The University of Manitoba

STRUCTURAL BEHAVIOUR OF INVERSIONS IN THE LOWEST 810 FEET DURING THEIR DEVELOPMENT AND DECAY IN WINTER AT WINNIPEG

by

Larry R. Partap

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the
Requirements for the Degree of
Master of Arts

Department of Geography

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MASTER OF ARTS

To my parents,

Francis Partap,

Alice Partap,

without whose unceasing encouragement,
inspiration and self-sacrifice this
dissertation would never have commenced;

and to

Shirley Mae, my wife

without whose devotion, patience and
understanding it would never have been
completed.

ABSTRACT

This study investigates the structural behaviour of winter inversions lasting not less than 10 hours in the lowest 810 feet at Winnipeg. Attention focuses on the development and decay processes in relation to synoptic meteorological conditions. The temporal range of inversion development and decay is examined. Inversion cases representative of Bell's (1974) classification scheme are identified and analyzed. The synoptic situation associated with each case study is determined and an attempt is then made to evaluate the structural behaviour in terms of weather processes. The results are interpretated with a view of providing an insight into their revelance to air pollution potential studies.

This study uses temperature and wind data observed on the C.B.C. television tower at Starbuck, Manitoba, hourly synoptic observational data from Winnipeg International Airport and daily weather maps (Surface, 500 and 850 m.b. Charts).

A model based on the cyclical component of diurnal temperature variation is used to assess the temporal distribution of inversions in two layers (25-200 and 35-810 feet). The majority of the 35-200 feet layer inversions develop in the radiative heat loss period from 1500 to 0700 hours and

decay in the radiational heat gain period from 0800 to 1400 hours. The greatest hourly frequency of development occurs at the mean time of sunset (1700 hours), and that of decay at the mean time of sharpest increase in temperature (1100 hours). The model is adjusted by a 2-hour factor to accomodate the temporal distribution of inversions in the deeper 35-810 feet layer.

Bell's (1974) numerical classification of winter 35-200 feet inversions lasting not less than one hour is adapted for use in this thesis. Among the 13 inversion clusters, 6 clusters include predominately inversions of duration not less than 10 hours. The selected clusters are approportioned into two groups identified as the 'Radiative Clusters' and the 'Advective Clusters'.

The structural behaviour of inversions in the radiative clusters is significantly related to the diurnal effects of solar radiation heating. The 35-200 feet layer inversions develop and decay first, and the processes are observed with a lag of up to 3 hours in the deeper 35-810 feet layer.

The irregular component of advective heating and cooling induced by air mass movement is the important factor controlling the structural behaviour of inversions in the advective clusters. The dynamic character of this component provokes complexities with respect to inversion structures and related weather processes. In general, the 35-810 feet layer inversions form before, and dissipate simultaneously with, the inversions in the 35-200 feet layer.

This study indicates that intense radiative inversions conducive to the highest air pollution potential hazard occur when the weather scene is influenced by an anticyclonic circulation of clear, cold Arctic air (cA). The higher inversion is presumably sustained by atmospheric advection, while the lower inversion is subject to temporary daytime decay around noon. This presumably facilitates an increase in the depth of the effective mixing layer so that air pollutants can be dispersed and diluted more readily. Intense advective inversions conducive to the greatest accumulation of potential air pollutants are associated with the advection of warm Maritime Polar (mP) westerly air under the control of a cyclonic system (usually Alberta low). A critical feature is the strong winds associated with these inversions which presumably aid the horizontal dispersion of air pollutants even in the presence of low level inversions.

ACKNOWLEDGEMENTS

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My gratitude is also owing to Mr. E. Pachanuk for his prompt and skillful preparation of all illustrations presented in this thesis. I wish to express my deep appreciation and thanks to my brother, Winston, and sisters, Betty, Joan and Loretta for their constant interest in my education, devotion and unceasing encouragement. Finally a special word of thanks is extended to Mr. and Mrs. N. Kingdon for their enthusiasm and constant concern during the course of this research.

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CHAPTER I

Introduction

The study of inversion structures is an important climatological problem, but one that is seldom considered and therefore not extensively studied in the literature. This thesis is an investigation of the structural behaviour during the development and decay of winter inversions lasting at least 10 hours in the lowest 810 feet near Winnipeg. The formation, maintainence and dissipation of inversions are significantly related to prevailing weather conditions. The latter are thus inescapable in any explanation of inversion structure behaviour. Satisfactory description and explanation of this relationship is lacking, especially with respect to specific synoptic systems in a particular area. It seems desirable therefore, to conduct an extensive investigation into inversion structure behaviour responsive to synoptic meteorological conditions in a continental environment.

It is expected that a climatological survey of this kind will be useful in air pollution potential studies. This arises because the fate of pollutants emitted into the atmosphere is largely a function of weather processes. The constraints imposed by natural processes are therefore the principal determinants of both inversion structure behaviour and air pollution accumulation.

The height and extent of inversion layers play critical roles in influencing the dispersion of air pollution by restricting vertical mixing (Williamson, 1973, p. 158). A progressive subsidence of air aloft in a slow moving or stagnant anticyclone, for example, can cause formation of a low-level inversion. Consequently, the scale of the effective mixing layer is decreased. This induces a greater pollution hazard as less pollutants are dispersed and diluted due to poor ventilation.

Many of the severe air pollution episodes (for example: Meuse Valley, Belgium, 1930; Donora, Pennsylvania, 1948; London, England, 1952) occurred in the winter months in the northern temperate zone when adverse meteorological conditions, such as stable stagnating air masses with shallow inversions, impeded ventilation and dispersion. Only a change in weather conditions such as the passage of a frontal system, can alter the existing lapse rate characteristics (Bach, 1972).

All weather processes which influence both lapse rate character and the dispersion of air pollutants take place in the lower atmosphere or the planetary boundary layer. A thorough understanding of the climatology of the lower atmosphere is thus of considerable importance.

Unfortunately, as the boundary layer is a very complex domain, description and explanation is generally inadequate, especially for particular areas. Awareness of and concern about this lack of knowledge prompted Bell (1974) to perform a comprehensive analysis of the vertical distribution of temperature, lapse rate and wind in the lowest 810 feet near Winnipeg.

The objective of Bell's (1974, p. 2) work was "to obtain a description useful for air pollution potential studies, of the variations of temperature, lapse rate, wind and inversions in the lower 810 feet, due to diurnal, seasonal and synoptic changes." The present study is a direct outgrowth from the availability of this detailed information. In particular, that area of Bell's research (Ch. 9) pertaining to the classification of winter inversions in terms of the normal observed meteorological elements, forms a basic conceptual framework of this study.

1.1 Objective

The objective of this study is to investigate the structural behaviour of winter inversions of duration not less than 10 hours in the lowest 810 feet. Attention focuses on the development and decay processes in relation to synoptic meteorological conditions. The temporal distribution of inversion development and decay is examined.

Inversion cases reasonably representative of Bell's (1974) classification scheme are identified and analyzed. Once the inversion case structure associated with a synoptic situation is determined, an attempt is then made to evaluate the results in terms of weather processes. It is hoped that a climatological survey of this kind, in addition to its general scientific value, will be specifically applicable to air pollution potential studies.

1.2 Data

From the Atmospheric Environment Service (Winnipeg International Airport) regular hourly synoptic observational data were obtained and merged with the tower data collected by Bell (1974) to form the data base of this thesis. Daily weather maps (Surface, 500 and 850 m.b. Charts) were obtained to provide a general insight into synoptic conditions. Only data for the core winter months December, January and February were used in the present study. All units of measurements used in this thesis are imperial.[1]

The Canadian Broadcasting Corporation (C.B.C.) 1000 feet high television tower at Starbuck (latitude 49°46' north, 97°31' west), located 19 miles

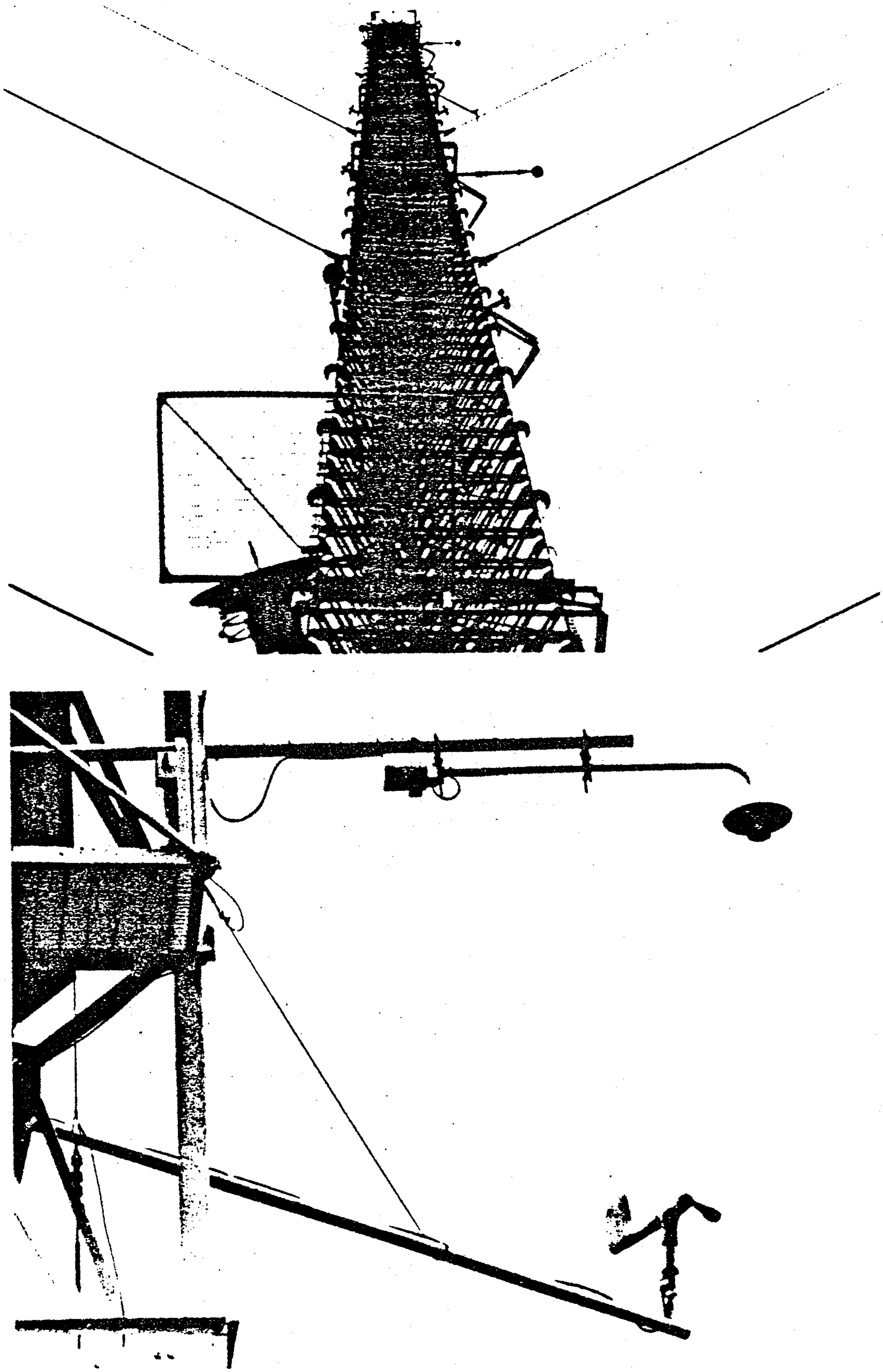
1. Conversion Tables are provided in Appendix 1.

west-south-west of the centre of Winnipeg, was instrumented with temperature and wind sensors (Figure 1.1). Bell collected the data on computer compatible magnetic tape over a 33 month period, from the winter of 1969 to the summer of 1972. Figure 1.2 shows the data acquisition system.

Temperatures at five heights (35, 200, 400, 600, and 810 feet) were measured using platinum bulbs (Rosemount 104 MACCA) mounted in aspirated Beckman and Whitley Radiation shields. Readings were taken every 30 seconds throughout the day; and, the error from one reading was found by summing the squares of the individual errors and taking the square of the sum. For a 10-minute mean (20 readings) Bell determined a standard deviation of 0.012°F in differential mode, and 0.039°F in absolute mode. In this thesis only the temperature data at three levels (35, 200 and 810 feet) were used.

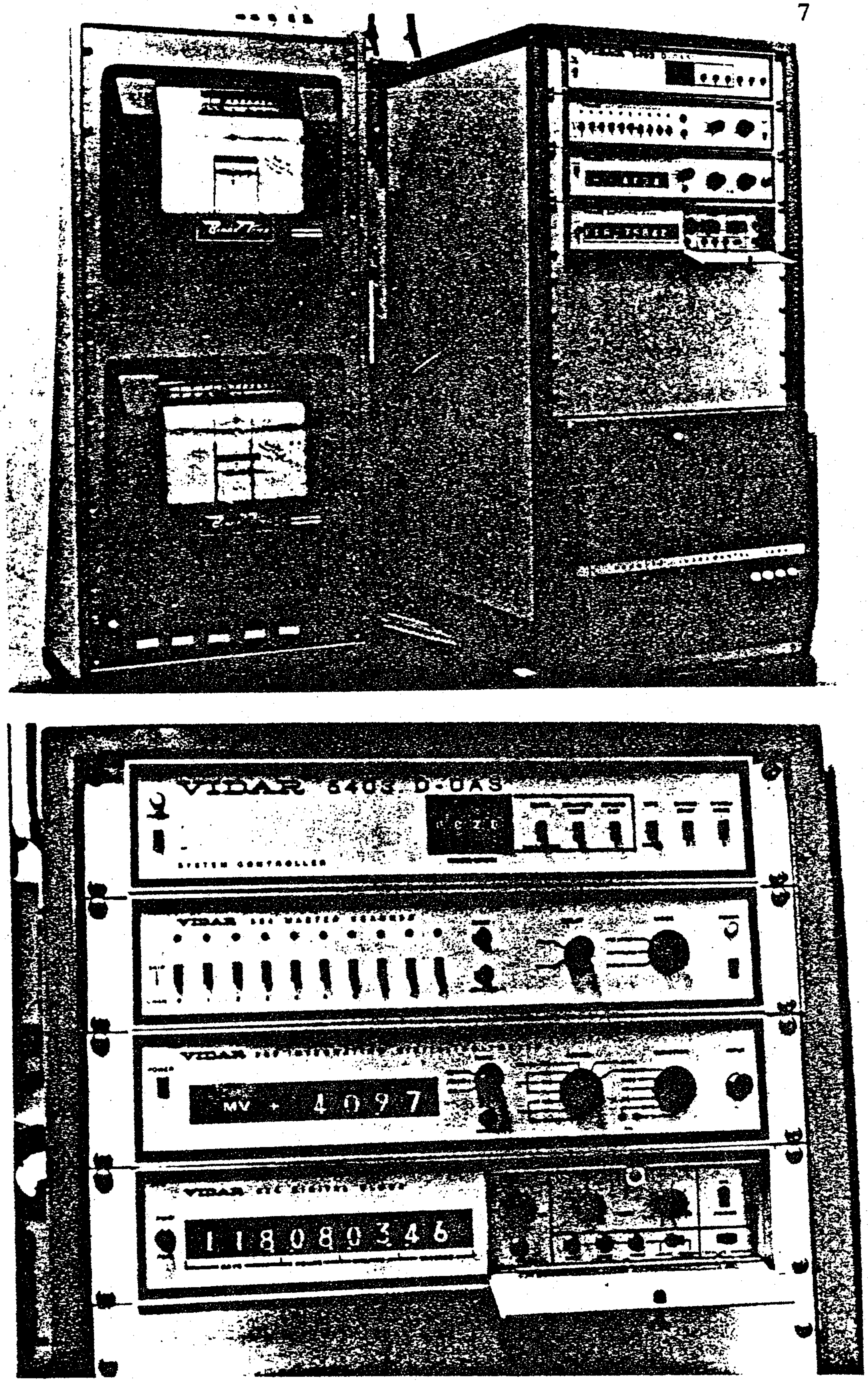
The Bendix-Friez model 120 aerovanes mounted at 35 and 810 feet levels measured both wind speed and wind direction. A Hewlett-Packard programmable calculator and digitizer replaced the earlier system of wind data collection from charts by visual scaling once per hour. "A ten minute average accurate to $\pm 3°$ for wind direction and $\pm 1/2$ m.p.h. for wind speed, was taken from the hour

Figure 1.1



Temperature and Wind Meteorological Instruments,
C. B. C. Tower, Starbuck
SOURCE: BELL (1974)

Figure 1.2



Data Acquisition System, C. B. C. Tower, Starbuck

SOURCE: BELL (1974)

to ten minutes past the hour" (Bell, 1974, p. 44).

The temperature and wind data were run through various error routines on the computer and bad data were eliminated. The data were edited several times and then placed on one reel of tape.

1.3 Methodology

The approach of this study is primarily descriptive. Structural behaviour of inversions during development and decay are investigated with the aid of tower data, regular hourly synoptic meteorological data and daily weather maps.

In Ch. 2 winter inversions of duration not less than 10 hours[2] are extracted from the 35-200 and the 35-810 feet layers tower data and subjected to a temporal examination. A model of the diurnal distribution of inversions is applied.

Utilizing six meteorological variables Bell (1974 Ch. 9) classified inversions using Ward's (1963) algorithm for cluster analysis. With respect to purpose of classification and efficiency measures, Bell identified 13 clusters among the 35-200 feet layer winter inversions.

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2. Criteria of inversion duration not less than 10 hours arbitrarily selected.

In this thesis these clusters are exposed to a dispersion technique to facilitate the selection of clusters reasonably representative of inversions lasting at least 10 hours in duration. The selected clusters are then subdivided on the basis of dissimilarity in their inherent properties (Ch. 3).

Inversion cases representative of each selected cluster of the resulting typology are chosen for detailed study of their structural behaviour during development and decay. Once the inversion structure of each case study associated with a synoptic situation is determined, an attempt is then made to assess the results in terms of weather processes (Chs. 4 and 5). Since a multitude of synoptic situations may contribute to either the thermally produced radiation inversion or, the mechanically produced advection inversion, the processes involved in each are examined in the respective chapters through case studies.

In concluding, the results are interpreted with a view to providing an insight into their relevance to air pollution potential studies.

CHAPTER II

Temporal Distribution of Development and Decay of Inversions

2.1 Introduction

Lapse rates vary considerably both in space and time. Since the spatial co-ordinate is fixed in a continental environment, the temporal range must be identified if meaningful patterns are to be established. With order introduced to the temporal distribution of inversions development and decay, the subject of inversion structure behaviour can be better appreciated and understood.

A diurnal cycle, characterized by the episodes of sunrise and sunset, provides a rational framework for the temporal examination of inversions frequency distribution. Winter inversions lasting at least 10 hours in duration in the lower 35-200 feet layer and the higher 35-810 feet layer are abstracted from the sampling period (October 1969 to June 1972) and examined.

The view is commonly held that lower level inversion occurrences are closely related to the times of radiational heating and cooling near the surface. During the hours of daylight, from shortly after sunrise to just before sunset, temperature generally decreases with height in the lower 100-300 meters, rapidly in the lower layers and more slowly at greater heights (Sutton, 1953, p. 190). For the most part, variations in the energy loss of the atmosphere are caused by changes in the radiative loss to the surface (Vowinckel et al., 1964, p. 491). Solar radiation which governs the heat exchange by day is lacking during the nocturnal period; and, with the development of an inversion both the atmospheric radiation and the net radiation will decrease (Liljequist, 1956, p. 127). It transpires that there is a definite bias for nocturnal stabilization (inversion) and daytime instability (adiabatic lapse conditions).

The above discussion is idealized, representing the cyclical component of diurnal temperature variation which is a function of solar radiation heating. Other meteorological factors, such as the state of the sky and advective processes, can effect irregular diurnal temperature changes. For instance cloud cover, particularly a low overcast one, reduces the diurnal variation by proportionally increasing the diffuse radiation. The connection between inversion and cloud cover is well documented (see Geiger, 1950; Best et al., 1952; Bell, 1974). There is a favourable tendency for inversions to increase when the sky clears due to cooling near the ground, with a reverse tendency when the sky becomes overcast.

The efforts of Hosler (1961), Stewart (1967) and Munn et al. (1970) provide considerable insight into the behaviour of inversions in relation to a diurnal cycle.

An attempt was made by Hosler to delineate, geographically and climatologically, the percentage frequencies of low-level stability for the entire United States. He found that the mid-section of the country, with a pronounced continental type climate, has inversion frequencies closely related to a diurnal cycle; that is, there is a definite tendency for nocturnal stabilization and daytime instability in the lower levels.

The work of Stewart (1967) and Munn et al. (1970), geographically based in Canada, showed similar results. Speaking of the diurnal cycle during the life of an inversion, Stewart (p. 25) stated that its intensity gradually increased during the night and rapidly decreased after sunrise. A study of ground-based inversion frequencies by Munn et al. (1970) indicated that, in virtually all instances, frequencies are closely related to sunrise and sunset.

2.2. A Model of the Diurnal Distribution of Inversions

In this section it is proposed to formulate a basic descriptive model useful for an examination of the diurnal distribution of inversions development and decay.

The fundamental feature of the model is the division of a 24-hour day into two periods by the times of sunrise and sunset. This procedure is not without inherent shortcomings. For example, sunset marks the inception of the nocturnal period, but it does not dictate the initial time of radiational cooling at the surface. Prior to sunset the radiation balance of the ground is negative; that is, outgoing exceeds incoming radiation and consequently nocturnal cooling sets in before nightfall (Geiger, 1950, p. 62).

The utilization of indices of "average time of diurnal maximum and minimum temperature" and "changes in temperature during the previous hour" will assist in smoothing incidental detail and in allowing fundamental aspects of reality to appear.

The model is discussed in a Winnipeg context for the representative winter months of December, January and February.

For the above months, the mean times of sunrise (0816, 0815, 0739 hours) and sunset (1939, 1700 and 1745 hours) are calculated from Labelle et al., 1966, Figure 25. The average winter times resolved for sunrise and sunset are 0803 and 1706 hours (C.S.T.) respectively.

By virtue of the importance of the two regimes to the model, the validity of the average times so ascertained should be considered. The meteorological observations of "Total Daily Radiation Received on a Horizontal Surface" (Atoms. Environ. Service, Monthly Radiation Summary) and "Mean Per Cent of Bright Sunshine Registered in Each Hour of the Day" (Dept. of Transport, Monthly Record), can be used for this purpose. On both a daily and monthly scale, hourly radiation is received predominantly between the hours ending at 0800 and 1700 hours. An insignificant amount (not greater than 1.0 and 0.4 langley) is received between 1700 and 1800 hours in the latter winter month of February (Figure 2.1).

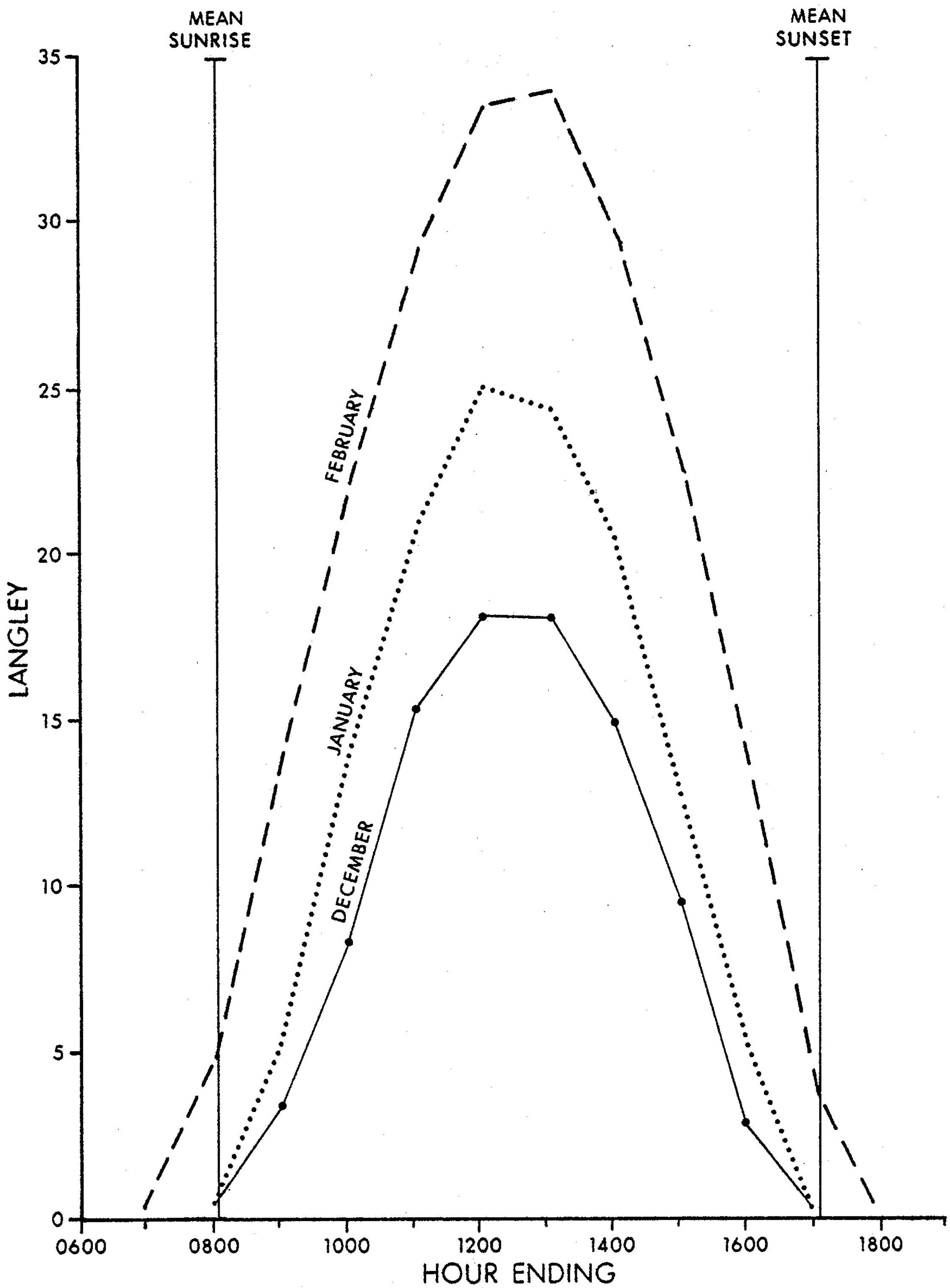
Basically, the above generalizations are applicable to the mean percentage frequency of hourly bright sunshine registered in winter. The majority of hourly bright sunshine is received between the hours ending at 0800 and 1700 hours. Minor amounts occurring outside the described period are observed in the months of December and February (Figure 2.2).

Although these relationships are not perfectly identical, these two meteorological elements do provide apt guidelines for appraisal of the average winter times of sunrise and sunset.

Average times of diurnal maximum and minimum temperatures, and changes in temperature during the previous hour (Table 2.1) were compiled from data based on hourly weather

Figure 2.1

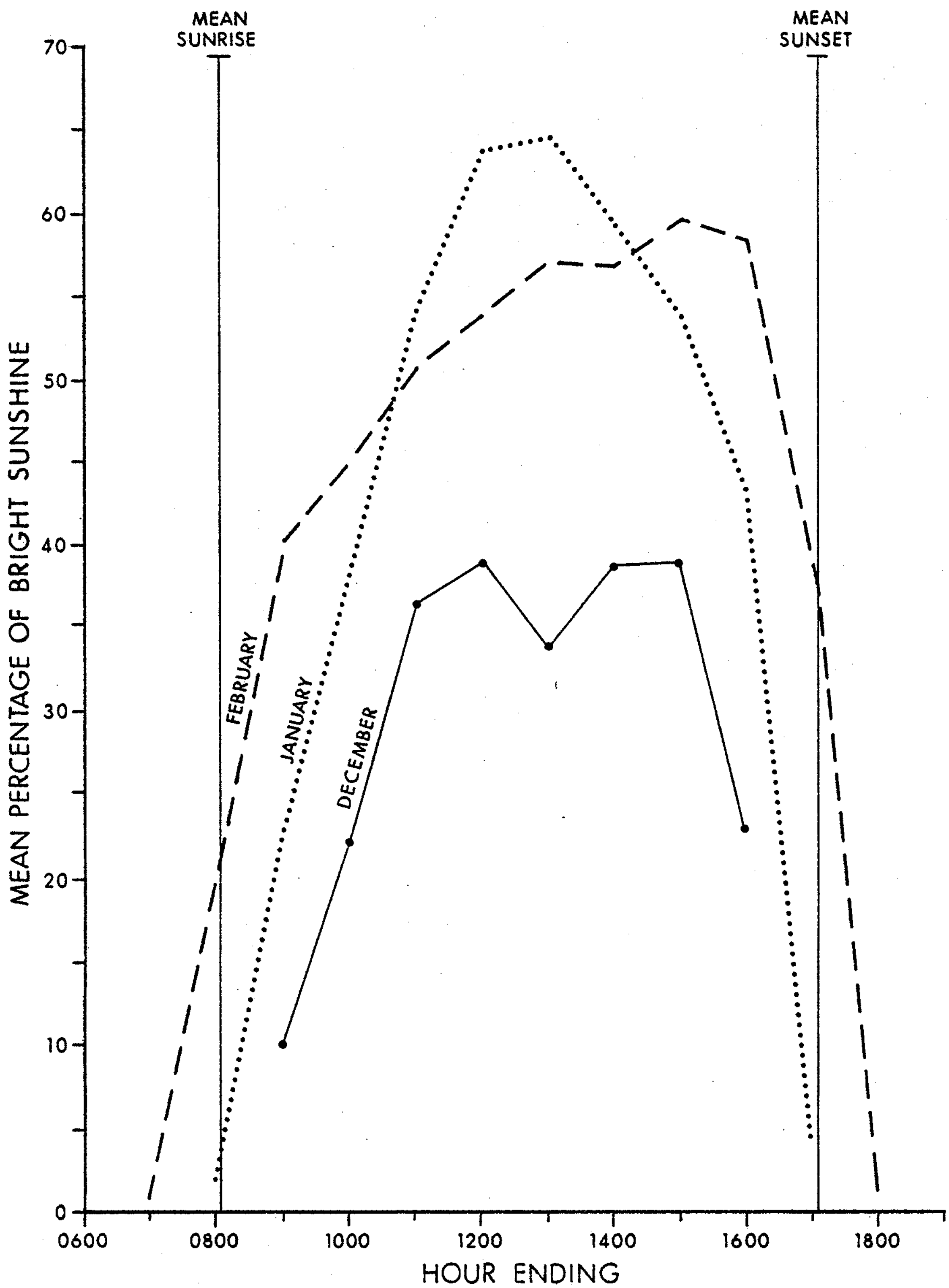
Mean Hourly Total Radiation Received in Winter at Winnipeg



SOURCE: ATMOS. ENVIRON. SERVICE, MONTHLY RADIATION SUMMARY (1969-71)

Figure 2.2

Mean Percentage Frequency of Hourly Bright Sunshine in Winter at Winnipeg



SOURCE: DEPT. OF TRANSPORT, MONTHLY RECORD (1969 - 71)

Table 2.1

Hourly Temperature and Temperature Changes in Winter at Winnipeg (1953-62)
[From Cudbird (1964)]

Hour of Day (C.S.T.)	December		January		February	
	Temp.(°F)	Mean	Temp.(°F)	Mean	Temp.(°F)	Mean
00	08.3		-01.0		04.3	
01	08.0	-0.3	-01.4	-0.4	03.6	-0.7
02	07.8	-0.2	-01.5	-0.1	03.1	-0.5
03	07.5	-0.3	-01.8	-0.3	02.6	-0.4
04	07.2	-0.3	-02.1	-0.3	02.1	-0.5
05	07.7	-0.2	-02.2	-0.1	01.7	-0.4
06	06.9	-0.1	-02.4	-0.2	01.4	-0.4
07	06.6	-0.3	-02.5	-0.1	00.9	-0.4
08	06.6	0.0	-02.7	-0.2	00.9	0.0
09	07.1	0.5	-02.3	0.4	02.3	1.3
10	08.4	1.3	-00.9	1.4	04.6	2.3
11	09.9	1.5	00.6	1.5	06.7	2.0
12	11.0	1.1	01.8	1.2	08.3	1.5
13	12.2	1.2	03.2	1.4	10.1	1.7
14	12.6	0.4	03.9	0.7	11.2	1.0
15	12.6	0.0	04.2	0.3	11.9	0.6
16	11.9	-0.7	03.6	-0.6	11.8	-0.1
17	10.7	-1.2	02.3	-1.3	10.7	-1.0
18	10.3	-0.4	01.5	-0.8	09.3	-1.3
19	09.7	-0.6	00.7	-0.8	07.8	-1.4
20	09.3	-0.4	00.1	-0.6	07.0	-0.8
21	08.9	-0.4	-00.5	-0.6	06.3	-0.6
22	08.6	-0.3	-00.9	-0.4	05.4	-0.8
23	08.2	-0.4	-01.1	-0.2	05.0	-0.4

observations for the period 1953 to 1962 (Cudbird, 1964, p. 24-25). Minimum temperatures occur at 0700 or 0800 hours and their average time of occurrence is 0736 hours (C.S.T.), which is approximately half an hour before sunrise. Singer and Raynor (1957) observed at the Brookhaven tower that during the winter season under clear sky conditions, minimum temperature at heights between 37-410 feet occurs about two hours before sunrise. Maximum temperatures occur in the period 1400 to 1600 hours with an average time 1500 hours (C.S.T.), which is roughly two hours prior to sunset.

Therefore, the transition from minimum temperature to sunrise is more rapid than the transition from maximum temperature to sunset (Figure 2.3). Deacon (1953, p. 60) found that the phase difference (wind speed variation lagging behind the temperature gradient change) between the wind and the temperature gradient variation causes the rate of change of stability with time to be smaller around sunset than the change-over from stable to unstable conditions in the morning.

Negative temperature change due to radiational heat loss is observed in the period from 1500 to 0700 hours. The period, 0800 to 1400 hours, accounts for radiational heat gain (Figure 2.4). In the former period, sharpest change in hourly temperature occurs approximately at sunset,

Figure 2.3

Average Hourly Temperatures in Winter at Winnipeg

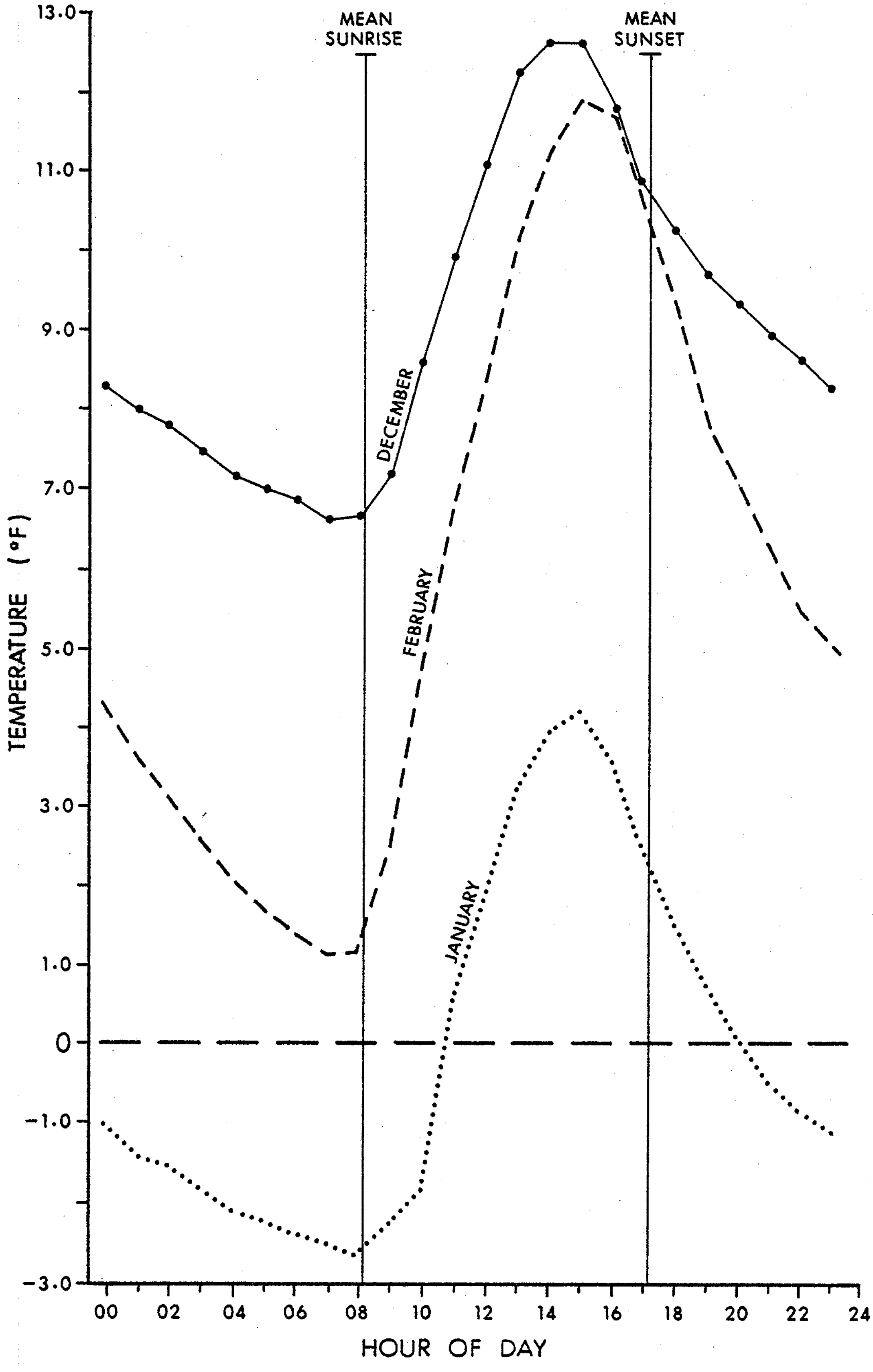
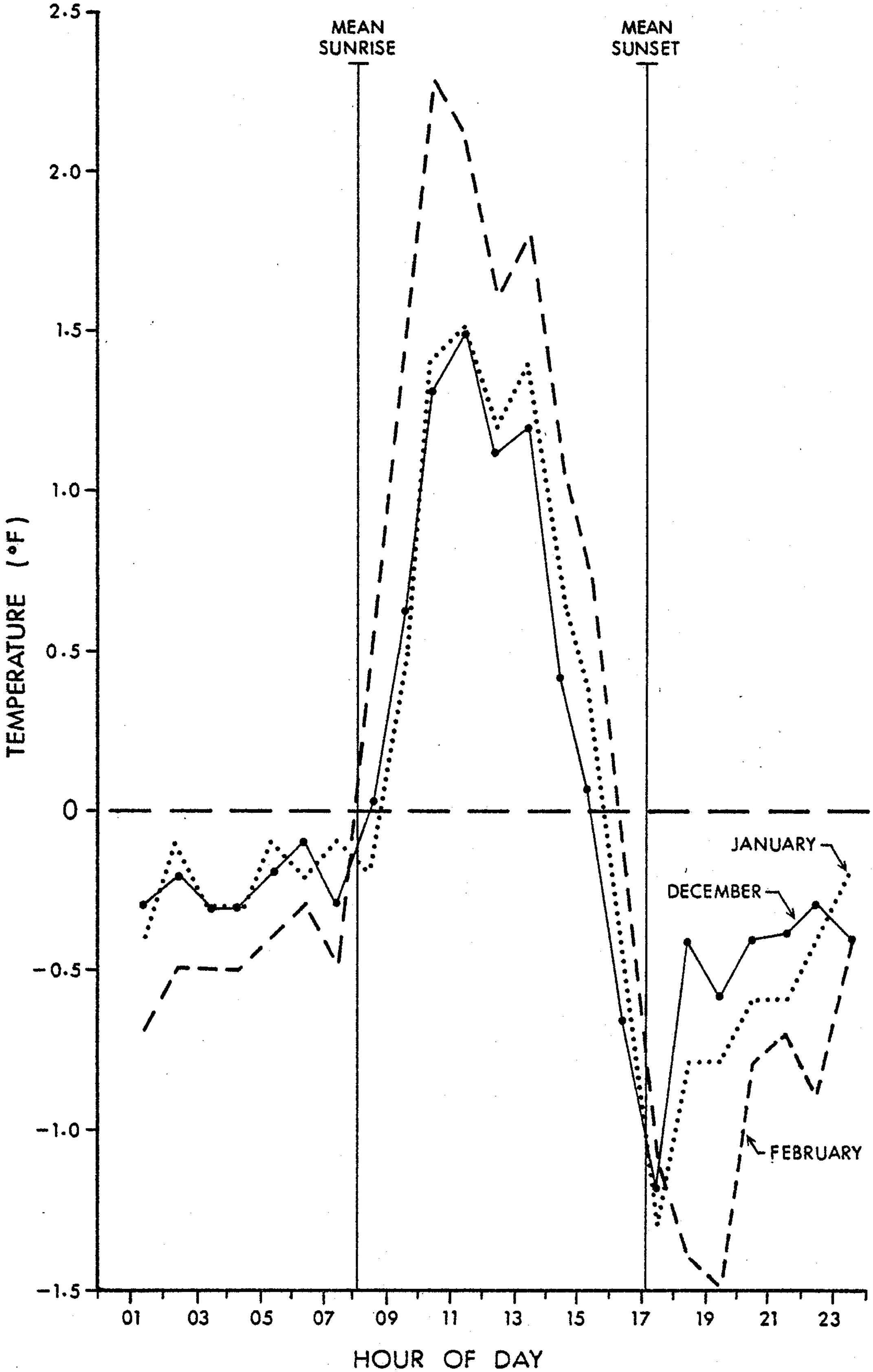


Figure 2.4

Changes in Temperature During the Previous Hour in Winter at Winnipeg



1700 hours. In the latter period, greatest change occurs primarily at 1100 hours with a secondary at 1000 hours.

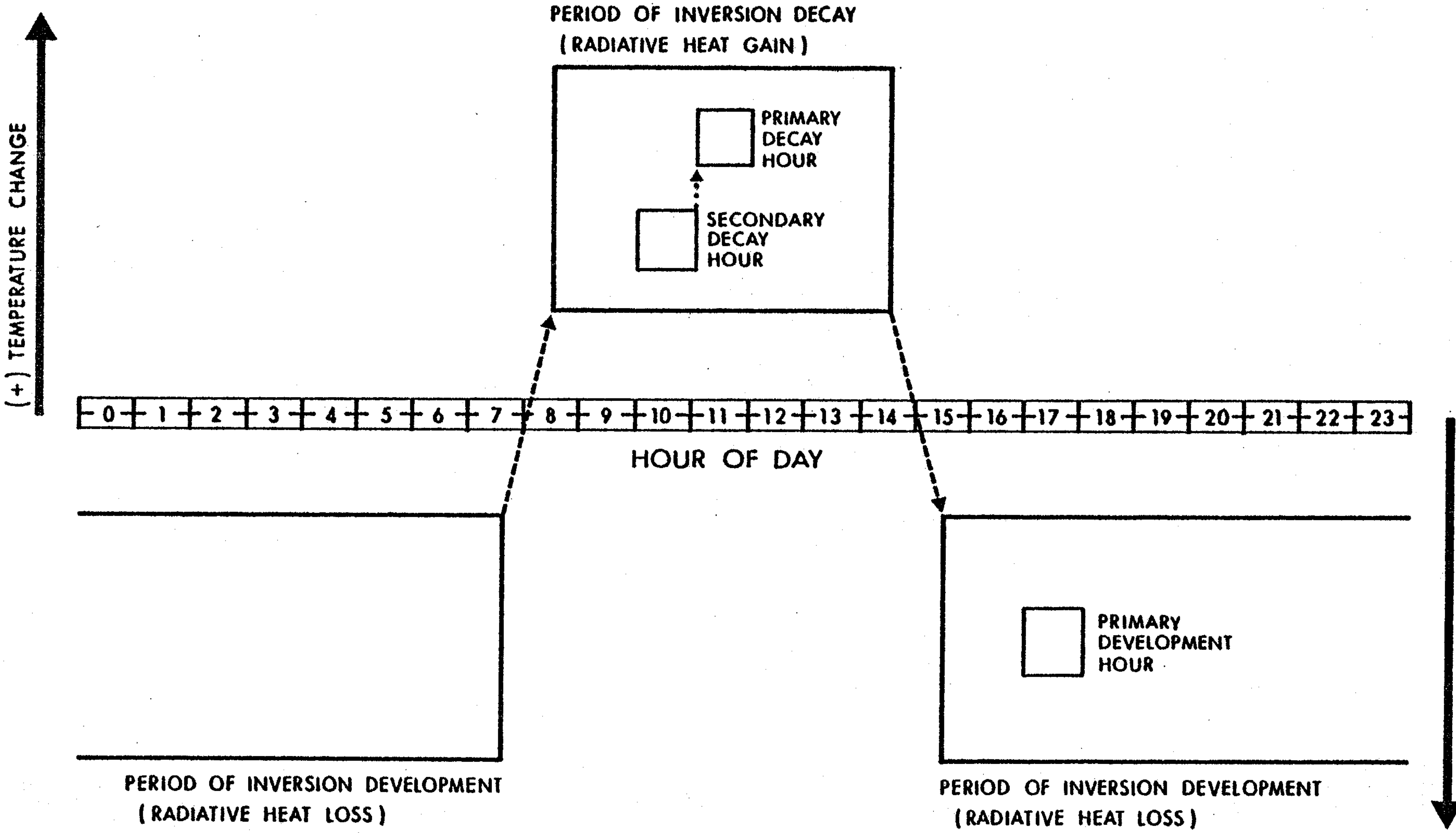
Thus, on an average, greatest radiational cooling occurs around sunset or two hours after maximum temperature is attained. On the other hand, with half an hour difference between minimum temperature and sunrise, greatest radiational heating occurs roughly three hours after sunrise.

This brief survey has sketched the backcloth for assessing the implications of the model. The designated mean times of sunrise and sunset have partitioned a day into two periods. The daytime period (0800 to 1600 hours) represents a period of solar radiation receipt; the nocturnal period (1700 to 0700 hours) represents a period when solar radiation is absent. These periods are further modified to accomodate the times of maximum and minimum temperatures. That is, the period of radiational heat gain is now consolidated between 0800 and 1400 hours, while that of heat loss is encompassed in the period from 1500 to 0700 hours. Each of the periods is most fully developed by 1100 and 1700 hours respectively, the times of largest amplitude of temperature changes from the previous hour.

The model (Figure 2.5) postulates that inversions develop in the period of radiational heat loss (1500 to

Figure 2.5

A Model of the Diurnal Distribution of Inversions



0700 hours) and decay in the period of radiational heat gain (0800 to 1400 hours). The greatest frequency of development is at 1700 hours, and that of decay is at 1100 hours.

The applicability of the proposed model is assessed through a temporal examination of inversions development and decay distribution. Two sets of inversions are subjected to examination: a) lower 35-200 feet layer inversions b) higher 35-810 feet layer inversions. Investigation follows the simple format of finding the percentage frequencies of inversion development and decay for each hour of the day. Before proceeding however, it is worth emphasizing certain factors that should be firmly borne in mind in the following discussion.

The model is based on the cyclical component of diurnal temperature variation which is a function of solar radiation heating. Though the loss of longwave radiation is known to be the principal cause of low-level inversions, its effect becomes less significant at higher levels including the free atmosphere (Staley and Jurica, 1968). In this perspective, it is perceivable that the model may have to be modified for temporal examination of the higher layer 35-810 feet inversions. Moreover, the model is formulated irrespective of the irregular component of diurnal temperature variation. This component arises essentially from advective heating and cooling induced by air mass movement.

With due consideration to these factors it is unreasonable to expect that the model will fully account for the temporal behaviour of inversions. Therefore, in Chs. 4 and 5 inversion cases that both adhere and depart from the model will be subjected to a more rigorous analysis using a wider spectrum of meteorological parameters.

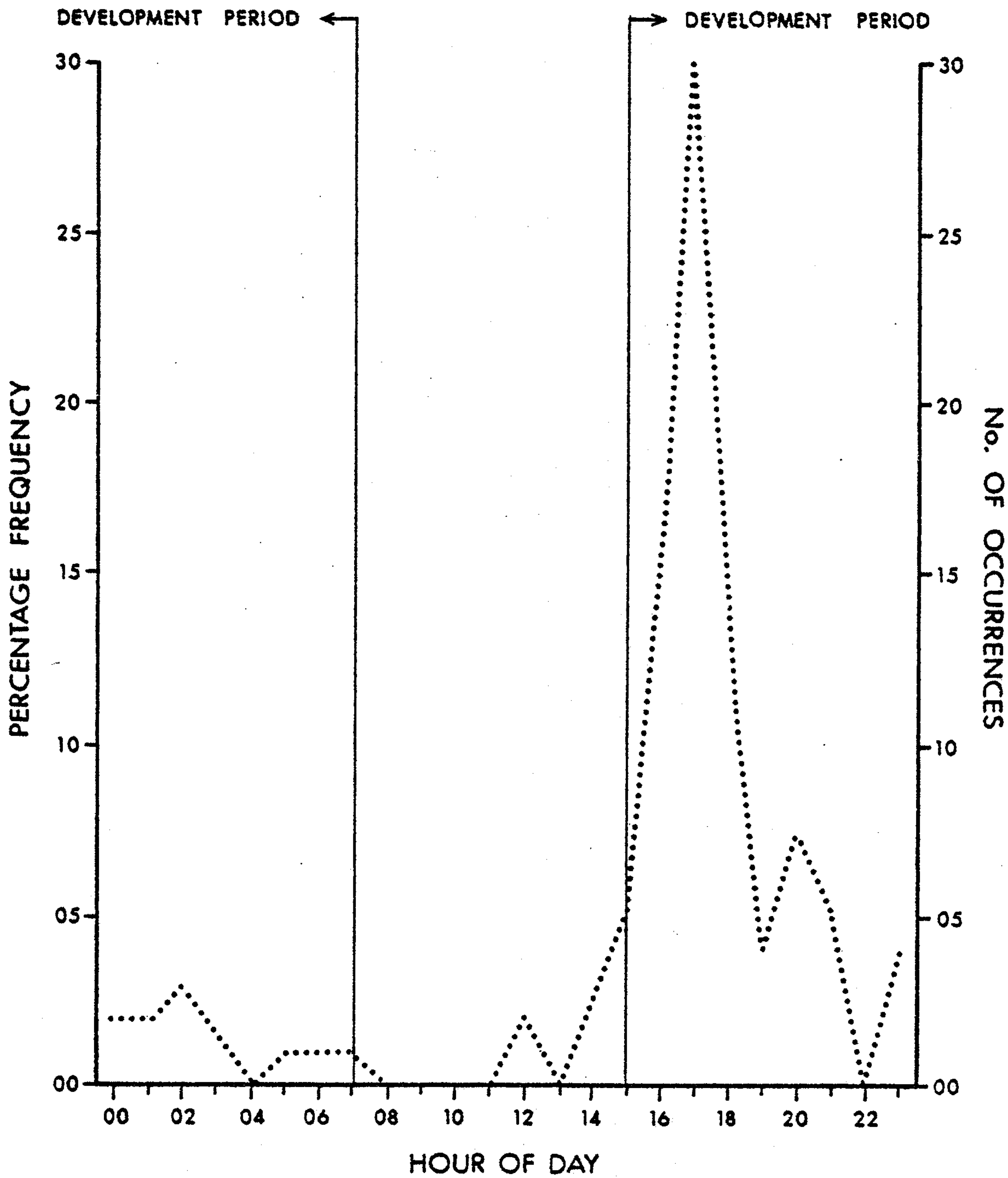
2.3 Lower 35-200 Feet Layer Inversions

Conceptually, by reason of proximity to the surface, inversion behaviour in the lower 35-200 feet layer, as opposed to that in any other layer, should be most consistent with the model. Analysis detected for the winter sampling period an inversion population of 100 cases at the lower layer.

Seventy-six per cent of inversion development occurred in the nocturnal period from 1700 to 0700 hours. The remaining 24 per cent developed in the daylight period from 0800 to 1600 hours. In the radiational heat loss period, 1500 to 0700 hours, development frequency increased to 96 per cent. The greatest hourly frequency (30 per cent) was exhibited at sunset, 1700 hours, when there is greatest hourly heat loss (Figure 2.6).

Figure 2.6

Hourly Frequency of Inversion Development in the 35-200feet Layer



SAMPLE SIZE (n) = 100 CASES

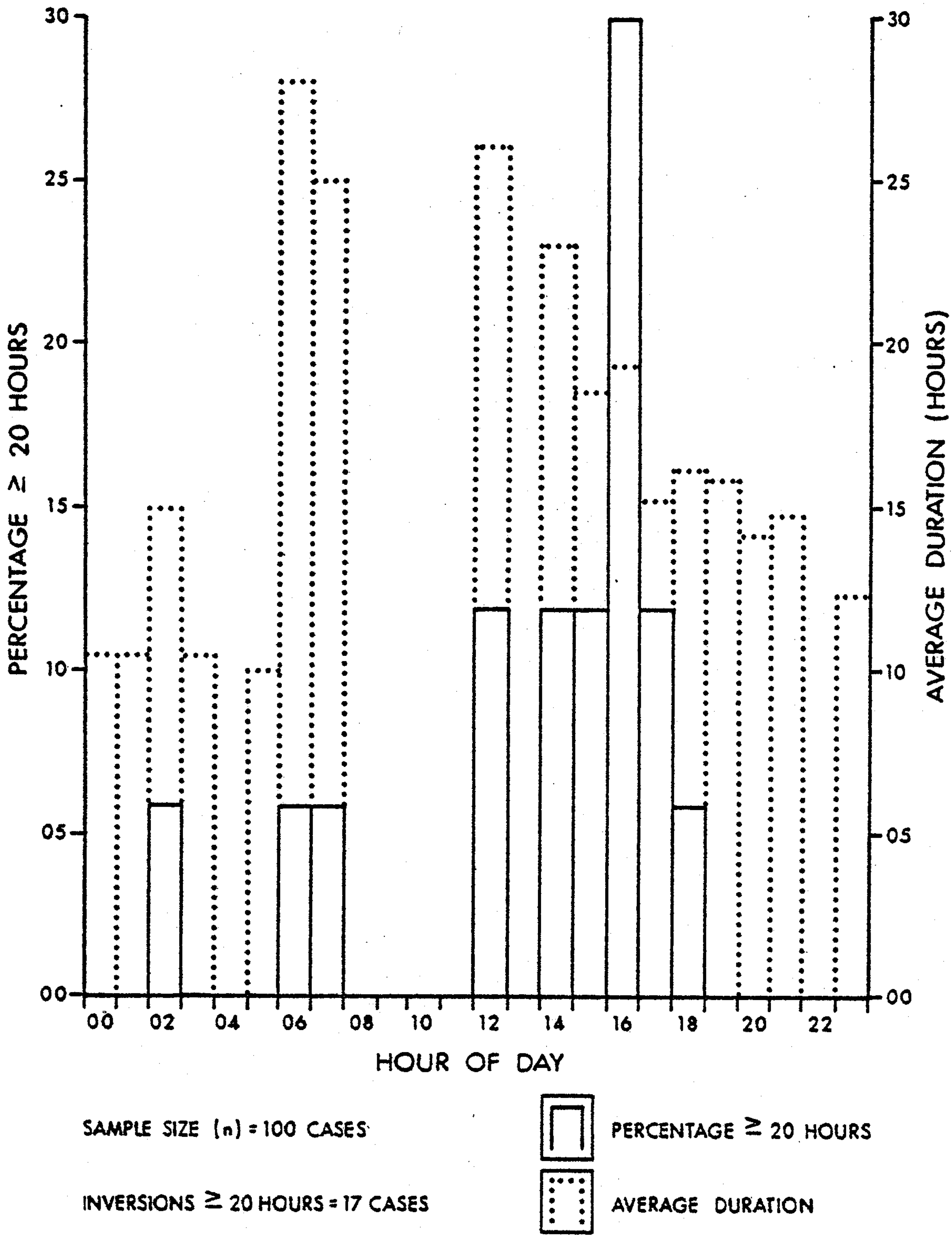
The 4 per cent of inversion development contained in the radiational heat gain period, occurred between 1200 and 1400 hours. All of these inversions were sustained for not less than 20 hours duration. Bell (1974) found that inversion durations are highly correlated with inversion intensities, with an increase in intensity yielding an increase in duration. The work of Baker et al. (1969 , p. 751) supports this finding. It therefore seems reasonable to state that only intense, persistent inversions develop in the radiative heat gain period.

Of the 96 per cent of development occurring in the heat loss period, 68 per cent were assembled in a virtual bell-shaped frequency distribution between 1500 and 1900 hours. This indicates that some two-thirds of development lay less than one standard deviation away from the mean at 1700 hours. Furthermore, no inversion development differed from the mean by more than two standard deviations.

An interesting feature of the average duration of inversions was observed in this distribution. Of the seventeen inversion cases lasting at least 20 hours, ten were contained in the period 1500-1900 hours. Seven of these developed in the two hours prior to 1700 hours (Figure 2.7). It transpires that more intense, persistent inversions form prior to sunset when outgoing exceeds incoming radiation.

Figure 2.7

Average Duration of 35-200 feet Layer Inversions Developing in Each Hour, and Hourly Frequencies of Development of Inversions Lasting ≥ 20 Hours



In the development period, 1500 to 0700 hours, natural breaks occurred as no inversions developed at 2200 and 0400 hours. The two hours, 2000 and 2100 hours, prior to the natural break at 2200 hours, contained 12 per cent of the development and these inversions averaged 14.5 hours in duration. Between the natural breaks, the period 2300 to 0300 hours, included 13 per cent of the development. The average duration of these inversions was 11.5 hours. Only 3 per cent inversions developed in the period from 0500 to 0700 hours.

From the preceding discussion several general features emerge. Average inversion duration and development frequency progressively decrease with approach to sunrise hour. The observations of Baker et al. (1969, p. 752) and Goff and Hudson (1972, p. 29) support these results. Speaking of inversion duration, Baker et al. reported that inversions that formed after midnight decreased in duration as inversion formation hour approached the time of sunrise. Goff and Hudson found that lower-level inversions form quickly after sunset because of heat loss by long-wave radiation and are most frequent prior to midnight; thereafter, there is a gradual downward trend in development frequency.

Temporal examination of the 35-200 feet layer inversion data has indicated that the development period can be divided into two sectors separated by three transitional zones. An analysis of frequencies of ground-based inversions according to hour of day at Sarnia for the summer months indicated that frequencies are characterized by two regimes, day and night, with transitional periods of approximately three hours in the morning and again in the evening (Munn et al., 1970, p. 57).

The transitional zones detected in this study are reflections of significant changes in the diurnal radiative cycle. This arises due to the low angle sun and the high reflectivity of the snow covered surface.

The two transitional zones relative to sunrise (0500 to 0700 hours) and sunset (1200 to 1400 hours) describe periods when the surface is adjusting to the addition of and loss of radiant energy. The other transitional zone (2000 to 2200 hours) represents a somewhat different physical process. There is a gradual decrease of outgoing radiation with decreasing temperature. The surface layer is progressively cooled and the net radiation decreased until stabilization or equilibrium cooling is more or less attained.

A plausible though idealized explanation was forwarded by Best et al. (1952, p. 30) to account for this physical effect. They explained that a rapid fall in temperature at the surface due to snow cover, combined with an originally lower temperature at sunset, produces a net result in which the temperature gradient at levels near the surface is enhanced and equilibrium reached quickly, after which temperature falls no further. Wexler (1936) adopted a model based on this physical effect in his study on "Cooling of the Lower Atmosphere and the Structure of Polar Continental Air".

