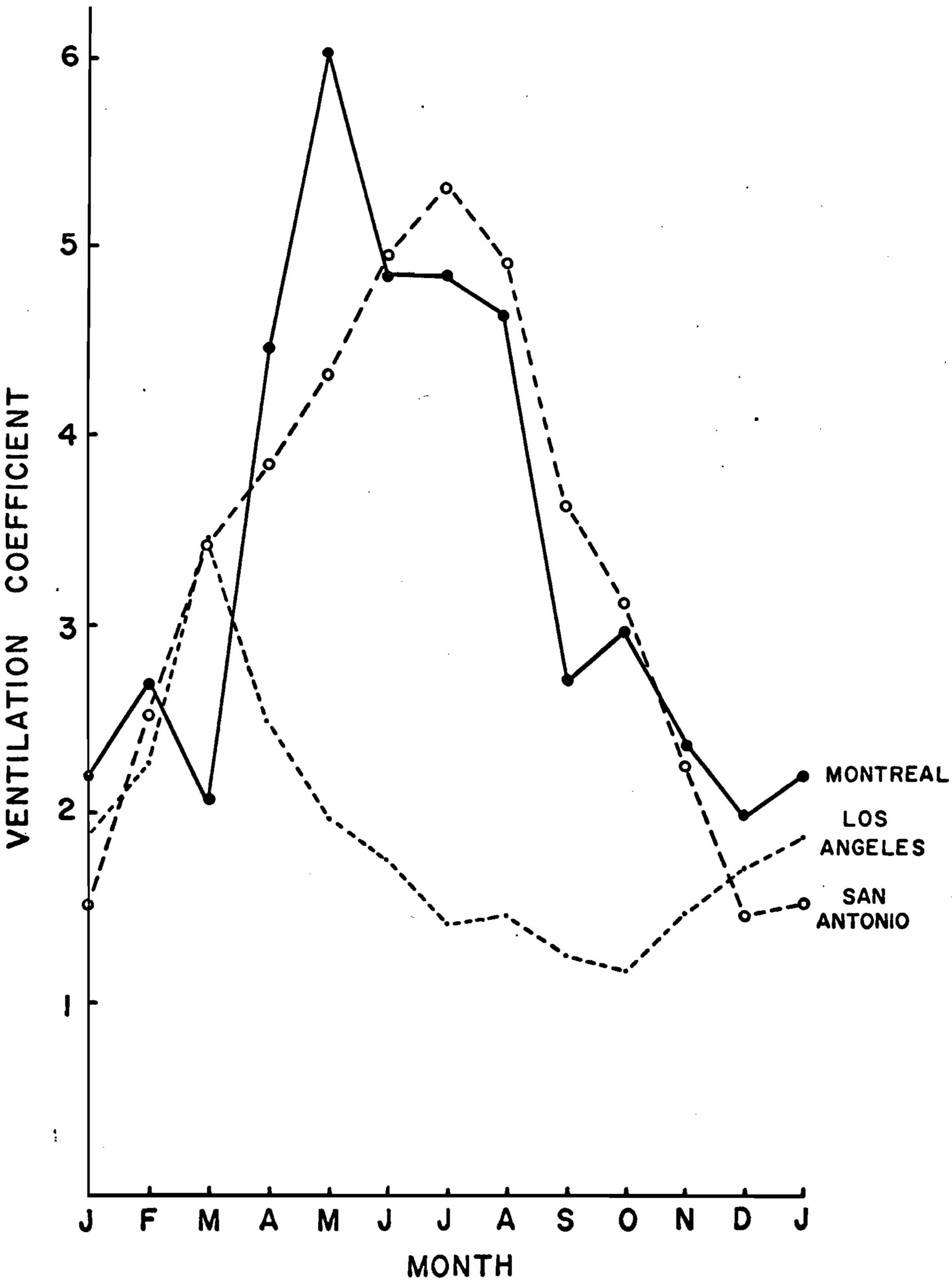


Figure 4.4 Monthly Variation of Ventilation Coefficient at Time of Maximum Mixing Depth

to combine the data presented in Figures 4.3 and 4.2 to obtain a useful estimate of the seasonal change in the ventilation coefficient. The wind data in Figure 4.3 ~~is~~ are for the whole day. Since data on afternoon winds only are not readily available, then as a first approximation it will be assumed that the afternoon winds show a similar seasonal variation to the daily mean wind. Thus by forming the product of h and $\bar{u}$ for each month of the year an indication of the seasonal trend in ventilation coefficient is shown in Figure 4.4. The afternoon ventilation is at a minimum in Montreal during the winter months. The effect of increased wind speed in winter offsets the low mixing depth to the extent that the ventilation coefficient at this time of year is now almost twice the value for Los Angeles during the late summer and fall months.

4.6 The Time Constant of Ventilation

Eq. 4.7 is an example of exponential growth or decay. It can be re-written and integrated giving a solution of the form

$$C = C_e - (C_e - C_o)e^{\frac{-\bar{u}t}{L}} \tag{4.9}$$

where the time constant of ventilation is $L/\bar{u}$.

Thus if the concentration in the volume is in equilibrium and either Q or $\bar{u}$ is suddenly changed to a new value, then from Eq. 4.9 one would expect the change to the new equilibrium value to take place exponentially with a time constant given by $L/\bar{u}$. This idea has been suggested by Smith (1961) and was applied to data in Philadelphia by Davis (1961).

The data in Figures 3.3 to 3.14 do indeed suggest that in many months of the year exponential increase or decrease of soiling index is taking place. Exponential curves were fitted to ~~this~~ these data wherever possible, by the method given in Brooks and Carruthers (1953), and the time constants evaluated. For the period of growth preceding the morning peak these time constants were found to be of the order of 1.5 to 3.0 hours. Using the corresponding wind speeds during these periods then L turned out to be in the range 17 to 24 miles. Although on the large side this is certainly of the same order as the actual built-up cross-city dimension (Summers 1963a, 1963b). Fitting exponential curves to the data also gives the value of Q/h. Thus if the seasonal variation in h were known in detail, then useful estimates of the seasonal variation of Q could be made.

4.7 Defects of the Model

Although this model is rather crude compared to the more sophisticated diffusion models it does have the one big advantage of simplicity. It also brings out the factors involved in large area pollution problems in a clear fashion. But when applied to observations at a single point, the assumptions made in its formulation lead to serious physical inconsistencies.

The basic principle of exponential growth or decay is that the rate of absorption or removal of a quantity from a given volume be proportional to its value at the point of exit. So in considering ventilation by a wind blowing through a reservoir it was necessary to make the assumption that the smoke was instantaneously mixed completely through the whole volume both horizontally and vertically. Otherwise any change in Q or $\bar{u}$ would alter the relation between C at the exit point (downwind end of city), and the mean C for the whole volume, and so Eq. 4.7 would be no longer valid. As long as there is any wind blowing across an area source it is physically unreasonable to assume that the smoke concentration is uniform everywhere. The idea of a limited depth of uniform vertical mixing can still be used and applied to a column of air moving across the city with the mean wind flow.

The effect of a change in Q, $\bar{u}$ or h on an observing point within the city will be as follows: The concentration will change with time in a way determined by the spatial distribution of the source upwind, and will continue changing until such time as it takes for the air entering the edge of the city to reach the sampling location. At this time the new steady state condition will be attained for the new set of values of Q, $\bar{u}$ and h. Thus instead of an infinite time required to reach the new steady state and the necessity of a time constant, there is now a finite time to reach the new steady state. If the sampling location is in the centre of the city then this time for equilibrium to be reached is $L/2\bar{u}$. If the source strength is distributed in such a way that it falls off exponentially from the centre of the city, then the change from one steady state to another will have an exponential appearance but the increase or decrease of concentration with time will be truncated after a time $L/2\bar{u}$.

A less serious objection to the model is the assumption of constant h over the city. Since the amount of heat added to the air at night increases as it penetrates further into the city then the depth of the adiabatic mixing layer will increase. This adiabatic mixing layer which forms over the city at night is of great importance in considering pollution concentrations, and its formation will now be discussed in detail.

CHAPTER 5

THE URBAN HEAT ISLAND EFFECT

5.1 Introduction

Detailed observations of the spatial distribution of temperatures have been made only in a few cities. The earliest comparisons of temperatures from a number of stations in and around a city were made in London by Luke Howard (1833). This was followed by comparisons from Paris (Renou 1862) and from St. Louis (Hammon and Duenchel 1902). However, all these were made using only a few fixed reporting stations. Automobiles were first used by Schmidt (1929) in Vienna. In this way many traverses could be made in a short period of time in the late night hours when meteorological conditions are changing with time least rapidly. In the next ten years several studies were made and country-city temperatures differences of up to 24°F were found in Berlin (Reichel 1933), and 34°F in Toronto (Middleton and Millar 1936). The first attempt to combine vertical as well as horizontal measurements was by Balchin and Pye (1947) in the City of Bath, England, which lies in a steep valley. Measurements taken on the surrounding hillsides showed that the formation of complete inversions over the city itself was prevented on 34 of the 138 occasions when inversions were present in the open country.

A very thorough study in Uppsala, Sweden, was reported by Sundborg (1959) in which cross-city temperature traverses were made on 200 occasions within one year. An approximate empirical formula was developed relating the nighttime urban-rural temperature difference D to the percent cloud cover N, and wind speed V as follows:

$$D = \frac{a - bN}{V}$$

where a and b are appropriate constants for Uppsala. But again no vertical temperature measurements were made.

The most comprehensive studies in North America were made in California by Duckworth and Sandberg (1954). Automobiles were used to make detailed temperature measurements at the two-meter height in three cities of different size, namely, San Francisco, San Jose and Palo Alto. Also simultaneous vertical temperature profiles were made inside and outside the cities using thermistors attached to a Kytoon or balloon cluster. These profiles suggested that the urban heat island tended to destroy the nocturnal inversion over the City in the lowest few hundred feet, whilst the inversion persisted aloft. Most meteorological towers are located in open country, but in July 1957 a vertical temperature difference measuring system was installed on a TV tower situated in the centre of Louisville, Kentucky. Temperatures were measured at heights of 60, 170 and 524 feet above ground level. DeMarrais (1961) has analyzed this data and comes up with the following conclusions:

"The vertical temperature differences observed at night over Louisville are considerably different from those observed over non-urban areas. Whereas surface inversions regularly occur at non-urban areas, they are comparatively rare over the urban complex. During more than half of the hours at night, a lapse between isothermal and adiabatic in the 60 to 524 foot layer is observed, and during 30 percent of the nighttime hours, a discontinuous lapse rate in which the lower part of the layer is less stable than the upper part is observed."

In the present study, on a few occasions temperature and soiling index measurements were taken by the Author from a car at several elevations on the highway passing over Mount Royal. All of these measurements were taken during anticyclonic weather conditions and in all cases inversions were absent in the lowest few hundred feet. One particularly interesting case occurred on 29th November 1962. This was in the middle of a prolonged spell of anticyclonic weather caused by a blocking high pressure system over New England (Andrews 1963). The data from the meteorological towers in southern Ontario and Montreal during this period have been analyzed in detail by Munn (1963). Observations on Mount Royal indicated a lapse rate half way between isothermal and the dry adiabatic up to a height of 400 feet above M.S.L. and an inversion of 10°F between this height and the top of Mount Royal (750 ft.). The soiling index measurements taken with a Bantam portable sampler indicated fairly uniform high readings between McGill and 400 feet, falling off rapidly to near zero at CBC. Looking across the city from Mount Royal indicated a fairly sharp top to the pollution layer at about 500 feet above M.S.L. (see frontipiece). Frequent visual observations taken while driving over Mount Royal often indicated a well defined top to the smog layer somewhere between 300 and 600 feet.

The data presented in Figure 3.1 and Figures 3.3 to 3.14 clearly indicate that the mean soiling index at the CBC location on top of Mount Royal is only from 0.15 to 0.35 times the values at the lower elevations. Although some of this reduction is no doubt due to the lack of nearby smoke sources, part of the reduction is also due to the elevation, and the fact that overnight much of the time the pollution is trapped in a mixing layer whose top is below the summit of Mount Royal.

Measurements made from a helicopter over Cincinnati, Ohio, have been analyzed by McCormick and Baulch (1962). On several occasions lapses of temperature were found from the surface up to a height of 100 to 150 meters with stable lapse rates above. In these cases it was found that most of the pollution was concentrated in the lower mixing layer.

Davidson (1942) analyzed data from seven smoke samplers located in New York City. The height of the samplers above ground and sea level ranged from 30 to 300 feet. Data presented in the paper both for July and January indicated no systematic change in smoke concentration with height. This suggests that the smoke over New York City is well mixed to a height of at least 300 feet.

Thus there is increasing evidence from many sources that large urban areas influence the temperature lapse rate up to a height of several hundred feet. One very important implication of this is that meteorological towers, set up within a City in order to measure the frequency of temperature inversions, are likely to give misleading results unless they are high enough to penetrate through the modified layer. A location outside the city will give more representative frequencies of inversions, and on most occasions when they form in the open country they will still be present at higher elevations over the city, and the pollutants will still be confined to the lower mixing layer. This raises the interesting speculation that perhaps large cities are able to mix the pollution through a greater depth at night, if the mixing depth is proportional to the amount of urban heating. According to Duckworth and Sandberg (1954) there is some evidence that the heat island effect is proportional to the size of the city.

5.2 The Montreal Urban Heat Island

The first weather observations were taken in Montreal in January 1862 and continuous daily observations were commenced in 1874. Apart from slight fluctuations the mean annual temperature has shown a marked upward trend of about 3°F since then. A similar upward trend has been noted in many other growing cities in North America (Mitchell 1953, 1962). By comparing urban trends with suburban trends the effect of long term climatic changes can be eliminated and the residual gives the temperature increase due to the growth of the city itself. Unfortunately no country stations are available near Montreal with a long enough continuous period of record. It may, however, be possible to make use of the observations obtained by Dr. Smallwood (founder of the McGill Observatory) at his house in St. Martin for many years prior to 1875. This is outside the scope of the present study.

Other stations in the Montreal area which provide hourly weather observations are the airports at St. Hubert and Dorval shown on the map in Figure 2.2.

Many other co-operative and climatological stations have been in operation from time to time and data from these will be used to define the limits and magnitude of the Montreal Urban Heat Island.

Two stations were selected far enough away from the City Centre to be unaffected by the heat island, yet close enough such that larger scale topographical features have little effect. These were Macdonald College at the western end of Montreal Island and St.

Hubert Airport to the southeast. The mean value of these two stations was then taken as the base country temperature above which the city excess was computed.

All of the stations shown in Figure 2.2 report minimum temperatures and this is the time when the urban heat island effect is most noticeable. For each month over a period of three years the excess of the mean monthly minima was computed. The months were grouped into the three seasons defined in Section 2.8 and the average excess for each season is shown in Figures 5.1, 5.2 and 5.3. McGill Observatory is located on the campus at the foot of Mount Royal (see Figure 2.3); it is, therefore, likely that other more densely built-up parts of the downtown area will have even higher temperatures. Temperatures taken by automobile suggested that on a few occasions this was so.

The greatest city excess temperatures occur in the summer and winter, whilst in the transition season they are somewhat less. An interesting point is that in the winter months both Dorval and the Botanical Gardens have a small excess temperature, i.e. they are on the edge of the area affected by the heat island. But in the summer months these two locations have a temperature excess of more than 1°F. A possible explanation of this is that the large areas of asphalt at Dorval Airport act as a heat source at night, releasing the heat gained from the sun during the daytime. The excess at the Botanical Gardens is harder to explain, but could be due to the increased frequency of southerly and southwesterly winds in the summer months (see Table 2.2).

