AN ANALYSIS OF TEMPERATURE, LAPSE RATE, AND WIND IN THE LOWER 810' NEAR WINNIPEG

by

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ABSTRACT

Two and one half years of temperature, lapse rate, and wind data from a rural 810' tower near Winnipeg are analyzed for mean characteristics in time and height. Selective stratification of these data has shown the dependence of lapse rates and inversions upon height, wind speed and direction, cloud cover and pressure.

Data are also analyzed for their characteristic thermal stratifications in different airmasses. Inversions are assumed to be caused by three principal factors in the boundary layer: radiation, advection, and subsidence. Case studies show examples of each of these, as well as the vertical structure of the boundary layer during frontal passages and thunderstorms.

Superadiabatics are usually confined to the lower 400'. Higher levels show a rapid decrease in superadiabatics, and even in summer they affect the highest layer for only two hours on average.

The boundary layer and the free atmosphere remain uncoupled until mid-morning in summer. In winter, coupling occurs in the 400 - 600' layer at 1600 hours, and not at all on average in the 600 - 810' layer.

The majority of surface radiation inversions are also confined to the lower 400 or 600 feet, and they rarely reach 810'. The long inversion season lasts from November to March and inversion durations can reach three days. Windspeeds of 2 to 13 m.p.h., cloud obscurities of <6 tenths, and southerly and south-westerly winds
favour longer durations.

The thermal stratification of the lower 810' strongly affects the mean profile through its influence on the distribution of turbulent momentum transfer. In general increased stability decreases the depth of the planetary boundary layer and increases wind shear. Frequencies of light winds show that Winnipeg can receive almost three days with winds ≤9 m.p.h., and over two days with winds ≤6 m.p.h. There is considerable variation by wind direction.

Finally lapse rates and inversions are classified quantitatively and cluster analysis is shown to be effective in establishing a genetic classification scheme for inversions.
ACKNOWLEDGEMENTS

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CHAPTER ONE

Introduction

1.1 Background

This thesis is an analysis of the vertical distribution of temperature, lapse rate and wind in the lower 810'. The climatology of the near surface layers of the atmosphere is both interesting and important because of the large variations in conditions occurring in these layers, both with respect to space and time. These occur from the fact that the sun initially heats the ground surface, and that it is mainly from the ground that the atmosphere is heated. The lower atmosphere or planetary boundary layer thus plays a vital role in the exchange of sensible heat, water vapour and momentum, between the earth's surface, and the free atmosphere above.

Such variations are highly significant in many applications. In agriculture for instance, plant climate is quite different from the climate at 14' above the ground. Likewise, the climate of the lower atmosphere strongly influences atmospheric diffusion and hence the dispersal of air pollutants.

Though meteorologists know the general nature of boundary layer processes, adequate description and explanation of these phenomena are rarely known especially for particular areas. This lack of knowledge is due to the extreme complexity of the planetary boundary layer. This layer, more than any other, is characterized by processes with many different scales and a continuous interaction between these
scales. Yet a description and understanding of planetary boundary layer processes will be necessary before accurate models can become a reality.

Even if the problem is restricted to specifying the seasonal variations in mean temperature, lapse rate, inversion duration, and wind speed and direction, present knowledge is incomplete; both in terms of a description of the variables, and the cause of the variations.

The pioneering efforts of Johnson and Heywood (1938) and Best et al. (1952) provided considerable description of the temperature and lapse rate distribution in the lower atmosphere over periods of more than a year in maritime environments. However, the description was limited to 300', and no analysis of inversions was performed.

Subsequent work was rarely over a year and analyses were very limited. A real need therefore existed to perform a comprehensive analysis over a continental area in a much deeper layer looking at temperature, lapse rate, wind and inversions over a period of 2 to 3 years. Winnipeg is situated in such a continental environment with high tower facilities, and topography which is as close to an infinite plain as you can get in a settled rural landscape.

1.2 Objective

The objective of this study is to obtain a description, useful for air pollution potential studies, of the variations of temperature, lapse rate, wind and inversions in the lower 810', due to diurnal, seasonal, and synoptic changes. Once the variability associated with each factor is determined an attempt is then made to assess the results in terms of previous work for other areas, and in
terms of the air pollution potential. The penultimate chapter then classifies inversions in terms of the normal meteorologically observed elements, and provides a basis for a crude estimate of a pollution potential.

1.3 Methodology

The objectives of the study are sought by instrumenting a 1000' high television tower with temperature and wind equipment, and by collecting a large quantity of data on tape over a 33 month sampling period. Regular synoptic observational data were then merged with this data to form the data base. Daily weather maps provided the broader meteorological picture. The data base was then subjected to numerous data stratifications. Interpretations and conclusions are based on the results of these stratifications.

1.4 History of the Study and Future Plans

This study grew out of the desire of the author to examine the urban microclimate of Winnipeg. Preliminary work with horizontal temperature traverses in 1967 indicated that the heat island in the suburbs was closely linked to the temperature stratification in the lower atmosphere. Plans were therefore made to measure the temperature and wind distribution to as great a height as was financially feasible in both the city and in the surrounding countryside. Permission was obtained from the C.B.C. to instrument their 1000' high T.V. tower outside the city but attempts to set up a tower in the city proved unsuccessful for various reasons. In the end a tethered balloon was used with limited success for vertical city temperature readings. Some 139 horizontal temperature traverses were made in 1970 before preliminary analysis indicated that the
rural tower data was much more interesting. Accordingly the tower data was edited and an attempt was made to perform a really comprehensive analysis of this data.

This thesis reports the results to the summer of 1972. At the time of writing (May 1974) data is still being acquired and edited. Plans for a wind sensor at 400' and a further 122' high tower with temperature, wind, dew point, uvw wind, pyranometers, net radiometers, heat flux and soil temperature sensors are presently being implemented and are expected to be operational by October 1974. This will permit a much more detailed analysis of the boundary layer based upon the results of this work.

1.5 Units of Measurement

All units used in this thesis are imperial. That is, temperature is measured in °F., wind in miles per hour, lapse rate in °F./1000' and height in feet. This was done since the C.B.C. Tower, Starbuck is part of the Canadian micrometeorological tower network and these are the standard units of measurement for all meteorological observations in Canada. It seemed inappropriate to convert the units later since there could be a considerable loss in precision. To facilitate interconversion between one system and another a degrees Fahrenheit - degrees Centigrade conversion table is provided in Appendix 1.
CHAPTER TWO

PREVIOUS WORK

2.1 Introduction

In the historical development of climatology and meteorology interest has centred on the broader aspects of climate and weather, processes which involve large regions of the earth's surface and great depths of the atmosphere. In recent years more and more attention had been paid to the phenomena which occur in the layers closer to the ground. This small zone encompasses only a tiny fraction of the atmosphere but it is important since it is the area that man, plants and animals live in.

Our understanding of this layer has improved considerably since 1945 but substantial problems still remain due to the complexity of the layer, difficulties of sampling and instrumentation, and the great costs involved. Since this thesis will only look at a few of the variables involved in boundary layer processes (temperature, lapse rate and wind) the literature review will also limit itself to these areas. It will, however, include much of the literature upon the meteorological aspects of air pollution due to the bias of much of the analysis in this area.

2.2 Temperature Field in the Lower Atmosphere

Literature on the variation of temperature with height can be conveniently divided into 3 main groups. Group 1 examines the
surface boundary layer in the lower 3 - 10'. Most of these micrometeorological studies examine selected aspects of the energy budget and need very sophisticated equipment to operate this close to the ground surface. The sensitivity of the equipment means that the data is not collected continuously. The processes are complex and most runs are made during ideal conditions which depend upon the nature of the study. These are micrometeorological studies and will not be discussed further here. The interested reader is referred to Sellers 1965, Deacon 1969, Miller and Budyko 1974.

Group 2 consists of those investigations based upon measurements made by hanging equipment from towers. These investigations cover the lower 1500' although most observations are in the 6 - 200' layer. Theoretical considerations are much simpler in this layer since the earth-atmosphere interface is further away, and so instruments can sample much slower and be larger and more robust. Data is normally collected on a continuous basis using high quality aspirated electrical resistance thermometers and hardy anemometers. Analysis is performed in such a way as to provide hourly and monthly summaries conducive to climatological analysis. A number of these observations have been analyzed in considerable detail. Table 2.1, modified from Geiger (1965, p.70), contains a summary of some of these evaluated measurements extending over at least a year. This table should not be treated as exhaustive.

Group 3 consists of those investigations extending from 100 - 200' up to the top of the planetary boundary layer at 3000 - 10,000'. A considerable portion of this zone is above the tower level and hence it must be investigated from radiosonde data which offers poorer temporal distribution and less accuracy (see Hosler 1961, Holtzworth 196h, Miller 1967, and Hoxit 1973).
The results from table 2.1 show that temperature generally exhibits a diurnal variation with a large range at the surface and a smaller one at higher levels. Best et al. (1952, p. 28) found a 5.5°F range at 1.1 metres in January. At 15 metres the range was 4.3°F; at 47 m. it was 3.5°F whilst at 107 m. it was only 3.0°F. Comparable figures for July were 14.3, 11.6, 9.9 and 8.8°F respectively.

Extreme values are usually delayed with increasing height. Flower (1937) showed that maximum temperatures at 61 m. occurred 38 minutes after maximum temperatures at 1.1 m.

In clear weather the temperature profile also exhibits a marked diurnal variation in the lower 100 - 300 metres. During the hours of daylight, from shortly after dawn, to just before sunset, temperatures generally decrease with height, rapidly in the lower layers and more slowly at greater height (Sutton, 1953, p. 190).

At night inversions are common, the temperature increasing with height, with the gradient again being greatest in the lower layers. Best et al. (1952, p. 16) found a lapse rate of 53.4°C./100 metres for the 47 to 107 metre layer. The magnitude of these variations varies with climatic zone, latitude, season, soil type, albedo, radiation, soil moisture, and vegetation. In winter at high latitudes temperature inversions may occur at all times.

Maximum lapse rates are also highest closest to the ground. Best et al. (1952, p. 21) shows that the average lapse rate lies between the adiabatic and isothermal lapse rate. They found that the uppermost layer of air (47 to 107 metres) showed a superadiabatic lapse in only 8% of all cases, and these hardly ever exceeded -2°C./100 metres. Inversions on the other hand, were found in 32% of all cases because of their stable stratification. In the highest layer (47 to 107 metres)
60% of all gradients lay between the adiabatic and isothermal; in the intermediate layer (15 to 47 metres) 27% were between 0 and 1° C./100 metres, whilst in the lower, 1 to 15 metre layer, only 9% lay in the 0 to 1° C./100 metre range.

Although the above represent the results of much detailed work in the lower 100 metres of the atmosphere, little was known prior to 1960 about the detailed conditions in the 100 - 400 metre layer. In 1955 the T.V. antenna of WJBK, Detroit, U.S.A. was instrumented at 20', 300', 600' and 870'. Temperature readings were taken over a two year period, and the results were analyzed (International Joint Commission, 1960). Seven different types of temperature profile were categorized, tabulated, and analyzed. These were:
1) Inversion in all layers. 2) Ground inversion, neutral aloft.
3) Neutral below, inversion aloft. 4) Ground inversion, adiabatic aloft. 5) Ground adiabatic, inversion aloft. 6) Adiabatic layer, or layers, with or without neutral layers. 7) Neutral. Graphs and tables were prepared of the percentage frequency of inversions by months and seasons for levels up to 870 feet.

Temperature measurements have been taken at three levels on a 500' T.V. tower at Minneapolis, U.S.A. from 1961 (Cowan and Paulus, 1964). Some of this data has been analyzed by Baker et al. (1969). Frequency, duration, time of commencement and intensity of inversions were analyzed for three levels. This work was the first with detailed analyses of the duration of individual inversions.

In 1962, the Cedar Hill T.V. tower, in Texas, U.S.A., was instrumented at 12 levels for wind and temperature with the highest level some 1460' above ground. Some case studies have used this data (Thuiller, 1964, Isumi, 1964, 1966), and more recently, 6 months temperature data has been analyzed (Goff & Hudson, 1972).
The first Canadian studies began in the early 1960's when information on local climate was required for siting atomic power stations (Munn and Richards, 1963, Munn et al., 1963, Ferland, 1964, Cork, 1964). Most of the data gathered was for the lower 200' of the atmosphere.

In 1967, the Atmospheric Environment Service commenced publication of the quarterly "Meteorological Tower Bulletin" containing summaries of temperature and wind measurements made from the meteorological towers in Canada. There are three distinct types of summary:

1) Tab 14'5 (Temp.) is a summary of hourly values of temperature difference in the layer between the higher level of temperature instrumentation and the lower level.

2) Tab 14'5 (Wind) is a summary of hourly values of wind speed and direction as measured at the higher tower level.

3) Tab 14'1 is a summary relating temperature difference to wind velocity. The table gives the number of hours in each month that wind observations within three wind speed classes and eight wind direction classes occurred within three categories of temperature difference:
   a) all classes of temperature difference
   b) inversions
   c) large temperature difference (Temperature difference greater than 5.0°F.).

The summary gives the number of occurrences in four time-of-day groupings (0-5, 6-11, 12-17, 18-23 hrs.), in addition to providing totals for the 24 hour day. Tables 2.2, 2.3, and 2.4 give examples of the above.

Considerable progress has thus been made in the investigation of the thermal properties of the lower atmosphere. However, most published studies to date have been very limited either in terms of height,
time, or in examination and analysis of the data. Studies have generally been confined to the lower 200 - 300 feet, since tower costs rise exponentially with increasing height. As a result very little is known about the thermal structure above 400'. The short duration of many studies also poses problems, since there is very little indication of the variability or representativeness of the data. Finally, most analyses are quite limited due to the great volume of data needed for processing and the high cost of computer time.

This study will attempt to overcome some of these difficulties by presenting a comprehensive analysis of 33 months of data in the lower 810'.

Chapter Five will deal mainly with the description of temperature, and, average and maximum lapse rate in the lower 810', whilst Chapter Six will concentrate on the frequency, duration, and intensity of inversions. Chapter Seven will follow up this general overview with detailed case studies.
2.3 Winds in the Lower Atmosphere

2.3.1 Introduction

The motion of air in the mid-troposphere primarily depends upon two forces, the Coriolis force and the pressure gradient force. As one approaches the surface, flow becomes more complicated, and the force of friction must be added, resulting in a wind of lower speed, and a backing in wind direction in the Northern Hemisphere.

There is a well-defined diurnal variation of wind, with a maximum speed just after noon, and a minimum at night near the surface. At 200 to 1000 feet the reverse is true - the maximum is at night with the minimum during the day. Intermediate levels are more complex.

2.3.2 Variation of Windspeed and Direction with Height

The exact nature of the variation of windspeed with height in the lower 1000' is a matter of considerable dispute. Problems are introduced due to surface roughness and rate of change of temperature with height. It was soon realized that the value of $p$ in the power law

$$\frac{u}{u_1} = \left(\frac{z}{z_1}\right)^p$$

varied between 0 and 1, where $u$ is the wind speed at height $z$, and $u_1$ is the windspeed at height $z_1$. The mean value of $p$ in the lower 30' is approximately 1/7. $p$ varies with the time of day, (highest at night), and is a function of height, increasing with proximity to the ground.

Sutton (1932a) used Heywood's (1931) observations for the lowest 300' to compute the daily variation of the exponent $p$, subdivided for summer and winter. From April to September $p$ varied from 0.07 at noon to 0.17 at night, and from October to March between 0.08 and 0.13.
The variation of the wind profile for different thermal stratifications has been treated observationally by numerous investigators. Geiger (1965, p. 118) used Flower's (1937) observations to show that \( p \) is a function of lapse rate. Frost (1947) used instruments suspended from a captive balloon at Cardington, England to measure the wind speed and temperature in the lower 1000'. He showed that \( p \) varied from 0.115 under superadiabatic conditions to 0.29 for isothermal conditions and to 0.77 under extreme inversions.

Thuiller (1964) has examined the Cedar Hill data (12 levels over 1500') and has found that during lapse conditions a logarithmic or power law expression provides a suitable description of the average wind speed profile. Midday profiles were better suited to a logarithmic formulation whilst morning and evening profiles were better suited to a power law representation. Inversion data showed marked variation and could not be fitted adequately to either.

The relationship of the wind profile to surface isobars and stability has been examined by Mendenhall (1967), Clarke (1970) and Hoxit (1973). The variation over ocean areas has been examined by Gordon (1952), Findlater et al. (1966) and Cattle (1971). Theoretical or modelling studies have been done by Kuroeaki (1967), and Yamamoto et al. (1968). All these studies suggest that the angle between the surface wind and surface isobars increases with increasing stability, whilst the depth of the Ekman layer decreases.

A marked diurnal variation of wind exists in the lower 10,000' as a result of variations in the downward flow of momentum (Epsy 1841, Koeppen 1883). Wagner (1936) showed that the daytime maximum windspeed in the surface layers is caused by the strong increase of eddy viscosity with height in this layer. Since the wind is supposed to be in quasi-equilibrium at all times it was predicted that the wind above the surface layer is retarded during the daytime and approaches
the geostrophic value at night. Thus none of the above explanations account for the strongly supergeostrophic winds which occur at night within the boundary layer.

Wagner (1939) made a study of the boundary layer winds in the mid-western United States and came to the conclusion that the diurnal variation of the wind could be completely explained by the superposition of three wind systems:

1. A circulation between the dry region in the south-west and south.

2. A circulation between the plains and the mountains to the west.

3. A circulation between the sea and the continent.

Wagner's conclusions are open to question since he neglected boundary layer mixing and did not make allowance for these effects in his analysis.

Byers (1959, p. 333) has shown that the temperature stratification of the lower atmosphere influences the amount of mixing or momentum transfer. In a stable atmosphere mixing due to buoyancy is not present and the vertical mixing due to mechanical turbulence is reduced. Thus the height at which the stress becomes negligible is reduced, whilst the vertical gradient of the stress is increased. The opposite conditions exist in an unstable atmosphere, with buoyant air parcels providing a second mechanism for vertical momentum transfer.

Deardoff (1972) has shown numerically that in unstable conditions eddies produced by buoyancy become the dominant mixing mechanism in all but the surface layers. The stronger vertical mixing increases the depth of the boundary layer but weakens the vertical stress gradient.

An additional problem exists when the thermal stratification changes rapidly with time. The most obvious is the diurnal heating and
cooling, typically giving rise to adiabatic lapse rates in mid-
afternoon and temperature inversions at night in the lowest few hundred
feet. This provides a mechanism for oscillatory changes in the planetary
boundary layer wind profile even when the synoptic flow is steady state.
Blackadar (1957) and Blackadar and Buajitti (1957) have developed
theoretical models of the diurnal oscillation in winds above the first
few hundred feet. They suggest that the oscillations of the ageostrophic
winds in the 500 to 5000' region are inertial oscillations resulting
from the change of eddy viscosity with stability. Hoxit (1973) has
treated this observationally and found good agreement.

The special case of diurnal variations over a sloping terrain
has been examined by numerous investigators. These include Lettau
In the Great Plains region the terrain slopes from west to east and
often gives rise to a day-night reversal in the direction of the
thermal wind. This amplifies the general oscillation due to stability
changes and produces what is termed a "low level jet" at night.

2.3.3 Frequency of Light Winds

The Atmospheric Environment Service publishes hourly data
summaries for each major station. These give the mean monthly wind
speed frequencies (16 wind directions vs. 12 wind speed classes). The
lower wind speed classes are calm, 1 - 3 m.p.h., 4 - 7 m.p.h., 8 - 12
m.p.h. Wind roses can be constructed from these to show the prevailing
wind speed and direction by months or seasons.

Hage and Longley (1967) have analyzed hourly wind speed
readings over a five year period and have derived a set of figures for
the number of consecutive hours with light winds less than or equal to
3, 6, and 9 miles per hour for the two months January and July. This
type of information is very valuable in providing a basis for the calculation of air pollution potential estimates for an area.

A real need exists to relate the light wind speed information with that of wind direction, inversion duration, intensity and frequency information. This has not been touched to date in any depth and will be attempted in Chapters Eight and Nine.

2.4 Meteorological Aspects of Air Pollution

2.4.1 Introduction

"The earth's atmosphere has served man in 2 ways: it has provided him with air to breathe and it has acted as a medium for disposing his refuse. As such the atmosphere has always been polluted to some extent. Since the 1940's, however, it appears that air pollution disasters have become more frequent as emissions have increased, and in the last few years our environmental awareness has greatly increased due to the great number of books dealing with environmental problems in general. An examination of this literature leaves the author with the view that although in most cases we have the technological ability to control pollution we still lack and are likely to lack for some time the legal authority to carry it through. Thus, when viewed realistically our atmosphere will be used as a giant sewer for some time to come" (after Bach, 1972).

Although it appears that the overall capacity of the atmosphere is still sufficiently large to handle the emissions it is clear that most of the pollution is emitted over small urban and industrial areas. At certain times, periods of stagnating air masses strongly limit the dispersing and cleansing power of the atmosphere resulting in critical air pollution levels. Logically, therefore, the long term cleansing power of the atmosphere can only be obtained if one understands the meteorological processes of dispersion and removal of
pollutants and introduces them into an air resources management system.

This is particularly relevant to Canada. Since World War II Canada has industrialized rapidly with a tremendous growth in the oil, gas, mining, and manufacturing industries. This has been accompanied by a rapid growth in urbanization especially in the Toronto and Montreal regions with a population of over two million in each case.

Although Canada is far from becoming another Ruhr, Midlands, or Boston-Washington megalopolis, urban expansion is sufficiently rapid to give rise to great concern. This is especially true since little is known about the dispersion capability of the atmosphere in this northern latitude country.

When looking at the dispersion capability of the atmosphere it is convenient to divide it into 2 main areas. In both cases the movement of the particles and gases will mainly be governed by the motions of the atmosphere. Some atmospheric motions determine the extent to which the contaminants will be diluted, other motions dictate the paths to be followed by the airborne pollutants. The branch of meteorology which looks at dilution is called atmospheric diffusion, that which looks at paths followed is called air pollution climatology or meteorology.

2.4.2 Atmospheric Diffusion

Atmospheric diffusion is discussed in a number of publications. (U.S. Public Health Service (1961), Stern (1968), World Meteorological Organization (1968), Summers (1964). A brief summary is given here for completeness.
Diffusion is defined (American Meteorological Society, 1958) as "the exchange of fluid parcels (and hence the transport of conservative properties) between regions in space, in the apparently random motions of a scale too small to be treated by the equations of motion".

Taylor (1915) made the first real study of the diffusive capacity of the air off the Grand Banks of Newfoundland. After seven months of experimental work measuring temperature and humidity over water, he explained the modification of air masses by vertical transfer processes similar to molecular conductivity. The eddy conductivity of turbulent transfer turned out to be ten thousand times greater than its molecular counterpart. The use of gas in World War I prompted extensive studies of atmospheric diffusion and much work was done at the British Army's Defence Research Establishment at Porton on the Salisbury Plains under Taylor. Virtually nothing was known except conditions were worst when stable conditions and/or light winds existed. Taylor's pioneer efforts were supplemented by Schmidt in Austria over the period 1918 - 1939. Studies were made of the vertical and horizontal diffusion of heat water vapour, and momentum. It was shown that the Austausch or exchange coefficient was not constant and the analogy with molecular diffusion was abandoned in favour of a statistical model.

This new approach was suggested by Taylor (1921) and developed by Richardson (1926) and Sutton (1931). The outcome was the "Gaussian plume model". Since then considerable refinements have been made as the results of temperature and vertical wind profiles, transport of water vapour, and pollution data, have become widely avail-
able for a great range of situations.

Diffusion theory has advanced rapidly due to the construction of nuclear reactors in the post-war period. The most comprehensive early studies were from Brookhaven National Laboratory in the U.S.A. These have been summarized in three textbooks: Sutton (1953), Priestley (1959), and Pasquill (1962).

Pasquill (1971) shows that the point and line source models are substantiated by a vast amount of experimental data and give excellent estimates in all but the most extreme cases.

Best results are obtained from these models when one has
1) uniform flow over a smooth surface; 2) a steady wing; 3) a homogeneous field of turbulence; 4) the absence of buoyancy forces, that is, lapse rates near neutral; and 5) distances less than ten miles.

Unfortunately urban air pollution problems are usually worse when none of the above conditions apply. A city is comprised of thousands of individual point sources making up an area source. Very few estimates exist of emissions and a real need exists for more work in this area. Further, cities are far from smooth, and are usually built near coasts or in valleys, and the worst air pollution problems occur under conditions when lapse rates are extremely stable. As a result of these shortcomings attempts have been made using empirical approaches based upon observational data.

From 1920 on, a large amount of pollution data had been assembled for English cities. Leicester had a good network of stations and it was chosen for an intensive study of regional air pollution in 1937 - 39. (Department of Scientific and Industrial Research, 1945) Smoke and sulphur dioxide readings were related to wind speed and Richardson number. From these empirical prediction equations were obtained.
Further studies were made in Los Angeles in the post war period. Edinger (1958) explained the importance of the Pacific high-pressure cell in terms of subsidence and upper-air inversions. Since then extensive studies have been made in most large cities and the spatial distribution of pollution is fairly well documented. One of the earliest Canadian studies was commenced in 1949. The International Joint Commission was set up to study problems of pollution in the Detroit - Windsor area (International Joint Commission, 1960). Meteorological tower data were used with pollution and standard meteorological data to predict mean concentrations of suspended particulates. Multiple correlation techniques were used with temperature, rainfall, wind speed, and pollutant concentrations as variables (Baynton, 1956).

Lucas (1958) using Sutton's (1947, 1950) formulae obtained an approximate formula for the concentration of sulphur dioxide and smoke over a city due to the emission of an area source. His cross city results compared favourably with those found in Leicester.

Pooler (1961) applied an empirical diffusion model to sulphur dioxide levels for Nashville, Tennessee, U.S.A. He computed mean monthly relative concentrations from the standard climatological summaries of wind speed and direction. Munn (1959) has applied Sutton's diffusion model to morning fumigation conditions in order to derive criteria as an aid to town planning.

Turner (1967) has published a "Workbook of Atmospheric Dispersion Calculations" which empirically extends the range of conditions under which Pasquill's (1961) Gaussian diffusion equation
can be applied. Substantial errors can still accumulate under 'extreme' conditions-complex topography, great distance (over 6 miles), or stabilities outside the range 0-5.4°F/1000'.

The widespread use of the electronic computer in the 1960's has lead to a great wealth of literature dealing with the simulation of various multiple source configurations. Pasquill (1971) states that there are two main types of model:

"one which is supposed to include some physics and meteorology as well as mathematics, in the sense that the basic element of the model is the distribution of material from an elementary source as a function of source strength and atmospheric conditions - the other being concerned simply with the representation and extrapolation of statistical trends in the pollutant concentration at a specified site".

Most of the effort in the last decade has gone into the former approach.

The numerical summation of a large number of individual sources on a high speed computer was first advocated by Freinkel around 1956. This method still assumes a dominant position as can be seen from an examination of recent papers. (see for example Stern, 1970).

The testing of multiple source calculations is difficult since the ideal sampling densities can never be attained due to the great number and variety of source sizes. Estimates of the degree of accuracy that can be attained can be found in Marsh and Withes (1969), and Fortak (1970). Pasquill (1971) feels that the only prospect of useful prediction lies in the statistics of cumulative
frequency distributions of a large number of values, when prediction of the rather extreme high concentrations encountered only occasionally, may be achievable with an error factor of about two.

Little progress has been made on the problem of vertical diffusion at long range. The adequate description of the vertical dispersion in a plume from a fixed source requires ampling traverses at a number of heights at different distances from the source and usually entails the use of several specially instrumented aircraft. Recent work includes Petterson (1969), Bush and Panofsky (1968), Murgatrayk (1969), and Clarke (1970). Success in this work is necessary if realistic calculations are to be achieved for the three dimensional distribution of air pollutants on a regional and global scale.

2.4.3 Air Pollution Climatology

(i) Introduction

Standard, routine, meteorological data are obtained by the various National Weather Services, at whose field stations regular weather observations are made and recorded. In Canada the Atmospheric Environment Service maintains these stations. There are approximately 200 stations at which 24 hourly observations are made of surface weather. The number of stations at which upper air observations are made is fewer than for surface observations. The nearest station to Winnipeg is approximately 200 miles away.

A considerable number of 'meteorological towers' are now in routine service operated by both private and public organizations
for purposes directly related to air pollution and atmospheric diffusion studies. Table 2.5 lists the present and projected Canadian towers.

In the past this data has been primarily used for research on extreme weather situations or for research on low pressure or cyclonic circulations. Severe weather was associated with low pressure circulation and high pressure systems were greeted as breathers between storms. Recently this situation has been reversed with attention focussing upon high pressure stagnating systems due to the sickness, death, and property damage associated with high air pollution episodes.

Except for a few localised sources, the effect of those high air pollution episodes tend to be felt most over urban areas. Under normal circumstances winds ensure that the volume of air over a city is changed rapidly by horizontal and vertical air movement. During these occasions dilution of air pollutants is vigorous and concentrations are generally below critical levels (Hage and Longley, 1967). Despite this, particular combinations of meteorological conditions can cause the diffusion process to be suppressed, resulting in critical local levels of pollution. These conditions are generally well known, namely, light winds, and weak vertical mixing, frequently accompanied by inversions of temperature (Munn, 1968).

(ii) Air Pollution Potential

(a) Introduction

A number of papers have been produced in the last decade
showing the major areas of subtropical anticyclones, (Klein, 1957), stagnating anticyclones (Korshover 1960, 1967, Holtzworth, 1962), and inversion frequency (Hosler 1961).

An experimental forecast program to recognize and forecast conditions of high air pollution potential was instituted in the U.S.A. in 1957. Results from certain periods have been reported (Neimeyer, 1960, Boettger, 1961, Miller and Niemeyer, 1963).