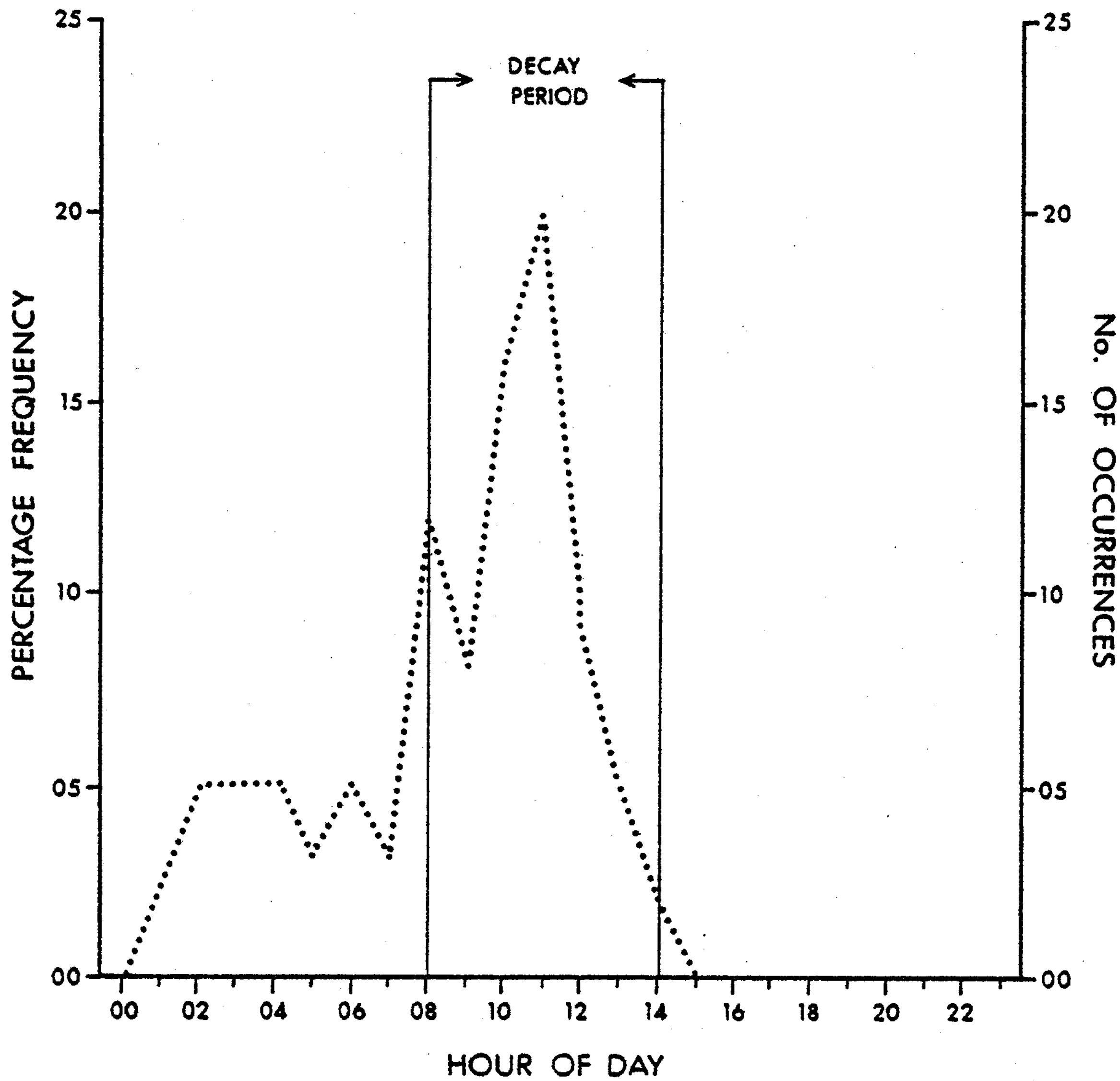
Attention is now focussed on a temporal examination of inversion decay. Of the 100 winter inversion cases counted, all decayed in the period from 0100 to 1400 hours (Figure 2.8). The model postulates however, that decay is restricted to the heat gain period, 0800 to 1400 hours. Consequently, decays that occurred prior to 0800 hours do not conform to the model.

The unconforming period, 0100 to 0700 hours, included 28 per cent of inversion decay and these inversions were of shorter average duration. This period included the decay of three of the total seventeen inversions lasting at least 20 hours in duration.

Seventy-two per cent of inversion decay occurred in the radiational heating period. Times of sharpest increase in temperature, 1000 and 1100 hours, accounted for 36 per cent of decays. No inversion decayed after the attainment of maximum temperature at 1400 hours. Inversions contained in this period were principally of longer

Figure 2.8

Hourly Frequency of Inversion Decay in the 35-200 feet Layer



SAMPLE SIZE (n) = 100 CASES

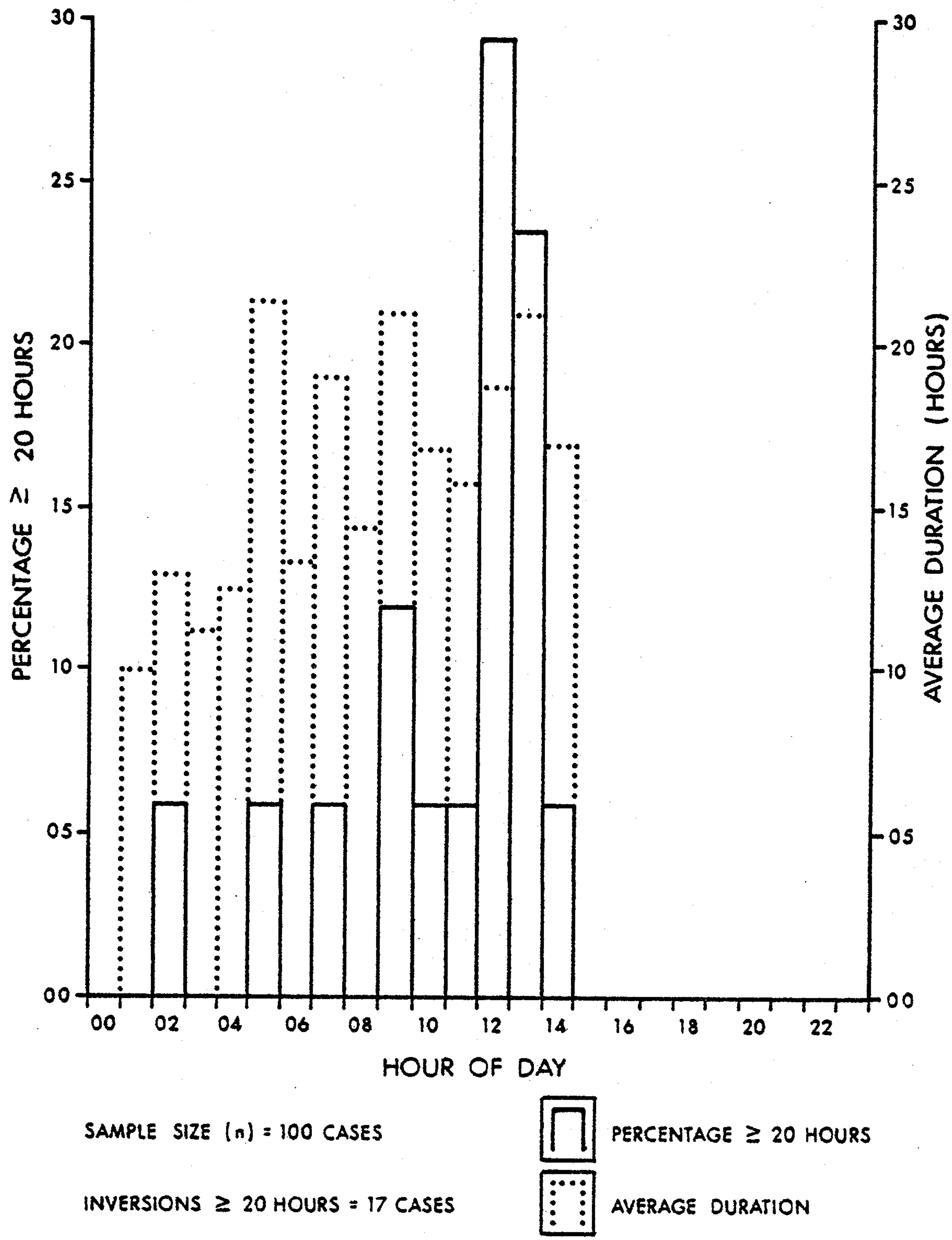
duration, as is reflected by the fourteen inversion cases not less than 20 hours duration. More than half of these intense, persistent inversions decayed at 1200 and 1300 hours, the times of maximum total radiation receipt (Figure 2.9).

From temporal examination of inversion decay three significant delimiting times emerge, 0800, 1100 and 1400 hours. Inversions of medium duration decayed in the period 0800 to 1100 hours, while those of longer duration were encompassed in the period of greater solar heating 1200 to 1400 hours. The unconforming period, 0100 to 1700 hours, accounted primarily for decay of weak or short inversions.

The above results for the radiative heat gain period is suggestive of the association between the reflection properties of a snow surface and the angle of solar incidence. Gerdel et al. (1954) claimed that in the upper layers of snow a diurnal temperature cycle is effected by change in the balance between shortwave and longwave radiation. Solar heating of the surface and the subsequent transfer of heat to the lower atmosphere leads to instability. This is accomplished soon after sunrise for the less intense inversions. Several hours of heating are required however, for dissipation of the stronger persistent inversions. Sufficient potential instability has

Figure 2.9

Average Duration of 35-200 feet Layer Inversions Decaying in Each Hour, and Hourly Frequencies of Decay of Inversions Lasting ≥ 20 Hours



to be generated in the near surface air layer before air can circulate in the vertical direction and convect energy upwards.

2.4 Higher 35-810 Feet Layer Inversions

It is instructive that temporal examination of higher 35-810 feet layer inversions be viewed in relation to its distance from the earth's surface. Bell (1974), in his analysis of mean diurnal variation of temperature at five different heights, reported that heating above the ground lags initial heating of the surface, and this lag of time is a function of height and season being five hours in winter and four hours in summer between 35 and 810 feet. Other investigators have reported results of a similar nature (Goff and Hudson, 1972), (Sutton, 1953), (Best et al., 1952). The lag in time for the transport of heat higher into the planetary boundary layer arises because convective mixing is a slow process, especially in winter.

During the winter sampling period there were 82 inversions in the higher layer. Thus, this layer yielded less cases than the lower 35-200 feet layer. This finding is not in agreement with the work of Baker et al. (1969) and DeMarrais (1961). They found that the occurrence of inversions at the lower 70-170 feet layer was less frequent than at the higher 170-500 feet layer. Their respective investigations were geographically based in St. Paul-Minneapolis and Louisville, and inversions lasting at least two hours and one hour were counted.

This irregularity is probably incurred by the greater percentage of inversions of duration not less than 20 hours (37 vs 17 cases) in the higher layer. In this duration category, the higher layer assembled 45 per cent of its total inversions, whereas the lower layer assembled only 17 per cent (Figure 2.7 vs Figure 2.10).

Twenty-eight per cent of inversions in the higher layer were of duration not less than 24 hours, compared to a meagre 7 per cent in the lower layer. The importance of this information cannot be over-emphasized because the proposed model is founded on a diurnal cycle (24-hours) of two periods. This phenomena demonstrates that surface heating is not sufficiently strong on several occasions to break-up intense higher layer inversions.

In the nocturnal period, 1700 to 0700 hours, inversions developed with a 78 per cent frequency. The residual 22 per cent were contained in the daylight period from 0800 to 1600 hours. Development frequency increased to 93 per cent in the heat loss period, 1500 to 0700 hours. In accordance with the model then, the heat gain period accounted for 7 per cent of the development (Figure 2.11).

The higher layer is lacking the normal frequency

Figure 2.10

Average Duration of 35-810 feet Layer Inversions Developing in Each Hour, and Hourly Frequencies of Development of Inversions Lasting ≥ 20 Hours

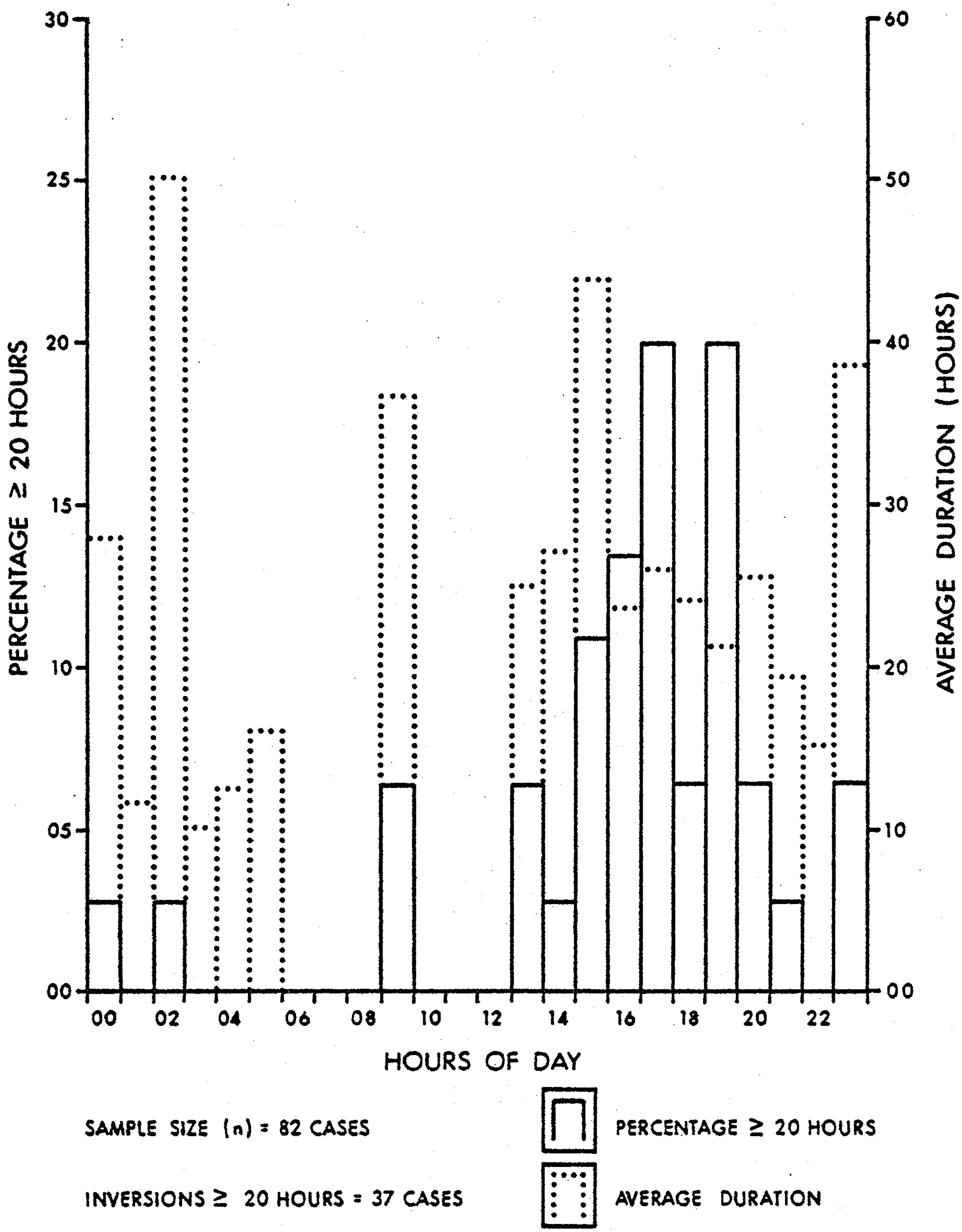
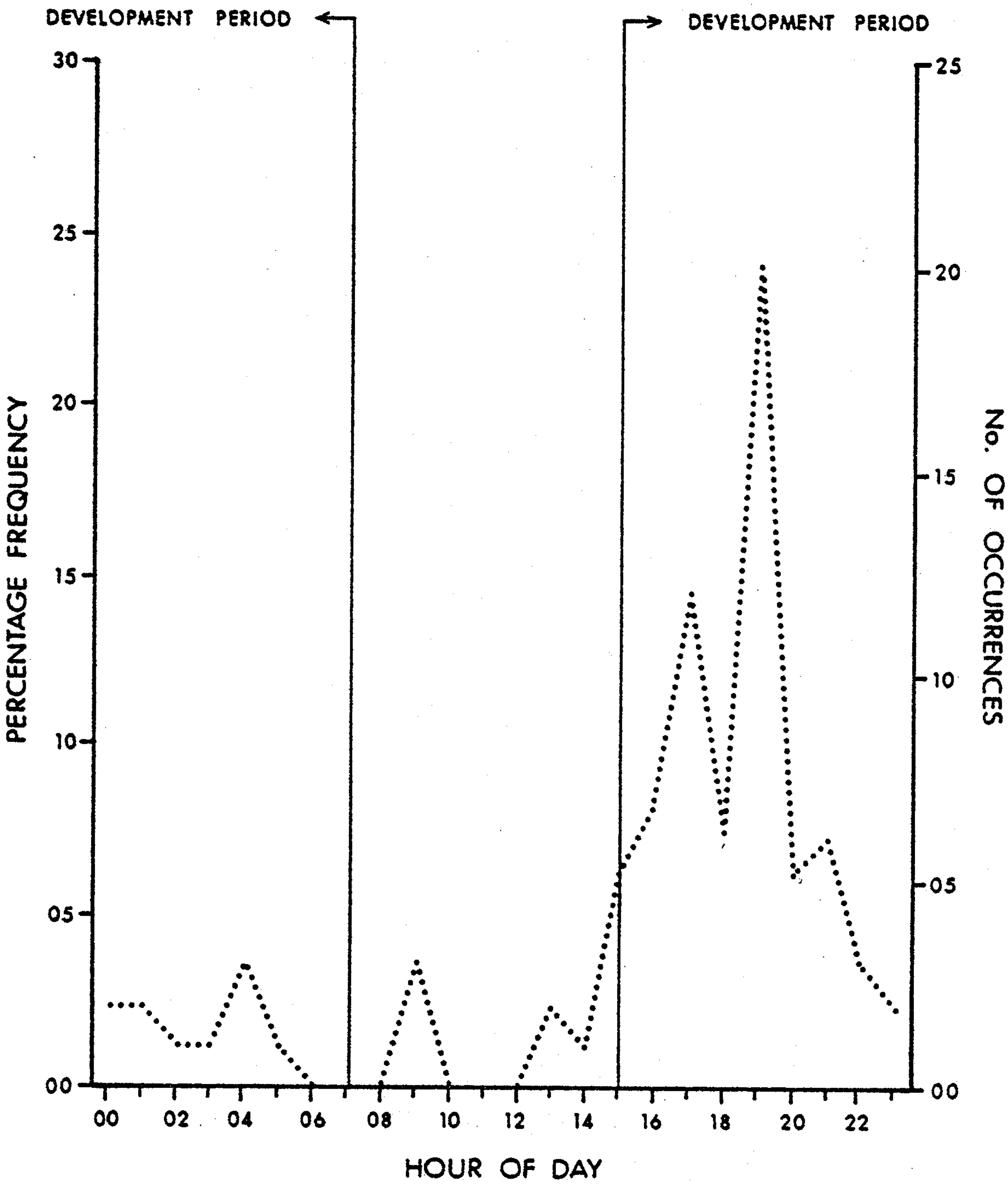


Figure 2.11

Hourly Frequency of Inversion Development in the 35 - 810 feet Layer



SAMPLE SIZE (n) = 82 CASES

distribution manifested between 1500 and 1900 hours at the lower layer. Moreover, peak frequency previously discerned at 1700 hours is now distinguishable at 1900 hours. This indicates that maximum inversion frequency development is delayed with height.

Examination detected for the lower inversion data three transitional zones: 2000 to 2200 hours, 0500 to 0700 hours and 1200 to 1400 hours. The two latter zones, relative to sunrise and sunset, are partially assimilated in the heat loss period to form an adjusted development period for the higher 35-810 feet layer. This adjusted period, 1300 to 0500 hours, exhibited a 96 per cent frequency development, the said percentage found for the lower layer in the heat loss period.

Rather than a transitional zone, 2200 hours can be assessed as demarcating the adjusted development period. The sector, 1300 to 2100 hours, with 78 per cent of the development, was contiguous with regards to inversions of duration not less than 20 hours and accounted for 84 per cent of the 37 inversions of this duration scale. The other sector, 2300 to 0500 hours, with 18 per cent developments had only 11 per cent inversions lasting at least 20 hours in duration (Figure 2.10).

Inversion decay in the higher layer was not rigidly confined to a contiguous period of day. Nevertheless, the period from 0200 to 1800 hours constituted a 95 per cent frequency and demonstrated uninterrupted hourly decay. The balance of the day accounted for the other 5 per cent which periodically decayed at irregular hours. In accordance with the model however, 64 per cent of decay is attributable to the heat gain period 0800 to 1400 hours. The greatest hourly frequency of decay occurred at 1300 hours (Figure 2.12).

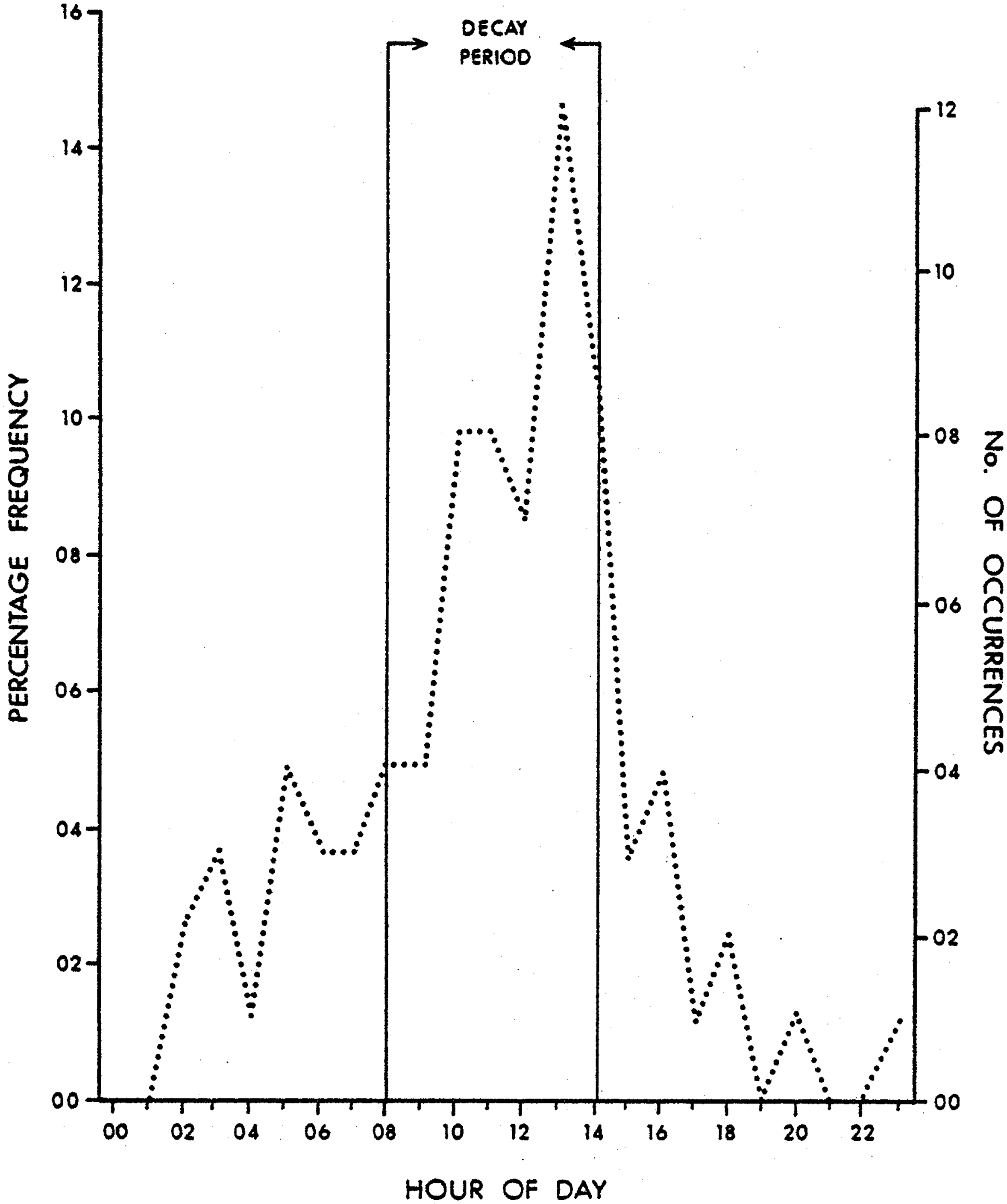
The above information indicates that the radiational heating period for the higher layer, further removed from the surface, should be adjusted. This period may be adjusted to sunset, 1700 hours. Reasoning is based principally on inversions average duration.

An assemblage of 72 per cent of decays in the period, 0800 to 1600 hours, formed an unbroken chain of hours that accounted for 73 per cent of inversions not less than 20 hours duration. At irregular hours in the rest of the day, the other 28 per cent decayed and 27 per cent of inversions of duration not less than 20 hours were contained (Figure 2.13).

Sunrise time is decidedly significant for the change-over from stable to unstable conditions for both layer heights. For the higher 35-810 feet layer however, the decay period was adjusted to 1600 hours. This circumstance suggests that the change-over from unstable to

Figure 2.12

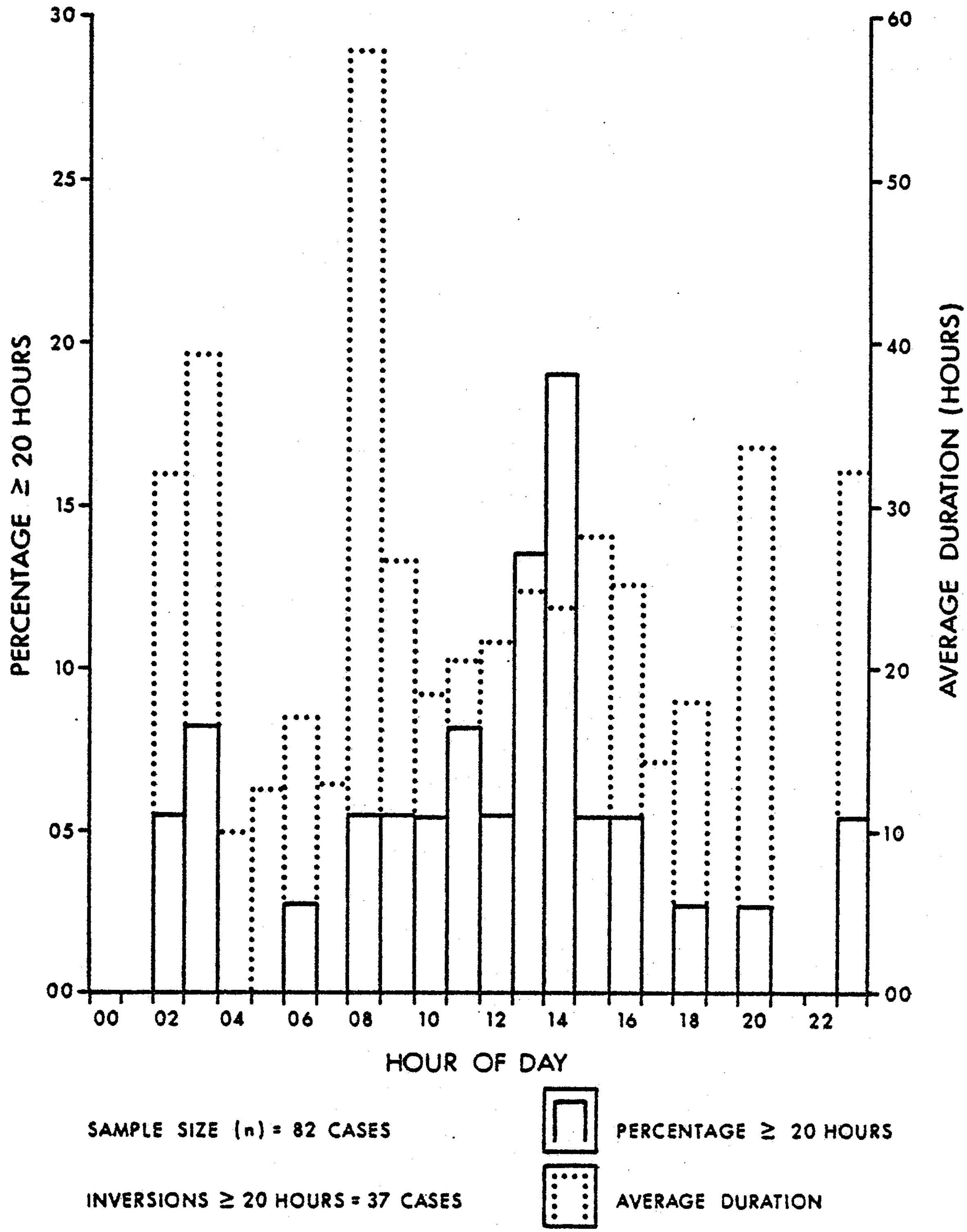
Hourly Frequency of Inversion Decay in the 35-810 feet Layer



SAMPLE SIZE (n) = 82 CASES

Figure 2.13

Average Duration of 35-810 feet Layer Inversions Decaying in Each Hour, and Hourly Frequencies of Decay of Inversions Lasting ≥ 20 Hours



stable conditions is a slower process at the higher layer. Johnson et al. (1935, p. 12) found that in the morning there is nearly simultaneous change at all heights from inversion to positive lapse; but, in the evening inversion is built upwards gradually.

2.5 Conclusion

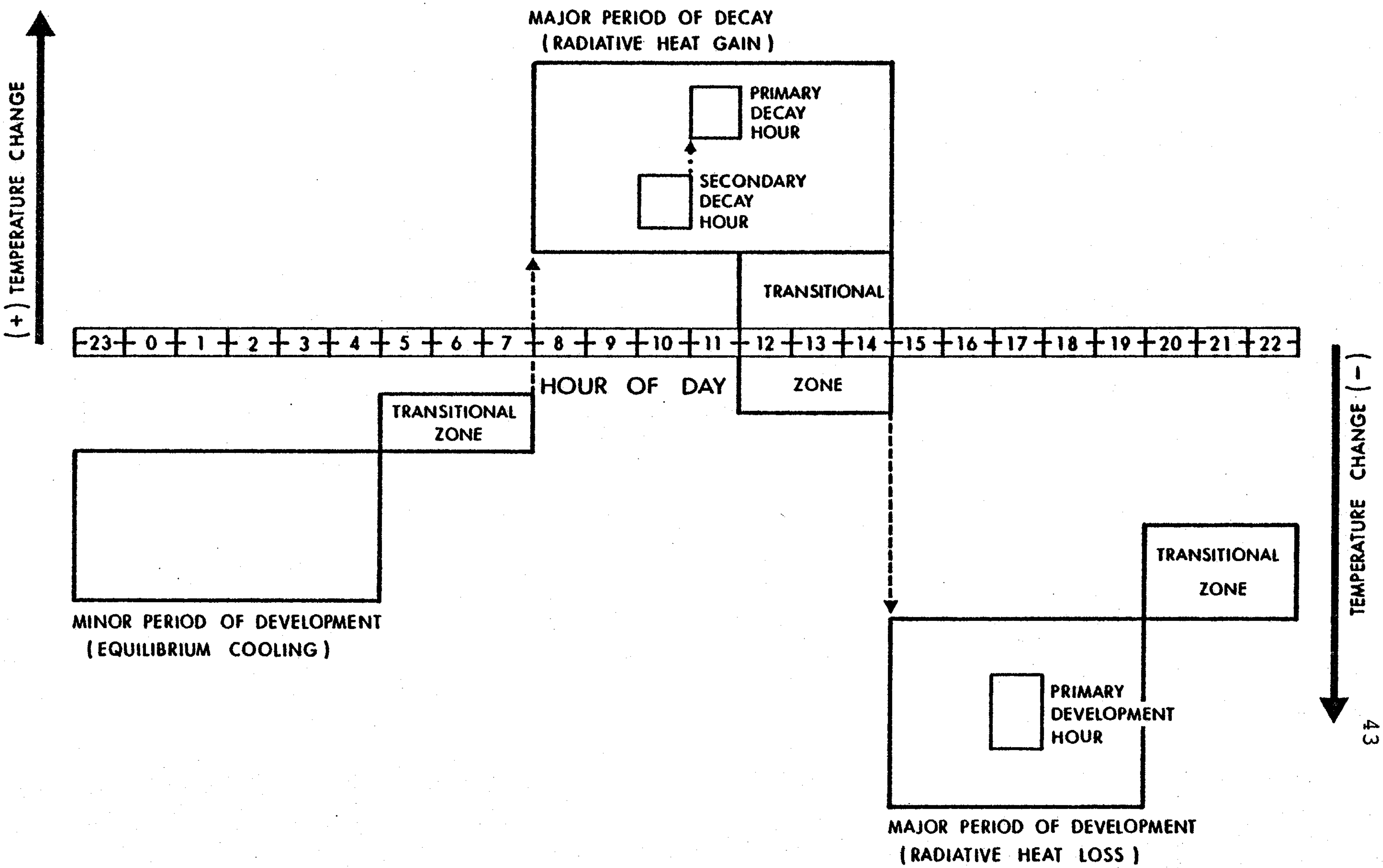
Temporal examination of the development and decay of winter inversions in the lower 35-200 feet layer yielded results consistent with the tenets of the fundamental model. The other set of higher 35-810 feet layer inversions required that adjustments be made to the model.

The model postulated the demarcation of a 24-hour day into two periods, one for inversion development and the other for decay. Examination of the lower inversion data revealed that these periods can be divided into three sectors separated by three transitional zones. The redefined model is schematically presented in Figure 2.14.

Virtually all inversions developed in the period of radiative heat loss from 1500 to 0700 hours which encompassed two sectors. The sector, 1500 to 1900 hours, described by a normal frequency distribution, accounted for the major portion of inversion development, many of which were of long duration. The other sector, 2300 to 0400 hours, contained a minor portion of developments and

Figure 2.14

Redefined Model for 35-200 feet Layer Inversions Diurnal Distribution



accounted for inversions that were for the most part of shorter duration. It is worth emphasizing that this sector also contained a small percentage of anomalous inversion decay. Nonetheless, inversions decayed mainly in the period of heat gain from 0800 to 1400 hours. Decay of intense, persistent inversions was confined mainly to the latter hours of this period.

As stated, the model has to be modified if it is to be consistent for the higher 35-810 feet layer inversions. The question thus to be considered is what magnitude of adjustment is necessary. An adjustment factor of two hours is satisfactory.

The periods, 1500 to 0700 hours and 1300 to 0500 hours, respectively accounted for the major portion of inversion development at the 35-200 feet and the 35-810 feet layers. Maximum development frequency at the lower layer occurred at 1700 hours, but for the higher layer at 1900 hours. The period between 0800 and 1400 hours assembled the major portion of inversion decay at the lower layer, with peak frequency at 1100 hours. For the higher layer, the period from 0800 to 1600 hours with peak frequency at 1300 hours, described the major decay pattern.

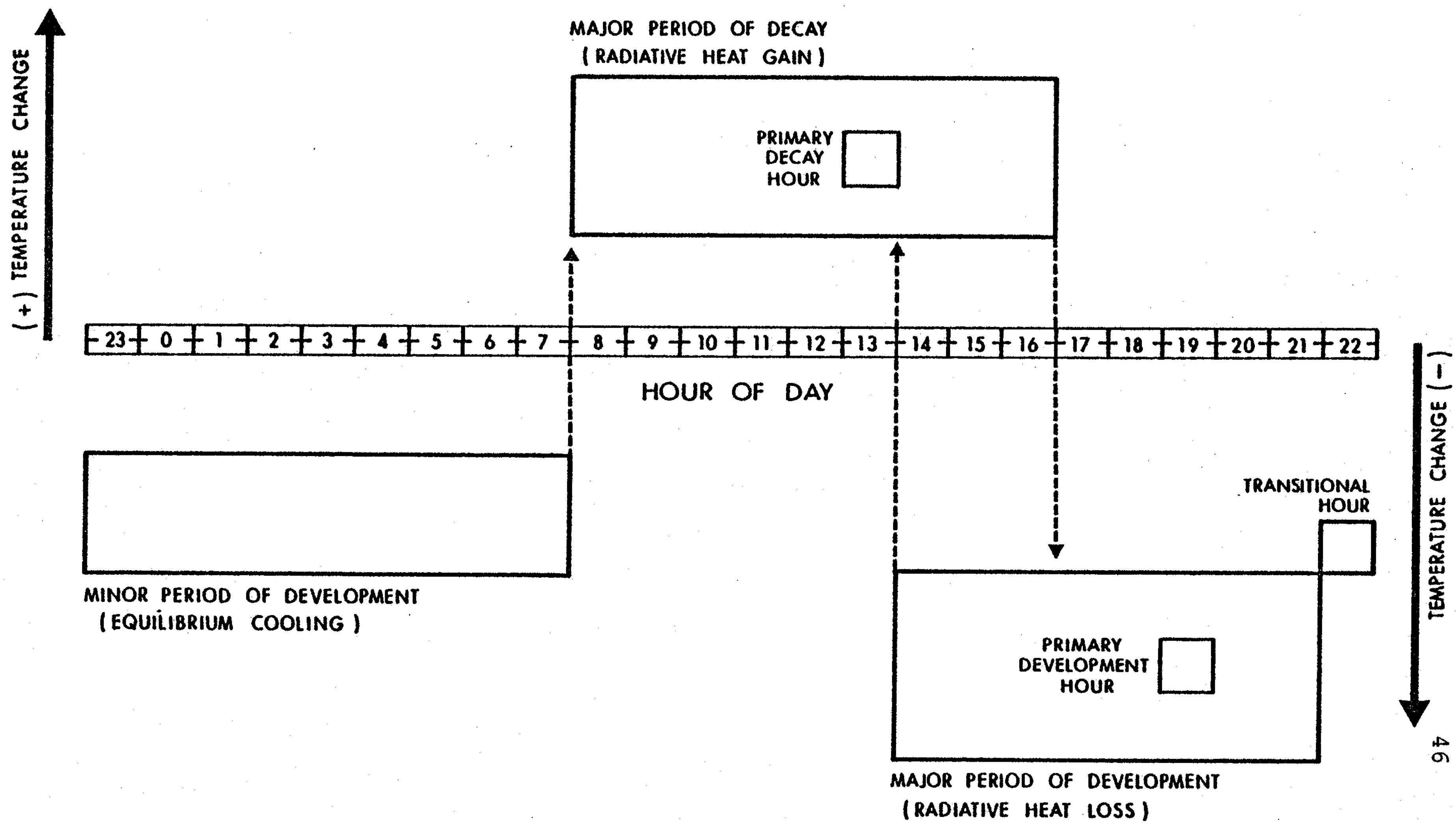
It is apparent that the foregoing information determines a two-hour time differential. Accordingly, if the model is adjusted by a factor of two hours it will be better suited to a temporal study of higher layer 35-810 feet inversions (Figure 2.15).

With adjustment to the periods, per cent frequencies resolved were identical to that reported for the lower layer. Higher 35-810 feet inversions developed with a 96 per cent frequency in the adjusted period, 1300 to 0500 hours, and decayed with a 72 per cent frequency in the adjusted period, 0800 to 1600 hours.

In summation, temporal examination has implied that a model based on the diurnal cycle of radiation heating and cooling at the surface can aid comprehension and understanding of inversions lasting at least 10 hours behaviour at development and decay. Depending upon the height of the layer, a time adjustment to the model has to be introduced. Some care must be exercised in interpretation however, for neglected in the formulation of the model was the irregular component of diurnal temperature variation. Relationships were thus imprecise, and several questions were left unanswered. An attempt will be made to bridge this gap, particularly in Chs. 4 and 5, when a detailed study of selected inversion cases will be pursued in a wider field of meteorological parameters.

Figure 2.15

Modified Model for 35-810 feet Layer Inversions Diurnal Distribution



CHAPTER III

A Review of Bell's Classification of Inversions

3.1 Introduction

A classification devised for a specific purpose is seldom equally effective for another purpose. Bell's (1974, Ch. 9) numerical classification of winter 35-200 feet layer inversions not less than 1 hour, is adapted for use in this thesis. A key feature of the present work however, is the study of inversions lasting at least 10 hours in duration. Consequently, the classification will be used to study inversions differing in duration from those for which it was devised. It is essential, therefore, that this classification scheme be reviewed.

The importance of such an exercise cannot be gainsaid, because inversion cases of the specified duration that are reasonable representatives of this classification scheme are abstracted for detailed structural analysis in Chs. 4 and 5. These chapters present the major theme of this thesis.

For many purposes it is found more useful to group data into classes rather than treat the whole frequency distribution. Classification produces order, enables the transmission of knowledge and permits inductive generalization. Classification must follow a definite plan, and there are two main methods for the grouping of objects into classes: by logically subdividing a population or by agglomerating like individuals (Abler et al., 1971, Ch. 6).

Both methods of classification were utilized by Bell (1974, Ch. 9) in devising a classification scheme for inversions in two layers (35-200 feet and 35-810 feet). The interest of the present thesis focuses however, on the method for numerically grouping like individuals using Ward's (1963) alogrithm for cluster analysis. This cluster technique is quite general and can be used to perform all types of classification. Further details and examples may be found in Spence (1968), Wishart (1969) and, Sneath and Sokal (1973).

Classification can achieve clarification. Each time observations are grouped into classes detail is lost in order to facilitate interpretation. For example, Bell found that the identification of 13 clusters using six inversion variables led to a 5 per cent loss of detail and efficiency. The variables in question were inversion duration, inversion intensity, cloud cover, wind speed, temperature, and pressure (Table 3.1).

Purpose determines the criteria selected (6 variables) and the number of regions (13 clusters) delimited

Table 3.1

Results of 6 Variable Cluster Analysis for the 35 - 200 feet Layer Data

[After Bell (1974)]

Cluster Number	Size	Variables Active in Clustering Avg. Inv. Durn. (Hours)	Avg. Inv. Inten. (°F/1000')	Avg. Wind Speed (m.p.h.)	Avg. Obs. (tenths)	Avg. Temp. (°F)	Avg. Pres. (m.b.)
1	7	28.1	-29.4	13.5	2.3	21.4	1016.2
2	7	19.6	-38.8	7.9	0.8	-25.4	1030.0
3	16	14.1	-24.5	10.7	3.4	2.5	1017.6
4	31	14.9	-26.0	9.6	1.7	-12.9	1026.1
5	25	5.7	-5.7	11.9	7.7	14.5	1022.5
6	25	3.9	-4.6	12.3	7.5	19.7	1005.1
7	9	15.6	-39.7	9.8	1.7	-0.8	1026.7
8	4	16.8	-53.1	9.1	1.5	13.5	1011.6
9	24	5.7	-5.9	13.1	3.1	0.6	1012.5
10	30	6.1	-5.1	15.0	1.7	-11.6	1023.3
11	11	6.3	-18.8	9.4	6.6	14.2	1008.5
12	27	4.0	-8.5	7.2	4.3	-0.1	1025.0
13	14	3.4	-3.9	5.3	2.0	-15.3	1031.8
ALL	230	8.7	-14.3	10.8	3.8	0.5	1020.0

(Chorley and Haggett, 1969). Bell's numerical classifcation was developed for the purpose of ascertaining whether certain wind directions favoured particular types of inversions during light to medium winds. This information was required in the analysis of the general problem of air pollutant dispersion in the Winnipeg area.

Some of the inversions classified by Bell were not of the required duration specified for this study. Consequently, some of the clusters, if not all, will either have to be modified or deleted from consideration. It is therefore essential that an investigation of this question be undertaken if appropriate clusters are to be selected for a meaningful study of inversions lasting not less than 10 hours. This phase of inquiry is pursued in Section 3.2. As the sample size is redefined, the question of relationship between the temporal distribution of inversions in the selected clusters and in the 35-200 feet layer sample population becomes a critical one (Section 3.3). From the ensuing results, an attempt is made in Section 3.4 to logically subdivide the representative clusters on the basis of dissimilarity in their inherent properties.

3.2 Clusters Representative of Inversions of Duration Not Less Than 10 Hours

The thirteen clusters for the winter 35-200 feet layer data included 230 inversion cases. Of these, 97 cases[1] (42 per cent) were of duration not less than 10 hours, with the remaining 133 cases of shorter duration. If the 97 cases were fairly uniformly distributed in each cluster, then all the clusters would warrant further investigation. This was not the case however, as some clusters included very few inversions of duration not less than 10 hours.

Clusters 1 to 4, 7 and 8 included only 74 inversion cases (32 per cent of the total), yet they contained 68 inversions (90 per cent) of duration not less than 10 hours[2]. The other seven clusters included 156 cases (68 per cent) of all inversions, and 29 cases (17 per cent) of inversions lasting not less than 10 hours. Therefore, the former set of clusters contained 70 per cent of inversions of the stipulated duration for this study, while the latter contained only 30 per cent of

---

1. Minor discrepancy arises (97 vs 100 cases) as inversions that extended either into or out of the core winter months are counted.

2. Original Cluster numbers from Bell's (1974) classification scheme are used (see Table 3.1).

these inversions.

Since this thesis studies inversions lasting not less than 10 hours, the unrepresentative 133 cases are eliminated from further consideration. Eleven of the 97 cases retained are also eliminated because of missing data. Of the 86 cases remaining, the set of six clusters (1 to 4, 7 and 8) included 60 cases (70 per cent) and the remainder occurred in the other seven clusters (Table 3.2).

In each of the six selected clusters, inversions lasting not less than 10 hours constituted over 68 per cent of all inversions. The lowest percentage manifested in Cluster 3 does not reflect a high frequency of brief inversions but rather a high frequency of missing data. Conversely, no cluster in the unselected seven clusters included a 28 per cent frequency of inversions not less than 10 hours in duration.

A question that deserves consideration is whether it is justifiable to use the six selected clusters for a structural behaviour study of inversions lasting not less than 10 hours. This raises the question of magnitude of difference between inversions of this duration in the six selected clusters and in the seven unselected clusters. The graphical technique of a dispersion diagram (Figure 3.1) focuses on presenting some insight to this inquiry.

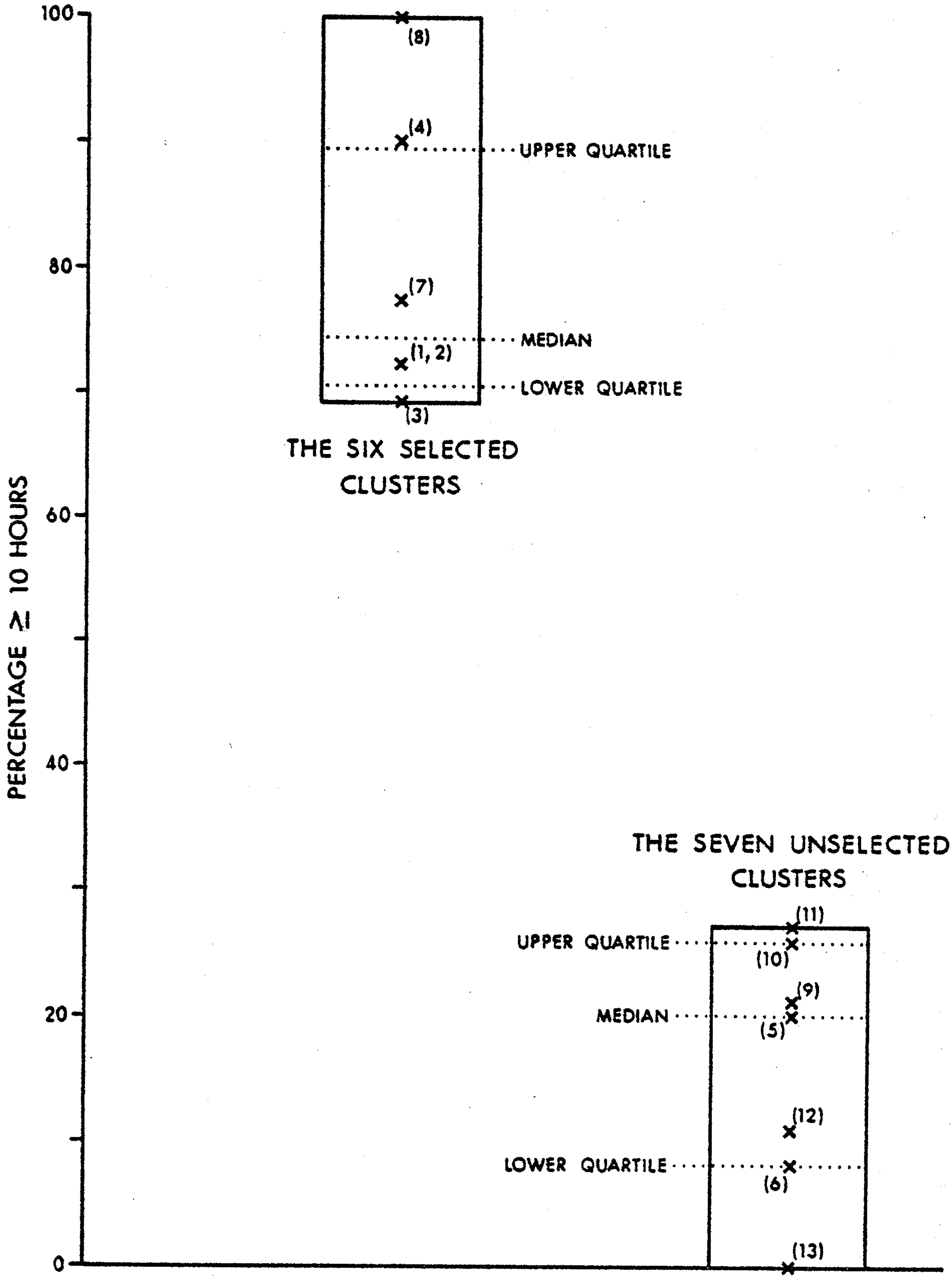
Table 3.2

Clusters Representative of Inversions of Duration ≥ 10 Hours

Cluster Number	Original Cases	Original Cases ≥10 Hrs.		Data Missing (cases omitted)		Cases < 10 Hrs. (cases omitted)		Extracted Cases ≥10 hrs.		Clusters Selected (*)
		No.	%	No.	%	No.	%	No.	%	
1	7	7	100	2	29	0	00	5	72	*
2	7	6	86	1	14	1	14	5	72	*
3	16	15	94	4	25	1	06	11	69	*
4	31	28	90	0	00	3	10	28	90	*
5	25	6	24	1	04	19	76	5	20	
6	25	2	08	0	00	23	92	2	08	
7	9	8	88	1	11	1	11	7	77	*
8	4	4	100	0	00	0	00	4	100	*
9	24	5	21	0	00	19	79	5	21	
10	30	10	33	2	07	20	66	8	26	
11	11	3	27	0	00	9	73	3	27	
12	27	3	11	0	00	24	89	3	11	
13	14	0	00	0	00	14	100	0	00	

Figure 3.1

Dispersion Diagram for Inversions ≥ 10 Hours Expressed as a Percentage of All Inversions in 2 Sets of Clusters



The dispersion diagram shows that there is no overlap between the two sets of clusters. The lower quartile of the six selected clusters is greater in magnitude than the upper quartile of the seven unselected clusters. A clear space on the diagram is thus discernable between the ranges of the central 50 per cent of the two cluster sets. This indicates significant difference (Gregory, 1963).

A scrutiny of various inversion duration scales illuminates basic differences between both sets of clusters (Table 3.3). The set of seven unselected clusters (26 cases) shows a disportionatly high 77 per cent incidence of inversions of duration not greater than 15 hours, while low frequencies of 15 and 8 per cent respectively describe duration scales of not greater than 20 hours and of not less than 20 hours. On the other hand, the set of six selected clusters (60 cases) shows reasonably uniform distribution with corresponding frequencies of 32, 46 and 22 per cent. For the 86 cases in all thirteen clusters, the corresponding frequencies are 45, 37 and 18 per cent.

It transpires that the percentage frequencies for the six selected clusters diverge far less from those for the thirteen clusters than do the frequencies of the seven unselected clusters. It thus seems advantageous

Table 3.3

Distribution of Inversions within Various Duration Scales in 2 Sets of Clusters

Duration Scales (Hrs.)	1 Selected Clusters (1,2,3,4,7,8)		2 Unselected Clusters (5,6,9,10,11,12,13)		3 All Clusters		Percent. Differ. (3-1)	Percent. Differ. (3-2)
	No.	%	No.	%	No.	%		
≥10 to ≤15	19	32	20	77	39	45	13	32
>15 to <20	28	46	04	15	32	37	09	22
≥20	13	22	02	08	15	18	04	10
TOTAL	60	100	26	100	86	100	26	64

to use the six selected clusters for a structural behaviour study of inversions lasting at least 10 hours, as they contain a better sample of inversions of various duration scales.

3.3 Temporal Distribution of Inversions in Selected Clusters

As the sample size is redefined, it is important that the relation between the entire 35-200 feet inversion sample population[3] and inversions in the six selected

3. Hereafter, figures within the brackets are for the entire sample population inversions.

clusters be assessed. A comparative temporal distribution study through application of the model (Ch. 2) is attempted.

A total of 60 (100) inversion cases occurred in the six selected clusters. A temporal examination of these inversions derived results that are consistent with the sample population.

In the nocturnal period, 1700 to 0700 hours, inversions developed with a 72(76) per cent frequency. This frequency enlarged to 93 (96) per cent in the radiational heat loss period from 1500 to 0700 hours. The remainder was constituted in the transitional zone between 1200 and 1400 hours. An hourly peak 27 (30) per cent of developments similarly occurred at sunset, 1700 hours (Figure 3.2).

The transitional zone, 2000 to 2200 hours, partitioned the radiational heat loss period into two sectors. In the sector, 1500 to 1900 hours, a true normal frequence distribution of inversions was exhibited. This sector accounted for 75 (68) per cent of the development and included 9 (10) of the 13 (17) inversions lasting not less than 20 hours. The other sector, 2300 to 0300 hours, contained 12 (13) per cent of the development and these inversions were of a shorter average 13 (11.5) hours duration (Figure 3.3).

All inversions decayed in the period from 0200 to

Figure 3.2

Hourly Frequency of Inversion Development for the Six Selected Clusters

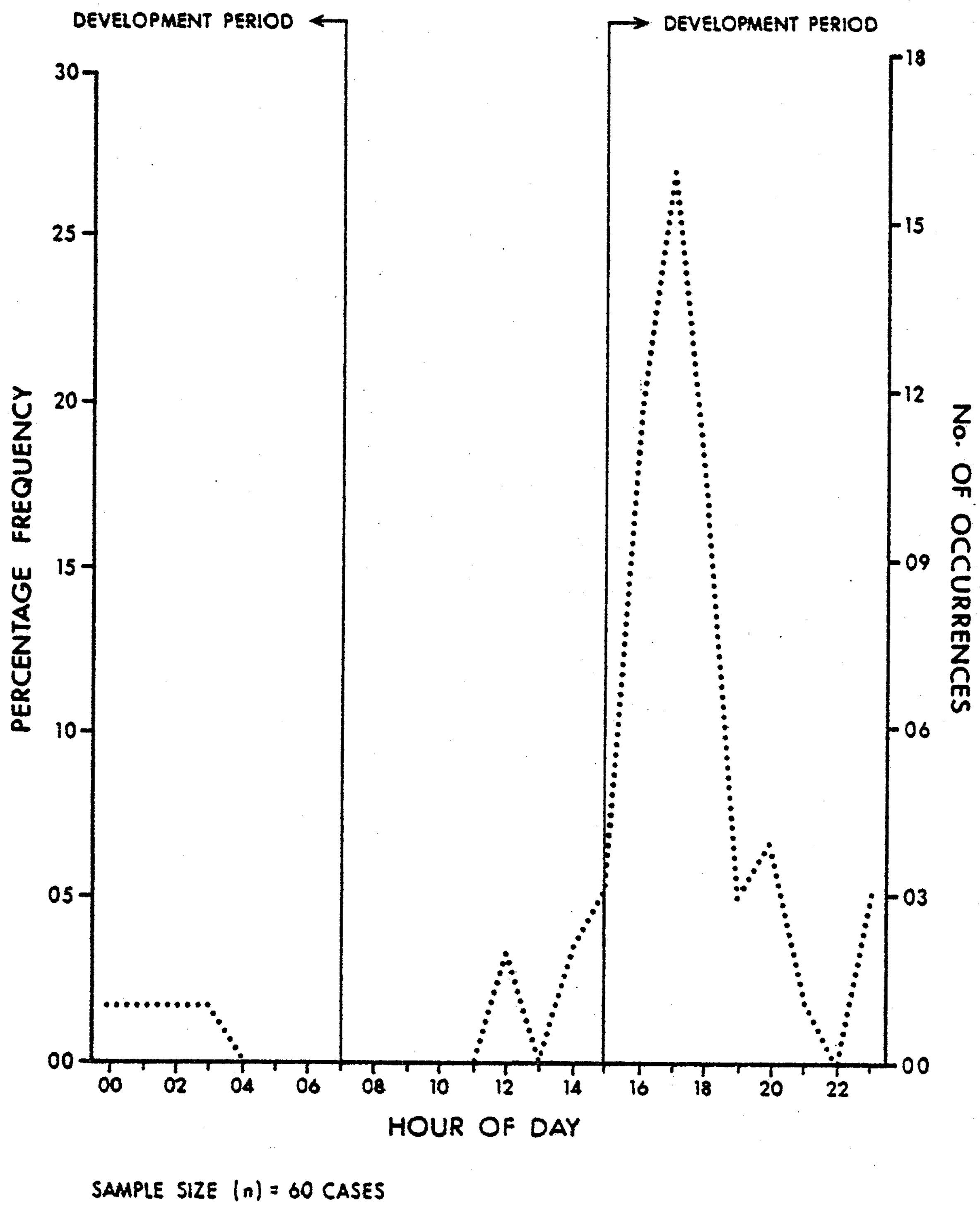
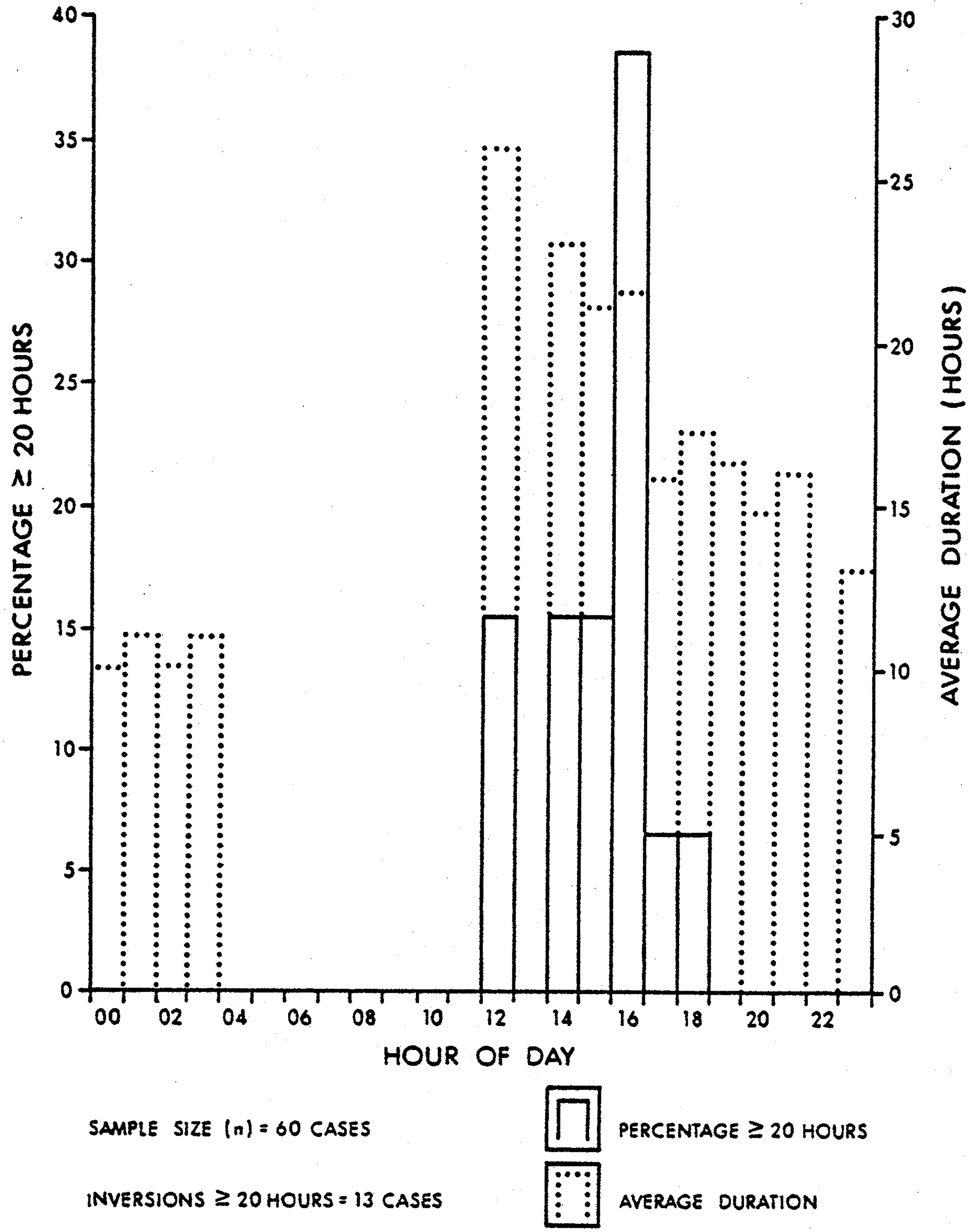


Figure 3.3

Average Duration of Inversions Which Develop in Each Hour, Among the Six Selected Clusters



1400 hours (Figure 3.4). Sunrise time, 0800 hours, divided this period. Within the radiational heating period, 0800 to 1400 hours, was 80 (72) per cent of the decay. At the time of greatest radiational heating, 1100 hours, a peak 27 (20) per cent frequency of decay was observed.