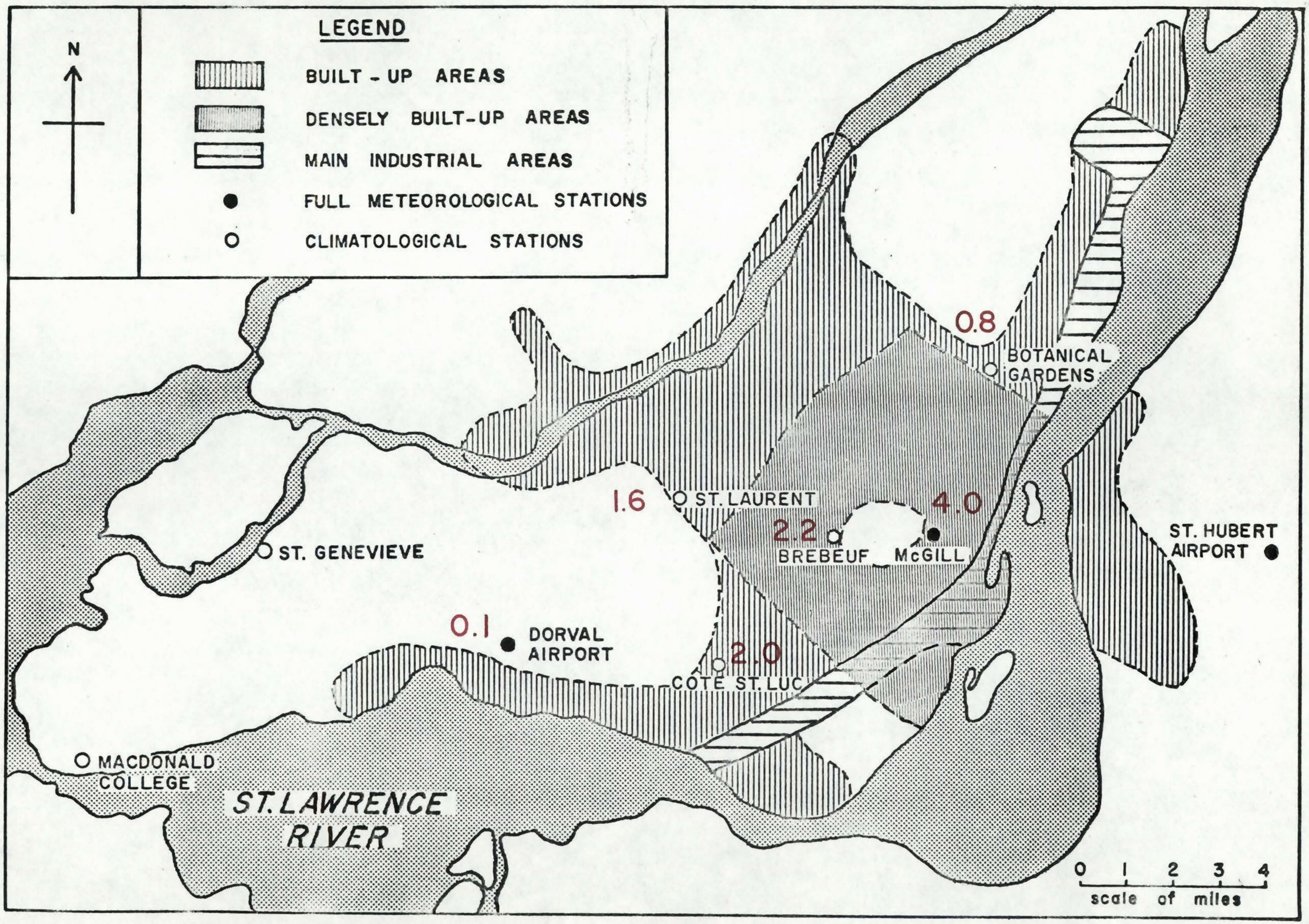


Figure 5.1 Average Excess in Mean Minimum Temperature at City Stations - WINTER MONTHS 1960-63

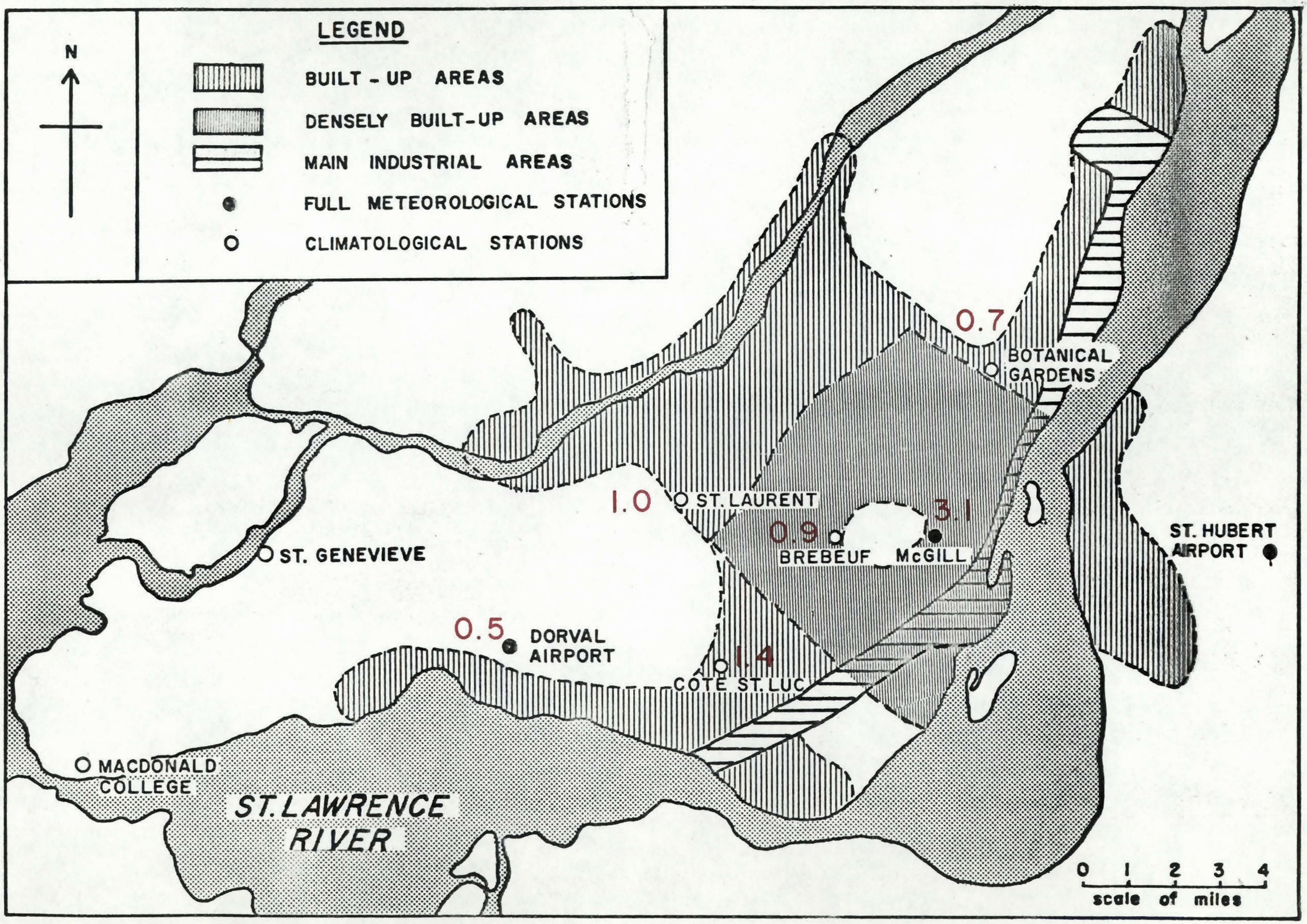


Figure 5.2 Average Excess in Mean Minimum Temperature at City Stations - TRANSITION MONTHS 1960-63

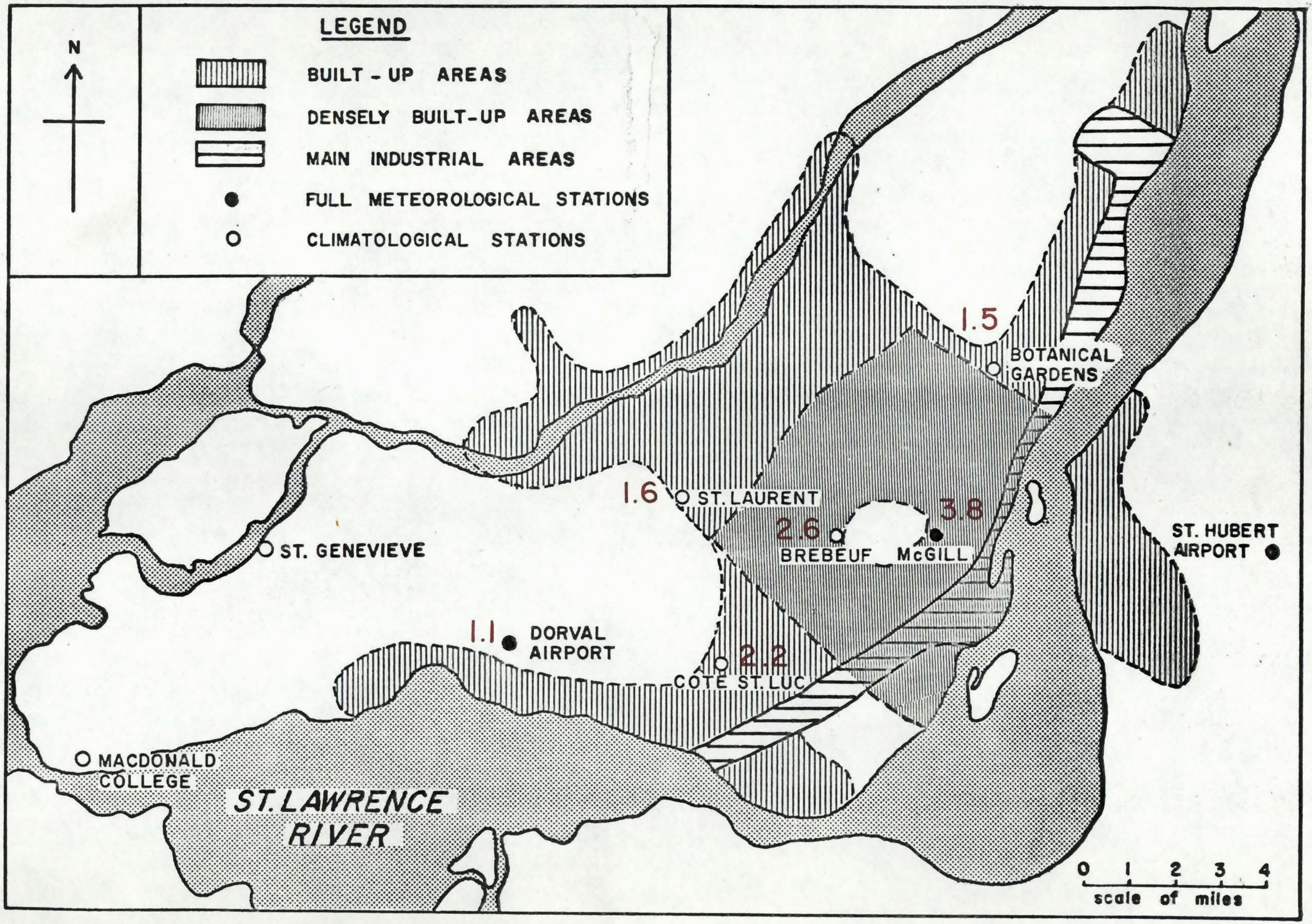


Figure 5.3 Average Excess in Mean Minimum Temperature at City Stations - SUMMER MONTHS 1960-63

The effects of the open water of the St. Lawrence River and Lake St. Louis have not been considered, but these could also affect both the Macdonald and Dorval temperatures.

On individual days the differences between city and country are even more striking. As an example the actual minimum temperatures for 9th March 1962 are shown in Figure 5.4. A difference of 18°F. shows up between McGill and St. Hubert, a distance of only seven miles.

The results of a limited automobile survey made by the Author on the morning of 2nd February 1962 between 0445 and 0555 EST are shown in Figure 5.5. At this time a north-northeast 11 mph wind was recorded at Dorval Airport. The highest temperatures were not in the centre of the city but near the downwind end of the densely populated apartment-complex area of the Cote des Neiges District. Also shown in parenthesis for reference are the actual minimum temperatures recorded at the meteorological stations, but these occurred between two and three hours after the survey. On two other occasions with a northeast wind blowing, a warm spot was found in the same location, although its lateral extent was not investigated.

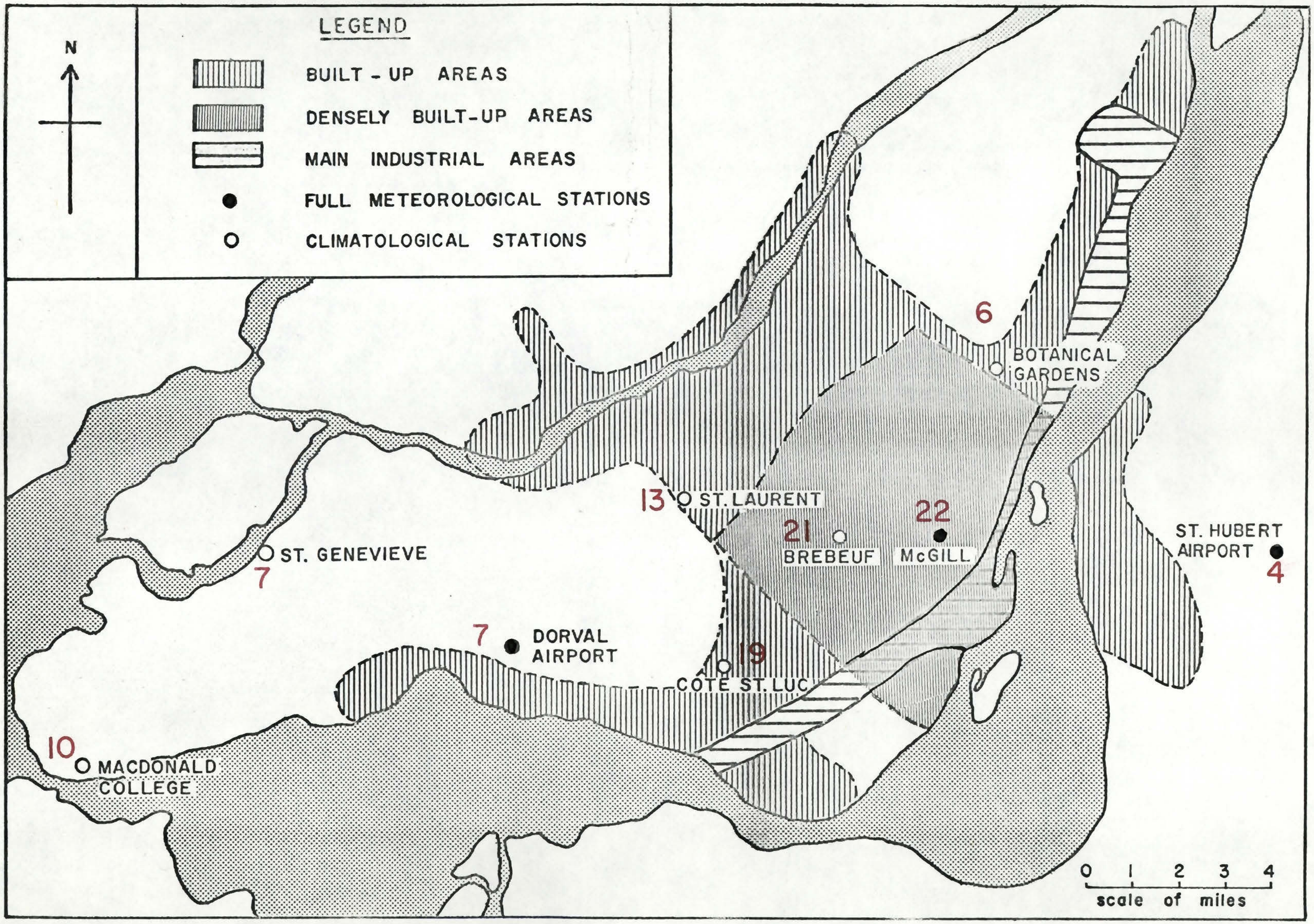


Figure 5.4 Actual Minimum Temperatures in Montreal Area 9 March 1962

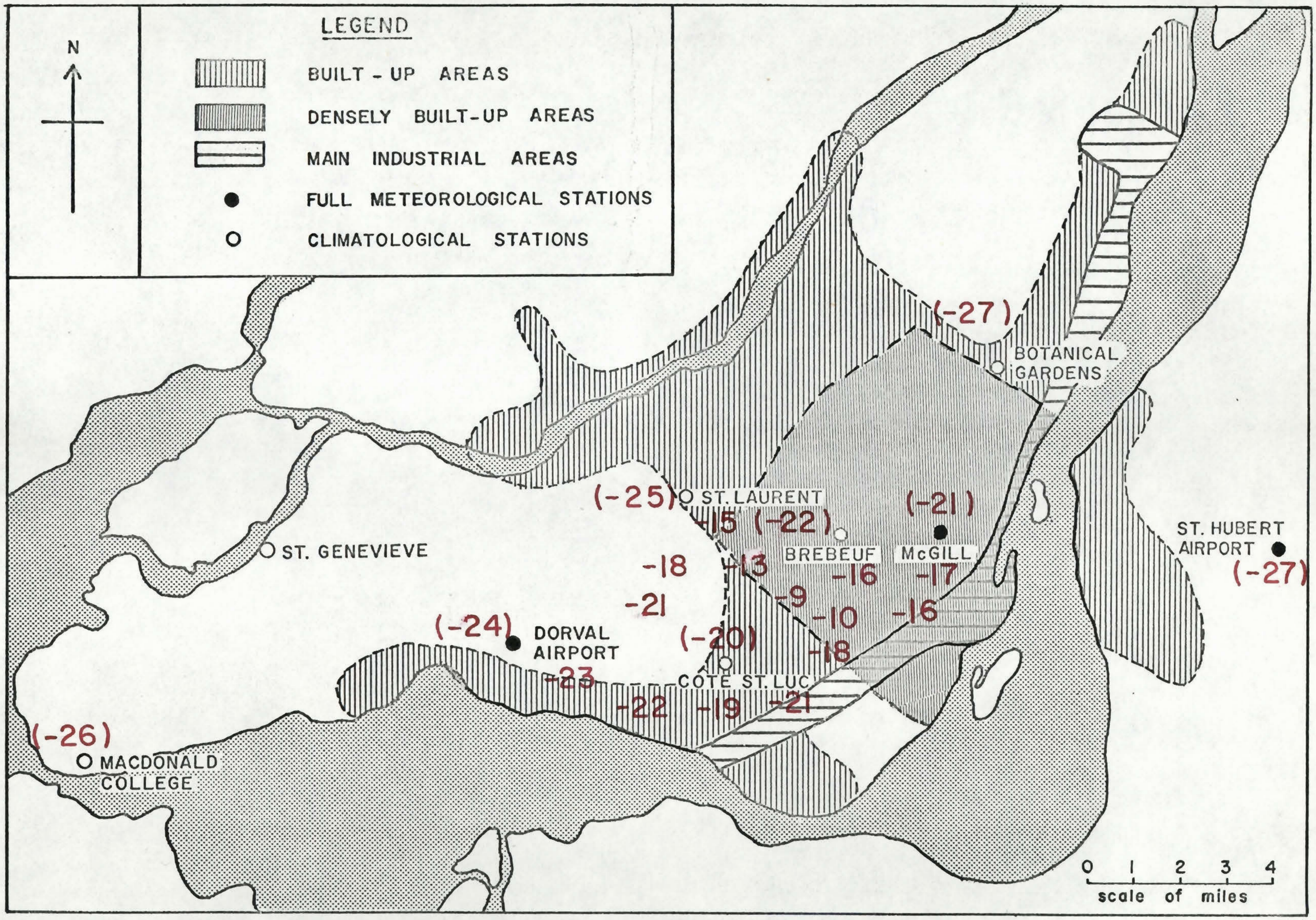


Figure 5.5 Automobile Temperature Survey 0445 - 0555EST 2 February 1962
(Minimum temperatures at Meteorological Stations in brackets)