(b) Inversion Frequency

Atmospheric dilution of pollutants is a function of the temperature gradient both in the vertical and horizontal as well as with time. Hosler (1961), presented a climatological study of frequencies of low level stability, which can be used to evaluate the pollution potential for a given region. His study covered the entire U.S.A. and was based upon the coarse resolution of radiosonde observations. Data must be adjusted to take local geographical factors into consideration. In particular great adjustments must be made in urban areas.

(c) Mixing Depth

The concept of mixing depth has attained widespread usage. Mixing depth is defined as the height above ground to which adiabatic or superadiabatic conditions prevail, and is thus a layer of vertical mixing. Holtzworth (1964) prepared estimates of the mean maximum mixing depths in the U.S.A. for each month, based on radiosonde observations.
The major assumption of the mixing depth method is that vertical mixing is a function only of the vertical temperature structure at the time of the sounding and surface maximum temperature. The method must therefore be used with other meteorological factors in indices of air pollution potential.

(d) Wind Speed

Wind speed is the parameter which determines the volume of air through which a pollutant is diluted as it is emitted. Holtzworth (1962) compiled average daily windspeeds for the Western U.S.A. He took winds less than or equal to five miles per hour accompanied by no rain as the critical case and classified 48 cities on this basis.

(e) Air Pollution Potential Climatology

Holtzworth et al. (1967) presented results of a study which combined estimates of morning and afternoon mixing depths with average wind speeds through the mixed layer. The resultant 'urban diffusion model' was applied to four cities - New York, St. Louis, Salt Lake City, and Los Angeles. This study is being extended to all states.

Miller (1967) has published a method of forecasting afternoon mixing depths and transport wind speeds through the mixing depth from rawinsonde data.

The above work emphasizes stagnation conditions, that is, conditions under which the diffusion models fail. None of the work adequately takes into account the complex changes induced by the urban area and detail is lacking both in terms of precision of
observations and the frequency of observations. Most are based on rural, or at best suburban radiosonde observations taken twice per day at the most. Although useful in a general way, they are usually of little use in individual city cases when considerable more detail is required.

This extra detail is secured by the use of tethersondes, helicopters, and towers to measure vertical temperature, wind structure, and turbulence in the lower atmosphere.

Tall towers if available, are the most useful since they produce continuous data which can be used to provide background historical information as well as up to the minute information for use in forecasting.

Munn and Stewart (1967) list the types of information towers are frequently required to provide and its uses.

a) Historical Information

1) What are the average mesoclimatic features of the urban area? What is the general wind flow, and how is it influenced by local orographic effects, the presence of lakes or oceans, etc.?

2) What extremes are to be expected, particularly in the duration of light winds and inversions?

3) What weather has occurred on specific dates and times?

b) Prediction

"1) Forecasting of air pollution potential a day or so in advance from large scale synoptic weather situations.

2) Short-term forecasting of air pollution levels from physical diffusion models, knowing the distribution of sources and the mesometeorology of the urban area.

3) Forecasting air pollution levels from statistical contingency tables of multivariate analysis, given a historical level of both ground-level concentrations of pollution and meteorological factors. This includes diurnal and seasonal cycles as well as long term annual trends to help in determining whether pollution control programs are effective."
A complete analysis of tower data to include all of the above would be a massive task and most previous studies have examined only one or two aspects of the above. Chapters Eight and Nine of this thesis will concentrate upon a (2) and b (1) above. In particular b (1) will be approached from an analysis of regularly observed weather elements, especially wind direction and cloud cover.
CHAPTER THREE

Climate of the Winnipeg Area

3.1 Introduction

3.1.1 Record Length

The first weather records for Winnipeg date back to 1872. The station was moved in 1932, and again in 1937. There was no effective overlapping of records during changeover and hence, it is impossible to evaluate whether a correction is necessary to ensure continuity. The present station, Winnipeg International Airport (A), is located on the west side of the airport in the extreme northwest sector of the city at 774' above sea-level.

3.1.2 Topography

Winnipeg is situated in the broad flat valley of the Red River, about 30 miles south of the southern end of Lake Winnipeg into which the river flows. The valley, which is the bed of former glacial Lake Agassiz, is approximately 100 miles wide near Winnipeg, and slopes away from the river at 2 to 3 feet per mile. The east side of the valley is a nearly level plain with extensive swampland. The west side terminates approximately 50 miles to the west with an abrupt rise known as the Manitoba escarpment. The slope to the north is approximately 1/4 to 1/2 a foot per mile.

The entire area is covered with lacustrine deposits of highly plastic clays with a large water capacity. Unmodified glacial drift lies at depths of \(4 - 60\)' below the surface.
Owing to the flat terrain local effects are minor. They include a channeling of wind along the Red River valley, a slight warming and drying during south-west winds, and a slight influence from the Manitoba lakes.

3.1.3 Geographic Influences

Winnipeg is located in the north centre of the North American landmass and as such has a typical continental climate - Rainfall with an early summer maximum, and wide ranges of annual, monthly, day to day, and diurnal temperatures.

The Winnipeg area, being situated on the 50th parallel, is in the middle of the belt of prevailing westerlies. Variations in the average path of the westerlies cause variations in seasonal weather from year to year as well as large variations within each season. Migrating weather systems embedded in the westerlies are the cause of day to day variations.

3.2 Fronts and Airmasses

The area is affected by three main fronts (Anderson, Boville and McClellan, 1955; Penner, 1955). The fronts and airmasses they separate are:

1) The Polar front. Maritime Tropical (mT) - Maritime Polar (mP)
2) The Maritime Arctic front. Maritime Polar (mP) - Maritime Arctic (mA) or wmP (mP moving over a warm surface) -cmP (mP moving over a cold surface).
3) The Continental Arctic front. Maritime Arctic (mA) - Continental Arctic (cA).

In summer only the first two are generally distinguished since there is no source for cA air. Reid (1959) verifies the
existence of this scheme but emphasizes the impermanency of the fronts.

Bryson (1966) provided the first detailed analysis of the mean summer positions of the fronts over North America. He employed three independent techniques to establish frontal locations; surface air mass trajectories for July 1945 - 51 and 1954 - 56, frequency analysis of daily maximum temperatures for July 1948 - 57, and resultant streamline charts of surface wind for each month using data for 1930 - 1945.

Bryson obtained five groups of airmasses for Canada using air mass trajectories (Arctic, Pacific, Atlantic, Hudson Bay, and 'United States' air). United States air could be further subdivided into northern Rockies and Gulf air.

On the basis of temperature collectives Bryson delimits eight categories of air mass affecting Canada. (Maritime Tropical, Canadian Rockies Pacific, Yukon Pacific, Alaskan, East-Arctic, West-Arctic, Hudson Bay, Atlantic).

If Bryson's air mass trajectory method is applied to Winnipeg in July the following percentage frequencies for air masses are obtained (extrapolated from his isoline maps (table 3.1)).

Bryson's results directly contradict those of Brunschweiler (1952) in that they indicate that unless both Pacific air and Arctic air are labelled cP, there is no portion of Canada dominated by cP in summer. Pacific air moves across the west coast of Canada as mP air. After crossing the Rockies it is much drier and warmer, and it is this modified mP air that many people call cP air. Bryson found the following % frequencies for July airmasses in Winnipeg using maximum temperatures as his classification system (table 3.2).
Barry (1967) re-examined Bryson's work on the Arctic front using 850 mb. contour charts and found a general agreement in the Winnipeg area. The median January location of the Arctic front was well south of Winnipeg. In April and October, it was between Winnipeg and Hudson Bay. In July, it is located over the northern ice cap and the Maritime front appears about 250 - 300 miles north of Winnipeg but subject to great variation in position.

3.3 Synoptic Climatology

Sands (1966) performed a synoptic climate study of the Western United States and adjacent areas over the period 1958 - 63 inclusive. He examined the individualistic secondary circulation systems and divided them up into 105 different but repetitive circulation features. Of these 60 were classed as upper air (500mb.) and 45 were classed as surface features.

It proved rather difficult to select the main upper air features affecting Winnipeg's climate but in the end six were chosen as representative. It proved much easier to select the surface features and five of these were chosen. A description of those 17 features follows.

Prairie Provinces-Western Ontario Low (fig. 3-1 after Sands feature 10) is an upper air closed low which occurs regularly from year to year, with slight peaks in June, July, and December when it is present on 10% of all occasions. It generally moves in from the west or south-west.

Oblong Low over Eastern Canada (fig. 3-2 after Sands feature 11) is an upper air closed low occurring in every month with a peak in July. It moves in from the west or south-west and occurs
on 25% of all days in July.

**Short Wave Cyclonic Impulse over the Great Plains** (fig. 3-3, after Sands feature 24) is an upper air feature (meridional polar trough) which occurs throughout the year, but more frequently in summer, and has a July peak. Just under 25% of all days are affected by it in July.

**Central or Eastern U.S.A. Meridional Trough** (fig. 3-4, after Sands feature 25) ranks second in overall frequency of upper air features. It occurs throughout the year with peaks January, June, August, November, and December. Often develops from feature 10.

**Minnesota-Dakota's Tilted Trough** (fig. 3-5 after Sands feature 27) is an east-west tilted polar trough which occurs only in winter and spring, and then with great variability from year to year. It often occurs when feature 10 moves south-east.

**Westerly Flow-Northern U.S.A.** (fig. 3-6 after Sands feature 58) This feature represents westerly zonal flow. It has a maximum occurrence in summer and a minimum in late winter and early spring.

**Alberta-Saskatchewan-Manitoba Low** (fig. 3-7 after Sands feature 66) is a medium sized surface closed low with average stability and little variation by months. It has a very high frequency, third out of 105 features, and is most frequent in June and September. The minimum occurs in February. It is present on 1/3 of all days in June, and over a 1/4 of all days from November - January and June - September. It moves in from the west, south-west or north-west.

**Alberta Low-Montana-Dakota's** (fig. 3-8 after Sands feature 67) is a surface closed low with much variation in size. It is most prevalent between June and October with marked peaking in August.
The minimum occurrence is in April. Although this feature moves to the south of Winnipeg, it is important in that it can affect cloud amounts and temperatures in the Winnipeg area.

**Surface Ridge East of the Rockies** (fig. 3-9 after Sands feature 102) is normally well developed in the cool or cold air. It is most prevalent in winter with a maximum in December-January and a minimum in April.

**Central Canada Surface Ridge** (fig. 3-10 after Sands feature 103) is a medium sized well developed ridge with cool or cold air. It is most prevalent from February to May (over 20% of all days), with a peak in May.

**Surface Ridge from Central Canada extending into S. Plains** (fig. 3-11 after Sands feature 104) This is a well developed, very large feature with cool or cold air. It is highly prevalent from February to April peaking in March. There is no occurrence in July.

Upper air features 10, 21, 58, bring in warmer westerly and south westerly air. Features 11, 25, and 27, on the other hand bring in colder north-westerly air aloft and often prevent surface westerlies from crossing the Rockies in Alberta. There were a total of 444 occurrences of features 10, 21, 58, and a total of 677 of features 11, 25 and 27 in the period 1958-1963.

On breaking these down seasonally, there were 49 occurrences of westerlies aloft in winter, against 179 occurrences of northwesterlies aloft. In summer the position balanced up with 219 occurrences of warmer westerlies aloft, and 235 occurrences of cooler north-westerlies aloft.
The importance of the surface westerlies in determining Winnipeg's weather is brought out by an examination of the surface synoptic patterns. In winter (December-February) there were 112 occurrences of feature 66 the surface low, whilst there were 155 occurrences of ridges of high pressure. There were also 60 occurrences of feature 67 to the south of Winnipeg, resulting in warmer temperatures.

The westerlies in winter bring in cool north-westerly, westerly, or south-westerly air and replace the very cold air brought southwards by features 102 - 104, the ridges of high pressure.

To a large extent the depressions are replaced by ridges of high pressure as they move eastwards. This replacement results in great fluctuations in day to day temperatures, and rapid temperature drops as cold waves move through. Monthly temperatures are largely determined by the strength of the westerly circulation and the number of depressions that move through in a given month.

In summer, the ridges of high pressure are much less important than the westerlies (77 occurrences versus 142) and weather is determined to a large extent by the relative positions of southerly Maritime Tropical air, north-westerly Maritime Polar air, and westerly or south-westerly Maritime Polar air with the latter being dominant.

3.1 Seasonal Variations in the Weather

The well defined rhythmic changes in the season to season weather of the Prairies are mainly due to north-south shifts and variations in strength of the prevailing mid-latitude westerlies.

As winter approaches, the interior of the continent becomes
colder and colder and the mT air retreats southward as the Polar front is pushed Equatorwards by the modified mP air.

With the onset of spring the annual retreat polewards occurs and by mid-summer mT air is affecting Winnipeg on 15% of all occasions.

The change from summer to winter is relatively abrupt and starts after the autumnal equinox. Nights begin to lengthen, the angle of the sun in the sky starts to decrease, and a period of net heat loss sets in. The October average temperature is +14°F, whilst November's is only +21°F, a fall of 20° compared to 10° for the two months before. During November the Arctic front is moving to the south of Winnipeg and by December winter is firmly established with an average temperature of only +7°F. There is little change in the average monthly temperature during December, January, and February. The mean temperature drops from +7°F to -1°F and then moves back to +1°F in February. Throughout this period there are constant influxes of cA air from the north and north-west and mP air from the zones of cyclogenesis in S. Alberta and N. Montana. Air mass changes result in large fluctuations of temperature.

Winter relinquishes its hold on Winnipeg during March and April as lengthening days and increases in the intensity of solar radiation bring higher temperatures. The average February temperature is +4°F, by March it is +17°F, whilst by April it is +38°F. During March - April, the Arctic front once again moves to the north of Winnipeg.

With the onset of summer the interior of the continent gradually becomes warmer. Outbursts of cold air are much rarer. By June mT air is much more common along with westerly air. The role of mT air continues throughout the summer bringing thunderstorms, hail,
and even tornadoes. Despite this, mP air from the Pacific is still as always the primary precipitation carrier. Rain often occurs as colder mP air pushes south and the warmer mP air is lifted up and over the cooler mP air.

3.5 Temperatures

Large annual variations as well as large day to day and large diurnal changes in temperature are features of a continental climate. These characteristics are evident in the Winnipeg records. (See Figure 3.12) The normal temperature cycle is at its lowest (-1°F.) during January 17th to 27th, and its highest (70°F.) from July 19th to 27th. The extreme maxima (1872 - 1971) (See Table 3.3) vary from +46°F. in January to +106°F. in July. Corresponding minima vary from -54°F. to +35°F. The greatest range occurs in March when extremes have varied from -38°F. to +74°F., a range of 112°F. The records also reveal large daily temperature ranges with an average of +41°F. in May. The largest diurnal variation occurred on January 25th, 1889 when 62.6°F. was reached.

Even monthly means show great variations. The highest monthly mean for December has been +25.9°F. whilst the lowest was -14.7°F. Corresponding values for July are +75.5°F. and 59.1°F. Table 3.3 lists the complete monthly and annual averages and extremes of record 1872 - 1971 (Atmospheric Environment Service, 1972).

The average daily temperature is below 32°F. for the five months November to March. Periods of up to three weeks have occurred when temperatures were continually below 0°F. Table 3.4 gives the percentage frequency of occurrence of minimum temperatures of -10°F.
and lower, and clearly illustrates the three core winter months of December, January, and February.

The heating season is important from a pollution emissions viewpoint. The number of heating degree days below 65°F. is listed in table 3.5 (1931 - 60 average) and once again the three core winter months are brought out.
3.6 Winds

Table 3.6 lists the percentage frequency of winds by direction on a monthly basis, and the average wind speed by direction and month. The primary wind direction is south in all months, with a secondary wind direction of north-west in all months except the spring ones of April, May, and June when the secondary wind direction is north. Lowest average wind speeds occur from the north-east, east, and east-north-east. South-west and west-south-west winds are also lightest especially in winter and summer.

Fig. 3.13 illustrates wind roses for the period corresponding to Table 3.6.

Windspeeds in Winnipeg are quite high (average annual value 12.1 m.p.h.) compared to its Prairie neighbours to the north and west. The Pas, Manitoba, 300 miles north has an average speed of 10.1 m.p.h., whilst Edmonton and Calgary to the west, experience average wind speeds of 8.8 m.p.h. and 10.1 m.p.h. respectively.

3.7 Fog

Fog is infrequent in Winnipeg because Winnipeg is not heavily industrialized and there are no major water bodies close by. The longest occurrence of fog was in 1969 when it lasted for 65 hours. No 30 year averages are available for fog and the following figures pertain to the 10 year period 1941-50. On average there are 21.7 days with fog, the worst months being December (3.3), and February (2.7).

3.8 Climatic Trends

Prior to 1900, temperatures were low in the Prairies, when
compared to averages and extremes today. There was a general increase of temperature from 1900 to the 1930's and then temperatures started dropping again reaching a low in the early 1950's (see Figs. 3.14 and 3.15 modified from Labelle (1966) to include data 1961-1970). The late 1950's and early 1960's saw a recovery, and Manitoba temperatures averaged as high as the previous maximum in the late 1940's.

Since the early 60's there has been a decrease in the 10 year mean and the 1962-71 mean stands only slightly higher than the early 1950's low. The winter 10 year mean has likewise decreased throughout the 60's and is now as low as the 1950's low.

Both summers and winters are now slightly colder than they have been over the last 40 years. Table 3.7 shows that the annual, summer and winter 30 year means have decreased since the 1930's and that weather during the last decade and during the sampling period was slightly colder than the 1961-70 average. This will be discussed in more detail in the following section.

3.9 Weather during the Study Period

The question might well be raised at this point as to how representative is the 27 month sample of October 1969 to December 1971.

Table 3.8 presents the mean monthly temperature averages for 1931 - 1960 and 1961 - 1970 and the monthly standard deviations of daily mean temperature along with the mean monthly temperature averages during the study period.

Seven of the twelve months are within 0.5 standard
deviation of the 30 year mean and only June is over one standard deviation from the daily mean temperature. Most of the twelve months are colder than the 1941 - 1970 average which is in line with the remarks made in the previous section.

The weather can therefore be taken as reasonably representative of the weather during a much longer period.

CHAPTER FOUR

Method of Investigation

4.1 Introduction

The present study commenced in 1967 when the decision was made to investigate the mesoclimates of the Winnipeg area. It was felt that this area was an excellent one for detailed studies since the city of Winnipeg is situated in the centre of the 100 mile wide former glacial Lake Agassiz bottom. It was the ideal situation with the city located in the centre of the 'infinite' plain, and well removed from lake and valley effects. In addition, no previous detailed studies existed on North American Prairie climates. The first problem was to establish a field station to supplement the first order station at Winnipeg International Airport.

An attempt was made to instrument an urban field station using a tower but had to be abandoned because of zoning regulations. It was then decided that a rural field station should be established. Initial research ideas dictated that it had to be far enough away from the city so it would not be affected by the urban heat island and yet not too far away since it had to be representative of the rural climate around the city.

Two tall television towers (over 1000 feet) were located close to the city. The Canadian Broadcasting Corporation (C.B.C.) were approached and asked if their 1000' tower could be used to place meteorological sensors on. After some time details were worked out with their lawyers and engineers and permission to go
ahead came in late summer 1968.

In autumn 1968 equipment was available to instrument the tower for wind at two levels. During 1968/69, sufficient funds were obtained to measure and record five levels of temperature and this was done during summer 1969. Recordings were made on punched paper tape which required changing three to four times a week. Access to the system, which was housed in the air conditioned and temperature controlled transmitter room, was limited especially during holiday periods.

In early 1970 funds became available for a data acquisition system and this was installed in April 1970. Nine channels of information were recorded, five channels of temperature information and two each of wind speed and direction. Data was recorded on computer compatible magnetic tape (plates 1 and 2).

4.2 C.B.C. Tower Instrumentation

4.2.1 Introduction

The C.B.C. tower, Starbuck (latitude 49°46' North, 97°31' West) is located 19 miles west-south-west of the centre of Winnipeg on the former glacial Lake Agassiz bottom. It is a total of 1060' high, with an 8 foot triangular cross-section. Radiation effects from the transmitter antenna reduce the usable height to 810' above ground level at 775'. The land around the tower is composed of flat, poorly drained heavy clays which are waterlogged in spring.

Plates 3 to 6 are air photographs of the tower and are located in the folder attached to the back cover. The scale of the photographs is one inch to 2000 feet. Figure 4.1 shows the bearings and distances to obstructions close to the tower. Plates 1, 2, 7, and 8 show the tower and its associated instrumentation.
4.2.2 Instrumentation

a) Wind

The wind instrumentation is mounted at 35 feet and 810 feet above ground, the levels being determined by the heights of the platforms available. The instruments are Bendix-Friez model 120 aerovanes measuring both wind speed and direction. (See plate 8.) They were selected for their ruggedness and dependability and, except for icing and annual inspections, have functioned flawlessly since October 1968 to the present. Ruggedness was important since there was no way of climbing the tower for servicing from November to May owing to danger from falling ice.

The transmitters were located on the ends of booms, extending ten feet out from the edge of the tower corresponding to one and a quarter tower widths. The limiting factor here was the maximum length of piping available, in this case, 14 feet.

Gill (1964, 1968) gives guidelines for the size of booms. His rule of thumb is that an anemometer should be mounted outward from a television tower at a distance greater than the diameter of the tower at that height.

Despite these precautions, wind shadow effects will be apparent. (Gill et al. 1966, Moses and Daubek, 1961) Moses and Daubek found that when the wind blew through the tower before reaching the anemometer there was a reduction in speed, the effect being greatest with light winds. When the wind was on the same side as the anemometer, there was an increase in speed. Moses (1968) states:

"The directions in which the booms extend should be selected with a knowledge of the least frequent wind direction, so as to minimize the tower wind shadow effect."
In the C.B.C. tower case, no choice was available as to the location of the booms, since the C.B.C. did not want them in the way of personnel performing normal tower servicing. Figure 4.2 shows the location of the wind sensors relative to the tower and the wind directions affected by the tower.

Winds coming from directions 86° to 149° will be slowed down by the tower, whilst winds from 266° to 329° will be speeded up as they approach the sensor.
b) Temperature

Temperatures were measured using platinum bulbs (Rosemount 104-MACCA) mounted in aspirated Beckman and Whitley Radiation shields extending 8 feet from the tower. Plates 7 and 8 show the wind and temperature sensors mounted on the tower. All instrumentation exceeded the minimum specifications for Canadian micrometeorological instrumentation as laid down in McLernon (1969).

The temperature signal was fed from the platinum bulb to the linear bridge using four wire 16 A.W.G. neoprene shielded cable. Two of the four wires carried the signal, whilst the other two were coupled to the opposite side of the bridge eliminating the temperature effect on the resistance of the lead in wires. The linear bridge converted the signal to one millivolt equals one degree Fahrenheit.

The signal was led from the linear bridge to a scanner, digital voltmeter, multiplexer, and clock, and then recorded on paper tape or incremental magnetic tape. Sampling was carried out every 30 seconds 24 hours a day. Computer programs were written to detect and throw out bad data. An error analysis of the entire temperature system follows.

1.2.3 Error Analysis of the Temperature System

A short summary of an error analysis for the system is given in Table 4.1.
The total error is obtained by summing the squares of the individual errors and taking the square root of the sum (Personal communication Rosemount Engineering).

This gives an error from one reading. If 20 readings are obtained the error can be calculated by dividing the above errors by $20^{\frac{1}{2}}$ yielding a standard deviation for a 10 minute mean of 0.012°F. in differential mode, and 0.039°F. in absolute mode. We can thus be 95% certain that a ten minute mean ($\bar{X}$) lies in the following range:

Confidence interval for a 10 minute Mean:

\[ \bar{X} \pm 0.024^\circ F. \text{ in differential mode;} \]
\[ \bar{X} \pm 0.077^\circ F. \text{ absolute mode.} \]

These 10 minute means were then carefully scrutinized by computer and any bad data were eliminated. Table 4.2 gives full details of sampling during the 27 and 33 month periods and shows the relatively high reliability of the system in extremely adverse physical conditions.

4.2.4 Wind Data Analysis

Wind data was obtained from charts by visual scaling once per hour. A 10 minute average accurate to $\pm 3^\circ$ for wind direction and $\pm \frac{3}{2}$ m.p.h. for wind speed, was taken from the hour to 10 minutes past the hour.

This procedure was later mechanized using a Hewlett-Packard programmable calculator and digitizer. The data was validated, edited, and put on punched cards which were run through various error routines on the computer. The wind data was then merged with the corresponding
temperature data.

In all some 750 million characters of information were treated during the 33 month sample. The data were edited several more times and then put on one reel of tape. The entire editing process took a considerable amount of computer time and over one year of full time work.

Atmospheric Environment Service regular hourly synoptic observations were obtained later and merged with the tower data to form the data base. This data base was then subjected to numerous data stratifications, the results of which are presented in the next five chapters.
CHAPTER FIVE

Analysis of Tower Temperature Data

5.1 Introduction

The ten minute averages of temperature, temperature difference and lapse rates discussed in the previous chapter, were analysed in a number of ways.

Section 5.2 looks at each hourly value of lapse rate\(^1\),\(^*\) each height individually. Negative lapse rates are regarded as inversions, that is, an increase of temperature with height. The analysis is based upon the categorization of lapse rates into one of thirty-one groups based upon the dry adiabatic lapse rate (D.A.L.R.) (Tables 5.1 and 5.20)\(^2\). In addition percentage and cumulative percent frequencies were prepared for the month. In all 120 tables were arranged, one for each of ten levels for each of twelve months. Tables 5.21 to 5.27 and Figures 5.1 and 5.2 are based upon this analysis.

Sections 5.3 and 5.5 look at monthly averages of temperature, temperature difference and lapse rates. This data is obtained by taking the hourly ten minute averages for each height, and finding the average value for each hour within each of twelve months. Each hourly average is obtained from approximately 60 values (90 from October to December). Each height yields 24 hourly values plus an average value for all 24 hours. Data are available for each month and are presented in tables 5.28 to 5.39 and figures 5.13 to 5.18.

* Numbers refer to notes at the end of each chapter.
Tables 5.28 to 5.39. 

Section 5.4 examines the maximum values of lapse rate. Each hour's data is scanned and maxima for each hour for each of 27 months are obtained. All 10 levels are examined giving 270 tables in all. Tables 5.52 to 5.56 are based upon these 270 tables. Table 5.62 summarizes the rest of the 270 tables and looks at all 10 levels.

Temperature measurements are available for the 35', 200', 400', 600' and 810' levels. Lapse rate and temperature difference data is available for all 10 layers, viz 35 - 200, 35 - 400, 35 - 600, 35 - 810, 200 - 400, 200 - 600, 200 - 810, 400 - 600, 400 - 810, and 600 - 810 foot levels. Selections are usually made from these ten levels for more detailed analysis.

Evidence will be presented in this chapter to show that all data involving the 600' temperature, and hence 200 - 600, 400 - 600, 600 - 810, and 35 - 600' layers, should be treated with caution.

In considering results based upon the above tables and figures, there are certain points which should be borne in mind. In the first place, individual hourly values show large departures from the mean monthly curves, for example inversions exceeding $15^\circ$F./200' are not uncommon and can easily alter the average value and affect the graphs of lapse rates.

Another point to remember is that since the times of sunrise and sunset vary considerably from beginning to the end of the month, the changes of lapse rate which occur about these times will appear smoothed in the mean monthly value. The smoothing effect will be most marked at the equinoxes.
5.2 Frequency of Occurrence of Lapse Rates of Various Magnitudes

5.2.1 Hourly Frequencies of Various Lapse Rates

The hourly values of lapse rate over 10 height intervals have been analyzed to show the frequency of occurrence of various values of the lapse rate expressed as multiples of the D.A.L.R. for each hour during the month. In all 120 tables were prepared (10 layers by 12 months). Part of the results of the analysis are shown in Tables 5.1 to 5.20 for the months of January and July. The frequencies are expressed as percentages of the total number of readings at the hour concerned. Only two months are presented here because of space considerations.

The values for January show that in the 35'-200' layer (Table 5.1) the afternoon lapse can attain a value of four times the D.A.L.R.. Around noon 9.2% of all values are greater than or equal to the D.A.L.R. compared to only 1.6% during hours 02 - 03. At night values of the inversion are distributed fairly evenly with maximum values reaching over -10 times the D.A.L.R..

With increasing height, for example, the 200-400 foot layer, (Table 5.5), the range of values declines with more grouping in the 0-5°F./1000' range (weak lapse conditions). Midday values have now dropped to 1.5 to 2 times the D.A.L.R. and at 14 - 15 hours only 27.3% of all values are greater than the D.A.L.R.. At night (04 - 05 hours), no values reach the D.A.L.R..

This pattern continues in the 400-810 foot layer (Table 5.9). No values reach the D.A.L.R. at this height during any hour in January and strong inversions are much less frequent. For example over 40% of all inversions are less than -1 times the D.A.L.R.
compared to 17% in the 35 - 200 foot layer (Table 5.1). The decline in the range of values and increased grouping around weak lapse conditions with increasing height is also brought out by Figure 5.1.

In July the 35 - 200 foot layer can attain values of five or more times the D.A.L.R.. Around noon (12 - 13 hours) 63% of all values are greater than the D.A.L.R. compared to 20 - 21 hours when the strongest lapses are less than the D.A.L.R.. At night inversions are distributed fairly evenly with over 40% greater than -5 times the D.A.L.R. at 0000 and 0100 hours.

The 200 - 400 foot layer has values of over three times the D.A.L.R. in early morning and over 93% of all noon occasions experience superadiabatic conditions. At night (04 - 05 hours), no values are greater than the D.A.L.R.

The reduction in the range of positive lapse rates continues in the 400 - 810 foot layer, when lapse rates greater than twice the D.A.L.R. are rare (1 occasion 2\(\frac{1}{2}\) - 3 times the D.A.L.R.). Superadiabatic conditions are present on only 21% of noon occasions and only one occasion exists in the ten hour period 2200 to 0800 hours.

The trend to weaker inversions begun in the 200 - 400 foot layer continues. There were 360 occasions of inversions greater than twice the D.A.L.R. in the 35 - 200 foot layer, 153 occasions in the 200 - 400 foot layer and only 27 in the 400 - 810 foot layer. Figures 5.1 and 5.2 illustrate the increased grouping around weak lapse conditions in graphical form.