The major decay period included the decay of 72 (82) per cent of inversions lasting not less than 20 hours in duration. These inversions decayed with greatest frequency 62 (52) per cent in the maximum solar radiation receipt period between 1200 and 1300 hours. The decay of shorter, less intense inversions was the hallmark of the minor decay period (Figure 3.5).

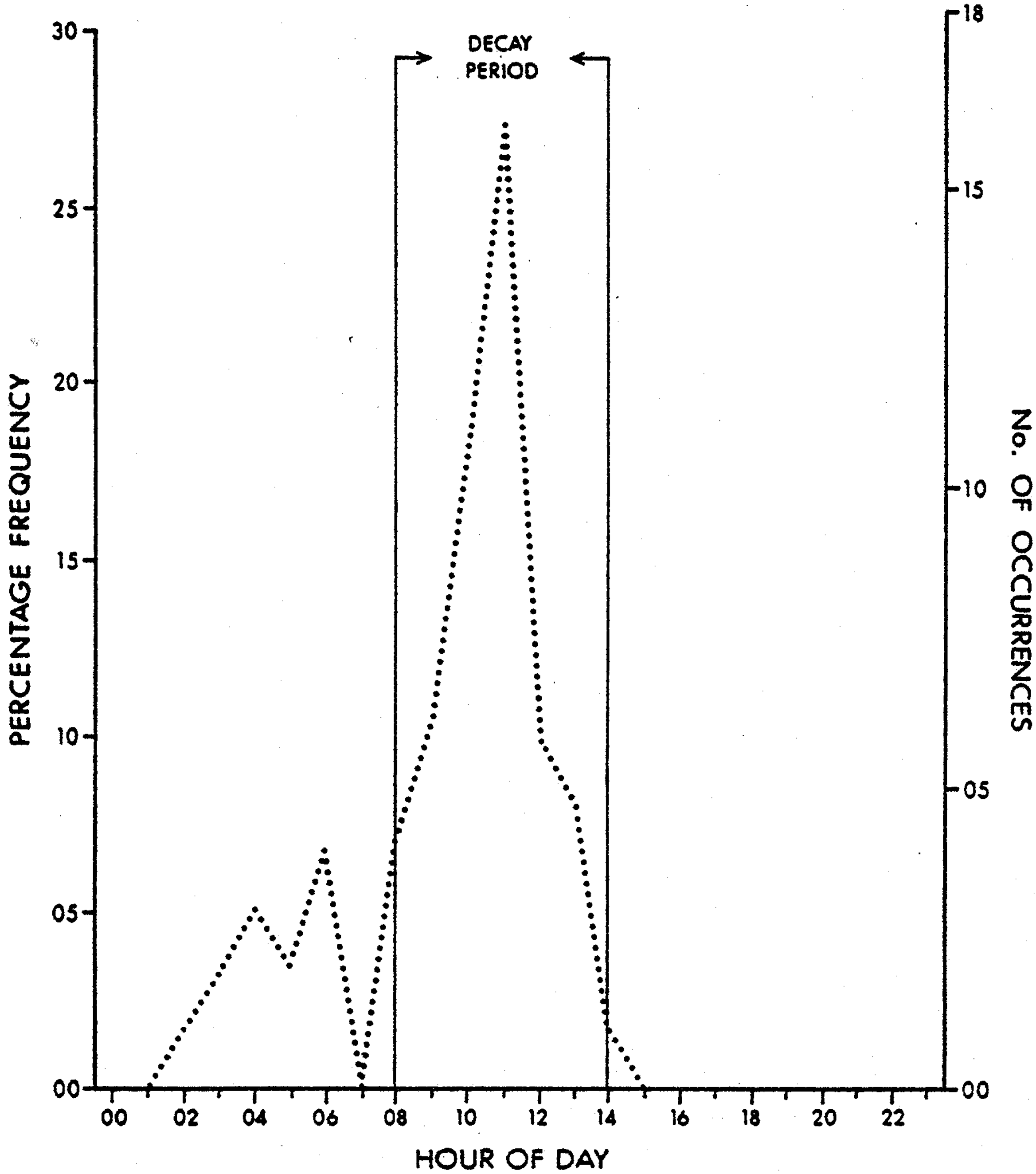
In this section, a comparative discussion was attempted to demonstrate the relation between the temporal distribution of inversions in the sample population and in the six selected clusters. The results are more suggestive than conclusive, but there exist strong indications that these two groups are positively correlated. This conclusion is supported when it is recalled that the estimate of the character of a population is more accurate the larger the sample size.

3.4 Typology of Selected Clusters

The thirteen clusters computed using six variables were subjectively tagged by Bell (1974, Ch. 9) as being

Figure 3.4

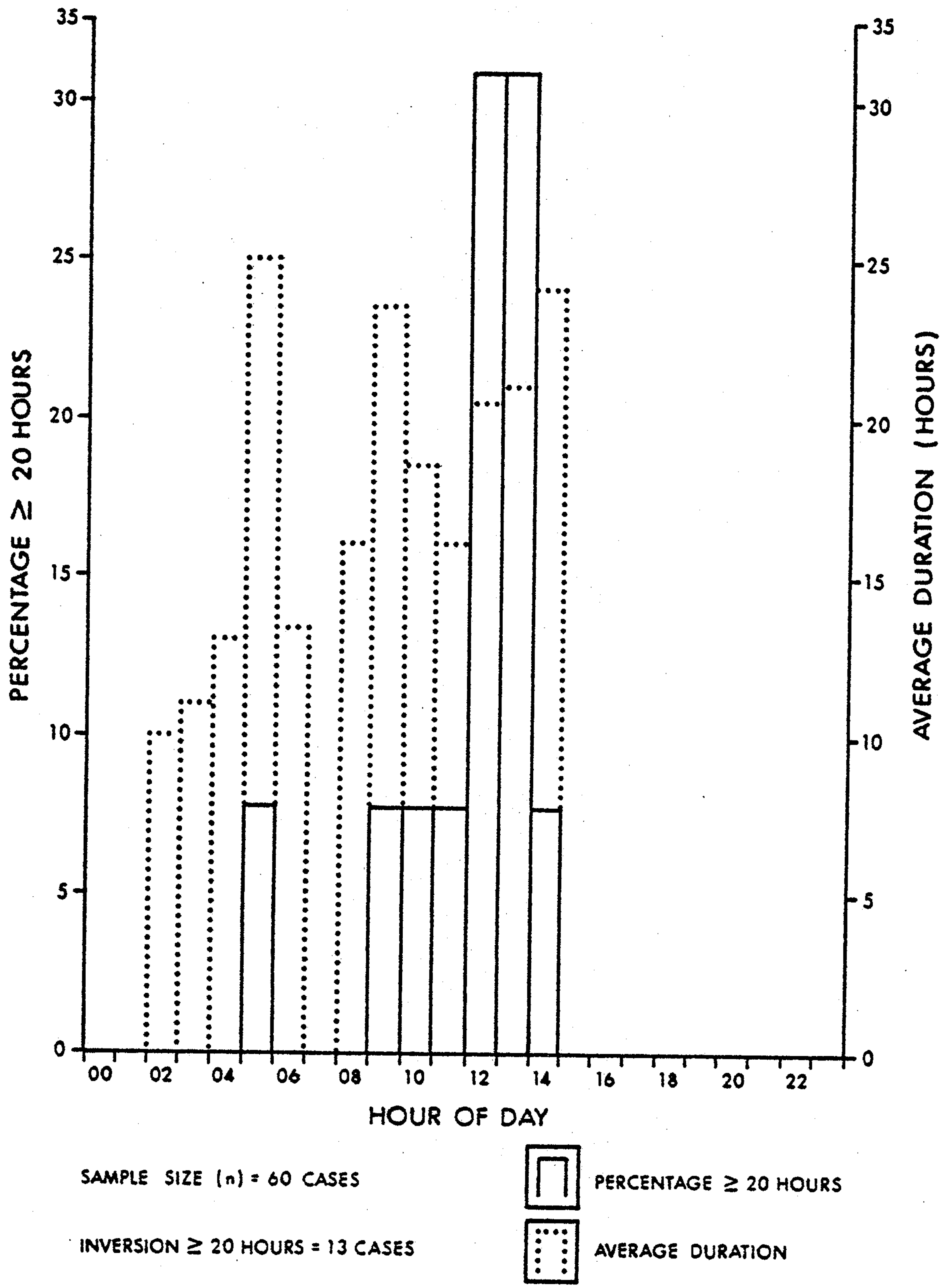
Hourly Frequency of Inversion Decay for the Six Selected Clusters



SAMPLE SIZE (n) = 60 CASES

Figure 3.5

Average Duration of Inversions Which Decay in Each Hour, Among the Six Selected Clusters



primarily of radiative and advective origin since other formation processes (subsidence and frontal) cannot be adequately detected by applying Ward's (1963) method to the data available. Bell included the subsidence type among the radiative inversions, and the frontal type among the advective inversions. Bell cautioned that care must be exercised in interpretation, because subjective tagging is liable to induce error, as marked variations of the variables existed within each cluster. Table 3.4 presents the subjectively tagged clusters.

This section endeavours to devise a typology of the six selected clusters based on dissimilarity in their inherent properties. Table 3.5, which contains values of seven properties of these clusters is a modified version of Table 3.1. This modification was necessitated by the reduction in the original number of cases. Furthermore, the values exemplified in Table 3.5, unlike the arithmetic means of Table 3.1, are the mean values of the central 50 per cent of inversion occurrences in each cluster. They were found using the relationship:

$$\frac{\text{Inter-quartile Range}}{2} \text{ (+) or (-) Lower/Upper Quartile}$$

This was implemented to alleviate to some degree the considerable variations that existed within each cluster.

Table 3.4

Winter 35 - 200 feet Layer Inversion Characteristics by Cluster
[From Bell, (1974)]

	Cluster	Wind Direction	Summary
Long Inversion	1	SW	SW winds, long inversions, high temperatures, low pressure and high wind speeds all point to advection inversions.
	2	Variable	Classical radiation inversions with light winds, low cloud, and high pressure.
Medium Inversion	8	S	Advection inversions.
	7	N	High radiation input.
	3	S & SW	Contains both advection and radiation inversions. Evidence suggests radiation inversions destroyed by changing synoptic conditions.
	4	W, NW & N	Radiation inversions
Medium-Short Inversion	11	W & SW	Advective/frontal inversions
	10	NW, W & N	Radiation inversions.
	9	NW, W & N	Short radiation inversions.
	5	NW & variable	Radiation/advection inversions
Short Inversion	12	Variable	Mainly radiational inversions.
	6	SW, N & W	Advection and frontal inversions.
	13	NW, N & W	Radiation inversions.

Table 3.5

Mean Values of 7 Variables Characteristic of The Six Selected Clusters

Group	Cluster Number	Cluster Size	Inversion Duration (Hours)	Inversion Intensity (°F/1000')	Wind Speed (m.p.h.)	Wind Shear (m.p.h.)	Sky Obscur-ity (Tenths)	Temperature (°F)	Pressure (m.b.)
	2	05	20.0	-36.1	09.2	03.6	0.5	-22.5	1030.1
A	4	28	16.0	-26.9	10.2	08.8	1.1	-14.2	1025.9
	7	07	19.0	-35.1	08.1	07.0	1.3	-01.5	1028.4
	TOTAL	40	18.3	-32.7	09.2	06.5	1.0	-12.7	1028.1
	1	05	26.0	-26.8	14.0	18.1	1.5	21.7	1019.1
B	3	11	13.0	-24.3	10.7	11.6	3.2	4.1	1016.7
	8	04	17.0	-53.7	09.1	05.6	1.2	13.7	1009.1
	TOTAL	20	18.7	-34.9	11.3	11.8	2.0	13.2	1015.0

The temperature variable was examined first to provide a basic framework for the better assessment of the other variables.

The mean temperature of the inter-quartile range (+1.3°F) was resolved using the average temperature of each of the six selected clusters. Based on this measure, the clusters were apportioned into two groups. Clusters 2, 4 and 7 formed a group distinctive from Clusters 1, 3 and 8.

At this juncture, the former clusters are termed Group A, with the latter designated Group B.

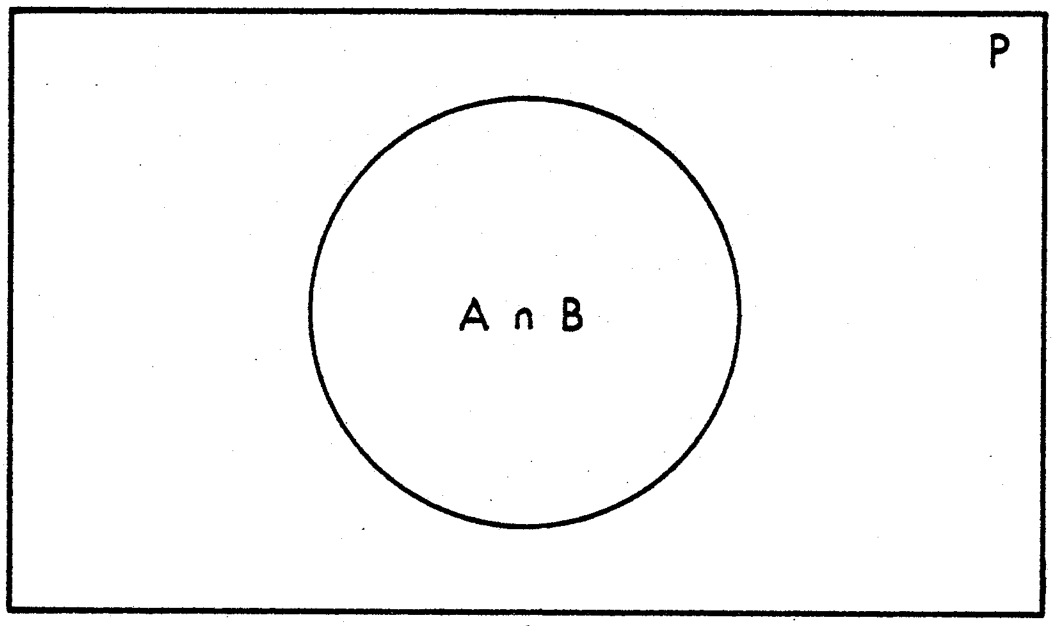
In Group A, Cluster 2 had the lowest temperature (-22°F), while Cluster 7 (-1.5°F) approached the mean temperature value of the inter-quartile range. Clusters 1 (+21.7°F) and 3 (+4.1°F) in Group B, displayed a similar but reversed pattern. It transpires that Clusters 4 (-14.2°F) and 8 (+13.7°F) assumed intermediate positions in their respective groups. Since Clusters 7 and 3 are the least apart in a temperature context, they are regarded as transitional or merging clusters of the two groups.

This phenomena can be viewed in different ways. With Clusters 1 and 2 at the apex of their respective groups, the other clusters extend outward as variegated shades with distance qualifying the degree of colour (Figure 3.6). For instance, in Group A, Cluster 2 had the brightest colour while the palest colour distinguished Cluster 7.

Average pressure values showed marked differences between both groups. Group A exhibited higher pressure than group B. High pressure systems are generally associated with low temperatures, sunny skies and light winds. Consequently, the former group had lower average values of sky obscurity, wind speed and wind shear than the latter.

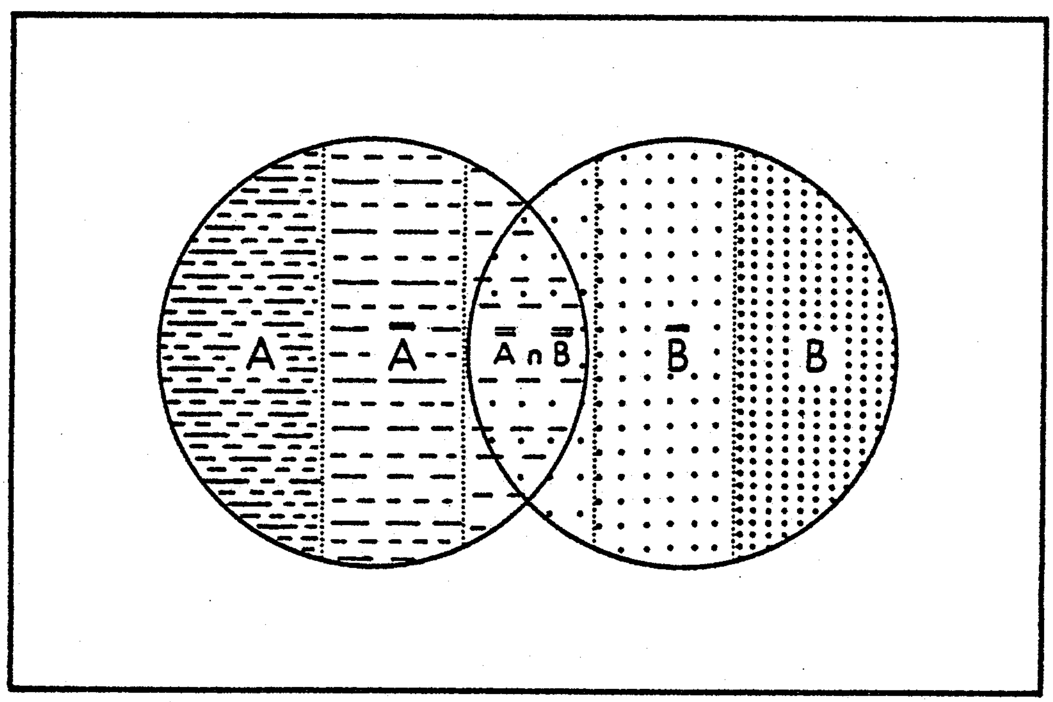
Figure 3.6

A Typology of the Six Selected Clusters Based on Temperature Properties



STAGE 1

P = INITIAL 13 CLUSTERS
$A \cap B$ = SELECTED 6 CLUSTERS



STAGE 2

A = CLUSTER 2
$\bar{A}$ = CLUSTER 4

B = CLUSTER 1
$\bar{B}$ = CLUSTER 8

$\bar{\bar{A}} \cap \bar{\bar{B}}$ = CLUSTERS 7 AND 3

Clusters 1 and 2 were of the longest average inversion duration in their respective groups. Inversion duration should vary with inversion intensity as they are highly correlated (Ch. 2). In general, this association was observed in Group A; but it was grossly transgressed by Clusters 3 and 8 in Group B. According to Fritz (1958, p. 131), it is not valid to generalize about inversion magnitude, because the question of whether or not it increases or decreases as surface temperature falls, depends on the rate of change of atmospheric 'emissivity' with air temperature. Baker et al. (1969) have pointed out that basic relations between inversion duration and inversion intensity are not yet fully understood.

The equated typology of the selected clusters may be strengthened through an investigation of monthly frequency distribution of inversions. Inversions in Group B, marked by higher temperatures, showed a definite preference to the months of December and February. On the other hand Group A inversions, distinguished by lower temperatures, demonstrated strong relation with the month of January (Table 3.6).

Labelle et al. (1966) determined that at Winnipeg January is normally the coldest month of the year and that prolonged cold spells are not infrequent. Temperature has fallen lower than -30°F for as many as sixteen days in

Table 3.6

Monthly Frequency Distribution of Inversions in the Six Selected Clusters

a) Individual Months and Clusters

Month & Year	GROUP A						GROUP B						Total Cases
	Cluster 2		Cluster 4		Cluster 7		Cluster 1		Cluster 3		Cluster 8		
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
Dec. 1969	--	--	1	3.6	3	42.9	1	20.0	1	9.2	--	--	13
Dec. 1961	--	--	2	7.2	2	28.6	1	20.0	2	18.3	--	--	
Jan. 1970	2	40.0	4	14.4	--	--	1	20.0	1	9.2	1	25.0	25
Jan. 1971	2	40.0	12	42.4	--	--	--	--	2	18.3	--	--	
Feb. 1970	--	--	6	21.6	1	14.3	2	40.0	1	9.2	--	--	22
Feb. 1971	1	20.0	3	10.8	1	14.3	--	--	4	36.6	3	75.0	
TOTAL	5	100	28	100	7	100	5	100	11	100	4	100	60

b) Monthly and Group Means

Month & Year	Group A		Group B	
	Total Monthly Cases X $\frac{60}{40}$	Total Per Cent	Total Monthly Cases X $\frac{60}{20}$	Total Per Cent
Dec. '69 & '71	8 x 1.5 = 12	44.5	5 x 3.0 = 15	55.5
Jan. '70 & '71	20 x 1.5 = 30	66.6	5 x 3.0 = 15	33.3
Feb. '70 & '71	12 x 1.5 = 18	37.5	10 x 3.0 = 30	62.5

one year. For the same geographically locality, Bell (1974) estimated that the normal temperature cycle is at its lowest (-1°F) in the period January 17-27.

Application of the model of the diurnal distribution of inversions (Ch. 2) to both cluster groups produced some interesting results.

Inversions in Group B (20 cases) developed with a 75 per cent frequency in the period from 1400 to 2000 hours[4]; and, with a 15 per cent frequency in the period from 2300 to 0300 hours. For identical periods, Group A (40 cases) had corresponding frequencies of 88 and 10 per cent (Figure 3.7). The former group included five inversion cases (25 per cent) of duration not less than 20 hours. These inversions developed in the period, 1200 to 1600 hours, with individual hours accounting for 100 per cent frequency of cases. Comparatively, the latter group contained eight inversion cases (20 per cent) of this duration scale. They developed in the period between 1200 and 1800 hours and for individual hours the minimum frequency was 10 per cent (Figure 3.8).

All inversions in Group B decayed in the period, 0200 to 1400 hours, which is one hour earlier and one hour

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4. Encompassed in this period is the normal frequency distribution, 1500 to 1900 hours (Ch. 2).

Figure 3.7

Hourly Frequency of Inversion Development
in 2 Cluster Groups

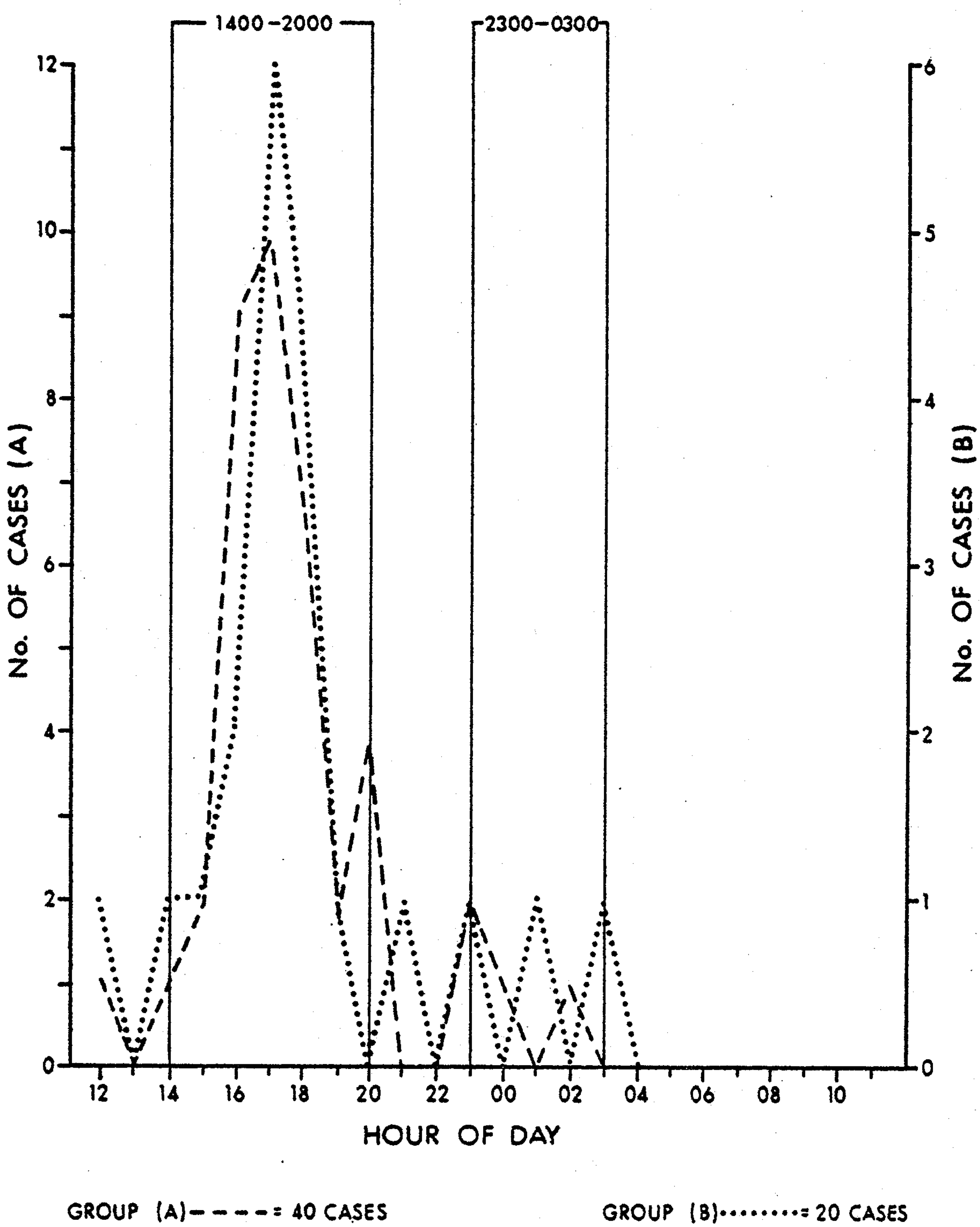
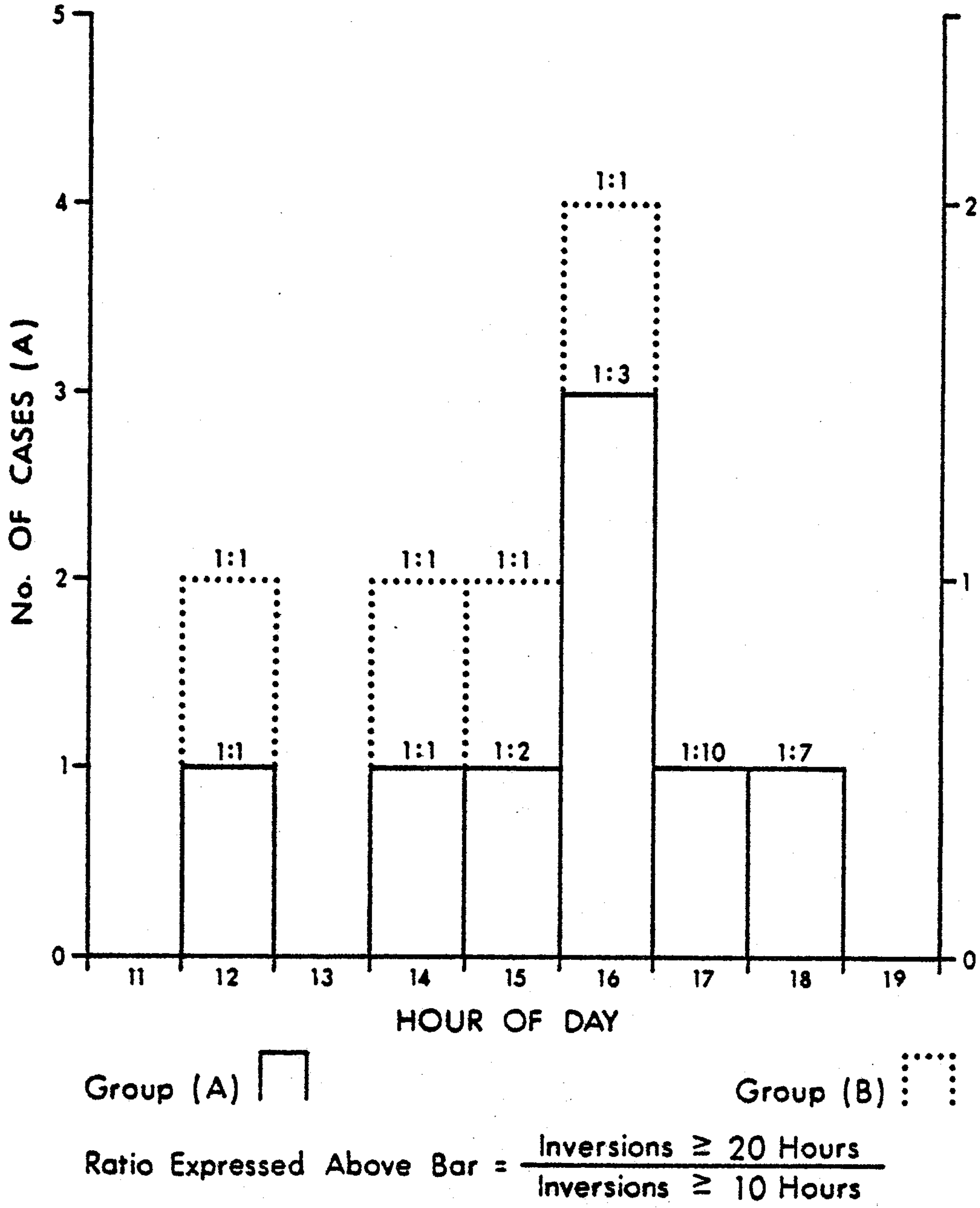


Figure 3.8

Frequency of Development of Inversions ≥ 20 Hours Duration in 2 Cluster Groups



later than for inversions in Group A. From sunrise time, 0800 hours, 75 per cent of inversions decayed in the former group as opposed to 83 per cent in the latter (Figure 3.9). Inversions lasting not less than 20 hours in Group A decayed only in the period from 1000 to 1300 hours, with 75 per cent decaying at 1200 and 1300 hours. Inversions of the same duration in Group B, decayed in the period from 0500 to 1600 hours, with 60 per cent decaying between 1200 and 1400 hours (Figure 3.10).

It is reasonable to suspect from the above information that the development and decay of inversions in Group B are less dependent on the effects of radiative heating and cooling.

The six selected clusters have been divided into two groups primarily on the basis of seven variables. This typology was also established on measures of the daily and monthly frequency distribution of inversions.

Group A, comprising Clusters 2, 4 and 7, was characteristic of lower temperature, sky obscurity, wind speed and wind shear, but higher pressure; prevalently occurred in the coldest month, January; and appeared more dependent on the diurnal effects of solar radiation heating. On the other hand Group B, including Clusters 1, 3 and 8, was characteristic of higher temperature, sky obscurity, wind speed and wind shear, but lower pressure; displayed

Figure 3.9

Hourly Frequency of Inversion Decay
in 2 Cluster Groups

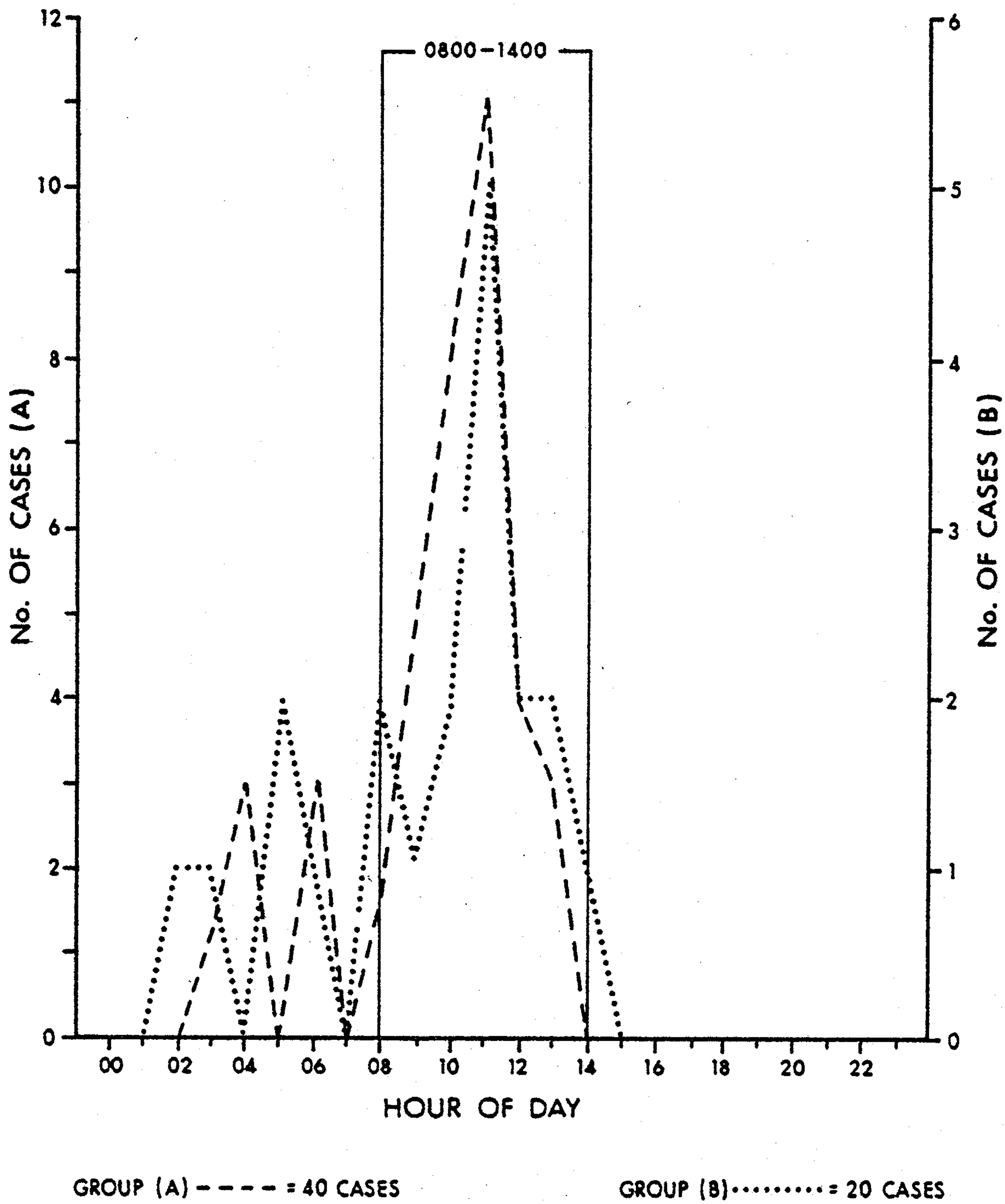
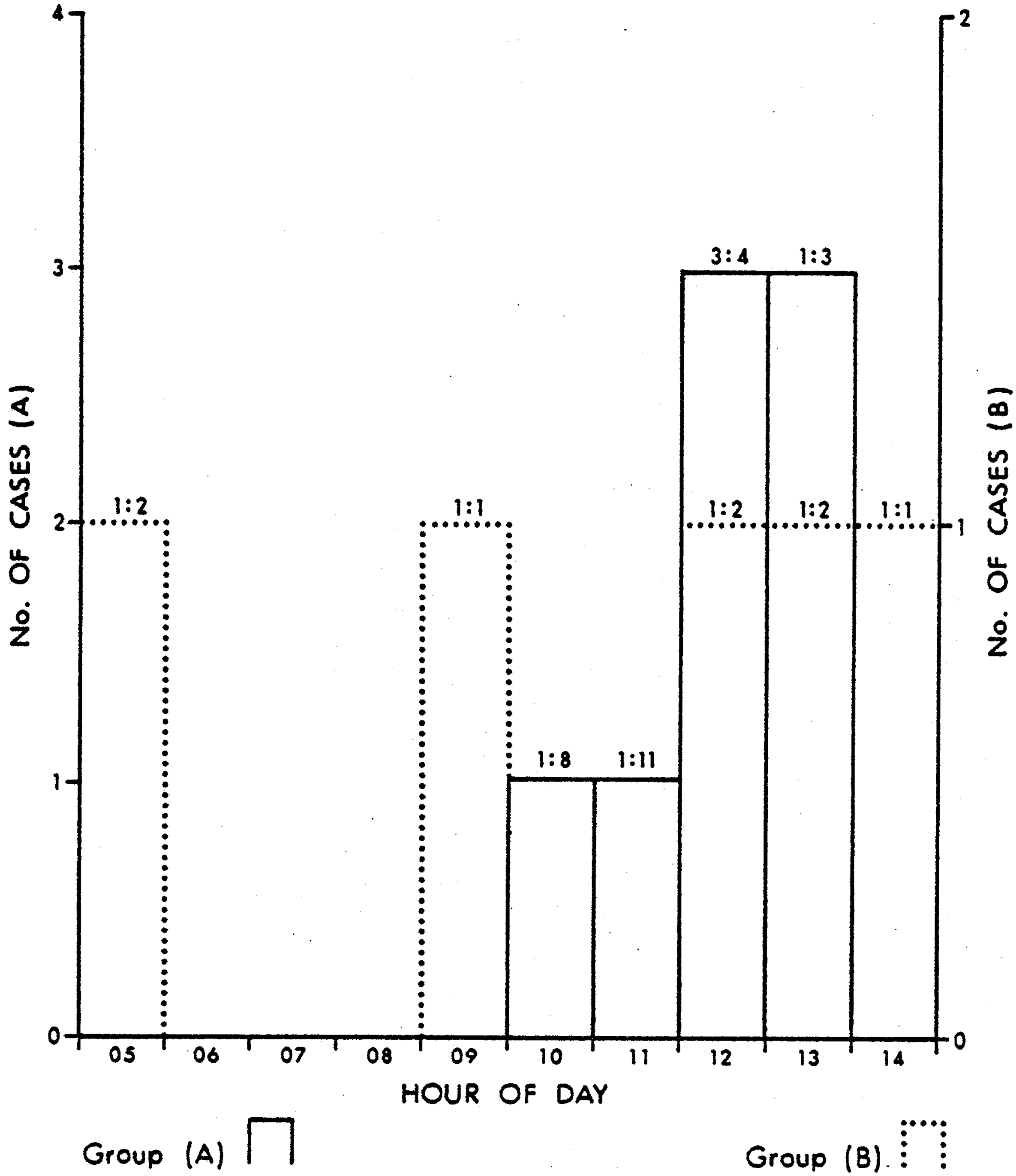


Figure 3.10

Frequency of Decay of Inversions ≥ 20 Hours Duration in 2 Cluster Groups



Ratio Expressed Above Bar = $\frac{\text{Inversions} \geq 20 \text{ Hours}}{\text{Inversions} \geq 10 \text{ Hours}}$

preference to the warmer months, December and February; and appeared less dependent of the diurnal effects.

The clusters included in Group A are typed as 'Radiative Clusters', while those contained in Group B are typed as 'Advective Clusters'. This typology provides ease in interpretation and analysis, for groups and thus clusters are distinguishable by certain attributes. It must be firmly borne in mind however, that of the six selected clusters, only Clusters 1 and 2 are distinct, the others are variegated shades in their respective groups.

Inversion cases that are reasonable representatives of each selected cluster of the typology are identified and analyzed in Chs. 4 and 5. Structural behaviour of the chosen inversion cases during their development and decay is investigated. Once the structure of each inversion case associated with a synoptic situation is determined, an attempt is then made to assess the results in terms of weather processes.

CHAPTER IV

Structural Behaviour of Inversions in the Radiative Clusters

4.1 General Comments and Method

The previous discussion was centered around selection and typology of clusters from Bell's (1974) classification scheme. An attempt will now be made to study the development and decay structures of inversions using representative case studies of each cluster in the radiative group. The synoptic situation associated with each case study is identified and an attempt is then made to evaluate the structural behaviour in terms of weather processes.

The structural behaviour of inversions during their development and decay was investigated with the aid of tower data collected by Bell (1974), regular hourly synoptic meteorological data (Atmos. Environ. Service), and daily weather maps (surface, 500 and 850 m.b. Charts).

Data were monitored for the development and the decay period of each inversion case study. Preliminary analysis determined the length of the periods that would provide sufficient insight into inversion structure and related weather processes.

It was essential that the atmospheric circulation be considered, since this is the setting within which the weather elements ultimately have to be understood. A description of the atmosphere was obtained principally from synoptic daily weather maps. However, certain problems should be borne in mind in the discussion to follow, since the interpretation of weather maps presents special difficulties. No two weather maps are identical. In combination with the almost infinite variety of synoptic patterns, synoptic systems differ markedly in size and intensity throughout their individual life cycle and from one sequence to the next (Barry and Perry, 1973, p. 92).

Two principal types of information were derived from weather maps: 1) source and movement of air masses; 2) migratory high and low pressure systems and the weather fronts associated with them. The importance of studying air mass types cannot be overstated, since both the radiative and convective fluxes between the surface and the atmosphere depend upon the nature of the prevailing air masses (Catchpole, 1969, p. 263).

Although research on air mass types has been quite extensive in the climatological literature -- for example, study on properties of North American air masses (Willet, 1938) (Anderson et al., 1955), and the study of air mass climatology (Miller, 1953) (James, 1970) -- yet, special problems of classifying air mass types still exist. No attempt is made here to discuss fundamentals of definition or analysis; instead, the air mass types identified by Bryson (1966) and presented in Figure 4.1, will be applied.

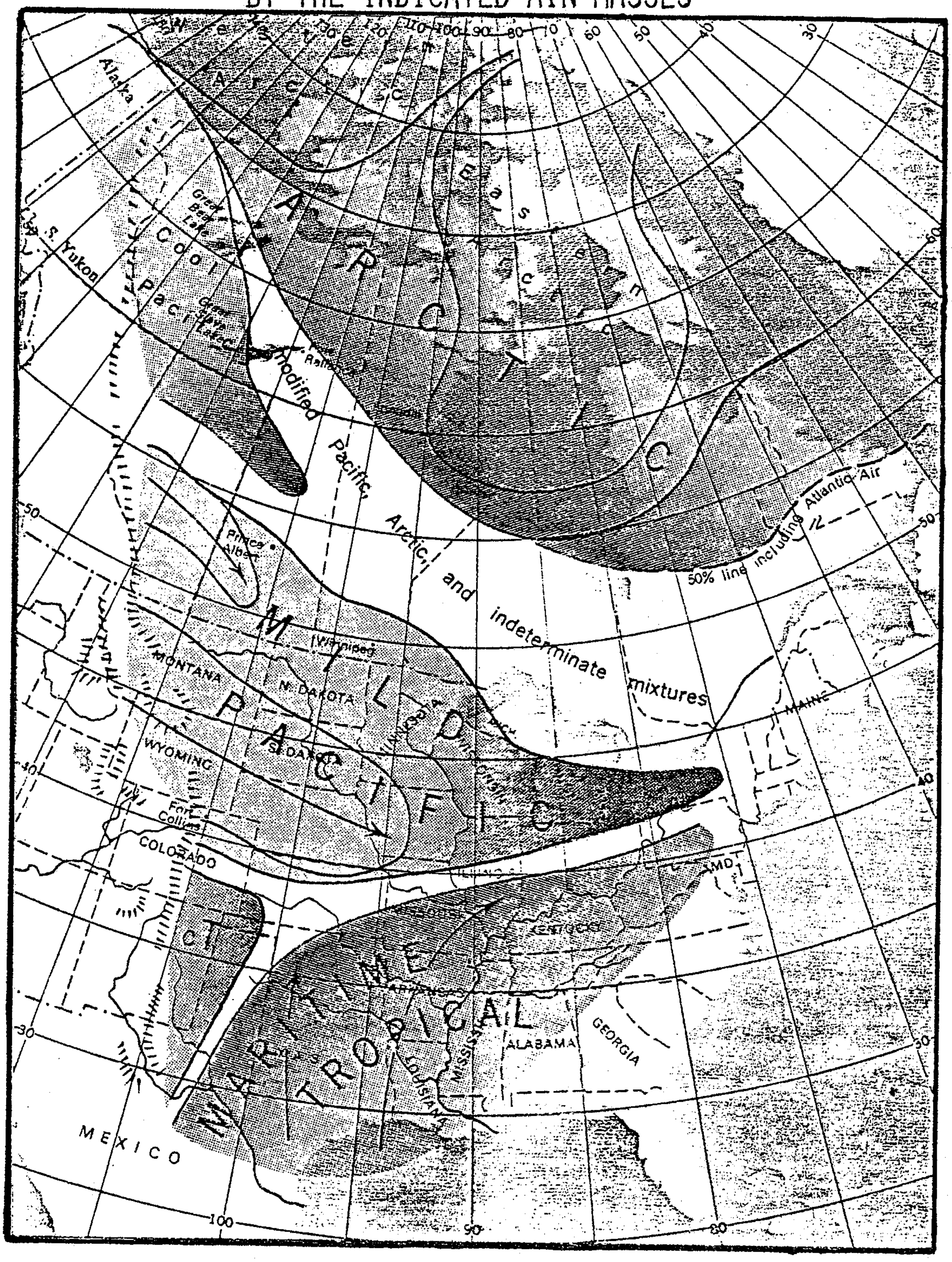
Winnipeg is in the middle of the belt of the circumpolar westerlies and is principally affected by a westerly airflow. This can be subdivided into south-westerly, westerly and northwesterly flows. Frequently these westerly airflows involve Maritime Polar (mP) air but they can involve other air masses.

Maritime Polar southwesterly originates in the Pacific and moves inland via Montana-Dakota's before angling north-eastwards towards Minnesota. The main disturbance associated with this air mass moves to the south of Winnipeg, and is important for it can increase cloud amounts and moderate temperatures in the Winnipeg area. Notwithstanding, a southwesterly flow can also involve Maritime Tropical air (mT), though frequently, this air mass type movement is southerly across the Great Lakes.

A common air mass is the mild and moist Maritime Polar westerly which is usually accompanied by depressions (Alberta-Saskatchewan-Manitoba low), but can also come

FIGURE 4.1

COMPOSITE CHART OF REGIONS DOMINATED BY THE VARIOUS AIR MASS TYPES. THE SHADED REGIONS ARE OCCUPIED MORE THAN 50 PER CENT OF THE TIME BY THE INDICATED AIR MASSES



SOURCE: BRYSON (1966)

under the control of a warm blocking or a warm travelling anticyclonic system. This air mass type normally crosses the coast in southern British Columbia and spreads inland via southern Alberta.

Maritime Polar northwesterly frequently crosses northern British Columbia to the Yukon before moving southeastward. It involves the cooler variety of air originating from over the Pacific. Cold continental Arctic air (cA) which predominates from the north, also comes from the north-west and north-east, and usually does so under the control of a high pressure system. These air masses are expected to favour inversions mainly of radiative and nocturnal origin for they frequently replace warmer air and experience advective heating.

Presumably the air mass associated with each case will be representative of the air mass generally associated with the cluster from which the case is derived. If so, conclusions can then be drawn for the cluster, and subsequently, for the typed cluster group.

It is relevant to outline the method adopted in selection of the inversion cases. Selection is based chiefly on a temporal examination of the development and decay of inversions using the model described in Ch. 2. Analysis detected that not all inversions reflect the general features of the model and consideration will be given to such cases in selection. Inversion cases that are consistent with the model are also selected. In this circumstance, one of the inter-quartile cases, preferably the median case is selected. In sum, the method permits reasonable representation of both consistent and inconsistent cases within a cluster.

4.2 Cluster 2

4.2.1. Preliminary Remarks

Cluster 2 is distinctive within the radiative cluster group especially with regard to temperature conditions (see Ch. 3). This cluster was identified by Bell (1974) as constituting classical radiation inversions with long duration during the long night, little cloud cover, low wind speed and high pressure. Average properties of each inversion in Cluster 2 are tabulated in Table 4.1.

Of the five inversion cases in this cluster, equivalent to 8 per cent inversions of the selected clusters, four occurred in the coldest month January. The other case occurred early in February.

Inversions of the cluster developed between 1400 and 1800 hours and decayed between 1000 and 1300 hours. These periods support sharp radiative heat loss and heat gain, during which many intense, persistent inversions developed and decayed. The foregoing information is

Table 4.1

Average Properties of Inversion Cases in Cluster 2

Case Number	Date	Development Hour	Inversion Duration (Hours)	Decay Hour	Inversion Intensity (°F/1000')	Sky Obscurity (tenths)	Temperature (°F)	Pressure (m.b.)	Wind Speed (m.p.h.)	Wind Shear (m.p.h./x feet)	Wind Direction
11	Jan. 14'71	1400	23	1200	-35.5	0.5	-22.5	1036.0	9.9	2.5	W
16	Jan. 12'70	1600	20	1100	-36.7	0.4	-22.8	1031.9	5.9	5.3	NE
17	Jan. 16'71	1500	20	1000	-58.0	1.6	-21.0	1028.5	9.2	2.1	NE
18	Jan. 16'70	1800	20	1300	-35.9	0.0	-29.8	1030.1	9.5	6.0	W
23	Feb. 2'71	1800	18	1100	-36.1	1.8	-21.3	1029.4	2.7	3.6	E

consistent with the model of the diurnal distribution of inversions (Ch. 2).

A cursory examination of Cluster 2 inversions reveals that the lower 35-200 feet layer inversions developed after and decayed before associated higher 35-810 feet layer inversions. That is, the former are encompassed in the latter. Consequently, the average duration of the lower inversions is only 20 hours compared to an average 45 hours for the higher inversions.

4.2.2 Selected Inversion Cases

Inversion Cases 11 and 16[1] are chosen for detailed analysis. The former is the median case of the cluster. It developed early at 1400 hours, was maintained for 23 hours, and decayed at the expected time of greatest solar radiation receipt, 1200 hours. The latter case is of 20 hours duration, which is similar to two other cases. This inversion developed one hour prior to sunset at 1600 hours, and decayed at the primary time of sharpest temperature increase, 1100 hours. Both inversion cases occurred in January.

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1. Original case numbers from Bell's (1974) clustering technique are used.

4.2.2. (a) Inversion Case 11

This inversion case behaved in accordance with the model (Ch. 2). It developed with initial radiative cooling and, due to its strength, several hours of heating were required to induce decay. The associated higher 35-810 feet layer inversion was less significantly affected by this process. Under an anticyclonic circulation system, the higher inversion was very likely sustained by atmospheric subsidence.

Analysis detected that the inversions in each layer actually developed simultaneously at 0200 hours. The lower inversion however, decayed between 1200 and 1300 hours before redeveloping as Case 11. Shortly after the decay of this inversion, another formed; but, it was destroyed two hours later at 1500 hours. For the remainder of that day positive lapses were established in this layer. This event is unexpected because it followed a nocturnal radiative period. The higher inversion persisted for 50 hours until 0300 hours the next day.

It seems reasonable to postulate that Case 11 is an extension of the inversion that preceded it. A moment's reflection on the basic principles of the daily rhythm of radiative heating and cooling lends support to this assumption.

4.2.2. (a) (1) Development of Case 11

On the 14th of January the day of development of Case 11, Winnipeg's weather was described as -- "Cold. Partly cloudy. Snow to 2.26 a.m. Ice crystals" (Atmos. Environ. Service, Monthly Meteor. Summary, 1971). Overcast skies with heavy amounts of snowfall covered southern Manitoba on January 13. These conditions were replaced by clear, cold weather as a strong high pressure ridge forced a northerly flow of Arctic air (cA) southward. The Arctic front was well to the south of Winnipeg. On the western boundary of the area of high pressure was a southward extending stationary front from a well-defined depression off the southern British Columbia coast (Figure 4.2).

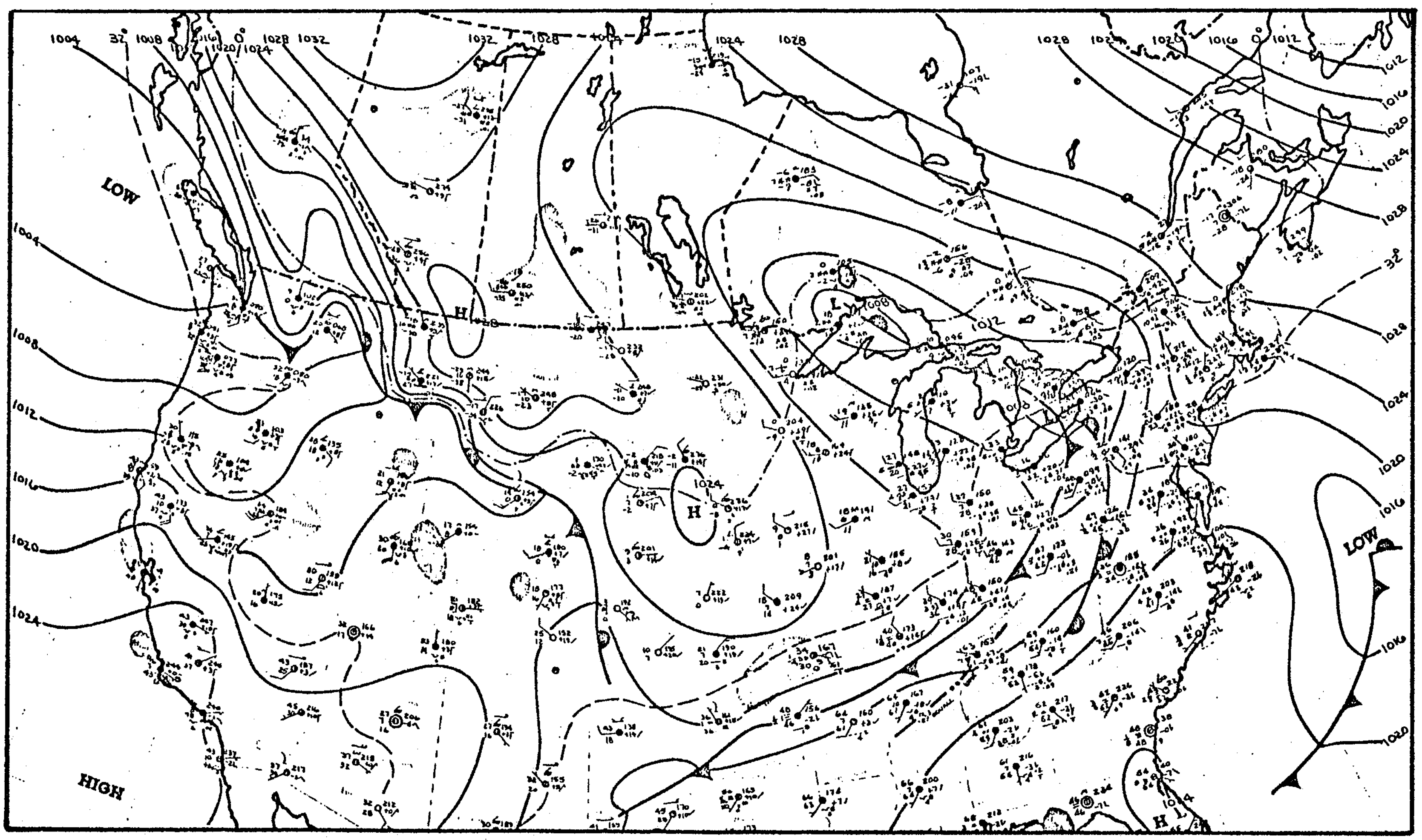
An interesting point is advanced by regarding the weather situation. The simultaneous development of the inversions in both layers at 0200 hours coincided with the culmination of snowfall. This snowfall had, significantly, persisted throughout the preceding day when there were positive lapses in the lowest 810 feet.

Hourly synoptic conditions for a development period from 0700 to 1600 hours are presented in Table 4.2. As the Arctic high pushed southward, pressure rose from 1021.8 to 1028.4 m.b. Sky obscurity was not greater than 5/10th's covered with AC and CI cloud types. At the lower 35 feet level light westerly winds were dominant,

FIGURE 4.2

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT OF INVERSION CASE 11

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. THURSDAY, JANUARY 14, 1971



<u>Table 4.2</u>

<u>Synoptic Conditions During Development Period</u>

<u>of Case 11</u>

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
0700	-37.3	-14.0	270	12	330	25	13	-20.2	-14.1	-9.4	1	AC	27.0	1021.8	A	12	0		
0800	-61.4	-19.0	280	12	330	24	12	-23.3	-13.2	-8.6	2	AC,Cl	10.0-27.0	1022.6	A	08	0		
0900	-33.1	-16.9	280	11	330	21	10	-21.8	-16.3	-8.7	2	AC,Cl	10.0-27.0	1023.4	A	12	7		
1000	-24.6	-15.8	270	11	310	17	6	-21.1	-17.0	-8.9	1	AC	10.0	1024.3	A	12	10		
1100	-13.9	-13.3	270	12	310	16	4	-19.1	-16.8	-8.8	1	AC	10.0	1024.6	A	12	10	7.6	8.5
1200	7.7	-6.2	270	12	310	16	4	-15.4	-16.6	-10.5	2	AC,Cl	10.0-27.0	1025.4	A	12	10		
1300	4.4	-3.6	250	10	290	17	7	-13.1	-13.8	-10.3	4	SC,Cl	6.5-27.0	1026.4	A	12	10		
1400*	-10.3	-7.8	260	10	290	14	4	-14.5	-12.8	-8.5	5	AC,Cl	13.0-27.0	1026.6	A	15	10		
1500	-0.9	-5.4	230	11	300	12	1	-13.4	-13.3	-9.2	5	AC,Cl	13.0-27.0	1027.7	A	15	10		
1600	-10.9	-3.5	250	8	310	12	4	-13.5	-11.7	-10.8	2	AC,Cl	13.0-26.0	1028.4	A	15	9		

*Inversion developed at 1400 hours in the 35-200 feet layer.

while at the higher 810 feet level fairly strong northwesterly winds decreased in speed with approach of the development hour. Speed shear[2] was moderate and dropped to less 8 m.p.h. from 1000 hours.

On the development day sunshine was recorded for 7.6 hours out of a possible 8.5 hours. Continuous sunshine was recorded from 1000 to 1600 hours. It is generally agreed, according to Munn (1966, p. 89), that during intense inversions temperature profiles are controlled mostly by radiation.

At the 35 feet level temperature continuously increased by 10.2°F in the period from 0800 to 1300 hours. This warming trend intensified at the expected time of sharpest change in temperature, 1100 hours. It was during this period of increased warming that the inversion that preceded Case 11 decayed. As temperature declined, the inversion case developed. A 4.2°F warming between 1000 and 1400 hours occurred at the intermediate 200 feet level. Although the temperature trend at the 810 feet level were irregular, there was a short period of warming from 1200 to 1400 hours. At this level, temperature varied over a narrow 2.3°F range throughout the

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2. Wind speed at the top level (810 feet) minus wind speed at the bottom level (35 feet).

development period.