5.3 Theoretical Discussion of the Heat Island Effect

We will now consider what happens when stable air is advected over a city acting as a heat source (a common nighttime occurrence in Montreal). Before putting forward a mathematical treatment some simple physical ideas will be discussed.

As the air moves across the city it will be warmed from below gradually developing an adiabatic layer. It is reasonable to imagine a sloping upper boundary between this adiabatic layer and the stable air above. In the country air the stability damps out any tendency for up or down turbulent motion and so the motion of the air will be along horizontal streamlines. When this air reaches the upper boundary, it will mix in with the city air in the vertical circulation of the adiabatic layer (see Figure 5.6). As the air moves

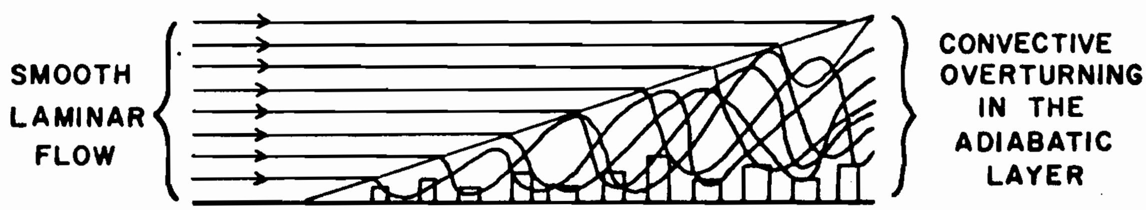


Figure 5.6 Schematic Cross-Section of City Showing Build-Up of Adiabatic Layer

further and further into the city it will gain more heat leading to an increase in both, the height of the mixed layer, and the surface temperature. Successive stages in this process are illustrated by the vertical temperature profiles shown in Figure 5.7.

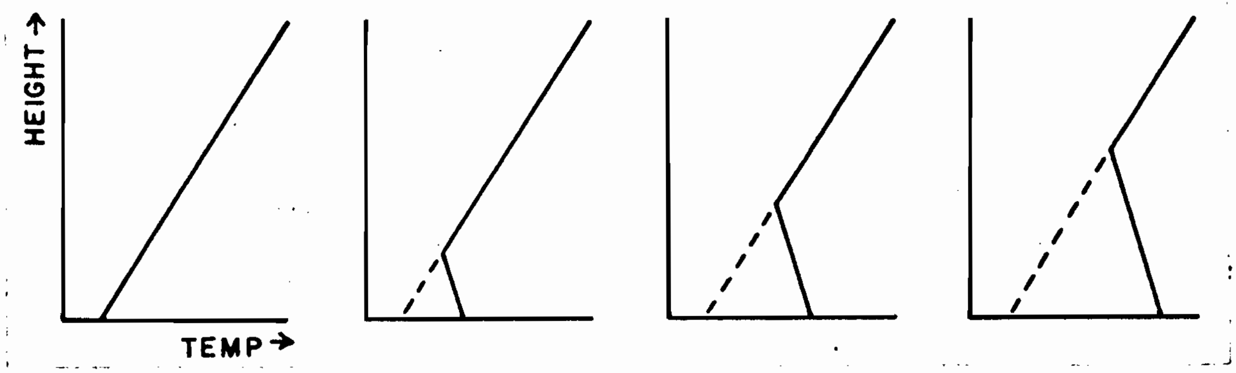


Figure 5.7 Successive Stages in Modification of the Vertical Temperature Profile as the Air Moves Over the City from Left to Right

Now consider what happens to the vertical wind profile as it moves in over the city. Assume a simple linear increase with height in the country as illustrated in the left-hand diagram in Figure 5.8. Neglect friction at the surface, and assume a smooth sharply defined upper boundary across which momentum is transported without any frictional loss. Then the mean wind up to a height z over the city must be equal to the mean wind up to this same height in the country. Since the air in the adiabatic layer is in vertical circulation then it can be assumed to have a uniform wind with height up to the boundary. Thus on these simple assumptions the vertical wind profile will be modified in successive stages as the air moves in across the city as shown from left to right in Figure 5.8.

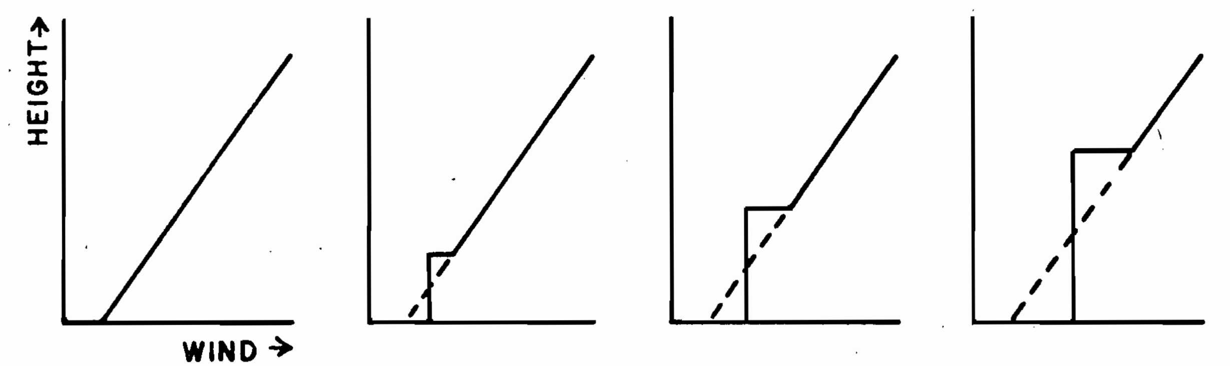


Figure 5.8 Successive Stages in Modification of the Vertical Wind Profile as the Air Moves in over the City from Left to Right

This concept can be made more realistic by including the effect of friction at the ground. Any tendency for the air near the surface to accelerate due to the downward transfer of momentum will be offset by the increased frictional drag due not only to this increase in speed, but also to the increased roughness of the city compared to the open country. This increase in friction also implies a loss in total momentum for the layer over the city compared to a layer of the same depth in the country.

The upper boundary will not be a sharp discontinuity as pictured in Figure 5.8. But rather there will be a transition zone, with air just arriving in the top of the adiabatic layer only gradually acquiring the mean velocity of the layer. Also at any given height within the adiabatic layer the wind speed will have considerable range; the rising air tending to be slow moving and the descending air faster moving. However, to keep the mathematical treatment simple, it will be assumed that the average speed in the adiabatic layer is equal to the average country speed over the same height interval.

Suppose that the lapse rate in the country air is less than the dry adiabatic by an amount α. This is shown in Figure 5.9 as the line T_0T. Now if the surface temperature has risen to T_x by the time the air has moved a distance x into the city, and the depth of the adiabatic mixing layer thus produced is z, then the following relations are true:

$$T = T_o - (\Gamma' - \alpha)z \qquad (5.01)$$

$$T = T_x - \Gamma' z \qquad (5.02)$$

Subtracting, then at height

$$T_x - T_o = \alpha z \qquad (5.03)$$

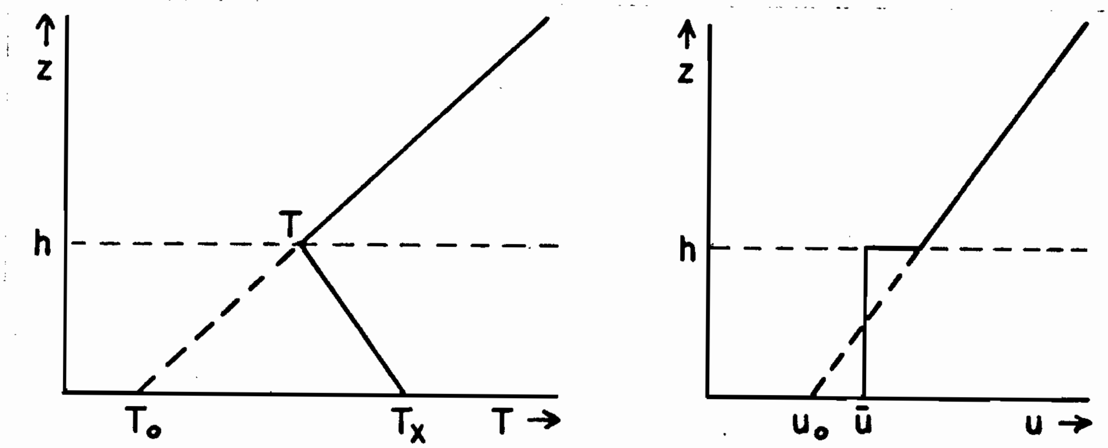


Figure 5.9 Modification of Temperature and Wind Profile at Distance x Inside City

Let the vertical wind profile in the country have a linear increase with height given by

$$u = u_o + bz \qquad (5.04)$$

thus the mean wind up to a height h is given by

$$\bar{u} = u_o + \frac{bh}{2} \qquad (5.05)$$

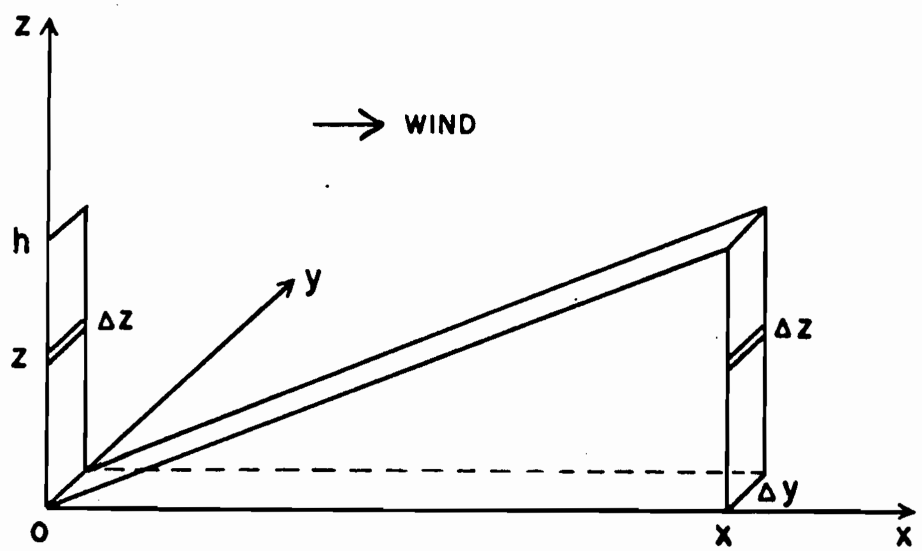


Figure 5.10 Schematic Illustration of Co-ordinate System for Mathematical Treatment

Consider a vertical cross-section width Δy and height h of the adiabatic layer at a distance x in from the upwind end of the city (see Figure 5.10). The potential temperature at height z will be T_x and the amount of heat passing through a depth Δz of the cross-section in unit time will be

$$c_p \Delta y \Delta z \rho (u_o + \frac{bh}{2}) T_x$$

The total heat B_x passing through the whole cross-section is obtained by integrating in z from o to h.

$$B_x = \rho c_p \Delta y \ (u_o + \frac{bh}{2}) T_x \int_o^h dz$$

$$B_x = \rho c_p \Delta y \ T_x \ (u_o + \frac{bh}{2}) \ h \tag{5.06}$$

The potential temperature at height z in the country air is given by $T_0 + \alpha z$. Thus if B_0 is the total heat passing through the cross-section in the country in unit time

$$B_0 = \rho c_p \Delta y \int_0^h (u_0 + bz)(T_0 + \alpha z)\, dz \tag{5.07}$$

Thus the total heat gained by the volume of air between the two cross-sections in unit time is given by $B_x - B_0$. Performing the integration and using Eq. 5.03 then

$$B_x - B_0 = \rho c_p \Delta y \alpha h^2 \left(\frac{u_0}{2} - \frac{bh}{6}\right) \tag{5.08}$$

Now let the heat output of the city at distance x from the edge be $H(x)$ cal $cm^{-2}sec^{-1}$. Then the total output into the volume per unit time is

$$\Delta y \int_0^x H(x)dx$$

In a steady-state condition this must be equal to the heat gained by the air in the volume therefore

$$B_x - B_0 = \Delta y \int_0^x H(x)dx$$

$$\boxed{h^2 \left(u_0 + \frac{bh}{3}\right) = \frac{2}{\alpha \rho c_p} \int_0^x H(x)dx} \tag{5.09}$$

This equation gives the height h of the mixing depth at a point distance x inside the city, in terms of the distribution of the heat source, and the meteorological parameters. Two simple cases will now be considered.

a) Uniform heat source Let $H(x)$ = constant H say, then from Eq. 5.09

$$h^2 \left(u_o + \frac{bh}{3}\right) = \frac{2Hx}{\alpha \rho c_p} \tag{5.10}$$

If there is no wind shear then b = o and thus

$$h = \left(\frac{2Hx}{u_o \alpha \rho c_p}\right)^{\frac{1}{2}} \tag{5.11}$$

The height of the mixing depth is, therefore, proportional to the square root of the heat added. With a wind shear the value of h will be reduced by an amount depending on the value of b.

From Eq. 5.11 and 5.3

$$\boxed{T_x = T_o + \left(\frac{2H \alpha x}{u_o \rho c_p}\right)^{\frac{1}{2}}} \tag{5.12}$$

Thus the surface temperature excess at a distance x inside the city is proportional to the square root of the heat input and intensity of the inversion, and inversely proportional to the square root of the wind speed.

b) Linearly increasing heat source Let the heat be distributed such that the total between the edge (x = o) and the centre (x = L) of the city is the same as in the uniform case.

$$H(x) = \frac{2Hx}{L}$$

Then from Eq. 5.9 we have

$$h^2 \left(u_o + \frac{bh}{3}\right) = \frac{2Hx^2}{L \rho \alpha c_p} \tag{5.13}$$

With no wind shear b = o and so

$$h = x\left(\frac{2H}{L \alpha \rho c_p u_o}\right)^{\frac{1}{2}} \tag{5.14}$$

and

$$T_x = T_o + x\left(\frac{2H\alpha}{u_o L \rho c_p}\right)^{\frac{1}{2}} \tag{5.15}$$

Now at the centre of the city x = L and so from both Esq. 5.11 and 5.14

$$h = \left(\frac{2HL}{u_o \alpha \rho c_p}\right)^{\frac{1}{2}} \tag{5.16}$$

$$\boxed{T_L = T_o + \left(\frac{2HL\alpha}{u_o \rho c_p}\right)^{\frac{1}{2}}} \tag{5.17}$$

Thus, as far as heat input is concerned, the value of the temperature excess at the centre of the city is dependent only on the total amount of heat added to the air in moving from the edge to the centre; it is independent of the way in which this heat input is distributed. With a uniform heat source the value of the temperature excess increases as the square root of the distance from the edge, but with a linearly increasing heat source the temperature excess also increases linearly towards the centre of the city. Duckworth and Sandberg (1954) considered the horizontal gradients of temperature near the centre of the three cities studied. They found that the larger the city the smaller the temperature gradient. This would follow from Eq. 5.11 since

$$\frac{dT_x}{dx} = x^{-\frac{1}{2}}$$

and the larger the city, the larger x, and hence the smaller $\frac{dT_x}{dx}$ near the centre. This suggests that the cities studied by Duckworth and Sandberg were acting as uniform heat sources. They also found that the temperature differential between city centre and suburbs increased rather slowly with increasing city size, which again follows from Eq. 5.17, since $T_L - T_o$ increases as the square root of L.