The distribution of various lapse rates throughout the year can be ascertained from Tables 5.2 to 5.3 for the three layers 35 - 200', 200 - 400', and 400 - 810'. In the 35 - 200' layer, March
has the most strong inversions (19.3% greater than -5 times D.A.L.R.), whilst May has the fewest (1.9%). Similar conditions exist in the 200 - 400' layer with March and May having the highest and lowest values respectively. In the 400 - 810' layer, December has the most strong inversions, whilst June has none.

The annual cycle of the distribution of superadiabatics shows marked monthly variations. A rapid increase occurs from March to April (17.6% to 31.6%), and again from May to June (33.9% to 41.5%, Table 5.21, 35 - 200'). Superadiabatic conditions decrease most quickly from October to November (29.3% to 19.4%) but at a rate less than the Spring increase. Inversion conditions are at a maximum in February in the 35 - 200' layer, in March in the 200 - 400' layer, and in December in the 400 - 810' layer (Tables 5.21 to 5.23).

Certain anomalies are present in the 200 - 600' layer (Tables 5.6 and 5.16), the 400 - 600' layer (Tables 5.8 and 5.18), and the 600 - 810' layer (Tables 5.10 and 5.20). These anomalies can be seen much clearer in Table 5.24 which lists the percentage frequency of hours/month with superadiabatic conditions. All 10 height intervals are presented.

The progression of percentages with superadiabatic conditions should decrease with height since the main heating processes take place from the ground up. The form of the curve showing the normal decrease of superadiabatic conditions with increasing height, is an exponential sloping up to the left with increasing height. The first four columns of Table 5.24 show that this is not so. There is a logical progression from 35 - 200' to 200 - 400', with a rapid decrease in winter and a slight increase in summer. The summer increase occurs because inversion conditions set in quickly in the
surface layer in the evening, but rise slowly to affect the upper layers. In the morning the changeover from inversion to lapse is much quicker (see Sections 5.3 to 5.4) and so upper levels reach D.A.L.R. conditions only slightly behind lower levels. The net effect of the slow upward cooling in the evening and the rapid changeover during morning conditions is to decrease D.A.L.R. frequencies slightly at lower levels during the warmer longer days.

Conditions at 400 - 600' appear to fit in with theory in general, with a further decrease in D.A.L.R. conditions, but 600 - 810' conditions reverse this process, and imply superadiabatic conditions on 18% of all occasions in January and 61% of all occasions in July. This is exceedingly unlikely and because of the much lower 400 - 600' figures well nigh impossible. Columns 5, 6, 7, of Table 5.24 also show an anomaly in the 35 - 600 figures. Superadiabatic conditions decrease in this layer and then increase in the 35 - 810 foot layer.

It thus appears that the 600' temperature is reading high. This would have the effect of lowering the 35 - 600', 200 - 600', and 400 - 600' lapse rates and boosting the 600 - 810 foot lapse rates.

Some computer runs were made to simulate the effect of a high 600' temperature reading and the results of a -0.6°F. correction are presented in brackets in tables 5.24 and 5.25. These results are more in accord with basic meteorological theory.

It is impossible to check whether this error is indeed present and if it is systematic as implied above or random or some combination of both. It can however be said that all results involving the 600' level should be treated with extreme caution and that it is likely that the 35 - 600' lapse rate should be increased by approximately 1.1°F., the 200 - 600' lapse rate by 1.5°F., and the 400 - 600'
lapse rate by 3.0°F., 600 - 810' readings on the other hand probably need a reduction of 3.0°F.. Further evidence for treating the 600' levels with caution will be discussed as it is encountered. All further results show unadjusted data unless otherwise indicated.

The percentage frequencies of hours with lapse rates greater than or equal to zero by heights and months is shown in Table 5.25\(^2\). The figures in brackets in columns involving the 600' level are obtained by applying a -0.6°F. temperature correction to the data. Using the unadjusted data, the increase in the percentages of positive lapse rates occurs through the 35 - 200, 200 - 400, 400 - 810 foot levels at all times except November to February when the 400 - 810' layer shows a decrease.

The largest increase in the percentages with positive lapse rates occurs from March to April with increases of approximately 15%. The December to January period experiences the largest trend to inversions at lower (400') levels, whilst higher levels are affected in November to December. Typical decreases are again of the order of 15%.

The maximum percentage of superadiabatics and inversions occurring during any two hour period in the day, for each month and three selected levels is presented in Tables 5.26 and 5.27\(^1\). It can be seen that the median time for the maximum of superadiabatics is 12 - 13 hours in the 35 - 200' layer, 12 - 15 hours in the 200 - 400' layer, and 12 - 13 hours in the 400 - 810' layer. On average, superadiabatics occur on 50% of all noon occasions in the 35 - 200' layer in January and 96% of all occasions in August. In the 200 - 400' layer in January only 27% of 14 - 15 hour occasions have superadiabatics, whilst 94% of July noon occasions are greater than the
The 400 - 810' layer has no superadiabatics at any time in January but 3 out of ten August noons have superadiabatics.

The trend is clear. In winter there is a rapid decrease level by level in the percentage of occasions with superadiabatics. In summer on the other hand, there is little difference between the 35 - 200' levels and the 200 - 400' levels at the times of their respective maxima. The biggest jumps from one month to the next occur from March to April in the 35 - 200' layer, from May to June in the 200 - 400' layer, and from April to May in the 400 - 810' layer. The biggest decreases occur from October to November at all heights.

Similar information for inversions is presented in Table 5.27. In the 35 - 200' layer in July to August 90% of midnight occasions have inversion conditions, whilst inversions are present on approximately 75% of 0200 to 0500 hour occasions in the 200 - 400' layer. In the higher 400 - 810' layer, six out of ten occasions experience inversions but the time of the maximum has been retarded by a further two hours to 0400 - 0600 hours.

The maximum percentages with inversions thus decreases with height in summer and occurs later in the night with increasing height, unlike superadiabatics, when there is little delay in the maxima. In winter the position is similar with a decrease in the maximum percentage of inversions with height but the delay in the maximum with increasing height is less clearly evident especially in the period December to February. The maximum percentage with inversions experiences a double peak; a primary peak in August with a secondary peak in February to March. The maximum percentage of superadiabatics on the other hand shows a single annual cycle with a summer maximum tied to solar insolation.
5.2.2 Summary and Discussion

The range of lapse rates is larger near the surface and decreases with height. Very strong inversions (-26 times the D.A.L.R.) and very unstable gradients (+8.2 times the D.A.L.R.) were observed in the 27 month record in the 35 - 200' layer. These are in line with values observed elsewhere. Best et al. (1952) observed values in England of 20 times the D.A.L.R. in the 3\(\frac{1}{2}\) to 50' layer, and 8.7 times the D.A.L.R. in the 50 - 155' layer. They also found inversions of -55 times the D.A.L.R. in the 3\(\frac{1}{2}\) - 50' layer and -26 times the D.A.L.R. in the 50 - 155' layer.

For levels above 200', the range of values generally decreases, ranging from +\(\frac{9}{2}\) to -1\(\frac{1}{2}\) times the D.A.L.R. in the 200 - 400' layer, and from +2.9 to -10.4 times the D.A.L.R. in the 400 - 810' layer. The distribution is thus clustered around weak lapse conditions, and is skewed towards more stable lapse rates.

Goff and Hudson (1972) found that above 300', the D.A.L.R. constitutes an upper limit for lapse rates. Below 300' they found that this was not the case. Evidence from the Winnipeg data suggests that this phenomenon also occurs close to this level (in the 200 - 400' layer). The 300' to 400' level seems to be the approximate depth necessary for the atmosphere to adjust from the strongly heated surface layer with a large thermal gradient to near neutral conditions.

Best et al. (1952, page 21) observed in England that 92% of all lapse rates at a mean height of 250' were below the D.A.L.R. compared to 62% at a mean height of 100'. Comparable Winnipeg results for the 35 - 400' layer (mean height 217') and the 35 - 200' layer (mean height 117') are 74% and 65% respectively. Brocks (1948) has
plotted many measurements of lapse rate in Europe and Egypt in one diagram. He shows the mean depth of the unstable layer to be about 30' in December and 200' in June. Winter values using Winnipeg data cannot be estimated due to the poor resolution in the air layers near the ground. Winnipeg summer values are much higher than Brock's estimate and appear to be at least 300'. This is more in line with Goff and Hudson's results (1972) in Oklahoma, U.S.A.

5.3 Mean Hourly Values of the Temperature Gradient

5.3.1 Diurnal Variation by Months

The mean temperature difference for ten levels is presented in Tables 5.28 to 5.39. Data involving the 600' level should be treated with caution. Tables 5.40 to 5.51 use the same 10 minute temperature averages as a base but calculate the lapse rate in °F. per 1000' between levels. Figures 5.3 to 5.6 use Tables 5.40 to 5.51 to calculate the mean diurnal lapse rates over four height intervals.

Inversion conditions prevail in most months (Table 5.52). In January inversions are present for 20 hours in the 35 - 200' layer, for 19 hours in the 35 - 400' layer and for 21 hours in the 35 - 610' layer. These high figures continue in February and March but by April the sun is sufficiently powerful and nights are much shorter (10.2 hours vs. 15.3 in January) to give positive lapse rates for 10 of the 14 daylight hours.

By July there are only 8 hours of darkness and inversion hours total 12 in the 35 - 200' layer. This is higher than the nine of the 200 - 810' layer and the 7 of the 400 - 810' layer since nocturnal inversions are propagated slowly from the ground up and
affect lower layers earlier in the evening (see Table 5.1.6). July inversion conditions form in the 35 - 200' layer at 1900 hours, in the 200 - 400' layer at 2100 hours, in the 200 - 810' layer at 2300 hours and in the 400 - 810' layer at 0200 hours.

The evening transition period\(^5\) begins with a rapid cooling at low levels and a reversal of the sign of the lapse rate (Tables 5.28 to 5.39). The time of this sign change with respect to sunset varies little throughout the year (Best, 1935). Winnipeg data for the 35 - 200' layer (mean height 117') indicate that the transition occurs about 1 hour before sunset on an annual basis. In early summer the transition occurs about 1.5 hours prior to sunset, whilst in late autumn, early winter this falls to 25 minutes. These figures are close to what has been observed elsewhere. Best (1935) found that the evening transition period began about 1.5 hours prior to sunset in the 30 - 120 cm layer. In the semi-desert it starts 30 minutes later and in mountain valleys, it may start as much as 1.5 hours after sunset (Gol'tsberg, 1967). Flower (1937) found a great variability in evening transition times in Egypt largely due to the influence of sky condition. More recent results by Goff and Hudson (1972) in Oklahoma, U.S.A., also confirm this.

The time of the most stable lapse rate is delayed with increasing height above the surface. The most stable lapse rate in the 35 - 200' layer occurs at 0100 hours, in the 200 - 400' layer at 0600 hours, in the 400 - 600' and 600 - 810' layers at 0900 hours. (Table 5.53) The delay is greatest in winter and least in summer. It appears that there is a systematic vertical growth of inversions throughout the night but this is only partly true. Low level inversions only grow to average heights of 500 - 600' in mid-latitudes (Gol'tsberg, 1967), and possibly higher in high latitude and desert regimes.
Highly stable lapse rates above 600' after sunrise are the result of convectively induced lifting of surface inversions. This is discussed in more detail in Section 5.5.

Stability increases with height during daylight hours. The sign of the lapse rate often does not change to positive until 1000 hours in the upper 400' on an all year basis. In summer the transition occurs at 0800 hours, whilst in winter it does not occur until 1600 hours in the 400 - 600' layer and not at all in the 600 - 810' layer. The boundary layer and the free atmosphere thus remain uncoupled until mid-morning in summer. In winter on average, no coupling takes place.

The changeover from inversion to lapse conditions in the morning is much more rapid affecting the 35 - 200' layer at 0700 hours, the 200 - 400' layer, 200 - 810' and 400 - 810' layers at 0800 hours. (Table 5.46, July).

The diurnal variation of average lapse rate is brought out by an examination of Tables 5.40 to 5.51. The contrast between the large values of the midday lapse in summer and the small lapse rates in winter, is noteworthy. In January the maximum value of the mean monthly lapse rate in the 35 - 200' layer is +5.2 or 95% of the D.A.L.R.. By the 200 - 400' layer it is down to +1.9 or 35% of the D.A.L.R. on average. In the entire 35 - 810' layer it is only 0.6°F., almost isothermal conditions.

In February lower layer conditions (35 - 200') are more extreme with a lapse rate of only 4.6°F. The other layers have a stronger lapse however, and contrasts between the layers are less extreme, for example the 200 - 400' layer has a lapse of +3.6°F.,
and the 35 - 810' layer has a lapse of +1.9°F.

There is very little change of values in March with the D.A.L.R. being reached for one hour in the 35 - 200' layer, and values of 0.5 times D.A.L.R. being reached in the 200 - 400' and 400 - 810' layers.

Conditions in April show a marked increase to seven hours of superadiabatic conditions in the 35 - 200' layer, with a maximum value of 1.5 times the D.A.L.R. Conditions in the 200 - 400' and 400 - 810' layer reach 85% of the D.A.L.R.

The D.A.L.R. continues to spread to higher levels in May, June, July, and by August values of twice the D.A.L.R. are reached in the 35 - 200' layer. Morning hours now experience a rapid change-over from very strong inversion conditions (-3 times the D.A.L.R.) to superadiabatic conditions (1.5 times the D.A.L.R.). All layers except those involving the 600' level show D.A.L.R. conditions at some time during the day.

From September to December similar conditions to April to July prevail but in reverse with superadiabatic and maximum lapse conditions declining. The sequence of changes from January to August is also marked by an earlier change of sign from negative to positive lapse rates in the morning and later in the evening.

The time of occurrence of maximum values in January is delayed with increasing height; for example the 35 - 200' maximum value occurs at 1100 hours, the 200 - 400' value at 1500 hours, the 400 - 600' at 1800 hours and the 600 - 810' value at 1700 hours. The same is true for December - a smaller maximum and a delay in the time of the maximum.
Some care must be taken in interpreting the summer conditions owing to equipment failure on 30% of the hottest afternoons in June to August, 1971. D.A.L.R. values will be lower than they otherwise would especially during the period 1600 - 1900 hours and this could affect the estimate of the time of occurrence of maximum values. All levels were affected by the equipment failure for the same periods.

In July the 35' - 200' layer maximum occurred at 1100 hours, the 200' - 400' maximum at 1300 hours, the 400' - 600' maximum at 1200 hours, and the 600' - 810' maximum at 1300 hours. There is thus less delay in the time of maximum temperature with height in summer than in winter. This is confirmed by the June and August results.

Figures 5.7 to 5.12 provide a quick visual impression of the variation of temperature with height. The 35' average temperature is given at the base of each graph for each hour. The D.A.L.R. would intercept the X axis from the left at an angle of just under 70°.

All of the graphs show a kink to the right at 600'. In summer afternoons when mixing is vigorous, it would be anticipated that the vertical distribution of temperature would resemble either (a) or (b) in Figure 5.13, since mixing is vigorous to levels well above 810 feet.
The vertical profiles for June to August show this kink to the right at all times and it is difficult to explain this except by invoking a high temperature at the 600' level on account of instrumentation errors. The magnitude of this departure to the right is of the order of 0.5 to 0.7°F. and tends to confirm the suspicions outlined in Section 5.2. Figures 5.14 and 5.15 show the January and July curves with un-adjusted data (top of page), and with the 600' temperature adjusted by -0.6°F. (bottom of page). A -0.6°F. correction was chosen as the best available. In addition to evidence presented earlier, several summer afternoons were chosen for further study. All showed a kink to the right at 600' during vigorous mixing. The magnitude of this departure was +0.6°F. ±0.05°F.

The visual impression of the January figures is one of inversions affecting all levels for much of the day with lower, lower levels warming up in mid-morning. The warmth then spreads to the 200 - 400' level, and after sunset, reaches the upper levels by which time inversion conditions are firmly re-established at the surface. The February and March figures are very similar, except that the inversion intensity is increasing during the night hours, whilst daytime heating spreads to the upper layers much faster.

By April, night inversion intensity begins to weaken, and lapse conditions have now spread to the 400' level by early morning, if un-adjusted data is considered, or to 810', if adjusted data is used or the 600' level ignored and the 400 - 810' layer used. Inversion intensity appears weakest in May and lapse conditions are present for most of the day.

In June, the nocturnal inversion intensity begins to strengthen once again but is quickly destroyed in the morning hours. There is a
dramatic change between 0600 hours and 0900 hours as daytime lapse conditions are quickly established at all levels. The development of the 200 - 400' inversion in the evening is clearly shown between 1800 to 2300 hours as first the 35 - 200' layer is affected, followed by a steady moving of the 200 - 400' lapse to the right. Similar conditions are evident in the July and August traces. Nighttime inversion intensity has increased and reached a secondary peak by August. The decay of this inversion occurs between 0600 and 0800 to 0900 hours and is visually dramatic. From September on, conditions are very similar to the changes in the spring but are in the reverse order.

5.3.2 Mean Monthly and Yearly Values of the Lapse Rate

The hourly temperature lapse rates given in Tables 5.40 to 5.51 are summarized in Table 5.54 which shows the mean values of lapse rate over 10 height intervals for each month.

The January results show that the mean temperature at all levels except the 600 - 810' level (which must be treated with caution) is an inversion. The first four columns show that the inversion intensity decreases with increasing height.

This pattern continues to March with the average intensity of inversions increasing in the 35 - 200' and 200 - 400' layers, and decreasing in the 400 - 600' to 600 - 810' layers. There is an abrupt change in April when mean values sharply decrease and the variation with height is less extreme. This continues into May before average inversion intensity starts increasing again to a secondary peak in August in the lower layers.

The average positive lapse rate intensity in the upper layers increases steadily from December to July. From September to December,
there is a slight decrease in inversion intensity as lapse rates tend more positive. At higher levels lapse rates tend more negative to inversion conditions. On all levels, all months average, the mean annual lapse rate is $-1.5^\circ F./1000'$.

The surface layer experiences an inversion of $6.7^\circ F./1000'$, the 200 - 400' layer a $1.1^\circ F./1000'$ inversion, the 400 - 600' layer a $2.6^\circ F./1000'$ inversion, and the 600 - 810' layer a $+3.0^\circ F./1000'$ lapse rate. These two latter values should be treated with caution. The 400 - 810' lapse rate is $+0.2^\circ F./1000'$. Inversion conditions were therefore typical at lower levels, with weak lapse rates or isothermal conditions on average at the highest level. These results should be compared to those of Flower (1937) at Ismailia, Egypt, Best et al. (1952) in England (table 5.55), and Goff and Hudson (1972) in Oklahoma (table 5.56). Table 5.57 provides a four way comparison for the two lower tower layers. The Winnipeg data shows stronger inversions than the other three.
5.4 Average and Maximum Values of Positive Lapse Rates

5.4.1 Introduction

This section considers only positive lapse rates. Maximum and average values during inversions will be looked at in more detail in chapter six due to their implications in the air pollution field.

Tables 5.58 to 5.61 list the maximum and average inversions for each of the 27 months sampled. Only selected levels are examined. Table 5.62 summarizes the information on maxima and looks at all 10 levels.

5.4.2 Maximum Values

In examining extremes it is difficult to come up with any conclusive evidence from a 27 month sample due to the great variability, and the following discussion should be read with this in mind.

In the 35 - 200' layer, the maximum values of the lapse vary from 15.1°F. per 1000 feet in February to 14.1°F./1000' in December, that is from 3 to 8 times the D.A.L.R. Eight of the 27 monthly extremes occur at 1300 hours, 3 at 11, 3 at 12, 4 at 10 - 11, 4 at 15 - 16, 3 at 8 - 9 and 2 at night. Considerable dispersion is thus evident in the diurnal distribution of maximum values. This is also true on a year to year and within year basis (see Tables 5.58 to 5.61).

Values in the 200 - 1000' layer vary from 5.8°F./1000' in April to 23.1°F./1000' in June, corresponding to one and a half to just over four times the D.A.L.R. A reduction in maximum values with increasing height is thus apparent.
The diurnal distribution of maximum values is as follows:
2 at 8, 6 at 10 - 11, 5 at 12, 2 at 13, 5 at 14, and 7 at night.
In both the 35 - 200' and 200 - 400' layers we have two thirds the maxima grouped in the two hour period on either side of noon, as would be expected. The nighttime frequency has increased however at the higher level. Values in the 200 - 400' layer are much more consistent between one year and the next. An annual cycle is just visible with a low in winter rising to a June to September summer peak, followed by a slight decrease in September before a rapid fall-off to December to January to February.

In the 400 - 810' level the range varies from 5.0 to 14.7°F./1000', that is from less than the D.A.L.R. to 2.75 times the D.A.L.R. The ratio of the highest of the maximum values to the lowest of the maximum values remains high but the actual values have decreased further at this higher level. Values in the cooler months are generally more consistent from one year to the next but great variations are evident in Spring and Autumn. The diurnal distribution of the maximum values is as follows: 3 at 10 - 11, 4 at 12, 7 at 13, 4 at 14, 2 at 15 - 17, 3 at 18 - 19, and 4 at night. Some of the values in the 400 - 810' layer are exceptionally high and were the subject of careful investigation. They were found to occur during frontal situations or during thunderstorms.

5.4.3 Average Values of Positive Lapse Rate

The average values in the 35 - 200' layer vary from 3.8°F./1000' in January, 1970 to 9.8°F./1000' in August, 1970. The minimum tends to occur in winter (December to February) and to steadily increase to a maximum in August. Fifteen of the 27 monthly values are greater than the D.A.L.R.
In the 200 - 400' layer the values increase from 2.3°F./1000' in April to 5.7°F./1000' in June. Only five of the 27 values are greater than the D.A.L.R. Great variation is evident from one year to the next, for example May varies from 3.3 to 5.6°F./1000'. This may not appear too much but it takes May from second lowest to second highest in the 27 month sample.

In the 400 - 810' layer the values continue to decline with no values greater than 0.8 times the D.A.L.R. The range varies from 2.2°F. in April, 1970 to 4.3°F./1000' in May, '1971.

In short the results show a decrease in the average value of the lapse rate with increasing height and great variations from one year to the next especially in spring.

5.5 Mean Diurnal Variation of Temperature at 5 Heights

The diurnal variation of temperature at 5 heights for each month of the year based on the period October 1969 to December 1971 is shown in Figures 5.16 to 5.19.

It will be seen that certain features are characteristic of all these curves. For instance the actual temperature at which the four curves cross is considerably higher in the evening than in the morning; the time interval between the 35 - 200' crossing, and the 200 - 400' crossing, to take two examples is shorter in the morning than in the evening. The increase of temperature during the morning is much more rapid than the decrease in the evening, especially during the winter months, whilst during the night the decrease in temperature is faster at lower levels than at higher levels.

Temperatures at 35' begin to rise from just before to just
after sunrise, but there is a delay with increasing height. Data between successive hourly ten minute averages has not been analyzed and the resolution is coarse. The general picture does however emerge. In January sunrise is at 0822 (Table 5.65, last column) and the temperature starts rising at the 35' level between 7 and 8, at the 200', 400', 600' levels between 11 and 12, and at 810' between 12 and 1. At all levels in January there is a kink in the temperature curves with temperatures increasing slightly around sunrise before stabilizing once again at all levels except the 35' level. This kink is also present in February.

In July sunrise occurs at 0436 and temperatures then begin to rise with a delay depending upon height. The 35' temperature rises between 4 and 5, the 200' one between 5 and 6, the 400' one between 6 and 7, the 600' one between 7 and 8, and the 810' one between 0800 and 0900 hours. This is a much more progressive rise than is the case in January when conditions slowly build up in the 35 - 200' layer before pushing through to the 200, 400, and 600' levels with little or no delay.

Several hours of insolation are therefore needed before the effects of heating are observed at higher levels. A thin layer nearest the ground is heated very quickly after sunrise, reversing the pre-sunrise inversion. This is accompanied by molecular heat transfer (conduction). Conduction processes, however, have a very small vertical scale and give way to convection a short distance above the surface. Convection is responsible for transporting heat higher into the planetary boundary layer. The greater the height of the layer heated the slower the heating since the convective mixing process spreads heat over a large vertical extent and only a small amount is contributed to a given height (Goff and Hudson, 1972).
Heating above the surface lags the initial heating at the surface, and the lag is a function of height and of season being five hours in winter and four in summer between 35' and 810'. Gol'tsberg (1967) reports a time differential of two hours in the warm season and four hours in the cold season. His data are taken from the work of Selikskaya (1962) at Voekikova, U.S.S.R.

The January curve brings out the contrast in the diurnal cycle with height quite clearly. At the 35' level the typical diurnal cycle is apparent with lower temperatures at night rising in a curve to the highest temperatures in the afternoon before decreasing again in late afternoon, evening. The amplitude of the diurnal cycle decreases quickly from 35' (5.4°F.) to 200' (3.3°F.), to 400' (2.0°F.). At levels above 400' there is little change in the diurnal cycle with height. (1.9 at 600', 2.1 at 810'). This is also shown in Table 5.63 - Diurnal Variation of Temperature with Height. Minimum temperatures at 35' occur at 0700 hours, whilst higher levels have their minima at 1100 hours. (Table 5.33) January maxima are delayed with height (Table 5.14) with the 35' level maximum occurring at 1500 hours and the 200 and 400 foot levels occurring at 1600 hours. The 600 and 810 foot levels are considerably delayed with maxima occurring at 0100 hours.

In February, the sun is higher in the sky and daytime temperatures rise considerably. The diurnal cycle is more pronounced, and decreases with height to 810'. There is now more evidence of phase shift in the diurnal temperature cycle in the lower three layers. Maxima occur at 1600 hours at 35', 1800 hours at 200', 2100 hours at 400', 600' and 810'. Minimum temperatures now experience a delay with increasing height to 600' (Table 5.65).
This tendency to a larger diurnal range in temperature with the range decreasing with height continues in March and April and takes a large jump in May (Figures 5.16, 5.17, Table 5.63). By now there is little difference in the time of occurrence of the maximum with height (Table 5.61). This continues into June when maximum values occur at 1600 hours at all heights. Minimum temperatures at this time are still substantially delayed with increasing height from 0500 hours at 35' to 0800 hours at 810'. As summer is established and the land mass is heated up, the curves begin to become less peaked at their maxima and to broaden out as in July and even more so in August when conditions from 1200 to 1600 hours show little change. This long warm period of relatively constant temperatures disappears in September and conditions then become a reversal of the January to April progression.

In general conditions are similar to those observed elsewhere. Goff and Hudson (1972) found surface temperatures to range from 43.1°F. at 0600 hours to 61.8°F. at 1500 hours. At 1450' mean temperatures ranged from 47.1°F. at 1000 hours to 52.3°F. at 1600 hours, a reduction in the diurnal variation from 18.7°F. to 5.2°F. This was accompanied by a shift in the phase of the temperature wave as reported by Sutton (1953) and others. Best et al. (1952, page 25) results also confirm this.
This chapter has examined the frequency of occurrence of lapse rates of different magnitudes, the mean hourly values of temperature gradient, the maximum values of positive lapse rates and the mean variation in temperature at 5 levels.

Lapse rate frequencies show increased grouping towards weak lapse conditions with increasing height and the extremes are much less severe. Superadiabatic conditions increase sharply from March to April and from May to June. The autumn decrease occurs around October to November. Inversion conditions show a maximum in winter to early spring.

The percentage occurrence of superadiabatics decreases rapidly with increasing height in winter but there is little change in summer in the sampling layers. The maximum percentage with inversions decreases with increasing height in summer and occurs later in the night, unlike superadiabatics when there is little delay with height in the maxima. In winter the position is similar with decreases in the maximum percentage with inversions with increasing height. The delay in the maximum with increasing height is less clearly evident than in the summer especially during the period December to February.

Values for the average lapse rate vary greatly. Winter midday lapse rates are less than the D.A.L.R., whilst summer conditions reach twice the D.A.L.R. The morning changeover to positive lapse rates occurs quickly especially in summer. Maximum values of the average lapse rate are delayed with increasing height in winter. The summer position is not clear.
The annual average lapse rate for the year is an inversion close to the ground with neutral conditions at higher levels.

Maximum values of positive lapse rates show very great variations and can reach values of 8 times the D.A.L.R. at the lowest level, before decreasing quickly with increased height. Maximum values also exhibit great variations from year to year especially in the spring.

The curves of diurnal variation of actual temperature with height show certain characteristic features:

(1) The actual temperature at which the four curves cross is higher in the evening than in the morning.
(2) The increase of temperature in the morning is faster than the decrease in the afternoon, especially in the winter.
(3) The decrease of temperature at night is faster at lower levels than at higher levels.
(4) The diurnal cycle of temperature decreases quickly to 400' and then changes relatively slowly in the next 400'.
(5) Minimum temperatures are delayed with increasing height in the winter half of the year.

The above results are in line with the earlier work of Best et al. (1952), Goff and Hudson (1972) and Gol'tsberg (1967).

The next chapter (c.6) will examine negative lapse rates (inversions) in much more detail, whilst chapter 7 will attempt to relate lapse rates to air masses.
CHAPTER FIVE

Notes and References

1. Lapse rates were computed by determining the temperature difference (\(^\circ\)F) per 1000' between two levels. The same definition applies throughout this thesis.

2. The value of the lapse rate in D.A.L.R. units was calculated as follows:

   If a lapse rate has a value of \(-27.2^\circ\)F/1000' it is divided by 5.4 (the D.A.L.R. value) to give a value of \(-5.04\) times the D.A.L.R. It is then entered as 1 count in the -5 to -5.5 row for the appropriate hour of the day. At the end of the month, all hours are added up to give total counts for that hour, and all lapse rate intervals are added up to give totals for the lapse rate interval. Finally, percentages are calculated by multiplying the lapse rate interval count by 100 and by dividing it by the total count for the hour.