The temperature stratification in the lowest 810 feet (Figure 4.3) demonstrated a significant reduction in the diurnal temperature variation, and a temporal shift in phase of the temperature wave with ascent. Goff and Hudson's (1972) investigation of the thermal structure of the lowest half kilometer in central Oklahoma showed that the surface mean temperature range from 6.2°C at 0600 hours to 16.6°C at 1500 hours, and at 444 meters mean temperature range from 8.4°C at 1000 hours to 11.3°C at 1600 hours. Other researchers have obtained results of a similar nature (Best et al., 1952), (Sutton, 1953), (Bell, 1974).

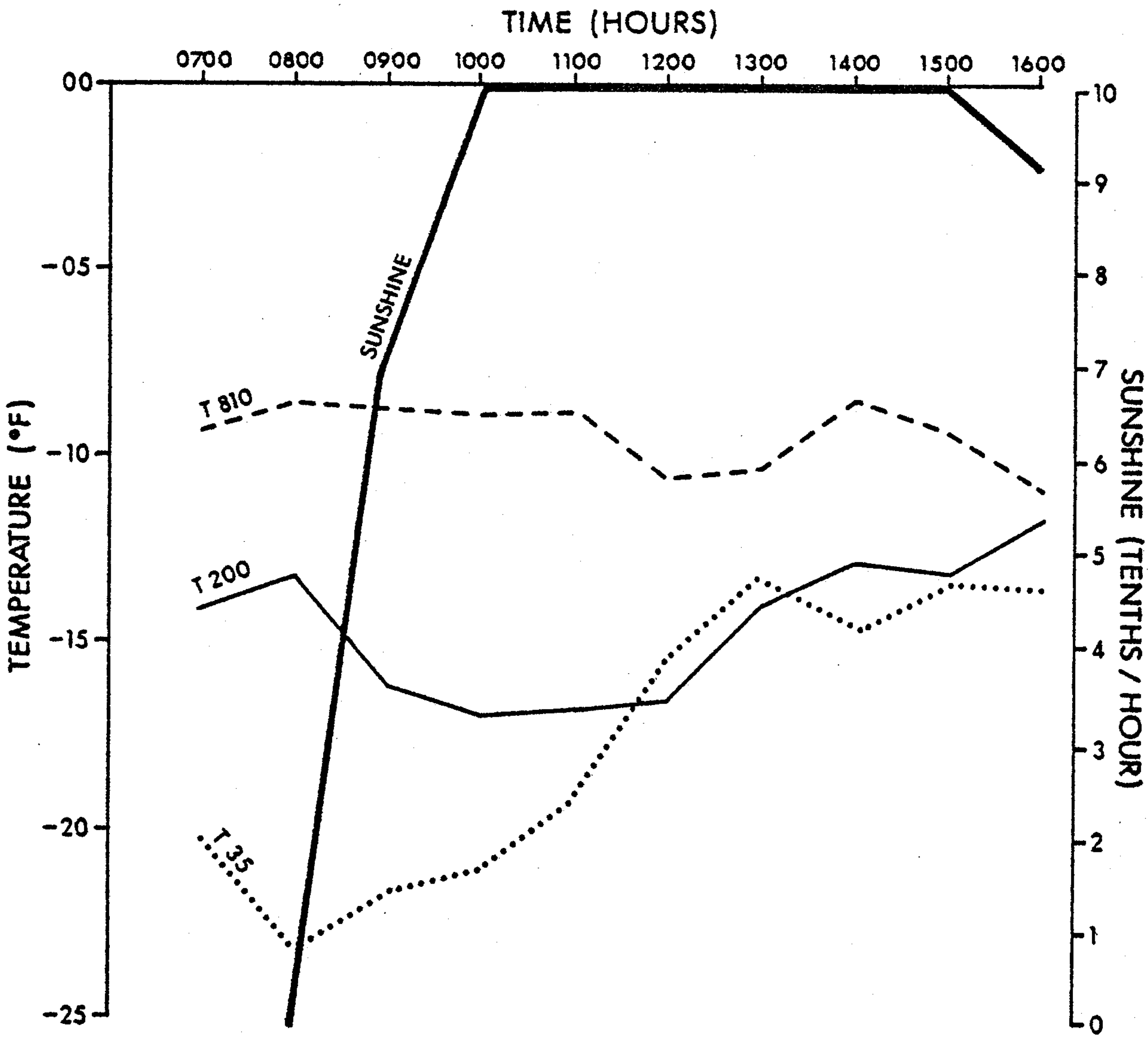
The development of the 35-200 feet layer inversion Case 11 appears to be dependent on radiative cooling.

When the surface of the earth is heated by the absorption of solar radiation it becomes a source of long-wave radiation. The effective outgoing radiation from the surface is the difference between longwave energy emitted from the surface, and, counter-radiation from the atmosphere which is a function principally of temperature, precipitable water vapour and cloud cover (Sellers, 1965).

During the development period the water vapour content of the atmosphere was probably small due to the small water holding capacity of air at low temperature. Winter Arctic flow originates from a source region that is

Figure 4.3

Temperature and Sunshine Variations During Development Period of Case 11



T-TEMPERATURE AT 3 LEVELS (FEET)

characterized by uniform surface conditions and distribution of insolation. Winds from this region, where large semipermanent high pressure zones are formed, are light, so that, the air in contact with the surface for a long time becomes cold and dry (Bilello, 1974, p. 8).

Cloud cover of any type and height responds to the effective outgoing radiation. Table 4.2 shows that during the development period the sky obscurity was not greater than 5/10th's covered with high AC and CI cloud types.

Budyko (1974, p. 15) explained that high clouds radiate less than a black body due to their small density and comparatively low temperatures; and, it can be concluded that their effect on net longwave radiation is negligible in comparison with the clouds of lower and middle layers. Gerdel et al. (1954) reported Wallen's conclusion that the decrease in incoming radiation is small with less 5/10th's cloud cover; but between 5/10th's and complete overcast, the decrease becomes large. Bell (1974) found that the average duration of 35-200 feet inversions at Winnipeg decrease with increasing cloud amounts, and the decrease is noticeable with greater than 5/10th's cloud cover.

In the development period, outward radiation was presumably negligibly compensated by re-radiation from the atmosphere. This was induced by the low sky obscurity and the low water vapour content of the atmosphere. As the air temperatures were well below freezing, the energy lost by radiation from the surface could not be compensated through heat conduction from the layers beneath the snow surface. The surface and the air in contact with the surface cooled radiatively, and caused the development of inversion Case 11 in the 35-200 feet layer. It is known, according to Goff and Hudson (1972), that longwave radiation is the principal cause of low level inversions, producing stronger inversions than any other source.

Analysis detected that the diurnal effects of radiative heating and cooling are less significant in the higher 35-810 feet layer.

In some portions of the boundary layer, certain atmospheric processes such as radiation, advection and subsidence are more influential, than in others. The higher level boundary layer is influenced more by factors of air mass process (subsidence or advection), rather than radiation (Goff and Hudson, 1972). Gol'tsberg (1967) found that in the mid-latitudes, low level inversions only grow to average heights of 150-200 meters. At Winnipeg, Bell (1974) determined that at levels above 400 feet there is little change in the diurnal cycle with height.

It is suggested that, as an anticyclonic circulation system was present, the higher inversion persisted through the radiative heating period because it was more significantly influenced by the atmospheric process of subsidence. With initial radiative cooling of the lower air layer, the downward extension of the higher layer inversion was effected.

Bayton et al. (1965, p. 509) reported that in areas where subsidence inversions are frequently based in the lower few hundred feet by day, very little cooling is required to convert an inversion aloft to a surface based inversion. Speaking of the Arctic, Jen-hu Chang (1972, p. 250) commented that, the radiation inversion may be reinforced by the subsidence inversion to a height of 4 kilometers with a temperature gradient of 25°C in winter.

4.2.2. (a) (2) Decay of Case 11

The Arctic front was well to the south along the Gulf of Mexico coast on January 15 when inversion Case 11 decayed. Southern Manitoba was dominated by a northerly flow of cold, clear Arctic air (cA) from a strong ridge of high pressure (1040 m.b.). A warming trend accompanied by cloud with snow spread eastward from a deep and intense cyclone (960 m.b.) off the southern British Columbia coast. The cyclonically-controlled Maritime Polar westerly air pushed the ridge eastward, and eventually excluded the Arctic air from the weather making scene (Figure 4.4).

Winnipeg's weather was described as -- "Very cold. Sunny becoming cloudy in the afternoon. Snow 10:52 p.m. continued. Ice fog in the morning. Smoke in the evening" (Atmos. Environ. Service, Monthly Meteor. Summary, Jan. 15, 1971).

Table 4.3 presents the hourly synoptic conditions for a decay period from 0500 to 1800 hours. A 3.3 m.b. rise to the inversion decay hour was followed by a fall in pressure with sharpest decline of 1.4 m.b. between 1200 and 1300 hours. Cloud cover, which was less 5/10th's prior to the fall in pressure, increased. As much of the wind data are missing, little viable remarks can be made in connection with its role in the synoptic scene. Wind speed at both the 35 and 810 feet levels appeared to decrease with approach of the decay hour.

Only 4.1 hours of sunshine out of a possible 8.5 hours were recorded on the decay day. The amounted received directs attention to the ice fog conditions that were present in the period, 0800 to 1100 hours, during which time visibility was reduced to less than 5 miles.

Ice fog usually occurs in clear, calm, very cold weather at high latitudes. It is rarely encountered with

FIGURE 4.4

SYNOPTIC SITUATION ON DAY OF DECAY OF INVERSION CASE 11

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. FRIDAY, JANUARY 15, 1971

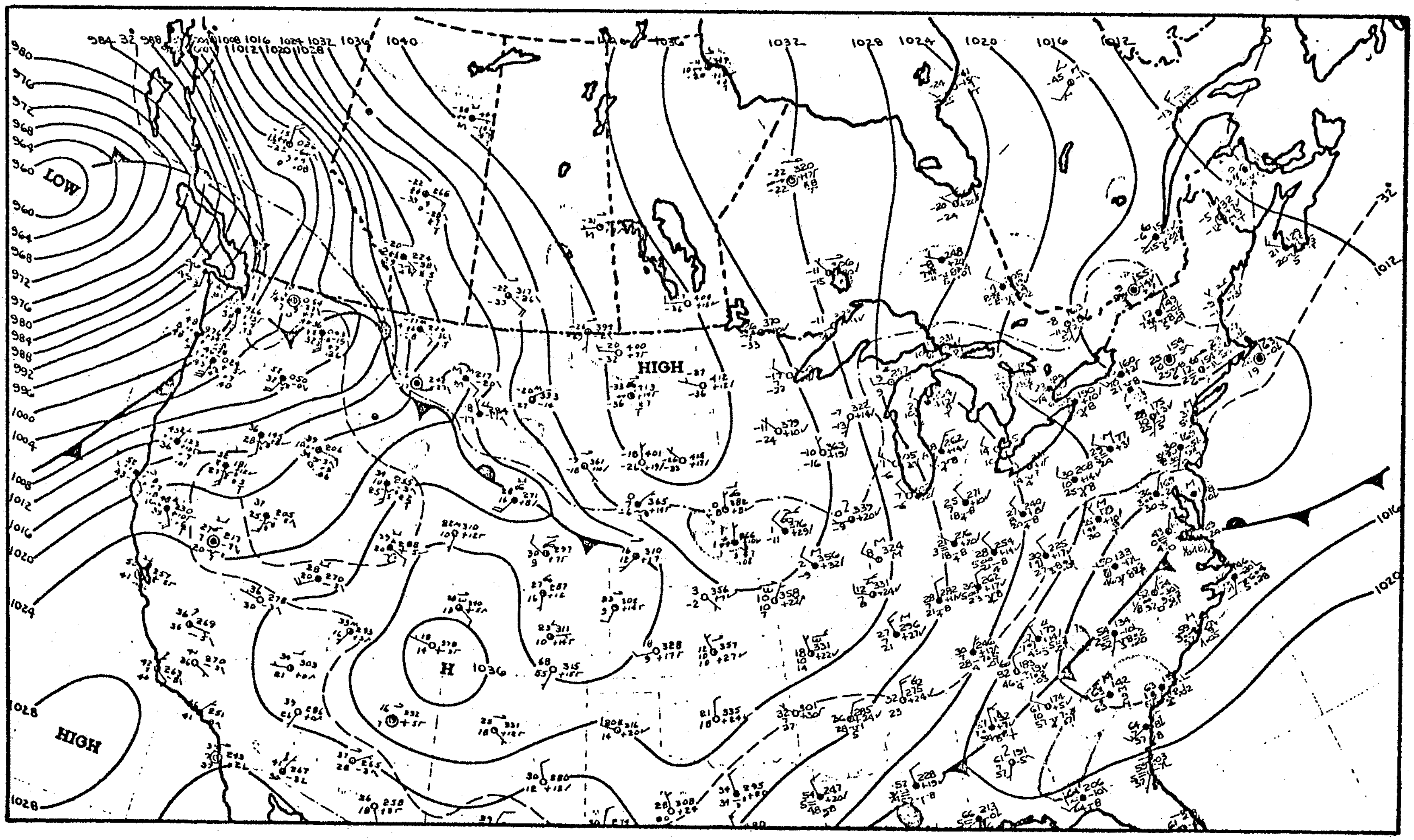


Table 4.3

Synoptic Conditions During Decay Period of

Case 11

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.ph.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (Tenths)	Cloud Type	Cloud Height (Feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (Tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
0500	-39.6	-16.1	280	10	360	13	3	-25.3	-18.7	-12.8	0	None	--	1040.2	A	15	0		
0600	-43.8	-16.9	300	13	360	15	2	-26.1	-18.9	-13.0	0	None	--	1040.4	A	15	0		
0700	-41.7	-19.6	310	8	310	12	4	-27.7	-20.9	-12.6	0	None	--	1040.3	A	15	0		
0800	-42.0	-20.2	270	11	330	10	-1	-28.5	-21.6	-12.9	1	F,1F	Unltd.	1041.5	A	1	0		
0900	-44.1	-19.9	260	10	310	9	-1	-28.4	-21.1	-13.0	4	F,1F,Cl	Unltd. -27.0	1042.6	A	1	4		
1000	-40.5	-19.0	280	10	320	5	-5	-27.4	-20.7	-12.7	3	1F,Cl	Unltd. -27.0	1042.8	A	3	10		
1100	-20.6	-14.4	270	6	---	-	-	-24.2	-20.8	-13.0	2	1F,cl	Unltd. -27.0	1043.5	A	5	10		
1200*	-8.2	-11.8	280	7	280	6	-1	-21.9	-20.5	-12.7	2	Cl	27.0	1043.6	A	15	10	4.1	8.5
1300	4.0	-8.7	---	-	---	-	-	-19.6	-20.3	-12.9	5	CS	25.0	1042.2	A	15	4		
1400	-1.9	-8.7	---	-	---	-	-	-19.8	-19.5	-13.0	7	CS	25.0	1041.3	A	15	3		
1500	-0.2	-8.0	---	-	---	-	-	-19.8	-19.8	-13.6	10	CS	25.0	1041.5	A	10	0		
1600	5.1	-7.5	---	-	---	-	-	-19.3	-20.1	-13.5	10	Smoke AC,CS	0.5-13.0 -25.0	1042.6	A	12	0		
1700	3.8	-7.9	---	-	---	-	-	-19.5	-20.2	-13.4	10	Smoke AC,CS	0.5-13.0 -25.0	1041.1	A	05	0		
1800	6.4	-7.2	---	-	110	8		-18.5	-19.6	-13.0	10	Smoke AC,CS	0.5-12.0 -25.0	1040.7	A	05	0		

*Inversion decayed at 1200 hours in the 35-200 feet layer.

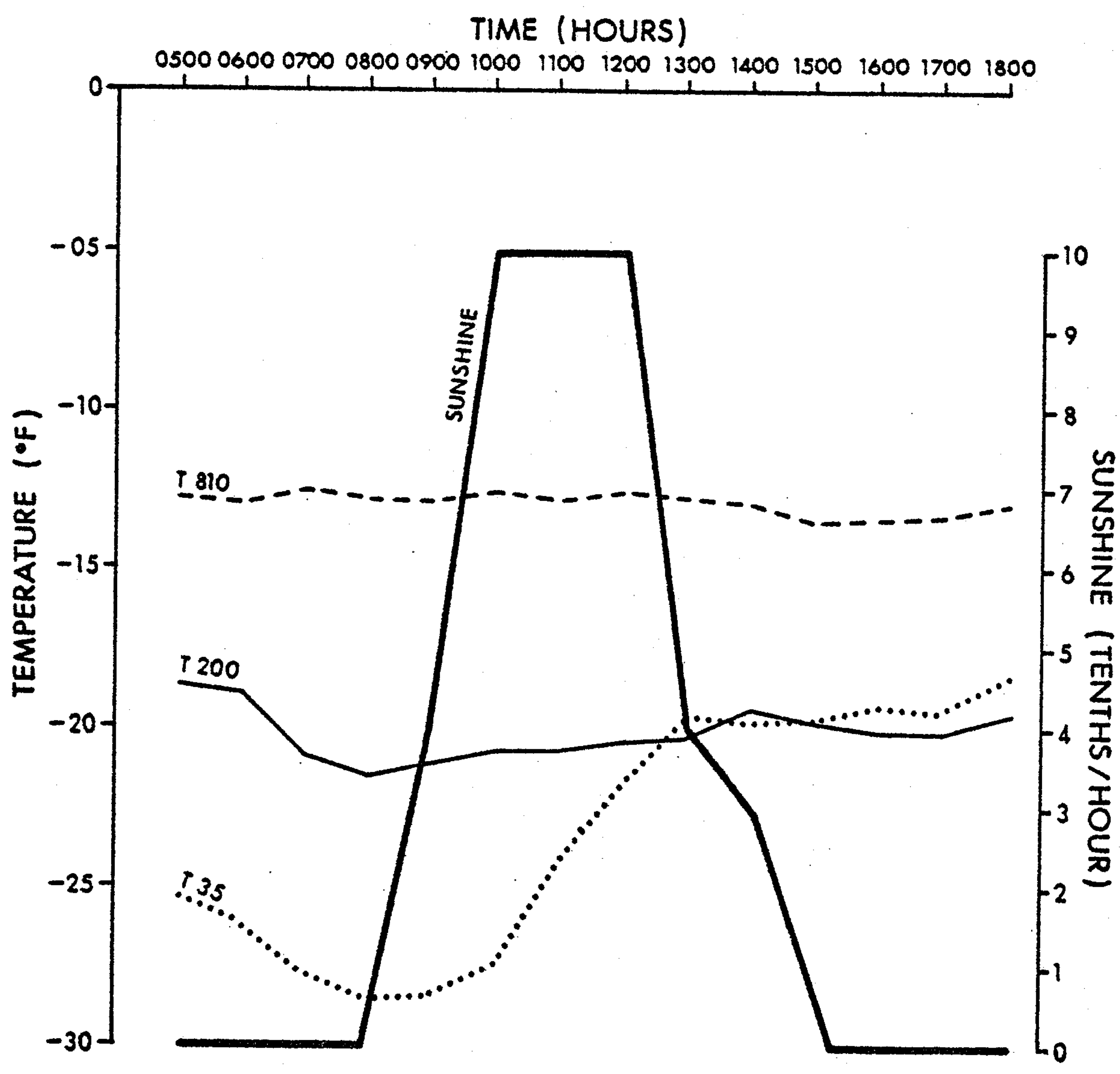
temperatures warmer than -20°F and increases in frequency with decreasing temperature (Bilello, 1974, p. 22). Stringer (1972, p. 113) reported that the extent of ice fog in Alaska depends on the strength and height of the low level inversion; and the downward transport of ice particles causes low horizontal visibility at ground level. Further information on ice fog can be found in Robinson et al. (1957) and Benson (1970).

The temperature variations during the decay period (Figure 4.5) are not only controlled by radiation but also by changing synoptic conditions. At the 35 feet level temperature increased by roughly 9.0°F in the period 0800 to 1300 hours. The increase was inconsiderable prior to 1000 hours, but steepened thereafter with a 8.2°F change in three hours. A short period of slight cooling to 1500 hours was then followed by a period of warming. The 200 feet level temperature variations were similar in trend to the former, but lesser in amplitude. Temperatures at the 810 feet level behaved differently to those at the lower levels and fluctuated in a narrow 1.0°F range throughout the decay period.

The ice fog was eventually broken down by solar heating, and this break down afforded greater direct solar heating of the surface. The earth's surface plays the most important part in the midday heat exchange, and the

Figure 4.5

Temperature and Sunshine Variations During Decay Period of Case 11



T—TEMPERATURE AT 3 LEVELS (FEET)

air layer near the ground is the part of the atmosphere that is most directly affected by the temperature conditions at the surface (Geiger, 1950).

The dissipation of the ice fog and the radiative heating of the air layer in contact with the surface are the important factors that induced the 35-200 feet inversion of Case 11 to decay at 1200 hours. Williamson (1973, p. 181) has aptly described this process. He stated that, after sunrise the fog usually lifts as solar radiation penetrates to warm the ground, and the vertical convection of sensible heat breaks the inversion.

With decline of the sun angle, the effective outgoing radiation, that controls the exchange of heat at night, become important. Radiational cooling caused the formation of another inversion at 1400 hours. However, with the change from low sky obscurity to overcast skies which included smoke at 200-500 feet, the cloud cover absorbed the emitted longwave radiation from the surface and re-radiated part of this energy back downwards. The positive longwave balance caused the destruction of this inversion at 1500 hours, even with the approach of a nocturnal period.

The associated higher 35-810 feet layer inversion continued to persist until 0300 hours the following day, presumably because the weather processes that dissipated the inversions were less effective at greater heights.

4.2.2. (b) Inversion Case 16

The analysis performed on the structural behaviour of inversion Case 16 yielded results that are, for the most part, consistent with inversion Case 11. The 35-200 feet inversion structure is more closely related to the diurnal effects of solar radiation; while, the higher 35-810 feet inversion appears to be influenced more by the atmospheric process of subsidence. Analysis attributed the dissipation of the inversions in both layers, especially the higher inversion, to an exchange in air mass types due to a change in synoptic systems.

Preliminary investigation revealed that the inversions in each layer actually developed simultaneously at 2000 hours on January 11. The lower layer inversion however decayed at 1100 hours the next day, and then, redeveloped at 1600 hours as Case 16. This 20-hour duration inversion case decayed at 1100 hours. The associated higher layer inversion was sustained for 42 hours, and dissipated two hours after the lower inversion at 1300 hours.

Since the inversion that preceded Case 16 behaved in accordance with the fundamental features of the model described in Ch. 2, it seems reasonable to regard the inversion case as an extension of it.

4.2.2. (b) (1) Development of Case 16

The Atmospheric Environment Service described Winnipeg's weather on the 11th January as -- "Normal temperature. Sunny with light snow 2 a.m., 5 p.m. to 7 p.m.". And on the 12th January -- "Cold and sunny with light winds" (Monthly Meteor. Summary, 1970). With respect to the former weather summary, it is again detected that the actual development of the inversions in both layers at 2000 hours coincided with the time when snowfall concluded.

A low pressure system that brought moderate temperatures and cloudy skies with snow to southern Manitoba, was replaced by an anticyclonic (1032 m.b.) circulation of cold, clear Arctic air (cA). A well-defined ridge extended well to the south with the Arctic front off the Gulf of Mexico coast. To the west of the area of high pressure was a south-eastward moving weak disturbance from southern British Columbia to the Dakotas (Figure 4.6).

Winnipeg under the influence of an Arctic high experienced clear, sunny skies with gentle winds during a development period from 1000 to 1700 hours (Table 4.4). High sky obscurity gave way to less 4/10th's cloud cover of the Cl type from 1300 hours. Also from this time, wind directions changed at both the 35 and 810 feet levels.

FIGURE 4.6

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT OF INVERSION CASE 16

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. MONDAY, JANUARY 12, 1970

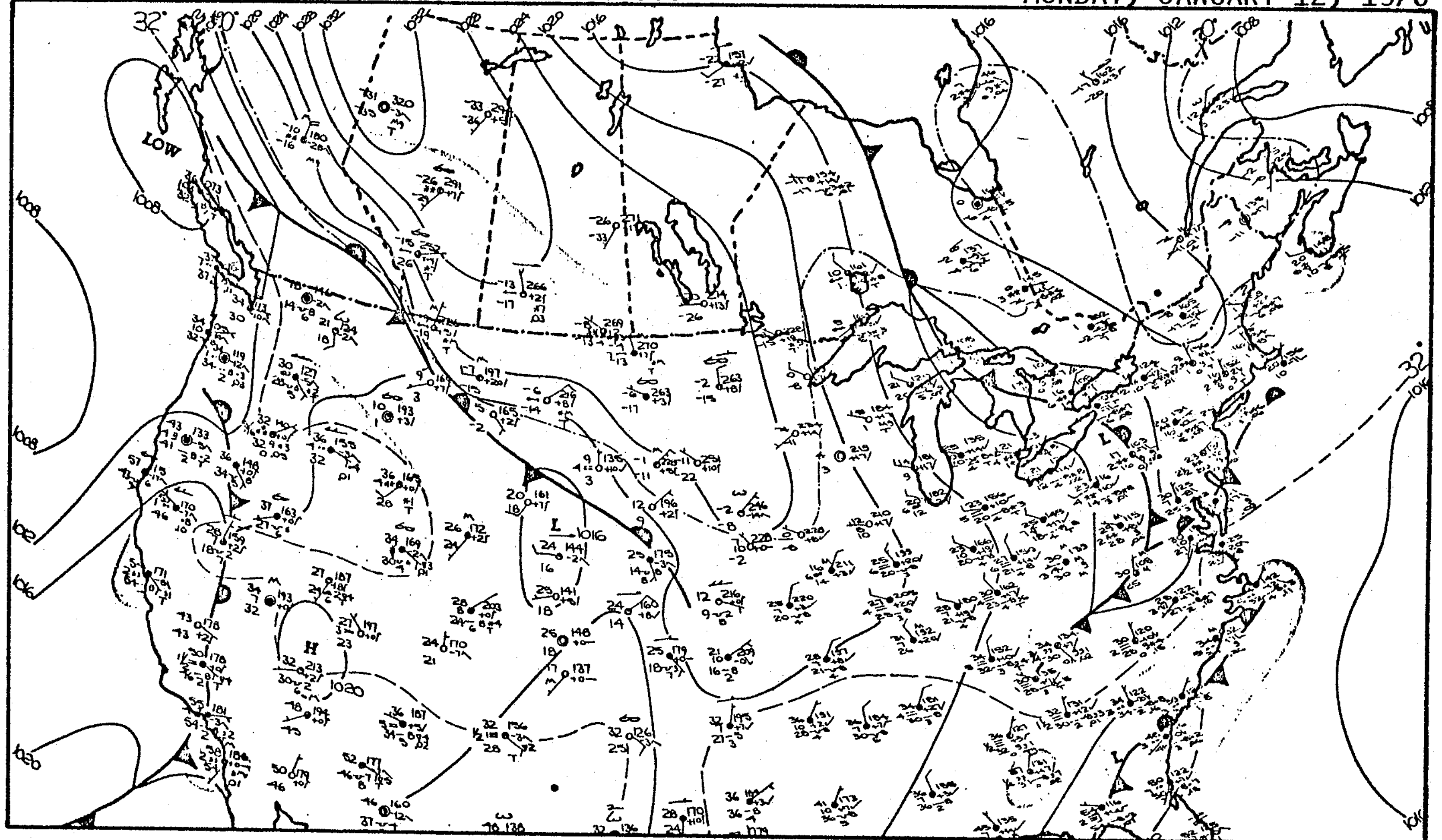


Table 4.4

Synoptic Conditions During Development Period

of Case 16

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
1000	-34.0	-11.0	280	6	300	15	9	-20.8	-15.2	-12.3	7	Cl	25.0	1030.1	A	15	10		
1100	-9.8	-6.2	290	6	300	13	7	-17.1	-15.5	-12.3	8	Cl	25.0	1030.8	A	15	10		
1200	0.1	-5.3	280	4	300	13	9	-15.6	-15.6	-11.5	8	AC,Cl	14.0-25.0	1030.5	A	15	9		
1300	1.0	-4.5	250	3	300	13	10	-14.1	-14.3	-10.6	3	Cl	25.0	1030.0	A	15	10	7.9	8.4
1400	-0.2	-3.2	190	3	270	13	10	-12.1	-12.1	-9.7	2	Cl	25.0	1030.2	A	15	10		
1500	0.5	-1.3	200	6	280	10	4	-10.9	-11.0	-10.0	1	Cl	25.0	1030.2	A	15	10		
1600*	-0.5	-0.2	200	5	280	9	4	-10.5	-10.4	-10.4	1	Cl	25.0	1030.7	A	15	10		
1700	-10.1	-2.0	200	6	270	9	3	-11.1	-9.4	-9.6	0	None	----	1030.7	A	15	1		

*Inversion developed at 1600 hours in the 35-200 feet layer

Southerly replaced westerly winds at the lower level, while westerly replaced north-westerly winds at the higher level. These winds were especially slight: at the lower level not exceeding 6 m.p.h., and at the higher level not exceeding 13 m.p.h. Relatively low speed shear dropped to less 5 m.p.h. prior to the development hour. Pressure though rising, practically stabilized at 1030 m.b.

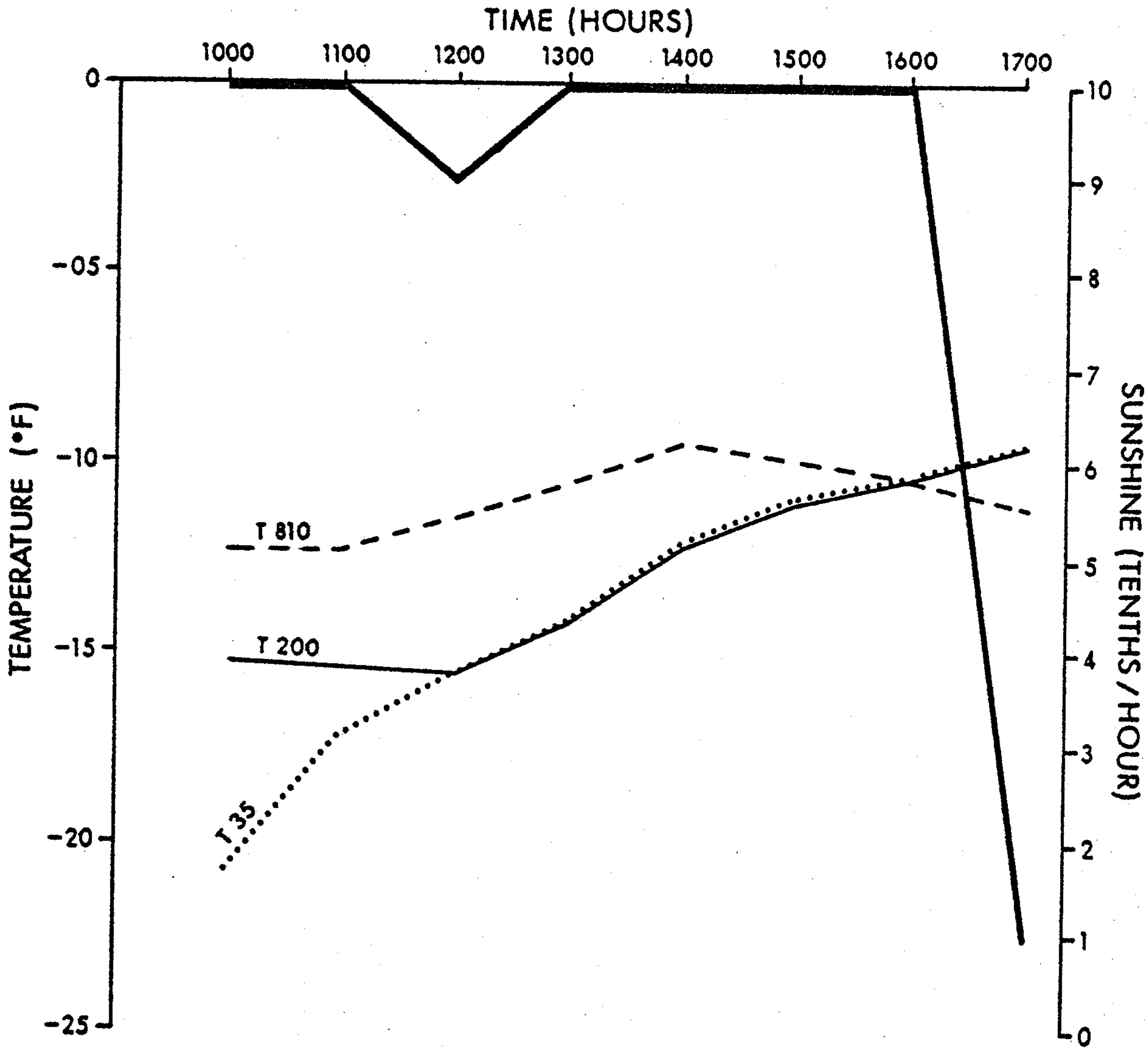
Under low sky obscurity, 7.9 hours of sunshine out of a possible 8.4 hours were received on the development day. Sunshine began at 0900 hours following which time there was maximum hourly sunshine until 1600 hours. As the amount of sunshine diminished, inversion Case 16 developed.

During the development period temperature stratification below 810 feet (Figure 4.7) showed a significant reduction in the temperature variation and a temporal shift of the temperature wave with increasing height. At the 35 feet level temperature increased by 10.3°F to 1600 hours. Inversion Case 16 developed as the temperature commenced to fall. A slight cooling of 0.4°F prior to 1200 hours at the 200 feet level was followed by a warming of 6.2°F. The 810 feet level temperatures varied within a 2.7°F range which included regular increases from 1300 to 1500 hours.

The daily rhythm of radiative heating and cooling

Figure 4.7

Temperature and Sunshine Variations During Development Period of Case 16



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functioned efficiently. As the sun lowered in the sky, the increase in optical mass reduced direct solar heating, and albedo increased at this time. In the presence of the cold Arctic air, the surface and the adjacent air layer quickly cooled radiatively; and, the 35-200 feet layer inversion Case 16 developed.

The associated higher 35-810 feet layer inversion, perhaps influenced more by atmospheric subsidence rather than radiation, continued to persist.

4.2.2. (b) (2) Decay of Case 16

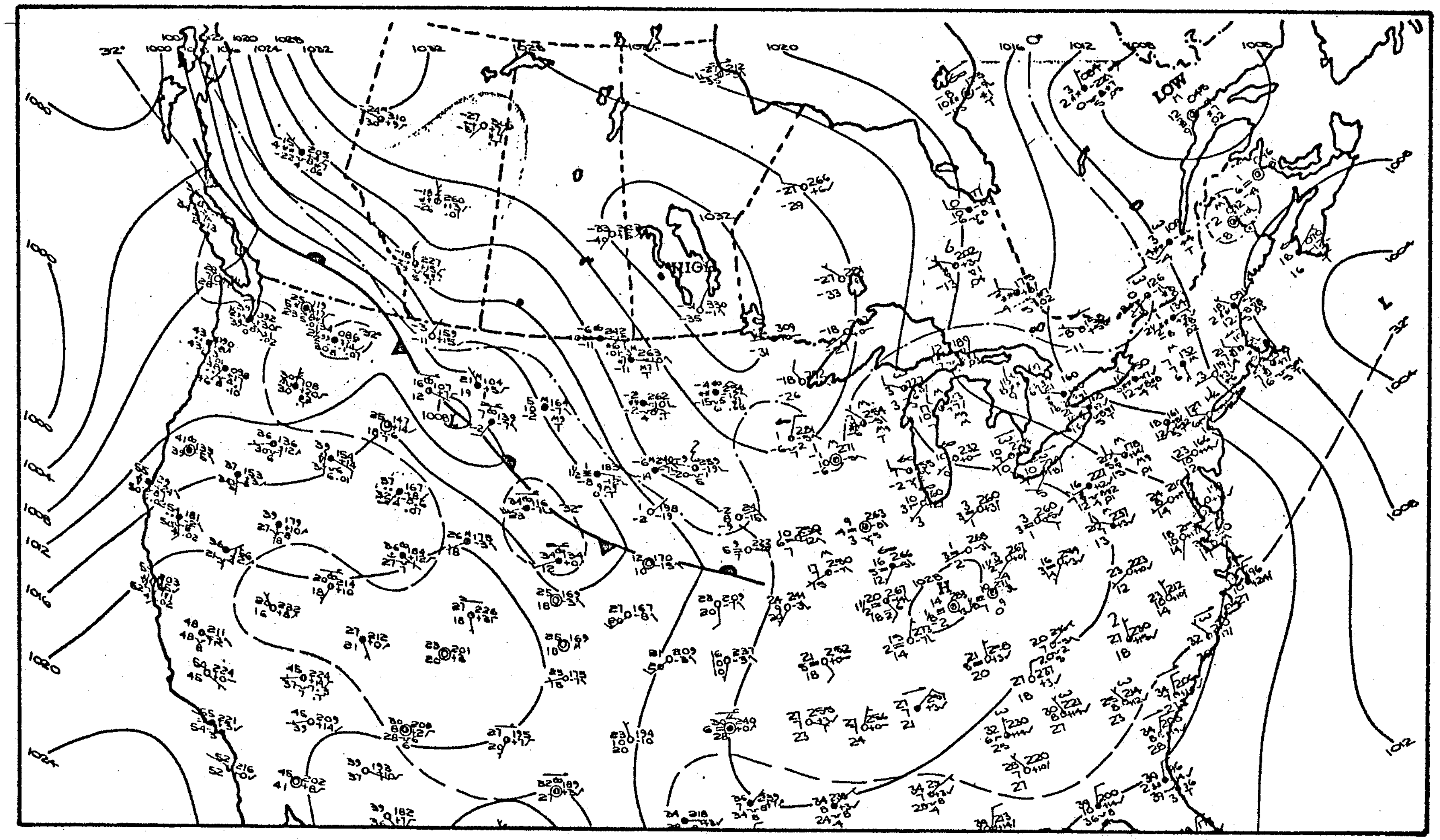
Though decay times of the inversions in both layers are in accordance with the model (Ch. 2), preliminary analysis raised doubts as to the functional relation between the diurnal effects of solar heating and the inversion decay structure. With only 2.5 hours of sunshine out of a possible 8.5 hours, temperature at the lowest level increased by 13.8°F in six hours.

Clear, cold Arctic weather in association with a high pressure cell (1032 m.b.) dominated southern Manitoba early on the decay day. The Arctic induced weather was subdued as a weak disturbance involving warm and moist Maritime Polar southwesterly air passed south of Winnipeg to the Dakotas (Figure 4.8). This disturbance effected increased cloud amounts with snow and moderation in

FIGURE 4.8

SYNOPTIC SITUATION ON DAY OF DECAY OF INVERSION CASE 16

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. TUESDAY, JANUARY 13, 1970



temperature. The weather was described as -- "Very cold. Ice fog and smoke 7 a.m. to noon. Cloud with flurries 5:30 p.m. continued" (Atmos. Environ. Service, Monthly Meteor. Summary, Jan. 13, 1970).

From the foregoing, a feature emerges that is worth emphasizing. The morning ice fog conditions induced by low temperature is noted here, as it was in inversion Case 11. Ice fog and smoke, seperately or in union, frequently occur with extremely low temperature during anticyclonic weather (U.S. Dept. of Commerce, 1970).

Hourly synoptic conditions for a decay period between 0400 and 1500 hours (Table 4.5) reflect these developments in the synoptic systems. Following a gradual 1.1 m.b. rise to 1100 hours, pressure commenced to fall. This development was accompanied by increased cloud amounts of greater than 7/10th's cover, and changes in wind direction at both the 35 and 810 feet levels. At the lower level easterly replaced north-easterly winds, while at the higher level south-easterly replaced easterly winds. Wind speeds were relatively light: at the lower level less than 11 m.p.h., and at the higher level less than 17 m.p.h. Though speed shear was slight, it intensified to 12-13 m.p.h. around the decay time.

In the early portion of the decay period the temperature profile (Figure 4.9) showed a sharp boundary

Table 4.5

Synoptic Conditions During Decay Period of

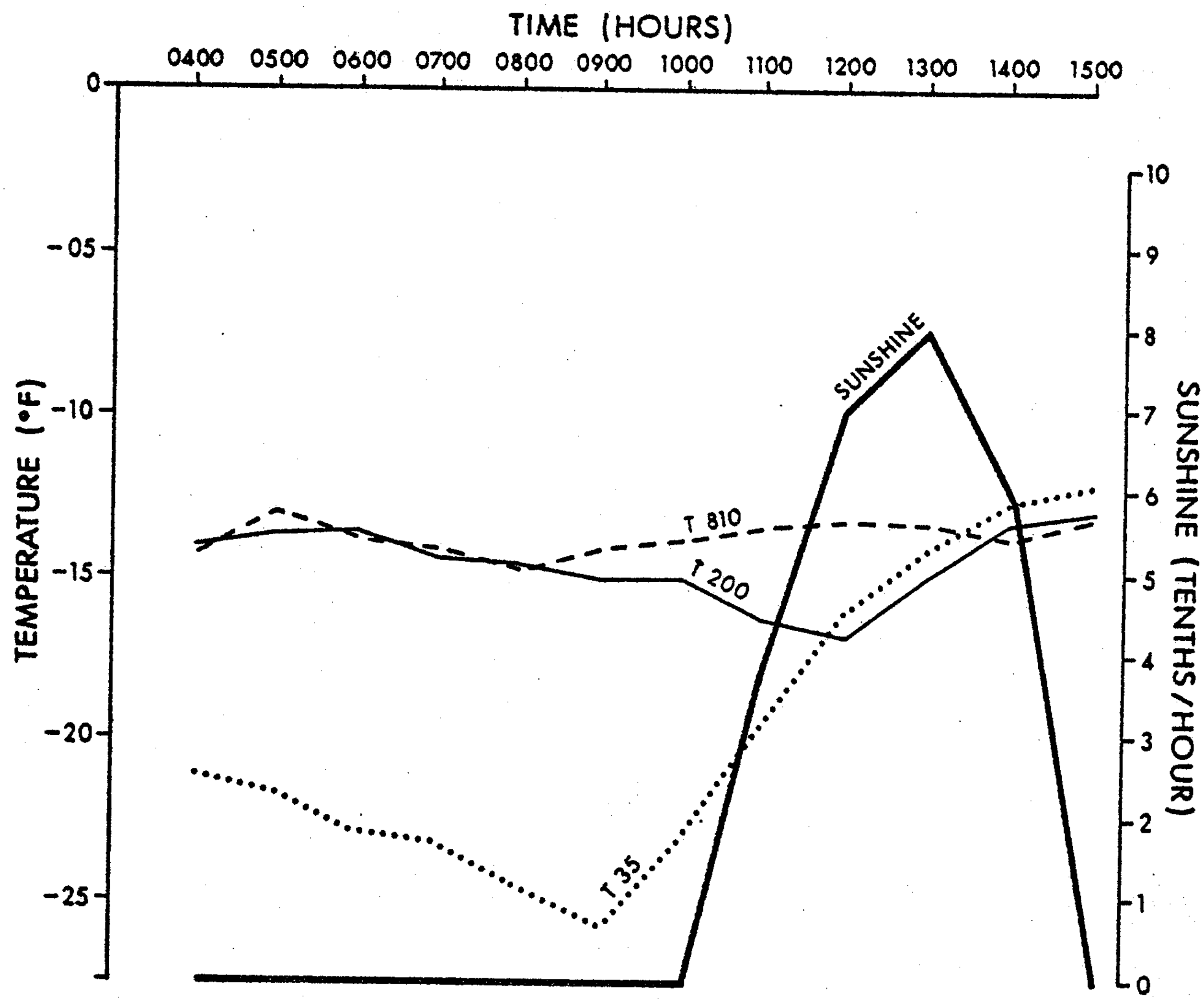
Case 16

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
0400	-42.7	-8.9	--	-	90	10	-	-21.1	-14.1	-14.2	0	None	--	1032.6	A	15	0		
0500	-47.9	-11.2	50	6	80	12	6	-21.6	-13.7	-13.0	0	None	--	1032.3	A	15	0		
0600	-56.5	-11.6	40	8	90	12	4	-22.9	-13.6	-13.9	0	None	--	1032.6	A	15	0		
0700	-52.4	-11.4	40	10	80	14	4	-23.2	-14.5	-14.3	0	None	--	1032.7	A	04	0		
0800	-60.8	-12.9	40	8	80	14	6	-24.7	-14.7	-14.8	3	F,1F,Cl	Unltd.-20.0	1032.9	A	00.7	0		
0900	-64.6	-14.9	50	8	100	10	2	-25.8	-15.1	-14.2	4	F,1F,Cl	Unltd.-20.0	1033.1	A	00.5	0		
1000	-48.9	-11.7	70	6	110	14	8	-23.0	-15.0	-13.9	4	F,1F,Cl	Unltd.-20.0	1033.2	A	00.7	0		
1100*	-17.8	-7.5	80	8	110	16	8	-19.4	-16.4	-13.5	2	F,1F,Cl	Unltd.-20.0	1033.4	A	00.7	4	2.5	8.5
1200	5.1	-3.3	90	1	120	14	13	-16.0	-16.8	-13.4	7	Cl	20.0	1033.0	A	10	7		
1300*	4.9	-1.0	80	-	120	12	12	-14.2	-15.0	-13.4	9	Cl	20.0	1032.6	A	10	8		
1400	4.3	1.4	110	1	130	10	9	-12.7	-13.4	-13.8	9	Cl	20.0	1032.3	A	10	6		
1500	5.0	1.4	90	-	150	8	8	-12.1	-13.0	-13.2	10	Cl	20.0	1032.4	A	10	0		

*Inversion decayed at 1100 hours in the 35-200 feet layer and at 1300 hours in the 35-810 feet layer.

Figure 4.9

Temperature and Sunshine Variations During Decay Period of Case 16



T—TEMPERATURE AT 3 LEVELS (FEET)

between the lowest level and the two higher levels. At the lower 35 feet level temperature continually fell by 4.7°F to a low of -25.8°F at 0900 hours. This was followed by a steep 13.7°F increase. Temperatures at the 200 feet level indicated a cooling trend to 1200 hours following which time there was a rise in temperature. The 810 feet level temperatures were virtually isothermal at roughly -13.5°F.

The ice fog and smoke began to dissipate as solar radiation penetrated to warm the surface, and vertical convection of sensible heat broke down the 35-200 feet inversion of Case 16 at 1100 hours.

The speed shear attained a maximum amount of speed around the decay time (1300 hours) of the 35-810 feet layer inversion. Under this type of circumstance, turbulence is caused by stronger wind shear which develops within an inversion and which is capable of supplying sufficient turbulent energy to overcome the stability (Blackadar, 1957, p. 286). Zobel (1965) has suggested that upward daytime convection can penetrate the subsidence inversion and that this is compensated by the downward movement of air of higher potential temperature. The air layers above are cooled because the air transferred upwards will be colder than the surrounding air once it has penetrated the inversion.

The passage of a weak disturbance south of Winnipeg to the Dakotas should not be discounted as an important factor, if not the most important, in causing the decay of the inversion.

Maritime Polar southwesterly air was associated with this synoptic feature. This air mass type is relatively mild and laden with moisture, and when it moves inland the surface has a strong tendency to adapt itself to the temperature of the invading air (Bryson, 1966). The commencement of snow flurries from 1700 hours may indicate a higher mixing ratio at that time. Water vapour absorbs longwave radiation emitted from the surface and a change in water vapour content would alter all radiation components (Vowinchel and Orvig, 1964). The decay of the inversions in each layer, especially the higher layer inversion, may have been caused by a change in air mass conditions and behaviour.

4.2.3 Summary

The structural behaviour of Cluster 2 inversions during their development and decay is apparently controlled by diurnal variations in radiative heating and cooling. This is indicated by the analysis of inversion Cases 11 and 16.

The inversions in the 35-200 feet layer developed during radiation cooling when outgoing exceeded incoming solar radiation. They decayed after solar radiation breaks down the ice fog, notably in the period of greatest solar radiation receipt. The diurnal radiation effects are, however, less significant when these inversions are studied in the 35-810 feet layer. These deeper inversions appear to be influenced more by atmospheric subsidence or change in airflow type, than are the shallower inversions.

Analysis detected that prior to the development of Cluster 2 inversions in the 35-200 feet layer, the inversions in both layers formed simultaneously when snow-fall ended. As the decay behaviour of the preceding inversions are predictable according to the diurnal effects of solar heating, the inversion cases are considered as extensions of them. Viewed in this perspective, both the lower and the higher layer inversions are of similar durations; but the former are subject to temporary daytime decay.

These inversions are associated with an anti-cyclonic circulation of cold, clear Arctic air (cA). With the Arctic front well to the south, these systems effect weather conditions that are favourable to the cyclical component of diurnal temperature variation which is a function of solar radiation heating. Although decay of the lower inversions are marked by the dissipation of ice fog through the agency of solar heating, the most important factor that induces complete destruction of the inversions in the lowest 810 feet is a change in air process.

4.3 Cluster 4

4.3.1. Preliminary Remarks

In the radiative group of inversions, Cluster 4 is the most closely related to Cluster 2 (Ch. 3). This cluster was identified by Bell (1974) as a radiation cluster because it is associated with north, north-west and west winds. In comparative terms (see Table 3.5), Cluster 4 is of a shorter duration, lower intensity and pressure, but higher wind speed, wind shear, sky obscurity and temperature than the average inversion. Table 4.6 provides the average properties of each of the 28 inversion cases in Cluster 4.

It is worth emphasizing the large size of this cluster. The 28 cases include almost half (47 per cent) of the total 60 cases in the six selected clusters. It transpires that this inversion type occurs most frequently in winter in the Winnipeg area. On a monthly frequency distribution basis, the cluster displays it close relation to Cluster 2. Over 55 per cent of its inversions occurred in January, as opposed to a meagre 10 per cent in December.

Table 4.6

Average Properties of Inversion Cases in Cluster 4

Case Number	Date	Development Hour	Inversion Duration (Hours)	Decay Hour	Inversion Intensity (°F/1000')	Sky Obscurity (tenths)	Temperature (°F)	Pressure (m.b.)	Wind Speed (m.p.h.)	Wind Shear (m.p.h./x feet)	Wind Direction
6	Jan. 3'70	1200	26	1300	-23.1	4.6	-9.0	1016.4	10.5	6.5	W
15	Jan. 23'71	1700	20	1200	-29.4	1.1	-17.5	1014.6	5.4	2.8	N
24	Dec. 22'69	1700	18	1000	-30.1	2.2	-9.6	1019.5	3.6	2.6	E
25	Jan. 11'71	1800	18	1100	-17.9	0.1	-23.7	1038.4	4.1	6.5	SW
28	Feb. 14'71	1800	18	1100	-24.2	0.4	-16.2	1024.4	8.7	9.1	NW
29	Feb. 7'71	1700	18	1000	-27.9	1.1	-15.2	1023.9	8.9	10.5	S
31	Feb. 24'70	1700	18	1000	-30.0	0.6	-10.0	1034.2	11.1	11.5	N
33	Jan. 18'71	1600	18	0900	-37.6	1.6	-14.1	1033.5	11.5	5.7	S
35	Feb. 1'71	1700	17	0900	-21.5	2.1	-17.8	1028.6	6.5	3.6	NW
36	Jan. 27'71	1600	17	0800	-26.6	1.1	-16.8	1027.4	10.1	9.7	W
38	Feb. 12'70	1900	17	1100	-41.6	000	-18.1	1029.4	10.8	13.1	W
39	Feb. 2'70	1800	17	1000	-28.1	0.8	-22.8	1023.9	11.7	10.7	W
40	Dec. 12'71	1900	16	1000	-15.2	4.1	-5.1	1026.1	6.3	4.8	NW
43	Jan. 8'70	2000	16	1100	-15.2	0.1	-9.6	1033.1	9.1	8.5	NW

Table 4.6

Average Properties of Inversion Cases in Cluster 4

Case Number	Date	Development Hour	Inversion Duration (Hours)	Decay Hour	Inversion Intensity (°F/1000')	Sky Obscurity (tenths)	Temperature (°F)	Pressure (m.b.)	Wind Speed (m.p.h.)	Wind Shear (m.p.h./x feet)	Wind Direction
44	Jan. 11'70	2000	16	1100	-31.9	0.4	-14.3	1025.7	9.5	13.6	N
45	Jan. 4'71	1700	16	0800	-14.8	4.3	-10.6	1025.2	10.7	12.1	NW
46	Feb. 6'71	1800	16	0900	-18.5	3.7	-14.3	1023.0	11.2	15.6	N
47	Feb. 26'70	2000	16	1100	-27.2	0.8	-9.5	1019.6	11.5	5.6	NW
56	Jan. 26'71	1700	14	0600	-22.7	3.0	-16.0	1034.1	5.7	19.0	W
57	Feb. 19'70	1700	14	0600	-21.5	0.9	-8.1	1028.6	11.4	34.0	SW
61	Dec. 27'71	1600	13	0400	-31.2	2.9	-5.5	1017.3	7.5	5.6	SW
62	Jan. 22'70	1600	13	0400	-29.0	2.2	-11.5	1019.6	7.9	6.9	W
63	Jan. 3'71	1600	13	0400	-27.4	2.0	-8.6	1028.9	8.4	3.3	W
65	Jan. 17'71	2300	13	1100	-21.0	0.5	-17.6	1032.5	10.9	7.6	NW
67	Jan. 31'71	2300	13	1100	-18.4	0.3	-15.4	1027.3	14.7	18.4	N
76	Jan. 5'71	2000	11	0600	-23.6	1.9	-4.5	1028.6	10.2	9.0	N
90	Jan. 7'71	0000	10	0900	-35.3	0.6	-6.6	1025.6	12.4	7.4	SE
92	Jan. 14'71	0200	10	1100	-36.2	2.4	-14.8	1020.8	13.4	11.8	W

Cluster 4 inversions developed in a comparatively long period from 1200 to 0200 hours. In accordance with the model (Ch. 2) however, inversion development prior to 1400 hours is anomolous. Only one case developed at the abnormal time of 1200 hours, and this was of the longest duration 26 hours. None of the other inversions developed before 1600 hours or were of duration greater than 20 hours. The 82 per cent assembled in the period from 1600 to 2000 hours were, for the most part, of longer duration than those that formed later.

In the radiative heat gain period between 0800 and 1400 hours, 78 per cent of the inversions decayed. These inversions were mainly of longer duration than those that decayed in the earlier period from 0200 hours.

The structures of Cluster 4 inversions follow definite patterns. The lower 35-200 feet layer inversions frequently developed before the associated 35-810 feet layer inversions, and in the remaining cases they both developed simultaneously. In instances where the lower inversions developed first, a time lag of up to 3 hours was required for the formation of the higher inversions. The lower inversions usually decayed before the associated higher inversions, and in the remaining cases they both decayed at the same time. A time lag of the same magnitude described above was required for the decay of the higher inversion if the lower decayed first.

The plausibility of the two hours factor used to adjust the model with respect to the diurnal distribution of 35-810 feet layer inversions (Ch. 2) is indicated by this lag.

The higher inversions followed the structural behaviour of the lower inversions, and so both were of similar duration. Bell (1974) found that the 35-810 feet inversion frequency is strongly influenced by the lower 35-200 feet inversion, and that the former follow the latter with a lag of approximately 75 minutes throughout the evening period. A significant feature is the period of positive lapses lasting at least 5 hours that preceded and followed the occurrence of Cluster 4 inversions.

4.3.2 Selected Inversion Cases

Inversion Cases 28 and 36 are chosen for detailed analysis of their structural behaviour during development and decay. The former is the median case of the cluster. It developed one hour after sunset, was maintained for 18 hours, and decayed at the primary time of sharpest change in temperature. The latter case, which is of almost the same duration, developed one hour prior to sunset and decayed at the expected time of sunrise.

Notwithstanding, the selection procedure took into consideration the different time lags involved in the structural behaviour of the inversions.

4.3.2. (a) Inversion Cases 28 and 36

Preliminary investigation indicated that both inversion cases may be studied together. Firstly this is because their temporal properties are in congruity with the postulations of the model (Ch. 2). And secondly because, the relationship between the different time lags required for the processes of development and decay to propogate to higher levels is brought out more clearly.

The 35-200 feet layer inversions developed and decayed before their associated 35-810 feet layer inversions. Case 28 developed at 1800 hours, and the higher inversion formed three hours later. The inversions in both layers decayed simultaneously at 1100 hours. Case 36 developed at 1600 hours in the 35-200 feet layer and at 1700 hours in the 35-810 feet layer. This case decayed at 0800 hours in the 35-200 feet layer and two hours later in the 35-810 feet layer.

Both inversion cases are of similar durations, but different time lags are required for the processes of development and decay to extent from the lower to the higher inversions. Bell (1974) found that once the 35-200 feet layer inversion reach a critical intensity they propogate upwards to higher levels. They are destroyed by solar radiation in the morning, by changing longwave radiation flux, or by changing synoptic situation.

4.3.2. (a) (1) Development of Cases 28 and 36

On the development day of Case 28 the weather was described as -- "Cold cloudy till the afternoon. Flurries 12:04 p.m. till 3:44 p.m.; 4:52 to 5:16 p.m." (Feb. 14, 1970). On the development day of Case 36 the weather was described as -- "Cold. Cloudy in the morning then mostly sunny. Snow in the a.m." (Jan. 27, 1971) (Atmos. Environ. Service, Monthly Meteor. Summary).

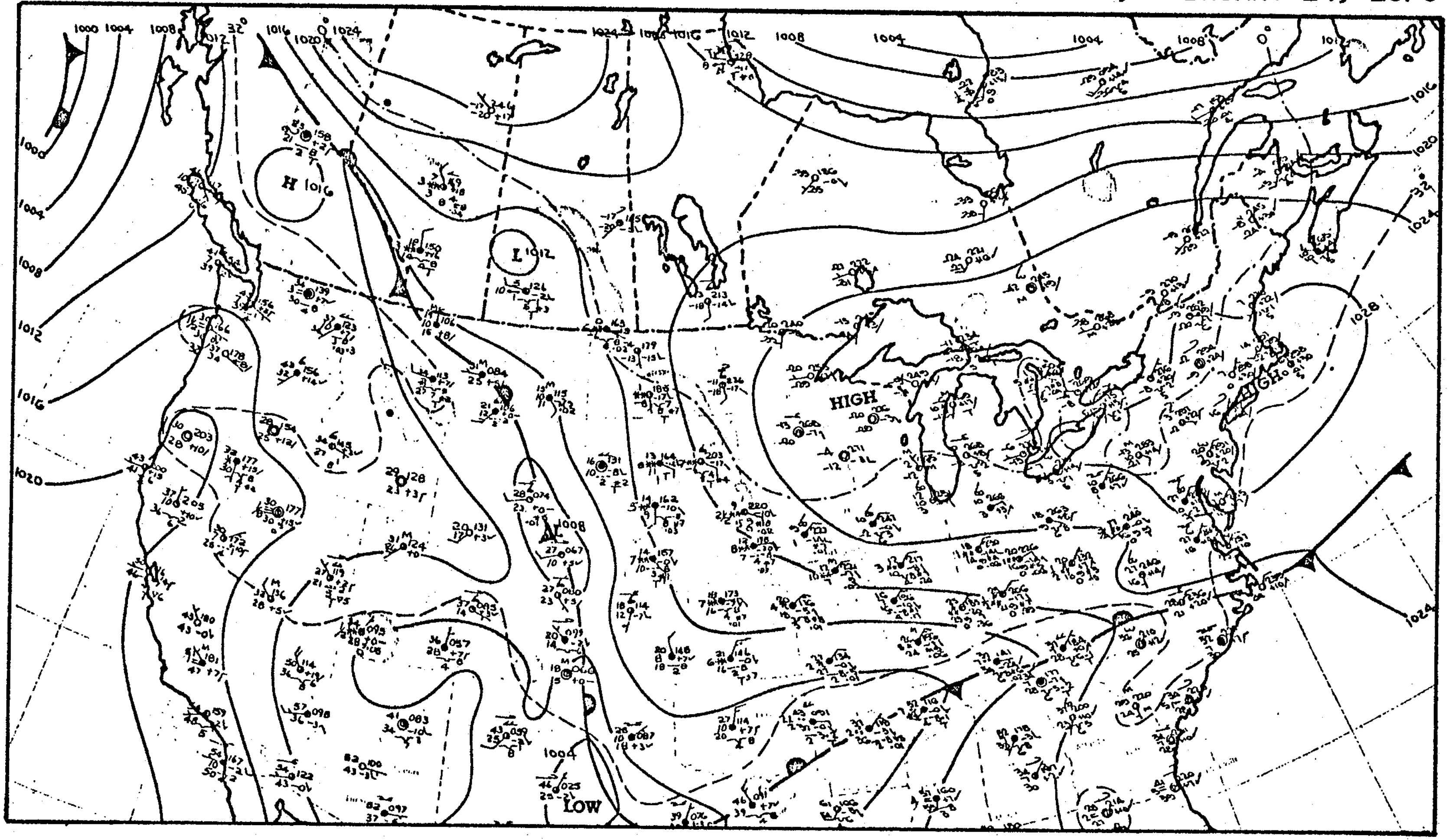
On the morning of the development day of Case 28, a minor disturbance brought cloud with light snow flurries to Saskatchewan and spread these conditions to southern Manitoba as it progressed eastward. From the north, an area of high pressure (1024 m.b.) pushed south in the wake of the disturbance bringing clear, cold weather to the eastern prairie provinces (Figure 4.10a).