It is also interesting to compare Eq. 5.17 with the empirical results obtained by Sundborg (see Section 5.1). For a given city and given heat source L and Q are constant, thus re-writing Eq. 5.17

$$T_L - T_o \propto \left(\frac{\alpha}{u_o}\right)^{\frac{1}{2}} \qquad (5.18)$$

The numerator in Sundborg's formula decreases with increasing cloud cover. On a cloudy night the lapse rate near the ground approaches the dry adiabatic and so α also decreases with increasing cloudiness. Thus Sundborg's empirical formula and Eq. 5.18 agree subjectively except for the square root sign. But α and u_o ~~and~~ are not independent, since strong inversions caused by noctural radiational cooling can only exist with light winds, and are destroyed completely with winds more than about 10-12 mph. Thus there is a relation between α and u_o, such that, as u_o increases, α decreases. The exact form of any such relation is not known. Before applying the derived equations for h and T_x the main assumptions will be discussed.

a) It is assumed that all of the heat output of the city is retained by the air and none radiated into space. The surface radiative temperature of the city is certainly greater than T_o, but the return radiation from the atmosphere will be greater over the city because of the larger amounts of CO_2, water and smoke in the air. Thus these two effects will tend to cancel each other out. If there is enough smoke in the adiabatic layer then the top of the smoke layer will be acting as the radiating surface with an effective black-body temperature T which is somewhere between T_o and T_x (see Figure 5.9). Assume that from this level on up the composition of the atmosphere is the same over the city and country, then the return radiation to earth will be the same in both cases. Thus there will be an excess of radiational cooling of the air as it moves in from the country over the city by an amount $\sigma (T^4 - T_o^4)$, where the T's are expressed in degrees absolute. In most cases this is a small fraction of the heat input from a densely populated city.

b) In the mathematical treatment it is assumed that the city is infinitely wide at right angles to the wind flow. In this way the lateral mixing of heat can be neglected.

c) Equation 5.09 can be solved analytically or graphically for h when simple distributions of H(x) are assumed. But no data ~~is~~ are available for Montreal from which the wind shear can be readily evaluated. Thus to simplify the application of the preceding ideas to actual data, as a first approximation b will be assumed to be zero. Any tendency for the air to accelerate as it moves across the city due to the shear term will be offset by an increase in the frictional drag imposed by the rough city surface. Thus there is some justification for neglecting the shear term on the average, although there may be individual nights when it is important.

CHAPTER 6

URBAN VENTILATION AT NIGHT

6.1 Smoke Concentration in the Nighttime Mixing Layer

In the previous chapter the urban heat island effect was discussed, and it was shown that over an urban area at night vertical mixing is generated within a finite mixing depth. We will now consider what happens to smoke which is introduced into this layer along with the heat. There are six ways in which this smoke can be removed from the volume of air over the city.

a) Deposition on the ground. This will be rapid for large particles such as fly-ash which normally fall-out close to the emitting source. For particles of one micron or less deposition is a slow process. Comparisons can be made between the total dust-fall over a period of one month and the mean observed atmospheric concentrations. In this way estimates have been made of the average life-time of suspended particulates. For the Midlands of England the half-life time was found to be about six days (D.S.I.R. 1945). Calculations by McDonald (1961) indicate a weighted mean residence time of five hours for New York City, but only two hours for Detroit. But it was pointed out that the coarser particles fall out very rapidly and this must be compensated for by a much larger residence time for the smaller suspended particulates. Thus in the few hours the air is normally over the city deposition is a negligible factor in decreasing smoke.

b) Impaction on buildings and trees. Perkins (1962) discusses this and concludes that for the small particulates which contribute to the soiling index this effect is negligible in most cases. Perkins also describes an experiment in Los Angeles where a known amount of a fluorescent tracer was released at Compton Airport. After five hours of travel the amount of material passing over an arc of 23 samplers was found to be only slightly less than the amount released. This experiment thus suggests that items a) and b) are small.

c) Wash-out by precipitation. This effect has not yet been satisfactorily described. Since rainy days are positively correlated with other meteorological conditions such as strong winds, the effect of rain itself is difficult to isolate. There is some slight evidence from two studies that pollution is lower on rainy days even after the effects of other meteorological factors have been taken into account (D.S.I.R. 1945; I.J.C. 1960). Even if some wash-out does occur its effect on mean pollution concentrations will be small due to the small percentage of the total time during which precipitation is actually falling.

d) Vertical diffusion through the top of the mixing layer. Since in this model a stable lapse rate is postulated above the mixing layer, vertical transport of pollution through the top of the volume will be small. Evidence for this is seen in the very low or zero smoke at CBC when WEC and McGill are exceptionally high.

e) Lateral spreading. In the stable conditions around the city lateral spreading will be at a minimum, and by postulating an infinitely wide city, will have no effect at the centre. Under actual conditions, the effect of lateral spreading of heat will be to make the maximum height of the mixing layer slightly less than that given by Eq. 5.09. Total mass of smoke over the city will also be slightly reduced, but the net effect on the concentration will be negligible.

f) Mass transport by the wind. This is the largest of all possible removal mechanisms, under the postulated simple model conditions, and is proportional to the mean wind speed.

Returning now to the picture in Fig. 5.10. Let the rate of production of smoke at a distance x inside the city by $Q(x)$gm $cm^{-2}sec^{-1}$. Then the total mass of smoke added to the volume between the two cross-sections if

$$\Delta y \int_0^x Q(x)dx$$

Now assume that the air entering from the country is clean, and that by the time it has moved a distance x inside the city it has a uniform concentration C in the vertical within the adiabatic layer. Again this assumption is not strictly true. Clean air enters the top of the adiabatic layer and subsides, and smoke enters from the bottom and rises. Even though there is a strong convective vertical circulation in this layer, the concentration of smoke will tend to be greatest near the bottom and least near the top. But for mathematical simplicity C will be assumed invariant with height. Then the total mass of smoke passing through the cross-section at distance x in unit time is

$$c \Delta y \left(u_o + \frac{bh}{2}\right)h$$

In the steady-state condition this must be equal to the smoke input from the city, therefore

$$c\,\Delta y\,(u_o + \frac{bh}{2})h = \Delta y \int_0^x Q(x)dx$$

$$\boxed{C = \frac{2}{h(2\bar{u}_o + bh)} \int_0^x Q(x)dx} \qquad (6.1)$$

This is the most general equation giving the smoke concentration in terms of the smoke input and the mixing depth h, which in turn is given by Eq. 5.09.

Again, neglecting the shear term and putting b=0, two simple cases will now be considered.

a) <u>Uniform smoke source</u> $Q(x) = \text{constant} = Q$

$$\text{Then} \quad C = \frac{Qx}{u_o h} \qquad (6.2)$$

b) <u>Linearly increasing smoke source</u>

As for heat, let the smoke be distributed such that the total between the edge (x = o) and the centre (x = L) is the same as in the uniform case, then

$$Q(x) = \frac{2Qx}{L}$$

From Eq. 6.1

$$C = \frac{Qx^2}{u_o L h} \qquad (6.3)$$

Thus from Eqs. 6.2 and 6.3 at the centre of the city (x = L) the smoke concentration in the steady-state condition is given by

$$\boxed{C = \frac{QL}{u_o h}} \qquad (6.4)$$

This expression is the same as that obtained in Eq. 4.8 from the simple model, but in this case some of the terms have a slightly different interpretation. The term L is now the distance from the edge to the centre of the city, and so is one half of the value in Eq. 4.8. The mixing depth h is not assumed constant in Eq. 6.4, but is given by the heat input and meteorological parameters from Eq. 5.09. Also in this case h and u_o are not independent. Furthermore, an increase in h can be caused by an increase in heat input, which in turn may imply an increase in smoke input. The implications of this will now be discussed.

6.2 Relation Between Smoke Input and Heat Input

Substituting the value of h from Eq. 5.16 in Eq. 6.4 then

$$C = \frac{QL}{u_o}\left(\frac{u_o \alpha \rho c_p}{2HL}\right)^{\frac{1}{2}}$$

$$C = \frac{Q}{H^{\frac{1}{2}}}\left(\frac{\rho c_p \alpha}{2u_o L}\right)^{\frac{1}{2}} \qquad (6.5)$$

The terms inside the brackets are constant for any given set of meteorological conditions. The smoke concentration in this case is thus proportional to the smoke input, but inversely proportional to only the square root of the heat input. Now suppose that $Q = KH$, where K can be considered as an efficiency factor. For processes and fuels which add a lot of heat to the atmosphere, but with little smoke then K is small. For example use of fuel oil instead of coal for household heating reduces K. In the case of fuel used for industrial purposes some of the energy is converted to mechanical and chemical energy. Although most of this reverts to heat within the heat island, it is probable that the value of K for industrial uses of fuel is slightly greater than for fuel used in space heating.

From Eq. 6.5

$$C \propto KH^{\frac{1}{2}} \qquad (6.6)$$

If the rate of heat output by a city is increased by a factor four, and K is kept constant (implying a fourfold increase in smoke production also), then the smoke concentration will only increase by a factor two.

The heat input H is made up of four components:

$$H = H_h + H_i + H_s - H_r \tag{6.7}$$

where:

H_h = heat required for heating of buildings, all of which eventually leaks out into the atmosphere. This is dependent on the ambient air temperature and is important in the winter only.

H_i = heat produced by industrial and commercial activities, water heating, incineration, automobiles, etc. This is independent of ambient temperature and is nearly constant the year round.

H_s = heat stored in buildings, brickwork, asphalt by absorption of incoming solar radiation during the day. This heat is then transferred back to the atmosphere at night by conduction and emission of long-wave radiation. This term is dependent on the amount of incoming daytime sunshine and the thermal properties of the city surface. It is only important in the summer months.

H_r = loss due to the increase in outgoing long-wave radiation caused by the increased radiative temperature in the city. It is important all year round and is dependent on both the absolute temperature and the city-country difference (see Section 5.3).

The type of dependence of the first three components on temperature is shown subjectively in Figure 6.1. It is generally accepted by heating engineers that the amount of fuel consumed for heating buildings is proportional to heating degree-days. The heating degree-day is defined as the departure of the mean daily temperature below 65°F, it being assumed that no heating is required inside of buildings when the ambient air temperature is in excess of 65°F. Thus

$$H_h = H_d(65 - T) \qquad (T < 65°F) \tag{6.8}$$

where H_d is the rate of production of heat per degree-day from fuel used for heating purposes.

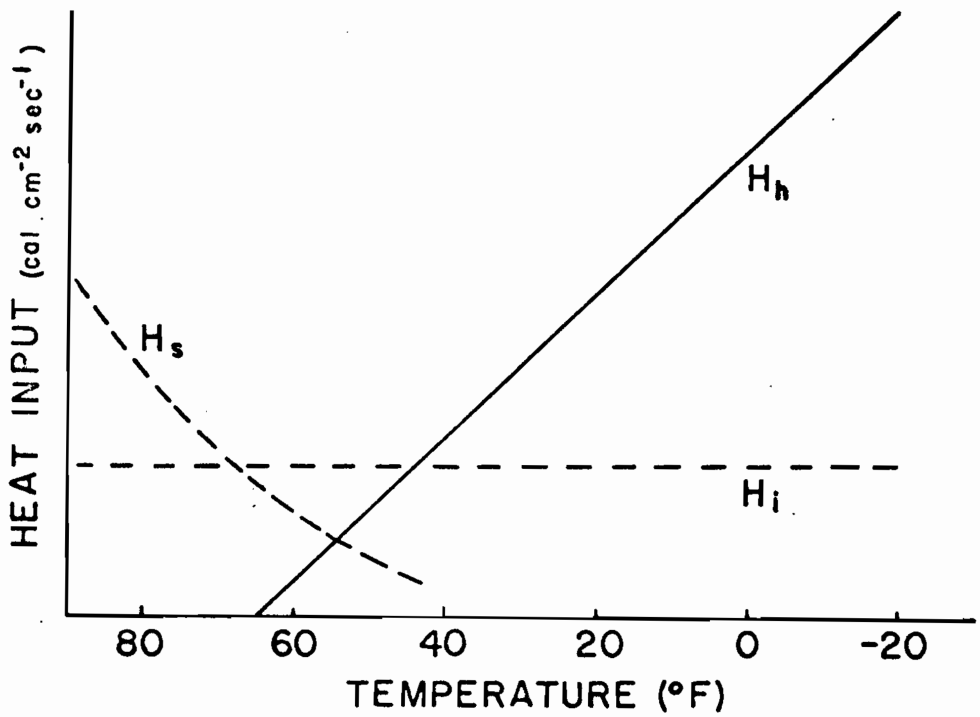


Figure 6.1 Schematic Variation of Components of Heat Input with Temperature

The amount of stored heat is very small in the winter months but increases rapidly as the temperature increases in the summer. It can be seen from Figure 6.1 that the decrease in H_h in the summer is compensated for by an increase in H_s, but the absolute magnitude of these two terms is not known.

Only the first two components of H in Eq. 6.7 are associated with a corresponding production of smoke. Thus

$$Q = Q_h + Q_i \tag{6.9}$$

Putting these in terms of degree-days then

$$Q = Q_i + Q_d(65 - T) \qquad (T < 65^\circ F) \tag{6.10}$$

where Q_d is the rate of production of smoke per degree-day. The term Q_i will be nearly constant throughout the year. The variation of the components of Q with temperature is shown schematically in Figure 6.2.

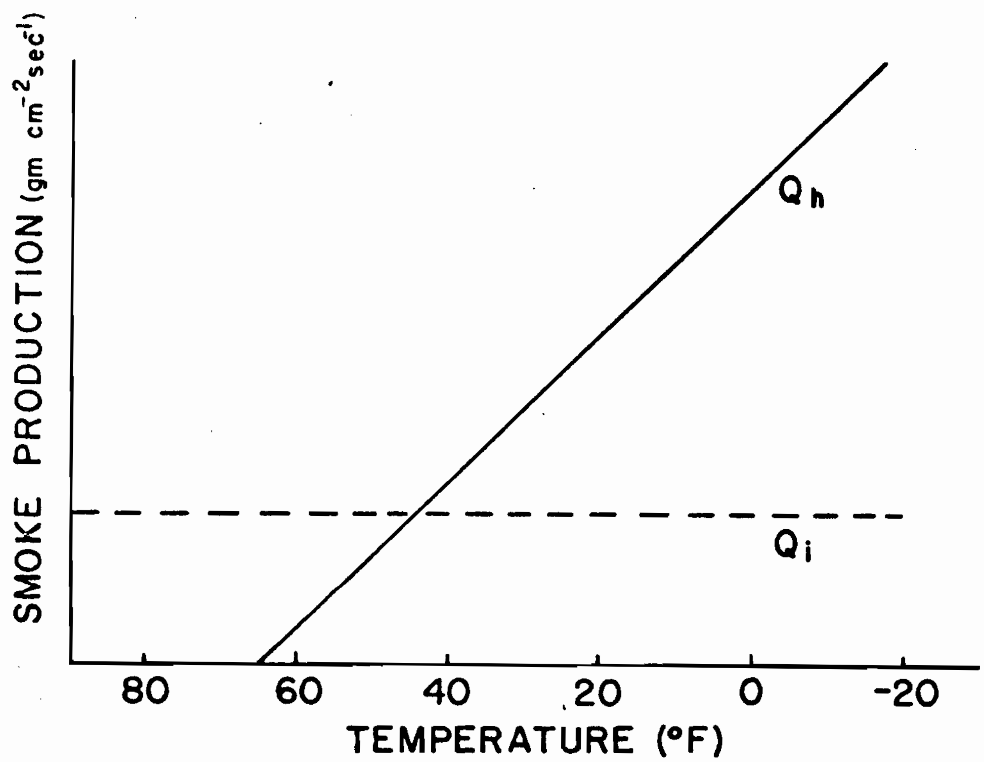


Figure 6.2 Schematic Variation of Components of Smoke Input with Temperature.

The theory of the preceding two chapters will now be applied to the data in the Montreal area, in an attempt to obtain at least a qualitative idea of the magnitude of the components of H and Q.