3. The table was obtained by examining each hour's data for the month, and adding one to the count if the lapse rate has <0. The total count was then multiplied by 100 and divided by the total count for the month to obtain the percentage.

4. The tables were obtained by dividing the day into 12 two hour periods. Tallies were then kept of the number of observations within the two hour periods in the month, and of the number of observations of inversions and superadiabatics. The data was then examined to find the maximum percentages of superadiabatics and inversions in the month for the 12 two hour periods. Examples of this can be seen in Tables 5.1 to 5.20. Tables 5.26 and 5.27 abstract the data from all 120 tables to produce tables of the maximum percentage of superadiabatics by 12 two hour periods for the three selected levels during all 12 months.

5. Transition periods occur after sunrise or sunset when the boundary layer is adjusting to the addition of or loss of radiant energy. The transition period after sunrise is most conspicuous.

6. Figures 5.7 to 5.12 are based upon the average of 60 - 90 readings which are available for each hour in each of the 12 months. One inch of displacement in the X axis for any given hour represents 5.5°F. For clarity, each successive hour has been displaced just over 0.2° to the next.

7. Tables 5.58 to 5.61 were obtained by scanning each hour's data for the month and finding the maximum value and the time of maximum.
Averages were obtained by adding up all the positive lapse rates during the month and dividing them by the total frequency to obtain the average.

8. $0.3^\circ F./1000'$ inversion with a $-0.6^\circ F.$ correction applied to the 600' temperature.

9. Isothermal conditions with a $-0.6^\circ F.$ correction applied to the 600' temperature.
CHAPTER SIX

Frequency, Duration, and Intensity of Inversions

6.1 Introduction

This chapter follows on from the previous one, by examining inversions in much greater detail, due to their importance in the dispersal of air pollutants. Little work has been done on inversions, especially in terms of their intensity, duration, and relation to weather elements. Munn (in I.J.C., 1960, page 164) looked at the seasonal and annual frequency, and to a lesser extent, the duration of inversions, at an 870' suburban/rural instrumented television tower in Detroit, U.S.A. from 1955 to 1957. Baker et al. (1969) examined the frequency, duration, time of commencement, and intensity of inversions at Minneapolis - St. Paul. Their study was based upon 70', 170' and 500' temperatures taken on an urban tower from 1961 to 1968. Data are presented in such a way that individual layers cannot be examined. A more recent study by Goff and Hudson (1972) has recently come to the authors attention (June, 1974). This study analyzed a six month sample from the 1450' Oklahoma City instrumented television tower. Inversions were examined in terms of frequency, persistence, and relation to wind, cloud cover and air masses. This is similar to, although less comprehensive, than the analysis of inversions, in terms of observed weather elements, developed by the author, and reported in chapters seven and nine.
The current chapter uses two main methods to determine inversion frequency. The first method was used in Canada when cost considerations necessitated the use of a small (32k) computer to examine the data. The small core size imposed severe programming restrictions and hence analysis had to be done using many small programs which looked at one months data at a time. Similar months were then summed and averaged. In all, twenty-seven months of data were analyzed.

The following information was calculated for one ten minute average per hour: 1) the number of inversions ≤ 2 hours 2) the duration of these inversions 3) the average intensity of the inversions 4) the maximum intensity of the inversions.

The second method was used at Edinburgh using a large computer. All inversion hours were calculated not just those ≤ 2 hours as above. Frequencies and maxima were calculated for the entire sampling period and for each season. These could also be looked at by wind speed and direction. Compound conditions could also be examined such as upper and lower inversions present with north winds of 4 to 9 m.p.h. A total of 33 months of data were examined. Table 4.1 presents details of equipment failure during the sampling period.

Tables 6.1^1, 6.2^2 and 6.6 to 6.18^3 are based upon the earlier 27 month sampling period, whilst Tables 6.3^4, 6.4^5 and 6.22 to 6.25^6 are based upon the 33 month sample as are figures 6.1 to 6.11.

Table 6.3 and 6.4 not only look at the number of hours with inversions in each layer (types 1 to 10) but also look at compound conditions (types 11 to 15). Details of the compound conditions follow:

Type 11 - Ground inversion, weak lapse aloft. 35 to 200' lapse rate < 0 and 200 to 810' lapse between 0 and 5.4°F./1000'.


Type 12 - Ground inversion, adiabatic aloft. 35 to 200' lapse < 0 and 200 to 400' or 400 to 600' or 600 to 810' lapse 5.4°F./1000'.

Type 13 - Upper inversion but not in the 35 to 200' layer (weak lapse below). 0 < 35 to 200' < 5.4°F./1000' and 200 to 400' or 400 to 600' or 600 to 810' lapse rate < 0°F./1000'.

Type 14 - Upper inversion, 35 to 200' superadiabatic. 35 to 200' < 5.4°F./1000' and 200 to 400' or 400 to 600' or 600 to 810' < 0°F./1000'.

Type 15 - Ground and upper inversion. 35 to 200' < 0 and 200 to 400' > 0 and 400 to 600 or 600 to 810' < 0°F./1000' or 35 to 400' < 0 and 400 to 600' > 0 and 600 to 810' < 0°F./1000'.

These categories are similar to those of Munn (in I.J.C., 1960, page 169 to 171). Section 6.2 has been modelled upon Munn's study whilst parts of 6.3 and 6.4 follow Baker et al.'s study.

6.2 Frequency of Inversions

6.2.1 Total Frequency of Occurrence

The frequency of inversions for the 35 - 200', 200 - 400', 400 - 810' and 35 - 810' layers for the period October 1969 to July 1972 are shown in Figure 6.1. The outstanding feature of this curve is the inverse normal type distribution with the lower layers showing greater variation about the mean. In the 35 - 810' and 35 - 200' layers at night (00 to 05 hours) approximately 75% of all occasions experience inversion conditions. This drops to 60% in the 200 - 400' layer and to 55% in the 400 - 810' layer, that is, a decrease with increasing height above the ground.
In late afternoon the heat loss starts at lower levels and then spreads to higher ones from the ground up. 35 - 200' inversions increase quickly, and surpass the 200 - 400' frequency at 15.15 hours, and the 35 - 810' and 400 - 810' frequencies at 1600 hours. The 35 - 810' inversion frequency is strongly influenced by the 35 - 200' frequency and follows it with a lag of approximately 75 minutes throughout the evening period. The 200 - 400' trace crosses the 400 - 810' trace at 1730 hours and the lag with the 35 - 200' and 35 - 810' layers steadily increases throughout the night.

There is a rapid increase in the number of inversions throughout the evening-early night period. The gradient is steeper at lower levels. The maximum frequency of inversions is delayed with height. In the 35 - 200' layer the maximum occurs between 2300 and 0100 hours; in the 35 - 810' layer it occurs at 0400 hours; in the 200 - 400' layer it occurs at 0500 hours, whilst in the 400 - 810' layer it occurs at 0700 hours. The 35 - 810' inversion frequency exceeds the 35 - 200' frequency at 0200 hours and remains at a higher level until afternoon. At about 0500 - 0600 hours the gradient increases again and there is a rapid decrease until late morning. The gradient is similar at all levels from about 0700 to 0900 hours and then it begins to decrease, first at the lower level, followed by the 200 - 400' and 35 - 810' levels, and finally the 400 - 810' level. The minimum frequency is delayed with increasing height and occurs as follows: 35 - 200', 1300 hours; 200 - 400', 1400 hours; 35 - 810', 1500 hours; 400 - 810', 1600 hours.

The curves of the annual frequencies of inversion types 11, 12, 13 and 15 are shown in Figure 6.2. These four types will now be discussed in detail.
Type 11, Ground Inversion but not to 810' (weak lapse aloft).

The minimum occurs by day when ground heating destroys the surface inversion on 98% of all days. As the sun dips in the afternoon inversion frequency increases in the 35 - 200' layer in mid-afternoon in winter (1400 hours) and early evening in summer (1800 hours). (See Figure 6.3 for diurnal variation of 35 - 200' inversions). Suitable ground inversion conditions therefore occur from 1500 to 1800 hours in winter and from 1800 to 2200 hours in summer. Conditions lie between these two periods in spring and autumn.

In winter upper air conditions show weak lapse rates in late afternoon whilst in summer weak lapse conditions appear later, resulting in a steady rise in the frequency of the feature from 1300 hours (and more so from 1600 hours) to 2100 hours. From 2100 hours on, the 200 - 810' lapse rate is now turning negative, with the result that the frequency of this feature declines rapidly throughout the night to a low just after noon.

Type 12 Ground Inversion, Adiabatic Aloft.

The maximum occurs in late afternoon - early evening when 35 - 200' inversions have formed and 200 - 400' superadiabatics have not yet cooled down. This occurs on about 12% of all occasions. The secondary peak in early morning is associated with 600 - 810' superadiabatics. One would expect positive lapse rates at this time but not superadiabatics so it may be that the -0.6°F. correction is slightly low or that the error is not totally systematic.

Type 13 - Upper Inversion but not in the 35 - 200' Layer (weak lapse below)

The maximum occurs about 0700 hours, just after sunrise, and is explained by the disappearance of the inversion near the ground.
Thirty percent of summer occurrences take place from 0600 to 0700 hours and contribute to one third of the peak. In winter the distribution is much more uniform during the day as the sun is not nearly so successful in breaking down inversions. Spring and autumn show a definite morning peak but not nearly as high as summer. Figure 6.9 shows the seasonal variation of percent frequency of hourly occurrence.

Type 15 - Ground and Upper Inversion

The minimum occurs during the day since ground inversions are burned off in most seasons as the sun gets higher in the sky. In winter ground inversions form again in mid-afternoon but intermediate layers still show weak lapse conditions, whilst upper layers remain negative, resulting in a gradual rise of type 15 frequencies from 1500 hours on.

In summer ground inversions form later starting around 1800 hours and hence there is a secondary rise in type 15 frequencies from 1800 hours on. Spring and autumn conditions lie between the two extremes. Frequencies decrease from the 2200 hour high to the noon minimum. The above results are in accord with those of Munn (in I.J.C. 1960, page 169 to 171).

6.2.2 Percent Frequency of Occurrence

The percent frequency of hours with inversions \(< 2\) hours is presented in Table 6.2. This shows that the percentage of hours with surface inversion conditions experiences an annual cycle with two peaks. The primary one occurs in February (57.3%), whilst the secondary one occurs in August (47.3%). The primary minimum occurs in May with 32.3%, whilst the secondary minimum occurs in December (32.8%).

The 200 - 400' level also has a double peak with a winter maximum in
January (46.1%) and a summer maximum in August (36.4%). The primary minimum occurs in May with 19.2%, whilst the secondary minimum occurs in November with 26.2%. The percentage frequency of inversions thus decreases with increasing height in the lower 400' and the winter/spring maximum and minimum are one month earlier.

Conditions in the 400 - 810' layer are much more complex. Percentage frequencies are lower than in the 200 - 400' layer for the eight months March to October but are higher in the winter third of the year. A double cycle is present with a primary winter maximum in January (18.1%) and a weak summer maximum in September (26.1%). The primary minimum occurs in May and the secondary one occurs in October. The percentage frequency of inversions thus decreases with height except in winter when the decrease is to 400' and an increase is experienced in the 400 - 810' layer. This is confirmed in Table 6.3 which uses the 33 month sampling period and presents the data by season. If the corrected data of Table 6.4 is used, then the decrease in frequency with increasing height occurs to 810' in summer and autumn, and to 600' in winter and spring.

This is as would be expected. In summer extreme conditions are experienced near the ground with rapid cooling in late afternoon resulting in long periods of nighttime inversions. The upper air on the other hand heats up quickly in the morning but cools down slowly in the afternoon and early evening. In winter, daytime heating does not take place to 810' on all days and upper inversions are common. Nights are long and surface inversions are also present for long periods of time resulting in a decrease in frequency from the surface to intermediate levels and then an increase again as the effect of daytime surface heating becomes minimal.
The late winter early spring primary peak is the result of the cooling down of the continent throughout the winter coupled with the long nights and low sun angles that prevail at this latitude. The secondary summer peak is especially prominent at lower levels and is caused by the rapid emission of long wave radiation during the hot afternoons not being balanced by the late afternoon short wave radiation. Surface cooling is thus rapid and inversion conditions prevail from 1600 - 1800 hours to 0500 hours. The secondary peak reduces in amplitude due to the slower cooling in the upper layers. For example the 400 - 610' layer experiences inversion conditions in summer about two hours later than the surface layer.

The percentage of inversions also fits the general streamline pattern around Winnipeg as outlined by Bryson and Sands and summarized in Chapter Three.

A minimum in the inversion frequency exists in October, November and December. The general airflow at this time is cyclonic westerly from northern Montana and southern Alberta.

By January the airflow is veering and has reached northwesterly by February. At this time there are four times as many anticyclones as cyclones. The veering of airflow continues in February and by March and April the main streamlines are from the north (Bryson, 1966). Airflow in May is north-northeasterly associated with feature 103 (Sands 1966). Airflow then backs to northerly in June and back to cyclonic westerly mP or southerly mT in July and August. A westerly airflow then returns in September.

Sands (1966) has identified certain cyclonic and anticyclonic features in the Winnipeg area (Table 6.57). High pressure features are less common in October.
There is a slight rise in December and January before the high becomes more important in late winter and spring. Highs will generally give more inversions in winter than lows since they are usually associated with lower cloud and drier air as well as exception-ally low temperatures. In addition inversion conditions usually extend to several 1000 feet with only the lower few hundred subject to surface daytime heating. In late spring and summer however, highs usually give weak lapse or superadiabatic conditions in the lower 1000 feet, as they are warmed by the warmer land surface on moving south, or by strong solar radiation by day.

The above results for the average annual percentage frequency with inversions in the lower 400' near Winnipeg are much higher than those found by Baker et al. (1969) in Minneapolis to St. Paul (42.6% versus 28.0%). This is not surprising when one considers the urban location of the tower and the height of the lowest sensor (70'). Some similarity does exist in the seasonal distribution of inversion frequency. The primary maximum occurred near Winnipeg in January and the secondary maximum occurred in August. The Minneapolis data show a primary maximum in August and a secondary maximum in February. Primary and secondary minima occurred in Winnipeg and Minneapolis to St. Paul in May and October, and December and April respectively. These results are in marked contrast to those of Munn (in I.J.C. 1960) for Detroit. He found an average of only 16% inversions in the 20 - 870' layer (in contrast to 43.3% for the 35 - 810' layer near Winnipeg). Such contrasts are not surprising however when one considers the large differences in the macroclimate between the two areas.

6.2.3 Diurnal Variation of Inversions By Season

The occurrence of inversions by hour of day and month for the three selected levels, 35 - 200', 200 - 400' and 400 - 810' is presented
in Tables 6.6 to 6.8. The actual number of inversions must not be compared from one month to the next due to variations in sampling.

The time of the maximum percentage occurrence of 35 - 200' inversions occurs at 1700 hours in November when approximately one third of all inversions form during this one hour. This is delayed by one hour in late winter early spring, to 1900 hours in April, and to 2000 hours from May to August. In May over half of all inversions form at 2000 hours. A pronounced cycle is in evidence especially in summer when few inversions form in the 0400 to 1600 hour period.

The pattern of the time of formation of most of the inversions in the 200 - 400' layer is not as clear but inversions form earliest in the July - August period (2100 hours) and latest in May to June. The winter period experiences a wide distribution in the time of occurrence of inversions, whilst the diurnal variation in summer experiences a pronounced nocturnal maximum. The distribution in the higher 400 - 810' layer continues this trend to greater dispersion, and hours experiencing no inversion formation are much fewer.

The percentage frequency of 35 - 200' inversions by hour and season is shown in Figure 6.3. The curve appears as an inverse normal or flattened inverse normal curve. In winter inversion conditions last longer and hence the maximum values of the curve are lower than in autumn or spring, which in turn are lower than in summer. This is because Summer has more daylight hours almost inversion free (<0.25% of the total).

In winter inversion frequency is fairly constant at night (2200 to 0800 hours). From 0800 hours to 1300 - 1400 hours there is a steady fall in the percent frequency. At 1500 hours there is a rapid rise to 1700 hours, followed by a much slower rise to 2000 hours.
hours before stabilization and a slight fall from 2200 to 0800 hours.

In the autumn spring period the burnoff of nocturnal inversions occurs earlier in the morning (0600 hours), and much more rapidly due to the much stronger sun. The curve reaches its minimum earlier and remains there a few hours before climbing to the nighttime maximum one to two hours behind the winter situation.

Summer experiences the greatest variation between highs and lows. A rapid fall occurs in the percentage frequency about 0500 hours. By 0800 hours the percentage frequency is down to < 0.25% and this lasts eight hours to 1600 hours. From 1600 to 1800 hours there is only a slight increase (to 1%), but at 1800 hours the steep rise commences and by 2000 hours 8% of inversion conditions in the layer take place at this hour.

The higher 200 - 400' level experiences a delay in the time of occurrence of inversions (Figure 6.5). In winter the maximum occurs at 1600 hours in contrast to 1300 - 1400 hours in the lower layer. The peak occurs at 2200 hours in contrast to 2000 hours in the lower layer. The features are, however, generally similar to those of the 35 - 200' layer. In winter, for example, both experience a long nighttime period with 5 - 5% frequency of occurrence/hour, followed by a steady fall in percentage occurrence to the post noon minimum. Afternoon conditions in the 200 - 400' layer are not quite as extreme with a 1.75% frequency of occurrence versus a 0.75% frequency of occurrence at the lower level.

On a seasonal basis summer conditions show the greatest range in the 200 - 400' layer as well as the lower 35 - 200' layer. The range of percent frequency of occurrence varies from 0.25% to 10.25% as against 0.25% to 9% in the 35 - 200' layer.
The 400 - 810' layer winter curve (figure 6.6) shows a further decrease in amplitude from the 200 - 400' layer and even more from the 35 - 200' layer. The maximum is further delayed at this higher level and occurs at 0700 hours against 2000 hours in the lowest layer and 2200 hours in the next lowest layer. The morning maximum will be helped by convective lifting of surface inversions. The minimum occurs at 1900 hours as against 1600 and 1400 hours at the lower levels.

In summer the maximum percent occurrence of inversions takes place at 0400 hours (11%) against 0500 hours (10.25%) in the 200 - 400' layer, and 0400 hours (9%) in the 35 - 200' layer. There is, however, a much shorter period with a high percentage at night. The 400 - 810' layer graph is much more peaked than the 200 - 400' graph which in turn is more peaked than the 35 - 200' layer graph. The late afternoon/evening rise is steeper than the 200 - 400' p.m. rise which in turn is steeper than the 35 - 200' increase.

The 35 - 810' curve (figure 6.4) shows many of the features of the 35 - 200' layer, such as the long relatively flat section from 2200 hours to 05-0700 hours. The daytime curve is similar to the intermediate layer.

The type 11 profile - Ground inversion but not to 810 (weak lapse aloft) - shows a minimum during the day when ground inversions are rarely present (figure 6.7). No occasions exist between 0900 and 1100 hours in summer. The main rise in percent frequency occurs in late afternoon/early evening. The actual time varies with season and in winter occurs from 1500 to the peak at 1800 hours; in autumn it is from 1600 to 1900 hours; in spring from 1700 to 2000 hours and in summer from 1800 to 2100 hours. The autumn situation is closer to winter, whilst the spring one is closer to summer.
This is explained by the partitioning of the seasons. Spring occurs from March to May, whilst autumn occurs from September to November, that is, further from the summer solstice.

There is a pronounced break of slope in the morning profile in summer between 0400 and 0500 hours. In spring the break of slope occurs from 0600 to 0700 and is slight in contrast to autumn when a pronounced break occurs from 0400 to 0700 hours. In winter there is a slight rise. This break of slope is caused when morning conditions change from inversion to weak lapse. This occurs earlier and faster in summer and slower in winter, when a secondary peak occurs.

The type 13 profile - upper inversion, 35 - 200' weak lapse is shown in figure 6.9. The winter curve shows the least diurnal variation since upper layer conditions show inversions for much of the time. Weak lapse conditions at the surface cause the greatest variation in the curve. The maximum occurs at 1000 or 1100 hours as surface ground inversion conditions are replaced by weak lapse conditions. This occurs slowly since the sun is very weak at this time of the year. The minimum occurs at 2000 hours, the time of occurrence of the 35 - 200' maximum (see figure 6.1).

The autumn and spring peaks occur earlier and are more pronounced. The spring peak occurs earlier as in the type 11 feature. The autumn peak is higher because the land surface is much warmer than in spring and the changeover from inversion to superadiabatic conditions is consequently much faster. The warmer land also results in a lower and earlier autumn minimum.

The summer morning peak is by far the most pronounced because the sun is highest and the land warmest. Weak lapse conditions therefore occur over a much shorter time. There is a very rapid falloff
in the morning and by 1000 hours a secondary low occurs. The secondary
maximum occurs at 2000 hours as lapse rates move from superadiabatic
to neutral in the surface layer (see figure 5.11 for the July case).
The minimum occurs at 2200 hours when the 35 - 200' inversion frequency
is highest.

The type 14 profile - upper inversion, 35 - 200' superadiabatic
is shown in figure 6.10. The morning peak occurs later than in the
type 13, since lower layer conditions have to be superadiabatic
rather than neutral. Spring conditions occur earlier in the day than
autumn conditions, as in earlier profiles, due to the greater proximity
of the spring sampling period to the summer solstice. The autumn peak
is higher because the land is warmer and superadiabatic conditions and
upper layer inversion conditions occur only for a very short time.
The summer peak is highest since upper inversions are quickly destroyed
once superadiabatics occur at the surface. The winter peak occurs
latest in the day and is high because upper inversions are nearly
always present and there are only a few possible hours of ground
superadiabatics. Spring has a double peak because March is more like
winter, whilst May is more like summer. Temperatures varied from
-24°F. to +88°F. in spring during the sampling period.

The type 15 profile - ground and upper inversion, is shown in
figure 6.11. The afternoon minimum is readily apparent and is especially
well developed in summer when inversions in the 35 - 200' or 35 - 400'
layer are most uncommon. There is a sharp rise in winter from 1100
to 1700 hours followed by a decrease and stabilization before a
further rise to the peak at 2000 hours. By then most of the 35 - 200'
inversions have formed and since these contribute most to feature 15
in winter there is a fairly rapid decrease to 2300 hours, followed by
a fairly rapid decrease to 2300 hours, followed by a fairly level
profile to 0700 hours. Autumn, spring and summer peaks are later (2000, 2200, and 2200 hours respectively). A secondary morning peak is in evidence as the 600 - 810' layer goes negative. This is small in winter since the 600 - 810' layer is rarely positive after 2200 hours. It does, however, become more apparent in autumn. In spring and summer two or three secondary peaks are in evidence decreasing in height as morning approaches. These may be due to different air masses cooling to their equilibrium at different speeds or may be due to the atmosphere reaching a newer, lower, equilibrium in successive stages.

6.3 Duration of Inversions

This section discusses the average duration of inversions \(< 2\) hours. Each inversion is examined and the number of consecutive hours during which inversion conditions are present are counted. Table 6.1, summarizes the average duration of inversions by months and ten levels, and in addition gives the actual number of inversions during that month. Actual frequencies should not be compared from month to month due to variations in sampling and all data using the 600' temperature should be treated with caution.

Great variations exist in the duration of inversions during the year and from layer to layer. June, May, and July are the minimum duration periods for the 35 - 200', 200 - 400' and 400 - 810' layers, that is, roughly one month on either side of the summer solstice. From this shorter period there is a gradual increase in the duration as winter approaches with its longer nights. Maximum values are reached at different times in different layers. The primary maximum at the surface occurs in March, whilst primary maxima for the 200 - 400' and 400 - 810' layers occur in January and December respectively.
It is clear that the above table is too general to offer any detailed explanation of inversion duration since it is made up of many long and short inversions which tend to cancel each other out. Much more information becomes available on duration of inversions if the cumulative percentage frequency of the duration of inversions of different lengths is examined. This is done in Tables 6.10 to 6.19 for all 10 layers. Those involving the 600' layer should be treated with caution.

Longer inversions are present in winter than in summer in the 35 - 200' layer (Table 5.10). The period November to March is the only one with inversions >18 hours. November has more two day inversions than any other month. An abrupt jump in the length of inversions takes place from March to April. (48 - 18 hours) and again from October to November (18 - 72 hours). The maximum duration in May and June is only 14 hours.

The most frequent inversion length varies greatly throughout the year. In the November to February period short inversions (of 2, 4, or 6 hours duration) are the most common despite the fact that dark hours are longest then. An abrupt change takes place from February to March as the most frequent inversions increase from 4 to 14 hours. Values of 14 + 2 hours hold until October before a reversal to winter conditions occurs in November.

The next highest layer (200 - 400') has a long inversion period extending from November to April (Table 6.1h). This is one month longer than that of the 35 - 200' layer. During the November to April period some inversions are at least 24 hours long and in November to December there are some between 48 - 72 hours long. From April to May conditions change and long inversions are no longer at least a
a day long since the stronger sun is much more able to destroy them. Inversion durations are typically 14 ± 2 hours from May to September increasing to 16 - 18 hours in October as night lengths increase to 13 hours. The most frequent inversion length is two or four hours except in August when it is ten hours.

Long inversions in the higher 400 - 810' are present from October to March (Table 6.17). No inversion is longer than 48 hours. Inversion length in summer is 12 ± 2 hours with May and July having the shortest inversions, with a maximum of eight to ten hours. The most frequent inversions are always two to four hours long.

The pattern is somewhat similar in the entire 35 - 810' layer (Table 6.12). Long inversions extend from October to April although both April and October only have 1 long inversion each. The shortest maximum durations occur from May to July with 12 - 14 hours.

The most frequent inversion duration varies by months from two to four hours in November to December, to four to six in January and to eight in February. There is then a large jump to 16 hours in March before a further fall to four hours in April. Longer durations are then present until November with 12 hours from May to August, 14 hours in September and 16 in October.

In summary the tables exhibit the following features:

1) A period of long inversions from November to March, increasing to October to March in the 400 - 810' layer, and October to April in the 35 - 810' layer. The longest inversions generally last two to three days although there are occasions when inversions are as long as three to four days.

2) Shorter inversions are much more common than longer inversions
except in layers involving the surface layer when a seasonal cycle is evident - shorter inversions in winter and longer inversions (12 hours + 2 hours) in summer.

6.4 Averages and Maximum Intensities of Inversions

6.4.1 Average Intensities of Inversions

The distribution of the average intensity of inversions is shown in Table 6.19. Data using the 600' level should be treated with caution.

March has the strongest inversions in the lowest layer and all levels including this layer. A strong decline occurs from March to May where a secondary minimum exists in the lowest layer. There is then a rise to a secondary maximum in August, followed by a fall to the primary minimum in December.

The 200 - 400' layer experiences maxima in December (14.2°F/1000'), August (14.1°F/1000'), and March (13.0°F/1000'). Minima occur in May (8.8°F/1000'), and September (11.8°F/1000'). The extremes are smaller and the ratio of high: low inversions is 1.4 : 1 versus 1.8 : 1 in the lowest level.

The annual cycle in the 400 - 810' layer is much simpler. A steady decrease is in evidence from December to July, followed by a fairly steady increase from July to December.

The strongest surface inversions occur in March, whilst 200 - 400' inversions are almost equal in strength in December and July. The higher 400 - 810' layer has its strongest inversions in December.
6.4.2 Maximum Intensities of Inversions

The maximum intensity of inversions by levels and months is presented in Table 6.20. Data using the 600' level should be treated with caution. Extremes of inversions decrease rapidly from the lowest level to the next lowest one and that maximum inversion intensity is roughly constant in the 200 - 400' and 400 - 600' layers when the 600' temperature correction of -0.6°F. is applied. There is then a further decrease in the 600 - 810' layer.

Minimum values of maximum inversion intensity appear in December and August in the 35 - 200' layer and maximum values appear in March. Spring and Autumn have the largest inversions as would be expected since influxes of warmer mT air can then advect over a very cold land surface. In winter, mT air cannot get in due to the blocking action of the high or the westerlies and in summer the land surface is much warmer resulting in smaller advection inversions.

Values are noticeably lower in the 200 - 400' layer. The maximum still occurs in March, and November experiences a secondary maximum. The minima occur in June and July.

It is not advisable to draw any widespread conclusions from data on maximum values due to the great variation from year to year as well as from month to month. The sample size (27 months) is also much too small to examine the extremes in any great detail.

The tables are interesting however, since they give a rough idea of the maximum values of temperature difference that can exist in the lower 810'. Table 6.21 presents this information for all 10 levels, and it should be compared to figures of 17.5°F. for the 20 - 300' layer (Munn in I.J.C. 1960).
Although these are the extreme values it can be seen from Tables 6.22 to 6.24 that other large values are common.

Further information can be derived from an examination of maximum inversions during single months. If additional information is added on 35' and 810' winds, and on sky obscurity then a much better picture can be obtained of conditions during maximum inversions. Tables 6.22 to 6.24 present this information for 6 selected levels.

Maximum values vary greatly within months from year to year. The annual cycle cannot be discerned readily from this small sample. Nonetheless data of this type is valuable since it gives us some idea of the range of values and extremes that can be expected.

The most extreme values in the 35 - 200' layer are not associated with calm conditions but with light winds of 6 - 8 m.p.h. at 35' (67% of all cases). This occurs because radiation inversions cannot propagate to any great height under calm and very light wind conditions. The strongest parts of very strong inversions thus lie below the 35' level. The average wind speed associated with maximum inversions is 7.7 m.p.h. with an average wind shear of 8.5 m.p.h. between the 35' and 810' levels. Ninety-three percent of all maximum values are associated with wind shears of 15 m.p.h., whilst 67% are associated with wind shears of 10 m.p.h. Maximum inversion intensity is closely tied to sky obscurity. Approximately one half of all maximum inversions occur with 0/10th's sky obscurity and 80% occur with < 1/10th sky obscurity. Data on average winds associated with inversions for 7 selected levels is presented in Table 6.25. Wind speeds and wind shears associated with maximum inversions are higher in the higher layers except in the case of 35 - 810' wind shear associated with 400 - 600' maximum inversion data. The
strongest wind shear occurs with 600 - 810' and 35' - 810' maximum inversions. The 600 - 810' maximum inversions are also accompanied with more cloud with only 25% of the inversions occurring when sky obscurities of \( \leq \frac{1}{10} \)th exist. This indicates the reduced importance of radiation inversions at higher levels. Maximum values of inversions are also closely tied to time of day (Table 6.26).
Layers with their base at the 35' level experience most of their inversions between midnight and 0500 hours, whilst higher layers have more or almost as many maximum values in the 0600 to 1000 hour period. The two highest layers also experience some maximum inversions during the afternoon period.