On the development day of Case 36, increased cloud amounts and moderate temperatures associated with a minor disturbance that had moved inland via Montana-Dakota's influenced the weather scene. Strong Maritime Polar westerly winds brought chinook conditions to the

FIGURE 4.10 A

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT OF INVERSION CASE 28

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. SATURDAY, FEBRUARY 14, 1970



prairie provinces, and these were especially dominant in Alberta. The cloudy conditions gradually cleared from the eastern prairie provinces as cold north-westerly Arctic air pushed south under the control of an anti-cyclonic system (Figure 4.10b).

For Cases 28 and 36, hourly synoptic conditions are provided for their development periods of 1100 to 2200 hours, and 0900 to 1800 hours respectively (Tables 4.7a and 4.7b). Basic similarities and differences in synoptic conditions are observed between the inversion cases. The similarities will be examined first, and the differences later.

As the highs pushed south, pressure rose gradually and irregularly on both occassions. Initially high sky obscurities declined with approach of the development hours, after which lower obscurities of CI and AC cloud types prevailed. Though some of the wind data are missing, there appears to have been changes in wind velocity at both the 35 and 810 feet levels around the times snowfall culminated and the skies cleared.

Basic differences in synoptic conditions pertain to the time when snow flurries ended and to the wind speed profiles. In Case 28, wind speed progressively declined until around 2000 hours: at the 35 feet level it reduced from 18 to 2 m.p.h., and at the 810 feet level from 22 to

FIGURE 4.10 B

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT OF INVERSION CASE 36

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. WEDNESDAY, JANUARY 27, 1971

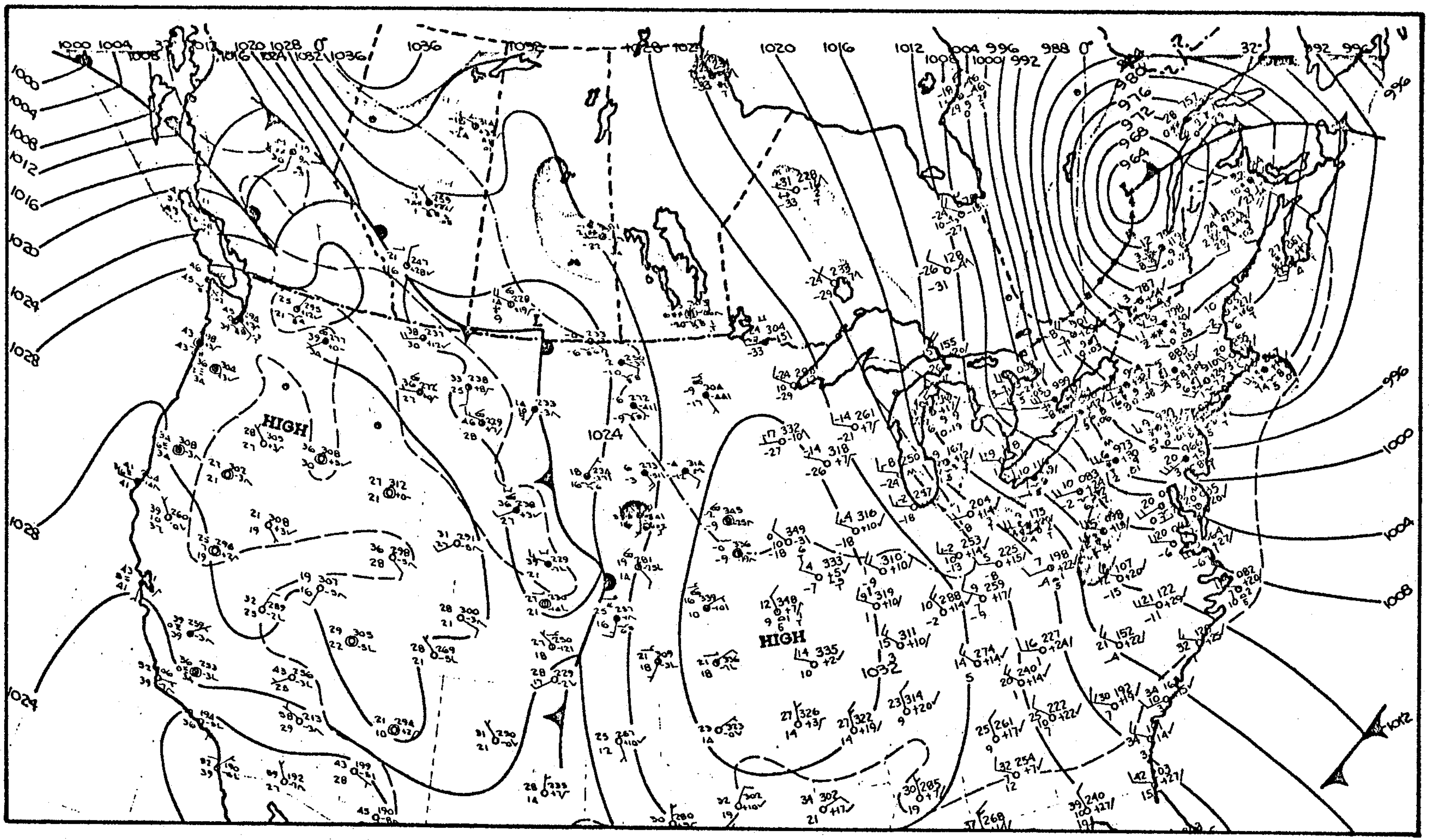


Table 4.7 a

Synoptic Conditions During Development Period of Case 28

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
1100	5.1	-5.0	170	14	180	20	6	-6.1	-6.9	-2.2	9	AC,Cl	7.0-22.0	1019.7	A	15	3		
1200	5.1	-3.4	170	15	170	22	7	-3.9	-4.8	-1.3	9	AC,Cl	12.0-25.0	1019.7	A	10	0		
1300	5.5	0.3	170	15	170	22	7	-2.6	-3.6	-2.9	10	AC,Cl	11.0-25.0	1019.2	P	08	0		
1400	5.4	4.2	170	18	180	17	-1	-1.9	-2.8	-5.1	10	AC,Cl	13.0-25.0	1018.7	P	02	0		
1500	4.6	2.9	180	14	190	12	-2	-1.1	-1.8	-3.4	9	AC,Cl	15.0-25.0	1018.5	P	03	7		
1600	4.7	3.7	190	11	210	8	-3	-0.7	-1.5	-3.5	5	AC,Cl	16.0-25.0	1018.5	A	12	4		
1700	3.1	3.6	210	6	260	4	-2	-1.3	-1.8	-4.1	5	AC,Cl	15.0-24.0	1018.5	P	15	0		
1800*	-0.8	2.5	180	4	---	--	--	-2.2	-2.0	-4.1	1	AC	15.0	1018.6	A	15	0	1.6	10.0
1900	-7.9	1.5	220	2	---	--	--	-3.2	-1.9	-4.4	1	AC	15.0	1019.1	A	15	0		
2000	-7.0	0.4	290	3	290	2	-1	-3.6	-2.4	-3.9	0	None	----	1019.5	A	15	0		
2100*	-12.5	-3.4	340	7	330	13	6	-4.8	-2.8	-2.2	0	None	----	1020.1	A	15	0		
2200	-28.8	-6.8	320	6	340	18	12	-8.0	-3.2	-2.7	2	AC	9.0	1020.6	A	15	0		

*Inversion developed at 1800 hours in the 35-200 feet layer and at 2100 hours in the 35-810 feet layer.

Table 4.7 b

Synoptic Conditions During Development Period of Case 36

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
0900	7.1	1.4	---	-	--	-	-	-11.8	-13.0	-12.9	8	SC	3.0	1028.7	P	05	0		
1000	6.0	-0.2	---	-	--	-	-	-11.6	-12.6	-11.5	10	AC	10.0	1028.5	P	04	0		
1100	7.0	2.1	---	-	--	-	-	-11.2	-12.3	-12.8	7	AC	10.0	1028.2	P	02	4		
1200	6.7	0.6	---	-	--	-	-	-10.9	-12.0	-11.3	10	SC,AC	3.0-12.0	1027.9	P	2-0.5	10		
1300	7.8	2.8	---	-	40	9	-	-10.2	-11.4	-12.4	1	AC	12.0	1027.1	A	5	10		
1400	6.1	2.3	---	-	20	7	-	-10.1	-11.1	-11.9	1	Cl	25.0	1027.2	A	15	10		
1500	4.0	3.0	310	8	350	8	0	-9.6	-10.3	-12.0	5	AC	12.0	1028.1	A	15	5	4.3	9.0
1600*	-0.5	0.1	310	8	330	18	10	-10.2	-10.1	-10.3	10	AC,Cl	12.0-25.0	1028.6	A	15	2		
1700*	-8.6	-1.0	290	7	330	16	9	-11.4	-9.9	-10.6	2	AC,Cl	15.0-25.0	1028.0	A	15	2		
1800	-30.3	-4.5	280	13	330	18	5	-14.6	-9.6	-11.1	1	AC	15.0	1028.2	A	15	0		

*Inversion developed at 1600 hours in the 35-200 feet layer and at 1700 hours in the 35-810 feet layer.

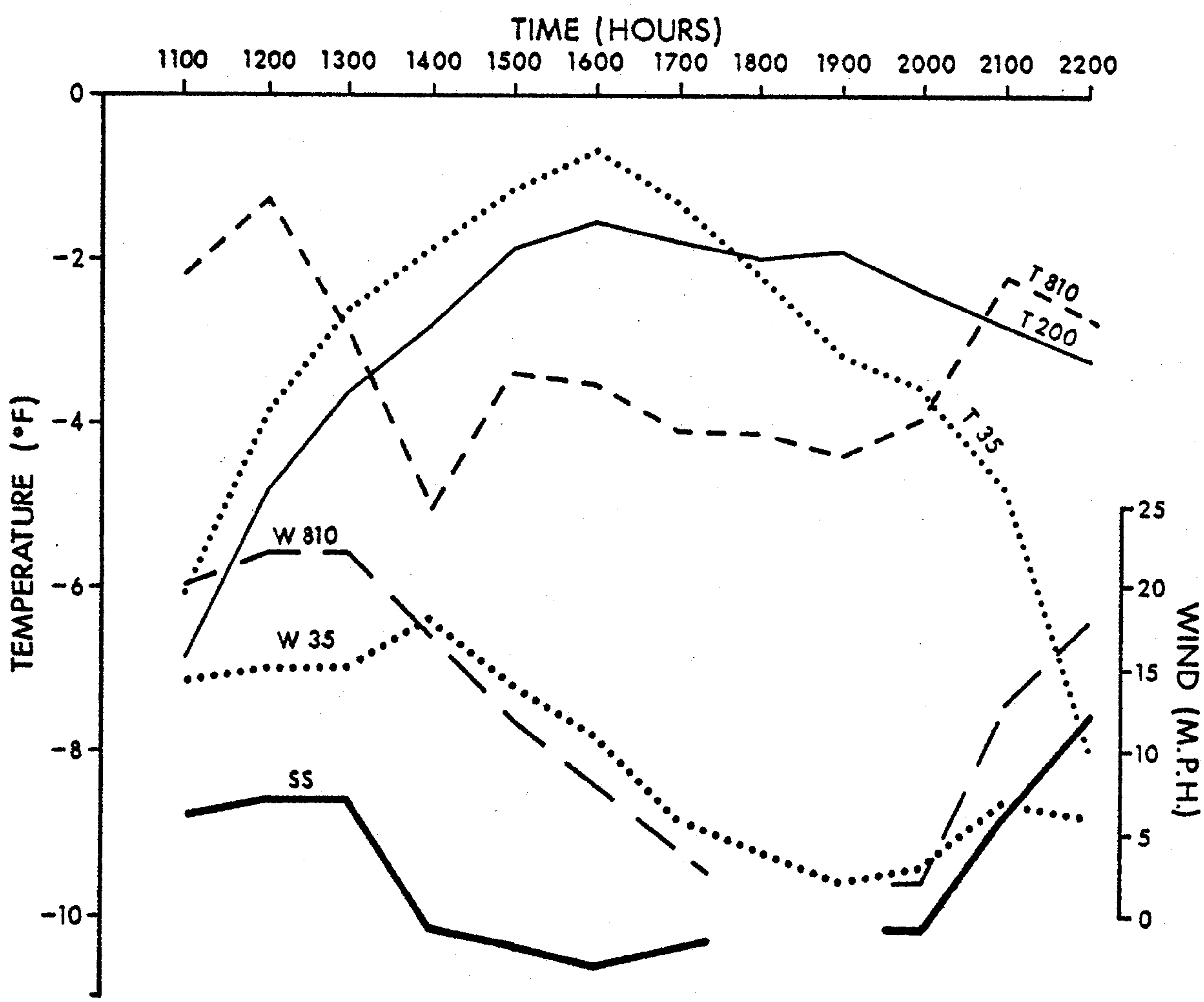
2 m.p.h. However wind speed increased, especially at the higher level, following development of the higher inversion. As expected, this event induced a stronger speed shear. With the development of the 35-200 feet inversion Case 36, wind speed at the higher level markedly increased. A change from zero speed shear to 9-10 m.p.h. was observed at this time. Case 28 developed immediately after snow flurries ended at 1700 hours, but Case 36 developed four hours preceding a similar event.

On the development day of Case 28, sunshine was recorded for only 1.6 hours out of a possible 10.0 hours. Meanwhile temperatures at the 35 feet level increased by 5.4°F from 1100 to 1600 hours and, thereafter, a continuous 7.3°F decrease occurred. The lower inversion developed at 1800 hours when the cooling amounted to 1.5°F, and the higher inversion formed three hours later after a further cooling of 2.6°F. The 200 feet level temperatures changed similarly. In fact, the same rate of increase of 5.4°F per five hours was observed. Although the 810 feet level temperatures changed irregularly over a 3.8°F range, yet they showed a general tendency to fall and rise opposite to the trend at the lower levels (Figure 4.11a).

Sunshine was recorded for 4.3 hours out of a possible 9.0 hours on the development day of Case 36. In the development period, temperature at the 35 feet level

Figure 4.11a

Temperature and Wind Variations During Development Period of Case 28



T — Temperature at 3 Levels (feet)

W — Wind Speed at 2 Levels (feet)

SS — Speed Shear

Interrupted Line — Missing Data

continually increased by only 2.2°F to 1500 hours. With initial fall in temperature the lower layer inversion developed. One hour later, with a 1.8°F cooling, the higher layer inversion formed. The 200 feet level experienced a 3.4°F warming throughout this period. At the 810 feet level temperature variations were irregular over a 2.6°F range (Figure 4.11b).

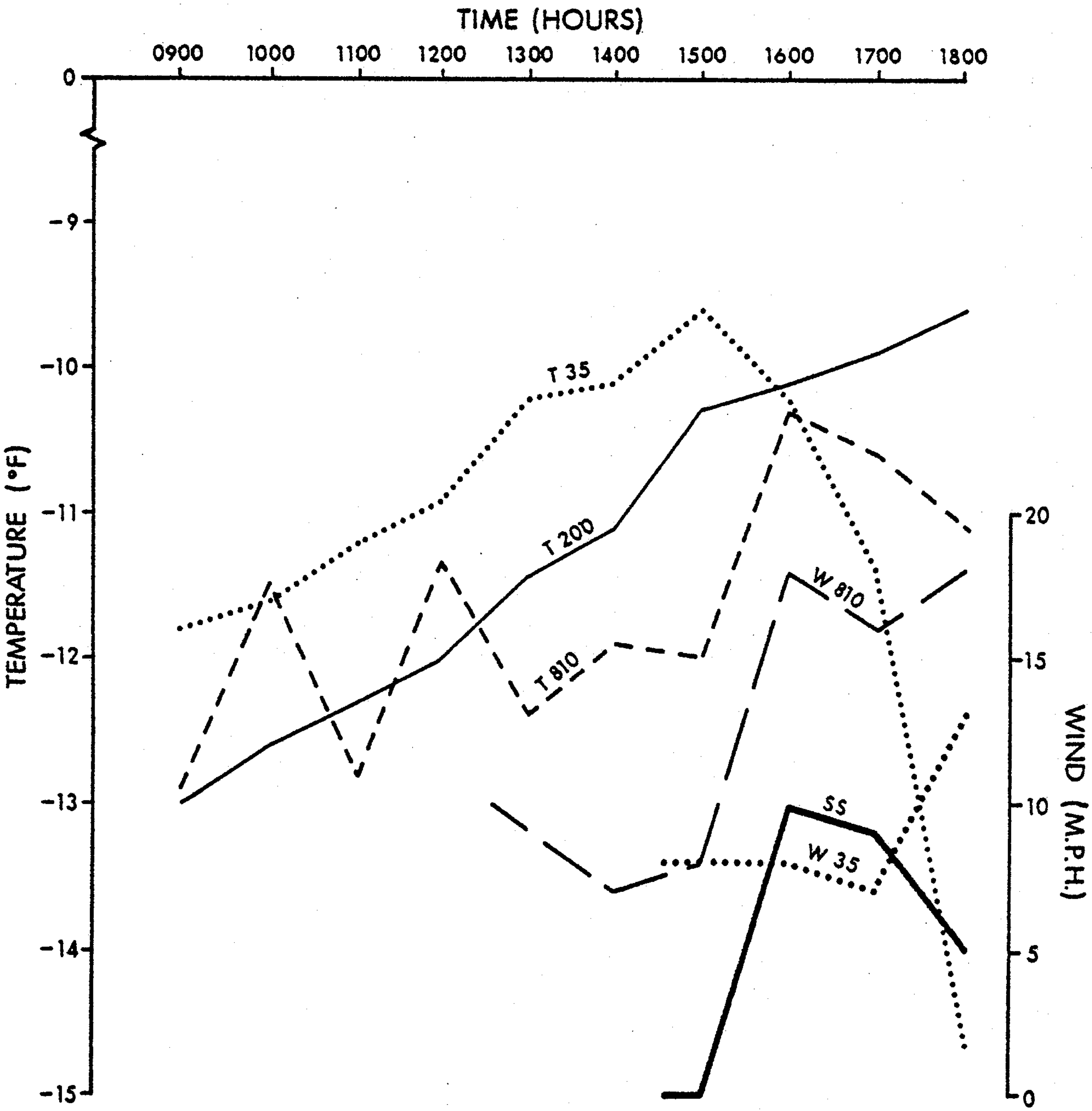
Since the temperature profiles are significantly influenced by the overcast, snowy conditions some background material should be provided to aid assessment.

Precipitation generally modifies surface temperatures since it usually originates in overlying layers that are warmer or colder than surface layers (Geiger, 1950). A thick cloud cover radiates almost as a black body with a temperature roughly equal to that at the base of the cloud. The development of a cloud sheet generally changes net radiation -- replacing an energy loss into energy income. The temperature of the air and the surface therefore increases, and any inversion tends to disappear. The snow surface, the cloud base, and the air between, attain roughly the same temperature, because the radiation is trapped between the cloud base and the snow surface (Liljequist, 1956).

Albedo varies with the age of snow. Fresh snow may reflect most of the solar radiation received at the

Figure 4.11b

Temperature and Wind Variations During Development Period of Case 36



T – Temperature at 3 Levels (feet)

W – Wind Speed at 2 Levels (feet)

SS – Speed Shear

Interrupted Line – Missing Data

surface, while old snow may absorb as much as half of the incident radiation. Over fresh snow albedos are 75-95 per cent, and over snow that has lain for a few days albedos are 40-70 per cent (Sellers, 1965, p. 21).

The early ending of snowfall, accompanied by the clearing of the sky, resulted in a relatively large amount of sunshine in Case 36. As the sun altitude lowered, the surface rapidly cooled radiatively because of the high emissivity of the new fallen snow and the low sky obscurity. With the radiative cooling of the surface, the lower atmosphere in contact with the surface, lost sensible heat through conduction, convection and especially radiation. In Case 36 the inversion developed in the 35-200 feet layer at 1600 hours while the associated 35-810 feet layer inversion developed one hour later. It is postulated that the increase in speed shear facilitated the quick upward propogation of the lower inversion surface by turbulent transfer.

Radiational cooling occurs near the surface first, and its effects gradually penetrate upwards. As the lower layer inversion strengthens, the higher layer eventually responds to the cooling. Thus, the cooling may be thought of as a vertically propogating wave (Goff and Hudson, 1972, p. 18). Blackadar (1957, p. 286) reported that, in some cases, when nocturnal cooling above the height of about a meter is too large to be accounted for by radiational or convective fluxes, the rate of upward propogation of the inversion surface is chiefly controlled by turbulent transfer. The character of the wind speed profile is important in determining whether the upward growth of the nocturnal inversion is orderly and controlled, or whether it is chaotic, or perhaps entirely absent.

The 35-200 feet inversion of Case 28 developed at 1800 hours when snowfall concluded and sky obscurity decreased. The surface and the air layer near the surface cooled quickly, due partly to the fresh fallen snow and partly to the time of day. However, the rate of vertical penetration of this cooling was not large as the winds were slight in the lowest 810 feet until 2000 hours. As they increased, the lower inversion surface was propogated upwards to the higher layer by turbulent transfer. With a time lag of 3 hours the associated 35-810 feet layer inversion formed at 2100 hours.

4.3.2 (a) (2) Decay of Cases 28 and 36

The weather on the decay day of Case 28 was described as -- "Very cold. Sunny with light winds" (Feb. 15, 1970). On the decay day of Case 36 the weather was -- "Cold. Mostly cloudy. Snow 11:15 a.m. to 2:35 p.m., 5:10 p.m. continued" (Jan. 28, 1971) (Atmos. Environ. Service, Monthly Meteor. Summary). The weather situation of the former case, unlike the latter, is favourably conducive to inversion decay through the agency of radiation heating.

On the decay day of inversion Case 28, southern Manitoba under the influence of a shallow Arctic high pressure system (1028 m.b.) experienced clear, cold weather. On the western boundary of the area of high pressure was a south-eastward extending deep trough from a low pressure system off the northern British Columbia coast. Associated with this system was a disturbance that moved rapidly eastward to the Dakotas. Warm and moist Maritime Polar southwesterly air was involved, and caused moderate temperatures and increased cloud amounts in the Winnipeg area (Figure 4.12a).

An intense low pressure system off the British Columbia coast on the decay day of Case 36, gave chinook conditions particularly to the province of Alberta. Large amounts of cloud persisted over the prairie provinces from the Rockies to western Manitoba. Over the eastern prairies cold northerly air flowed southward in a shallow ridge of high pressure. The Arctic front passed through British Columbia and ran along the eastern border of Alberta (Figure 4.12b). Under such a weather scene the prairie provinces experienced contrasting

FIGURE 4.12 A

SYNOPTIC SITUATION ON DAY OF DECAY OF INVERSION CASE 28

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. SUNDAY, FEBRUARY 15, 1970

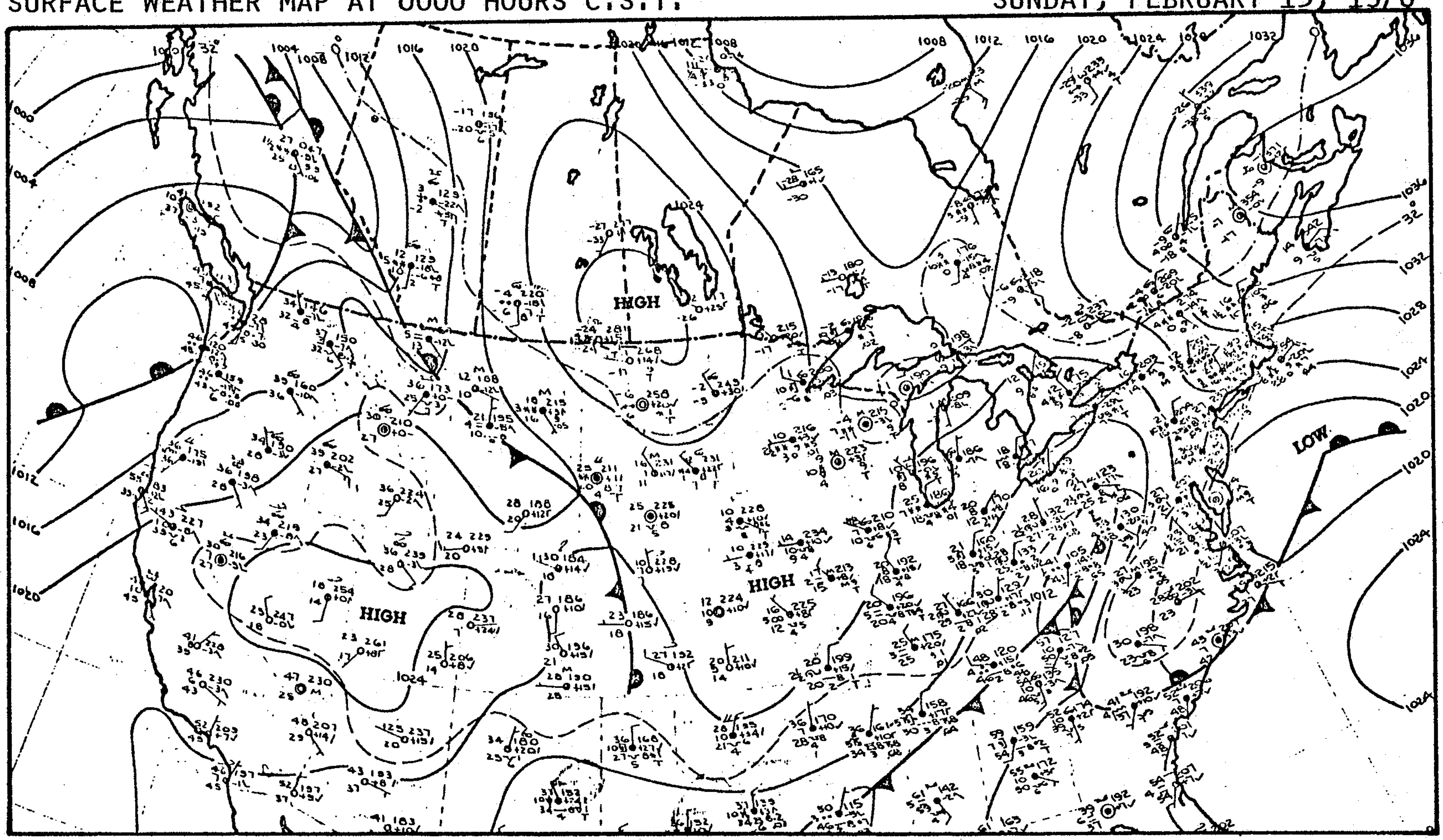
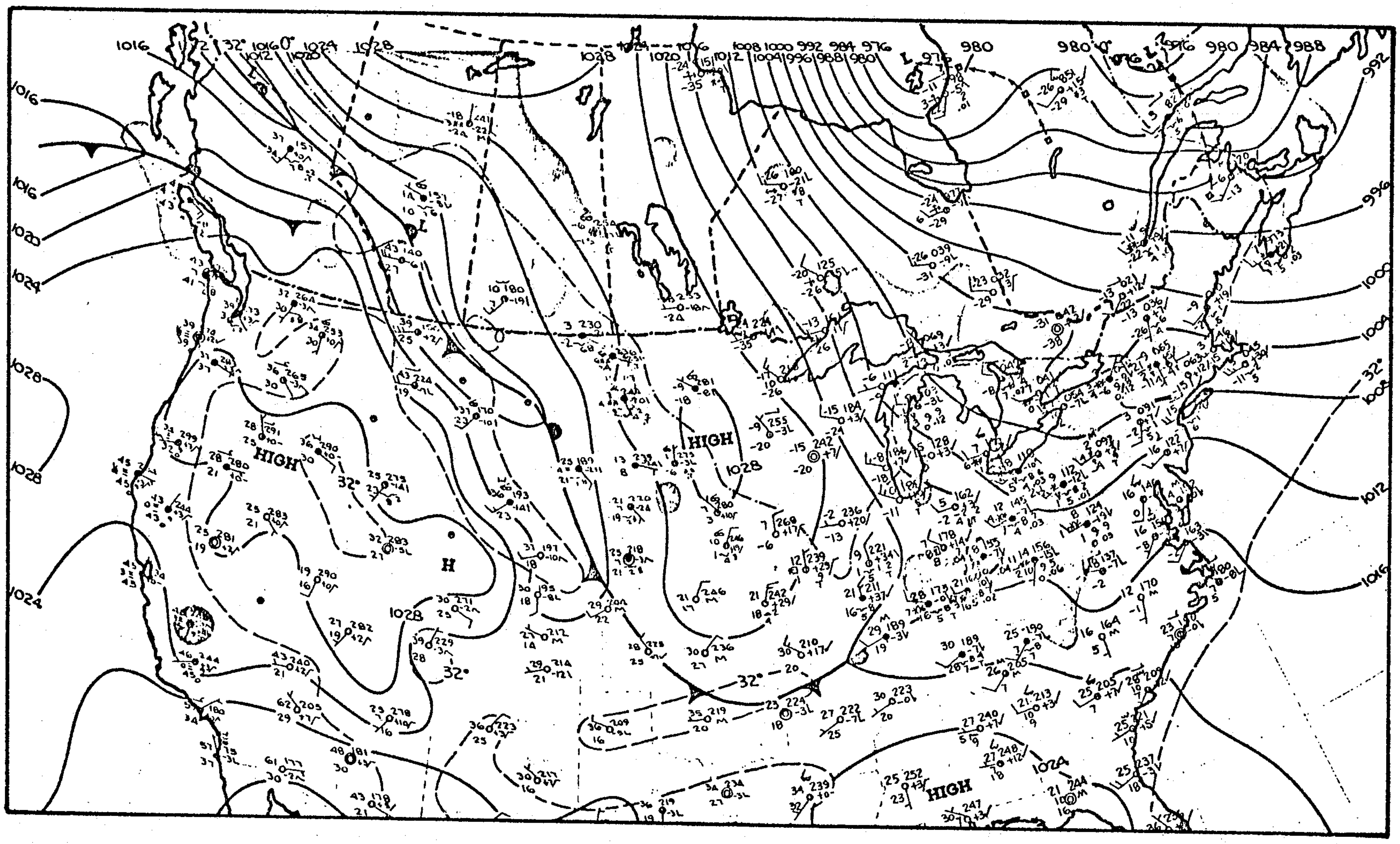


FIGURE 4.12 B

SYNOPTIC SITUATION ON DAY OF DECAY OF INVERSION CASE 36

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. THURSDAY, JANUARY 28, 1971



temperatures with a warm west and a cool east. The warm western provinces were under heavy cloud cover with snowfall, while the cooler eastern province of Manitoba received only patchy cloud with light snow flurries.

The basic difference in hourly synoptic conditions observed in the decay periods of Cases 28 (0500 to 1400 hours) and 36 (0300 to 1200 hours), is the magnitude of sky obscurity (Tables 4.8a and 4.8b). The former case had low sky obscurity of less 4/10th's cloud cover; while, clear skies gave way to overcast conditions from the decay hour of the latter case. Though both cases eventually showed a fall in pressure, this only occurred after the decay hour in Case 28, and, prior to that time pressure rose continually. Wind velocity at both the 35 and 810 feet levels, and speed shear reduced in intensity with the approach of the decay hours of both cases. The latter variable however, increased slightly around the expected time of sunrise in Case 36. At both levels, the changes in air mass type were effected around the decay times of the inversion cases.

The temperature trends during these two decay periods are dissimilar to those observed in the development periods. The decay periods are both marked by warming trends. In general terms, this warming is caused by the advance of warm air masses to replace cold air masses.

Table 4.8 a

Synoptic Conditions During Decay Period of

Case 28

Time (Hours)	Lapse Rate (°F/1000')[35-200']	Lapse Rate (°F/1000')[35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
0500	-28.9	-7.6	320	10	250	24	14	-19.7	-14.9	-13.8	0	None	---	1026.7	A	15	0		
0600	-24.9	-7.2	320	10	350	23	13	-20.5	-16.4	-14.9	0	None	---	1027.7	A	15	0		
0700	-19.7	-6.8	320	11	340	20	9	-20.4	-17.2	-15.2	0	None	---	1028.3	A	15	0		
0800	-27.4	-8.8	290	10	320	16	6	-22.4	-17.9	-15.7	0	None	---	1029.0	A	15	0		
0900	-30.1	-7.2	290	8	330	14	6	-22.2	-17.3	-16.6	0	None	---	1029.9	A	15	0		
1000	-28.2	-5.5	280	8	320	12	4	-20.0	-15.4	-15.7	0	None	---	1030.8	A	15	0	6.3	10.1
1100*	-14.5	-3.8	260	6	330	10	4	-17.3	-14.9	-14.4	0	None	---	1030.6	A	15	8		
1200	5.7	0.1	240	8	280	6	-2	-13.0	-13.9	-13.1	0	None	---	1030.5	A	15	10		
1300	1.9	1.5	230	6	---	--	-	-11.7	-12.0	-12.8	2	Cl	28.0	1030.4	A	15	10		
1400	1.4	2.6	240	6	230	4	-2	-9.7	-10.0	-11.8	3	Cl	28.0	1029.7	A	15	10		

*Inversion decayed at 1100 hours in the 35-200 and 35-810 feet layers.

Table 4.8 b

Synoptic Conditions During Decay Period of

Case 36

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
0300	-36.8	-10.9	280	9	340	25	16	-21.1	-15.1	-12.7	0	None	---	1026.8	A	15	0		
0400	-20.9	-7.7	250	7	330	20	13	-18.7	-15.2	-12.7	0	None	---	1025.9	A	15	0		
0500	-26.1	-7.2	260	9	300	16	7	-18.0	-13.7	-12.3	0	None	---	1025.6	A	15	0		
0600	-18.0	-5.9	260	7	290	15	8	-16.0	-13.0	-11.5	0	None	---	1025.3	A	15	0		
0700	-11.9	-4.2	270	6	280	13	7	-14.1	-12.1	-10.8	0	None	---	1024.9	A	15	0		
0800*	-0.5	-3.3	240	5	270	15	10	-12.5	-12.4	-10.0	9	SC	2.8	1024.5	A	15	0		
0900	0.8	-3.3	240	5	280	15	10	-11.5	-11.6	-8.9	9	SC,AC	2.8-9.0	1023.6	A	15	0	0.0	9.1
1000*	4.7	-1.0	---	-	280	11	--	-9.5	-10.3	-8.8	10	SC,AC	2.8-12.0	1023.3	A	15	0		
1100	4.2	1.4	240	5	300	7	2	-8.3	-8.9	-9.3	10	AC	12.0	1023.1	A	15	0		
1200	7.6	4.9	---	-	---	--	--	-7.1	-8.3	-10.9	10	AC	12.0	1022.1	P	12	0		

*Inversion decayed at 0800 hours in the 35-200 feet layer and at 1000 hours in the 35-810 feet layer.

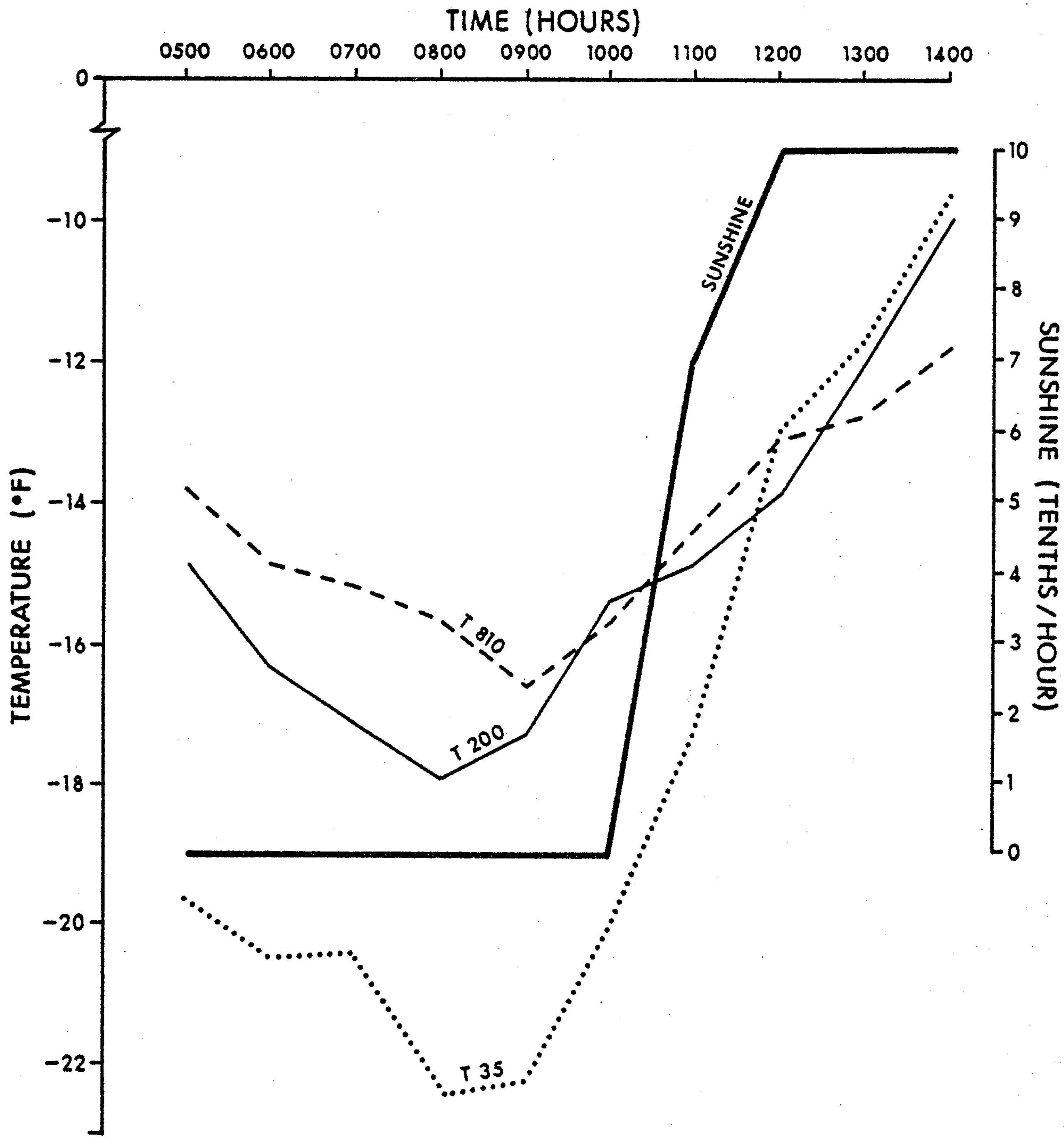
On the decay day of Case 28 sunshine was recorded for 6.3 hours out of a possible 10.1 hours. A rapid 12.7°F warming occurred from 0800 hours at the 35 feet level. The 200 feet level temperatures also increased but by a smaller amount of 7.9°F. The 810 feet temperatures increased by 4.8°F from 0900 hours (Figure 4.13a).

No sunshine was recorded on the decay day of Case 36. In the decay period, a 14.0°F temperature increase was observed at the 35 feet level. Temperature likewise continually increased at the 200 feet level by 6.9°F from 0400 hours. At the higher 810 feet level temperature changed differently. After a 3.9°F increase to 1000 hours, temperature fell (Figure 4.13b). The higher layer inversion decayed at the beginning of this cooling.

The decay of these inversions was caused primarily by an exchange in air mass types. The simultaneous decay of inversion Case 28 in the 35-200 feet layer and in the 35-810 feet layer at 1100 hours, apart from being functional of the above factor, depended to some measure on the direct solar heating afforded by the low sky obscurity. On the other hand under overcast skies, the decay of inversion Case 36 in the 35-200 feet layer at 0800 hours and in the 35-810 feet layer at 1000 hours, depended principally on the air mass interchange. Furthermore, turbulent mixing through increased speed shear may have

Figure 4.13a

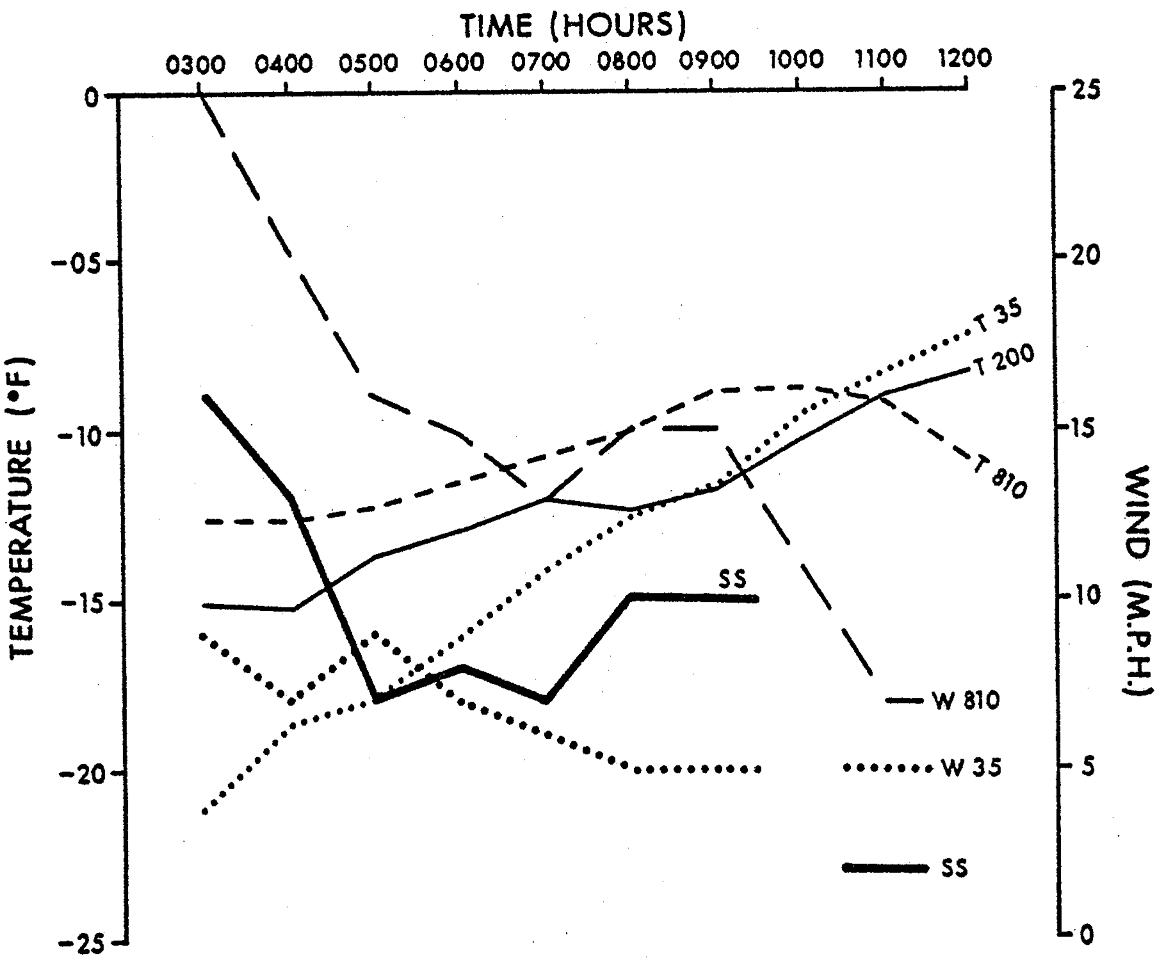
Temperature and Sunshine Variations During Decay Period of Case 28



T—TEMPERATURE AT 3 LEVELS (FEET)

Figure 4.13b

Temperature and Wind Variations During Decay Period of Case 36



T — Temperature at 3 Levels (feet)
WS- Wind Speed at 2 Levels (feet)
SS — Speed Shear
Interrupted Line — Missing Data

played an important role.

Treidl (1970, p. 155) reported that in the presence of an energy source, such as strong vertical wind shear, the damping effect of stability may be overcome by turbulent mixing. From Cedar Hill tower observations, Izumi (1963) determined that turbulent mixing which intensifies at or soon after sunrise apparently plays a significant role in the breakdown of the nocturnal inversion. The mixing process starts at the surface and proceeds upwards in a systematic manner.

4.3.3 Summary

The inversion cases studied indicate that the structural behaviour of Cluster 4 inversions is basically determined by solar radiation heating. The sun initially heats the ground and it is mainly from the ground that the atmosphere is heated. The lower 35-200 feet layer inversions usually develop and decay first, and the processes are generally observed with a lag of up to 3 hours in the 35-810 feet layer.

The above process however, is significantly affected by other meteorological parameters. During inversion development, snowfall and the wind speed profile are important. A change in air mass conditions and behaviour is critical in the decay process.

With the development of the inversions, cold Arctic air under the control of an anticyclonic system replace warm, moist air, so that, snow flurries end and sky obscurity lowers. The earlier in the day these events happen, the earlier in the nocturnal period the inversions develop. As the sun angle lowers, the surface cools rapidly because of the high reflectivity and high emissivity of a newfallen snow covered surface. The lower 35-200 feet layer inversion forms and strengthens quickly. With increased speed shear, the vertical propogation of the lower inversion surface by turbulent transfer is accelerated. Analysis detected that a lag of up to 3 hours is required for propogation to the higher 35-810 feet layer.

The decay structure of the inversions is usually favoured by an air mass change in which cold air is replaced by cyclonically-controlled mild Maritime Polar air. If this process is complemented by direct solar heating, the decay of the inversions in both layers is simultaneous. If the latter component is absent or negligible, the relative times of decay are determined principally by the time air masses interchange.

4.4 Cluster 7

4.4.1 Preliminary Remarks

Great care and caution must be exercised in the analysis and interpretation of the structural behaviour of Cluster 7 inversions. This cluster is regarded as transitional between the radiative and advective cluster groups (Ch. 3). In this context, inversions may either be of the radiative or advective type, or a combination of both. Bell (1974) identified these inversions as of the radiative type, but cautioned that they may be a misfit. Cluster 7 is quite unlike other clusters of the radiative group, since none of its seven inversions occurred in January, while 70 per cent occured in December.

According to the averages of the seven diagnostic properties (see Ch. 3), Cluster 7 is of a relatively long duration, high wind shear, sky obscurity, pressure and intensity, but low wind speed and temperature. Average properties of each inversion case in the cluster are given in Table 4.9.

Inversions of the cluster developed between 1500 and 1800 hours and decayed between 0900 and 1300 hours. They were maintained for durations ranging from 18 to 22 hours. However, Case 77 transgressed. It was of a much shorter duration, 11 hours, and decayed at the unconforming time, 0300 hours. This inversion developed on November 30

Table 4.9

Average Properties of Inversion Cases in Cluster 7

Case Number	Date	Development Hour	Inversion Duration (Hours)	Decay Hour	Inversion Intensity (°F/1000')	Sky Obscurity (tenths)	Temperature (°F)	Pressure (m.b.)	Wind Speed (m.p.h.)	Wind Shear (m.p.h./x feet)	Wind Direction
13	Dec. 20'71	1600	22	1300	-32.7	0.1	-7.8	1024.0	9.0	15.8	NW
14	Dec. 19'69	1600	21	1200	-40.3	2.0	3.6	1021.1	7.4	7.0	S
19	Dec. 14'69	1500	19	0900	-35.1	1.3	-1.5	1030.3	5.9	7.6	NW
20	Feb. 20'71	1800	19	1200	-33.0	0.2	3.4	1029.1	7.5	6.1	W
21	Dec. 26'69	1600	19	1000	-35.7	1.0	-2.5	1023.0	8.1	6.4	SE
27	Feb. 27'70	1700	18	1000	-47.0	2.6	-2.8	1028.4	8.7	2.7	SW
77	Nov. 30'71	1700	11	0300	-41.3	2.2	1.9	1030.4	10.2	13.9	S

but decayed in the core winter period. Apart from this case, the described development and decay times are in agreement with the model (Ch. 2).

On an average, positive lapses for a 10-hour period in the 35-200 feet layer preceded the development of Cluster 7 inversions. The structural behaviour of these inversions are of a composite character. That is, the lower layer inversions developed either before, after, or simultaneous with the associated higher layer inversions. A notable feature nonetheless, is that irrespective of the development structure, a one hour lag is required.

The decay structure of these inversions are better defined. The lower inversions decayed before the higher inversions. Apart from this however, no definitive statements can be made as to the time lag involved. In some instances, the higher inversion decayed one hour later; in others, it was maintained ten hours longer.

4.4.2 Selected Inversion Cases

Inversion Cases 20 and 21 are chosen for detailed development and decay structure analysis. Since virtually all the cases are consistent with the model, the major factor that influenced selection was the difference between their development structures. Case 21 developed first in the 35-810 feet layer and one hour later in the 35-200 feet layer, whereas Case 20 developed first in the 35-200 feet layer and one hour later in the 35-810 feet layer.

4.4.2. (a) Inversion Case 21

Though development and decay times of this inversion case are in accordance with the model, yet, its structural behaviour is in discord. This indicates that the diurnal effects of solar radiation heating do not control the inversion structure.

Eleven hours of positive lapses in the 35-200 feet layer preceded the development of Case 21 at 1600 hours. The 35-810 feet layer inversion developed one hour earlier. The inversion in the lower layer persisted for 19 hours before it decayed at 1000 hours. The higher inversion was sustained for 25 hours until 1700 hours when data became missing.

4.4.2. (a) (1) Development of Case 21

A couple of days prior to the development day (December 26), mild Maritime Polar westerly air from a low pressure system spread chinook conditions over the southern portion of the prairie provinces. An elongated north-south weak ridge of high pressure (1020 m.b.) dominated the weather scene in southern Manitoba. This synoptic feature was flanked on both the right and left sides by low pressure areas (Figure 4.14).

Winnipeg's weather on the development day was described as -- "Near normal temperatures. Cloudy with light snow till early afternoon" (Atmos. Environ. Service, Monthly Meteor. Summary, Dec. 26, 1969).

Synoptic conditions for a development period from 1000 to 1700 hours are presented in Table 4.10. Snowfall concluded at 1200 hours as the weak ridge dominated and pressure rose gradually from 1400 hours. It was at this time that overcast skies gave way to less 3/10th's cover of higher clouds. A south-easterly flow was gradually established at the 35 feet level around development hour of the lower inversion. Southerly air prevailed at the higher 810 feet level. Though winds were slight at both levels, they gained momentum from 1600 hours at the higher level.

On the development day sunshine was recorded for 2.9 hours out of a possible 8.1 hours. As snowflurries ended and sunshine was received, temperature at the lowest level continually dropped by 5.8°F. This cooling was pronounced until the lower inversion developed. At the 200 feet level temperature decreased by 3.2°F to 1500 hours following which time there was a warming trend. The 810 feet level temperatures varied in a 1.3°F range throughout the development period (Figure 4.15).

FIGURE 4.14

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT OF INVERSION CASE 21

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. FRIDAY, DECEMBER 26, 1969

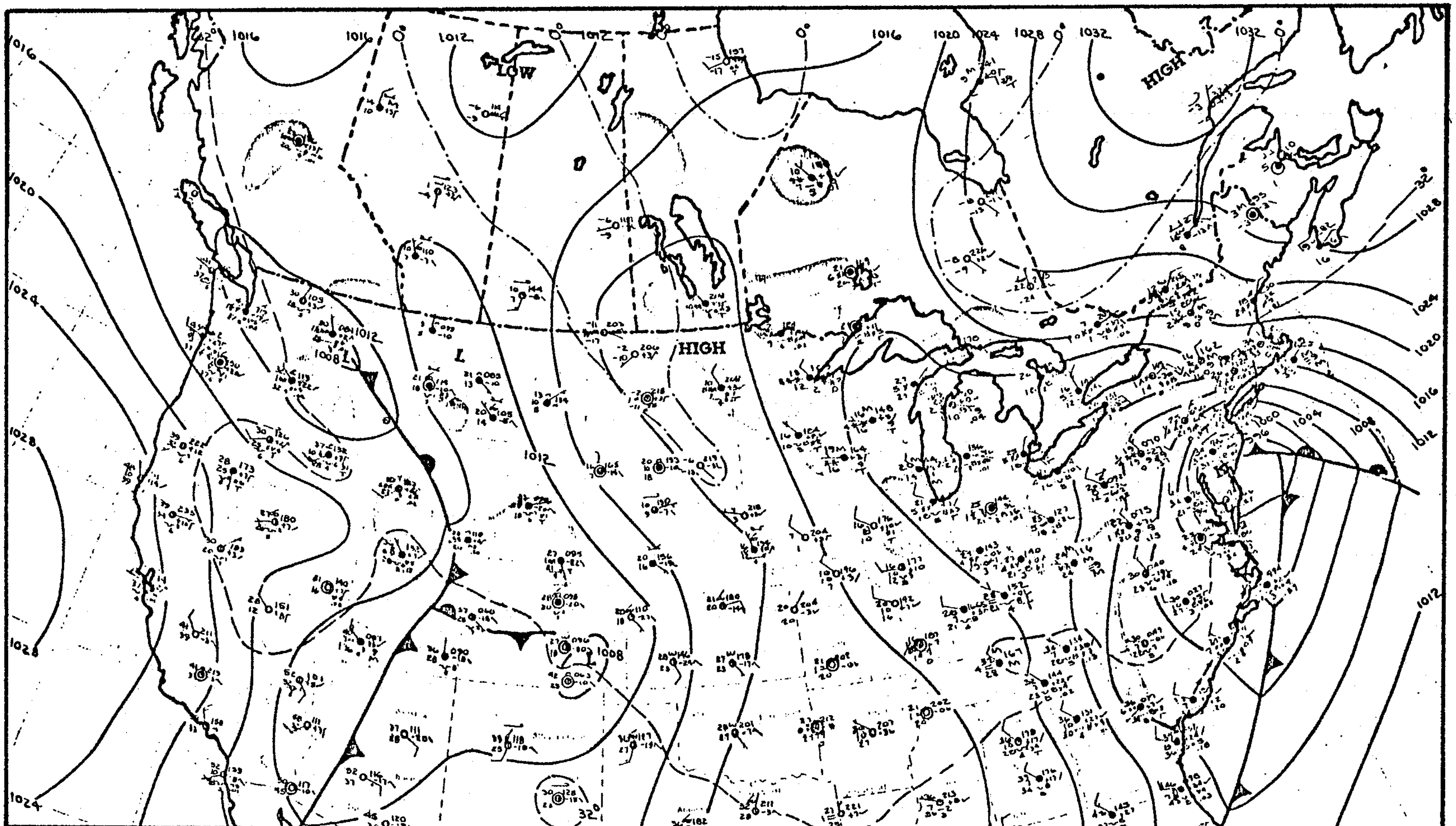


Table 4.10

Synoptic Conditions During Development Period

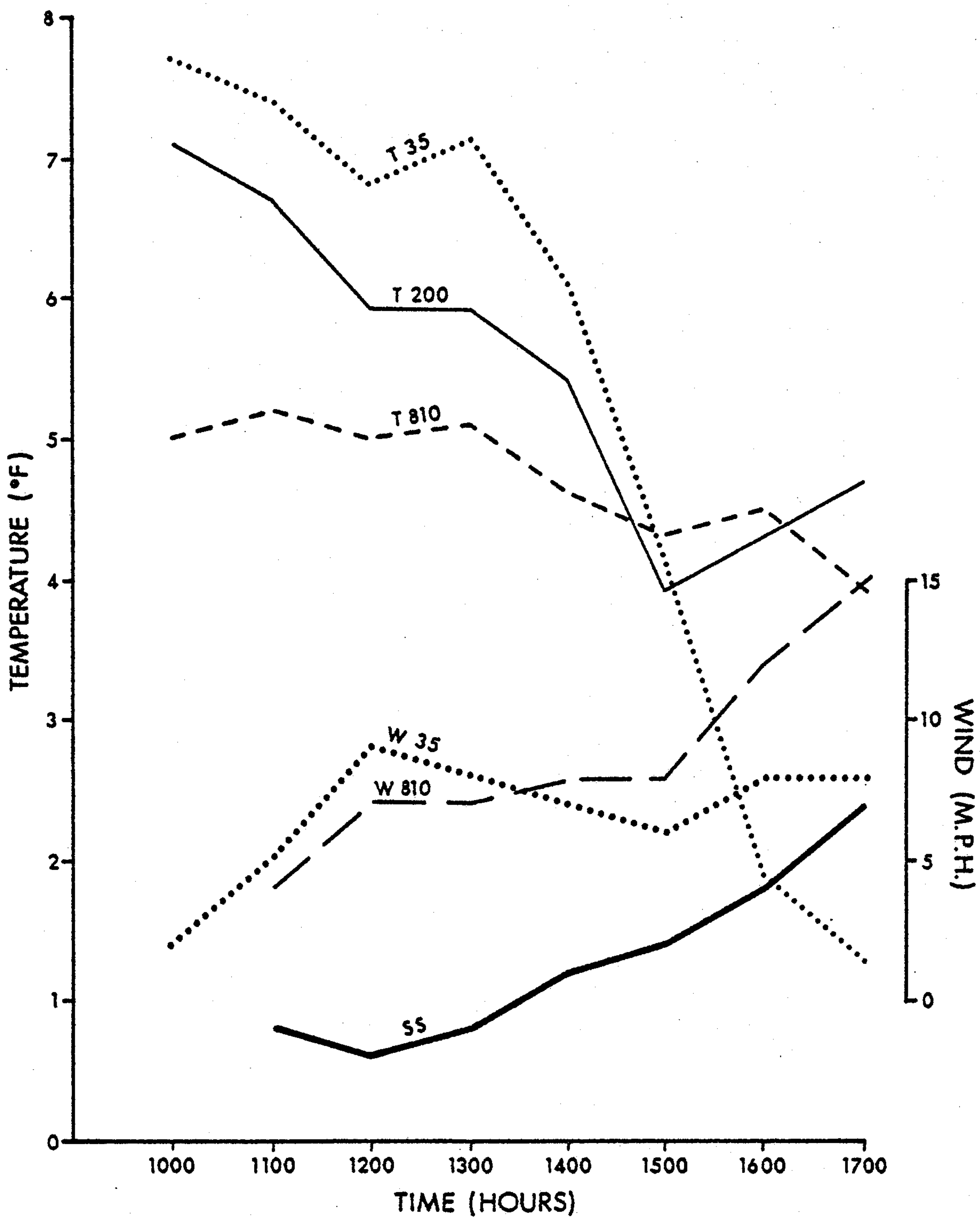
of Case 21

Time (Hours)	Lapse Rate (°F/1000')[35-200']	Lapse Rate (°F/1000')[35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
1000	3.4	3.5	190	2	---	--	--	7.7	7.1	5.0	10	ST	0.9	1022.3	P	05	0		
1100	4.3	2.8	160	5	180	4	-1	7.4	6.7	5.2	10	ST	1.3	1022.6	P	10	0		
1200	5.4	2.4	160	9	180	7	-2	6.8	5.9	5.0	10	ST,SC	1.1-5.7	1022.1	P	10	0		
1300	7.4	2.6	140	8	180	7	-1	7.1	5.9	5.1	10	SC	3.4	1021.6	A	12	2		
1400	4.7	1.9	160	7	180	8	1	6.1	5.4	4.6	8	SC, AC,Cl	3.4-9.0-26.0	1020.9	A	15	10	2.9	8.1
1500*	0.9	-0.3	150	6	180	8	2	4.1	3.9	4.3	2	SC	4.0	1021.3	A	15	10		
1600*	-14.7	-3.4	130	8	160	12	4	1.9	4.3	4.5	1	SC,AC	4.0-14.0	1021.6	A	15	7		
1700	-20.2	-3.4	130	8	170	15	7	1.3	4.7	3.9	0	None	---	1021.9	A	15	0		

*Inversion developed at 1600 hours in the 35-200 feet layer and at 1500 hours in the 35-810 feet layer.