CHAPTER 7

APPLICATION OF THE URBAN VENTILATION MODEL TO MONTREAL

7.1 Availability of Suitable Data

Surface wind and temperature measurements are available in the Montreal area (see Section 2.9), but for applying the theory developed in the previous two chapters, vertical profiles of wind and temperature are required. If wind shear is neglected, then the other critical parameter required is the value of α for the country air.

The radio-sonde station nearest to Montreal is at Maniwaki, 130 miles away to the northwest. The time of release for the morning ascent is 0630 EST, which during most of the year is after sunrise. In the summer months it is as much as two hours after sunrise, and so the overnight inversion will already be partially or wholly destroyed by release time. We also need the detailed structure in the lowest few hundred feet which is not given by a radio-sonde. The detailed structure is as dependent on local topographical features as it is on the large scale synoptic situation. Data is available from the meteorological tower at the Ottawa Experimental Farm and covers the whole period of this study. But, as with Maniwaki, the distance of over 100 miles away makes its application for detailed studies in Montreal uncertain. This leaves the Botanical Gardens tower in Montreal which was only in operation for the last 13 months of this pollution study. Much of the time though this data will be affected by the heat island as pointed out by Munn (1963).

There are two ways in which the tower data can be used to minimize this deficiency. Firstly, it can be seen from Figure 2.2 that the Botanical Gardens are on the northern edge of the heavily built-up part of the city. Thus, if only occasions with a northerly wind are considered, then the lapse rate given by the tower will be close to that in the open country. A second and less direct method is to correct the surface temperatures for the heat island effect, and estimate the lapse rate in the country air. These two approaches will now be considered in detail.

7.2 Nighttime Mixing Depth with North Winds

Temperature differences are available from the Botanical Gardens tower from March 1962 to April 1963. All days during this period, with a north wind reported at Dorval Airport during the three hours preceeding the time of the morning minimum in temperature, are listed in Table 7.1. Days on which the temperature minimum occurred at some other time of the day, due to an air-mass change or strong advection, were neglected. Also days with an indefinite minimum were not considered. The second column of Table 7.1 gives the mean north wind velocity averaged over the three hours. The third column contains the difference between the surface minima reported at the McGill Observatory and the Botanical Gradens (T_d), as obtained from the Monthly Record, Meteorological Observations in Canada, published by the Meteorological Branch, Department of Transport. The temperature difference obtained from the thermometers at 20 and 196 feet on the Botanical Gardens tower, again averaged over the three hours, is evaluated. The dry adiabatic lapse between these two heights is 1.0^{o}F. Thus, by adding 1.0^{o}F to these temperature differences, the value of α is found, and entered in the fourth column. The mixing depth shown in the fifth column is then evaluated using Eq. 5.03.

The value of α given by the tower is only valid for the height interval 20 to 196 feet. As can be seen from Table 7.1, the height of the mixing depth is always greater than this. In these calculations it was assumed that the same value of α occurred above 196 feet. Data from the Detroit tower (Munn 1963) indicates that α

Table 7.1 Evaluation of Mixing Depth, Heat Input and Smoke Production at McGill with North Winds.

Season and Date	u_o (mph)	T_d (^oF)	α (^oF/176ft)	h (ft)	H (10^{-3} ly sec^{-1})	C	Q (Mcm^{-2} sec^{-1})	T_{min} (^oF)
SUMMER								
6 June 1962	14	2	0.6	625	2.9	0.7	32.6	54
12 " "	7	5	1.6	550	3.4	0.7	15.3	53
13 " "	7	8	3.5	400	4.0	1.9	30.4	58
18 " "	9	5	2.0	440	3.5	0.6	13.5	53
26 " "	7	3	1.2	440	1.6	0.9	15.7	60
27 " "	6	7	3.2	385	2.9	1.0	13.1	58
1 July "	14	3	0.8	680	4.9	0.5	26.2	59
3 " "	6	10	4.8	365	3.9	2.1	26.2	55
6 " "	7	7	3.8	325	2.8	1.4	18.1	52
7 " "	7	7	2.4	515	4.5	1.2	24.5	54
24 " "	9	4	1.5	470	3.0	0.7	16.8	56
11 Aug. "	8	1	0.6	315	0.4	0.9	12.0	58
29 " "	6	3	1.5	355	1.1	1.0	12.0	65
2 Sept. "	7	4	1.6	440	2.2	0.4	7.0	59
24 " "	7	8	5.7	245	2.5	2.6	25.6	42
MEAN	8.1	5.1	2.7	437	2.90		19.3	56
TRANSITION								
11 May 1962	3	9	2.6	610	2.9	2.4	24.9	43
12 " "	7	8	3.8	370	3.7	3.5	51.6	46
15 " "	10	4	1.2	590	4.2	2.4	80.0	50
16 " "	13	2	0.8	455	2.0	1.5	48.7	52
21 " "	14	2	0.4	950	4.4	0.4	28.0	53
23 " "	8	8	3.2	440	5.0	1.5	30.0	50
28 " "	3	9	4.5	350	1.7	4.6	27.6	51
14 Oct. "	7	4	2.8	250	1.3	1.0	10.0	44
12 Nov. "	9	2	0.9	410	1.3	1.6	32.0	25
17 " "	9	5	1.5	590	4.7	1.8	16.2	30
18 " "	8	3	0.4	1430	5.7	1.3	78.0	27
9 Apr. 1963	5	5	3.1	285	1.3	3.5	28.2	30
11 " "	12	2	0.4	950	3.8	1.3	78.0	35
13 " "	9	4	2.3	305	2.0	1.0	15.7	37
14 " "	11	4	2.2	320	2.5	0.6	12.0	33
24 " "	11	1	0.9	205	0.4	2.4	29.3	35
28 " "	5	7	4.0	310	1.9	1.3	11.4	40
1 May "	15	1	0.7	265	0.7	1.2	25.7	33
MEAN	8.8	4.4	1.9	505	2.75		34.8	40
WINTER								
8 Mar. 1962	9	7	2.3	535	6.0	3.1	84.9	20
10 " "	11	10	3.5	500	13.8	2.9	91.1	23
21 " "	15	2	0.5	740	3.8	3.3	198.0	28
22 " "	15	3	1.3	405	3.3	2.7	93.4	29
4 Jan. 1963	5	8	2.0	700	5.0	4.7	94.0	23
31 " "	7	14	3.6	685	12.0	4.8	130.7	3
5 Mar. "	5	14	4.0	620	7.7	6.9	120.7	18
13 " "	4	2	0.3	1330	1.7	4.1	109.3	26
19 " "	4	8	1.2	1175	7.0	1.5	60.0	15
MEAN	8.3	7.6	2.1	743	6.70		109.1	21

decreases with height, and so the values of h obtained in Table 7.1 are an underestimate of the true value. The greater the mixing depth, the more serious the error, introduced by extrapolating α. But with greater mixing depths, the more important the shear term, and this reduces h. Thus the two effects are in opposite directions and tend to cancel out each other. In the future it may be possible to utilize the wind and temperature data from the 1000 foot level atop Mount Royal, to obtain better estimates of α over a more relevant layer, and to incorporate wind shear into the calculations. For now wind shear will be neglected and α will be extrapolated as high as required.

The data ~~has~~ have been grouped into the three seasons as defined in Section 2.8, and the mean value of the parameters calculated for each group. These are shown in the last row for each group in Table 7.1. The standard error of h in each of the three seasons was evaluated and the "Students" t-test (Brooks and Carruthers 1953, p. 66) was applied to test for significant differences between the mean values of h.

The mean mixing depth in summer is 437 feet, and in winter is 743 feet. This difference is significant at the 99.5% level. It is, therefore, concluded that the height of the mixed layer over the city at night with a north wind is significantly less in the summer than in the winter months.

The mean mixing depth in the transition months is 505 feet. This lies between the heights for summer and winter and statistically is not significantly different from either.

7.3 Heat Input with North Winds

Using Eq. 5.15 it is now possible to evaluate the heat input required to produce the observed temperature difference. Re-writing Eq. 5.15.

$$H = \frac{(T_L - T_o)^2 u_o \rho c_p}{2L\alpha} \qquad (7.1)$$

The distance L from the Botanical Gardens to McGill is 3.8 miles. Putting in the necessary conversion factors for the units used in Table 7.1 then

$$H = \frac{3.14 T_d^2 u_o}{\alpha} \times 10^{-5} \text{ cal cm}^{-2} \text{ sec}^{-1} \qquad (7.2)$$

This is then evaluated for each day and entered in the sixth column of Table 7.1 and expressed in langleys per sec, where the langley is defined as cal cm^{-2}.

Once again the mean value of H, and the standard error of this mean, was evaluated for each season. In this case both the summer and transition mean values are significantly less than the winter value at the 99.5% confidence level.

It is interesting to note that, H is less in the transition months, than in either summer or winter. A tentative relation between H and temperature is shown in Figure 7.1.

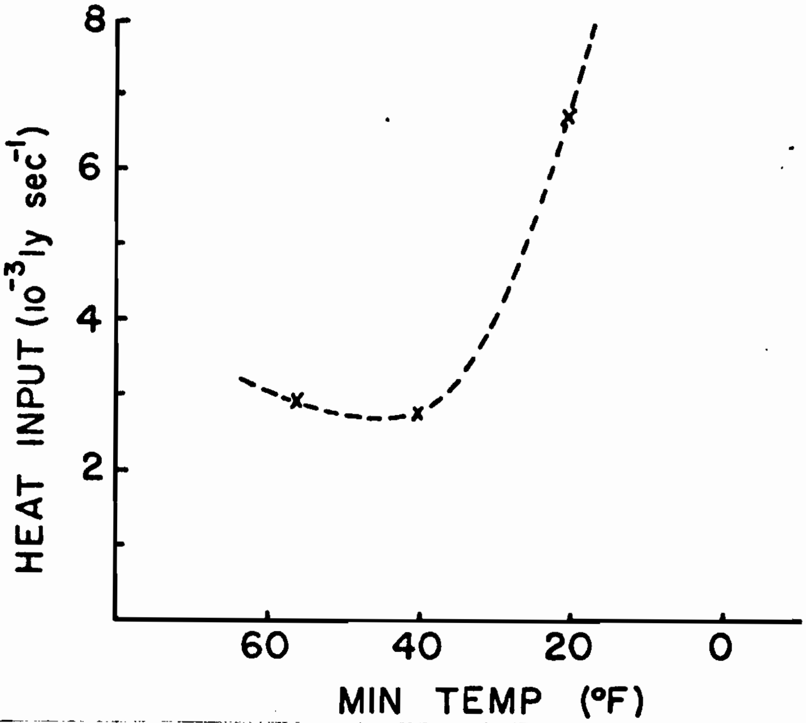


Figure 7.1 Tentative Relation Between H and T with North Winds.

Quite obviously more data are required to confirm this relationship, but it is consistent with the components of H discussed in Section 6.2. From Figure 6.1 the sum of all the H components would have a similar shape to that shown in Figure 7.1.

The agreement between this relation and Figure 6.2 is not too good. Although the mean minimum temperature with north winds in summer is 56°F, there is no space heating at this time of the year. Thus the estimated value of Q_i is 19.3. But this would mean that the Q_h component in Figure 7.2 would be zero at a temperature of approximately 45°F. This does not agree with the principle of degree-days discussed in Section 6.2. There is considerable variation in both Q and H within each of the three seasons, and it must be remembered that a north wind as tabulated in the monthly summaries is defined as a wind blowing from any direction between 340° and 020°. It can be seen from Figure 2.2 that, within this small range of wind direction, L will vary considerably. Also a reported wind direction of north from Dorval Airport does not necessarily mean a north wind over the city. Mount Royal will affect the flow, particularly in light winds and stable conditions. Not nearly enough wind data are available to attempt a streamline analysis of the wind flow over and near the city. These factors then, may account for the discrepancy between Figures 7.2 and 6.2.

7.4 Smoke Input with North Winds

The maximum soiling index (C) at McGill during the three hour period considered is shown in column seven. Re-writing Eq. 6.4 in terms of the observed meteorological variables, then

$$Q = \frac{C u_o \, (T_L - T_o)}{L \alpha} \tag{7.3}$$

The soiling index is not strictly a mass concentration (see Section 2.3d) but it will be assumed here that C is a concentration in some arbitrary mass units (M) per unit volume. Thus no conversion factors are required and Eq. 7.3 becomes

$$Q = \frac{C u_o \, T_d}{\alpha} \quad \mathrm{M cm^{-2} \, sec^{-1}} \tag{7.4}$$

This is evaluated for each day and entered in the last column but one of Table 7.1. The mean value of Q shows a large seasonal variation, and all the differences between the seasons are very highly significant. A tentative relation between Q and T is also shown in Figure 7.2.

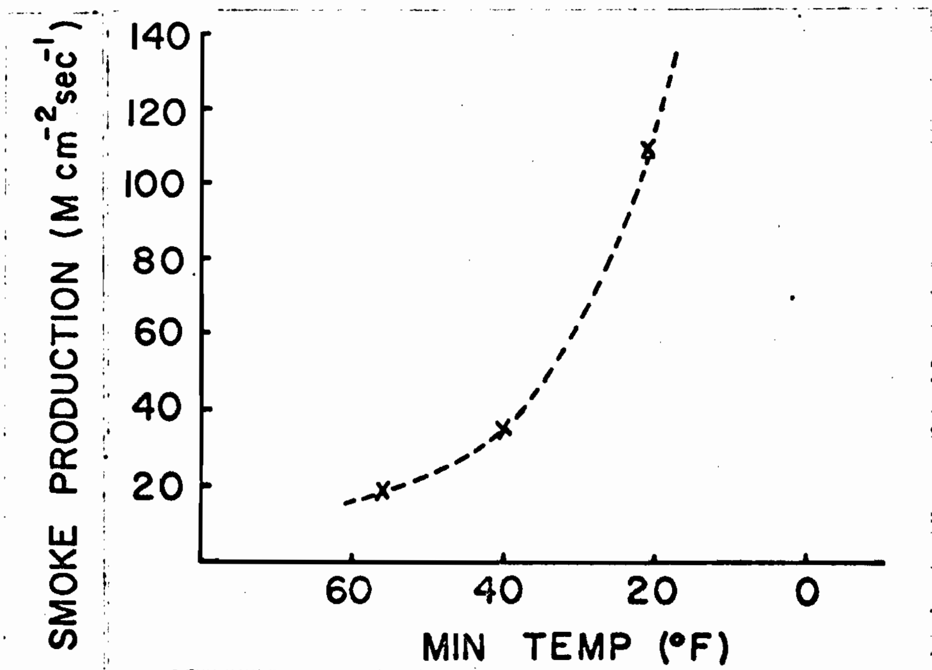


Figure 7.2 Tentative Relation Between Q and T for North Winds

7.5 Mean Monthly Nighttime Mixing Depth, Heat Input and Smoke Input, with All Winds

There are only enough occasions with due north winds to obtain meaningful averages of mixing depth, heat and smoke input on a seasonal basis. An attempt will now be made to utilize the available data to obtain mean monthly values. The Botanical Gardens data became available too late for inclusion on the punched cards. Use has, therefore, been made of the published monthly summaries, and it was not possible to readily separate out the days of the weeks. The calculations which follow thus apply to all days of the week combined together. The appropriate calculations are shown in Table 7.2.

Since the Botanical Gardens will often be within the area affected by the heat island then the mean monthly minimum surface temperatures will be somewhat higher than in the open country as shown in Section 5.2. Defining the country temperature as in Section 5.2, the excess in the minimum temperature for each month is shown in the column headed I. The mean vertical temperature differences between the 20 and 196 foot levels on the tower averaged over the three hour period before the minimum temperature are shown in column II. If it is now assumed that the lower temperature has been increased by the amount shown in the second column, then the estimated vertical temperature difference in the open country is simply obtained by adding columns two and three. By adding another 1°F the difference from the dry adiabatic (α) is shown in the fifth column. The next column contains the excess at McGill over the country surface minimum (T_d). Using Eq. 5.3 the height of the mixing depth at McGill is evaluated and entered in

Table 7.2 Evaluation of Mean Monthly Mixing Depth, Heat Input and Smoke Production at McGill. March 1962 - April 1963.