6.5 Summary

This chapter has examined the frequency, duration, average and maximum intensity of inversions.

Annual averages show that the inversion intensity is high in the surface layers, and decreases with height. A delay in the maximum and minimum frequency with increasing height is also evident.

Seasonal averages show a decrease in inversion frequency throughout the sampling height in summer and autumn, with a decrease to 600' in winter and spring (using data corrected by -0.6°F. at 600').

Most inversions form in the late afternoon - early evening period, and few form during the summer in the 12 hour period 0400 to 1600 hours. Greater dispersion in the time of formation is in evidence at higher levels compared to lower levels.

Inversion durations are highest in the winter half of the year; for example, in the 35 - 200' layer, inversions greater than 18 hours duration are present from November to March. The transition from longer to shorter inversions occurs from March to April (48 to 18 hours), and the transition to longer inversions occurs from October to November (18 to 72 hours). This corresponds to the time of decay in the snow cover (March-April), and to the reestablishment of permanent snow cover (October-November) once again. Modal inversion durations are shorter in winter (2 to 6 hours), whilst March to October values
are 1½ hours to 2 hours. All higher layers experience modal inversion durations of 2 to 4 hours.

Average inversion intensities show a bimodal distribution with maxima in March and August in the lower 400', and a single annual cycle with a maximum in December/November in the upper 400'.

The March maximum affects all levels which include the 35 - 200' layer, that is the 35 - 200', 35 - 400', 35 - 600', and 35 - 810' layers, as well as the 200 - 400' layer. These layers also experience the secondary peak in August. Minima occur in May in the 200 - 400' layer and all layers which include the 35 - 200' layer. Higher levels experience a June/July minima.

Maximum inversion intensities decrease rapidly from 35 - 200' to 200 - 400'. They then remain fairly steady from 200 - 400' to 400 - 600', before further decreasing in the 600 - 810' layer.

Spring and autumn experience the largest inversion intensities, and temperature differences of up to 32.9°F. have been observed in the 35 - 810' layer, and up to 22.7°F. in the 35 - 200' layer. The maximum values vary greatly and the annual cycle is obscured due to the small sample size. Inversions at higher levels tend to be associated with higher wind speeds and higher wind shears. The most common time of the maximum is in the period 0000 to 0500 hours for the lower levels, and 0000 to 0100 hours for the upper levels.

Chapters Five and Six have presented data on lapse rates and inversions in the lower 810' on an annual, seasonal, and monthly basis. Chapter Seven will follow on from this background material and examine a few individual cases based upon airflow type, in more detail. Chapter Nine will examine the influence of weather elements upon inversions and derive a classification scheme for inversions.
CHAPTER SIX

Notes and References

1. Table 6.1 was derived by calculating the starting time and the finishing time of an inversion. The two times were then subtracted to give the duration in hours. The frequency was incremented once for each inversion regardless of length. Frequencies must not be compared from month to month since the sampling time varies (see Table 4.1).

2. Table 6.2 was obtained by multiplying the frequency by the duration in hours times 100 and dividing the result by the total number of hours sampled.

3. Tables 6.6 to 6.18 summarize data from 120 tables showing the duration of inversions by time of day and months for all ten levels. Tables 6.6 to 6.8 show the percent occurrence of 35 - 200', 200 - 400' and 400 - 810' inversions < 2 hours duration by hour of day and month. These were obtained by multiplying the frequency of inversions starting at that hour by 100 and dividing by the total number of inversions. Tables 6.9 to 6.18 show the percent time inversions are greater than or equal to a given number of hours, for any level by months, for each of the ten levels.

4. The percent hours of occurrence is obtained by multiplying the number of hours of occurrence by 100 and by dividing by the sample hours at the top of the table. Seasons last three months with winter starting in December.
5. Table 6.4 was obtained in a way identical to Table 6.3 except that the 600' ten minute temperature averages first has 0.6°F. subtracted from them to obtain figures more in accord with theory. All references to layers including the 600' level should be treated with caution. The correction has greatly reduced the frequency of type 12 inversions because the 600 - 810' superadiabatic frequency has been reduced. Type 13 and 14 inversion frequencies have decreased due to the reduction in the 400 - 600' inversion frequency. Type 15 frequencies show a marked seasonal redistribution.

6. Tables 6.22 to 6.24 show the maximum values of lapse rates by 27 individual months for eight selected levels. Table 6.20 summarizes this data and includes further data from 270 individual tables to give the maximum intensity by months for all ten levels. All inversion hours are examined during this 27 month sample. Data on cloud cover was obtained from Winnipeg International Airport, fifteen miles north-east of the tower.

7. This data refers to a six year period (approximately 180 days/month), and although these features cover only 60 - 65% of all cases, they nonetheless provide the general picture.
CHAPTER SEVEN

Vertical Temperature Gradient During
Selected Airflow Types

7.1 Introduction

The previous discussion has centred around monthly and seasonal averages of temperature and temperature gradient. An attempt will now be made to examine conditions during certain characteristic airflow types. No attempt is made to set up a classification system of airflow or airmass types for Winnipeg. Instead the generally accepted flow types of Bryson, 1966 (Table 7.1) and Sands, 1966 (see figures 3.1 to 3.11) will be used.

Bryson found that airflow types can be identified by using a number of different criteria such as maximum temperature, airmass type, and direction of flow toward the area under study.

These criteria point to westerly flow as the principal flow affecting the climate of Winnipeg, and this flow predominates in all seasons. The westerly air can be further subdivided into SW, W and NW flow.

South-westerly flow originates in the Pacific and crosses the Rockies in Washington - Oregon, moving inland via Montana before angling north-eastwards towards Minnesota. The main disturbances associated with this flow frequently pass to the south, accompanied by increased cloud amounts and a moderation of temperatures in Southern Manitoba.
Westerly flow is usually associated with Pacific air which has crossed the coast in S. British Columbia and then moved inland via S. Alberta. This is the most common airflow type and is frequently accompanied by depressions. (Figure 3.8, Table 6.5).

Northwesterly flow is more difficult to identify but frequently crosses from N. British Columbia to the Yukon before moving south-eastwards.

These features are present in all seasons. In addition there are certain features which only appear at certain times of the year.

Maritime tropical air moves in from the south and south-east in summer, whilst cooler maritime arctic air flows from the north. Cold continental arctic air comes from the north, north-east, and north-west in winter. Table 7.1 presents the generalized airflow types that will be considered in this chapter.

The data was examined by looking at a sequence of weather covering several days rather than selecting one 'typical' day. This was done since it was felt that the rapidity of change from one airflow type to the next was as important as the airflow type itself, due to the importance of the underlying surface in the formation of advection inversions or heating of the overlying air.

Most days selected occurred either in winter or in summer since airflow types were easiest to identify at these times. Spring and autumn experienced similar conditions although extreme advection inversions were frequently more severe since it was possible for example, for $mP_{nw}$ to be replaced by $mT$ for a few hours.

Secondary circulation features such as warm and cold fronts
are discussed when encountered as are smaller features such as thunderstorms.

Daily weather maps were examined for the period October 1969 to June 1972 to obtain a general impression of the main weather types. Some 75 days were selected for further analysis and from these five case studies covering 27 days in all (Table 7.2) were chosen as being reasonably representative of the features presented in Table 7.1.

All tower data presented in this chapter has been corrected by applying a -0.6°F. correction to the 600' temperature. Tower data interpretation was based upon surface and upper air charts, hourly weather reports, and monthly weather summaries. Upper air charts were not available prior to 1971 owing to cost and hourly surface weather reports for 1972 were not published at the time of analysis. Tower data was missing on a number of random occasions.
7.2 Vertical Temperature Gradients during Winter Airflow

7.2.1 Northerly and Westerly Airflow - cA and mP Air

The period 14th - 17th January, 1972 was fairly typical of a cold spell in January to February.

The period began with mP\textsubscript{NW} air being replaced by cA air on the 13th and by the 14th cA air was firmly entrenched throughout the Prairies. Surface flow was WNW05, and 810' flow was WNW25. The 850 mb. flow was due north from the Canadian Arctic Ocean.

The diurnal range was small (Figure 7.1(a)) and inversions were weak or absent (Figure 7.1(c)) and confined to the lower 200' although skies were clear. The surface inversion was not destroyed until 1000 hours but by 1200 hours the lower 400' of cA air exhibited lapse rates of 1.0 to 1.1 times the D.A.L.R., whilst the upper 400' exhibited 0.9 to 1.0 times the D.A.L.R.

A surface radiation inversion was established by 1700 hours under NW winds of 3 to 6 m.p.h. Development upwards of the inversion was slow and it was not until 2100 hours that it reached 400'. The surface inversion and 200 - 400' inversion intensified throughout the night of the 14th to 15th under clear skies but because of the light winds did not reach the 400 - 600' and 600 - 810' layers until around 0700 hours (Fig. 7.2(c)). By this time WNW flow had been replaced by southerly flow (6 m.p.h. surface, 20 m.p.h. 810') as the high over Alberta-Saskatchewan-Montana moved to the south-east of Winnipeg resulting in a northerly flow of air ahead of a warm front now appearing in Alberta. This was accompanied by a backing in the 850 mb. flow which was now westerly from southern British Columbia. It is impossible to tell whether the upper air inversions during the
period 1100 to 1300 hours were due to lifting of the surface inversion or due to warmer air advecting in at higher levels. Temperatures rose steadily throughout the afternoon and evening and lapse rates remained neutral in the warmer air (0.9 - 1.0 times the D.A.L.R. in the lower 600', 0.5 - 0.6 times the D.A.L.R. in the upper 200') due to strong winds and strong wind shear (20 - 30 m.p.h. at 35'; 40 - 65 m.p.h. at 810') in the southerly airflow.

The 16th started 23°F. warmer than the 15th, with neutral conditions due to strong winds, in all layers. Upper air advection inversions developed in the early hours of the 16th. The warm, southerly surface airflow, accompanied by cloud, continued at about 20 m.p.h. throughout the day. The resultant strong mixing in the lower 200' gave rise to neutral lapse rates with advection inversions aloft. Temperatures rose throughout the day and the 810' temperature rose from -12°F. to +38°F. a rise of some 50 F.° in 24 hours. This was accompanied by a pressure fall of 15 mb. from 101+1 to 1026 mb. Advection inversion conditions persisted throughout the day and lapse rates in the upper layers showed great fluctuations in intensity over 3 to 5 hour periods.

The period from approximately 1000 hours on the 16th to the evening of the 17th (Fig. 7.4) was a very complicated one and fairly typical of the variety of weather than can be experienced in the Winnipeg area in a brief period.

An occluded front passed through around 1700 hours on the 16th and the upper 400' lapse rate changed from inversion to neutral whilst the lower 400' tended towards inversion conditions. Westerlies then moved in for a few hours, whilst a warm front passed through during the first few hours of the 17th. This was then replaced by
colder north-westerlies and the temperature dropped some 25 F.° from 0400 to 0800 hours and snow fell. A warm front then moved through from the southwest and temperatures quickly rose 25 F.° between 0800 to 1300 hours. The south-westerly flow was then forced back by a northerly flow moving in behind the depression of the 16th. Temperatures dropped 35 F.° in the period 1300 to 2300 hours as the cold front pushed well to the south. Superadiabatic lapse rates were formed in the lower 200 to 600' due to strong surface heating. Lapse rates remained close to the D.A.L.R. throughout the 18th (Fig. 7.5) and surface inversions were retarded that night.

Conditions from 0600 to 0900 on the 17th are particularly interesting. A second warm front moved through again resulting in superadiabatic conditions in the 35 - 200' and 400 - 600' layers and inversion conditions in the 200 - 400' and 600 - 810' layers.

In summary, the weather sequence of the period 14th to 17th January, 1972 is fairly typical of deep winter conditions in the Winnipeg area. A high to the west or north-west initially results in a cold north-westerly or northerly flow. This high either decays or moves south-eastward allowing a westerly disturbance to cross the Rockies. Airflow over Manitoba then becomes southerly from a high to the south-east. This lasts until a warm front crosses the Prairies and then westerlies move in before another wave of cold northerly or north-westerly air appears from another high to the north-west.

With this sequence of weather, radiation inversions are retarded for the first day or so after the cold air has moved south. They then develop at night once the region has cooled down. By this time warm air is usually on the way and advection inversions form as this air moves in.
Period 2. cA Air 23rd to 26th January, 1972

The arctic front was well to the south of Winnipeg during the period 23 to 26th January. An occluded front accompanied by cloud and snow was moving east-south-eastwards on the 23rd from a low in S. Alberta. Once this had moved through, a ridge of high pressure located in the Yukon developed and moved south-eastwards on the 24th into Alberta-Saskatchewan attaining a pressure of 1052 mb. A low then moved north-eastwards from Colorado on the 24th/25th towards Lake Michigan and a strong northerly flow of cA air developed from the eastern side of the ridge of high pressure to behind the low over the Great Lakes.

Lapses on the 23rd lie in the range 0.9 - 1.1 D.A.L.R. except for the 600 - 810' layer where they attain 0.5 D.A.L.R. (Fig. 7.6 (c)). Winds were light north-westerly and skies were cloudy with snow falling from the occluded front between 0730 and 1530 hours. The diurnal temperature range was small (Fig. 7.6(a)) but normal in shape, and maximum temperatures were reached in late afternoon with little delay with increasing height.

A surface radiation inversion formed at 1700 hours as skies cleared and 35' temperatures dropped. It increased steadily in intensity until 2300 hours under calm conditions and 2/10th's cloud but because of the light winds did not spread to the other layers which remained neutral. The surface inversion was destroyed shortly after midnight (Fig 7.7) as calm conditions were replaced by northerly winds of 6 m.p.h. to 10 m.p.h. which lifted the inversion to the 400 - 810' layer. The inversion lasted 2 to 4 hours at this higher layer before it was destroyed by mixing.
Superadiabatic conditions were established in the lower 400' in the morning, with neutral conditions in the 400 - 810' layer as cold air, associated with a disturbance in the northern United States, pushed south, and was heated from below. This cold air was accompanied by cloud and an 8 hour period of snow commenced at 0800 hours on the 24th.

Temperatures dropped steadily throughout the day as cold north-north-westerly air moved in and lapse rates remained at about 0.9 D.A.L.R. as the air was heated from below. By 2000 hours winds were 10 m.p.h. and remained westerly 10, with clear skies, all night from the 1052 mb. high to the west.

Inversions were slow to develop due to the warming influence of the land but the surface inversion finally formed at 2000 hours (3 to 4 hours later than normal) and intensified until 2300 hours. It then weakened in the early hours of the 25th (Fig. 7.8). The 200 - 400' and 400 - 600' layers became negative between 3 and 400 hours but it was not until 0800 hours that the 600 - 810' layer turned negative.

Inversion conditions were quickly destroyed in the lower 400' but it was not until 1400 hours that the 400 - 600' layer became neutral, and 1500 hours for the 600 - 810' layer. The lower 400' attained 1 to 2 hours of D.A.L.R. conditions in early afternoon.

One and a half to two hours after 810' inversion conditions were destroyed 35 - 200' radiation inversions were forming once again under clear skies and 5 to 10 m.p.h. winds, now that the surface had cooled down. These developed rapidly and reached 600' by 2100 hours on the 25th. The position was complicated during the night because warmer subsiding air resulted in strong elevated
inversions which persisted for 44 hours. The subsidence inversion was strongest in the 400 - 600' layer. Surface and 200 - 400' inversions disappeared in the morning but the 400 - 600' inversion persisted until 1500 hours, whilst the 600 - 810' inversion remained all day. Temperatures at the 35 - 200' and 400' levels exhibited a normal type cycle but 600 and 810' temperatures continued to climb all day and did not decrease in the pm period. An examination of the general weather situation suggests that the temperature rise was due to subsidence of air and not due to horizontal advection. The pressure remained steady all day at 1042 to 1043 mb.

The period shows the importance of wind in determining the thickness of radiation inversions, and the importance of advection influences in determining the intensity of lapse rates and the duration and time of formation of radiation inversions. It also shows that inversions in the 600 - 810' layer are slow to form at night and may still exist in the morning during the period of heavy pollution emissions. The importance of subsiding air from shallow cold highs is also shown in creating elevated inversions under CA air. These could last several days if the high became well established.

Period 3. Passage of Alberta Low, 16th to 19th February, 1971

This period illustrates the sequence of changes associated with the passage of an Alberta low slightly to the north of Winnipeg.

The period began on the morning of the 16th February with southerly winds of 21 m.p.h., ahead of a warm front to the west, associated with a low over C. Saskatchewan. The sky was covered by 10/10th's Sc, St at about a 1000'. Lapse rates were neutral except for a weak inversion in the 600 - 810' layer (Fig. 7.10(c)).
The cloud base sank throughout the night and by 0600 hours was located at 500 - 600' above ground. The warm front was now immediately west of Winnipeg and rain fell through the warmer air aloft into the colder surface air giving freezing rain. The passage of the front was accompanied by a strong frontal inversion in the 400 - 810' layer at 0500 hours, in the 200 - 600' layer at 06 and 0700 hours, and in the 35 - 810' layer at 0900 hours. The 600 - 810' lapse was strongly positive from 06 to 0800 hours as the frontal boundary was crossed from the warmer to colder air. The 35 - 810' frontal inversion lasted 7 hours. After the passage of the front, lapse rates were positive throughout the morning in all but the surface layer, where either surface cooling was taking place or the cold air had still not been fully displaced. Once the warm front had passed through at 0900 hours, neutral conditions were present in all but the surface layers, throughout the afternoon. The radiation inversion started developing at 1700 hours and intensified until midnight under decreasing cloud amounts (3/10th's Ac, Ci at 1900; 0/10th's to 0000 hours). After midnight (Fig. 7.11) the inversion weakened due to advective or dynamic causes, despite the lack of cloud to 0500 hours. Cloud cover began to build up from 0500 hours as a cold front approached and by 0700 hours 8/10th's Sc, Ac was present. The front passed through at 0800 hours accompanied by strong mixing and neutral lapse rates. Winds veered westerly and north-westerly throughout the day and lapse rates remained close to adiabatic as the colder air was heated from below. Temperatures continued to fall steadily throughout the day (20°F in the 8 hours 0900 - 1700).

Cloud cover decreased from 1700 hours on and a weak ground inversion formed in the lower air under clear skies. At 2200 hours cloud amounts rapidly increased and remained until 0400
hours accompanied by light snow to midnight and snow to 0300 hours. A light surface inversion (Fig. 7.12) formed once again under 2/10th's Sc, but was destroyed during the day under relatively clear skies ($\leq$ 2/10th's) and superadiabatics were present in the lower 400'.

The night of the 18/19th was clear to midnight and less than half covered at 13,000' and above for the rest of the night. Strong radiation inversions formed now that the underlying surface had adjusted by cooling down (Fig. 7.13).

The lapse rate graph (Fig. 7.13(c)) shows great variation in intensity of inversions from one 2 to 4 hour period to the next. The 35 - 200' layer is also relatively independent of the other 3 layers which in turn have a similar pattern despite reduced amplitude and phase shifts in the higher layers.

The 19th had little cloud, north-north-easterly winds at 6 m.p.h. and was clear throughout the day, resulting in a more normal temperature cycle and diurnal range.

In short, the period demonstrates southerly winds from stagnating $m_{SW}$ air being replaced by $m_{W}$ air which in turn is replaced by Hudson's Bay air.

Daytime lapse rates are neutral in the stagnating $m_{SW}$ and the $m_{W}$ air with weak inversions at night. Superadiabatics are present in the $m$ Hudson's Bay air as it moves southwards over a warm underlying surface and first night conditions remain neutral except for a 35 - 200' inversion. This air is superadiabatic the next day in the 35 - 200' layer, and adiabatic in the 200 - 400' layer.

The upper 400' is neutral. The second night experiences strong inversions in all layers, and the second day has neutral conditions in all but the 35 - 200' layer which is superadiabatic.
7.3 Vertical Temperature Gradient during Summer Airflow

7.3.1 Period 4. mP Northerly Air, July 27th - 30th, 1971

The period 27th to 30th July, 1971 is fairly typical of an outbreak of moist mP_n air. Upper air flow at 850 mb. was from Hudson's Bay and the Canadian Arctic Ocean from 26th to 28th July and the Polar front was located well to the south of Winnipeg.

Surface winds began as southerlies from the high to the southeast, but were replaced by northerlies and north-westerlies after the cold front passed through. Winds then returned to westerly and south-westerly on the 30th as upper air westerlies were established at 850 mb. and zonal flow returned between a high to the south and a low to the north.

The 27th July began with advection conditions caused by southerly winds. The sky was overcast and it was raining due to an occluded front. A cold front then moved through in the afternoon accompanied by more rain. A steady stream of cool moist air from Hudson's Bay moved in behind this cold front giving superadiabatic lapse rates during the evening. Cloud opacity decreased from 8/10th's at 2200 and remained low for most of the night. As a result radiation inversions formed from the ground up but the intensity quickly decreased with increasing height (Fig. 7.14).

Cloud opacities rose around 0600 hours and cumulonimbus was present in the cool moist, northerly airstream as it was heated from below. Lapse rates were superadiabatic except when it was actually raining. Rain occurred periodically throughout the day and the evening rain, which lasted 4 hours, was accompanied by hail. Dips can be seen in the temperature and lapse rate profiles corresponding to this (Fig. 7.15).
The night of the 28th/29th remained cloudy and only weak inversions were formed. Lapse rates on the 29th were superadiabatic in the lower 400', and 0.8 to 0.9 D.A.L.R. in the upper 400' during a predominantly cloudy day (7 to 8/10ths Sc, St) during which temperatures rose 18°F.

Cloud opacities decreased from 1800 hours on and the wind began to back to westerly where it remained all night accompanied by 2/10ths cloud. (Cirrus at 30,000'). Strong surface inversions formed from 1900 hours on, with the 200 - 400' layer following at 0200, the 400 - 600' layer at 0500, and the 600 - 810' layer at 0800 hours. Higher inversions were weaker and lasted only three hours (400 - 600'), and 1 hour (600 - 810'). (Fig. 7.17). By the time the 600 - 810' inversion was formed, the 35 - 200' one had been destroyed and by 0900 hours all inversions were gone.

The 30th was sunny with cumulus (2 to 3/10ths) and superadiabatic lapse rates in the lower 400' as zonal westerlies were established once again with a low and its associated fronts in Alberta.

The period is typical of one where cool moist air pushes the Polar front far south in summer resulting in cloud, rain, and thunderstorms as the cooler air is warmed from below. Radiation inversions are retarded at first as the air is heated by the warmer underlying surface, and their intensity and duration decreases quickly with height. Daytime conditions are unstable in the moist air with lapse rates greater than the saturated lapse rate.

Period 5. mP and mT Air, 10th to 19th August, 1970

The period 10th to 19th August is typical of a spell of summer weather and illustrates westerly, south-westerly, and south-
easterly flow.

The Winnipeg area was covered with a westerly flow of dry Pacific air on the 10th August. Strong radiation inversions developed upward to 600' throughout the night (Fig. 7.18). Temperatures rose into the mid-eighties under mainly sunny skies resulting in superadiabatic lapse rates in the lower 400' and neutral lapse rates in the 400 - 810' layer. The night of the 10th to 11th was clear until 0400 hours and radiation inversions formed first in the surface layer and then spread to 500 - 810'. The inversions decreased in duration and intensity with increasing height and exhibited great fluctuations in intensity. The inversions were quickly destroyed at sunrise and conditions during the 11th August were typical of those during dry south-westerly flow in summer.

The temperature curve (Fig. 7.19(a)) shows nighttime inversion conditions being destroyed in the period 0700 to 0900 hours with strong heating from the ground. Surface inversions are destroyed first (0800 hours) and 600 - 810' inversions disappear one hour later. Superadiabatics are quickly established in the lower 400' with 0.9 times the D.A.L.R. in the upper layers. The maximum surface temperature occurs at 1300 hours. Higher levels follow with the 200' and 400' levels attaining their maxima at 1700 hours, and the 810' level attaining its maximum at 1800 hours. The lower level begins to cool at 1600 hours, and by 1800 hours it is cooler than all other levels. The 200' level follows one hour behind the 35' level and the 400', 600', and 810' levels all fall together. Nighttime radiation inversions follow the same sequence as on the 10th, that is, there is a decrease in the duration and intensity with increasing height.
The 12th August was similar to the 11th (Fig. 7.20). Winds veered through $330^\circ$ due to the passage of a low to the north. Cloud amounts were low all day and only built up in late afternoon when 5/10th cumulus was present due to the strong heating. Cloud amounts decreased again in early evening and nighttime radiation inversions developed as on the 10th and 11th.

Conditions changed on the 13th and a strong south-easterly flow was established. Temperatures (Fig. 7.21(a)) rise to 95°F under almost clear skies ($<1/10$ Ac, Ci). The morning inversion (Fig. 7.21(e)) is quickly destroyed, first at the lower levels and then at the higher ones (0700 hours, 35 - 200'; 0800 hours, 200 - 400'; 0840 hours, 400 - 600'; 0930 hours, 600 - 810'). Lower layer lapse rates change from $-30^\circ F./1000'$ to 2.5 times D.A.L.R. between 0600 and 0800 hours. Superadiabatic conditions (in the 35 - 200' and 200 - 400' layer) last for 7+ hours, whilst the 400 - 600' layer just exceeds the D.A.L.R. for 1 hour, and the 600 - 810' layer does not quite make it. Temperatures reach their maximum at 1500 hours at the surface and 1600 hours aloft. The lower heights then cool first followed by the next higher level. The 35' temperature trace crosses the 810' one at 1900 hours, with the 200' trace following at 1930, the 400' trace at 1940, and the 600' at 2110 hours (Fig. 7.21(c)).

The night of the 13th/14th started with light cloud and ground inversions formed quickly in most layers. At about 0200 hours the pressure started rising and cloud cover increased between 0300 and 0400 hours as a cold front passed through. This is clearly seen on the temperature trace of the morning of 14th August (Fig. 7.22(a)). A westerly flow was established with superadiabatic lapse rates in the 200 - 35' layer and 0.95 times the D.A.L.R. in
the three higher layers, as the air was strongly heated from below. The cloud cover decreased throughout the day and a radiation inversion formed at 1800 hours in the 35 - 200' layer despite the warmer surface earlier in the day.

Another cold front passed through on the night of the 14th/15th and the nocturnal inversions were destroyed (Fig. 7.23). Cloud remained high all day and in the afternoon Sc and Ac gave way to 7/10th's Cu and Cu+. Rain occurred several times during the day resulting in striking up/down pattern in the temperature and lapse rate profiles. Lapse rates were superadiabatic in the morning and early afternoon but by late afternoon they were neutral in the north-westerly airflow.

Cloud amounts decreased to 2/10th's by 2300 hours and remained low all night but despite this only a weak radiation inversion formed due to the heating by the underlying surface (Fig. 7.24). Heating was still strong during the 16th and 4/10th's - 6/10th's Cu was typical. The temperature buildup was fairly slow and the maximum temperature occurred at 1600 - 1800 hours. The cloud then disappeared and it was clear all night. Strong inversions developed in the lower 400' by 0000 hours but they were halted by an influx of south-easterly air during the night. Temperatures rose strongly on the 17th increasing from +51°F. at 0500 hours to +90°F. by 1400 hours (Fig. 7.25). Superadiabatics were present all day in the lower 600' under clear skies. The strong heating led to Cu and Cb in the early evening and heavy rain fell between 20 - 2200 hours.

A cold front moved in during the night and westerly flow was re-established (Fig. 7.26). Surface heating was strong with
superadiabatics in the 35 - 200' layer and 0.9 times the D.A.L.R. in the upper 600'. Rain occurred throughout the morning of the 18th and cloud remained high until 1100 hours. Cloud amounts decreased to 2/10ths in the afternoon with Cu and Cu+. Surface radiation inversions developed by 1800 hours but were destroyed by a cold front which passed through beginning at 2200 hours. By 0200 hours the disturbance had passed and radiation inversions developed again from the ground up. The 19th was cloudy all afternoon under westerlies and superadiabatics were present in the lower 200' with neutral conditions in the 200 - 810' layer (Fig. 7.27).

7.4 Discussion and Conclusion

The vertical temperature gradient in the Winnipeg area as in other areas is not only influenced by the actual weather at the time, but also by the sequence of weather that has occurred during the last 24 to 48 hours. This is particularly true in winter.

Winter lapse rates are strongly influenced by advective influences since the percentage heat received from solar sources is low. In summer, solar heating is by far the most important and advective heating and cooling is proportionately much less important. In addition, temperature contrasts between airmasses are much less in summer than in winter, and they in turn are less than in spring and autumn. The intensity and duration of advection inversions is therefore greatest in spring and autumn, less so in winter, and considerably less in summer. Spring and autumn will also show the greatest variation.

Radiation inversions are common at night in all seasons. Summer radiation inversions generally form in late afternoon, and
develop in intensity and height during the night. Surface inversions are destroyed about 2 to \(2\frac{1}{2}\) hours after sunrise, and all inversions are generally gone by 0930 hours - 1000 hours as strong solar heating establishes superadiabatics in the lower 400'.

In winter low level inversions generally develop about 1600 hours and last all night gradually increasing in intensity and height. In the morning the 35 - 200' and 35 - 400' inversions are usually destroyed pretty quickly but upper inversions persist under cA air until mid-afternoon and it is possible that these upper inversions may persist a further day resulting in 24 to 36 hour inversions.