Figure 4.15

Temperature and Wind Variations During Development Period of Case 21



T — Temperature at 3 Levels (feet)
W — Wind Speed at 2 Levels (feet)
SS — Speed Shear
Interrupted Line — Missing Data

Over freshly fallen snow surface albedo is greatly enhanced. The snow surface, even in the presence of maximum hourly sunshine, quickly cooled radiatively. Heat was transported downwards towards the surface in the form of sensible fluxes. As the overlying air lost heat both upwards and downwards, the lower 35-200 feet inversion Case 21 developed at 1600 hours. Rider and Robinson (1951, p. 375) attributed the formation of many surface inversions at night largely to the turbulent transfer of heat downwards to the ground which is being cooled radiatively, though direct radiative cooling of the air layer themselves also play a part.

The associated 35-810 feet inversion developed one hour earlier at 1500 hours. At the 810 feet level, temperature variations were moderate as warm southerly air advected. As soon as sky obscurity reduced to 2/10th's cover, temperature at the level near the surface fell sharply by 2.0°F between 1400-1500 hours. This set up a thermal stratification which produced a stable condition.

4.4.2. (a) (2) Decay of Case 21

Preliminary analysis indicated that the presence of fog on the morning of the decay day is the single most important factor controlling the inversion structure. Stringer (1972, p. 113) has remarked that fogs are commonly associated with inversions, and that, under such a weather condition, there is usually a very shallow inversion at the ground, with a nearly isothermal layer above extending to the fog top, then a steep inversion layer above the fog.

On the decay day (December 27), a weak high pressure area (1024 m.b.) was located to the immediate east of Winnipeg. To the south-west, was a broad, well-defined low pressure system associated with a southerly airflow. Southern Manitoba was therefore under the influence of cyclonic and anticyclonic airflows (Figure 4.16). The weather at Winnipeg was described as -- "Temperature below normal. Most cloudy with ice prisms or ice fog till 7 p.m." (Atmos. Environ. Service, Monthly Meteor. Summary, 1969).

The synoptic conditions for a decay period from 0400 to 1300 hours are given in Table 4.11. Warm southerly winds of diminishing strength affected the 810 feet level, while at the lower 35 feet level south-easterly winds of slight velocity were dominant. Pressure rose to attain a maximum of 1025.6 m.b. at 1200 hours. Low sky obscurity gave way to greater than 6/10th's cloud cover of the ST type at roughly 300 feet from 0800 hours. Visibility was reduced to 4 miles as a result of fog.

At the end of a cloudless night in areas of

FIGURE 4.16

SYNOPTIC SITUATION ON DAY OF DECAY OF INVERSION CASE 21

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. SATURDAY, DECEMBER 27, 1969

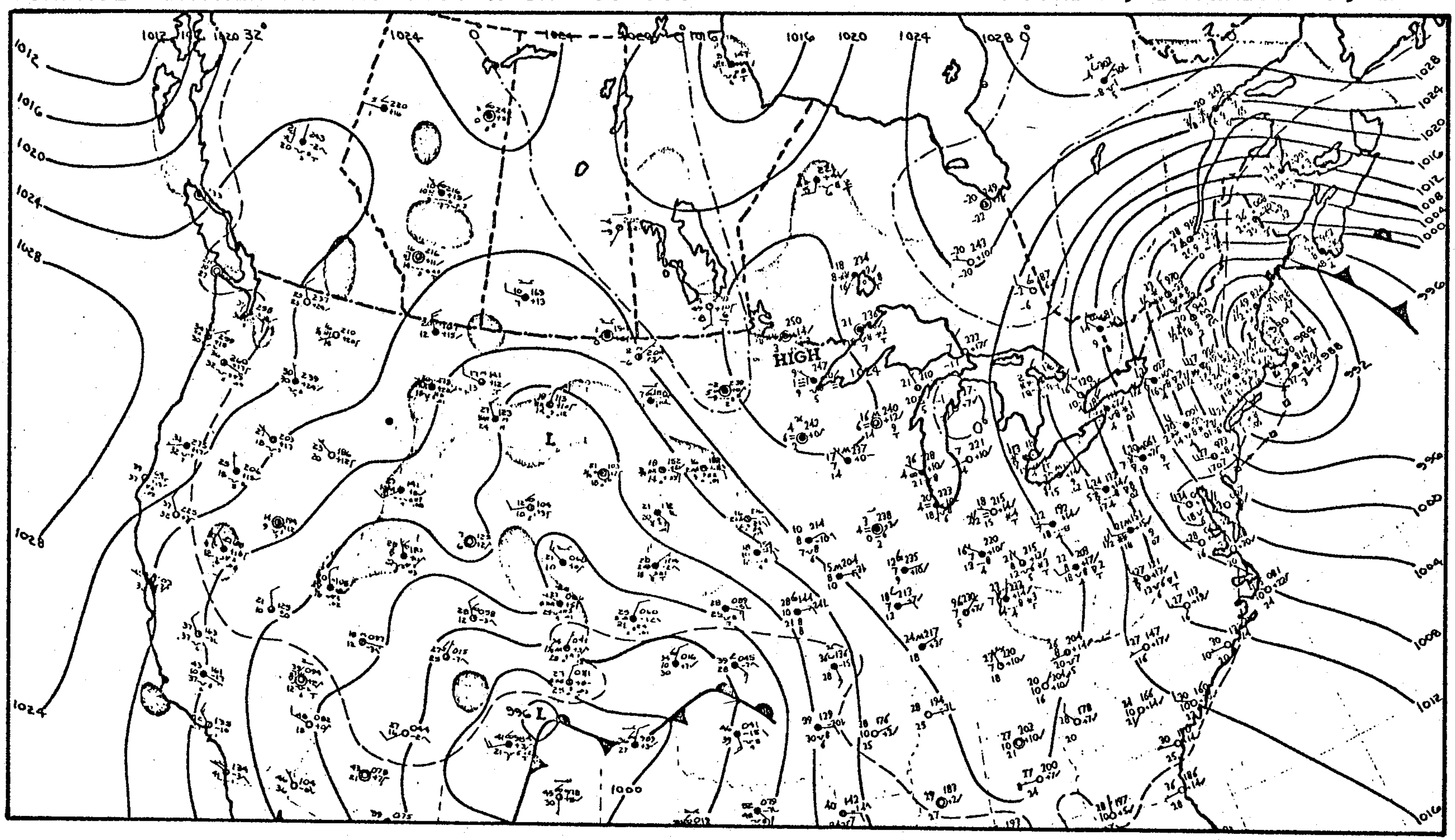


Table 4.11

Synoptic Conditions During Decay Period of

Case 21

Time (Hours)	Lapse Rate (°F/1000')[35-200']	Lapse Rate (°F/1000')[35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
0400	-37.3	-21.3	170	8	170	22	14	-7.2	-1.0	9.3	2	Cl	26.0	1023.3	A	12	0		
0500	-36.5	-22.2	170	9	180	26	17	-7.6	-1.6	9.6	2	Cl	26.0	1023.7	A	12	0		
0600	-36.2	-25.2	160	7	190	22	15	-8.1	-2.1	11.5	2	Cl	26.0	1023.9	A	15	0		
0700	-25.0	-24.5	150	8	190	20	12	-8.2	-4.1	10.8	3	Cl	26.0	1023.7	A	10	0		
0800	-30.1	-25.3	150	8	190	19	11	-8.8	-3.8	10.8	6	Fog,ST,Cl	0.3-26.0	1024.0	A	04	0		
0900	-6.1	-21.7	150	7	180	20	13	-6.6	-5.6	10.2	10	Fog,ST	0.2	1024.8	A	04	0		
1000*	-12.4	-21.7	150	7	190	18	11	-5.4	-3.4	11.4	10	Fog,ST	0.3	1025.4	A	04	0	00	8.1
1100	0.1	-17.7	160	9	200	13	4	-3.6	-3.7	10.2	10	Fog,ST	0.3	1025.5	A	04	0		
1200	1.2	-17.0	150	6	200	13	7	-2.0	-2.2	11.1	7	Fog,ST	0.3	1025.6	A	04	0		
1300	-1.3	-17.0	160	6	200	12	6	-0.8	-0.6	12.4	9	Fog,ST,Cl	0.3-26.0	1025.3	A	04	0		

*Inversion decayed at 1000 hours in the 35-200 feet layer.

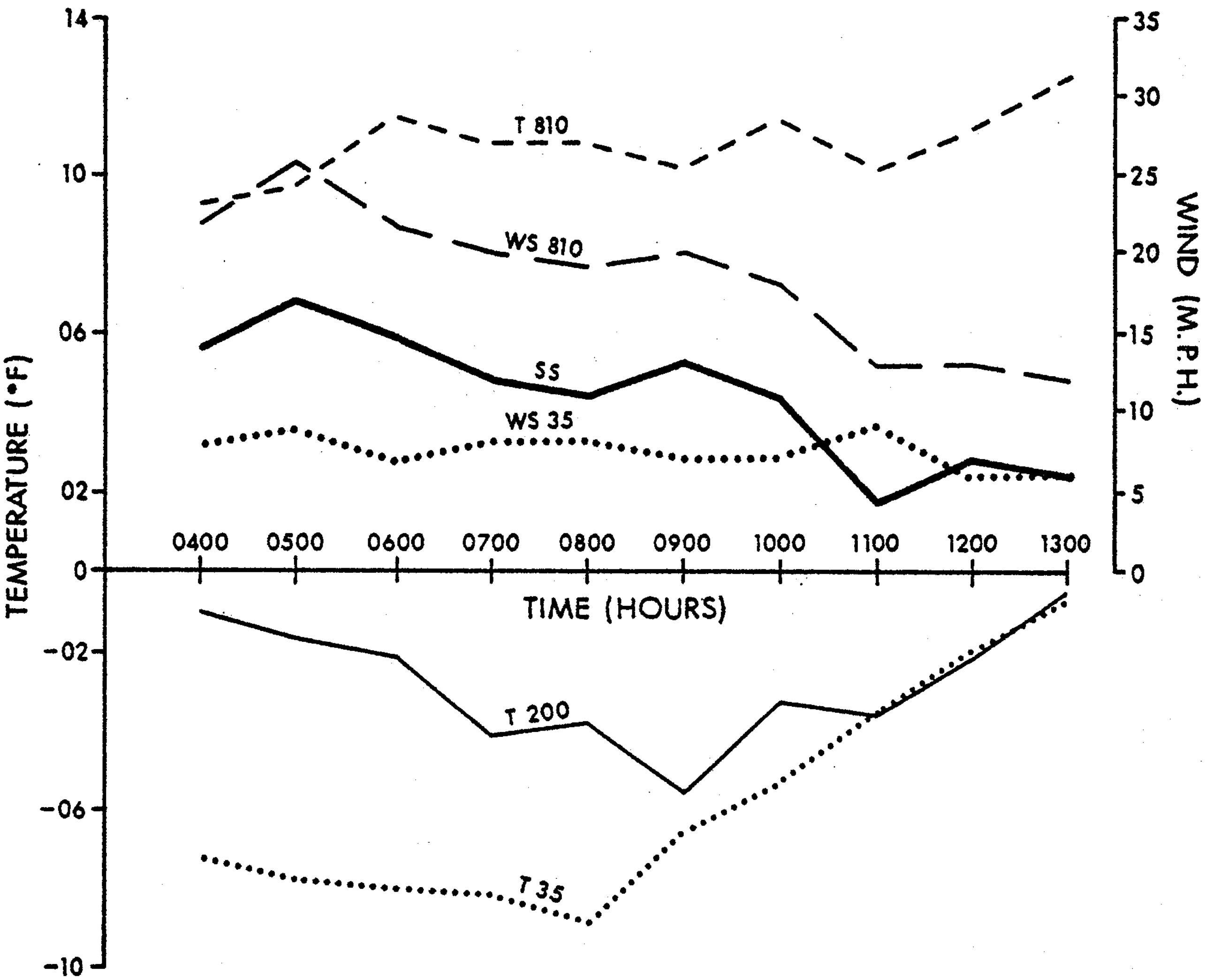
stagnant air radiative fogs often form. After sunset the earth's surface loses heat and cools below the air temperature. Heat is therefore transferred from the overlying air to the surface. The water vapour pressure of the air does not change at first, but when the temperature of the surface layer drops below the dew point, condensation of the water vapour begins (Amelin, 1967, p. 101). This process likely accounted for the fog formation from 0800 hours.

With the clouding-over, longwave radiation from the surface is re-radiated back downwards. Net longwave radiation exchange is a simple function of temperature difference between ground and cloud. If the cloud base temperature is greater than that of the ground the snow surface will experience a net heat gain. This physical process produces radiative warming of the snow surface (Oke, 1970, p. 81).

The temperature profile (Figure 4.17) demonstrate that the above process took place in the lower 200 feet. In the decay period, temperature at the 35 feet level continually increased by 8.0°F from 0800 hours. One hour later, the 200 feet level acted similarly but for a smaller amplitude of 5.0°F. Initially, temperature at the former level was lower than that at the latter. Energy was therefore radiated downwards until an almost

Figure 4.17

Temperature and Wind Variations During Decay Period of Case 21



T — Temperature at 3 Levels (feet)
WS — Wind Speed at 2 Levels (feet)
SS — Speed Shear

isothermal layer was formed with both the surface and the fog top radiating equally. During this process the thermal structure changed towards a more unstable condition; and the 35-200 feet layer inversion of Case 21 decayed at 1000 hours.

A two layer temperature structure was implemented by the low layer cloud cover. With warm southerly air advecting at the 810 feet level, sharp temperature differences existed between this level and the 200 feet level. Temperature differences of greater than 10.0°F were observed. The 35-810 feet layer inversion continued to persist until 1700 hours when data became missing.

Williamson (1973, p. 181) reported that since the upper layers of fog (also stratus clouds) radiate their energy into the air above, the top layers of the fog cool with respect to the overlying air, and an elevated inversion is thus formed. This stable layer acts as a lid to confine the fog and its burden of pollutants.

4.4.2. (b) Inversion Case 20

Nine hours of positive lapses in the 35-200 feet layer preceded the development of inversion Case 20 at 1800 hours. After a 19-hour duration it decayed at 1200 hours. With a one hour lag to the above times, the associated 35-810 feet layer inversion correspondingly developed and decay. The structural behaviour of this inversion follows the pattern predicted by the model (Ch. 2). In fact, the actual times of development and decay of this inversion are practically the same as the times of greatest average frequency of development and decay.

4.4.2. (b) (1) Development of Case 20

On the development day (February 20), a broad, weak high pressure area stretched across the southern portion of the prairie provinces. Eastward advancing Maritime Polar westerly air, in combination with a northward flow of Gulf air, excluded Arctic air from the southern prairies (Figure 4.18). With the Arctic front well to the north, Winnipeg's weather was described as -- "Above normal temperatures. Mostly sunny with light winds" (Atmos. Environ. Service, Monthly Meteor. Summary, 1971).

This weather situation was favourable to the formation of nocturnal radiative type inversions. Meteorologists expect clear skies and light winds at night to favour inversions of radiative and nocturnal origin.

In the development period from 1200 to 2100 hours (Table 4.12), pressure fell initially and then gradually

FIGURE 4.18

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT OF INVERSION CASE 20

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. SATURDAY, FEBRUARY 20, 1971

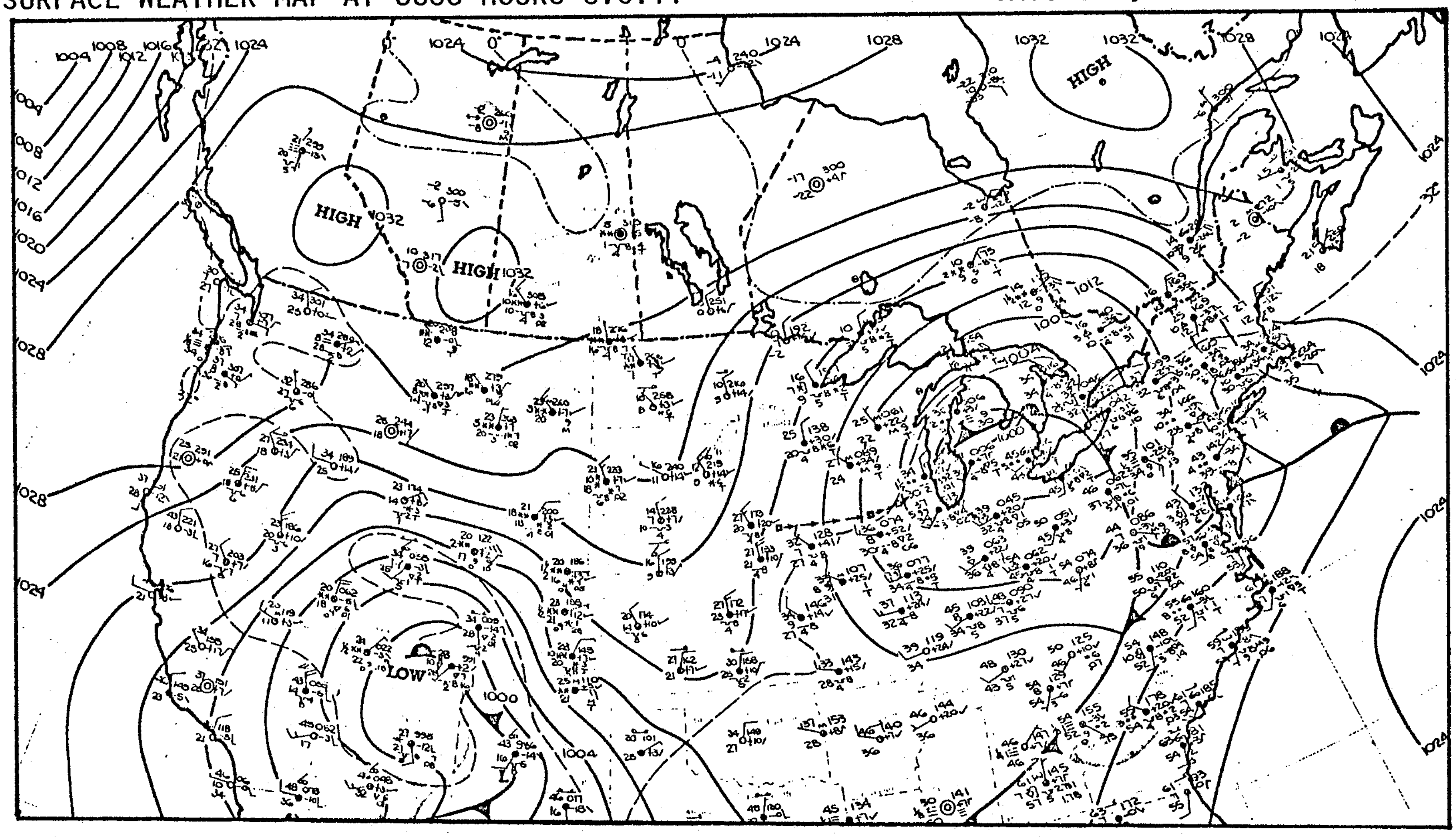


Table 4.12

Synoptic Conditions During Development Period of Case 20

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
1200	10.0	2.6	340	16	350	21	5	11.4	9.8	9.4	6	AC,Cl	15.0-27.0	1027.6	A	15	6		
1300	8.4	5.6	330	16	340	22	6	14.2	12.8	9.9	7	AC,Cl	15.0-27.0	1027.2	A	15	10		
1400	8.7	5.9	340	16	340	23	7	16.4	14.9	11.8	3	AC,Cl	15.0-27.0	1026.9	A	15	10		
1500	7.7	5.9	330	15	330	21	6	17.1	15.8	12.5	2	AC,Cl	15.0-27.0	1026.8	A	15	10		
1600	6.0	5.3	340	14	340	23	9	17.6	16.6	13.6	1	Cl	27.0	1026.8	A	15	10		
1700	3.5	4.4	320	15	330	22	7	16.4	15.8	13.0	3	Cl	27.0	1027.4	A	15	9	8.9	10.4
1800*	-7.9	0.3	310	11	330	20	9	13.5	14.8	13.2	2	Cl	27.0	1027.7	A	15	0		
1900*	-14.7	-3.6	320	12	350	21	9	10.8	13.3	13.6	2	Cl	27.0	1027.7	A	15	0		
2000	-17.4	-6.5	320	10	360	17	7	8.8	11.6	13.8	0	None	----	1027.8	A	15	0		
2100	-26.3	-8.2	310	11	350	18	7	7.2	11.6	13.6	0	None	----	1028.3	A	15	0		

*Inversion developed at 1800 hours in the 35-200 feet layer and at 1900 hours in the 35-810 feet layer.

rose by 1.5 m.b. from 1600 hours. The general direction of wind movement was north-westerly at both the 35 and 810 feet levels. These winds, particularly those at the lower level, reduced in speed with the approach of the development hour. Speed shear, at an average 8 m.p.h., was moderate. Low sky obscurity of less 3/10th's cover from 1500 hours was mainly of the Cl cloud type at 27,000 feet.

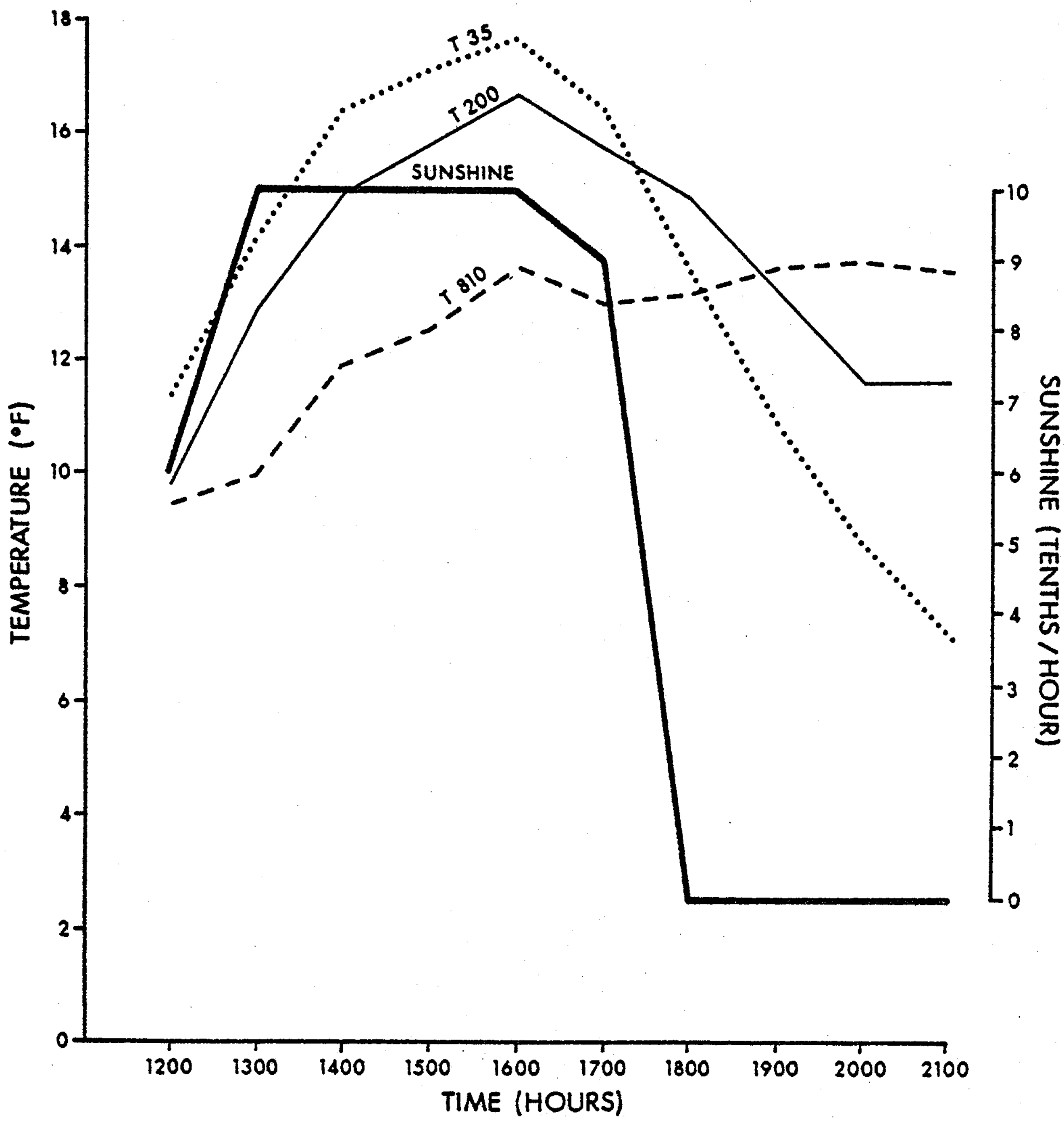
A striking feature of Case 20, when compared to the other cases studied thus far, is its high temperature. Out of a possible 10.4 hours of sunshine, the development day received 8.9 hours, most of which occurred between 0900 and 1600 hours. The temperature changes (Figure 4.19) indicate a strong relation with the sunshine record.

At all three levels temperature increased as long maximum hourly sunshine was received. The 35 feet level temperature increased by 6.2°F until 1600 hours, after which time a sharp 10.4°F cooling occurred. Similar temperature variations were observed at the 200 feet level, but the decrease was of a lesser magnitude. At the 810 feet level, temperatures rose by 4.2°F to 13.6°F at 1600 hours, after which, temperature virtually remained constant.

The cyclical diurnal effects of solar radiation

Figure 4.19

Temperature and Sunshine Variations During Development Period of Case 20



T – TEMPERATURE AT 3 LEVELS (FEET)

heating and longwave radiation cooling is the important control of the inversion structure during development. Cold north-westerly air was heated from below by the radiatively heated surface. However as the sun angle lowered, the surface and adjacent air layer cooled quickly through outward radiation under low sky obscurity. At the time of sunset (1700 hours), a 3.0°F fall in temperature was noted at the level nearest the surface. The inversion developed in the 35-200 feet layer at 1800 hours. The 35-810 feet layer inversion developed one hour later, as temperature at the 35 feet level continued to fall sharply while at the 810 feet level it virtually stabilized.

4.4.2. (b) (2) Decay of Case 20

On the decay day (February 21), a broad, weak high pressure area (1028 m.b.) that stretched across the Great Plains and the Midwest influence the weather scene in southern Manitoba. A minor trough located over southern Alberta drifted eastward (Figure 4.20). With the Arctic front to the north, Winnipeg's weather was described as -- "Mild and sunny with light winds" (Atmos. Environ. Service, Monthly Meteor. Summary, 1971).

Table 4.13 presents the hourly synoptic conditions for a decay period from 0600 to 1500 hours. Though

FIGURE 4.20

SYNOPTIC SITUATION ON DAY OF DECAY OF INVERSION CASE 20

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. SUNDAY, FEBRUARY 21, 1971

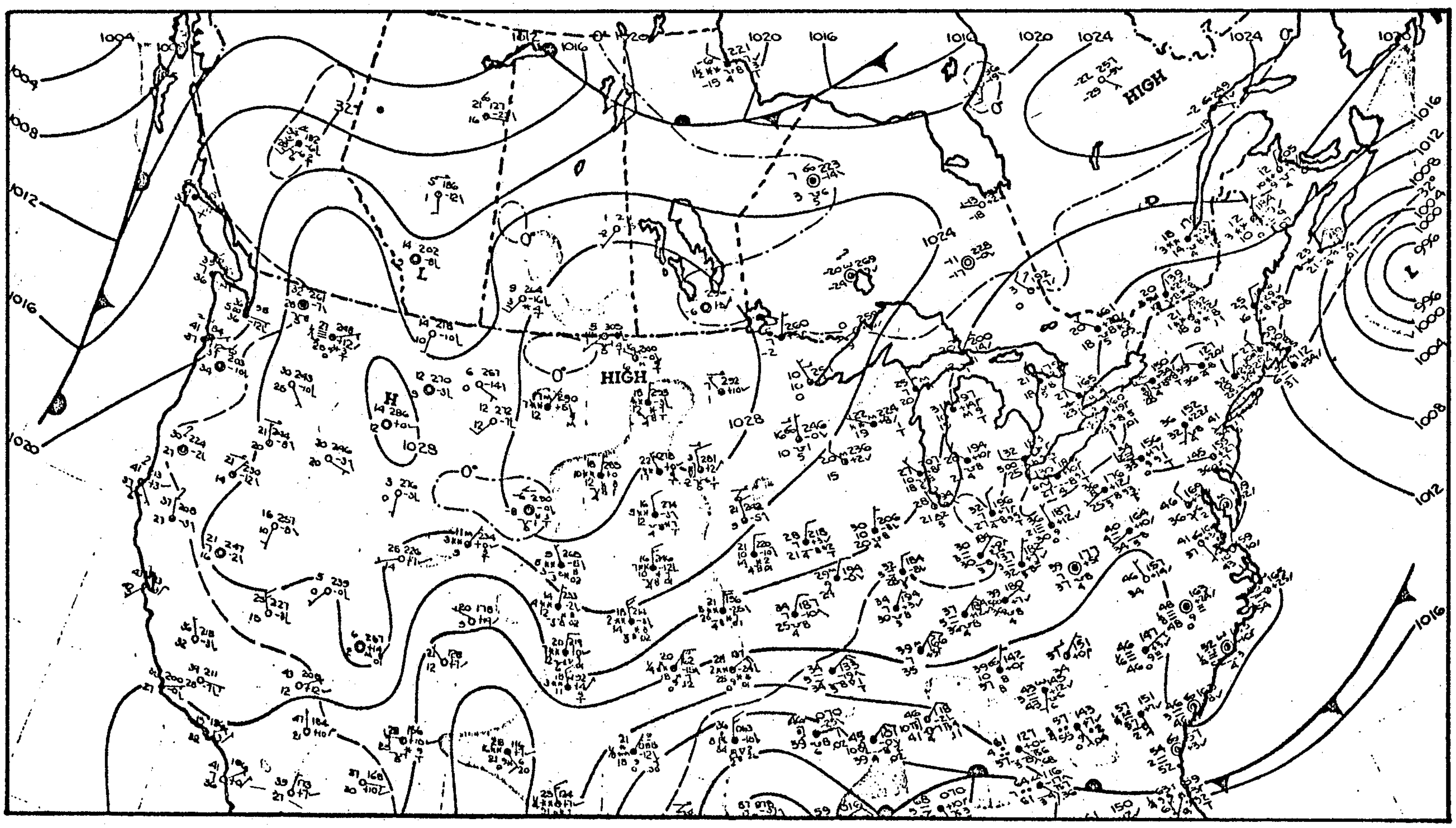


Table 4.13

Synoptic Conditions During Decay Period of

Case 20

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate [°F/1000'] [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (tenths)	Cloud Type	Cloud Height (feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (tenths)	Sunshine Daily Total (hours)	Sunshine Total Possible (hours)
0600	-44.4	-13.2	---	-	320	10	-	1.6	8.9	11.8	0	None	---	1029.6	A	15	0		
0700	-43.4	-11.9	280	6	330	11	5	3.4	10.6	12.6	0	None	---	1029.6	A	15	0		
0800	-39.8	-11.2	290	7	310	11	4	4.1	10.7	12.8	3	ST	0.1	1029.8	A	15	0		
0900	-38.5	-9.7	290	5	300	9	4	4.9	11.2	12.4	0	None	---	1030.5	A	15	0		
1000	-31.1	-9.7	---	-	320	6	-	6.5	11.6	14.0	0	None	---	1030.5	A	15	2		
1100	-0.3	-6.4	---	-	---	-	-	9.5	9.6	14.5	0	None	---	1030.4	A	15	10	7.3	10.4
1200*	-8.4	-3.8	---	-	---	-	-	11.8	13.2	14.8	0	None	---	1029.8	A	15	10		
1300*	4.7	-0.4	190	6	220	8	2	14.8	14.0	15.1	1	SC	1.0	1029.7	A	15	10		
1400	3.7	1.7	190	8	210	8	0	17.3	16.7	16.0	1	SC	1.0	1029.2	A	15	10		
1500	2.9	3.2	200	9	210	9	0	18.7	18.2	16.2	0	None	---	1028.6	A	15	10		

*Inversion decayed at 1200 hours in the 35-200 feet layer and at 1300 hours in the 35-810 feet layer.

some of the wind data are missing, it appears that an exchange in airflows took place around the decay time. At the 35 feet level southerly replaced westerly winds, whereas at the higher 810 feet level south-westerly replaced north-westerly winds. Wind speed and speed shear were slight, with neither exceeding 11 m.p.h. Initially pressure rose to 1030.5 m.b. at 1000 hours after which time it gradually fell. Sky obscurity was low with less 3/10th's cloud cover.

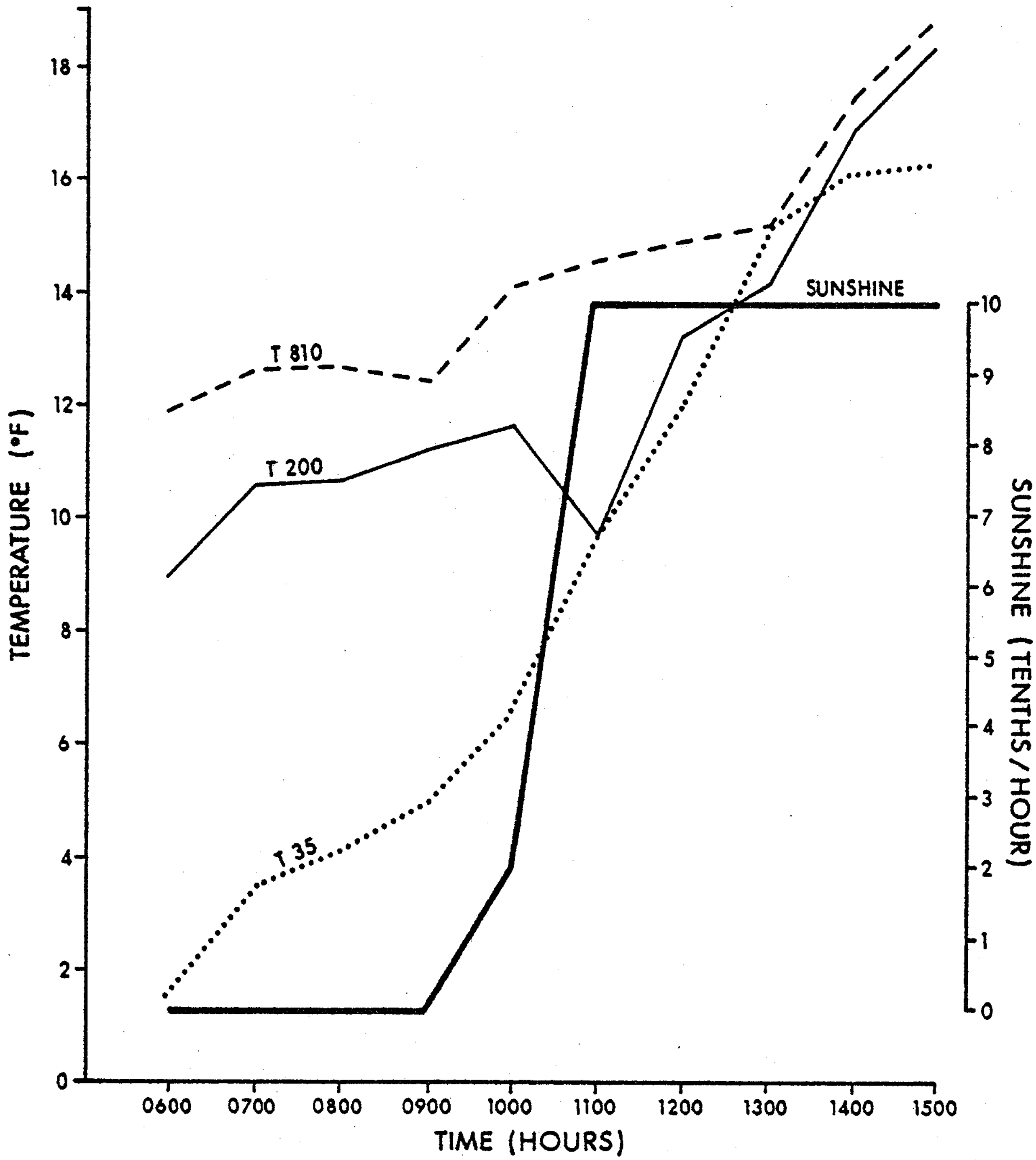
On the decay day 7.3 hours of sunshine were recorded out of a possible 10.4 hours. Seven consecutive hours of maximum hourly sunshine were received from 1100 to 1700 hours.

In the decay period, a steep, continuous warming of 17.0°F was observed at the 35 feet level. The 200 feet level temperature behaved similarly, except for an irregularity at 1100 hours. After a 2.7°F increase, this hour experienced a 2.0°F fall in temperature, after which a continuous 8.6°F increase occurred. A regular temperature increase of 4.4°F throughout the period was exhibited at the 810 feet level.

The temperature changes (Figure 4.21) are the integrated result of radiation and exchange in airflow types. Though air temperatures increased markedly during the period of sunshine, especially at the lowest level,

Figure 4.21

Temperature and Sunshine Variations During Decay Period of Case 20



T – TEMPERATURE AT 3 LEVELS (FEET)

warming was initiated well before the sunshine commenced. Moreover, analysis detected (see Section 4.2.2) that the 810 feet level is less significantly influenced by the diurnal effects of solar radiation heating since convective mixing is a slow process.

Based on the above results it is proposed that, the decay structure of the inversion was significantly controlled by solar radiation heating, and the interchange in airflow types contributed in the decay process. The inversion in the 35-200 feet layer decayed at 1200 hours and with a lag of one hour the 35-810 feet layer inversion decayed.

4.4.3 Summary

At the outset of this investigation the structural behaviour of Cluster 7 inversions during development and decay appeared by the haphazard. This cluster was regarded as transitional between the radiative and advective cluster groups. Perceived in this framework, it is possible to better appreciate the variations in the structural behaviour of the inversion cases analyzed as they responded to different weather processes.

The inversion cases studied indicate that the structural behaviour of Cluster 7 inversions are controlled by both radiative and advective processes. Depending on the synoptic situation, these processes may function individually and/or collectively in determining the inversion structure.

When the advective process is operating, diurnal temperature variations are irregular. The temperature stratification is largely a function of changes in synoptic conditions associated with airflows of contrasting properties. Under this circumstances, the 35-810 feet layer inversion develops shortly before and decays long after the 35-200 feet layer inversion.

Solar radiation heating occurs at the surface first, and its effects gradually penetrate upwards. The diurnal effects are significant when the lower inversion develops and decays before the higher inversion. A lag of one hour is involved. However, as the boundary layers at higher elevations are less significantly affected by radiation processes, an important contribution is made by advective processes in the inversion structural behaviour.

CHAPTER V

Structural Behaviour of Inversions in the Advective Clusters

5.1 Introduction

Basically, the same analytical approach and method used in the preceding chapter, are employed in the investigation of the structural behaviour of inversions in the advective clusters during their development and decay. Once the structure of the inversion case is identified with a synoptic situation, an attempt is then made to assess the results in terms of weather processes. In the assessment of related weather processes, greater emphasis is placed on the roles of airflow type and character of the wind speed profile.

An important factor influencing lapse rate character arises from advective heating and cooling induced by air mass movement. Advective processes may be a particularly important cause of temperature change at Winnipeg because of its 50° parallel situation in the interior of a continent, its location within the gently undulating Great Plains, and its proximity to the common position of the Arctic front in winter (Bryson, 1966).

In a wider geographical and climatological context, Hare and Thomas (1974) stressed the importance to Canada's climates of atmospheric advection by the variable westerly wind systems that import and export heat and moisture from the oceans. This causes the products of the local energy balance to be redistributed, and consequently make large differences to local climates.

The frequent exchange of migrating weather systems embedded in the westerlies can cause lapse rates to vary considerably both spatially and temporally. Generally speaking, according to Bell (1974), it is expected that in winter at Winnipeg warm westerly, southwesterly and southerly air that crosses over flat snow covered arable land would favour strong advective inversions. This arises because these winds are moving from a warmer source region into progressively colder areas and frequently circulate in low pressure features, thereby acquiring cyclonic rotation and uplift.

The model (Ch. 2) was formulated irrespective of the irregular component of diurnal temperature variation induced through advective influences. It is therefore conceivable that the model may be less readily applicable to the study of inversions in the advective clusters. It should be borne in mind however, that most advective inversions are acted upon by nocturnal radiation.

Analysis determined that the diurnal cyclical component of solar radiation heating is the salient control of inversion structures in the radiative Cluster 2. As cluster distance increased (variegated shades) from this cluster, the diurnal effects became increasingly less conspicuous (see Ch. 4). In this perspective, a similar relation to the structural behaviour of inversions is anticipated in the advective clusters. Briefly stated, this means that atmospheric advection may be the most important control of inversion structures in Cluster 1. This process is modified and punctuated by other meteorological parameters in the context of the structural behaviour of Cluster 8 inversions, and especially so, for the labelled transitional Cluster 3.

5.2 Cluster 1

5.2.1 Preliminary Remarks

Of the advective clusters, Cluster 1 is distinctive. Its distinctiveness is apparent in that it has the longest duration, highest wind speed, wind shear, pressure and especially temperature (Ch. 3). Averages of these properties are presented for each of five inversions in Cluster 1 in Table 5.1. This cluster includes 25 per cent of the inversions in the advective group. Of these, two are assembled in each of the winter months December and

Table 5.1

Average Properties of Inversion Cases in Cluster 1

Case Number	Date	Development Hour	Inversion Duration (Hours)	Decay Hour	Inversion Intensity (°F/1000')	Sky Obscurity (Tenths)	Temperature (°F)	Pressure (m.b.)	Wind Speed (m.p.h.)	Wind Shear (m.p.h./x feet)	Wind Direction
1	Jan. 29'70	1600	42	0900	-17.4	4.1	19.2	1008.7	14.0	18.1	SW
2	Dec. 16'69	1600	38	0500	-23.5	5.4	21.7	1018.1	9.9	14.6	S
7	Feb. 21'70	1200	26	1300	-26.8	0.9	27.2	1019.1	15.4	23.0	N
10	Feb. 22'70	1500	24	1400	-40.7	0.7	25.0	1020.5	13.6	20.5	SW
12	Dec. 1'71	1400	23	1200	-29.7	1.5	19.0	1027.5	14.9	16.2	SW

February. The other case occurred in the latter part of the coldest month January.

All the inversions were of duration not less than 20 hours. They developed in the period from 1200 to 1600 hours and decayed between 0500 and 1400 hours. The stronger, persistent inversions lasting at least 30 hours (2 cases), developed at the latest time 1600 hours but decayed early at 0500 and 0900 hours. These inversions, therefore, are not well-adapted to the main features of the model described in Ch. 2.

The structures of Cluster 1 inversions may be divided into two classes. The longer duration inversions (not less than 30 hours) developed some two to three hours earlier in the 35-200 feet layer than in the 35-810 feet layer. Both layer inversions decayed simultaneously. It is noticed, that, unlike the persisting lower inversions, the accompanying higher inversions were irregularly interrupted for brief one hour periods.

The other three cases exhibited structures similar to that ascertained for Cluster 2. That is, the lower layer inversions developed after and decayed before their higher layer counterparts. As two of the lower inversions occurred in proximity, they were encompassed in a higher inversion of duration 61 hours. The other case was encompassed in a higher inversion that persisted for an unusually long period of 138 hours.

5.2.2 Selected Inversion Cases

Inversion Cases 2 and 12 are chosen for detailed analysis of development and decay structures. The former case represents the class of inversions lasting not less than 30 hours. It developed at 1600 hours in the 35-200 feet layer and three hours later in the 35-810 feet layer. Both layer inversions decayed simultaneously in the early morning at 0500 hours. The latter case represents the class of the other three inversions. This 23-hour duration inversion, developed at 1400 hours and decayed at 1200 hours in the 35-200 feet layer. The associated 35-810 feet layer inversion lasted 138 hours, developing long before and decaying long after the 35-200 feet layer inversion.

5.2.2. (a) Inversion Case 2

This inversion case clearly demonstrates that the model (Ch. 2) cannot satisfactorily account for the structural behaviour of all winter inversions lasting not less than 10 hours. The irregular component of diurnal temperature variation, through the agency of advective heating and cooling induced by air mass movement, is dominant. The structural development and decay of inversion Case 2 are related to the atmospheric process of advection.

After four hours of positive lapses in the 35-200 feet layer, an inversion developed in this layer at 1600 hours. Three hours later the associated 35-810 feet layer developed. The inversion case was maintained for 38 hours, and decayed simultaneously in both layers at 0500 hours. For the balance of that day positive lapses were established.

A prominent feature of the accompanying higher inversion was its brief, temporary one hour decay at 1400 hours. Even if this break in continuity is disregarded, the higher inversion lasted for a comparatively short period of 35 hours.

5.2.2. (a) (1) Development of Case 2

The Atmospheric Environment Service, described Winnipeg's weather on development day as -- "Mild. Cloudy late morning to late evening. Very light flurries 10 a.m. to 4 p.m." (Monthly Meteor. Summary, Dec. 16, 1969). Attention is drawn to the now commonly observed relation between snowfall and lapse rate character. As snowfall ended the lower inversion developed, but the higher inversion did not form until three hours later.

This weather was connected with the passage of an

Alberta low slightly to the north of Winnipeg. This depression was associated with Maritime Polar (mP) westerly airflow that had crossed the southern British Columbia coast and moved inland via southern Alberta. Frontal disturbances accompanied this cyclonic wave circulation system (Figure 5.1).

According to Matthewman (1955, p. 15), the identification and location of frontal boundaries may be uncertain and arbitrary because modification of air temperatures near the surface presents some difficulty in deciding the most probable location of frontal zones.

Hourly synoptic conditions for a development period from 0500 to 2000 hours are displayed in Table 5.2. The period began with the backing of fairly strong southerly winds while a warm frontal surface crossed Winnipeg from 0600 to 0900 hours. Pressure though falling, practically stabilized at 1013.8 m.b. Low sky obscurity gave way to overcast skies of the SC cloud type at roughly 2,000 feet from 0600 hours.

As the frontal boundary crossed, the wind veered, and a westerly flow became dominant in the lowest 810 feet. Wind speed at the 35 feet level reduced slightly to less than 18 m.p.h., while high speeds of 27-40 m.p.h. were maintained at the 810 feet level. As is expected from such speed differences, speed shear was high.

FIGURE 5.1

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT OF INVERSION CASE 2

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. TUESDAY, DECEMBER 16, 1969

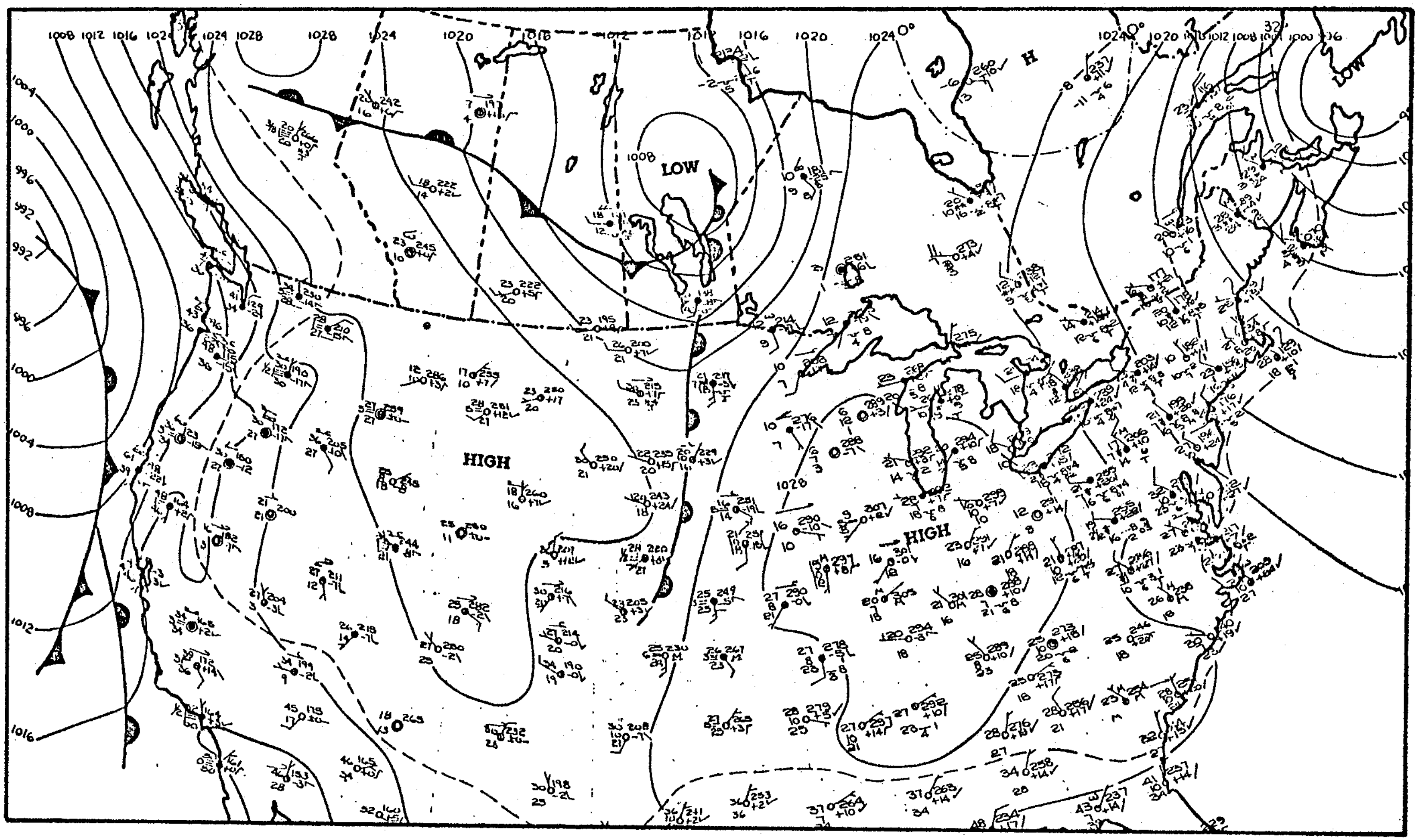


Table 5.2

Synoptic Conditions During Development Period

of Case 2

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (Tenths)	Cloud Type	Cloud Height (Feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (Tenths)	Sunshine Daily Total (Hours)	Sunshine Total Possible (Hours)
0500	-26.5	-21.8	190	16	240	35	19	15.2	19.6	32.1	1	SC	2.5	1014.2	A	12	0		
0600	-16.9	-17.5	190	20	240	37	17	19.2	21.9	32.8	9	SC	2.6	1013.8	A	12	0		
0700	-23.7	-10.4	210	18	250	40	22	24.6	28.5	32.7	10	SC	2.0-3.1	1013.8	A	15	0		
0800	-19.2	-7.6	210	12	260	31	19	25.8	29.0	31.7	8	SC	3.0-3.1	1013.8	A	15	0		
0900	-2.4	2.0	280	13	260	28	15	32.2	32.6	30.7	9	SC	2.6-4.3	1014.3	A	15	0		
1000	-1.0	2.9	280	16	270	34	18	33.6	33.7	31.3	10	SC	2.6-3.4	1014.4	P	15	0		
1100	-0.5	3.5	270	13	260	27	14	33.4	33.5	30.7	10	SC	2.8-3.4	1014.8	P	15	0	0.0	8.1
1200	1.3	4.0	270	17	260	34	17	34.3	34.1	31.1	9	SC	2.4-3.4	1014.3	P	15	0		
1300	2.3	4.3	270	18	260	36	18	34.3	33.9	30.9	9	SC	2.4	1014.1	P	15	0		
1400	1.5	3.9	270	15	260	35	20	33.5	33.2	30.4	10	SC	1.8	1014.3	P	12	0		
1500	1.1	3.4	280	18	270	40	22	32.7	32.5	30.0	10	SC	1.7-2.6	1015.1	P	12	0		
1600*	-0.5	3.2	280	11	280	29	18	32.0	32.1	29.5	9	SC	1.9-2.6	1015.7	A	15	0		
1700	-1.2	2.6	280	12	270	32	20	31.4	31.6	29.4	9	SC	1.9-2.6	1016.1	A	15	0		
1800	-2.0	2.0	260	12	270	33	21	30.5	30.8	29.0	9	SC	3.1	1016.4	A	15	0		
1900*	-17.5	-2.4	250	11	280	35	24	27.6	30.5	29.4	9	SC	2.8	1016.4	A	15	0		
2000	-37.0	-2.8	230	9	270	36	25	23.1	29.3	29.4	8	SC	3.1	1016.7	A	15	0		

*Inversion developed at 1600 hours in the 35-200 feet layer and at 1900 hours in the 35-810 feet layer.

Pressure rose gradually by 2.4 m.b. from 0900 hours. Sky obscurity remained unaltered, and snow flurries started at 1000 hours. As the latter event concluded at 1500 hours, the wind subsided to less than 13 m.p.h. at the lower level, and the inversion developed in the 35-200 feet layer.

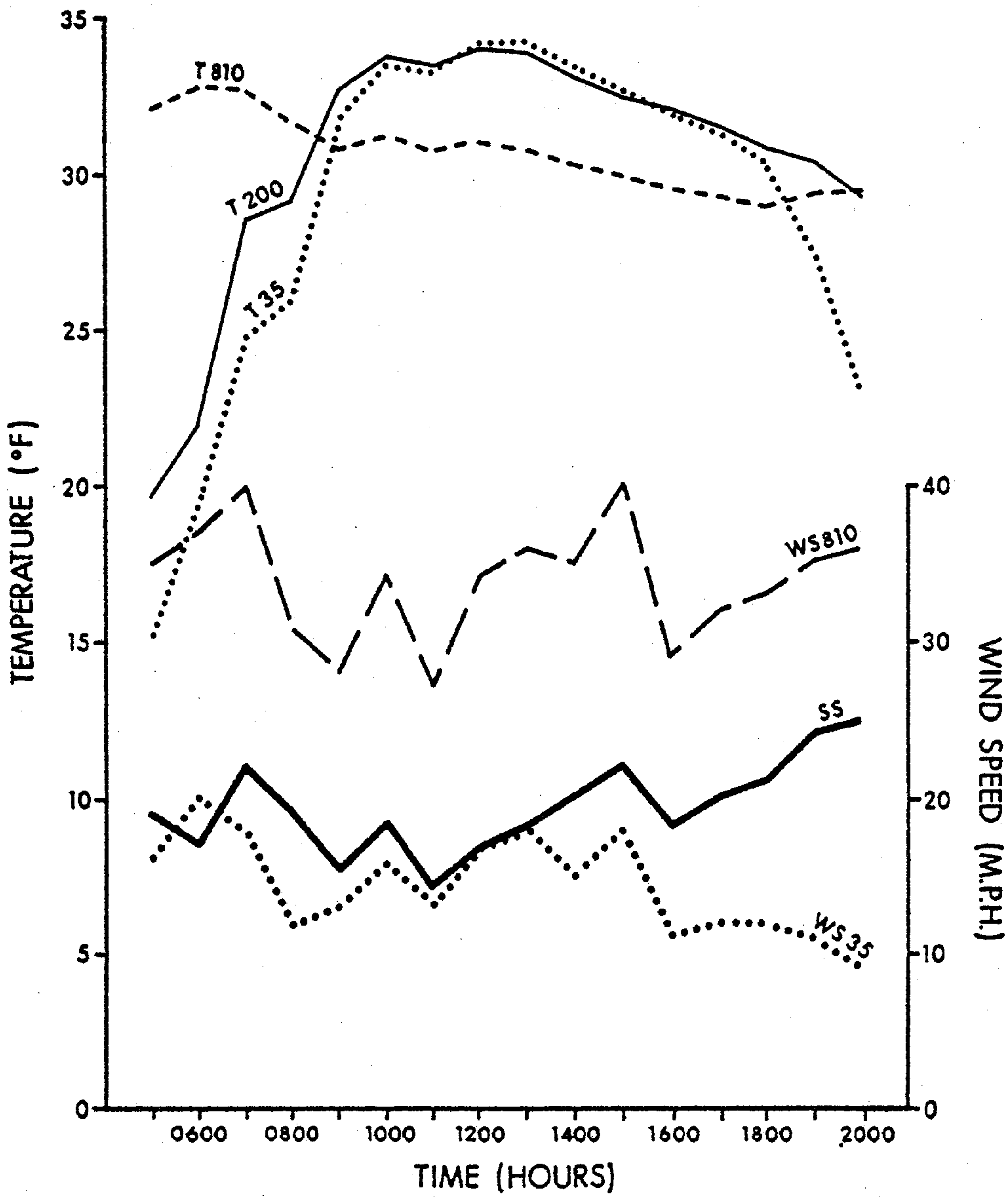
No sunshine was recorded on the development day. Temperature stratification is shown in Figure 5.2 and apparently responded to advective influences and the sequence of weather associated with passage of the Alberta low.

During the period of frontal passage from 0500 to 0900 hours, temperatures at the two lower levels increased pronouncedly. A rapid 17.0°F warming at the 35 feet level, with a 13.0°F warming at the 200 feet level, were observed. The 810 feet level temperatures indicated a cooling trend which amounted to roughly 1.0°F.

Once the frontal surface had passed through, lapse rates became positive. This happened first in the higher layer at 0900 hours, and with a lag of three hours the lower layer followed. Temperature continued to increase but slightly in the lower 200 feet until about 1300 hours. Thereafter, it decreased. The decrease was especially sharp from 1800 hours at the lowest level. The 810 feet level lacked a systematic temperature trend as

Figure 5.2

Temperature and Wind Variations During Development Period of Case 2



T – Temperature at 3 Levels (feet)
WS – Wind Speed at 2 Levels (feet)
SS – Speed Shear

temperatures varied over a narrow 2.3°F range in the development period. An interesting feature observed at this level was the virtual stabilization of temperature around 29.4°F from the time snow flurries ended.

Warm westerly air advecting over freshly fallen snow undergoes rapid cooling from below. Most of the advective heat is transported downwards towards the snow surface in the form of sensible and latent heat fluxes. Treidl (1970, p. 165) reported that when warm air advects over snow cover of considerable thickness large quantities of heat may be extracted from the air mass by eddy diffusion of heat and water vapour.

The possible loss of sensible heat is determined by the temperature excess of the advective air above the temperature of the surface over which the air is advected, rather than, by its absolute temperature (Vowinckel, 1964, p. 7).

As the warm Maritime Polar westerly air currents passed over the cooler snow surface, downward sensible and latent heat fluxes occurred. The near surface air layer cooled; and the 35-200 feet layer inversion developed at 1600 hours. Williamson (1973, p. 159-160) attributed the formation of ground-based advective inversions to convective cooling of the lowest layer of air as warm air flows over a cold surface.

Three hours later the associated 35-810 feet layer inversion developed at 1900 hours. It is worth emphasizing that one hour prior to development, temperatures at the lowest level commenced to decline sharply. The depth and rate of cooling of the overlying air depends mainly on the horizontal wind speed, the presence of high wind shear, and the vertical temperature gradient.

Wind speed at the lower level subsided to less than 13 m.p.h. from 1600 hours. The horizontal displacement of the warm advecting westerly air thus diminished; that is, it remained longer over a given area. The longer the stay of an air mass over a relatively uniform underlying surface, the more completely it acquires new properties characteristic of the area. The larger the temperature difference between the air and the underlying surface, the faster the air is heated or cooled (Pogosyan, 1965, p. 139).