Month	I (°F)	II (°F)	III (°F)	α (°F/176 ft)	T_d (°F)	h (ft)	u_o (mph)	H (10^{-3} ly sec^{-1})	C	Q (Mcm^{-2} sec^{-1})	T_{min} (°F)
1962											
Mar.	0.9	1.0	1.9	2.9	5.0	305	10.4	2.7	1.68	29.3	26.4
May	0.0	0.6	0.6	1.6	3.5	385	10.1	2.3	1.23	26.5	50.7
June	1.9	0.6	2.5	3.5	5.0	250	8.3	1.8	0.93	10.7	60.2
July	1.2	0.6	1.8	2.8	4.4	275	8.4	1.8	0.77	9.9	59.7
Aug.	2.9	0.7	3.6	4.6	5.0	190	7.0	1.2	1.08	8.0	61.6
Sept.	1.7	0.3	2.0	3.0	4.9	285	10.5	2.5	0.95	15.9	52.4
Oct.	0.7	0.4	1.1	2.1	3.3	275	10.5	1.7	1.63	26.2	43.0
Nov.	0.3	0.4	0.7	1.7	3.8	395	8.6	2.2	2.41	45.1	30.4
Dec.	0.9	-0.1	0.8	1.8	3.9	380	10.6	2.7	2.11	46.2	15.3
1963											
Jan.	1.0	-0.1	0.9	1.9	4.2	390	10.8	3.0	2.20	51.1	12.1
Feb.	1.6	-0.2	1.4	2.4	4.2	310	11.5	2.6	1.61	36.3	4.7
Mar.	1.5	0.3	1.8	2.8	5.3	335	10.7	3.6	1.99	39.3	22.0
Apr.	0.5	0.5	1.0	2.0	3.1	275	10.2	1.5	1.46	22.5	36.0

I Minimum temperature excess at Botanical Gardens
II Observed vertical temperature difference on tower
III Estimated vertical temperature difference in country

column seven. The mean wind speed at Dorval Airport during the three hours is shown in the eighth column.

The calculation of Q is not quite as straightforward as for the case of northerly winds discussed in Section 6.6. In that case L was the distance between McGill and the north edge of the built-up city area (assumed to be the Botanical Gardens). In this case we are dealing with monthly means, and so we should use a monthly mean L weighted according to the wind frequency from all directions. Each direction will have a different distance L to the edge of the city. Using the annual wind direction frequencies for Dorval shown in Table 2.2, and estimating the value of L for each direction from McGill to the city's edge (see Figure 2.2), the weighted mean L was found to be 3.9 miles. A problem is raised by Mount Royal: what is L with west and southwest winds? In this case the distance across Mount Royal was subtracted from the total distance to the edge of the city. There is also considerable difficulty in defining the exact effective limits of the city. Also in Figure 2.2, it can be seen that there are long extensions of built-up area spreading northeast and west along the north shore of the St. Lawrence River. These could have a marked effect on L within a very narrow range of wind direction. In view of all the uncertainties mentioned above, no attempt will be made to refine the evaluation of L on a month by month basis to take into account variations in the wind direction frequencies. On the basis of L = 3.9 miles, then Eq. 5.15 becomes

$$H = \frac{3.06\, T_d^2\, u_o}{\alpha} \times 10^{-5} \text{ ly sec}^{-1} \qquad (7.5)$$

This was then evaluated for each month.

A plot of H against T is shown in Figure 7.3. There is considerable scatter, with no simple relation between H and T immediately obvious, apart from a general increase in H with decreasing T. This is in accordance with an increase in the component H_h with decreasing T. Part of the scatter in Figure 7.3 may be due to the variability of the radiation component H_r. This is dependent on T_d, the absolute value of T, and the amount of smoke in the air, so is very variable from month to month.

Finally Q is evaluated in arbitrary units of mass cm^{-2} sec^{-1} as in Section 7.4, using as before the maximum two hourly average value of soiling index occurring at or just after the minimum temperature. In the last column of the table the mean minimum at McGill is listed. It can be seen that there is a high correlation between Q and the minimum temperature; this is illustrated in Figure 7.4. The values of Q based on C obtained from two hourly samples of soiling index (i.e. in the summer months) are shown as circles in Figure 7.4. Sanderson and Katz (1963) compared the soiling index obtained simultaneously from several A.I.S.I. smoke samplers using different sampling times over the range 3/4 hours to 3 hours. They found that the longer the sampling time, the lower the average soiling index, and suggest that for any meaningful comparisons of data the sampling time should be standardized. This, of course, raises some of the problems presented in Sections 2.3 and 2.7. Thus the circled points in Figure 7.4 are an underestimate of the true value of Q. The method of least squares was used to obtain the best-fit relation between Q and T for the remaining nine months. This relation was found to be

$$Q = 48.3 - 0.467T \quad (50 > T > 5) \tag{7.6}$$

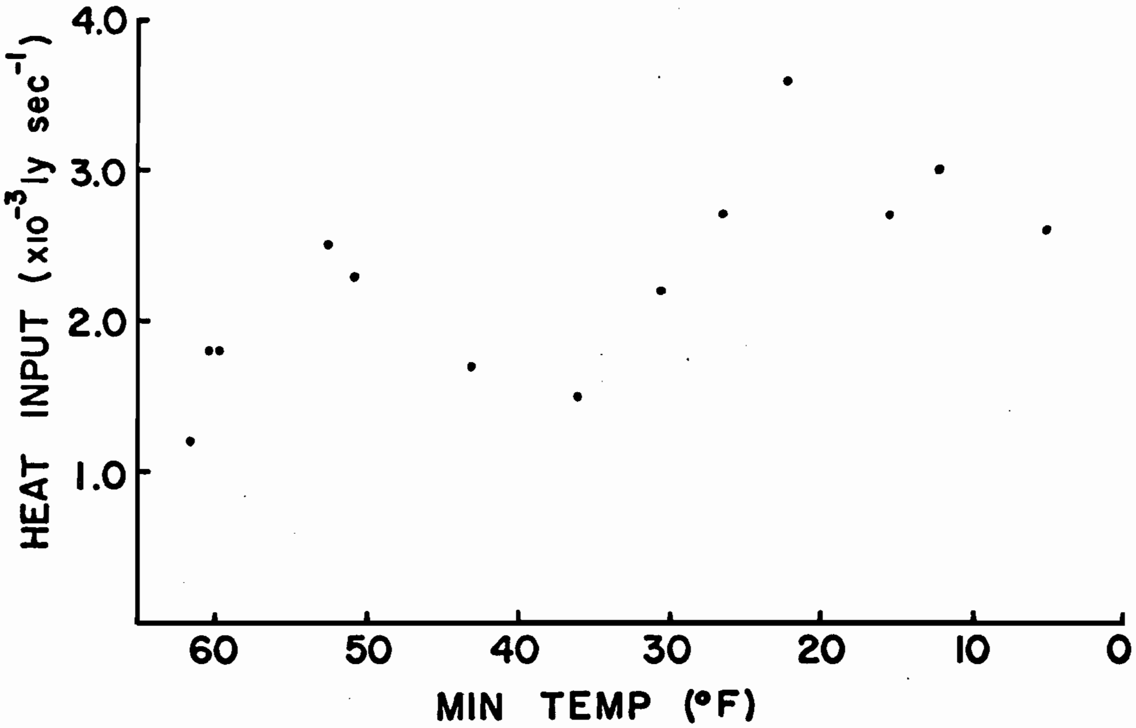


Figure 7.3 Relation Between H and T for All Winds

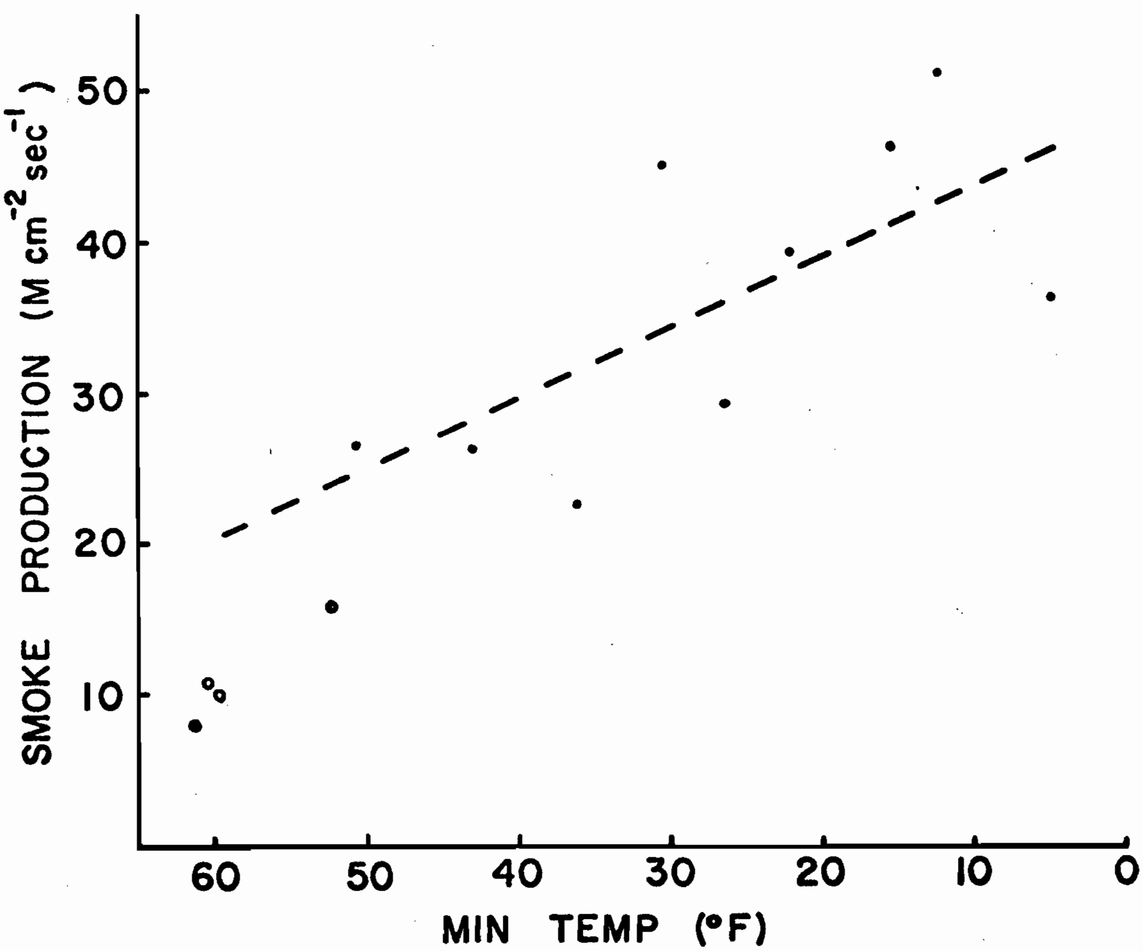


Figure 7.4 Relation Between Q and T for All Winds

The correlation coefficient between Q and T is -0.68 which is significant at the 97.5% level. Re-writing this relation in the form of Eq. 6.10 then

$$Q = 17.9 + 0.467\,(65 - T) \tag{7.7}$$

Therefore, the components of Q averaged over all days of the week including Saturday and Sunday are as follows

$$Q_i = 17.9 \quad \text{and} \quad Q_d = 0.467$$

Equation 7.7 is valid for $T \leqslant 65^\circ F$ and so the complete relation between Q and T can now be described as follows:

$$\boxed{\begin{array}{ll} Q = 17.9 + 0.467(65 - T) & T \leqslant 65^\circ F \\ Q = 17.9 & T > 65^\circ F \end{array}} \tag{7.8}$$

7.6 Comparison between North Winds and All Winds

In order to compare the values of h, H and Q with those obtained for north winds only, the data in Table 7.2 are grouped into the three seasons. The comparisons can now be readily made from Table 7.3.

Table 7.3 Comparisons of h, H, Q, K for North Winds and All Winds.

Season	North Winds Only					All Wind Directions				
	h	H	Q	K	T_{min}	h	H	Q	K	T_{min}
Summer	437	2.9	19.3	6.7	56	250	1.8	11.1	6.2	58
Transition	505	2.7	34.8	12.7	40	332	1.9	30.1	15.8	40
Winter	743	6.7	109.1	16.3	21	344	2.9	40.5	14.0	16.1

The most obvious feature of Table 7.3 is that the values of h, H and Q obtained for all wind directions are considerably less than with north winds only. This could mean that the city is more densely built-up in a north direction from McGill, than the average for all other directions. But it is more likely due to the uncertainties in estimating L, and errors introduced by the rather crude method of estimating the country lapse rate. In fact, it is perhaps rather surprising to see that the differences in Table 7.3 are as little as a factor two. The ratio of smoke input to heat input (K) shows good agreement between north winds and all winds and is about two and a half times greater in the winter than in the summer. This is in accordance with the ideas expressed in Section 6.2 and confirms that much of the heat input in the summer is not associated with any smoke production and thus must be due to the H_s component.

Table 7.3 shows the amount of heat required to produce the observed city-country difference. An attempt will now be made to estimate the amount of heat available for the H_h and H_i components from fuel consumption figures.

7.7 Estimate of Heat Output of City from Fuel Consumption Data

The total amount of fuel oil consumed in the Greater Montreal area for heating purposes in the year 1961 (Dominion Bureau of Statistics, 1962a) was 11,342,829 barrels of 35 imperial gallons, giving a total of 397×10^6 gallons. The fuel value of oil is approximately 11,000 cal/gm. So using a conversion of

$$1 \text{ imp. gal.} = 10 \text{ lbs} = 4.536 \text{ kg.}$$

then the heat value of 1 gal. of fuel oil is approximately 4.8×10^7 cal.

Thus the total heat production from fuel oil was

$$1.9 \times 10^{16} \text{ cal/year}$$

But only 82.3% of the dwellings were heated by oil (D.B.S. 1963a), so assuming that the other 17.7% using other fuels such as coal, gas and wood produced a proportionate amount of heat, then the total heating of buildings in Greater Montreal in 1961 was 2.3×10^{16} cal/year. The total number of degree-days at Dorval Airport for the year 1961 was 8009. Degree-days are not tabulated at the McGill Observatory. If we assume that averaged over the whole of the built-up area the mean temperature is about 2°F warmer than Dorval Airport, then over the eight month heating season the number of degree-days will be 8009 less 2 x 8 x 30 giving 7529. Assuming as in Section 6.2 that the heating is directly proportional to degree-days, then if T is the ambient air temperature the rate of heat output for the whole city is given by

$$3.7 \, (65 - T) \times 10^7 \text{ cal sec}^{-1}$$

The area of the densely built-up part of the city shown in Figure 2.2 is 30mi^2 or 7.7×10^{11}cm^2. Now if two-thirds of the heat output is concentrated in this densely built-up area, then the average heat output is given by $4.8(65 - T) \times 10^{-5}$ cal cm^{-2} sec^{-1}. When $T = 16^{o}F$ the heat output is 2.4×10^{-3} ly sec^{-1}. This is certainly of the right order of magnitude to provide the heat required, as shown in the bottom line of Table 7.3, but is slightly too small. However, no account has been taken of the industrial and commercial component. This is harder to estimate because it is not uniformly distributed over the city.

Figures for industrial consumption of fuel oil are given only for the whole Province of Quebec (D.B.S. 1962a). The ratio of fuel oil used for industrial and commercial purposes to that used for heating, for the whole province is 0.52. If anything the ratio would be higher for Montreal. This means at least 368×10^{6} gal/yr. Also the consumption of natural gas in 1962 amounted to an estimated daily load of 74×10^{6} ft^{3} (D.B.S. 1962b), and a total of 1.01×10^{6} tons of coal and coke was used in 1962 (D.B.S.1963b). Using a fuel value of 2.75×10^{5} cal ft^{-3} for gas, and a value of 3.6×10^{6} cal lb^{-1} for coal, the total heat output from industrial uses of fuel oil, natural gas and coal amounts to approximately 9×10^{13} cal day^{-1}. If this is distributed uniformly throughout the 24 hours of the day, then the rate of heat output H_i is at least 1.04×10^{9} cal sec^{-1}, or the same as the rate of production due to heating when the temperature is $37^{o}F$. If this industrial heat output were uniformly distributed over the densely built-up area, then the rate would be 1.35×10^{-3} ly sec^{-1}. All of this does not immediately escape into the atmosphere, since a small amount is converted into mechanical and chemical energy, but there will be sufficient heat released such that, when added to the

H_h term, more than enough is available to produce the observed temperature increase in the city.

It is interesting to compare the heat input from the city with the heat received from the sun. The average daily insolation received at the earth's surface at Lat. 45°N in January is 90 langlies, assuming a transmission coefficient of 0.7 (Haltiner and Martin 1957). In a 15 hour night in January, the total heat input from the city, based on the figure of 3.0×10^{-3} ly sec^{-1}, is 16.2 langleys per night. This then is almost one-fifth of the heat received from the sun during the day.

Finally an estimate will be made of the magnitude of the excess radiative loss of heat from the city compared to the country. In winter the mean minimum at McGill is 16°F, and the country temperature is 4.5°F colder (see Table 7.2). Converting these temperatures to degrees absolute, and using the Stefan-Boltzmann law, then from Section 5.3 the excess radiative loss from the city will be less than $\sigma (T_L^4 - T_0^4)$, i.e., less than 0.23×10^{-3} ly sec^{-1}. This is one order of magnitude less than the heat input and so can be neglected in most cases. It will, however, be important on those occasions when a large city-country temperature difference occurs. In order to get a radiative heat loss equivalent to the heat input of the city, a city-country temperature difference of about 30°K (or 50°F) is required. Thus if there is zero ventilation, the temperature of the city would continue to rise until an equilibrium condition is obtained, when the radiative heat loss exactly balances the heat input. The maximum temperature difference will never be reached in actual practice since the wind is never completely calm over an extended period of time, but the above figure does give an idea of the upper limit of the city-country difference possible.