Frontal inversions are common, but, due to the open nature of the E. Canadian Prairies, and their relative position to the main pressure belts, do not last long. Durations of 4 to 10 hours are typical.

Subsidence inversions from cold anticyclones are rare in the E. Prairies but can result in strong, persistent, elevated inversions. This is likely to be more of a problem in N. Saskatchewan and N. Alberta.

Any analyses of lapse rates in the atmosphere should attempt to take variations in the general weather pattern into account. Whilst the monthly and seasonal averages presented in Chapters Five and Six are useful in themselves their use can be considerably enhanced if adjustments can be made, based upon case studies, past and present weather, and, not least, the experience of the local forecaster.
Chapter Nine will attempt to include the influence of present weather upon positive lapse rates and inversions. These will be classified in terms of pressure, wind speed, wind direction, cloud cover, intensity, and duration. No attempt is made to include the influence of past weather, although this could be done by considering weighted variables such as temperature or wind direction changes over the last 12, 24, or 48 hours.
CHAPTER EIGHT

Analysis of Wind Speed and Direction

8.1 Diurnal Variation of Wind Speed and Direction at 35 feet and 810 feet

8.1.1 Introduction

The wind speed and direction in the lower 1500 - 3000 feet are determined primarily by 3 forces: the horizontal pressure gradient force, the coriolis force, and friction.

The equilibrium of the pressure gradient force and coriolis force gives the geostrophic wind which flows parallel to the isobars with low pressure on the left in the northern hemisphere. In the upper layers of the atmosphere, observed winds are close to the geostrophic wind. Near the ground great variations are in evidence, and a third force, friction, must be invoked to explain conditions.

This frictional force not only decreases the windspeed near the surface but also changes the vector balance of forces so that air near the surface flows at an angle to the geostrophic wind, this angle being across the isobars, in towards low pressure or out from a high. This angle varies with the time of day and roughness of the surface but is generally 15° by day over a smooth surface and 35° at night (Slade (1968, page 41; Hoxit, 1973, p88).

The angle of flow across the isobars decreases with increasing height and disappears at 1500 - 3000 feet. The time of day also affects the angle and winds veer by day and back by night (Sutton, 1953, page 230).
The height to which frictional forces are felt varies with the time of day. Turbulent mixing is stronger by day and hence the influence of the surface extends to a greater height. At night the air is more stable and only the lowest layers are affected.

Certain levels of the atmosphere will be affected by friction during the day but not at night, or in summer but not in winter. This will result in a higher wind at night than during the day. Below this level highest wind speeds occur during the day when faster moving air above is mixed downwards towards the surface (Singer and Rayner 1957). Lower level wind speed and direction is closest to upper level wind speed and direction during the day and furthest away at night due to the greater degree of vertical mixing associated with daytime unstable conditions which result in great homogeneity in the vertical.

Hoxit (1973) has observed that during the night and morning hours variations in both veering and speed above 500 feet appear to be independent of changes in the lower 500 feet. He maintains that the physical processes in the 500 to 5000 feet layer are apparently not directly related to surface friction during this period. His observations suggest that the lower atmosphere with its associated ageostrophic flow is made up of two sub-layers during the night and morning hours. The layer adjacent to the surface is the momentum boundary layer or Eckman layer. The top of this layer is the level at which the turbulent mixing induced by surface friction becomes negligible. At night the momentum boundary layer is only a few hundred feet thick. The second layer is formed shortly after sunset when the deep afternoon momentum boundary layer disappears. Blackadar (1957) and Blackadar and Buajjiti (1957) have shown that variations in the ageostrophic wind in this layer correspond to inertial oscillations. We shall therefore refer to this layer as the
'inertial boundary layer' (after Hoxit, 1973).

8.1.2 Diurnal Wind Speed Variations

a) Results

The arithmetic mean windspeed for each hour was calculated for the entire year and for each season (figures 8.1 to 8.5). Annual surface windspeeds, at a minimum during the night, increase from sunrise to a maximum of 13 m.p.h. at 1400 hours and remain fairly high throughout the afternoon before beginning to decrease around sunset (figure 8.1). This rapid decrease stops around 2000 hours and remains fairly constant to 0300 hours. The mean annual surface speeds increase slightly after this time and remain near 10.5 m.p.h. until sunrise.

At upper levels the annual average wind speeds are higher at night than during the day and reach a maximum of about 23 m.p.h. at around 2300 hours. They are then fairly constant until around sunrise when there is a rapid decrease to a minimum of 19 m.p.h. around 1300 hours. A one hour lag exists between the time of upper level minimum and surface level maximum.

Windspeed changes usually occur in a short time period after sunrise between 0600 and 0800 hours when the upper level winds decrease by about 20% from their nighttime maxima.

Speed changes occurring around sunrise indicate the importance of momentum transfer due to convective mixing in the daylight hours. For instance, surface windspeeds begin to increase around 0600 hours, whilst upper level winds begin their marked decrease around 0700 - 0800 hours. There is thus a one to two hour lag between the time of influence of sunrise on surface and upper level winds.
The picture for individual seasons is similar although it differs in detail. In winter, the diurnal variation in windspeed is reduced especially at the surface. The surface maximum still occurs at 14:00 hours but the minimum, due to an earlier sunset and weaker solar radiation, occurs earlier at 1800 hours. Windspeeds remain fairly constant until 10 a.m. the next morning when solar radiation is strong enough to encourage convective mixing (see figure 5.3). Upper level winds reach their minimum one hour before surface winds reach their maximum as in the all year case, but the rate of upper level wind speed decrease is less than in the all year case. Maximum upper level winds occur earlier in winter than in the all year case (2000 hours versus 2300 hours). Summer exhibits the greatest diurnal variation in windspeed as well as the best evidence of the relationship between upper and lower layers.

Surface windspeeds reach their maxima at 14:00 to 1600 hours and decrease rapidly (by 35%) to their minimum with the establishment of stable surface conditions between then and 2100 hours. Windspeeds remain low until sunrise at 0600 hours when there is a rapid and steady increase to the mid-afternoon maximum. Upper level winds reach their maximum at 04:00 hours (versus 2000 hours in winter) and 2300 hours all year) and decrease rapidly after 0600 to 0700 hours, with increased vertical mixing, to a minimum at 1000 hours. The minimum is established much earlier in the day (1000 versus 13 - 14:00 hours) due to the greater intensity of solar radiation. Windspeeds then increase slightly during the afternoon before rapidly increasing when stable surface conditions are established in late afternoon.
b) Qualitative Model of Diurnal Wind Variations

The observed diurnal variation of the windspeed has been shown above. The reasons for these variations will now be associated with diurnal changes in stability. The typical diurnal variation of the potential temperature profile for the lowest 10,000 feet, is given in figure 8.6. This diagram is representative of clear sky conditions with no significant synoptic changes. The profiles in figures 8.1 to 8.5 represent average diurnal changes since data for both clear and cloudy conditions have been combined. The amplitudes of the wind variations in clear conditions are therefore somewhat depressed. Nevertheless the essential features of the daily variation in the wind speed and wind direction profiles can be related to the potential temperature profile in figure 8.6.

As indicated earlier, current theory suggests that the lower 6000 feet is made up of two layers - the momentum boundary layer and the inertial boundary layer. A schematic diagram of the diurnal variation in the depth of these two layers is included in figure 8.7 (after Hoxit, 1973, page 98). The following discussion is based upon Hoxit's results and will commence with conditions during mid-afternoon (1500 CST).

Surface heating and subsequent transfer of this heat to the lower atmosphere has produced a deep layer with adiabatic lapse rate conditions. The momentum boundary layer is much thicker than the tower layer. Both the kinetic energy generation and dissipation rates are large with an approximate balance between terms.

Just after sunset the surface cools rapidly. In turn the lowest layers of the atmosphere are cooled, whilst the temperature in the remainder of the layer remains essentially unchanged. The
low level cooling suppresses mechanical and buoyant mixing and leads to the formation of a new and much thinner momentum boundary layer. The veering and speed profiles in the new layer adjust with a time scale of the mixing process (typically of the order of minutes). The dissipation of kinetic energy by the turbulence process now becomes confined to the lowest few hundreds of feet. The total kinetic energy dissipation for the lowest 5000 feet decreases significantly. Above the developing ground based stable layer the turbulent mixing decreases rapidly. Frictional forces become insignificant. The adjustment time for the motion increases to that for large scale motion (that is inertial motion). As a result the kinetic energy generation in the layer remains significant for several hours. With the dissipation mechanism largely eliminated the windspeed increases rapidly. Eventually the Coriolis force becomes greater than the pressure gradient force and the flow towards low pressure decreases to zero. In mid-latitudes windspeeds typically reach their maximum around midnight. An important consequence in the development of the inertial layer is that the flow at the top of the Eckman or momentum boundary layer will no longer be in geostrophic balance.

By sunrise the low level stable layer is very well developed. The height of the momentum boundary layer is probably within the tower layer with the veering angle and speed changing rapidly with height. In the inertial layer an ageostrophic component towards high pressure has developed in response to the formation of supergeostrophic windspeeds. This up gradient flow produces negative kinetic generation values - the conversion of kinetic energy to potential energy. As a result the wind speeds decrease. After sunrise surface heating eliminates the ground based stable layer. The mixing in the boundary
layer is enhanced by eliminating the restraining effects of a stable atmosphere. The rate of wind veering and speed changes with height are reduced.

Between 0900 and 1500 hours, the surface heating produces a deepening layer in which the lapse rates are essentially adiabatic. The adjustment of the depth of the Eckman or momentum boundary layer occurs on a time scale associated with the turbulent mixing process. Thus the depth of the layer will at times correspond roughly to the depth of the adiabatic layer. As the mixing reaches higher and higher the layer exhibiting inertial motion is eliminated. By afternoon the inertial layer has been completely destroyed and the boundary conditions at the top of the Eckman layer become once again those specified by gradient or geostrophic balance.

8.1.3 Diurnal Resultant Wind Vector Variations

a) Method

The resultant, or vector mean wind, was calculated on an annual and seasonal basis for each hour of the day. It was obtained by converting each wind observation into north-south and east-west components, summing over a given time interval, obtaining the arithmetic mean for each component, and reconverting these components into a single vector. This mean quantity must be used with care, since the wind direction distribution is frequently composed of north-south and north-west – south-east winds.

b) Results

There is a distinct veering of the wind vector with elevation. This veering is not uniform throughout the day. Significant veering
occurs from 1700 to 1100 hours (figure 8.1) with a peak value of \(16^\circ\) occurring at 2000 hours (\(15\frac{1}{2}^\circ\) at 0500 hours). These times are similar to those that Crawford and Hudson (1973) found on their tower in Oklahoma (\(30^\circ\) at 0600, \(28^\circ\) at 2000 hours). Veering with height is a minimum during midday hours with values at 1100 hours within the instrumental error limits (\(3^\circ\)). Values from 1100 to 1500 hours are at less than \(6^\circ\). The times of minimal variation between upper and lower levels correspond to the times that the lower layer was well mixed by convective motions. The essentially uniform wind speeds and directions during the midday - early afternoon period, indicate uniform momentum in the tower layer. Since convective mixing is well established between 0900 and 1100 hours, there appears to be a one to three hour lag between the time mixing begins and the re-establishment of a balance of forces at the higher level. Thus, whilst the wind does veer with height, veering is best developed at certain parts of the day.

The diurnal oscillation of boundary layer winds, that is the backing and veering of the wind vector with time during the day (Bonner and Paegle 1970, Crawford and Hudson 1973) is also apparent in the C.B.C. tower data. Except for minor interruptions the wind veers with time from 20/2100 hours to 08/0900 hours, then backs from 1500 to 2000 hours with variations between levels in the 0900 to 1500 hour period.

Backing is a minimum between 1500 and 2000 hours as surface stability is re-established. Veering with time is a maximum from 2000 hours to 0400 hours at the surface, and from 2100 hours to 0200 hours at 910 feet and is irregular around sunrise.
Thus winds veer longer than they back and hence the C.B.C. tower data confirms Crawford and Hudson's view that the average backing rate is greater than the average veering rate.

8.2 Wind Speed and Direction Frequency

Data is available on wind speed and direction frequencies for Winnipeg Table 8.1 (Atmospheric Environment Service, Hourly Data Summaries, 1958). The figures are based upon 10 year wind averages from Winnipeg International Airport (33 feet above ground).

Seasonal wind speed and direction data for C.B.C. tower, Winnipeg is presented in Tables 8.2 to 8.11. The wind speed categories are in accordance with Canadian micrometeorological practice (Table 2.4). These tables are designed to supplement the W.M.O. type B monthly table. (Table 8.1)

The prevailing wind at Winnipeg is north-westerly, followed by southerly, westerly, and northerly. Easterlies and south-easterlies are the least important in terms of frequency. On an annual basis easterlies followed by westerlies are the most common of the light winds (< 4 m.p.h.), whilst westerlies followed by southerlies are the most important of the <4 - 9 m.p.h. winds. During the worst air pollution emission season, that is, winter, westerlies and south-westerlies are the most common of the <4 m.p.h. winds, whilst westerlies and north-westerlies are the most common of the >4 - 9 m.p.h. winds.

The percent frequency of light winds falls off quickly with increasing height. Twelve percent of all 35 feet cases have winds < 4 m.p.h. but only 5% of 810 foot winds are < 9 m.p.h. against 40% at the 35 foot level.
Although the above tables and data are quite useful, they do not provide adequate information for an air pollution climatology. No information is available on the duration of light winds, that is, the number of consecutive hours with winds speeds $\leq X$ m.p.h., or on the length of light wind runs by direction. This data is presented in the next section.

8.3 Duration of Light Winds

Little is known about the duration of light winds. Most research effort has gone into examining gusts and high winds due to their importance in engineering, and it is only recently that data has appeared on the number of consecutive hours with winds less than or equal to a given wind speed (Hage and Longley, 1967).

It is now clear that this work is important owing to the significance of light winds in helping to create and maintain episodes of high air pollution potential. The remainder of this section will look at the results of similar work to that of Hage and Longley done in Winnipeg.

Tower wind data was examined at both the 35 feet and 810 feet levels and the number of consecutive hours with winds $\leq 1, 2, \ldots 9$ m.p.h. were tabulated by season and all year for the sampling period. Cumulative and cumulative percent frequencies were then calculated. Data for the 35 foot tower level is presented in figures 8.8 to 8.12 for speeds of $\leq 3, 6, 9$ m.p.h. These speed classes were selected in order to correspond to the work of Hage and Longley in Edmonton and Calgary. Three, six and nine miles per hour represent maximum values during a run and average winds for the run will be lower.
The frequency of light winds of a given duration decreases rapidly as the duration increases and only a very small percentage last more than a few hours. Maximum values of duration for winds $\leq 3$, 6, 9 m.p.h. respectively are 18, 51, and 66 hours for the 35' tower level and 24, 24, and 36 hours for the 810' level and 19, 25, 37 hours for Winnipeg International Airport (1961 - 70 sample). Difficulties always exist with a small sample size and maximum values. If the next largest value is taken, the 810' tower maxima becomes, 15, 22, 36 hours. The 33' airport figures are low compared to the tower 35' figures and this may be due to the reduction in wind velocity as air moves across the tower although the position is complicated by the fact that the airport average speed was 0.9 m.p.h. lower than the 35' tower reading during inversion conditions. No figure is available for the airport and tower wind speed averages during the entire sampling period. Tables 8.12 and 8.13 summarize the maximum figures for all year and seasons and also present 99th percentile values for the 35' tower level and 33' airport level.

Light winds $\leq 3$ m.p.h. are longest in winter and spring during the high air pollution emission season but even then they last less than one day. Extreme durations of winds $\leq 6$ m.p.h. can reach over two days (35' tower data) but are generally under one day.

If 99th percentile durations are examined the figures begin to group closer together with the differences between adjacent wind speed classes and seasons being much less. Taking all three groups as a whole winter still emerges as the worst from an air pollution point of view followed by autumn, spring, and summer.

Maximum values for Edmonton and Calgary are much larger,
especially in winter owing to their closer position to cold high pressure conditions. This is particularly true in the case of more northerly Edmonton (table 8.14).

Whilst the above analysis is a useful supplement to wind speed and direction information, it would be of much greater use in a planning context if the directions from which the longest durations of light winds came from could be identified. This has been done for Winnipeg in tables 8.15 to 8.24 for windspeeds <4 and <9 m.p.h. Table 8.25 summarizes the information by direction for the three windspeed classes <3, <6, and <9 m.p.h.

Light wind conditions are generally poorest when easterlies or south-easterlies are present, and medium wind conditions are poorest when westerlies, easterlies, or north-easterlies are present. Easterlies are second in importance for winds ≤ 6 since periods of easterlies are generally short. With stronger winds (≤ 9) northerlies north-westerlies, and westerlies are the main problem.

In winter light easterlies and northerlies are one problem but much longer periods of northerlies, north-westerlies, and westerlies occur with winds ≤ 9 m.p.h. contributing to another problem (Table 8.20).

From a practical standpoint this makes things very difficult in terms of advising locations for heavy polluting industries as far as wind is concerned. Easterlies and northerlies bring shorter periods of very light winds, whilst northerlies, north-westerlies, westerlies bring longer periods of slightly stronger winds. This problem will be considered further when stability of air by wind directions is examined in the next chapter.
CHAPTER NINE

9.1 Introduction

Traditionally meteorological classifications of inversions have distinguished inversion types on the basis of mode of formation, for example, radiation, advection, frontal and subsidence inversions. The arrival of the computer has opened up new possibilities not only for subjective classifications but also for objective and repeatable classification systems.

There are two main methods of grouping or classifying objects, logical subdivision and the grouping of like individuals (Grigg, 1965). Both methods will be used in this chapter. The scheme of logical subdivision shown in Figure 9.1 forms the basis of the classification scheme in Section 9.2. The grouping of like individuals is done subjectively in Section 9.3 and numerically, using Ward's (1963) algorithm for cluster analysis, in Section 9.5. The advantage of techniques such as cluster analysis is that there is no reason to base classifications upon one or two characteristics. We can use n variables to define a classification space in n dimensions. This is done in Section 9.5 for six variables. It should be noted that the cluster analysis technique used is quite general and can be used to perform all types of classifications. For examples in geography see Spence (1968) and Johnson (1968). For examples in the social sciences see Sneath and Sokal (1973, page 443-446).
9.2 Classification of Lapse Rates

9.2.1 Introduction

Climatological work on lapse rate analysis generally subdivides lapse rates into superadiabatics (favoring mixing), weak lapses (weakly suppressing mixing), and inversions (strongly suppressing mixing). Further work is aimed at finding factors responsible for the development and decay of these three groups, such as season, time of day, wind speed, wind direction, cloud cover, airmass and so on.

Some analysis of this type has been done in earlier chapters. Lapse rate frequencies were examined in Chapter Five with emphasis upon the diurnal, monthly and annual variation. No attempt was then made to relate these variations to weather present at the time. Reference was later made (Chapter Seven) to lapse rates during case studies of different flow types, and it was shown that lapse rates were closely related to the existing and past weather. In particular the importance of cloud cover, direction and speed of flow and time of day were noted. The diurnal and seasonal variation of wind speed and direction was examined in the previous chapter as well as the number of consecutive hours of light winds. An attempt will now be made to integrate much of this previous work by proposing a simple classification scheme for lapse rates.

The purpose of this classification scheme is twofold. It was desired to assess the importance of stream lines in favouring certain types of lapse rate and it was also desired to know whether certain wind directions favoured inversions during light to medium winds. The first information would be of general help in any
discussion of the climate of Winnipeg, whilst the information about inversions during light to medium winds would help in an analysis of the general problem of dispersal of air pollutants in the Winnipeg area. The two analyses are combined because of the similarity in the method of processing and presenting the data.

The analysis was performed as follows: The population of lapse rates was first broken down by layer, and data for the 35 - 200' and 35 - 810' layers was selected. Lapse rates were then subdivided into superadiabatics, weak lapses and inversions. Further breakdowns were made according to season, wind speed, and wind direction (Figure 9.1). The wind direction subdivision was done by eight major directions. Seven wind speed groups were found necessary to retain sufficient information of the effect of wind speed upon lapse rate. Lower wind speed values were established in accord with Canadian micrometeorological practice (See Table 2.3), whilst the higher values were chosen after some test runs.

The analysis of the data was facilitated by a computer program which examined each hours data from October 1969 to June 1972 and incremented counters everytime a lapse rate was observed in the appropriate lapse rate interval, season, wind direction, and wind speed class.

The data was further analysed to see if the proportions in the three lapse rate classes exceeded their share for each of the eight wind directions. In other words, if north-west winds in winter accounted for 26.6% of all winter winds and 32.1% of superadiabatics existed with north-west winter winds, then superadiabatics exist 32.1% / 26.6% x 100% - 100% or 22% more than their proportional share. Superadiabatics are therefore 22% more common with north-west winds than for all winds in general, and it can be further
generalized by stating that north-westerly winds favour superadiabatics. This type of analysis was also done for the various wind speed classes. The results of the above analysis will now be presented.

2.2.2 Percentage Frequency of 3 Lapse Rate Types by Wind Direction and Speed

Generally speaking, it would be expected that warmer westerly, south-westerly, and southerly air would favour inversions, since this air is moving from a warmer source region into progressively colder areas. In addition, this air frequently replaces high pressure features in winter resulting in strong advection inversions. Northerly and north-westerly air would be expected to favour superadiabatics, especially in the cooler half of the year, since this air frequently replaces warmer westerly air and is strongly heated from below. This is largely substantiated in this section but in addition some unexpected patterns emerge with winds from the south-east and to a lesser extent the east.

Great seasonal variations exist. In summer inversion conditions are favoured by light winds (Tables 9.1 and 2). Overnight radiation inversions form in late afternoon and last the night before being quickly dispersed in the morning. Advection inversions are much more important in the winter half of the year since temperature contrasts between different airflow types are considerably greater. In the 35 - 200' layer in winter all winds except south-westerlies and westerlies are colder than the underlying surface, and hence superadiabatics are high for these directions and low for south-westerlies and westerlies. Radiation inversions affect all air for much of the day in winter. These are supplemented by advection inversions when warmer air flows over a colder underlying
surface. This is generally the case with westerlies and south-westerlies (69.9 and 66.1% inversions respectively). Certain wind directions favour greater basal chilling due to the nature of the surface. Southerly, westerly, and south-westerly air all flows over a predominantly flat, arable snow covered land surface with a high albedo and low roughness. South-easterly, easterly, north-easterly and northerly air flows over a much rougher Canadian Shield type topography with a fair number of trees and a much lower albedo which tends to reduce the stability of air flowing from these directions.

Lapse Rate frequencies in the 35 - 810' layer, (Tables 9.3 and 9.4) differ from the 35 - 200' layer in several respects. Superadiabatics are much less frequent in the higher layers (3.3% versus 19.4%, Table 9.4). This decrease is split fairly evenly between inversions and weak lapses. The decrease is not uniform however, and north-westerlies, northerlies, south-easterlies and westerlies are affected less than easterlies, north-easterlies, southerlies and south-westerlies. This is because the first group have superadiabatics due to heating from below or, in the case of south-easterlies, due to vigorous vertical mixing. Inversion frequencies reach over 75% for southerly and south-westerly winds in the 35 - 810' layer in winter with westerlies slightly lower with 66%.

Once again the change is not uniform for all directions. North-easterly, easterly and south-easterly inversion frequencies, increase since the effect of topography and albedo does not affect air as high as 810'. North-westerlies and northerlies are slightly down because radiation inversions in this overriding cold air do not always reach 810'.
Windspeeds affect the distribution of lapse rates as well as wind directions. Windspeeds above 13 m.p.h. generally decrease the frequency of inversions in the 35 - 200' layer, whilst superadiabatics and weak lapse rates increase with increasing wind speed above 13 m.p.h.

Percent frequencies of inversions in winter increase with windspeeds to 9 - 13 m.p.h., remain high in the 13 - 17 m.p.h. range and decrease in the 17 - 21 and >21 m.p.h. ranges. In spring and summer the decrease occurs faster and at lower wind speeds (13 - 17 m.p.h.). A similar picture occurs in the 35 - 810' layer, but since the 422' wind is used, the minimum values are higher. The rate of decrease appears slower but may well be due to the lack of detail available above 21 m.p.h. for the higher 422' wind.

In summary lapse rate frequencies vary greatly by wind direction and season as well as by wind speed. South-westerlies and westerlies yield the largest inversion percentages, whilst south-easterlies, north-westerlies and northerlies yeild the greatest percentages of superadiabatics. The next section will examine the variations in the 35 - 200' layer in more detail by examining variations in the percentages by windspeed within wind direction subclasses.

9.2.3. Relative Importance of Lapse Rates by Wind Speed for each Wind Direction

The importance of wind speed on the distribution of lapse rates varies greatly according to the wind direction and season. This subsection will examine the variation for the 35 - 200' layer first in winter and then in summer in order of importance of the
the wind direction. It will also examine the importance of the relative wind direction in influencing the lapse rate distribution.

(a) Winter

(i) North-West Winds

North-westerlies account for 26.6% of all winds in winter and are by far the most frequent (Table 9.5). They are generally strong winds (11.6% of all north-westerly are <17 m.p.h.), which bring 32.1% of all winter superadiabatics or 21% more than their share (32.1 vs. 26.6%). Winds less than 17 m.p.h. have less (65% - 80%) than their share of superadiabatics, whilst winds greater than 17 m.p.h. have more than their share. Superadiabatics occur on 23.4% of all north-westerly occasions in winter. This proportion is highest at highest speeds (40% at >21 m.p.h.) and decreases to 14.9% at 9 - 13 m.p.h. before slightly rising at lower speeds. Superadiabatics occurring at lower wind speeds occur primarily during the day, whilst those occurring with windspeeds >21 m.p.h. have almost 1/3 of their frequency during the dark hours.

This is as would be expected since strong north-westerlies in winter will bring cold air in to replace warmer air over the warmer Manitoba surface. This air will be heated from below resulting in superadiabatics or weak lapses. Strong winds will also bring down warmer air from aloft which will further favour positive lapses.

Inversions are also slightly more important with north-westerlies in winter (27.5% vs. 26.6%) but this is because of the higher proportions with winds less than 17 m.p.h. (which yield 40% more than their share of inversions). The proportion decreases rapidly between 17 to 21 and 21 m.p.h. as superadiabatics and
weak lapses increase in percentage with increased mixing.

The overall distribution of lapse rates with north-westerlies in winter is approximately 50% inversions and 25% each of superadiabatics and weak lapses. Inversions are dominant from 2 to 17 m.p.h. and occur for approximately 70% of the time. This decreases rapidly in the higher 17 to 21 and >21 m.p.h. classes when weak lapses and superadiabatics make up as much as 40% each, leaving only 20% inversions with winds >21 m.p.h. and these are concentrated in the nighttime hours. The critical speed for north-westerly inversions thus appears to be approximately 17 m.p.h. This, together with the predominantly nocturnal occurrence of inversions favours the view that most north-westerly winds bring radiation inversions and these have approximately a 70% probability of occurrence with winds less than 17 m.p.h.

(ii) North Winds

Northerly winds are the second most frequent wind in winter, (17.9%, Table 9.6). They are generally lighter winds than north-westerlies, but are similar to north-westerlies inasmuch as they contain proportionately more superadiabatics especially at the higher wind speeds. The critical wind speed class is 13 to 17 m.p.h. rather than 17 to 21 m.p.h. Inversion percentage frequencies are proportionately less overall but this is largely a reflection of the low relative percentage of inversions at the higher wind speeds. Weak lapse conditions are proportionately more important with winds speeds greater than 17 m.p.h.

The percentage distribution of the three main lapse rate groups is very similar to that associated with north-westerlies although inversion percent frequencies are slightly down, whilst
weak lapse rates and superadiabatics are slightly up. This may well be due to greater heating of the colder air by the warmer ground surface.

(iii) West Winds

West winds bring conditions which give rise to lapse rates quite different from those of northerly and north-westerly winds. Superadiabatics and weak lapse rates are of much less importance proportionally, whilst inversions are of much greater importance at all speeds. Superadiabatics make up a significant proportion with winds of 2 to 4 m.p.h. (Table 9.7). Inversions account for 60 to 80% of all lapse rates in the 4 to 21 m.p.h. range, and approximately 50% in the 2 to 4 and >21 m.p.h. classes. As a result of these high figures westerly winds give rise to more inversions than northerlies although northerly winds are more frequent.

The lapse rate distribution is once again what one would expect from the synoptic climatology. Westerlies generally bring warmer air which is cooled from below creating advection inversions by day, and advection/radiation inversions by night. The inversions can stand greater wind speeds because of the advective nature of the inversion compared to northerlies and north-westerlies which are primarily radiation inversions.

(iv) South Winds

Southerly winds are generally strong winds with over 40% greater than 21 m.p.h. (Table 9.8). Mixing is vigorous, and hence weak lapse conditions are proportionately more important. The proportionate occurrence for superadiabatics is about normal, whilst
inversions are less important. Considerable variation exists within wind speed classes with inversions proportionately more important and weak lapses less important with winds to 17 m.p.h. The 17 to 21 m.p.h. class is a transition class, and with winds >21 m.p.h., the transition to weak lapses, at the expense of inversions, is very nearly complete.

The overall lapse rate distribution shows approximately 40% inversions, 40% weak lapses, and 20% superadiabatics. Inversion percentages are much higher with winds of 2 to 17 m.p.h. (50 to 60%). With winds >17 m.p.h. increased mixing destroys the inversions and conditions tend to weak lapses. Superadiabatics remain fairly constant at 20% regardless of wind speed and occur almost exclusively by day as one would expect with an airflow which is generally as warm or warmer than the underlying surface.