It is expected that with high wind speeds at the 810 feet level, speed shear would transfer momentum from the level of strong winds to the level of light winds. That is, downwards. Bryers (1959, p. 333) has shown that the amount of mixing or momentum transfer is influenced by the temperature stratification of the lower atmosphere. In the period under survey, the lower air layer cooled sufficiently to form a stable stratum which precluded vertical mixing. Sellers (1965, p. 152) explained that under stable conditions there is relatively little vertical exchange, though turbulence is still present but weak. The momentum of the fast moving air at the higher layers is not easily transferred to the slower-moving layers.

Earlier turbulence which caused mixing of the air in the lowest 810 feet became weaker after 1600 hours. As the lower level wind speed subsided, the depth and rate of cooling of the overlying air increased. While temperatures fell quickly at the 35 feet level due to the downward transport of heat to the cooler surface, air temperatures at the 810 feet level virtually stabilized. This was probably because air situated in the higher layers did not have sufficient time to cool down to the same extent as the air close to the surface. Three hours proceeding Case 2 development in the 35-200 feet layer, the associated 35-810 feet layer inversion developed at 1900 hours.

5.2.2. (a) (2) Decay of Case 2

On the decay day, the Alberta low that had influenced the weather scene on the development day, shifted to the north-east and the depression centre was located over the Hudson Bay. A broad, weak high pressure area associated with a circulation of cool north-westerly air moved eastward to dominate the weather scene (Figure 5.3). Winnipeg's weather was described as -- "Mild. Mostly cloudy with light winds. Very light flurries noon to 5 p.m." (Atmos. Environ. Service, Monthly Meteor. Summary, Dec. 18, 1969).

The hourly synoptic conditions for a decay period from 2100 to 0800 hours (Table 5.3) indicate that from 0300 hours the weather was increasingly influenced by the exchange in synoptic systems.

As the high advanced, pressure rose steadily by 4.4 m.b. from 0200 hours with a sharp change of 1 m.b. at the decay hour. Westerly winds were replaced by north-westerly and the change-over became significant from around 0300 hours. Prior to decay, winds at the 35 feet level were slight (less than 12 m.p.h.) but were strong (greater than 20 m.p.h.) at the 810 feet level. As expected, speed shear was high ranging between 13-23 m.p.h. For the most part, skies were overcast with SC cloud at 1200-1600 feet.

The temperature profile (Figure 5.4) showed rapid shifts in the temperature wave with time and the largest rate of cooling at the highest level. After an initial 5.4°F increase at the 35 feet level, temperature fell by 6.0°F between 0000 and 0400 hours. A few hours of warming

FIGURE 5.3

SYNOPTIC SITUATION ON DAY OF DECAY OF INVERSION CASE 2

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. THURSDAY, DECEMBER 18, 1969

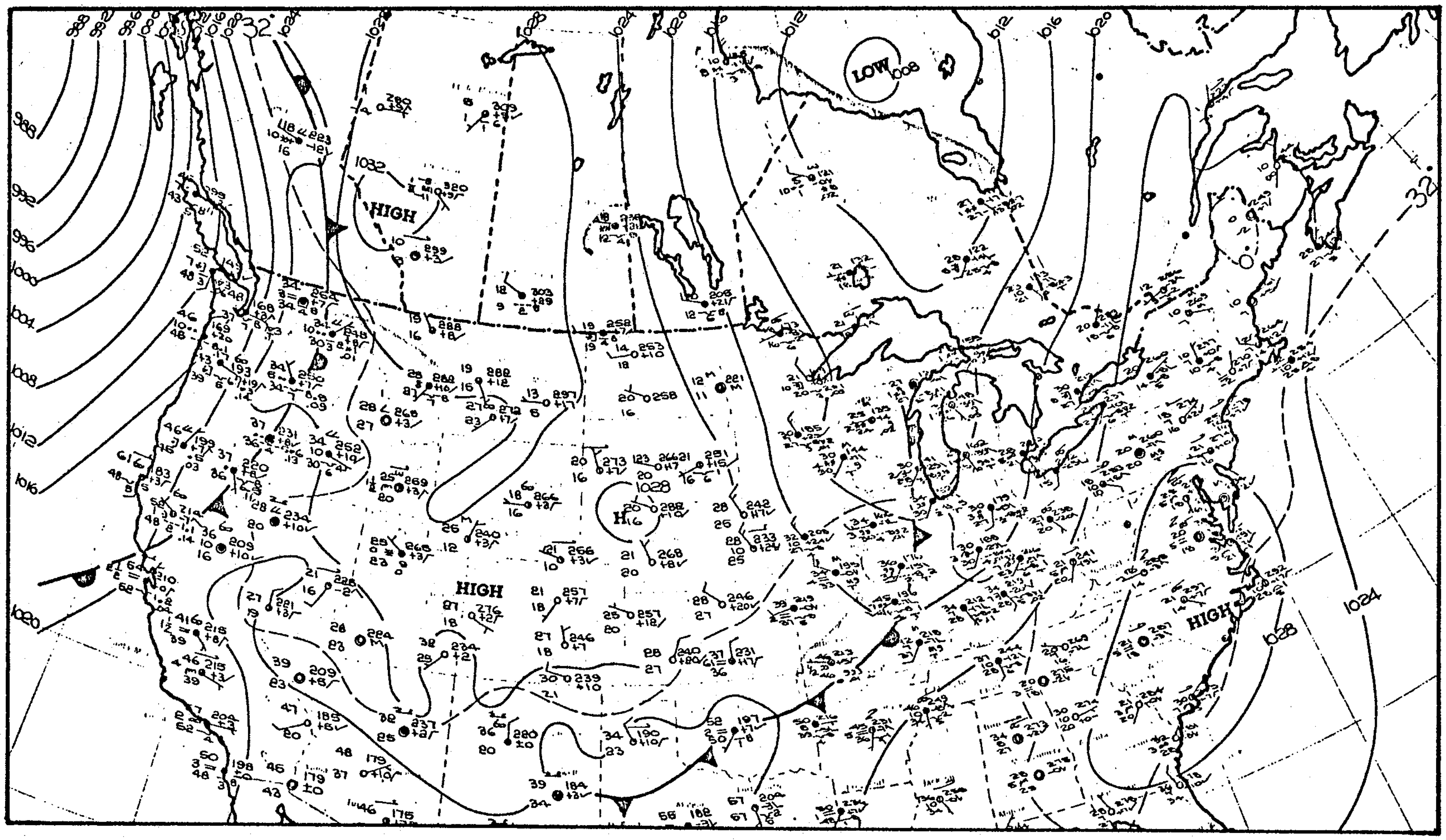


Table 5.3

Synoptic Conditions During Decay Period

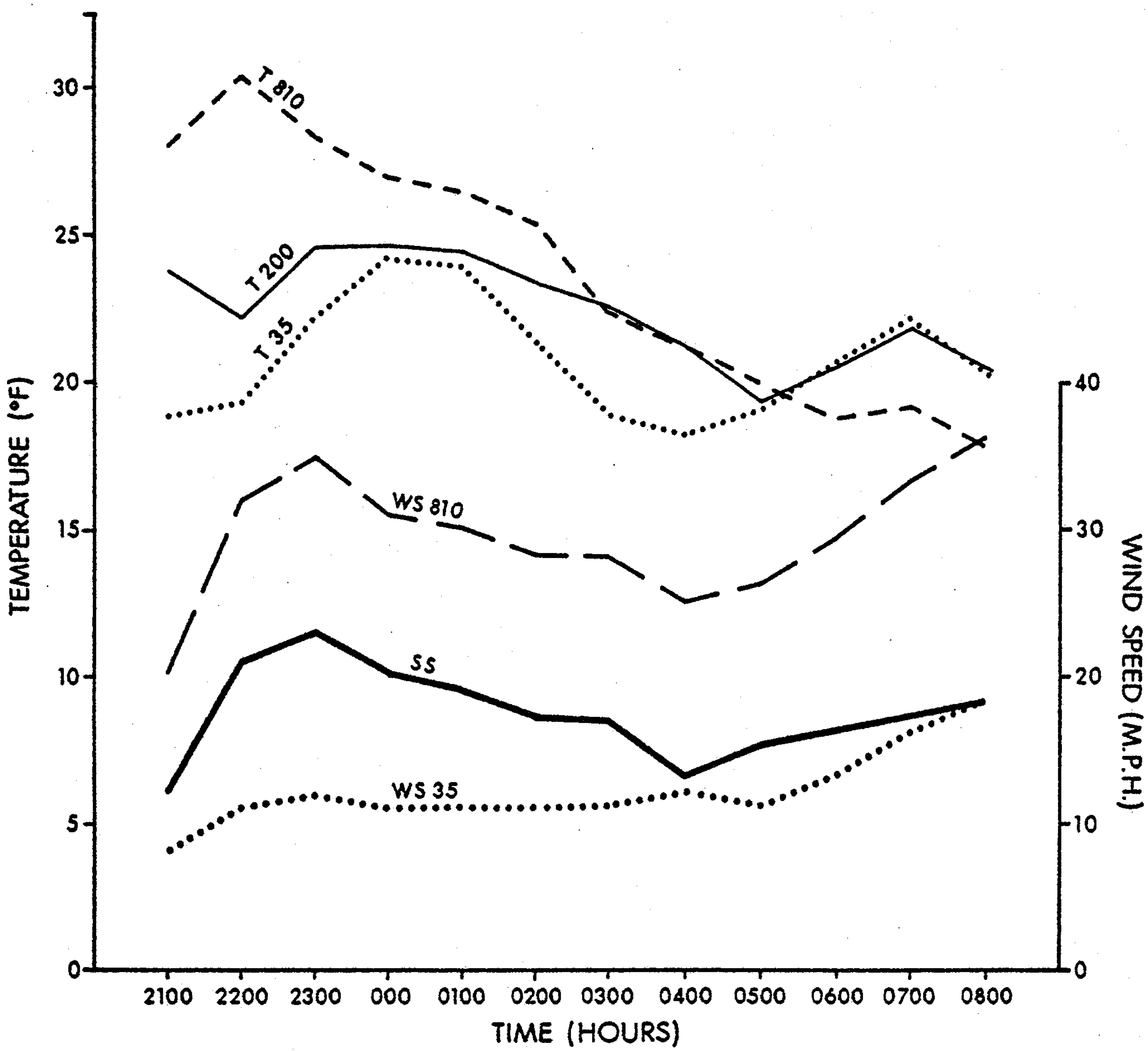
of Case 2

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (Tenths)	Cloud Type	Cloud Height (Feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (Tenths)	Sunshine Daily Total (Hours)	Sunshine Total Possible (Hours)
2100	-34.2	-12.7	250	8	250	20	12	18.8	23.8	28.0	4	AC,CI	7.0-22.0	1018.5	A	15	0		
2200	-17.5	-14.2	260	11	270	32	21	19.3	22.2	30.3	9	SC	5.0	1018.4	A	15	0		
2300	-12.0	-7.3	280	12	280	35	23	22.7	24.6	28.3	10	SC	5.5	1018.3	A	15	0		
0000	-2.1	-3.4	260	11	280	31	20	24.2	24.6	26.9	10	SC	6.0	1017.9	A	15	0		
0100	-3.1	-3.3	270	11	290	30	19	23.9	24.4	26.4	10	SC	2.0-6.0	1017.9	A	15	0		
0200	-12.8	-5.1	280	11	300	28	17	21.3	23.4	25.3	9	SC	2.0-4.9	1017.9	A	15	0		
0300	-22.2	-4.3	290	11	310	28	17	18.9	22.5	22.2	3	SC	2.0	1018.1	A	15	0	2.9	8.1
0400	-18.1	-3.9	320	12	340	25	13	18.2	21.2	21.2	8	SC	2.4	1018.8	A	15	0		
0500*	-1.4	-1.2	310	11	330	26	15	18.9	19.2	19.9	10	SC	2.6	1019.5	A	15	0		
0600	0.1	2.5	310	13	320	29	16	20.6	20.5	18.6	10	SC	3.1	1020.5	A	15	0		
0700	2.2	3.9	320	16	310	33	17	22.0	21.7	19.0	10	SC	1.3-2.8	1021.7	A	15	0		
0800	-0.2	3.5	320	18	310	36	18	20.3	20.4	17.6	10	SC	1.2-2.8	1022.3	A	15	0		

*Inversion decayed at 0500 hours in the 35-200 and 35-810 feet layer.

Figure 5.4

Temperature and Wind Variations During
Decay Period of Case 2



T —Temperature at 3 Levels (feet)
WS—Wind Speed at 2 Levels (feet)
SS —Speed Shear

was then followed by cooling. The 200 feet level temperature warmed up by 5.4°F between 0000 and 0500 hours, after which time temperature behaved similarly to the lower level. The temperature behaviour at the 810 feet level was different, as a continuous 12.7°F cooling began at 2200 hours.

These temperature profiles are the integrated result of slow vertical motion connected with the synoptic change in air mass types.

To appreciate the generation and release of instability it is necessary to consider the dynamical factors associated with synoptic systems as well as the vertical structure of the air mass observed at a given time (Palmén and Newton, 1969, p. 396).

The snow surface was heated by the downward fluxes of sensible and latent heat as warm westerly air advected. In the period under survey, air masses of dissimilar properties were interchanged -- cool north-westerly replaced the warm westerly air. Although low level temperature changes were dominated by the horizontal advection of the cool north-westerly, they were modified by advective heating due to proximity to the warmer surface. This process is suppressed at higher levels in the boundary layer, with distance from the surface qualifying the magnitude of the process activity.

From the above, it is apparent that the effects of advection will vary in the lowest 810 feet. Differential temperature advection, explained Jarvis (1969), is an important destabilizing mechanism for stability will decrease if cold air advection increases with height, or if warm air advection decreases with height. It should be noted however, that horizontal advection does not release instability. Rather, the upward motion leading to such release tends to be associated with areas where differential advection contributes to growth of potential instability (Pálmén and Newton, 1969).

The presence of the strong 35-810 feet layer inversion prevented large-scale convective uplift. Nonetheless, the early morning strong speed shear (greater than 13 m.p.h.) could have initiated slow vertical motion in the lower atmosphere. Izumi (1963, p. 81) found that even in the presence of an inversion, when the wind shear becomes sufficiently large, turbulent energy can be transported vertically and turbulent mixing can occur within the stable layer.

It is postulated that, in the inversion layer convective lifting of the air beneath resulted in the formation of overcast low level ST cloud which produced snow flurries at 1200 hours. Jarvis and Kagawa (1969) attributed the formation of low layer clouds in winter to an upward moisture flux from below the base level. With no vertical motion regardless of the magnitude of advection or evaporation, latent heat is not released. And even with vertical motion, release occurs only if ascent is strong enough to lift the air above condensation level (Vowinckel, 1964).

The mechanism causing the simultaneous decay of the inversions in both layers at 0500 hours, is the slow vertical motion connected with change in synoptic circulations and the resultant advective heating. Blackadar (1957) found that in the lower atmosphere advection is strongest in the early morning when low level jet streams are best developed. Potential instability can thus be generated during this period. As convective overturning took place, early morning generated potential instability may have been released; and the inversion in the lowest 810 feet thus destroyed. This occurred even though the additional agency of solar heating which favours daytime onset of convection was absent.

5.2.2. (b) Inversion Case 12

This inversion case provides an example of the effects of solar radiation heating on the structural behaviour of inversions in the presence of advective processes. The behaviour of the 35-200 feet layer inversion depends mainly, though not entirely on diurnal effects. The 35-810 feet layer inversion is influenced more by atmospheric advection, rather than radiation.

Six hours of positive lapses in the 35-200 feet layer were followed by the development of inversion Case 12 at 1400 hours. After persisting for 23 hours it decayed at 1200 hours. The associated 35-810 feet layer inversion formed four days earlier on November 27 at 1500 hours, persisted for 138 hours and, decayed at 0800 hours on December 3. Though the 35-200 feet layer inversion case was of a much shorter duration, inversion in this layer were present during the period of the higher inversion maintainence, but these temporarily decayed on some days mainly in the period between 0800 and 1400 hours.

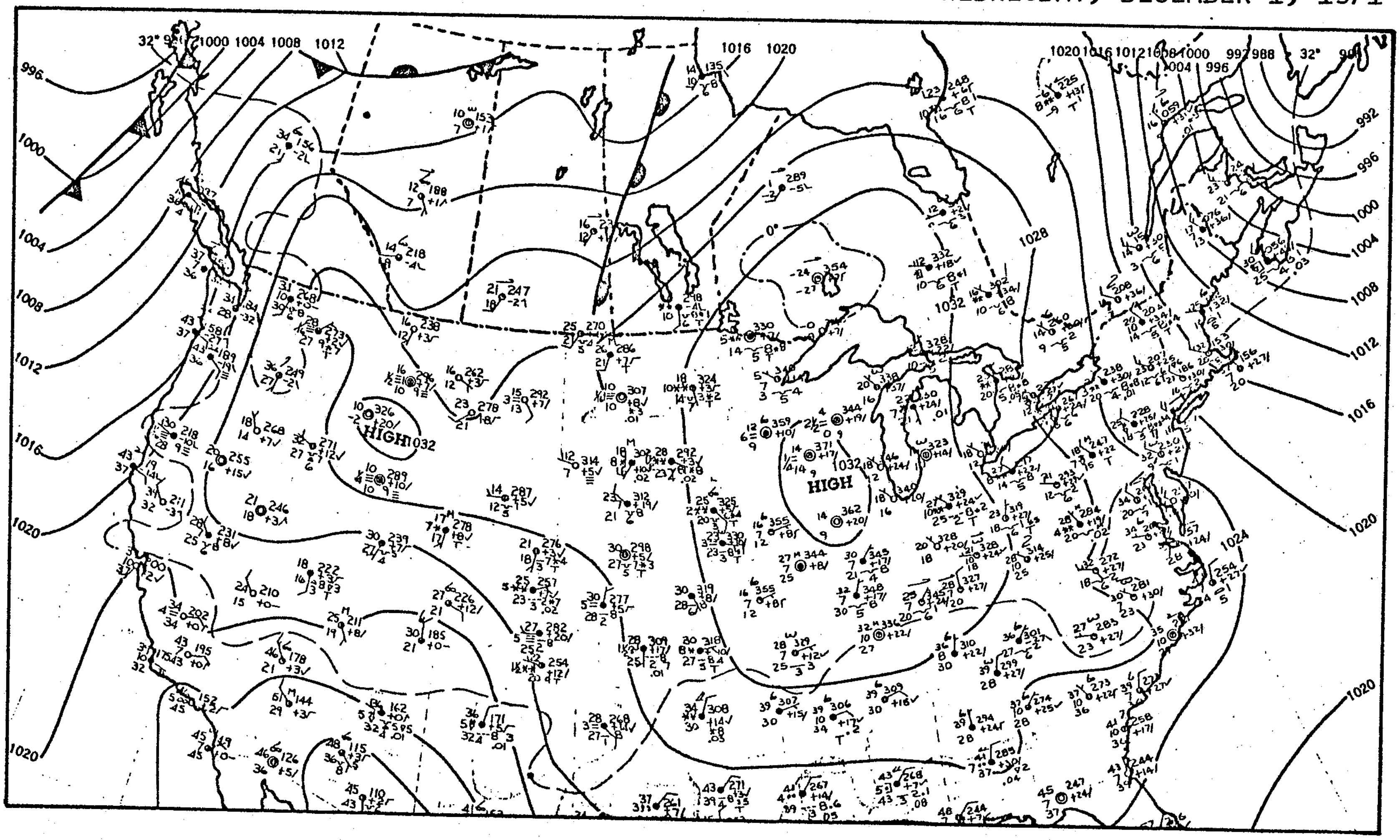
5.2.2. (b) (1) Development of Case 12

On the development day of Case 12, a broad, weak high pressure system over most of the U.S.A. extended to cover south-eastern Manitoba. Fast westerlies from south of the Gulf of Alaska low split into two segments producing a blocking type pattern. Ahead of the low pressure segment to the south of the Alaskan coast was a warm front that was located west of Winnipeg (Figure 5.5). Weather at Winnipeg was described as -- "Near normal

FIGURE 5.5

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT OF INVERSION CASE 12

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. WEDNESDAY, DECEMBER 1, 1971



temperatures. Cloudy in the morning then sunny. Flurries 3:45 to 11:28 a.m. Occasional gusty south winds" (Atmos. Environ. Service, Monthly Meteor. Summary, Dec. 1, 1971).

Table 5.4 presents the hourly synoptic conditions for a development period from 0700 to 1600 hours. As the weak trough advanced and the anticyclone moved south eastward, pressure fell slowly from 1030.1 m.b. at 1000 hours to 1028.5 m.b. Fairly strong southerly winds ranging in velocity from 14 to 18 m.p.h. influenced the 35 feet level; while, at the 810 feet level south-westerly winds varied in strength between 19 and 26 m.p.h. Relatively low speed shear maximized to 11 m.p.h. at the development hour. Overcast skies with snow flurries gave way to less than 4/10th's cloud cover at 1400 hours.

In the development period, the magnitude of temperature increase is similar at the three levels in the lowest 810 feet (Figure 5.6). There is present however a basic difference. Temperatures at the 810 feet level are much higher than the closely related temperatures at the two lower levels.

At the 35 feet level, a warming of 9.7°F to 1500 hours was followed by a fall in temperature. A continuous increase of almost 11.0°F occurred at the 200 feet level. The 810 feet level temperatures increased by 9.5°F to 1300 hours, and included was a steep 5.5°F warming between

Table 5.4

Synoptic Conditions During Development Period

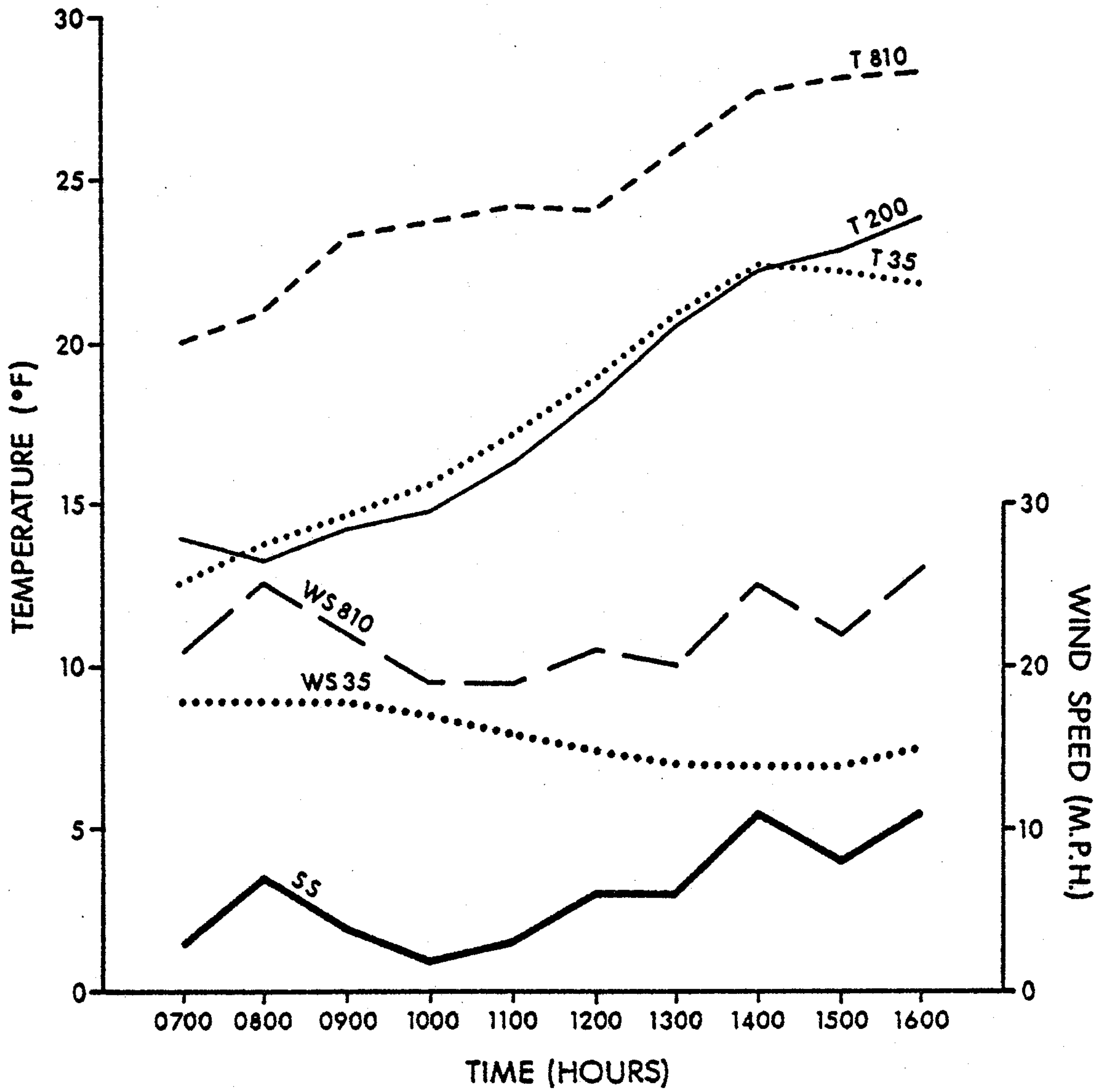
of Case 12

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (Tenths)	Cloud Type	Cloud Height (Feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (Tenths)	Sunshine Daily Total (Hours)	Sunshine Total Possible (Hours)
0700	-1.9	-9.6	180	18	210	21	3	12.6	12.9	20.0	9	SC	3.4	1029.9	A	15	0		
0800	2.4	-9.3	180	18	220	25	7	13.7	13.3	20.9	8	SC	3.0	1029.9	A	15	0		
0900	2.4	-10.8	180	18	230	22	4	14.7	14.3	23.1	8	SC	2.8	1029.9	P	12	0		
1000	4.6	-10.3	180	17	240	19	2	15.6	14.8	23.6	10	SC	3.1	1030.1	P	10	0		
1100	5.6	-8.9	180	16	230	19	3	17.2	16.3	24.1	9	SC	3.1	1030.1	P	06	0	3.7	8.4
1200	3.4	-6.8	180	15	230	21	6	18.7	18.2	24.0	5	SC	2.8	1029.3	A	15	9		
1300	2.4	-11.1	180	14	230	20	6	20.9	20.5	29.5	9	SC	2.5	1029.3	A	12	2		
1400*	-0.4	-6.9	180	14	220	25	11	22.3	22.3	27.6	3	SC	2.5	1028.7	A	12	6		
1500	-1.9	-7.4	180	14	220	22	8	22.3	22.7	28.1	2	SC,CI	2.5-25.0	1028.5	A	15	10		
1600	-12.0	-8.3	180	15	210	26	11	21.8	23.8	28.3	2	CI	25.0	1028.5	A	15	10		

*Inversion developed at 1400 hours in the 35-200 feet layer.

Figure 5.6

Temperature and Wind Variations During Development Period of Case 12



T – Temperature at 3 Levels (feet)
WS – Wind Speed at 2 Levels (feet)
SS – Speed Shear

1200-1300 hours when snowfall ended. A 1.9°F cooling in the next hour was followed by warming.

These events may possibly be accounted for by Treidl's (1970, p. 162) reasoning regarding the heating of a column of air by condensation. His reasoning follows.

The cooling of an air column is effected mainly by the removal of heat through turbulent downward flux and to a lesser degree through radiative flux divergence. When saturation is attained, condensation liberates the latent heat which slows the cooling process. Thus, the cooling of a column of air is effected by the removal of water vapour from the atmosphere and subsequently the boundary layer specific humidity is lowered. The released latent heat is brought to the snow surface together with sensible heat by the process of turbulent mixing.

As snowfall concluded, the 35 feet level wind speed lowered slightly. The warm southerly air was thus less quickly displaced horizontally, and the lower air layer acquired, through turbulent diffusion and other vertical-exchange processes, some of the physical properties of the newfallen snow. The high albedo of the snow surface caused it to cool even in the presence of an increasing amount of sunshine. With increased speed shear, the rate of cooling of the overlying air was enhanced and the downward transfer of heat was facilitated. This led to the development of the inversion in the 35-200 feet layer at 1400 hours.

An interesting feature of this inversion case was the maintainence of the deeper 35-810 feet layer inversion during the duration of snowfall. This circumstance represents a deviation from the now commonly observed circumstance that the 35-810 feet layer inversion development and decay are associated with snowfall termination and commencement respectively.

5.2.2. (b) (2) Decay of Case 12

On the decay day of Case 12, while Alberta was cloudy under the influence of a trough of low pressure, southern Manitoba was predominantly sunny with mild temperatures. A broad high pressure system influenced the weather scene. The centre of this anticyclone was gradually displaced south-eastward from over the Great Lakes. The Arctic front was well to the north (Figure 5.7). Weather at Winnipeg was described as -- "Above normal temperatures. Mostly sunny. Drifting snow" (Atmos. Environ. Service, Monthly Meteor. Summary, Dec. 2, 1971).

Hourly synoptic conditions for a decay period from 0500 to 1600 hours are provided in Table 5.5. As the centre of the anticyclone moved further away, pressure fell from 1027.2 to 1022.5 m.b. with a sharp change of

FIGURE 5.7

SYNOPTIC SITUATION ON DAY OF DECAY OF INVERSION CASE 12

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. THURSDAY, DECEMBER 2, 1971

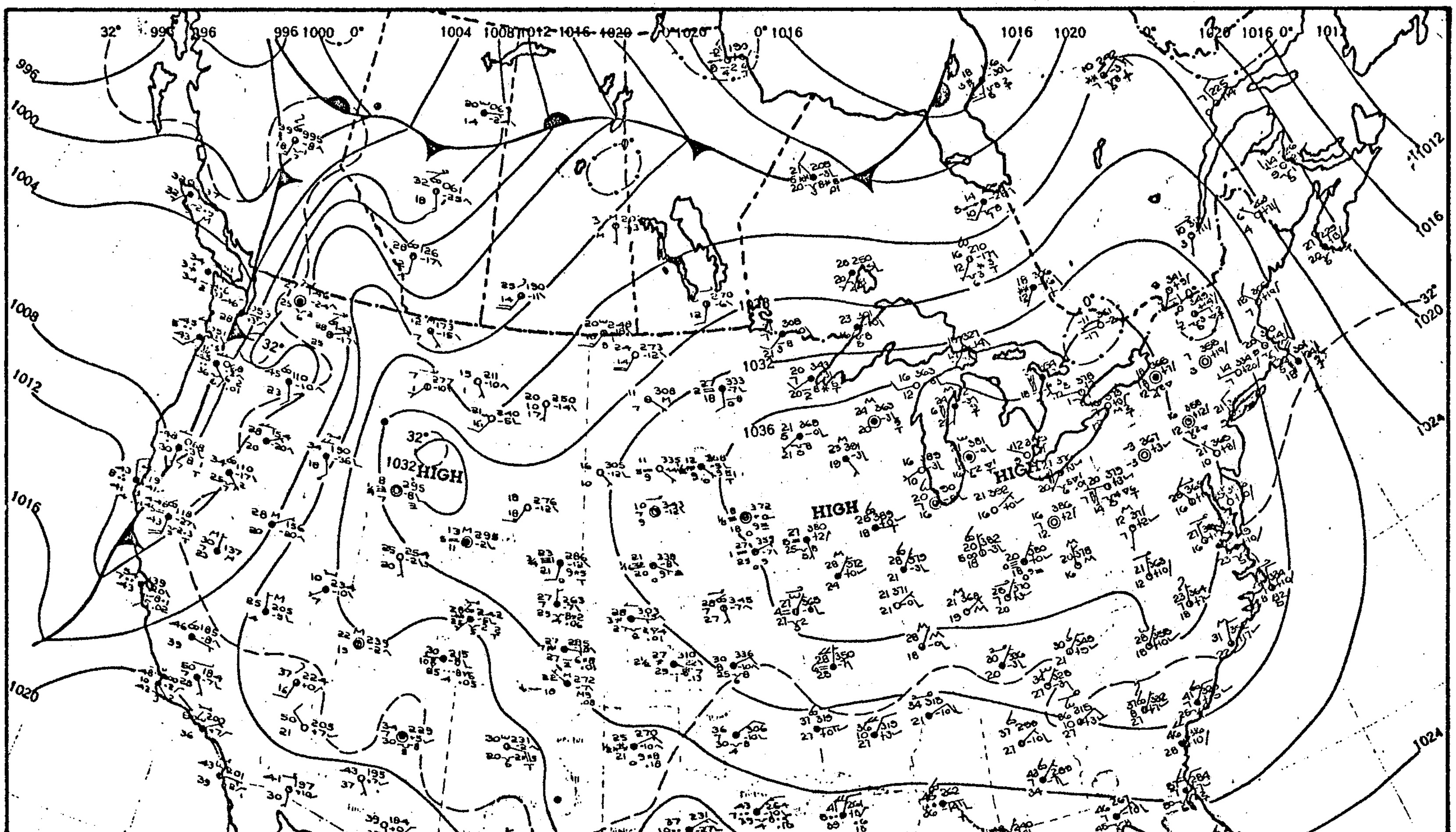


Table 5.5

Synoptic Conditions During Decay Period of Case 12

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (Tenths)	Cloud Type	Cloud Height (Feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (Tenths)	Sunshine Daily Total (Hours)	Sunshine Total Possible (Hours)
0500	-47.1	-32.7	180	11	250	28	17	13.1	20.9	38.5	0	None	-----	1027.2	A	15	0		
0600	-52.5	-30.7	180	14	240	20	6	12.7	21.4	36.5	1	CI	25.0	1027.0	A	15	0		
0700	-55.2	-30.7	180	11	240	23	12	11.9	21.0	35.7	1	CI	25.0	1027.0	A	15	0		
0800	-37.1	-35.4	170	16	230	25	9	11.7	17.9	39.2	3	CI	25.0	1026.6	A	15	0		
0900	-22.2	-34.4	170	17	230	30	13	13.9	17.6	40.6	8	AC,CI	10.0-25.0	1026.3	A	15	5		
1000	-3.5	-31.3	170	11	230	38	27	15.9	16.4	40.1	7	CI	22.0	1026.2	A	15	8		
1100	-4.5	-20.9	180	12	220	40	28	20.4	21.2	36.6	8	CI	22.0	1026.1	A	15	8	6.5	8.4
1200*	-3.4	-17.6	180	16	220	37	21	22.2	22.8	35.9	7	CI	22.0	1024.8	A	15	6		
1300	0.6	-10.2	180	15	210	35	20	22.9	22.7	30.8	7	CI	22.0	1024.4	A	15	8		
1400	0.6	-7.9	180	19	210	34	15	23.7	23.6	29.8	6	CI	22.0	1023.5	A	15	10		
1500	-3.7	-8.8	170	16	210	35	19	25.5	26.1	32.3	2	CI	22.0	1022.8	A	15	10		
1600	-11.5	-9.7	180	15	210	38	23	26.9	28.8	34.4	1	CI	22.0	1022.5	A	15	10		

*Inversion decayed at 1200 hours in the 35-200 feet layer.

1 m.b. between 1100-1200 hours. Initially low sky obscurity increased to greater than 6/10th's cover of the CI cloud type, but at 1500 hours reverted to its initial obscurity. Relatively brisk southerly winds of velocity 11-19 m.p.h. were dominant at the lower level; while, at the higher level fast-moving south-westerly winds (20-40 m.p.h.) showed a tendency to increase with approach of the decay hour. Speed shear was high, and was 21 m.p.h. when the inversion broke down.

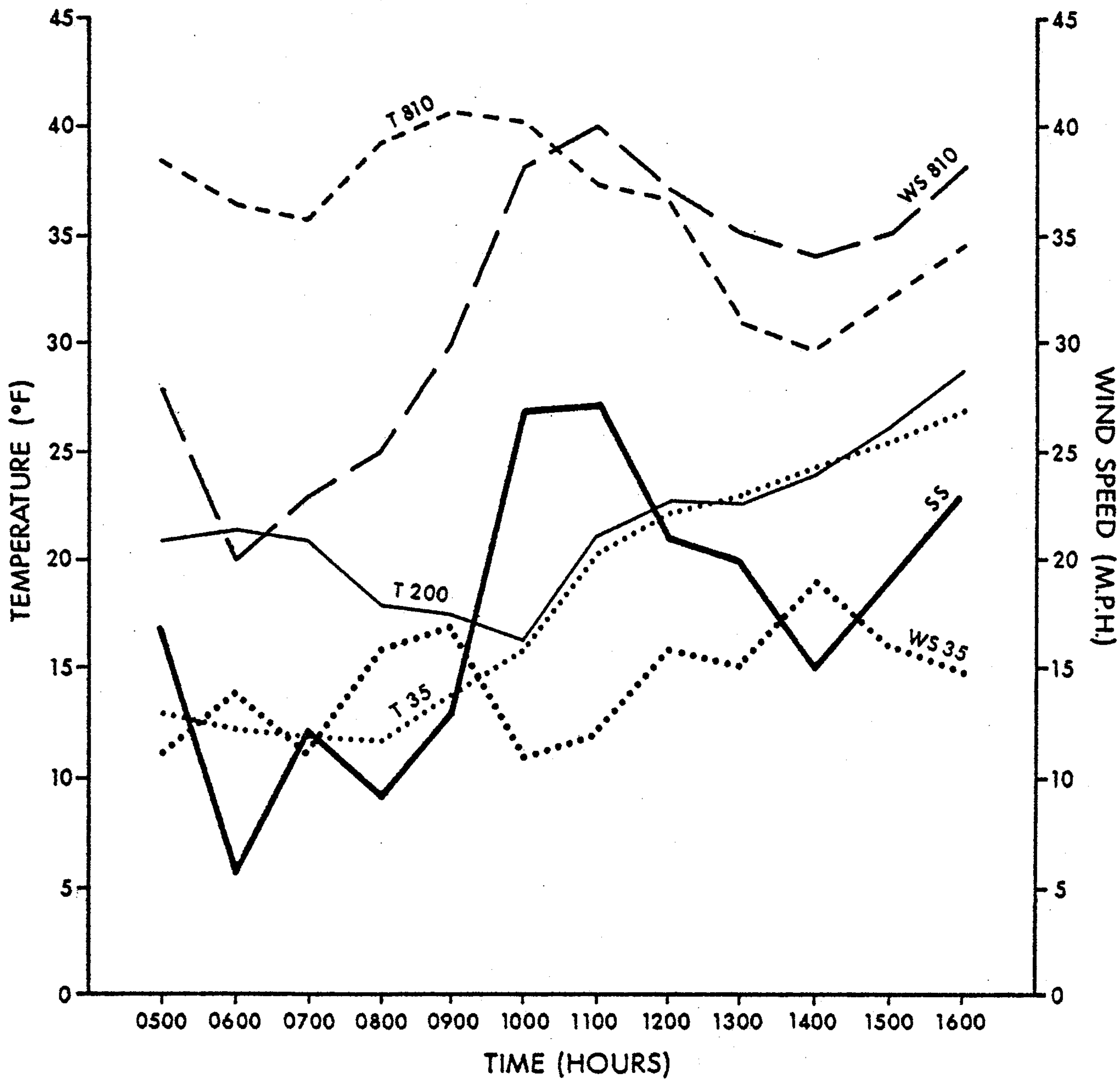
On the decay day 6.5 hours of sunshine were recorded out of a possible 8.4 hours. The temperature stratification (Figure 5.8) is a function of solar radiation heating, but is not solely controlled by it.

In the decay period, temperatures at the 35 feet level increased by 15.2°F from the beginning of sunshine receipt at 0900 hours. The 200 feet level temperatures behaved in much the same way, but the warming was smaller (12.4°F) and began at 1000 hours. A steep 3.5°F increase between 0700-0800 hours at the 810 feet level coincided with a 3.1°F cooling at the intermediate level. In the period from 0900 to 1400 hours temperatures markedly decreased by 10.8°F at the highest level, and this cooling period was concurrent with the sharp warming periods observed at the lower levels.

Appreciation of the temperature profile is

Figure 5.8

Temperature and Wind Variations During Decay Period of Case 12



T – Temperature at 3 Levels (feet)
WS – Wind Speed at 2 Levels (feet)
SS – Speed Shear

enhanced by regarding the vertical temperature gradients. Two hours prior to the dissipation of the inversion, temperature difference was roughly 24.0°F between the lower levels and the highest level. Although the magnitude of this difference diminished substantially thereafter, yet it was always in excess of 5.0°F. The maximum difference between the two lower levels was 9.1°F, and this occurred prior to sunrise. During the duration of sunshine temperature differences were significantly diminished.

The vertical temperature gradient is the integrated result of two factors, namely, turbulent mixing and radiative transfer (Munn, 1966, p. 89). Turbulent mixing transfers heat to and from the lower layers because the turbulent structure in the atmosphere depends upon many factors including the thermal structure of the atmosphere (Best et al., 1952, p. 31). On this decay day, solar heating aided by the turbulent transport of heat downwards caused the decay of the 35-200 feet layer inversion Case 12 at 1200 hours.

Although temperatures noticeably decreased at the highest level, particularly when speed shear was in excess of 20 m.p.h., yet high temperatures were maintained because of the warm south-westerly air advection. The 35-810 feet layer inversion was therefore sustained.

5.2.3 Summary

The mean daily range of temperature is made up of two largely independent components. That is, the true diurnal temperature range which is a function of the daily rhythm of radiative heating and cooling; and, the effects of advection which may bring in warmer or cooler air at any time in the diurnal cycle. Thus, the passage of a front usually causes large shifts in temperature.

The structures of Cluster 1 inversions were divided into two classes -- inversions lasting not less than 30 hours behaved differently to those maintained for shorter periods. The inversion cases analyzed indicated that, the difference in structural behaviour during development and decay can be assessed in terms of the more effective operation of either one of the two components in the weather process.

The inversions that are maintained for at least 30 hours are associated with the advection of warm Maritime Polar westerly air under the control of cyclonic circulations (usually Alberta low). Since temperature variation in these cases are not controlled by solar heating, the structural behaviour of these inversions are not diurnally rhythmic.

These inversions develop in the 35-200 feet layer due to basal chilling of the warm air stream as it flows over the cold winter continental surface. Analysis ascertained that a time lag of 3 hours is required for the development process to extend to the deeper 35-810 feet layer. The lag of time depends on the rate and depth of cooling of the air near the surface and is a function of the wind speed and temperature profiles. Inversions in both layers decay simultaneously in the early morning when the increase in speed of lower atmosphere advection is favoured. Potential instability is thus probably generated. The mechanism causing its release is slow vertical motion with respect to differential advection associated with change in synoptic circulations.

The structural behaviour of inversions lasting less than 30 hours is related to the diurnal effects of solar radiation heating in the presence of advective influences. The behaviour of the 35-200 feet layer inversions depend mainly, though not entirely on diurnal effects. Since the 35-810 feet layer inversions are more significantly influenced by atmospheric advection rather than radiation, they are strong, intense inversions that develop long before and decay long after the lower layer inversions.

5.3 Cluster 3

5.3.1 Preliminary Remarks

Cluster 3 has been delimited as transitional, and forms, with Cluster 7, the merging zone between the advective and radiative cluster groups (see Ch. 3). The average properties of the cluster show that Cluster 3 is of the shortest duration, lowest intensity, lowest temperature, and highest sky obscurity. Table 5.6 provides the average properties for each of the eleven inversions in the cluster.

This cluster contained 55 per cent of all twenty inversions in the advective clusters. December and January each included 27 per cent of the inversions, and 46 per cent occurred in February.

The limits of the periods of development and decay of these inversions were 1700-0300 hours and 0200-1300 hours respectively. The inversions which developed early (1700-1900 hours) were generally of longer duration than those that developed later. Thirty-six per cent of these inversions decayed before sunrise and these were mainly of shorter duration than the 64 per cent that decayed thereafter. Inversions of the cluster commonly decayed during the early morning nocturnal period. None of the inversions were of duration greater than 20 hours.

Cluster 3 inversions have distinctive structures

Table 5.6

Average Properties of Inversion Cases in Cluster 3

Case Number	Date	Development Hour	Inversion Duration (Hours)	Decay Hour	Inversion Intensity (°F/1000')	Sky Obscurity (Tenths)	Temperature (°F)	Pressure (m.b.)	Wind Speed (m.p.h.)	Wind Shear (m.p.h./x feet)	Wind Direction
22	Dec. 28'71	1700	19	1100	-25.5	1.6	3.3	1017.6	9.4	11.6	NW
32	Feb. 8'71	1700	18	1000	-24.3	4.2	-3.2	1018.5	11.3	17.2	SW
42	Feb. 18'71	1900	16	1000	-29.5	2.6	3.6	1024.5	7.4	2.4	NW
51	Feb. 19'71	1700	16	0800	-14.9	0.3	9.6	1023.5	13.6	15.2	E
58	Jan. 28'70	1700	14	0600	-20.2	3.9	-3.3	1021.7	11.6	10.0	S
64	Jan. 1'71	2300	13	1200	-27.5	0.9	4.1	1014.4	10.1	15.8	SW
71	Jan. 2'71	1800	12	0500	-20.4	6.0	4.5	1023.0	9.7	9.4	S
75	Dec. 19'69	0300	11	1300	-24.2	1.0	9.2	1031.1	8.9	11.6	W
78	Feb. 8'70	0100	11	1100	-25.1	7.5	15.1	1024.2	10.7	14.6	S
79	Dec. 30'71	1700	11	0300	-21.3	3.2	6.0	1009.9	12.8	11.1	S
88	Feb. 5'71	1700	10	0200	-25.1	4.5	-0.5	1014.4	11.2	13.5	N

at development and decay. The 35-200 feet layer inversion usually developed first, and the associated 35-810 feet layer inversion usually followed with a time lag of up to 3 hours. However, in rare instances, development is simultaneous in the two layers. Usually these inversions decayed simultaneously in both layers but in some cases the 35-810 feet layer inversion decayed a few hours later. The inversions in both layers are of similar durations.

From informal discussion with Bell, an important and interesting point emerges. This cluster was labelled transitional, as was Cluster 7; yet, general indications are that the former cluster closely resembles Cluster 4 in several respects. Inversions in these clusters developed and decayed within wide time limits, though Cluster 3 has a slightly larger percentage of decays in the nocturnal period. Their cluster sizes are the largest in their respective groups. None of the inversions are maintained for greater than 20 hours. The lag factor detected for development and decay processes to extend to the deeper 35-810 feet layer is the same.

5.3.2 Selected Inversion Cases

Selection of inversion cases is made irrespective of duration, but rather on the basis of structural behaviour and times of development and decay. Inversion

Cases 88 and 78 are chosen for detailed analysis of development and decay structures. The former is an interquartile case of duration 10 hours. It developed at 1700 hours in the 35-200 feet layer and at 1800 hours in the 35-810 feet layer. Both layer inversions decayed simultaneously in the early morning at 0200 hours. Case 78 lasted 11 hours and developed simultaneously in both layers at 0100 hours. The decay structure of this case represents a rare departure from the expected, as the lower inversion decayed one hour after the higher at 1100 hours.

5.3.2. (a) Inversion Case 88

The earliest development and decay hours of Cluster 3 inversions are exemplified in this case. Eight hours of positive lapses in the 35-810 feet layer preceded the development of inversion Case 88 in the 35-200 feet layer at 1700 hours. The associated 35-810 feet layer inversion formed one hour later. The inversion lasted 10 hours and decayed simultaneously in both layers at 0200 hours. In brief, the development hour is in accordance with the model, but the decay hour is anomalous as it happens in the nocturnal period.

5.3.2. (a) (1) Development of Case 88

On the development day, cool Maritime Polar (mP) northwesterly air from northern British Columbia and the Yukon spread southward under the control of a high pressure system over western Canada. A fast-moving, well-defined, intense depression from the Gulf of Mexico advanced northwards to the Hudson Bay. In its migration this system passed over the Great Lakes (Figure 5.9). Winnipeg's weather was described as -- "Normal temperatures. Partly cloudly. Ice crystals in the a.m. Flurries 11:15 p.m. continued. Blowing snow 10:10 to 11:20 a.m." (Atmos. Environ. Service, Monthly Meteor. Summary, Feb. 5, 1971).

Hourly synoptic conditions for a development period from 1200 to 2000 hours are provided in Table 5.7. As the high strengthened, pressure rose gradually under a cloudless sky. Strong, north-westerly winds were dominant at both the 35 and 810 feet levels. In general, wind speed lowered with the approach of the development hour; though high speeds were maintained at the 810 feet level. Relatively high speed shear attained maximum strength of 16 m.p.h. at the formation hour.

The development day received 7.8 hours of sunshine out of a possible 9.5 hours. Seven hours of maximum hourly sunshine were received until 1600 hours. As sunshine reduced to 30 minutes in the next hour, the inversion

FIGURE 5.9

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT OF INVERSION CASE 88

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. FRIDAY, FEBRUARY 5, 1971

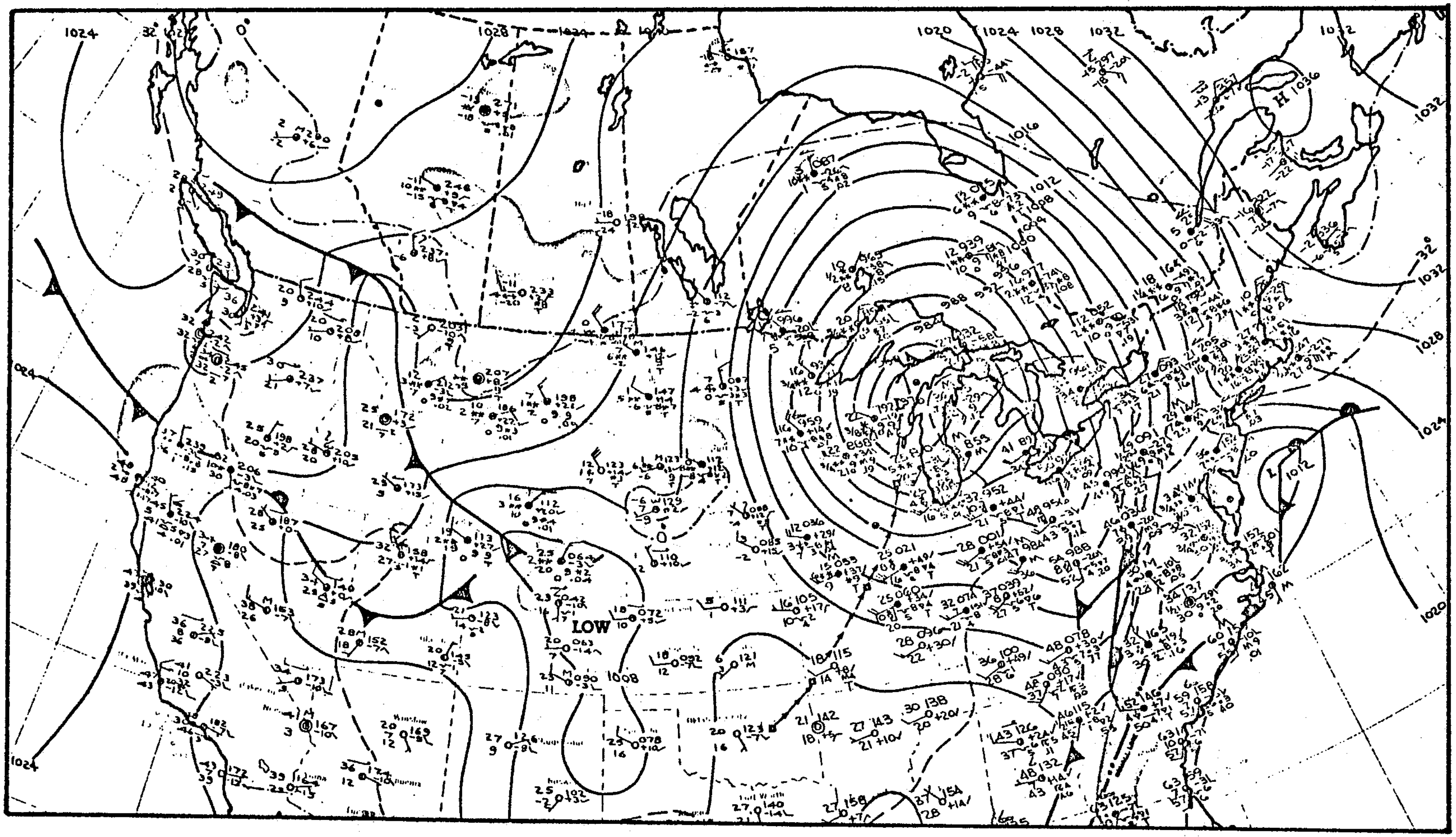


Table 5.7

Synoptic Conditions During Development Period

of Case 88

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (Tenths)	Cloud Type	Cloud Height (Feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (Tenths)	Sunshine Daily Total (Hours)	Sunshine Total Possible (Hours)
1200	7.8	3.0	320	22	330	35	13	1.0	-0.3	-1.3	2	CI	25.0	1013.5	A	12	10		
1300	7.5	4.6	320	24	320	31	7	2.3	1.1	-1.2	2	CI	25.0	1013.3	A	15	10		
1400	6.4	4.7	310	20	310	31	11	3.1	2.1	-0.5	0	None	---	1013.2	A	15	10		
1500	5.6	5.1	310	22	300	34	12	3.7	2.8	-0.3	0	None	---	1013.2	A	15	10	7.8	9.5
1500	4.6	4.5	310	18	310	22	4	4.5	3.7	1.0	0	None	---	1013.7	A	15	10		
1700*	-7.8	1.5	300	12	300	28	16	2.4	3.7	1.2	0	None	---	1014.0	A	15	5		
1800*	-19.0	-0.8	300	10	310	26	16	0.7	3.8	1.3	0	None	---	1014.4	A	15	0		
1900	-20.2	-2.0	280	10	310	24	14	0.2	3.5	1.7	0	None	---	1014.8	A	15	0		
2000	-29.8	-2.8	290	9	290	20	11	-0.2	4.7	2.0	0	None	---	1014.8	A	15	0		

*Inversion developed at 1700 hours in the 35-200 feet layer and at 1800 hours in the 35-810 feet layer.

developed in the 35-200 feet layer.

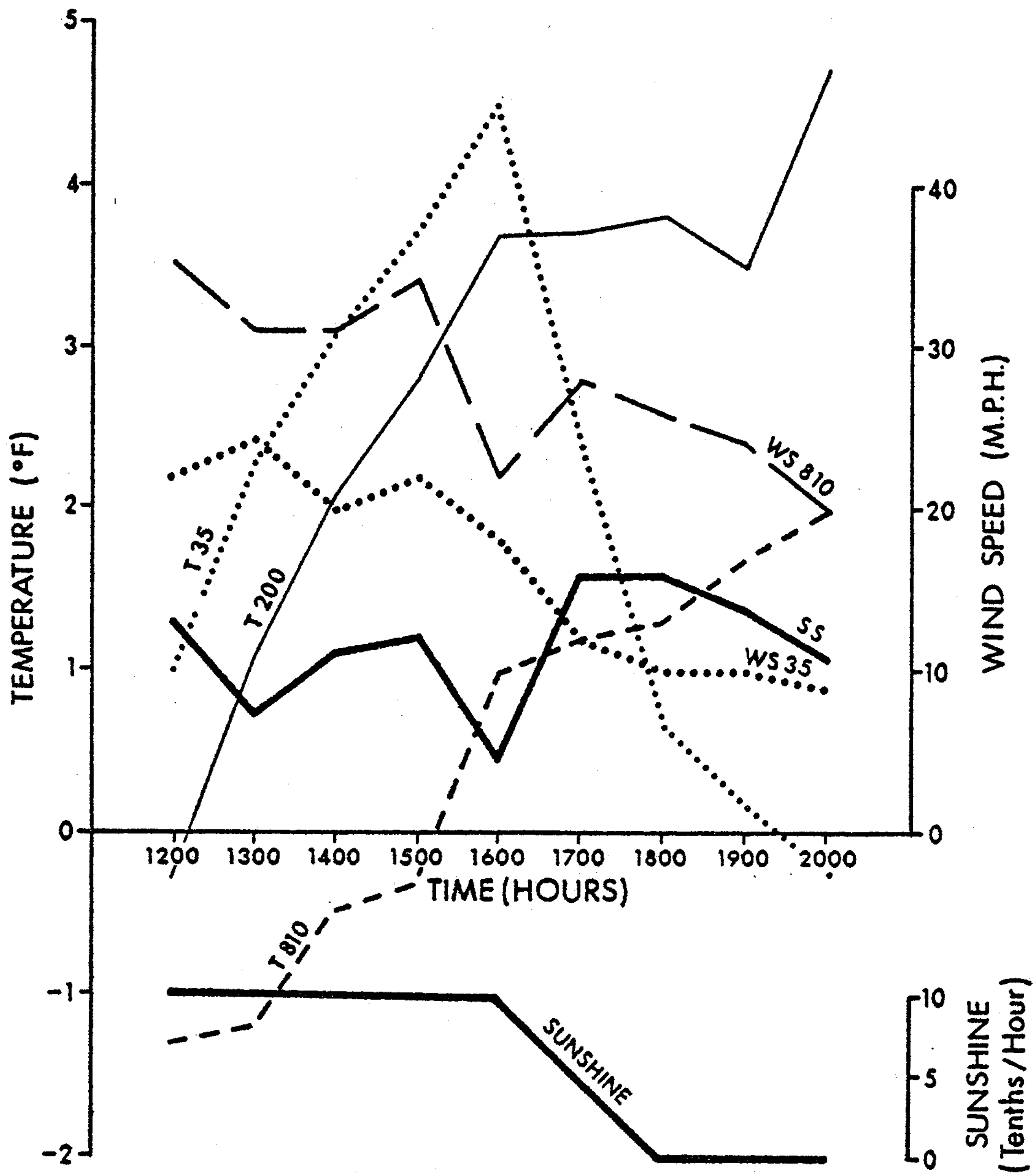
A notable feature of the development period temperature profile (Figure 5.10) is the smallness of the increases observed at the three levels. This is curious, especially for the level near the surface, in view of the amount of sunshine received. The 35 feet level experienced a 3.5°F warming to 1600 hours after which time a 4.7°F cooling occurred. Temperatures at the 200 feet level increased by 4.1°F to 1800 hours. A continuous 3.3°F warming throughout this period was observed at the 810 feet level.

In the lower atmosphere turbulent kinetic energy is mostly generated either by wind shear (mechanical turbulence) or an upward transfer of heat (thermal turbulence). Mechanical turbulence is mainly confined to the surface layers, and its total rate of energy generation is typically about one-tenth of that of thermal turbulence. The latter occurs in a deeper convective layer and is large scale (hundreds of meters to kilometers) (Ball, 1960).

Under high wind speeds and strong wind shear, turbulent motion generated by mechanical or forced convection near the surface, is replaced by free or natural convection (buoyancy forces) at greater heights. Deardoff (1972) has shown numerically that in unstable conditions eddies produced by buoyancy become the most important mixing

Figure 5.10

Temperature, Sunshine and Wind Variations During Development Period of Case 88



T —Temperature at 3 Levels (feet)

WS—Wind Speed at 2 Levels (feet)

SS —Speed Shear

mechanism in all but the surface layers. Free convection is an energy source when temperature decreases with height and an energy sink when temperature increases with height. In the former case, an air parcel displaced upwards will be less dense than its environment and will accelerate (Sellers, 1965, p. 153).

Prior to sunset, in the presence of the cool, strong north-westerly winds, convection transported heat upwards almost as fast as it was generated by solar heating of the ground. As the altitude of the sun angle lowered, the increase in optical mass reduced direct solar heating and albedo increased. The surface and the air layer near the surface cooled quickly, and the inversion in the 35-200 feet layer formed at sunset (1700 hours). With a time lag of one hour the associated 35-810 feet layer inversion followed. It is postulated that, the shallow inversion surface was displaced upwards to the deeper layer by the efforts of convective processes.

Goff and Hudson (1972, p. 29) found that strong inversions above 200 meters are also caused by the lifting of strong surface inversions by convective processes after sunrise instead of by radiational cooling. Izumi (1964, p. 81) attributed the lifting of inversions at the Cedar Hill tower principally to the combined efforts of mechanical turbulence and heating.