7.8 Estimation of Relative Contribution of Smoke Sources

In Section 3.3 it was shown that there was a considerable and significant reduction in soiling index at all three locations over the week end. Table 3.4 shows the reduction at McGill on a year-round basis. The reduction in the summer months is even more striking, because the effect is not swamped by the larger heating component which does not have a weekly cycle. The day-to-day synoptic weather variations are not nearly as large in the summer as in the winter, also making it easier to separate out the effects of varying smoke production rates. We will now use the data for the summer months to estimate the percentage contribution of smoke from various broad source categories.

Figure 7.5 shows the diurnal variations of soiling index for the summer months of 1961 and 1962 at McGill on weekdays, compared to Saturday and Sunday. Curves for the WEC location show an identical pattern (Summers 1961). The mean weekday soiling index at McGill is 0.69, on Saturday the mean soiling index is 0.52 (a reduction of 25%) and on Sunday it is 0.47 (a reduction of 32%). Both of these reductions are statistically significant at the 99.5% level.

Figure 7.5 indicates an even more striking difference on week ends at the time of the morning peak. In fact the peak is non-existant on Sunday. In the early hours of Sunday morning, man's activities are at a minimum, with the only source of smoke being those commercial and industrial operations which carry on continuously

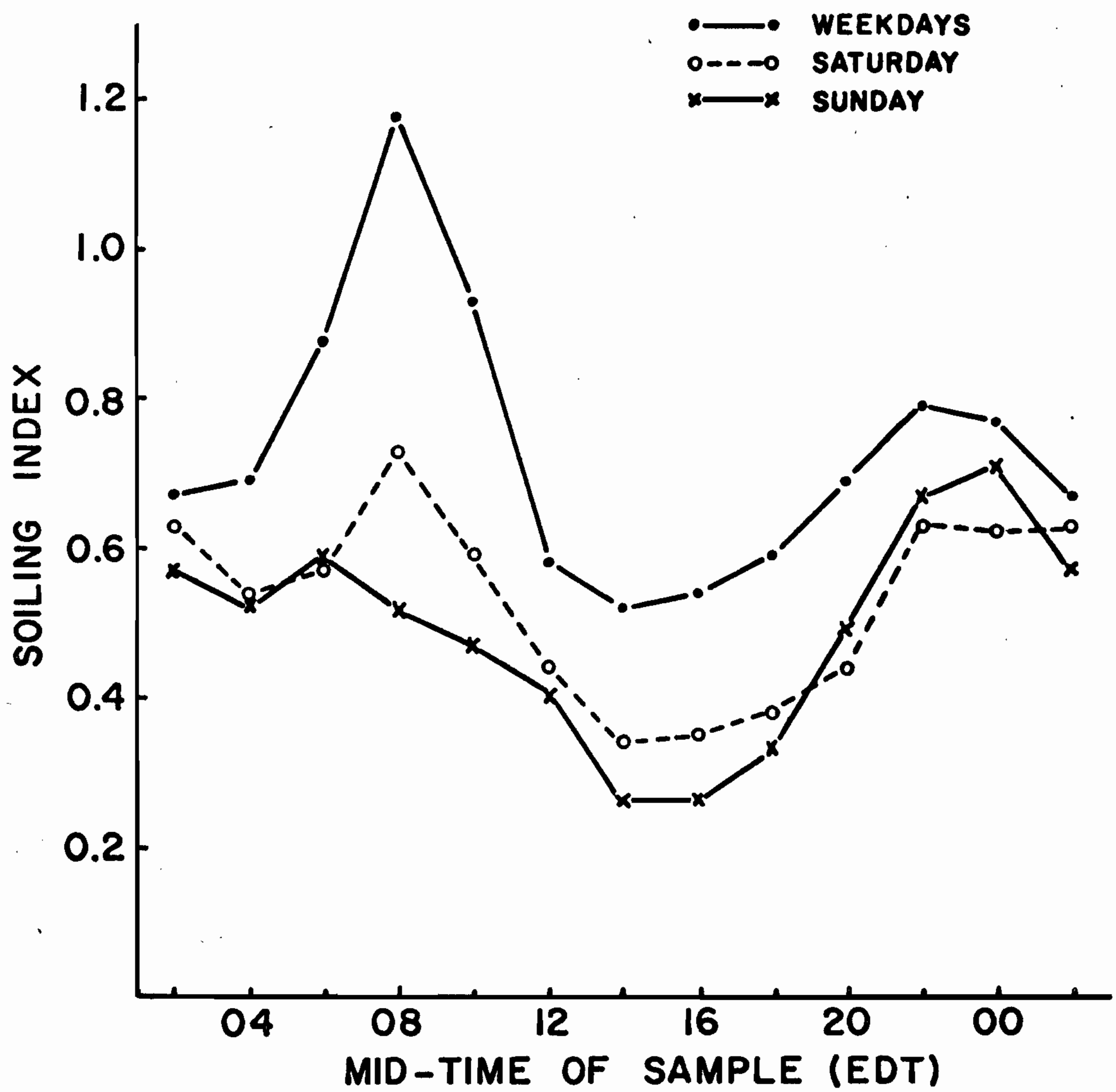


Figure 7.5 Diurnal Variation of Soiling Index at McGill on Weekdays compared to Saturday and Sunday

through the 24 hours every day of the week, all year round. On Saturday the daily pattern is very similar to weekdays but with the general reduction of 25% spread fairly evenly through the whole day.

Now suppose that Q_i can be further split up into components.

Let $Q_i = Q_c + Q_w + Q_t$

where Q_c = production of smoke from continually operating industry, commercial establishments and incinerators.

Q_w = production due to weekday only commercial and industrial operations.

Q_t = production to vehicular traffic

Thus during the morning peak period in the summer months the various sources will be contributing to the total production as follows:

$$\left.\begin{array}{ll} \text{Weekdays (Monday-Friday)} & Q_i = Q_c + Q_w + Q_t \\ \text{Saturday} & Q_i = Q_c + Q_t \\ \text{Sunday} & Q_i = Q_c \end{array}\right\} \qquad (7.9)$$

If there is no difference in the average meteorological conditions on each day of the week then from Eq. 6.5

$$C \propto QH^{-\frac{1}{2}}$$

Now H will be less on Saturday or Sunday because of a reduction in the H_i component. The component H_s will not be reduced. But since the absolute values of H_i and H_s are not known we cannot estimate by how much H ($= H_i + H_s$) is reduced on the week-end. Because of the square root dependence of C on H, then a reduction in Q will have a greater effect on C. In order to get a rough estimate of the components of Q we will assume no reduction in H; then the values of Q will be directly proportional to the values of C obtained from Figure 7.5. On this basis, solving Eq.. 7.9, we have $Q_c : Q_w : Q_t = 51 : 45 : 22$ at the time of the morning peak.

The value of Q_i found in Eq. 7.8 was for all days of the week combined including Saturday and Sunday. Using that value and the above ratios, the value of Q_i on weekdays is 20.7, on Saturdays is 12.8 and on Sundays is 8.9. These values can now be combined with the value of Q_d and the average monthly minimum temperature at McGill to give Figure 7.6. This shows at a glance the contribution to the total smoke at the time of the morning peak from each of the source categories for each month of the year. Although the mean daily temperature is below $65^{\circ}F$ by September 1st, furnaces are not normally in operation until the end of the month. Thus in Figure 7.6 no heating component has been included for September. In the mid-winter months the use of fuel for heating buildings is the largest single source of smoke.

The percentage contributions (rounded off to the nearest 5%) for summer and mid-winter are given in Table 7.4. Also added for comparison are the results of a study made in Paris by Grisollet and Pelletier (1957). The Paris figures refer to the whole day and not to just the morning peak. In Paris also, winter heating is the main producer of smoke. The large contribution of traffic in Paris is difficult to explain since a well-tuned car should produce little smoke. It should be emphasized that the figures in Table 7.4 refer only to smoke, and that for other pollutants such as CO_2, CO and SO_2 the percentages would be very different.

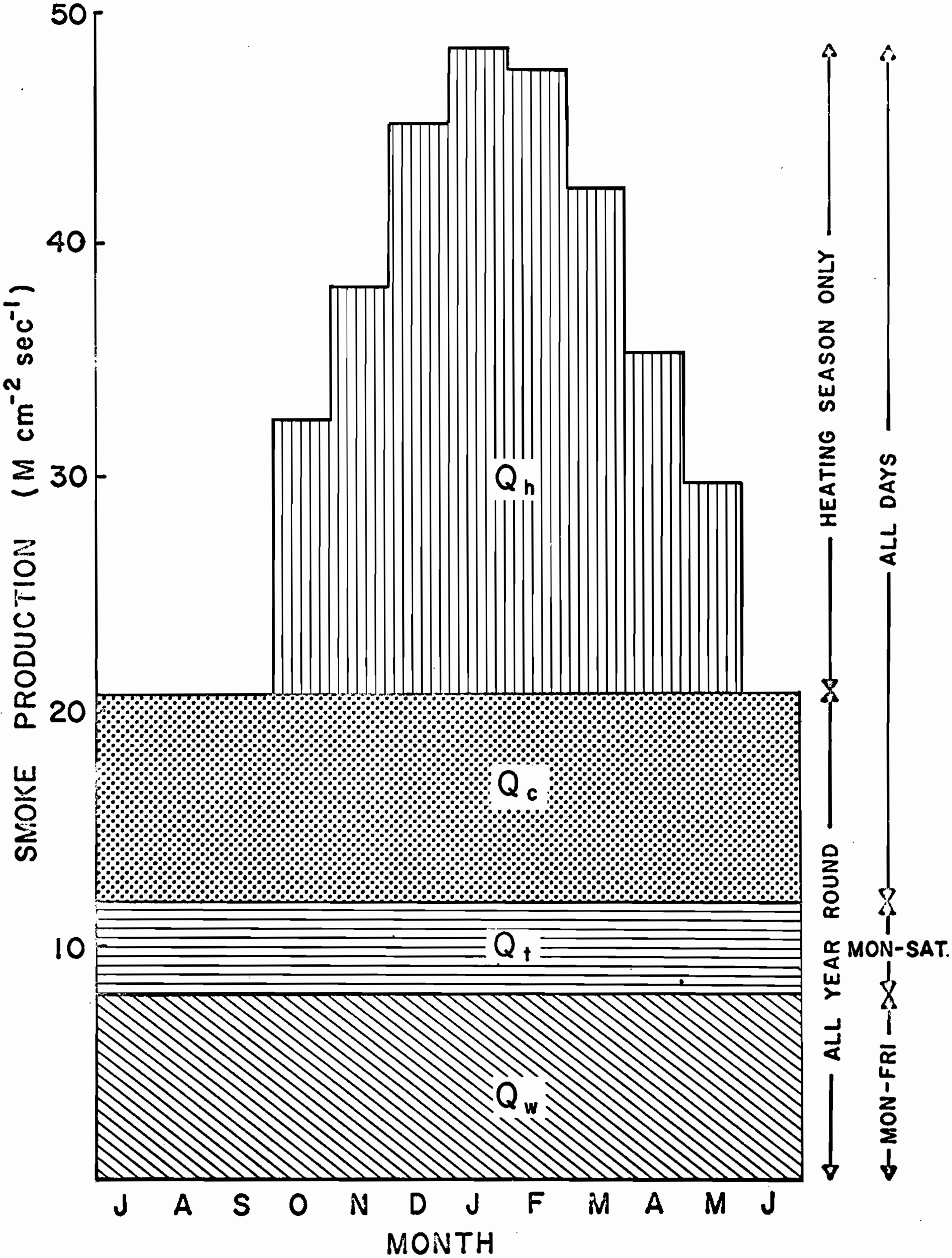


Figure 7.6 Diagram showing Contribution to Smoke Production at McGill from various source categories (see p. 125 and 149) at time of morning peak

Table 7.4 Estimated contributions of smoke to the morning peak at McGill compared to all-day figures from Paris.

Smoke Source	Mid-Winter		Summer	
	Montreal %	Paris %	Montreal %	Paris %
Winter heating of buildings	55	60-65	-	-
Continuous industrial and commercial operations, incinerators	20	10-15	45	20-40
Weekday industry and commerce	15		35	
Traffic	10	25-30	20	60-80

CHAPTER 8

DISCUSSION AND SUMMARY

Using some of the ideas discussed in the precedding four chapters, we will now return to the diurnal variations shown in Figs. 3.3 to 3.14, and attempt a qualitative explanation of the daily cycle of smoke.

At the time of the early morning minimum in soiling index, which occurs between 0000 and 0400 EST, conditions appear to be in equilibrium, with the rate of production of smoke balanced by the rate of ventilation. The nighttime mixing layer is well established at this time, and since there is no abrupt change in the meteorological conditions, the rise in soiling index which commences some time between 0300 and 0600 EST, and usually before sunrise, must be due to an increase in production. Many industries preparing for the day's activities will be turning up their furnaces at this time. From the top of Mount Royal, at first light on a summer morning, one can see industrial stacks belching forth smoke for periods of up to half an hour, before their furnaces have reached an efficient combustion temperature. As the city gradually comes to life, more and more smoke sources become operative, and the smoke concentration continues to rise until a peak is reached just after sunrise. Figs. 3.3 to 3.14 show the minimum temperature occurring about one hour after sunrise; but these are for Dorval Airport and the minimum in the city will occur about one hour later

(Mitchell 1961). Thus the peak in soiling index occurs at just about the same time as the minimum temperature in the city. As the temperature begins to rise the height of the mixing depth will begin to increase. Since there is now no further increase in smoke production the concentration will begin to decrease. This decrease will continue until the maximum mixing depth (see Section 4.2) occurs in the afternoon. Then towards sunset vertical mixing decreases, and the lowest layers in the atmosphere begin to stabilize in the country air. This will mean a limited mixing depth in the city again. The soiling index begins increasing until man's daytime commercial and industrial activities begin to close down. In the winter the country air stabilizes before production decreases and hence the high early evening peak in concentration. In the summer the air does not begin to stabilize until well after production has started to decrease, and hence the lower and less well defined peak in concentration, occurring later in the evening. Production continues to decrease slowly in the late evening and into the early morning hours when the cycle starts all over again. The change to daylight saving time (EDT) in the summer months keeps the morning peak in production nearer to the time of minimum ventilation. This change also delays the evening decrease in ventilation to a time even later after production has started to decrease. This then explains the general shape of the seasonal cycle in the relative magnitudes of the morning and evening maxima as shown in Fig. 3.17.

The second evening maximum occurring in the winter months is more difficult to explain. There is no discontinuity in the meteorological conditions at this time and so one is left with a possible increase in production. One feature of Montreal is the large number of apartment buildings in the heavily built-up central area. Each of these has its own incinerator which is usually fired-up sometime in the late evening. For a period of one month during February-March 1961 a sampler was operated in the centre of the apartment complex in Cote des Neiges, and showed a very high peak (greater than 6.0 Coh units) occurring between 2100 and 2300 EST on 6 days out of 32. However, if this is the cause of the second evening peak, its time of occurrence would not be expected to vary as widely, from month to month, as in Figs. 3.15 and 3.16.

Other studies using two or three hour sampling times have found the same general daily cycle of soiling index in many other cities. The morning peak has generally been ascribed to the fumigation mechanism proposed by Hewson (1951). Briefly this is as follows: Any pollutants emitted into an inversion layer at night will remain at the level of neutral buoyancy, with little or no vertical spreading. Shortly after sunrise the ground is heated and an adiabatic layer builds up from the ground. This has a similar effect to the case of air moving over a heat source (as shown in Fig.5.7). The layer eventually builds up to the level of the smoke, which is then mixed rapidly downwards leading to a sudden high concentration at the surface. It was a study of conditions in a deep valley at

Trail, B.C., which led Hewson (1945) to propose this mechanism. But Hewson was dealing with an individual source of pollution, which itself did little to modify the vertical temperature structure. Over a large urban area conditions are different, and in fact, the ideas put forward in Chapter 5 amount to a continuous fumigation process operating all night. The effect of sunrise, and consequent heating of the surface, is now merely to increase the strength of the vertical circulation in an already existing mixing layer.

If the nighttime mixing layer is shallow enough, then some of the emission from the higher stacks may penetrate up into the inversion layer above, and remain there until morning. As the mixing layer extends upwards after sunrise,this pollution will then be incorporated and could lead to a further rise in surface concentration. This may happen in Montreal during the summer when the nighttime mixing depth is least (see Table 7.2). It could also happen near the upwind edge of the city where the overnight mixing depth is shallow.