(v) South-West Winds

South-west winds in winter yield the smallest proportionate percentage of superadiabatics (Table 9.9). This is to be expected since a south-westerly airflow is warmer than that prevailing previously and hence, it will be subjected to basal chilling and advective inversions will be common. The proportion with weak lapse conditions is slightly less overall due to the large percentage of inversions. Superadiabatics occur by day under light winds (2 to 4 m.p.h.). At higher wind speeds superadiabatics always average 10% of the total. Inversions average approximately 2/3 of all lapse rates between 4 and 17 m.p.h. There is then a decrease from 17 to 21 m.p.h., before a further rise to 73.1% with winds >21 m.p.h. as colder air is brought from aloft.
South-westerly winds therefore bring primarily advection inversions with radiation/advection inversions occurring at the lower wind speeds. No decrease in inversion intensity is observed with winds >21 m.p.h. unlike westerlies.

(vi) South-East Winds

South-east winds are strong winds (Table 9.10). As a result weak lapses and superadiabatics are proportionately more important, whilst inversions are of lesser importance. At low and medium wind speeds inversions attain approximately 3/4 of their proportionate share, whilst with winds >13 m.p.h., and especially >21 m.p.h. this drops off considerably.

The percentage distribution of lapse rates shows weak lapses as the most important group for all speeds except 4 to 9 m.p.h. At speeds >21 m.p.h. weak lapses account for approximately 70% of all lapses. Inversions are best developed at speeds <9 m.p.h. and are almost exclusively nighttime features, that is probably radiation inversions.

The higher percentage of superadiabatics may well be related to the trajectory of south-easterlies over rougher Canadian Shield topography.

(vii) East Winds

Most easterlies are light to medium winds (4 to 13 m.p.h.) and weak lapses and superadiabatics are favoured over inversions (Table 9.11). Superadiabatics are best developed in the 2 to 4 m.p.h. range, whilst weak lapses are most favoured in the 4 to 13 m.p.h. range which comprises the majority of east winds. Once again it appears that the rougher Canadian Shield type topography
with trees has a strong influence upon lower level lapse rates.

The overall winter average distribution of lapse rates favours weak lapses (46%), followed by inversions (31%), and superadiabatics (23%). Light winds (2 to 4 m.p.h.) show approximately 1/3 in each category. Medium winds (4 to 13 m.p.h.) have approximately 50% of all lapses in the weak lapse category. Inversions are more common from 4 to 9 m.p.h. than from 9+ m.p.h., that is radiation inversions are favoured.

(viii) North-East Winds

North-east winds like east winds are light to medium winds which favour weak lapses and superadiabatics over inversions (Table 9.12). Weak lapses are favoured at all speeds except 2 to 4 m.p.h., whilst superadiabatics are favoured at all speeds over 9 m.p.h.

The overall distribution of lapse rates shows 40% with weak lapses, 35% inversions, and 25% superadiabatics. Inversion percentages decrease steadily from 62% with 2 to 4 m.p.h. winds to 7% with winds over 21 m.p.h. Weak lapses generally show an upward trend with increasing wind speed. North east winds over 21 m.p.h. give approximately 80% weak lapses. Superadiabatics increase to 13 to 17 m.p.h. and then decrease with increasing mixing. Inversions appear to be primarily radiational and are best developed with winds below 9 m.p.h.
(b) Summer

The summer situation is quite different from the winter one in one main respect - the contrast between air masses is very much less resulting in a dominance of inversions of the radiation type and a relative absence of advection inversions. This will be examined by wind direction.

(i) South Winds

Southerly winds are the most frequent in summer. Approximately 2/3 of all summer southerly winds are greater than 13 m.p.h. and over 80% are greater than 9 m.p.h. (Table 9.13).

Weak lapse rates and inversions are proportionately more important and superadiabatics are less so. Inversions are proportionately best developed with winds of <17 m.p.h., whilst superadiabatics are best developed with winds >13 m.p.h. The distribution of lapse rates shows that light winds favour inversions, whilst strong winds favour superadiabatics. Inversions are the most common lapse rate except with winds over 21 m.p.h. and this is expected since southerly winds will generally be lightly cooled from below and this will contribute to the development of nocturnal radiation inversions.

(ii) North-West Winds

North-West Winds in summer are strong winds with 60% >13 m.p.h. and 85% >9 m.p.h. (Table 9.14). Superadiabatics are proportionately more important especially at the higher speeds. This contrasts with inversions which are best developed with winds <13 m.p.h. Weak lapse conditions are more similar in pattern to superadiabatics and are proportionately more important with winds greater than 17 m.p.h.
The distribution of lapse rates during north-westerlies shows that weak lapses are unimportant. Inversions are dominant with winds <13 m.p.h., whilst superadiabatics are dominant with winds >13 m.p.h. and overall. This is as would be expected when cool air overlies a warm surface resulting in superadiabatics by day and radiation inversions by night.

(iii) North Winds

The distribution of lapse rates during north winds in summer shows that superadiabatics and inversions are almost of equal overall importance and like other directions in summer inversions are more important at the lower windspeeds, whilst superadiabatics are more important at the higher windspeeds (Table 9.15). Weak lapses are much less frequent except during strong winds of over 21 m.p.h. when there is vigorous mixing. In general the pattern is very similar to that with north westerlies with cool air overlaying a warm surface.

(iv) West Winds

Superadiabatics are proportionately more important, whilst weak lapses are proportionately less important (Table 9.16). Inversions just about hold their own. When lapse rate categories are broken down by speed, inversions are found to be more important to 17 m.p.h. Superadiabatics are proportionately higher for all speeds >14 m.p.h. except for the 13 to 17 m.p.h. band. At speeds over 17 m.p.h. weak lapses also become significant as inversions are destroyed by mixing.

The distribution of lapse rates is fairly complex with inversions more frequent than superadiabatics from 2 to 9 m.p.h.,
and 13 to 17 m.p.h. Superadiabatics are more important than inversions from 9 to 13 m.p.h. and over 17 m.p.h. Weak lapses are unimportant below 17 m.p.h. but account for 20 to 25% of all frequencies above 17 m.p.h. when the strong winds result in vigorous mixing and lower inversion frequencies.

(v) South-East Winds

Superadiabatics are proportionately more frequent with south-easterly winds especially at the higher wind speeds when inversions and weak lapses are proportionately less frequent (Table 9.17). Inversions are stronger to 13 m.p.h., whilst superadiabatics are proportionately more frequent at all speeds except 9 to 13 m.p.h. Weak lapses become more frequent at higher wind speeds as increased mixing destroys the inversions.

The percent frequency distribution of lapse rates shows that superadiabatics are the most important group overall especially at the higher wind speeds. Inversions attain their highest frequency in the 14 to 13 m.p.h. range before decreasing with mainly radiational in nature although there is some advection of warmer air which favours early evening development of inversions.

(vi) South-West Winds

Weak lapse rates and inversions are proportionately more frequent, whilst superadiabatics are less frequent. Inversions are important to 21 m.p.h. after which increased mixing gives way to weak lapse rates (Table 9.18). Superadiabatics are proportionately less frequent at all speeds up to 21 m.p.h. This is not too surprising when one considers that south westerly air is generally warm air which is slightly cooled by the underlying surface.
The percentage frequency of lapse rates shows inversions as the dominant category at all wind speeds up to 21 m.p.h. when mixing favours weak lapse rates over all others. Superadiabatics reach a low at 9 to 13 m.p.h. as inversions increase, before increasing again with increased mixing which brings warmer air down from above.

(vii) North-East Winds

Weak Lapse rates and to a lesser extent inversions are proportionately more important with north-east winds in summer (Table 9.19). Superadiabatics never attain their proportionate share even at higher wind speeds. Inversions are proportionately more frequent with winds to 13 m.p.h. Above this increased mixing brings weak lapses and to a lesser extent superadiabatics.

The percentage distribution of lapse rates shows inversions as the most frequent followed by superadiabatics and weak lapses. This is also true up to 13 m.p.h. Above this speed mixing destroys inversions and weak lapses and to a lesser extent superadiabatics increase. Wind speeds above 21 m.p.h. are not common but when they do occur mixing is strong and weak lapses are dominant.

(viii) East Winds

The picture with east winds is almost identical to that with north-east winds except that inversion percentages do not decrease to the same extent with winds of over 17 m.p.h. (Table 9.20). This means that easterlies have a slightly higher inversion percentage and a slightly lower weak lapse rate percentage.
9.2.1 Summary

North-easterlies, northerlies, north-westerlies, and easterlies favour superadiabatics in winter in the 35 - 200' layer, whilst westerlies and south-westerlies strongly disfavour them. North-westerlies and northerlies favour superadiabatics with stronger winds (13 to 17 m.p.h.), whilst the others favour them in the 9 to 17 or 21 m.p.h. ranges.

Westerlies and south-westerlies favour inversions by 30 to 40%, whilst north-westerlies and northerlies retain their share. South-easterlies, easterlies, north-easterlies and southerlies have 50 to 80% of their share. South-westerlies and westerlies favour inversions at all windspeeds >2 to 4 m.p.h. North-westerlies, northerlies and southerlies are similar except that the high speed cutoff is 17 m.p.h. With north-easterlies inversions are favoured only with lighter winds (<9 m.p.h.). Easterlies and south-easterlies never favour inversions.

Weak lapses are best favoured from the south-east (177%), east, north-east, and south (132%). They are least favoured from the west followed by the north-west, north, and south-west. South-easterlies, easterlies, and north-easterlies have more weak lapse rates regardless of speed, whilst all other directions favour weak lapses only at speeds over 17 or 21 m.p.h.

Three basic groups emerge from the above discussion (Table 9.21). Group 1 consists of south-easterlies, easterlies and northeasteasterlies which favour weak lapse rates and to a lesser extent superadiabatics. Southerlies can also be included with this group although they only hold their own with superadiabatics.
Group 2 consists of north-westerlies and northerlies which favour superadiabatics and to a lesser extent inversions. Superadiabatics are favoured at high speeds unlike the previous group, whilst inversions are slightly favoured at lower speeds.

Group 3 consists of westerlies and south-westerlies which favour inversions and strongly disfavour superadiabatics. Windspeed makes little difference to the proportionate excess of inversions.

Group one is largely a reflection of the rougher Canadian Shield topography and the lower albedo of the tree covered landscape which results in stronger surface heating and mixing. Group two is largely a reflection of surface heating from a warmer underlying surface as cold northerly air heads equatorwards. Group three occurs because warm air is cooled as it advects over a colder underlying surface.

Summer 35 - 200' lapse rates do not show the same variation as winter ones but certain broad patterns still emerge (Table 9.22). Superadiabatics occur proportionately more frequently from all other directions. Superadiabatics are generally favoured at higher wind speeds (13 to 17 m.p.h.) although westerlies and south-easterlies favour superadiabatics at lower wind speeds as well.

Weak lapse rates are only favoured from the northeast, east, south-west, and to a lesser extent from the south. Very strong wind speeds of over 17 to 21 m.p.h. lead to a favouring of weak lapses regardless of wind direction.

Inversions in summer are generally favoured from the east, north-east, and south at lower windspeeds (<13 m.p.h.) and from the south-west at all speeds < 21 m.p.h.
Three basic patterns emerge (Table 9.22):

**Group 1** consists of winds from the north-east, east and south-west. Weak lapses are favoured as are inversions but to a lesser extent. Southerlies should also be included in this group since they are closer to this group than to any other but not distinct enough to form a group of their own.

**Group 2** consists of northerlies, westerlies and south-easterlies. Superadiabatics are slightly favoured, weak lapses are proportionately less and inversions are about average.

**Group 3** consists only of north-westerlies and is characterized by proportionately more superadiabatics, and proportionately less inversions and weak lapse rates.

The overall synoptic situation through its effect on isobaric curvature and hence subsidence and convergence in the airmass as a whole may also play an important role. This cannot be verified owing to the absence of available data.
9.3 Classification of Inversions

9.3.1 Introduction

The relationship of all lapse rates to wind speed and direction was examined in the previous section by utilizing each hours lapse rate as the criterion for classification. Since inversions are one of the important factors in air pollution dispersal, they warrant special examination utilizing the inversion with its associated average meteorological conditions, regardless of length, as the basis for classification. In particular it is important to know which factors favour the development of inversions and which factors facilitate their decay.

Subsequent sections will look at this problem in more detail in terms of the effect of time of formation, season, cloud cover, wind direction and wind speed on the growth, decay, and intensity of individual inversions. It will hopefully shed light on such important questions as the effect of wind direction on the occurrence of extra long inversions in the winter high pollution season, and the direction from which the longest inversions occur with light winds. This type of information is necessary in terms of assessing the air pollution potential of Winnipeg, and is of use in advising planners on the climatological and air pollution implications for particular types of land zoning. For example, if the longest inversions accompanied by light winds come from the north-east, and this sector is zoned for heavy industry, then dispersion will be poor, and high air pollution levels will slowly drift across the majority of the city.

In summary, the objective of this section is to classify
inversions in terms of factors favouring their growth and decay and to tabulate the characteristics of those inversions favouring high or low air pollution potential.

2.3.2 Method of Analysis

Inversions, regardless of length, were felt to be the important factor, rather than the occurrence of inversions on an hour by hour basis, when each hour was considered independently of the next, or previous one. Information was extracted from the data base on each inversion for the two selected layers, 35 - 200' and 35 - 810'. Since it was not known which variables were important prior to the analysis all possible information upon weather conditions during the inversion was extracted and stored on a sorted tape for each level and season. The following information was derived for each inversion:

1. Inversion duration in hours.
2. Average, maximum, and minimum intensity in °F./1000'.
3. Average, maximum, and minimum windspeed in miles per hour for the average height in the layer.¹
4. Average and modal wind direction.
5. Average, maximum, and minimum cloud obscurity.
6. Average, maximum, and minimum pressure, the total pressure change, and the hourly pressure change.
7. Average, maximum, and minimum temperature in °F., and the temperature range.
8. Number of hours of smoke, fog, rain, snow, thunderstorms and so on.

The resultant distributions were then examined graphically and basic statistics were calculated using the "Statistical
Package for the Social Sciences" programs, codebook and condescriptive (Nie et al., 1970). The data was then grouped to give a number of classes for each variable. This was done by examining the distributions for each variable and selecting 'natural' breaks in the data whenever possible. SPSS program breakdown was also run on the original data for a large number of variables. Similar runs were made using 'crosstabs' for the grouped data. This was done for both seasons and for the entire year.

9.3.3 Difficulties and Limitations

Not surprisingly, any attempt to examine inversions in terms of factors favouring their growth or decay runs into a multitude of problems, since regular meteorological data on the overall radiation balance, advection, and subsidence for air is simply not available. Instead, data on such available variables as wind speed and direction, sky obscurity, pressure and pressure change must be used in an examination of inversion intensity and duration.

The limitations of this approach are well understood but it is felt justified since little detailed work has been done on inversions despite their implications for air pollution potential. Even such basic relations as those between inversion duration and inversion intensity are not fully understood (Baker and Enz, 1969).

9.3.4 Duration and Frequency of Inversions by Inversion Intensity

Inversion durations generally increase with increasing average inversion intensity (Table 9.23a). Maximum durations in
the 35 - 200' layer occur at -35 to -40°F./1000' and at
<-50°F./1000'. Higher level inversions do not attain such high
intensities and the 35 - 810' layer maximum occurs at -15 to
- 20°F./1000'. Strong winter inversions last longest especially
in the 35 - 810' layer when the average strong inversion lasts
over 24 hours.

Inversion frequencies are highest in the - 2 to -10°F./1000'
range and taper off steadily as intensity increases. Weak inver-
sions ( -2°F./1000') are also less than in the -2 to -10°F./1000'
categories (Table 9.23b).

In summary inversion durations are highly correlated
with inversion intensities with an increase in intensity yielding
an increase in duration. Average intensities are -15°F./1000'.


Preliminary analysis of the data indicated that natural breaks in the data did not correspond to the traditional four six hour periods starting at 0000, 0600, 1200, 1800 hours. As a result the data was grouped into four six hour periods starting at 0500 hours (or $>0400$ hours), 1100 hours, 1700 hours, and 2300 hours.

Inversions formed between 1100 and 2200 hours last longest whilst those formed between 2300 and 1000 hours are shortest taking the year as a whole, (Table 9.24a). Great seasonal variation exists with shorter inversions occurring in summer from 1100 to 1600 hours in the 35 - 200' layer and in summer/autumn from 1100 to 1600 hours in the 35 - 810' layer.

By far the majority of inversions are formed between 1700 and 2200 hours, especially in the warmer seasons (Table 9.24b). These are primarily nocturnal radiation inversions.

Winter shows the least diurnal variation in inversion formation. These results are not surprising since inversions formed by day (1100 to 1600 hours) will frequently be strong advection inversions which can survive that day and the next night. These long inversions will cancel many shorter ones able to withstand only a few hours of daytime surface heating. Likewise inversions formed between 1700 and 2200 hours will generally survive the night under a stable synoptic situation.

Winter inversions formed between 0500 and 1000 hours are generally less than six hours long, and only rarely do they survive
the afternoon period (Table 9.25). It thus appears that surface heating in the lower 200' in winter is sufficiently strong on most occasions to break up even an intense inversion. Those formed between 2300 and 0400 hours generally survive the night and like the 0500 to 1000 ones they rarely survive the next afternoon. This is not true of the 35 - 810' layer (Table 9.26). The 35 - 200' inversions are longer however since they form earlier in the night. Inversions less than or equal to six hours are found at all times of the day. Those inversions over 6 hours and under 10 hours and less than 20 hours are generally formed from 1600 to 2200 hours. Inversions over 20 hours are formed anytime since they are generally advection inversions.

In summer short inversions are slightly dispersed throughout the day, but there is a pronounced tendency for the 2300 - 0400 period for 2 to 6 hour inversions. Those inversions > 6 hours are almost exclusively formed between 1700 and 2200 hours and are nocturnal radiation inversions.
9.3.6 Duration and Frequency of Inversions by Intensity and Six Hour Period

Strong, long inversions occur from 1100 to 1600 hours as well as from 1700 to 2200 hours since advection inversions forming at this time are frequently strong enough to survive the hot part of the day (Table 9.27 and 28). Nighttime conditions favour an increase in their intensity by radiation loss and hence 18 to 20 hour advection/radiation inversions frequently occur in the 35 - 200' layer. Whilst the number of such inversions formed between 1100 and 1600 hours is small, they are important on account of their duration and intensity.

Some intense inversions in winter are formed between 6 and 10 but their durations generally remain short and vary little with increasing intensity since they are quickly burned off in the morning especially in the lower 35 - 200' layer.

The duration of inversions formed from 1100 to 1600 hours in the 35 - 200' layer, increases rapidly to -15 to -20°F./1000' and then increases slightly to -50°F./1000'. This is also true for those inversions formed from 1700 to 2200 hours, and whilst these last longer for lower intensities, the durations at higher intensities are less than the durations of those inversions formed between 1100 and 1600 hours with similar intensities. Those inversions formed between 2300 and 0400 hours increase at a slower rate again and maintain lower inversion durations than those inversions formed between 1700 and 2200 hours. This is to be expected, since inversions formed earlier in the day will usually last the night and are therefore longer by the time of morning breakup.
In summer inversion intensities are generally weaker and only nocturnal inversions reach values of \(-20^\circ F./1000'\) since air mass temperature contrasts are much weaker and hence advection inversions are weaker. This results in tighter duration groupings since the 12 to 16 hour advection inversion is absent, and the 10 to 12 hour nocturnal radiation inversion is dominant.

In the 35 to 200' layer in spring and autumn, 12 to 16 hour inversions are common as are 17 to 22 hour ones in the latter season. These larger values occur since daytime advection inversions generally last the night, whilst nighttime advection inversions are usually burned off in the morning.

Inversions in the 35-810' layer (Table 9.26) are longer in all seasons and durations over 24 hours occur in all but the summer season. The long inversions generally develop at night and are not burned off during the next day since surface heating does not spread to 810' on many days in winter, late autumn and early spring.
The longest inversions are associated with southerly and south-westerly winds on average, whilst the shortest inversions on average come from the north, north-east, and east (Table 9.29a).

Inversions generally last longer in the 35 - 810' layer than in the 35 - 200' layer (9.5 versus 7.9 hours), although there are fewer of them (976 versus 1153) (Table 9.27b). Considerable seasonal variation exists. For example, in the 35 - 200' layer northerly winds have their longest inversions in winter, south-easterlies their longest in spring, easterlies their longest in summer, and north-easterlies their longest in autumn. Southerly 35 - 810' inversions average 20 hours in winter and only 11.1 hours in spring.

The general pattern is as would be expected except for south-easterly winds in the 35 - 200' layer. Daytime south-easterlies are frequently superadiabatic, whilst at night, they are frequently weak lapse, due to strong mixing and turbulence as fast moving air crosses over the treed Canadian Shield. South-easterlies thus favour short inversions. In contrast southerly, and south-westerly air moves over flat snow-covered arable land which strongly chills the air from below favouring long inversions. Northerly and north-westerly air frequently replaces warmer westerly and south-westerly air and hence most inversions are radiation and nocturnal in origin, and often slightly shorter due to basal heating by the warmer underlying surface which hinders inversion formation in the earlier part of the night.

The most common frequency of 35 - 200' inversions is northerly followed by southerly, south-westerly, westerly, and
north-westerly. (Table 9.29b). Thirty five to eight hundred and ten foot inversions are commonest from the south-west, south, west and north-west. North-easterlies and easterlies are the least frequent in both layers. Although northerlies bring more 35 - 200' inversions for the entire year, and all seasons except winter, westerlies and north-westerlies are the most common directions in the winter high pollution season.
Calm and light winds result in inversions of short duration partially due to the short run of such winds (see Chapter Eight) and also to the weak vertical mixing which will keep radiation inversions in the lower few tens of feet rather than the lower 200.

The longest inversion durations in the 35' - 200' layer are associated with winds of 2 to 13 m.p.h. (Table 9.30a). Durations become progressively shorter as winds increase from 9 to 34 m.p.h. High winds generally result in considerable mixing of air which tends to destroy radiation inversions and establish weak lapse conditions.

Longer inversion durations over a wider and higher range of wind speeds are characteristic of 35' - 810' inversions. Maximum durations occur in the 9 to 13 m.p.h. range which corresponds well with the 4 to 9 m.p.h. range in the lower 35' - 200' layer when one takes into account that we are using the wind at the midpoint of the layer.

Seasonal variations alter these patterns slightly. Summer durations are longest in the 35' - 200' layer with lighter 3 to 4 m.p.h. winds, whilst winter and spring have the longest durations with stronger 9 to 13 m.p.h. winds. The 35' - 810' layer also shows seasonal variation with maximum durations associated with lighter winds in spring and summer and stronger winds in winter.

The frequency of 35' - 200' inversions by wind speed classes rises rapidly from 2 to 4 m.p.h. to a peak at 4 to 9 m.p.h. and then remains high before decreasing rapidly again.
above 13 m.p.h. (Table 9.30b). Frequencies in the 35 - 810' layer are spread out over a larger wind speed range and reach a maximum at 13 to 17 m.p.h. (422' wind).

Inversion intensities are closely tied to windspeed with strong inversions (\(-20^\circ F./1000\)' being commonest with winds of \(>1\) to 13 m.p.h. Long inversions are found with winds \(>2\) to 17 m.p.h. and with intensities \(-16^\circ F./1000\)' . In general strong inversions cannot occur with strong winds.

9.3.9 Duration and Frequency of Inversions by Average Cloud Obscurity

The average duration of inversions in the 35 - 200' layer decreases with increasing cloud obscurity. This decrease is most apparent with cloud obscurities \(>6/10\)'s. Inversion durations in the 35 - 810' layer do not decrease with increasing cloud obscurity until cloud obscurities are greater than 6/10th's (Table 9.31a). Durations at lower obscurities in this layer show pronounced seasonal variations with winter durations at a maximum (20.2 hours) under 2 to \(1/4\)'s cloud obscurity. Spring and autumn show a similar pattern and only summer shows a steady decrease in duration with increasing cloud obscurity. This is probably because summer inversions are almost exclusively nocturnal radiation in origin, whilst other seasons have proportionately more advection inversions.

Maximum annual frequencies of inversions occur with average obscurities of 0.5 to 2/10th's, and decrease from there to 8 to 9/10th's before increasing substantially with 10/10th's
obscurities (Table 9.31b). Slight seasonal variations are evident with spring showing maximum frequencies of inversions with 0 to 0.5/10th's obscurities and autumn showing maximum frequencies at 2 to 4/10th's obscurity.

In winter the modal durations is 17 to 20 hours with 2/10th's 13 to 14 hours with 2 to 4/10th's, 9 to 10 hours with 4 to 6/10th's, 5 to 6 hours with 6 to 8/10th's, 3 to 6 hours with 9/10th's and 1 hour with 10/10th's obscurity. (Table 9.30).

That is, inversion durations are strongly linked to cloud cover. This is also apparent in summer when 87% of inversions with < ½/10th obscurity are 9 to 12 hours long, whilst 80% with 10/10th's cloud obscurity have durations < ¼ hours.

9.3.10 Inversion Duration and Frequency by Pressure Change and Hourly Pressure Change during Inversions

As expected, inversion durations are not greatly affected by hourly pressure changes up to 1mb./hour, although summer durations are longer with low hourly pressure changes (table 9.33(a)). Most inversions occur with hourly pressure changes <0.5mb. (table 9.33(b)). In general, Winnipeg inversions are favoured by more stable weather situations.

Summer inversions exhibit the least pressure change during the entire inversion whilst winter shows the greatest (table 9.33) Spring and autumn are very similar and show intermediate results. This again confirms the view that most summer inversions are radiation ones whilst winter ones are frequently due to advective or frontal causes when the pressure is changing rapidly with time.
9.3.11 Inversion Duration and Frequency by Average Sea Level Pressure.

In winter, 35 to 200' seventeen to twenty-four hour inversions are accompanied by high pressure (table 9.34), whilst inversions greater than 24 hours generally occur with lower pressures indicating westerly disturbances and advective origins. The rest of the winter pattern is not clear but high pressure is associated with 7 to 8 hour and 13 to 14 hour inversions. Further data analysis indicates that many of these are nocturnal radiation inversions, delayed in formation, due to heating from below, as with northerly and north-westerly winds, during the early part of the night. In summer and autumn there is little variation in pressure with duration since pressure and temperature contrasts are very much less than in winter or spring and radiation inversions are thus by far the most important.

9.3.12 Summary

Certain broad patterns can be identified from the previous discussion of the relations between meteorological factors and inversions, and these will be summarized here for convenience.

Inversions generally increase in duration with increasing average inversion intensity, and most inversions lie in the range -2 to -10°F./1000'. Inversions formed between 1100 and 2200 hours generally last longest, with the 1100 to 1600 hour ones being primarily of advective origin whilst the 1700 to 2200 hour ones are primarily of radiative origin. Most inversion form in the 1700 to 2200 hour period, with the greatest diurnal variation in time of
formation occurring in winter.

Surface heating in the surface layer is sufficiently strong in all seasons to burn off almost all inversions during the day. This is not true in the deeper 35 - 810' layer when several inversions have lasted two to three days. Long inversions do not occur in summer since daytime heating is always strong enough to destroy any inversions and as a result summer inversion durations are grouped fairly tightly around ten to twelve hours.

Wind direction greatly affects the duration of inversions. Southerlies and south-westerlies bring the longest durations whilst northerlies, north-easterlies and easterlies bring the shortest durations. Winds speeds above 13 or 17 m.p.h. reduce inversion durations, and winds of 34 m.p.h. appear to be the maximum for even the shortest durations. Winds speeds in the 2 to 13 or 17 m.p.h. range have only a small effect on durations but winds less than two m.p.h. result in substantially shorter durations. Some seasonal variation is evident with maximum durations occurring at 3 to 4 m.p.h. in summer and 9 to 13 m.p.h. in winter and spring.

Durations generally decrease with increasing cloud but there is little effect with obscurities <6/10th's. Above this level durations rapidly decrease with increasing obscurity to 10/10th's. Most inversions occur with obscurities of $\frac{1}{2}$ to 2/10th's and frequencies decrease up to 10/10th's where there is a substantial rise.

Hourly pressure change as an indicator of general stability of the synoptic situation appears to be of little help in assessing
possible durations. Pressure on the other hand helps a little, especially in winter when high pressures (>1025 mb.) favour 17 to 24 hour inversions and low pressure (<1015 mb.) favours over 24 hour durations.
9.4 Occurrence of Long and Short Inversions

This section will examine inversions \( \leq \frac{1}{4} \) hours and \( \leq 8 \) hours in some detail in order to provide further understanding of inversions as a basis for evaluating and classifying the types of inversions affecting the Winnipeg area.

(i) Short Inversion Occurrence

Considerable seasonal variation exists in the percent frequency of short inversions (those \( \leq \frac{1}{4} \) hours) in the 35 - 200' layer, with short inversions being commonest in autumn, followed by winter/spring and finally summer (Table 9.35). Thicker layer (35 - 810') inversions show less seasonal variation but are still highest in autumn.

Summer short inversions are easiest to explain. Approximately 90% of those formed in early morning are burned off as the sun gets higher in the sky. Eighty to eighty-five percent of inversions formed between 1100 and 1600 hours are destroyed in \( \frac{1}{4} \) hours or less. These would generally be advection or frontal inversions. Once an advection inversion has formed in late afternoon or early evening in summer, it is much more likely to survive the night than in any other season and only 18% are destroyed in \( \leq \frac{1}{4} \) hours probably due to changing synoptic situations.

In winter approximately 2/3 of all inversions formed between 0500 and 1000 hours last \( \leq \frac{1}{4} \) hours since even the low sun is capable of destroying them. A surprising 31% of the inversions in the 35 - 200' layer formed between 1700 and 2200 hours last only \( \frac{1}{4} \) hours or less. Spring conditions are even higher than those in winter (42%), whilst autumn conditions are closer to summer.
These will be primarily due to changing synoptic conditions. The 35 - 810' layer is less likely to have short inversions than the 35 - 200' layer (35 versus 40%). This is because 35 - 810' inversions form less readily than the 35 - 200' inversions which are closer to the earth's active interface. Once 35 - 200' inversions become strong enough there is an upward development of the inversion to higher levels. This will only be destroyed by solar radiation in the morning or by a changing radiation and/or synoptic situation.