The daily range of soiling index as shown in Fig. 3.17 is also of considerable interest. The seasonal cycle of this daily range is very similar to the seasonal cycle of the maximum mixing depth shown in Fig. 4.2. The summer <u>nighttime</u> mixing depth is less than in winter, but the summer <u>daytime</u> mixing depth is considerably greater than in winter. Thus the daily range of mixing depth in summer is much greater than in winter. This then shows up as a greater daily range in soiling index. The effect of snow cover is important in restricting the daytime mixing depth during the months of December through March.

Several other aspects of the Montreal pollution problem have been considered but are not included here since they have no direct bearing on the urban heat island effect. One of these however will be mentioned briefly. It was pointed out in Section 3.1 that the reduction of soiling index at McGill compared to WEC is due to Mount Royal Park. The effect of a park on smoke concentrations has been studied in detail (D.S.I.R. 1945),but there may be an additional mechanism caused by Mount Royal as an obstacle to a westerly flow at McGill. If the top of the mountain is above the mixing layer, then it will be acting as a country surface and chilling the air that flows over in contact with it. This clean air would then descend as a katabatic flow down the lee side of the mountain and mix with the polluted air at lower elevations in the vicinity of the McGill Campus, leading to lower soiling index readings.

Finally, as with all meteorological problems, there is a need for more data of the right kind. Up to now,most meteorological towers have been deliberately located away from any undesired influences. Thus a considerable amount of information is available on the daily and seasonal changes in lapse rates in the lowest few hundred feet of the atmosphere over the open country. More towers are now needed at several locations within a large urban area to study the heat island effect in more detail than has previously been done. This should be accompanied by an extensive network of surface tmperature and wind measurements. Montreal, with its tall buildings acting as height gauges, is an excellent city for visual and photographic observations. In fact, it was the frequent observations on a daily basis whilst driving over Mount Royal, which led the author to consider the nighttime mixing depth hypothesis.

During the last two months an independent observer (Mr. G. Vali) has been noting the appearance of the smoke pall from the south side of the St. Lawrence (near the 0 on scale of miles in Fig.2.2). He has observed, on several occasions, a sloping top to the smoke on the upwind side of the city and only a gradual lowering downwind of the city. Also, some interesting distortions to the top of the smoke layer have been seen near Mount Royal. Photography from this location as well as the top of Mount Royal should therefore be a useful tool in studying the large scale features of the smoke pall.

To summarize: This study has concentrated on the nighttime ventilation processes at work over a large urban area. The hypothesis of a continuous fumigation mechanism, caused by urban heat, and operating all night rather than just after sunrise, is proposed. A simplified mathematic treatment of the problem yields formulas which can be applied to available data in Montreal. The heat required, to produce the observed temperature increase in the city, is in good agreement with that available from fuel consumption. The height of the mixing depth produced is proportional to the square root of the heat input. Knowing the mixing depth, it is then possible to estimate the total mass production of smoke necessary to give the observed concentrations. A comparison of weekdays against Saturday and Sunday gives useful estimates of the rates of production of smoke from various sources.

One method of reducing smoke concentrations at night is to increase the height of the mixing depth, without a corresponding increase in smoke. An alternative is to increase the ratio of heat input to smoke production, in such a way that if the extra heat is accompanied by extra smoke, then there is still a net reduction in concentration. This involves the relations discussed in Section 6.2. It also raises the question of whether, under certain circumstances, it may not be better to place a new industrial smoke source within an already existing large heat island, rather than in a smaller neighbouring town where the smoke may be diluted in a much shallower mixing depth.

REFERENCES

Absalom, H.W.L. (1954): "Meteorological Aspects of Smog". Q.J.R.Met.S., 80, p. 261

Andrews, J.F. (1963): "The Circulation and Weather of 1962". Weatherwise, 16, p. 33

Anonymous (1873): "Floating Dust". Godey's Lady Book, 86, p. 280

Anonymous (1872): Harper's New Monthly Magazine, 44, p. 786

Balchin, W.G.V. and Pye, N. (1947): "A Micro-climatological Investigation of Bath and the Surrounding District". Q.J.R.Met.S., 73, p. 297

B~~o~~aynton, H.W. (1956): "Multiple Correlations of Particulate Air Pollution with Weather Factors in Detroit and Windsor". Bull. A.M.S., 37, p. 333

Brooks, C.E.P. and Carruthers, N. (1953): "Handbook of Statistical Methods in Meteorology". M.O. 538, H.M.S.O. London

Clark, J.G. (1916): "Calibration of Dr. Owens Apparatus for the Estimation of Solid Pollution in the Atmosphere". Advisory Committee on Air Poll. Report for year 1916-1917

Crow, L.W. (1964): "Airflow Related to Denver Air Pollution". J. Air Poll. Control Assoc., 14, 2, p. 56

Davidson, W.F. (1942): "A Study of Atmospheric Pollution". Monthly Weather Review, 70, p. 225

Davis, F.K. (1961): "The Air over Philadelphia". Symposium Air over Cities, SEC Technical Report A62-5, p. 115

Dehalu, et al. (1931): "The Causes of the Symptoms Found in the Meuse Valley During the Fogs of December 1930". Bul. acad. royale de med. de Belgique., 11, p.683

DeMarrais, G.A. (1961): "Vertical Temperature Differences Observed over an Urban Area". Bull. A.M.S., 35, p. 198

Denison, P.J.; Power, B.A. and Summers, P.W. (1960): "Analysis of Air Pollution Levels in Montreal Related to Meteorological Variables". Presented Can. Branch, R.Met.S. (unpublished)

Department of Scientific and Industrial Research (1945): "Atmospheric Pollution in Leicester". H.M.S.O. London

Department of Transport (1948): "Climatic Summaries for Selected Meteorological Stations in Canada, Newfoundland and Labrador". Met. Branch, Toronto

Department of Transport (1959): "Climatic Summaries for Selected Meteorological Stations in Canada". Met. Branch, Toronto

Dominion Bureau of Statistics (1962a): Consumption of Petroleum Fuels, 1961, Cat. No. 45-206, Ottawa

Dominion Bureau of Statistics (1962b): Gas Utilities 1960, Cat. No. 57-205, Ottawa

Dominion Bureau of Statistics (1963a): 1961 Census of Canada, Housing - Heating Equipment and Fuel, Cat. No. 93-526, Ottawa

Dominion Bureau of Statistics (1963b): Coal and Coke Statistics Dec 1962, Cat. No. 45-002, Ottawa

Duckworth, F.S. and Sandberg, J.S. (1954): "The Effects of Cities upon Horizontal and Vertical Temperature Gradients". Bull. A.M.S., 35, p. 198

Edinger, J.G. (1958): "The Meteorology of Los Angeles' Polluted Layer". Final Report, University of Cal. Los Angeles

Evelyn, J. (1661): "Fumifugium; The inconvenience of the aer, and the smoake of London dissipated". Reprint by National Society for Clear Air, London

Foran, M.R.; Gibbons, E.V. and Wellington, J,R, (1958): "Measurements of Atmospheric Sulphur Dioxide and Chlorides". Chem. in Canada, 10, 5, p. 33

Freinkiel, F. (1956): The Scientific Monthly, 82, p. 194

Grisollet, H. and Pelletier, J. (1957): "La Pollution Atmospherique au centre de Paris et ses Relations avec quelques Facteurs Climatologique". La Meteorologie, p. 393

Haltiner, G.J. and Martin, F.L. (1957): Dynamical and Physical Meteorology, McGraw-Hill, New York, p. 96

Hammon, W.H. and Duenchel, F.W. (1902): "Abstract of a Comparison of the Minimum Temperatures recorded at the U.S. Weather Bureau and the Forest Park Met. Observatories, St. Louis, Missouri, for the year 1891". Monthly Weather Review, 30, p. 11

Hemeon, W.C.L.; Haines, G.F.Jr. and Ide, H.H. (1953): "Determination of Haze and Smoke Concentrations by Filter Paper Samplers". J. Air Poll. Control Assoc., 3, 1, p. 22

Hewson, E.W. (1945): "The Meteorological Control of Atmospheric Pollution by Heavy Industry". Quart. J.R.Met.S., 71, p. 266

Hewson, E.W. (1951): "Atmospheric Pollution". Compendium of Meteorology, p. 1139

Hilst, G.R. (1961): "Source Configurations and Atmospheric Dispersion in Mathematical Models of Urban Pollution Distributions". Symposium Air Over Cities, SEC Technical Report A62-5 p. 209

Holzworth, G.C. (1962): "Some Physical Aspects of Air Pollution". Seventh Conf. on Ind. Hygiene and Air Poll., Un. of Texas, Austin, June 1962

Hosler, C.R. (1961): Low-level "Inversion Frequency in the Contiguous United States". Mon. Weather Review, 89, p. 319

Howard, Luke (1833): "Climate of London deduced from Meteorological Observations". 3rd Ed. Harvey and Darton 1833

International Joint Commission (1960): "Pollution of the Atmosphere in the Detroit River Area". Ottawa

Katz, M. et al. (1958): "Evaluation of Air Borne Particulates in Atmospheric Pollution Studies". Analyt. Chem., 30, p. 1172

Katz, M. (1961): "Air Pollution as a Canadian Regional Problem". Resources for Tomorrow Conference, Montreal, Oct. 1961

Katz, M. (1963): "Air Pollution in Canada - Current Status Report". Am. J. Pub. Health, 53, p. 173

Landsberg, H.E. (1962): "City Air - Better or Worse". Symposium Air over Cities, SEC Technical Report A62-5, p. 1

Longley, R.W. (1954): "The Climate of Montreal". Met. Branch. Dept. of Transport, Canada

Lucas, D.H. (1958): "The Atmospheric Pollution of Cities". Int. J. Air Poll., 1, p. 71

Manos, N.E. (1957): "Comparative Mortality among Metropolitan Areas of the United States, 1949-50". U.S. Pub. Health Service

Martin, A.E. (1959): "Atmospheric Pollution in Great Britain: The London Fog of 2-5 December, 1957". Int. J. of Air Poll., 2, p. 84

Mateer, C.L. (1961): "Note on the Effect of the Weekly Cycle of Air Pollution on Solar Radiation at Toronto". Int. J. Air and Water Poll., 4, p. 52

McCormick, R.A. and Baulch, D.M. (1962): "The Variation with Height of the Dust Loading over a City as Determined from the Atmospheric Turbidity". J. Air Poll. Control Assoc., 12, p. 492

McDonald, J.E. (1961): "Mean Atmospheric Residence Times for Particulate Air Pollutants". Bull. A.M.S., 42, p. 664

McLeod, C.H. (1896): "Soil Temperatures". Trans. Roy. Soc. Canada, 7, sec 3, p. 13

McLeod, C.H. (1902): "Soil Temperatures". McGill Engineering Dept., Paper No. 6, pt. 2

Middleton, W.E.K. and Millar, F.G. (1936): "Temperature Profiles in Toronto". Roy. Ast. Soc. (Toronto) Journal, 30, p. 265

Mitchell, J.M.Jr. (1953): "On the Causes of Instrumentally Observed Secular Temperature Trends". J.Met. 10, p. 244

Mitchell, J.M.Jr. (1961): "The Thermal Climate of Cities". Symposium Air over Cities, SEC Technical Report A62-5, p. 131

Munn, R.E. (1959): "The Application of an Air Pollution Climatology to Town Planning". Int. J. Air Poll., 1, p. 276

Munn, R.E. (1961): "The Interpretation of Air Pollution Data, with examples from Vancouver". CIR-3454, TEC-351, Met. Branch, Dept. of Transport, Canada

Munn, R.E. and Ross, C.R. (1961): "Analysis of Smoke Observations at Ottawa, Canada". J. Air Poll. Control Assoc., 11

*Munn, R.E.; Emslie, J.H. and Wilson, H.J. (1963): "A Preliminary Analysis of the Inversion Climatology of Southern Ontario". CIR-3834, TEC-466, Met. Branch, Dept. of Transport, Canada

New Jersey Dept. of Health (1958): "State Wide Air Pollution Survey - Smoke Index". Public Health News, Aug. 1958

*Note - This paper has inadvertently been referred to in the text as Munn (1963).

Owens, J.S. (1918): "Technical Paper No. 1". Advisory Committee on Atmospheric Poll. D.S.I.R. London

Pack, D.H. and Hosler, C.R. (1958): "A Meteorological Study of Potential Atmospheric Contamination from Multiple Nuclear Sites". 2nd U.N. Geneva Conf. on Peaceful Uses of Atomic Energy, A/Conf. 15P/426, p. 265

Pasquill, F. (1962): Atmospheric Diffusion. D. Van Nostrand Co. Ltd., London

Perkins, W.A. (1961): "Some Effects of City Structure on the Transport of Airborne Material in Urban Areas". Symposium Air over Cities, SEC Technical Report A62-5, p. 197

Pooler, F.Jr. (1961): "Dispersion Calculations for Multiple Sources". Symposium Air over Cities, SEC Technical Report A62-5, p. 189

Pooler, F.Jr. (1961): "A Prediction Model of Mean Urban Pollution for use with Standard Wind Roses". Int. J. Air and Water Poll, 4, p. 99

Priestley, C.H.B. (1959): Turbulent Transfer in the Lower Atmosphere. U. of Chicago Press

Reichel, E. (1933): "An Example of Great Temperature Difference between Town and Country Stations". Preussisches Meteorologisches Institut, Veröffentlichungen, Bericht No. 402, p. 72

Renou, E. (1862): "Différences de Témperature entre Paris et Choisyle-Roi". Soc. Met. de France, 10, p. 105

Richardson, L.F. (1926): "Atmospheric Diffusion shown on a Distance-neighbour Graph". Proc. Roy. Soc. A, 110, p. 709

Rossano, A.T.Jr. (1959): "Sources of Community Air Pollution". Interdisciplinary Conference on Atmospheric Pollution, Santa Barbara, Calif. June 1959

Rupp, W.H. (1956): "Air Pollution Sources and their Control". Air Pollution Handbook, McGraw-Hill, New York, pp. 1-5

Sanderson, H.P. and Katz, M. (1963): "The Optical Evaluation of Smoke or Particulate Matter Collected on Filter Paper". J. Air Poll. Control Assoc., 13, p. 476

Schmidt, W. (1929): "Distribution of Minimum Temperatures during the Frost Night of 12 May 1927 within Vienna". Fortschritte der Landwirtschaft, 2, p. 681

Smith, M.E. (1961): Advance Papers, Int. Symposium on Chem. Reactions in the Lower and Upper Atmosphere, San Francisco 1961, p. 273

Stalker, W.W.; Park, J.C. and Keagy, D.M. (1960): "Developments and Use of the A.I.S.I. Automatic Smoke Sampler". J. Air Poll. Control Assoc., 12, p. 303

Stalker, W.W.; Dickerson, R.C. and Kramer, G.D. (1962): "Sampling Station and Time Requirements for Urban Air Pollution Surveys - Part III Two - and Four - hour Soiling Index". J. Air Poll. Control Assoc., 12, p. 171

Sullivan, J.L. (1962): "Sydney: Potential Los Angeles of the Southern Hemisphere". J. Air Poll. Control Assoc., 12, 9, p. 431

Sullivan, J.L. (1962): "The Calibration of Smoke Density". J. Air Poll. Control Assoc., 12, 10, p. 474

Summers, P.W. (1961): "Smoke Concentrations in Montreal related to Local Meteorological Factors". Symposium Air over Cities, SEC Technical Report A62-5, p. 89

Summers, P.W. (1963a): "An Urban Ventilation Model". Presented at Canadian Branch, R. Met. S. Quebec June 1963 (unpublished)

Summers, P.W. (1963b): "Urban Ventilation in Montreal". Smokeless Air, No. 128 Winter 1963, J. Nat. Soc. for Clean Air, London p. 108

Sundborg, A. (1959): "Local Climatological Studies of Area". Tellus, 2-3, p. 222

Sutton, O.G. (1932): "A Theory of Eddy Diffusion in the Lower Atmosphere". Proc. Roy. Soc. A., 135, p. 143

Sutton, O.G. (1947): "The Theoretical Distribution of Airborne Pollution from Factory Chimneys". Q.J.R.Met.S., 73, p. 426

Sutton, O.G. (1950): "The Dispersion of Hot Gases in the Atmosphere". J.Met., 7, p. 307

Sutton, O.G. (1953): Micrometeorology, McGraw-Hill

Taylor, G.I. (1915): "Eddy Motion in the Atmosphere". Proc.Trans. Roy. Soc., 215, p. 1

Taylor, G.I. (1921): "Diffusion by Continuous Movements". Proc. Lond. Math. Soc., 20, p. 196

U.S. Public Health service (1949): "Air Pollution in Donora, Pa.". Bulletin No. 306

Wilkins, E.T. (1954): "Air Pollution Aspects of the London Fog of December 1962". Q.J.R.Met.S., 80, p. 267

World Health Organization (1961): "Air Pollution". Geneva