Cloud cover greatly affects the incidence of short inversions with an increase in cloud cover generally resulting in an increase in the percentage of short inversions particularly at 9 and 10/10th's obscurity (Table 9.36).

The effect of cloud on 35 - 200' inversions appears greatest in spring/winter and least in autumn/summer. Approximately 80% of all spring inversions occurring with 10/10th's cloud, lasted < 4 hours irrespective of time of day, whilst only 12% of those occurring with 2/10th's cloud lasted < 4 hours. The 35 - 810' layer inversions show less variation for small cloud obscurities and are most affected at 9 and 10/10th's obscurities.

In short high-cloud obscurities are thus an important factor in the incidence of short inversions irrespective of the time of day.
The wind direction also influences the percentage occurrence of short inversions (Table 9.37). Only 2.8% of 35 - 200' inversions occurring with southerly winds last \( \leq 2 \) hours, whilst 38.5% of inversions with easterly winds are \( \leq 2 \) hours. The range of percentage occurrence of short inversions is lower but there is still a substantial variation from 13.6% with southerly winds to 47.4% with westerly winds. The deeper 35 - 810' layer also shows great variations by wind direction with southerlies giving the lowest and northerlies giving the highest percentages of inversions of short duration. These figures also vary greatly seasonally.

In summer only 4.6% of 35 - 200' inversions with southerly winds last less than 4 hours. The corresponding value for the 35 - 810' layer is 9.7%. This is not surprising since southerly winds will generally be lightly cooled from below and in addition will be helped by radiation cooling at night. North-westerlies in summer have approximately 50% of their 35 - 200' inversions \( \leq 4 \) hours and this is due primarily to heating from below resulting in radiation inversions in the latter part of the night as lapse rates slowly decline from superadiabatics through weak lapses and finally to inversions due to surface heating offsetting radiational cooling.

In winter in the 35 - 200' layer 57.9% of easterlies are \( \leq 4 \) hours. Comparable figures exist for other directions from which winds flow over the rougher and lower albedoed tree covered Canadian Shield. This contrasts to southerlies and south-westerlies which experience strong advective cooling over predominantly flat snow covered arable land of high albedo.

In summary wind direction affects the percentages of
short inversions North-easterly, easterly and south-easterlies have high percentages because of good mixing over rougher topography, northerlies and north-westerlies are high because of surface heating, westerlies are high because of high cloud and fronts, whilst southerlies and south-westerlies are low because of advective cooling.

(ii) Long Inversion Occurrence

For convenience in analysis long inversions have been split up into 4 groups; >24 hours, >16 hours, >22 hours, >8 hours. There are so few >24 hour inversions that it is hard to generalize from such a small sample. However, no long inversions come from the north-east, east, and south-east in the 35 - 200/ layer, whilst south-westerlies have long inversions in 3 out of 4 seasons, and southerlies, westerlies, and north-westerlies in 2 out of 4 (Table 9.38). Winter has the most long inversions with 1 in 35 longer than 24 hours against 1 in 40 in spring. Sixteen hour inversions are common for all directions in winter because of the longer night length. Roughly 1 inversion in 6 is >16 hours long, and this is as high as 1 in 4 for southerlies and south-westerlies, and as low as 1 in 10 for easterlies, north-westerlies, and south-easterlies. Most of these inversions are advection in origin and frequently formed during the day and further developed by nighttime radiational cooling.

In spring the shorter nights result in a reduction of >16 hour inversions which now occur with a frequency of approximately 1 in 10 from the south, south-west, west, and north-west. In summer the short nights and rapid burnoff in the morning mean no inversions >16 hours in duration.
On an annual basis south-westerlies and southerlies result in three to four times as many >16 hour inversions as northerlies, north-easterlies, easterlies and south-easterlies.

Inversions over 12 hours occur on one inversion occasion in every five on an annual basis. Once again great variations exist by wind direction and season. South-westerlies and southerlies experience inversions of 12 hours or longer on one inversion occasion in three, and this rises to one in two with south-westerlies in winter. North-easterlies in contrast experience 12 hour and longer inversions on only one occasion in twenty.

Inversions over eight hours occur on just under one half of all inversion occasions, but this rises to four inversion occasions in five with south-westerlies and southerlies in summer and falls to one occasion in every four for easterlies and south-easterlies in winter.

In general the pattern in the 35 - 810' layer is similar to that in the surface layer although the actual percentages with long inversions are generally 10 to 20% higher (table 9.39). Nevertheless some differences do exist. Northerly wind directions in winter show much lower percentages of long inversions in the 35 - 810' layer than in the 35 - 200' layer. North-easterlies are also affected but to a lesser extent. This is probably due to the delay in formation and the slow vertical development of nocturnal radiation inversions which develop from the superadiabatic lapse rates prevailing with northerly winds during the day. These superadiabatics are due to heating by the ground into the very cold air aloft.

Cloud obscurities also strongly influence inversions of durations up to 16 hours but the effect is considerably reduced in
the 16 to 24 hour class and again in the >24 hour class.

The percentage occurrence of >8 hour inversions in the 35 - 200' layer (Table 9.40) is greater under clear skies and decreases steadily with increasing cloud obscurity. This illustrates the importance of nocturnal radiation loss in the development of >8 hour inversions in the lower layer. This is especially noticeable in summer when advection influences are at a minimum. At this time there is a 90% chance than an inversion will be >8 hours with 0 - 3/10th's cloud obscurity, and only an 8% chance when the sky is obscured. The decrease with increasing cloud is steady.

In winter, there is a 65% chance than an inversion once formed, will last for at least 8 hours when there is less than 0.5 tenth's sky obscurity. This decreases for 1/4 to 2/10th's obscurity and then increases to a secondary maximum with 2 to 4/10th's obscurity, illustrating the influence of the advective effect. Since there are more strong disturbances in winter than in summer, the percentages are also lower (66 versus 90%) since nocturnal inversions are frequently destroyed before the morning burnoff due to frontal passages and/or airmass changes.

The maximum value in the 35 - 810' layer (Table 9.1) occurs with 0 - 1/4/10th's obscurity in summer. There is a steady decrease with inversions >8 hours as cloud intensities increase but there is little change with increasing cloud for inversions >12 hours since many of these are not nocturnal radiation inversions.

In winter, inversions >8, 12, 16, 24 hours are all at a maximum with 2 to 4/10th's cloud obscurities indicating an advective
element in inversion formation. In winter there is a 72% chance that an inversion once formed will last over 8 hours when there is 2 to 4/10th's cloud, and only a 42% chance when there is 3/10th of cloud. With inversions over 12 hours the corresponding figures are 67% and 31%, and 47% versus 19% with 16 hour or greater inversions. The percentages for 3/10th obscurities are almost identical to those with obscurities of 9/10th's (31 versus 30% and 19 versus 20%).

In summer, the tables show that long durations of inversions are proportionately more likely to occur with 3/10th's cloud in the 35 - 200' layer and 2 to 4/10th's cloud in the 35 - 810' layer. In this higher layer the proportionate chance of a long inversion is the same as with 9/10th's cloud illustrating the greater importance of the advective element in inversions in this higher layer.
9.5. Numerical Classification of Inversions

9.5.1 Introduction

General Comments and Method

This section will use numerical taxonomy to help identify clusters and hence to classify inversions on the basis of several meteorological variables.

The data was prepared by first abstracting the summer and winter results for the 35 - 200' and 35 - 810' layers. Several test runs were then made using different variables to 'get a feel for' the data. Six variables were chosen for the final runs. These were inversion duration, inversion intensity, cloud cover, wind speed, temperature, and pressure. These were chosen since it was desired to generate a classification which would be of use in general terms for air pollution potential studies. All six variables are available from first order weather stations and from micrometeorological tower data. The relationship of the variables to the air pollution problem is summarized in table 9.42.

Wind direction is absent from the list since it could not be used directly as it was not a continuous variable. Difficulties would arise when north-westerly and north-easterly winds were compared because they are closer to each other than the average value (a south wind) indicates. Wind direction is related to variables such as pressure, obscurity, and intensity and subsequent examination after classification revealed that each cluster had concentrations in one or two wind directions.
The procedure used in the cluster analysis was as follows: A 230 by 230 (or similar) matrix of distances between all observations, expressed as points in orthogonal six dimension space, is calculated. The problem is to group the observations in this similarity matrix with respect to some objective function. A grouping procedure developed by Ward (1963) was used (see Wishart 1968 for a comparison with other methods).

Ward's method permits reduction in the number of groups (original observations) from n to n-1 in a way which would minimize the loss of information and similarly systematically repeat the process until the number of groups is reduced from n to one. At each stage of the grouping procedure, two groups, either single or multiple membered, are joined to form a new group. The objective function used in this method is to join the groups such that the new group adds the least possible increment to the pooled within group sum of squares calculated from the distance squared matrix. The function has the advantage of producing groups of relatively equal size (Wishart, 1969), at least compared to such other methods as centroid grouping or gravity grouping. However, in all these types of grouping the result is a complete hierarchy of groups of observations.

Efficiency in Grouping

A 'linkage tree' can be drawn up to display each stage in the grouping analysis, together with the makeup of the groups in terms of the original observations (figures 9.2 to 9.5). They also show a quantitative measure of the efficiency of grouping, that is, the loss of information with respect to the objective function is calculated at each stage. This amounts to what is essentially a scale
of efficiency. Sharp breaks in the scale may be some significant level of grouping. In this study a reduction of the 230 observations into 23 groups would result in a loss of detail of less than 1%, that is, less than 1% of the total variation will be lost.

Stages in Grouping

Preliminary analysis showed that the loss of efficiency started increasing at between 15 and 10 groups, and so these were looked at in detail and finally subjective decisions were made. All that now remained was to choose the level of grouping required for the particular study. This was done with respect to the purpose of the classification and the efficiency measures.

The above, together with intuitive concepts of the structure of inversions formed the basis for the choice at steps 217 in winter and 213 in summer for the 35 - 200' data. This produced 13 and 12 categories respectively with associated measures of efficiency of 95.0% and 96.6%. In other words, the number of inversions has been reduced from 225 - 230 to 12 - 13 groups for a loss of detail of less than 5%. (tables 9.43 to 9.46)

9.5.2 Numerical Classification of Inversions

Introduction

The 13 clusters produced by Wards clustering method for the winter 35 - 200' data are presented in table 9.43. The clusters were produced using six active variables. These were inversion duration (hours), inversion average (°F/1000'), wind speed (m.p.h.), average sky obscurity (tenth's), average temperature (°F.), and average
sea level pressure in millibars. Information upon wind direction and other meteorological variables is presented as background information as an aid to interpretation. These variables did not affect the clustering process in any way.

It should be emphasized once again that the clusters in tables 9.43 to 9.46 are not by any means the only possible ones. They simply represent one set of groupings based upon six selected variables which may help in classifying and synthesizing the vast mass of data on inversions. Six variables greatly exceeds the two or three which could have been looked at using ordinary subjective analysis techniques.

The analysis of the clusters which follow will attempt to fit these into a broad meteorological framework on a subjective basis. Further grouping has been done on the basis of duration and clusters have been labelled as being primarily of radiation or advection origins or both. This was done intuitively using the results of other analyses done in this work but it must be remembered that most advection inversions are acted upon by nocturnal radiation. Considerable variation also exists within each of the clusters although by definition it is less than that between clusters. There is thus considerable room for error in subjectively tagging these clusters.

Some modes of formation cannot be adequately detected using this method on readily available data. These include subsidence inversions and frontal inversions. The former will be put in with radiation inversions whilst the latter will probably be masked by the greater number of advection inversions. Nonetheless it is
felt that such a split into long, medium, medium-short, and short inversions is some use as is some general indication of mode of formation. Such a classification scheme follows.

Numerical Classification of 35 - 200' Winter Inversions

Thirty-five to two-hundred foot inversions in winter have been grouped into 13 clusters. The characteristics of these clusters are summarized in table 9.47. Two basic levels of classification are outlined. The basic fourfold division is based upon duration and is important from an air pollution potential standpoint owing to the importance of this variable in the accumulation of pollutants in the air. Very few long inversions are in evidence and these are equally split between the longer advection inversions of cluster one and the shorter radiation inversions of cluster two. The cluster one inversions are primarily from the south-west and are accompanied by above average wind speeds and temperatures. The long radiation inversions of cluster two result in a much higher air pollution potential since they are accompanied by below average wind speeds and temperatures, resulting in decreased mixing and increased heating, and therefore increased pollution emissions and concentrations. It is more difficult to plan to reduce their effect since they come from many different wind directions depending upon the location of the high pressure cell relative to Winnipeg.

Medium duration inversions are much more common. Approximately 25% of all winter inversions lie in the 14 to 17 hour range, and of these, approximately 67% of of radiation origins and 33% of advection origins. The radiation inversions in this group are
primarily nocturnal radiation inversions which are destroyed by solar radiation the following morning.

Medium-short inversions are also common and make up a further 40% of the total. Mean durations are around six hours and the majority are of radiation origin. A final 25% are short inversions and many of these are of frontal and advection origins.

The thirteen cluster classification scheme yields considerably more insight into inversions. Pressure, temperature, wind speed, wind direction, and cloud information all combine to give a fair picture of the overall synoptic situation associated with different types of inversion and vice-versa. The classical radiation inversion with long durations during long nights, and low cloud cover, low wind speed and high pressure exists in the form of cluster two. Inversions in cluster ten identify a synoptic type based upon north-westerly winds, whilst those in clusters eight and eleven are frontal/advection inversions.

Further insight into the groupings can be obtained if we examine which clusters join up with each other (figure 9.2). Clusters ten and thirteen are radiation inversions based upon north-westerly flow and they remain as one cluster to the five cluster stage, that is, they are very distinct as a group. Clusters six and eleven, advection/frontal inversions, join and also remain distinct as a group based upon south-westerly and westerly flow. Clusters five, nine, and twelve all join to form a group of radiation inversions based upon north-westerly, northerly, and westerly flow. They eventually join with clusters two and four (radiation, west, north-west, northerly) at the four group stage to form a huge group of radiation inversions.
based upon north-westerly, westerly, and northerly flow. In contrast clusters one, three, and eight (advectional) as well as seven (radiational) combine to form a large group of advectional inversions based upon southerly and south-westerly flow. Cluster seven is included although it appears to be a misfit.

The entire technique offers considerable promise in grouping since much of the above would have been almost impossible to do by applying subjective analysis techniques to two or three variables at a time.

In short, it is felt that cluster analysis has not only aided in the grouping of inversions but has also helped in understanding the general weather conditions associated with the inversion picture in the 35 - 200' layer in winter.

Numerical Classification of 35 - 810' Winter Inversions

The 35 - 810' layer was examined in a manner similar to that used for the 35 - 200' layer (table 9.48, figure 9.3). Preliminary analysis of the output indicated that it would be best to examine the 15 cluster level in detail rather than the 13 cluster level due to the greater variability of the data.

The clusters produced for the 35 - 810' layer were less satisfactory than those produced for the 35 - 200' layer. This occurred primarily because of the greater variation within clusters, and subjective analysis of the original data did produce conflict between the numerical and intuitive approaches on occasion. This occurred primarily because the processes responsible for inversion development
and decay in the 35 - 810' layer appear to be much more complex than those in the closer to the surface 35 - 200' layer. It may also be due to the increasing importance of variables not measured, such as large scale subsidence or advection.

Despite these comments the clustering process has still produced a reasonable classification scheme, and a better general one than could have been produced solely by an examination of the data two or three variables at a time. A summary of this scheme now follows.

Clusters one, two, and three are all primarily long radiation inversions lasting between one and three days. All wind directions except north are present with a favouring of north-westerly and south-westerly flow. In one case easterly winds averaged 2-4 m.p.h. and never exceeded 10-4 m.p.h. throughout the entire 51 hour inversion, thereby contributing to very high air pollution potential. Clusters four and seven are long and medium advection inversions which join to make a large cluster of advection inversions associated with south-westerly flow. These later join with clusters six and ten to form a large group of inversions of diverse origins based upon south-westerly and westerly flow. Clusters twelve and fourteen are advection inversions from the south-east and south. They join to make a distinctive cluster of advection inversions which remains to the four cluster level, when it joins to make a huge cluster based upon southerly airflow in general. Clusters nine and thirteen, advection/frontal inversions of diverse airflow types, join to form a group of short inversions distinctive to the three cluster level.

In short, the cluster analysis program has identified six fairly distinct groups of inversions, namely:
1) Long radiation inversions from the north-west and south-west
2) Medium and medium-short radiation inversions from the west and north-west
3) Long and medium advection inversions from the south-west
4) Medium radiation inversions from the south-west and west
5) Short advection inversions from the south and south-east
6) Short frontal/advection inversions primarily from the west and north

It must be admitted however, that considerable within group diversity exists.

Numerical Classification Scheme for 35 - 200' Summer Inversions

There is much less variation in summer than in winter and no long inversions persist in summer. As a result, early attempts to classify this data subjectively met with little success. Radiation is the main mechanism for inversion formation although advection of warm air over a cold surface can result in earlier inversion formation in late afternoon, whilst cold air over a warmer underlying surface usually results in inversions forming later in the evening.

The cluster analysis scheme for this data can only be described as marginally successful (figure 9.4; table 9.49). Some distinctive synoptic situations do emerge, however. Cluster eight is based upon north-westerly and northerly mP airflow, whilst cluster six consists mainly of advecting mT air. Clusters nine and ten make up a distinctive group based upon northerly, north-easterly, and easterly airflow. However, only two distinctive groups emerge at the six cluster level. Groups three and six have joined to give a group based upon westerly, south-westerly, and southerly flow whilst groups nine
and ten have joined to make a large group based upon northerly, north-easterly, and easterly airflow. The four other clusters are very diverse in terms of the six variables.

Numerical Classification Scheme for 35 - 810' Summer Inversions

The overall pattern of 35 - 810' summer inversions is not unlike the 35 - 200' pattern with no long inversions (table 9.50, figure 9.5). Longest durations are associated with southerly and south-westerly airflow (clusters 2 and 4) and seem to be fairly independent of wind speed. Cluster five has a large north-easterly and easterly component and high cloud obscurities. Cluster seven is dominated by south-easterlies with exceptionally high average wind speeds, very low pressures and high obscurities.

There is little variation among inversions in general as evidenced by the short distance along the x axis between the 207 cluster and the three cluster level (compare with figures 9.2 to 9.4). Generally speaking the three main types are south-easterly flow, north-easterly/easterly/north-westerly/westerly flow, and southerly/south-westerly/westerly flow.
9.5.3 Discussion and Conclusions

The effectiveness of the above numerical classification scheme largely depends upon the choice of the clustering variables. If the variables truly account for the variation in inversion character then the clustering technique will work well. On the other hand, if the character is not well explained by these variables, as in the summer case, then the technique will only have limited success. Cluster analysis must not, therefore, be applied blindly. Some understanding of the relationships between inversions and weather conditions is a necessary prerequisite to grouping.

This understanding need not be obtained by an examination of the relationship between two or three variables at a time, as for example, between inversion duration, cloud obscurity and season. It can also be obtained by performing multivariate statistical analysis, such as factor analysis, to the data. Many variables can be inputted to the factor analysis and principal factors and factor loadings will give a good idea of the important variables. Such a technique was applied to this inversion data and results indicated that the main factors influencing inversion duration were based upon the same six variables as had been selected from the initial analysis using crosstabulation techniques. The main advantage of factor analysis is its speed and ability to compress the output. Its main disadvantages lie in the many assumptions made about the distribution of the data (normality) and the relationships among variables (assumed to be independent). Such statistical constraints do not apply in crosstabulation, and this is why it was favoured over factor analysis.
It is felt that the above numerical classification schemes are as satisfactory as can be obtained using regular hourly numerical weather observations. A more efficient classification scheme could only be obtained by utilizing weather factors not reported upon a regular basis, such as advection, subsidence, and the radiation balance of the inversion layer.

Despite the above limitations it must be concluded that the above numerical grouping of inversions on the basis of six variables shows considerable promise. It has produced groups which can be labelled genetically, such as long radiation inversions, short advection inversions and so on. In addition it provides full details of the average and extreme weather for such groups, as well as measures of variability based upon standard deviations of the variables within each cluster.

In conclusion it is felt that the technique of numerical classification offers substantial advantages, in terms of repeatability, speed, flexibility, and number of identifying variables, over classical methods of analysis. It does not replace such methods but rather it supplements them, especially at the final time consuming classification stage.
1 Windspeeds are calculated for the mean height of the layer as follows: For the 35 - 200' layer the mean height is

\[
35' + \frac{200 - 35}{2} = 117'.
\]

For the 35 - 810' layer the mean height is

\[
35' + \frac{810 - 35}{2} = 422'.
\]

The windspeed for 117' and 422' is calculated using a power law expression where the exponent is based upon the 35 and 810 foot windspeeds.
CHAPTER TEN

Discussion and Results

10.1 Review

Extensive analysis of temperature, lapse rate, wind, and inversion tower data have been performed for the lowest 810' of the planetary boundary layer. Selective stratification of these data has shown the dependence of lapse rate and inversions upon height, wind speed and direction, cloud cover and pressure. Conclusions concerning the physical processes associated with these variations have been made within each chapter. The impact of these variations upon inversion duration and intensity has been examined in some detail. Lapse rates and inversions have been classified quantitatively and cluster analysis has been shown to be effective in establishing a genetic classification scheme for inversions. The diurnal distribution of wind speed and direction has also been explained.

10.2 Results and Conclusions

The results of the analysis of temperature, lapse rate, and wind in the lower 810' near Winnipeg generally confirm existing theory.

Lapse rates have a larger range near the surface and this decreases with increasing height as more lapse rates fall into the weak lapse category. Average lapse rates are more negative in Winnipeg compared to published results for other areas (35 - 200' layer, -6.7°F).
/1000' versus -4 to -4.5°F./1000' elsewhere). Inversion conditions prevail for an average of 20 hours per day in winter and between 12 (35 - 200' layer) and 7 (400 - 810' layer) hours in summer.

Superadiabatics are usually confined to the lower 400'. From 400 - 600' and again from 600 - 810' there is a rapid decrease of superadiabatics, and even in summer, they affect the highest layer for only two hours per day on average. They are most frequent when windspeeds are over 15 m.p.h. Superadiabatics show their greatest monthly increases from March to April to May associated with increased solar radiation and the disappearance of snow resulting in lower albedos.

Lapse rates are strongly influenced by the nature of the underlying surface and wind direction, especially in the winter half of the year. For example, superadiabatics are common in the lower 400' when cold northerly air advects over a surface previously warmed by westerlies. Overall south-easterlies, easterlies, and north-easterlies favour weak lapses in winter; north-westerlies and northerlies favour superadiabatics, whilst westerlies and south-westerlies favour inversions.

The boundary layer and the free atmosphere remain uncoupled until mid-morning in summer. In winter coupling occurs in the 400 - 600' layer at 1600 hours, and not at all in the 600 - 810' layer.

The diurnal variation of temperature with height exhibits a rapid decrease in the diurnal cycle to 400' followed by a relatively slower change in the next 400'. Maximum temperatures exhibit a phase shift with increasing height.
The majority of surface radiation inversions are also confined to the lower 400 or 600' and they very rarely reach 810'. Inversions propagate upwards in summer at about 100'/hour. Many inversions in the 400 - 600' and 600 - 810' layers are due to the lifting of surface inversions associated with increased morning turbulence. Such inversions are usually destroyed by mixing within two hours. Like superadiabatics most inversions in the 600 - 810' layer are also associated with winds of greater than 15 m.p.h.

The long inversion season (>18 hours) lasts from November to March. Inversions increase from 18 to 72 hours between October and November, and decrease from 48 to 18 hours between March and April. Summer inversions never exceed 16 hours. The strongest inversions generally occur in spring and autumn (35 - 810' temperature differences of 33°F.) in association with winds of six to eight miles per hour (67% of all occasions).

On average, windspeeds of 2 to 13 m.p.h. in winter and 3 to 4 m.p.h. in summer yield the longest inversions. Inversion durations decrease above these speeds and all inversions are destroyed with winds over 34 m.p.h. Annual cloud obscurities under six tenth's have little effect on durations but above this, durations quickly decrease. In winter cloud obscurity is a more critical factor and durations decrease above four tenth's. Streamlines also affect inversion durations, and the longest inversion average durations come from the south and south-west, whilst the shortest durations come from the north, north-east, and east.

The thermal stratification of the lower 810' strongly affects the mean wind profile through its influence on the distribution
of turbulent momentum transfer. In general increased stability decreases the depth of the planetary boundary layer and increases wind shear.

The diurnal change in the lapse rate results in variations in the depth of the momentum or Eckman boundary layer, and the formation of an inertial boundary layer below 810' shortly after sunset. Throughout the night and morning hours the planetary boundary layer is made up of the momentum and inertial boundary layers. The influence of the inertial layer thus eliminates the feasibility of explaining wind profiles in terms of the existing lapse rate, except during the afternoon when the inertial boundary layer is destroyed and a balance exists among the coriolis, pressure gradient and frictional forces.

Frequencies of light winds show that Winnipeg can receive almost three days of winds less than nine miles per hour, and over two days of winds less than six miles per hour. In the winter air pollution season long runs of northerly, north-westerly, and westerly winds constitute one problem whilst shorter runs of lighter (<3 versus <9 m.p.h.) winds from the east and north-east pose another problem in terms of the atmospheric dispersion of air pollutants. This will be considered further in the next section.

10.3 Applications

Much of the latter part of the present work has dealt with the problem of identifying groups of inversions and relating these groups to the weather present at the time. This section will use these results to establish an inversion index and an air pollution classification scheme based upon inversion duration and wind in the lower 810'.
The main features of inversions are their intensity, duration, and frequency. None of these alone adequately describes inversion character. If all three are multiplied together to form an empirical index then we get a better idea of this character. This has been done in table 10.1 for each month and level. The numbers have no physical meaning and hence units are left out.

Whilst most inversions occurred in December, the longest and strongest inversions occurred in March. Taking all three characteristics together March shows values 40% higher than the next highest month (February), whilst December and May are lowest. The table also points out the striking decrease in the index from 200 to 400\(^\text{′}\) (7219 to 2865), and from 600 to 810\(^\text{′}\) (2513 to 905), with little difference between the 200 - 400\(^\text{′}\) and 400 - 600\(^\text{′}\) layers.

Although the above table is of considerable theoretical interest it is of little practical use. Town planners, for example, are much more interested in knowing the probability of a long inversion, along with its associated wind speed. This information can readily be extracted from the results of the last two chapters. Comments will be restricted to the 35 - 810\(^\text{′}\) layer in winter since this is the one with the longest inversions in the season of high air pollution potential. This layer can be expected to give fairly good results (within the limits set by the fairly short sampling period of 27 months) since surface heating has almost died out at this height on most occasions resulting in a stabilizing of inversion durations.

In winter 22\% of all south winds have inversions over one day (table 9.39) compared to 3.6\% for west winds. However, inversions from certain directions are associated with light winds and others, with
moderate winds so table 9.39 must be interpreted with caution as far as air pollution potential is concerned. We really need a list of long inversions with their associated wind speed characteristics. This is done in table 10.2.

The greatest frequency of long inversions occurs from the south, south-west, and north-west. However the lightest winds associated with long inversions are from the east. Of the two long easterly inversions one (which lasted over two days), had an average wind speed of only 2 to 4 m.p.h., and the other had an average speed of 4 to 9 m.p.h. Inversions from the north and south also had low average wind speeds of 4 to 9 m.p.h. Easterlies, northerlies, and southerlies are thus the directions with the worst air pollution potential since they have both long durations and low average wind speeds, unlike the other directions which have long inversions with moderate or high windspeeds. Easterly winds, although they rarely bring long inversions, have a greater probability of very high air pollution potential than southerly winds although the two are very close.

It is significant that it is the east side of the city that is going to experience the greatest increase of industry in the future. This means that should emission rates increase substantially as Winnipeg industrializes, then we can expect serious air pollution hazards in the future. Whilst it must be admitted that the conscientious town planner in Winnipeg has a difficult choice (all eight major wind directions experience long inversions), the safest sector is undoubtedly the south-east, since this is the direction where long inversions are always coupled with high wind speeds (>17 m.p.h.).

North-easterlies, south-westerlies, westerlies, and north-westerlies
experience average wind speeds of at least 9 - 13 m.p.h. during long inversions. Such speeds are probably sufficient to provide adequate dilution of air pollutants but this would have to be checked out using appropriate diffusion equations.

In conclusion it must be restated that industrial growth is scheduled for the east side of the city and that this side, closely followed by the south side, will cause the highest air pollution potential over Winnipeg as emissions slowly drift westwards over the majority of the city.

10.4 Extension of the Present Work

One of the greatest needs in microclimate is to expand the period of observations. This is currently being done for the C.B.C. tower observations and five year averages will soon be available. This will enable more definitive statements to be made about the air pollution potential of Winnipeg as well as the distribution of temperature, lapse rate, and wind in the planetary boundary layer.

The relationship of lapse rates to specific air masses is poorly understood. This is best approached by identifying several characteristic types, categorizing each day, and merging this information with tower and regular hourly observations for subsequent stratification and analysis.

The morning and evening transition periods also warrant further investigation. This would best be done by reorganizing times to correspond to sunrise and sunset. Data stratifications could then be performed from X hours before to Y hours after sunrise or sunset. Several ten minute averages per hour would be necessary to give the entire picture rather than one based upon the start of each hour.
The rapid fluctuations in intensity of nocturnal radiation inversions also warrant detailed investigation. Several case studies should be undertaken using the full range of available data rather than simply hourly ten minute averages.

The greatest difficulty experienced in this study was the lack of detail available in the lowest 100' on temperature and wind. This is about to be corrected by installing a 122' tower close to the present one. Data will be gathered on temperature (5 levels), wind (3 levels), UW wind (2 levels), dew point (2 levels), net radiation (2 levels), and solar radiation (2 pyranometers). In addition a wind sensor is being placed at 400'. It is expected that this will greatly facilitate detailed studies of the planetary boundary layer.
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