5.3.2. (a) (2) Decay of Case 88

Winnipeg's weather on the decay day was described as -- "Below normal temperatures. Cloudy. Flurries to 12:20 p.m. Blowing snow 2:35 p.m. to 3:40 p.m." (Atmos. Environ. Service, Monthly Meteor. Summary, Feb. 6, 1971). The anticyclone that was over western Canada on the development day, continued to strengthen and advance south-eastward on the decay day. Southern Manitoba experienced clear, cold weather. These conditions were interrupted as cloud accompanied with light snow spread into the area overnight. Change in the synoptic pattern was associated with the northward progression of the intense low from the Gulf of Mexico. By 0600 hours, the centre of this depression had passed to the east of Winnipeg and was in James Bay (Figure 5.11).

Hourly synoptic conditions for a decay period from 2100 to 0500 hours are shown in Table 5.8 and are quite dissimilar to those reported for the development period. Pressure though rising slowly, practically stabilized at 1014.5 m.b. For a few hours, in connection with the depression passage, cool north-westerly winds were replaced by warm westerly. Wind speed increased at both the 35 and 810 feet levels with approach of the decay hour. Speed shear varied within a 10-16 m.p.h. range and was strongest when the inversion dissipated. Sky obscurity

FIGURE 5.11

SYNOPTIC SITUATION ON DAY OF DECAY OF INVERSION CASE 88

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. SATURDAY, FEBRUARY 6, 1971

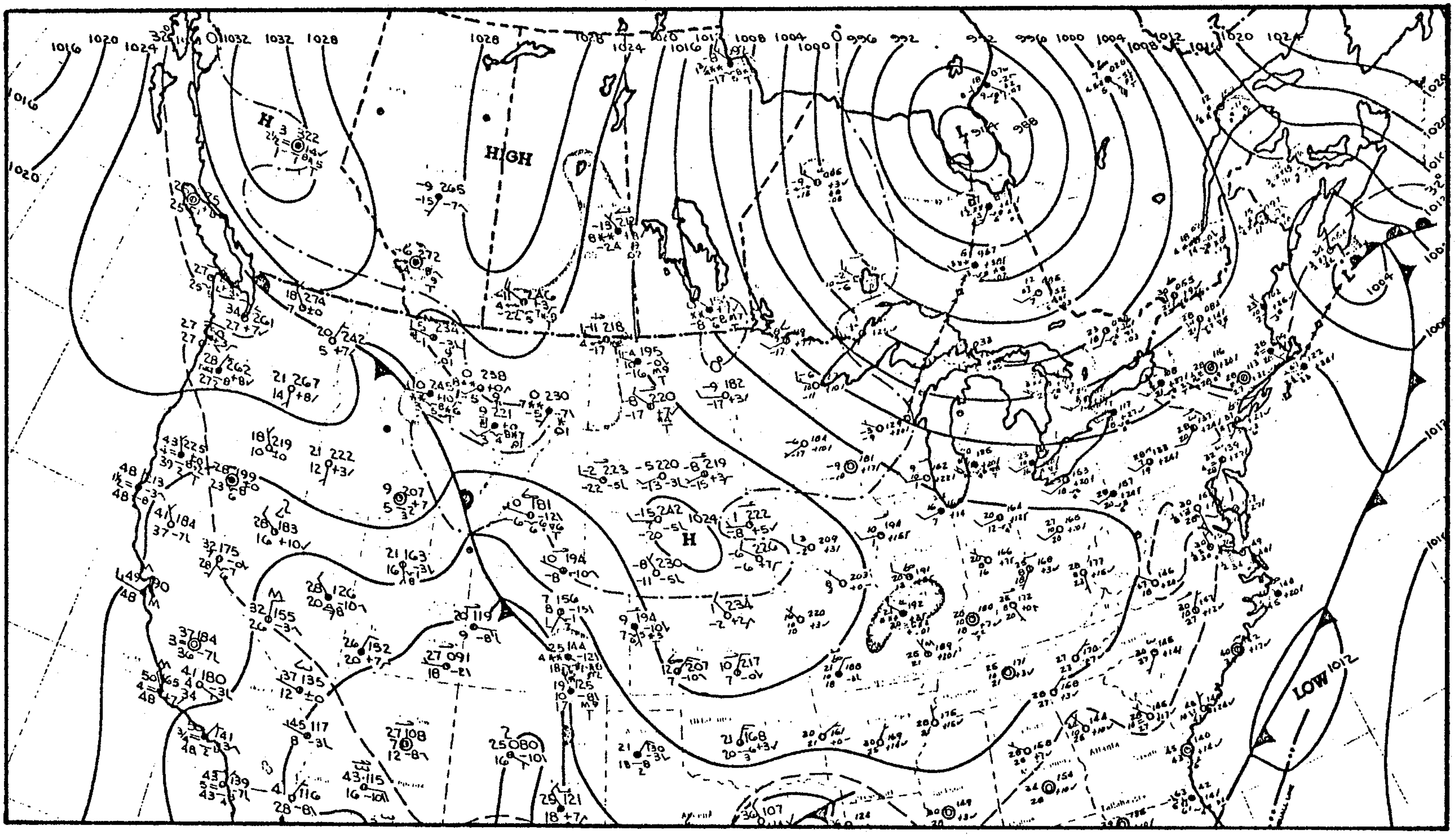


Table 5.8

Synoptic Conditions During Decay Period of Case 88

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (Tenths)	Cloud Type	Cloud Height (Feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (Tenths)	Sunshine Daily Total (Hours)	Sunshine Total Possible (Hours)
2100	-40.6	-0.9	280	8	300	21	13	-3.2	3.5	3.7	0	None	----	1014.5	A	15	0	7.8	9.5
2200	-34.9	-7.3	270	9	310	20	11	-3.3	2.5	2.4	8	SC,CI	5.5-25.0	1014.3	A	15	0		
2300	-46.9	-10.8	270	12	300	22	10	-6.4	1.4	2.0	9	SC	4.9	1014.3	A	15	0		
0000	-39.0	-11.3	280	10	320	24	14	-8.0	-1.6	0.8	10	SC	3.8	1014.4	A	15	0		
0100	-12.5	-1.4	300	13	330	27	14	-2.0	0.0	-1.0	10	SC	3.5	1014.1	P	12	0		
0200*	-1.2	-0.5	280	12	320	28	16	-1.6	-1.4	-1.2	10	SC	3.4	1014.5	P	12	0	5.1	9.6
0300	0.7	2.1	290	12	310	28	16	0.0	-0.1	-1.7	10	SC,SC	1.6-3.4	1014.7	P	12	0		
0400	3.2	4.6	320	14	320	26	12	0.0	-0.5	-3.5	10	SC,SC	1.6-3.4	1014.7	P	12	0		
0500	3.4	4.5	320	12	320	24	12	-0.1	-0.6	-3.5	10	SC	3.4	1015.2	P	12	0		

*Inversion decayed at 0200 hours in the 35-200 and 35-810 feet layers.

increased to a complete cover of the SC cloud type. One hour proceeding the commencement of snowfall at 0100 hours, the inversions decayed in both layers.

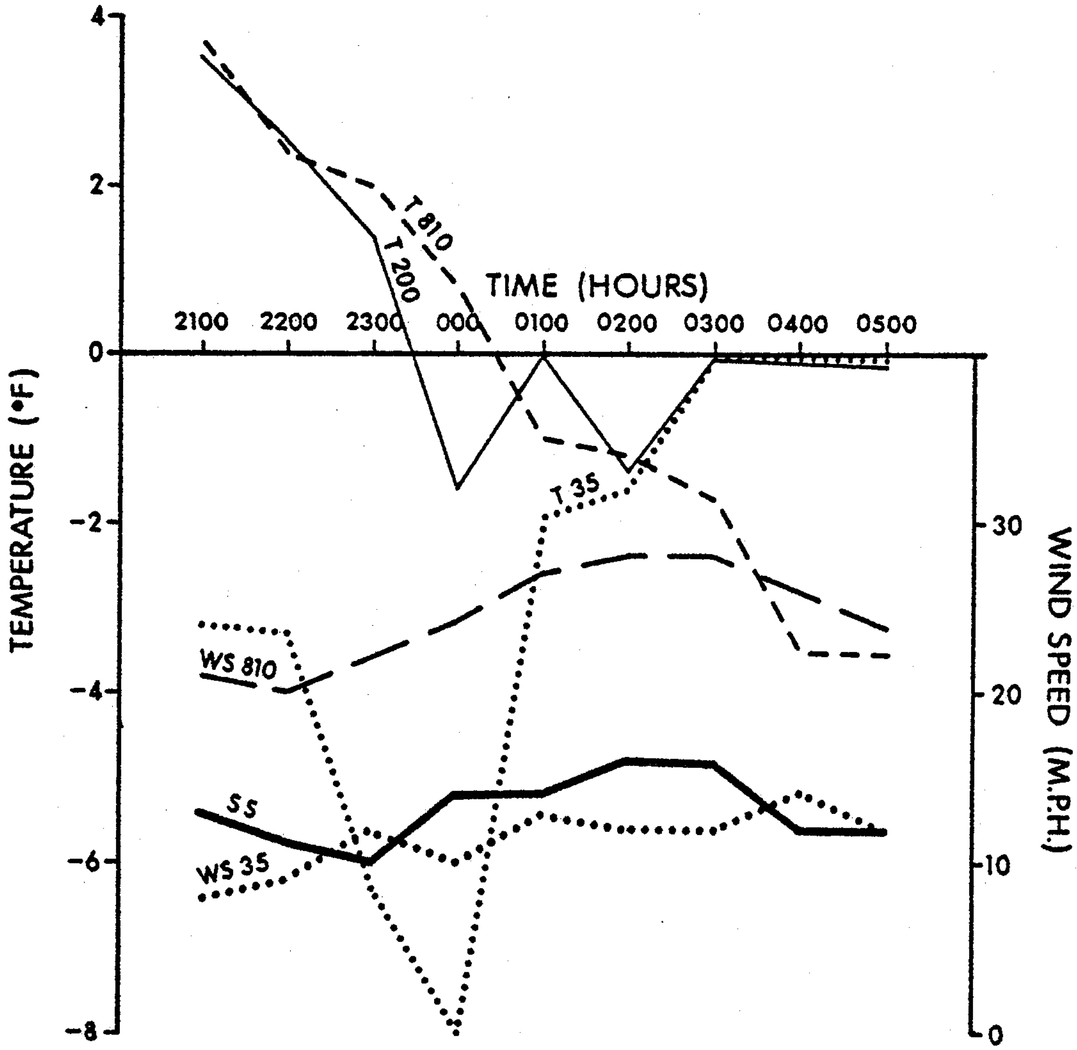
The decay period temperature profile (Figure 5.12) reflected the change in synoptic conditions. The 35 feet level temperatures decrease by 4.6°F to 0000 hours, with the next hour experiencing a sharp 6.0°F increase as snow flurries commenced. Thereafter, temperatures continued to increase slowly. A similar 5.1°F cooling to 0000 hours at the 200 feet level was followed by a less regular 2.0°F temperature fluctuation. At the 810 feet level, a continuous 7.2°F cooling, which steepened during the period of snowfall, was observed.

It seems reasonable to propose that the interchange in synoptic circulations accompanied by snowfall caused the simultaneous decay of the inversions in both layers. The effects produced by snowfall on the thermal stratification have been dealt with previously. Readers are referred to Ch. 4, Section 4.2.2, and Ch. 5, Section 5.2.2.

The development of this inversion was ascribed to convective processes; and this, in combination with passage of the depression over the Great Lakes was what may have initiated the formation of the SC cloud and snowfall. Bernachi and Medlicott (1969, p. 11) in their study of stratus

Figure 5.12

Temperature and Wind Variations During Decay Period of Case 88



T —Temperature at 3 Levels (feet)
WS—Wind Speed at 2 Levels (feet)
SS —Speed Shear

behind cold fronts in Regina found that, turbulent mixing contributes to saturation and that an external moisture source contributes appreciably to the formation of stratus in a cold north-westerly flow.

5.3.2. (b) Inversion Case 78

Preliminary investigation indicated that the development and decay structures of this inversion case can best be treated together since this 11-hour inversion developed and decayed on the same day. Moreover, rapid changes in weather in a brief period were experienced. The dynamic and transient character of the weather associated with this case complicated the analysis.

The inversion developed simultaneously in both layers at 0100 hours. The 35-200 feet layer inversion decayed one hour after the 35-810 feet layer inversion at 1100 hours. Four hours of positive lapse rates then followed.

5.3.2. (b) (1) Development/Decay of Case 78

Since development occurred soon after the preceding day, the macroscale weather situation of that day is also considered. Weather for the preceding day was described as -- "Temperatures above normal. Cloudy with fog 0039 to 0222 a.m., flurries 0543 to 1540 p.m." (Feb. 7). On the development/decay day the weather was described as -- "Mild. Cloudy with light flurries 10:25 to 11:10 a.m." (Feb. 8) (Atmos. Environ. Service, Monthly Meteor. Summary, 1970). From the foregoing description the pattern is noted, as in Case 88, that the inversion decayed when snowfall commenced.

A broad, weak anticyclonic system associated with the circulation of mild Maritime Polar westerly air dominated the weather scene of the Prairie provinces. Overnight on the 7-8 February however, a minor surge of Arctic air from the north-west invaded southern Manitoba. Patchy cloudiness and some fog occurred along the southern boundary of the cool north-westerly air. This air was rapidly modified as the day progressed by the mild Pacific air mass (Figures 5.13a and 5.13b).

The development and the decay periods are combined, and hourly synoptic conditions for a period from 2100 to 1400 hours are tabulated in Table 5.9. The period began with the backing of fairly strong southerly winds in the lowest 810 feet until around 0300 hours as the frontal surface approached. Speed shear was not in excess of 6 m.p.h. during this period. Pressure fell by 3.8 m.b. to 0500 hours, with a sharp 3.1 m.b. fall in the period prior to the development hour. The sky was overcast with SC cloud at roughly 300 feet until the inversion formed at 0100 hours.

FIGURE 5.13 A

SYNOPTIC SITUATION ON DAY PRECEDING THE DEVELOPMENT / DECAY OF INVERSION CASE 78

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. SATURDAY, FEBRUARY 7, 1970

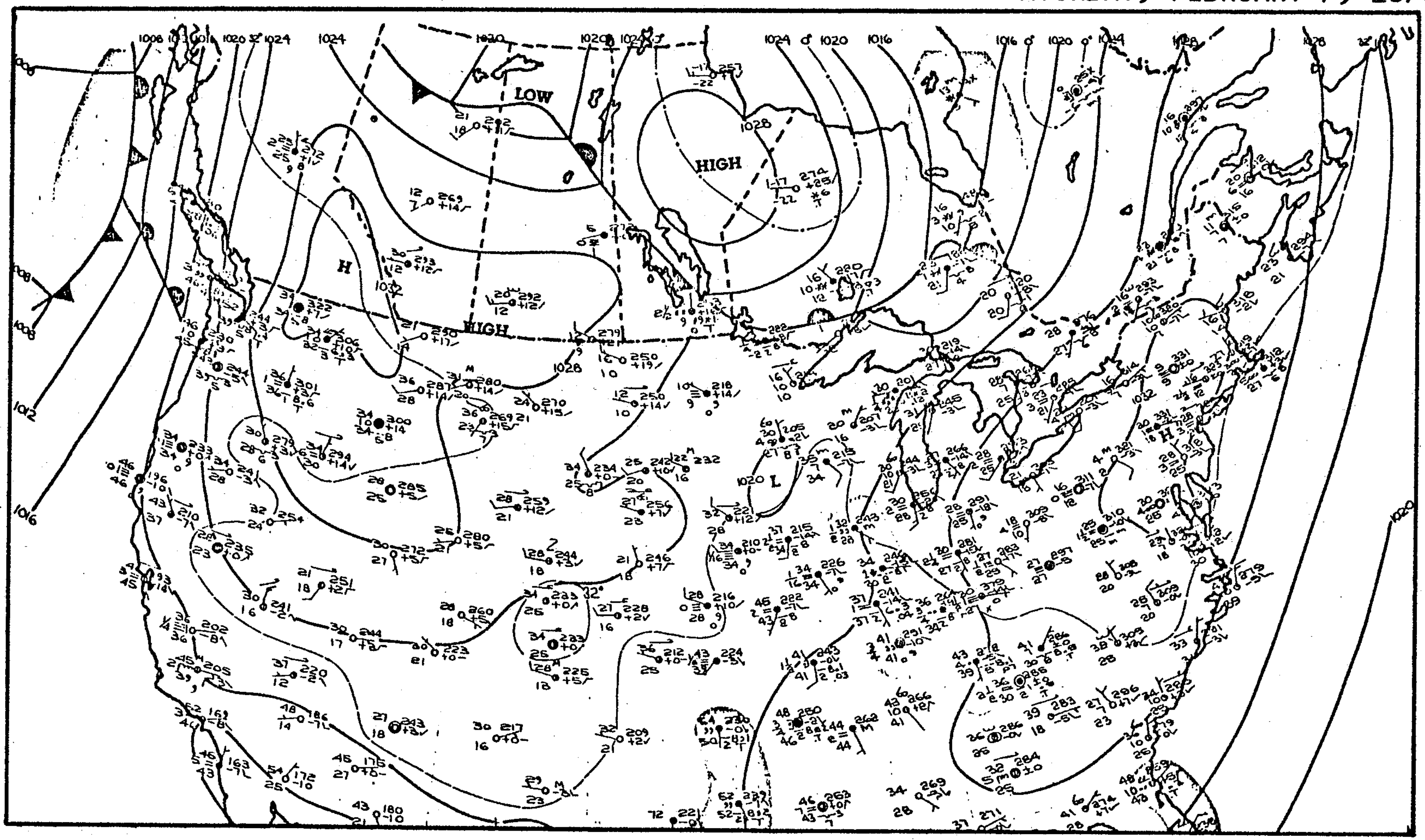


FIGURE 5.13 B

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT / DECAY OF INVERSION CASE 78

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. SUNDAY, FEBRUARY 8, 1970

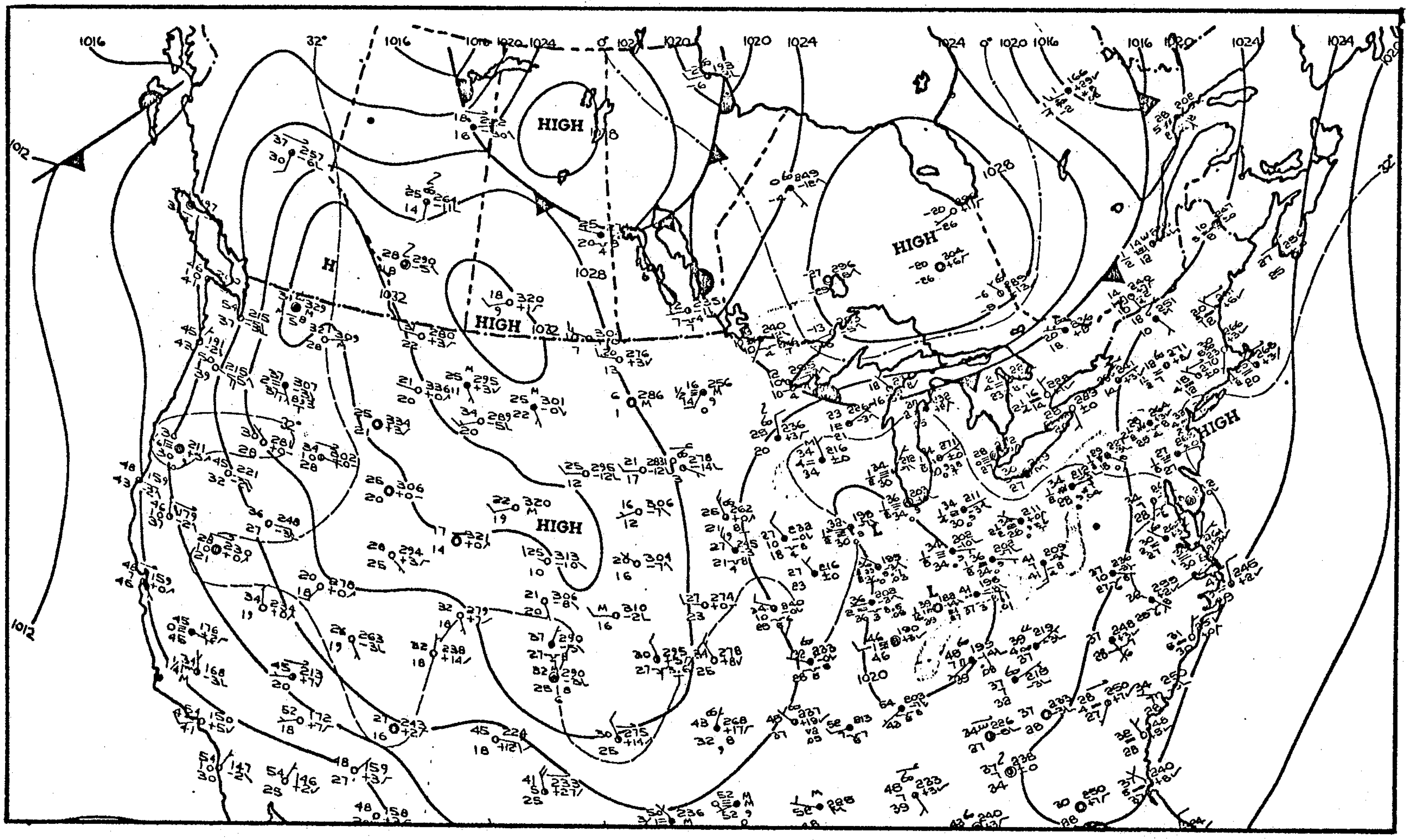


Table 5.9

Synoptic Conditions During Development/Decay Period of Case 78

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (Tenths)	Cloud Type	Cloud Height (Feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (Tenths)	Sunshine Daily Total (Hours)	Sunshine Total Possible (Hours)
2100	-3.4	0.6	170	12	210	14	2	17.4	18.0	17.0	10	FS,ST	0.1-0.3	1027.0	A	12	0	0.1	9.6
2200	-1.2	2.3	190	10	210	16	6	18.7	18.9	17.0	10	ST	0.2	1026.4	A	12	0		
2300	1.2	3.0	210	12	210	17	5	19.8	19.6	17.4	10	ST	0.2	1025.4	A	12	0		
0000	0.8	1.7	190	15	220	16	1	18.9	18.8	17.7	10	ST	0.3	1024.6	A	12	0		
0100*	-17.9	-4.1	190	14	220	16	2	13.9	16.9	17.1	10	ST	0.3	1023.9	A	12	0		
0200	-32.8	-7.8	190	10	240	14	4	10.2	15.6	16.2	1	ST	0.3	1023.5	A	15	0		
0300	-51.8	-10.4	200	9	280	16	5	7.6	16.1	15.7	5	SC	6.0	1023.6	A	15	0		
0400	-31.7	-17.3	200	7	330	20	13	9.1	14.3	22.5	9	SC	5.0	1023.3	A	15	0		
0500	-32.0	-13.1	260	7	330	22	15	10.9	16.2	21.1	10	SC	6.0	1023.2	A	15	0		
0600	-39.2	-16.9	270	10	340	31	21	10.4	16.9	23.5	5	SC	5.0	1023.5	A	15	0		
0700	-43.2	-17.1	280	11	350	31	20	12.9	19.1	25.2	10	SC	2.8	1023.7	A	15	0	1.6	9.7
0800	-8.0	-9.4	300	13	350	32	19	17.4	18.7	24.6	10	SC	2.0	1024.3	A	15	0		
0900	-7.4	-6.2	320	10	350	36	26	17.2	18.4	22.0	10	ST	1.0	1025.3	A	15	0		
1000**	-12.1	-2.2	320	8	350	28	20	19.8	21.8	21.4	10	ST,SC	1.0-3.1	1026.1	A	15	0		
1100**	-0.9	2.2	330	10	350	24	14	23.4	23.5	21.6	10	ST,SC	1.0-2.5	1026.7	A	15	0		
1200	3.2	3.7	330	12	340	27	15	25.5	25.0	22.6	10	ST,SC	1.5-3.5	1027.6	A	15	0		
1300	3.5	4.3	350	13	340	25	12	26.7	26.1	23.4	10	SC	2.0-3.1	1028.4	A	15	0		
1400	3.9	3.0	350	16	330	22	6	25.3	24.7	23.0	9	SC	3.8	1028.8	A	15	4		

*Inversion developed at 0100 hours in the 35-200 and 35-810 feet layers.

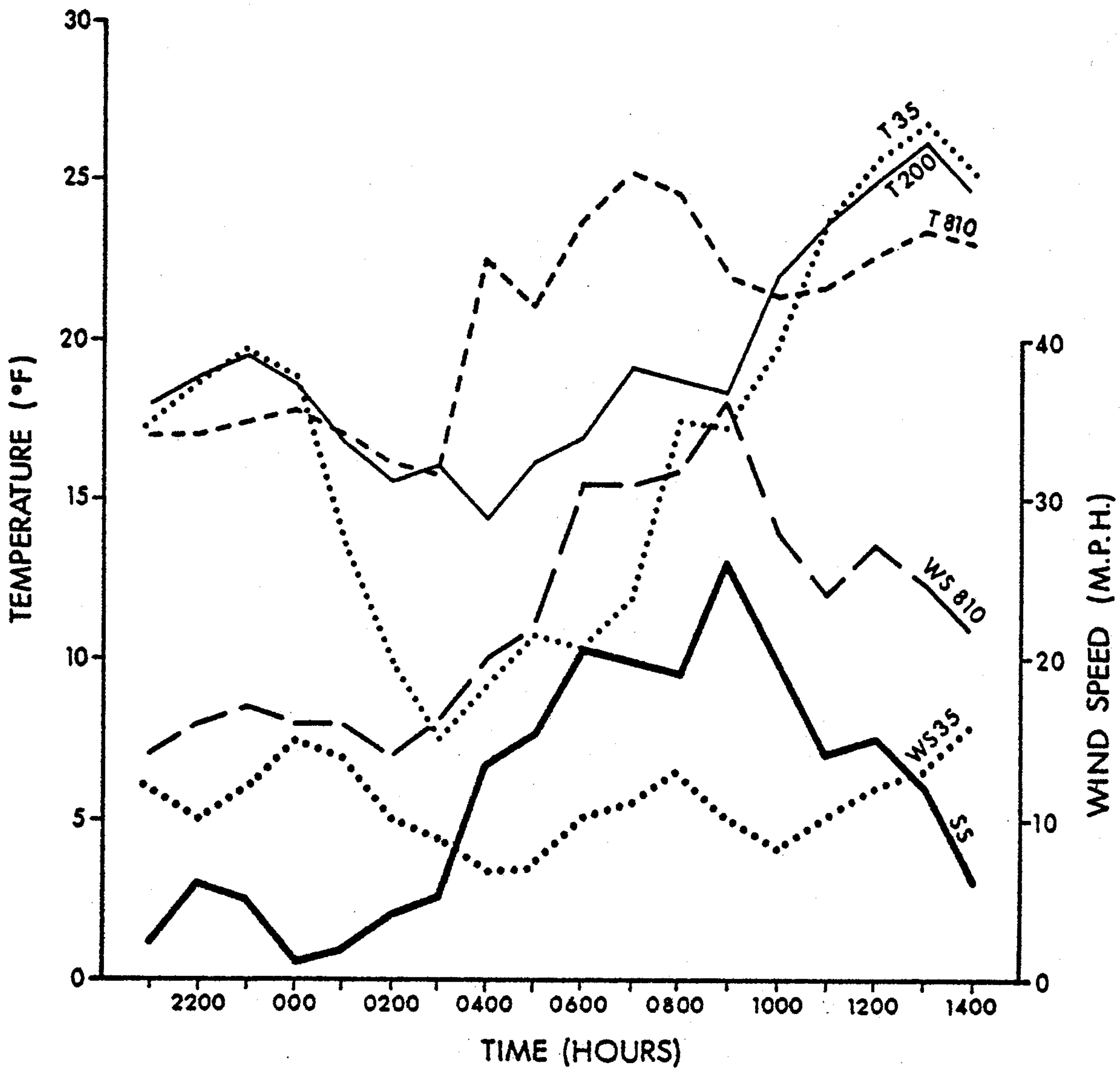
**Inversion decayed at 1100 hours in the 35-200 feet layer and at 1000 hours in the 35-810 feet layer.

As the frontal boundary crossed, light winds veered westerly for a few hours at the 35 feet level. This was replaced by a slightly stronger north-westerly flow from 0900 hours. At the 810 feet level, the latter flow was strong (greater than 20 m.p.h.) and became dominant a few hours earlier at 0400 hours. Relatively high speed shear intensified to 20-26 m.p.h. around the decay time. Pressure rose by 5.6 m.b. with a sharp change of 1 m.b. between 0800-0900 hours. For the most part, the sky remained overcast with low layer SC and ST cloud types.

The temperature profile (Figure 5.14) showed quick temperature changes and steep thermal gradients during the period from 2100 to 1400 hours. Temperatures at the 35 feet level cooled by 12.2°F during the period from 2300 to 0300 hours, and included was a sharp 5.0°F cooling at the development hour. In the nine hours that followed, a steep 19.1°F warming was observed and there were significant temperature changes of 4.6 and 3.6°F at 0800 and 1100 hours respectively. The 200 feet level temperatures fell by 5.3°F in the period between 2400 and 0400 hours. Thereafter, in general, temperatures increased by roughly 12.0°F with a marked 3.4°F change at 1100 hours. A cooling trend between 0000 and 0300 hours at the 810 feet level was followed by a sharp warming of 6.8°F in the next hour. During the remainder of the period temperature varied

Figure 5.14

Temperature and Wind Variations During Development/Decay Period of Case 78



T —Temperature at 3 Levels (feet)

WS—Wind Speed at 2 Levels (feet)

SS —Speed Shear

over a narrow 4.1°F range.

The period under survey was a very complicated one, and difficulty was encountered in the assessment of the weather processes responsible for the inversion development and decay. In general terms, the inversion structure is related to frontal disturbance.

As the frontal boundary approached, the near surface air layer cooled markedly due to radiative processes in the cold dry air. The higher air layers were less significantly affected as they were influenced by the mild Pacific air. The inversions in both layers developed simultaneously at 0100 hours. As the frontal boundary crossed, air of dissimilar properties flowed subadjacently, and a zone of strong speed shear (20-26 m.p.h.) formed between them. That is, large differences in velocity existed between the lower level and the higher level. Turbulent mixing of the warm air mass induced snowfall. As the base layer of the cloud descended to 1,000 feet and snowfall started, the inversion in the 35-810 feet layer decay at 1000 hours. With a lag of one hour the inversion in the 35-200 feet layer dissipated. The time lag involved for the decay process can be presumably explained by the forward tilt of the warm front at a slight angle, thereby causing the 810 feet level to be most effectively heated first.

Frontal inversions, reported Williamson (1973), arise in connection with the interface of two air masses of different density and temperature. Though the motion of a cold or warm front is principally horizontal, an inversion exists for both. The temperature difference between the air masses determines the strength of the inversion; and, the inversion serves to sustain the front as it forms a blanket which prevents the vertical transfer of heat and moisture between the air masses.

5.3.3 Summary

A striking aspect of the development and decay of Cluster 3 inversions is their temporal variability in the diurnal cycle. This arises because of the dynamic and the transient character of the weather situation associated with them. Synoptic systems differ markedly in size and intensity throughout their individual life cycle and from one sequence to the next, and their pattern can change quickly at any time of the day or night. The foregoing is reflected by these short-lived inversions of duration less than 20 hours.

Cluster 3 inversions developed early in the nocturnal period when the weather scene is influenced by anticyclonically controlled cool north-westerly air. The development structure responded to the diurnal effects of solar radiation heating. With the development of the 35-200 feet layer inversion, convective processes lifted the inversion surface with a time lag of up to 3 hours to the higher 35-810 feet layer. Complications in structural behaviour arise if fronts are present. These are caused by their dynamic activity and thermal properties. Analysis attributed the simultaneous development of the inversions in both layers, late in the nocturnal period, to frontal activity.

Complexity in inversion structure and related weather process is also encountered at decay. Investigation revealed that the decay structure, in one instance, was caused by Gulf air as it drifted into the area; and in another instance, it was caused by frontal disturbance associated with a minor surge of Arctic air. Regardless of the dynamic changes, the notable synoptic condition when the inversions decay simultaneously in both layers, is snowfall commencement.

5.4 Cluster 8

5.4.1 Preliminary Remarks

Cluster 8 inversions were identified by Bell (1974) as advectional based upon southerly and southwesterly air. The average properties of this cluster indicate that it is characterized by the lowest pressure, wind speed, wind shear and sky obscurity, but the highest intensity. The latter is the most striking property of the cluster and it has a -53.7°F average inversion intensity. Table 5.10 provides the average properties for each inversion in the cluster.

An assemblage of four inversion cases makes the cluster size the smallest of the selected clusters. This quantity is equivalent to 20 per cent of the inversions in the advective clusters. A noticeable aspect of three of the inversions is their temporal proximity -- they occurred one after another between the 21-23 February 1971. For the winter months, in February the sun is highest in the sky and daytime temperature rise may be considerable. The other inversion case occurred late in January.

The three February inversions developed at the same time (1800 hours), persisted for durations ranging from 15-18 hours, and decayed in the period delimited by sunrise (0800 hours) and time of greatest change in temperature (1100 hours). The January case developed later at 2100 hours, and was sustained for 16 hours before it decayed at 1200 hours.

Cluster 8 inversions in the 35-200 feet layer are of shorter duration than their counterpart in the 35-810 feet layer. The lower inversions developed either simultaneously with or after, and decayed before, the

Table 5.10

Average Properties of Inversion

Cases in Cluster 8

Case Number	Date	Development Hour	Inversion Duration (Hours)	Decay Hour	Inversion Intensity (°F/1000')	Sky Obscurity (Tenths)	Temper-ature (°F)	Pressure (m.b.)	Wind Speed (m.p.h.)	Wind Shear (m.p.h./x feet)	Wind Direction
26	Feb. 21'71	1800	18	1100	-55.9	0.2	9.6	1023.4	7.6	6.1	S
30	Feb. 22'71	1800	18	1100	-64.6	00	14.3	1010.0	10.5	5.1	S
49	Jan. 26'70	2100	16	1200	-40.3	2.1	13.2	1008.2	11.8	7.0	SW
52	Feb. 23'71	1800	15	0800	-51.6	3.8	16.8	1004.9	6.6	2.6	S

higher inversions.

5.4.2 Selected Inversion Case

Although Case 49 deviated by developing at a later hour in January, yet its structural behaviour and average properties were similar to the other inversion cases. Furthermore, its development and decay times are in accordance with the tenets of the model (Ch. 2). Inversion Case 30 is chosen for detailed analysis, because it is the median case of the cluster and is encompassed by the two other February inversions.

5.4.2. (a) Inversion Case 30

On the day prior to inversion Case 30 development, Case 26 had developed at 1800 hours and, after persisting for 18 hours, it had decayed at 1100 hours. Six hours of positive lapses in the 35-200 feet layer were then followed by the development of Case 30 at 1800 hours. This 18-hour duration inversion decayed at 1100 hours. The associated 35-810 feet layer inversion developed one hour earlier than Case 26, was maintained for 44 hours, and decayed one hour later than Case 30. Positive lapses for six hours then preceded the simultaneous development of Case 52 in both layers at 1800 hours.

Mild and sunny weather prevailed across the

Prairies throughout this period of time. After the 15 February, Pacific air advanced eastward over the Great Plains and the Midwest, while Gulf of Mexico air pushed northward into the upper south and north-east of the U.S.A., displacing Arctic air. Fast moving westerlies across central Canada excluded Arctic air from the weather making scene, and southern Canada experienced a warm ten days. It was not until the very end of the month that a strong northerly stream of air penetrated southward to change the weather pattern (Weatherwise, 1971, p. 82).

5.4.2. (a) (1) Development of Case 30

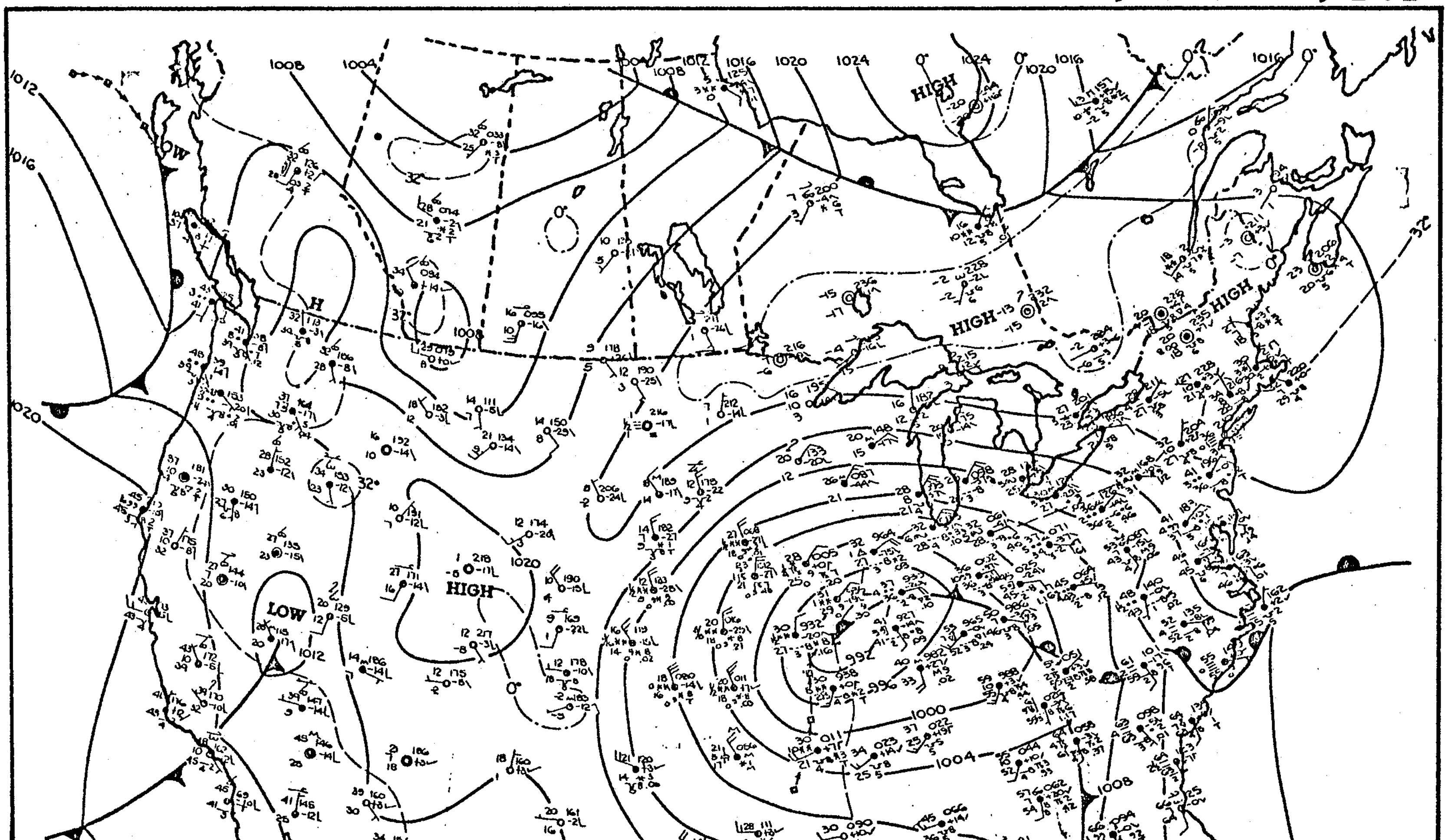
On the development day of Case 30, February 22, the weather scene was very much as that described above. Winnipeg's weather was influenced by a weak ridge of high pressure that was slowly being pushed to the north-east. Cyclonically controlled Maritime Polar (mP) westerly air in its progression from the southern British Columbia coast pushed the ridge eastward. Gulf air associated with a well-defined depression (990 m.b.) pushed the ridge to the north (Figure 5.15). Winnipeg's weather was described as -- "Mild and sunny with fog in the morning and light winds" (Atmos. Environ. Service, Monthly Meteor. Summary, 1971).

Hourly synoptic conditions for a development

FIGURE 5.15

SYNOPTIC SITUATION ON DAY OF DEVELOPMENT OF INVERSION CASE 30

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. MONDAY, FEBRUARY 22, 1971



period from 1000 to 1900 hours (Table 5.11) were favourable for the formation of nocturnal, radiative type inversions. Sky obscurity was 1/10th cloud cover of the CI type at 25,000 feet. Moderate winds reduced in speed with approach of the development hour. At the 35 feet level, south-easterly winds were less than 13 m.p.h.; while at the 810 feet level, southerly winds were not in excess of 21 m.p.h. Relatively low speed shear dropped to less than 6 m.p.h. from 1500 hours. A sharp 7 m.b. pressure fall occurred during this period.

Out of a possible 10.5 hours of sunshine, the development day received 7.6 hours with an initial thirty minutes at 1000 hours due to the presence of fog. Seven consecutive hours of maximum hourly sunshine were then followed by a reduction to six minutes at 1800 hours. It was at this time that the inversion developed in the 35-200 feet layer.

The temperature profile (Figure 5.16) showed marked increases, especially at the near surface level, during the period of sunshine. At the 35 feet level, temperatures increased by 16.3°F until 1600 hours. After an initial 1.0°F drop in the next hour, the magnitude of the cooling increased thereafter. A continuous, weaker warming of 12.5°F was observed at the 200 feet level. The 810 feet level temperature exhibited a similar trend,

Table 5.11

Synoptic Conditions During Development Period

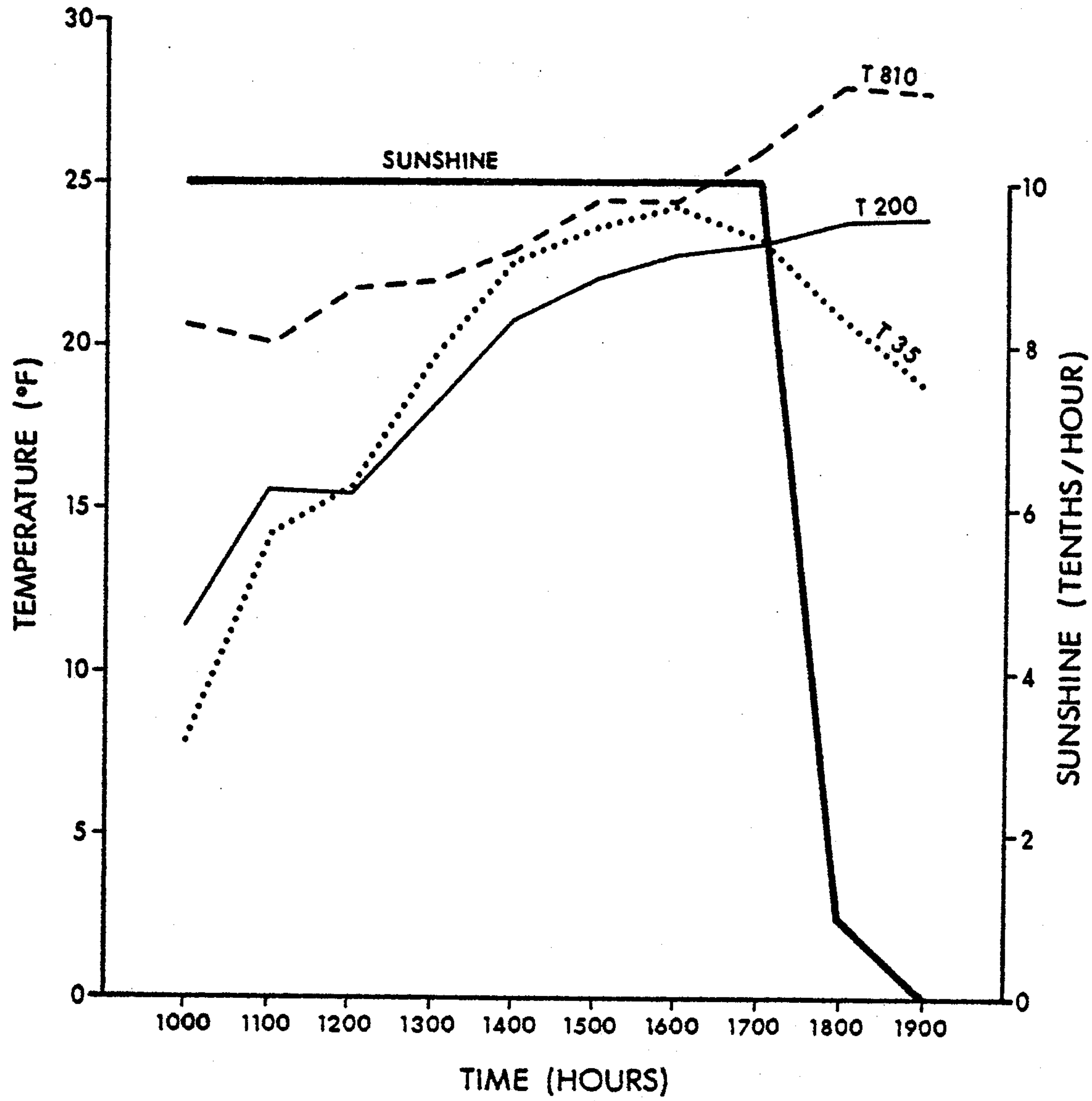
of Case 30

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (Tenths)	Cloud Type	Cloud Height (Feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (Tenths)	Sunshine Daily Total (Hours)	Sunshine Total Possible (Hours)
1000	-20.6	-16.4	170	8	180	17	9	8.0	11.4	20.7	1	F,IF	Unlmtd.	1019.8	A	15	5		
1100	-8.6	-7.7	160	8	170	20	12	14.2	15.6	20.1	0	None	----	1019.1	A	15	10		
1200	0.2	-7.9	170	13	180	21	8	15.6	15.5	21.7	0	None	----	1018.3	A	15	10		
1300	9.1	-3.1	150	13	170	20	7	19.6	18.1	22.0	0	None	----	1017.2	A	15	10		
1400	10.1	-0.4	140	10	180	19	9	22.6	20.9	22.9	0	None	----	1016.2	A	15	10		
1500	9.4	-1.0	150	12	180	16	4	23.6	22.0	24.4	0	None	----	1015.3	A	15	10		
1600	10.3	-0.1	150	10	200	11	1	24.3	22.7	24.4	1	Cl	25.0	1014.3	A	15	10	7.6	10.5
1700	1.3	-3.3	140	9	190	14	5	23.3	23.1	25.9	1	Cl	25.0	1014.1	A	15	10		
1800*	-17.4	-9.1	150	11	200	15	4	20.9	23.8	28.0	1	Cl	25.0	1013.2	A	15	1		
1900	-30.5	-11.6	150	13	200	14	1	18.8	23.9	27.8	1	Cl	25.0	1012.8	A	15	0		

*Inversion developed at 1800 hours in the 35-200 feet layer.

Figure 5.16

Temperature and Sunshine Variations During Development Period of Case 30



T – TEMPERATURE AT 3 LEVELS (FEET)

but the amplitude of warming was smaller amounting to 7.3°F until 1800 hours.

Temperature stratification in the lowest 810 feet is significantly controlled by the diurnal effects of solar radiation heating. The sun initially heats the ground and it is mainly from the ground that the atmosphere is heated. Molecular heat transfer (conductive processes) gives way to convective processes a short distance above the surface.

As the sun angle lowered, the surface cooled radiatively. To preserve a balance sensible heat from the overlying warmer air is transferred to the cooler surface. This process probably caused inversion Case 30 to develop in the 35-200 feet layer at 1800 hours. Since the 810 feet level was further removed from the surface and was presumably less significantly influenced by solar heating, the 35-810 feet layer inversion persisted through this time.

This physical process has been described by Ball (1960, p. 483). He explained that when the ground is strongly heated by solar radiation, convective mixing occurs in the lower atmosphere, and while this heating is in progress there is a shallow layer, often less than 30 meters deep, which is markedly superadiabatic. This shallow mixed layer is often surmounted by a well-defined stable layer which may have been formed mainly by convective mixing of the layers below, or more frequently results from the sharpening of the pre-existing inversion which has a limited vertical extent in the convective column.

5.4.2. (a) (2) Decay of Case 30

As the decay times of the inversions in both layers virtually coincided with the hours of greatest decay frequency (Ch. 2), it is anticipated that the decay is primarily due to solar radiation heating. The sunshine record reinforces this assumption. On the decay day 10.2 hours of sunshine out of a possible 10.6 hours were received.

Furthermore, the weather situation at Winnipeg was favourable to the decay of inversions in the radiative heat gain period. On the decay day, February 23, the weather was described as -- "Mild and sunny with light winds" (Atmos. Environ. Service, Monthly Meteor. Summary, 1971).

Maritime Polar (mP) westerly air under the control of a low pressure system dominated the weather pattern. To the south-east of Manitoba was a well-defined cyclonic system associated with Gulf air that was curving north-eastward to the Atlantic Ocean. A trowel of Maritime

Pacific air was to the immediate south-west of southern Manitoba (Figure 5.17).

Hourly synoptic conditions for a decay period from 0500 to 1400 hours are shown in Table 5.12 and are similar to those described for the development period. Sky obscurity was 1/10th cloud cover of the CI type at 25,000 feet. Winds were slight: at the 35 feet level southerly winds were less than 11 m.p.h., while at the 810 feet level south-westerly winds were not in excess of 21 m.p.h. As expected, speed shear was relatively low. As the depression strengthened, pressure fell gradually from 1009.0 to 1006.8 m.b. during this period.

In the early portion of the decay period, prior to sunshine receipt, large temperature differences existed between the 35 feet level and the two higher levels (Figure 5.18). This point is well borne out by the 35-200 feet inversion lapse rate: it was -65.4°F one hour prior to the decay hour.

A rapid 20.6°F warming which began at 0800 hours was observed at the 35 feet level. Temperatures at the 200 feet level after initially fluctuating over a 4.5°F range until 1100 hours, continuously warmed up by 7.6°F. The 810 feet level displayed a somewhat different temperature trend. A regular 7.2°F cooling to 1200 hours was followed by a weak warming.

FIGURE 5.17

SYNOPTIC SITUATION ON DAY OF DECAY OF INVERSION CASE 30

SURFACE WEATHER MAP AT 0600 HOURS C.S.T. TUESDAY, FEBRUARY 23, 1971

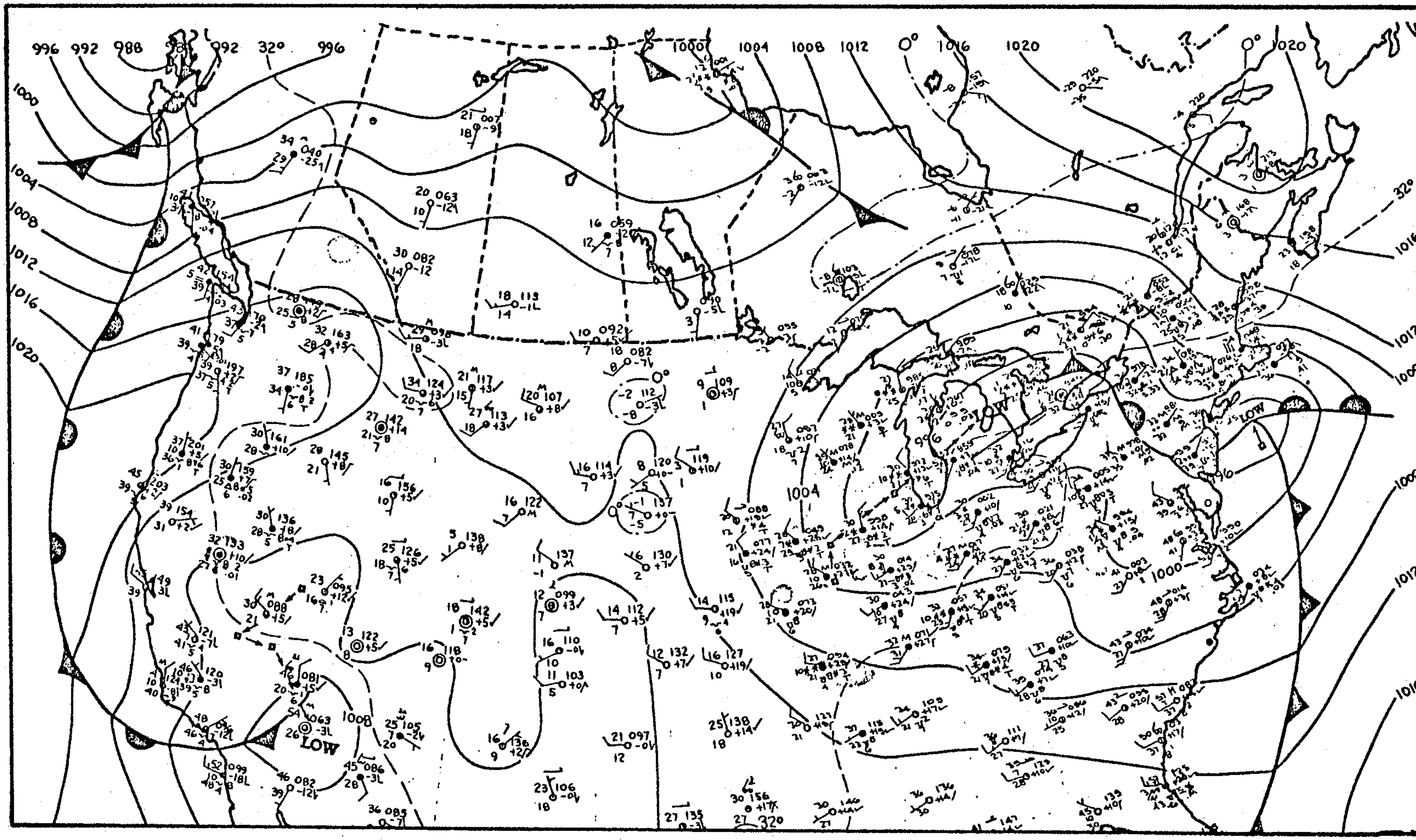


Table 5.12

Synoptic Conditions During Decay Period

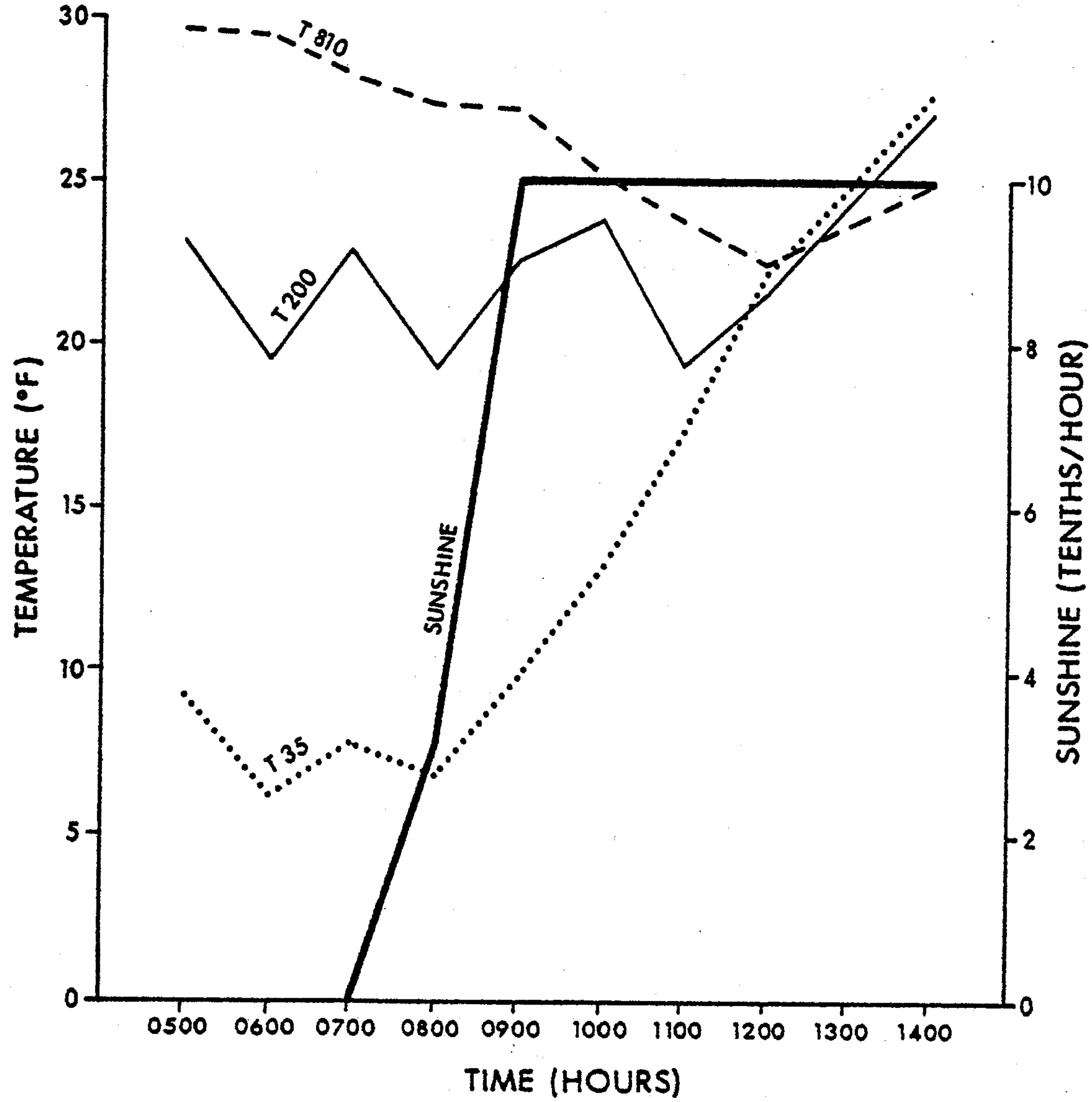
of Case 30

Time (Hours)	Lapse Rate (°F/1000') [35-200']	Lapse Rate (°F/1000') [35-810']	Wind Dirn. [35']	Wind Speed (m.p.h.) [35']	Wind Dirn. [810']	Wind Speed (m.p.h.) [810']	Speed Shear (m.p.h.)	Temp. (°F) [35']	Temp. (°F) [200']	Temp. (°F) [810']	Sky Obs. (Tenths)	Cloud Type	Cloud Height (Feet)	Pressure (m.b.)	Snowfall (A-Absent) (P-Present)	Visibility (miles)	Hourly Sunshine (Tenths)	Sunshine Daily Total (Hours)	Sunshine Total Possible (Hours)
0500	-84.1	-26.2	190	8	220	16	8	9.3	23.2	29.7	0	None	----	1008.8	A	15	0		
0600	-79.8	-29.9	170	11	230	21	10	6.3	19.5	29.5	0	None	----	1009.0	A	15	0		
0700	-91.8	-26.2	180	9	240	13	4	7.8	22.9	28.1	1	Cl	25.0	1008.9	A	15	0		
0800	-74.9	-26.3	170	8	250	11	3	6.9	19.3	27.3	1	Cl	25.0	1008.8	A	15	3		
0900	-78.3	-22.6	190	8	250	11	3	9.7	22.6	27.2	1	Cl	25.0	1008.7	A	15	10		
1000	-65.4	-15.6	210	9	250	14	5	13.0	23.8	25.1	1	Cl	25.0	1008.4	A	15	10	9.4	10.6
1100*	-13.2	-8.5	200	8	230	13	5	17.2	19.4	23.8	1	Cl	25.0	1008.4	A	15	10		
1200*	2.8	-0.5	200	5	240	12	7	22.1	21.6	22.5	1	Cl	25.0	1008.0	A	15	10		
1300	2.3	1.5	180	8	230	12	4	24.8	24.4	23.6	1	Cl	25.0	1007.3	A	15	10		
1400	3.1	3.3	180	9	230	11	2	27.5	27.0	24.9	1	Cl	25.0	1006.8	A	15	10		

*Inversion decayed at 1100 hours in the 35-200 feet layer and at 1200 hours in the 35-810 feet layer.

Figure 5.18

Temperature and Sunshine Variations
During Decay Period of Case 30



T – TEMPERATURE AT 3 LEVELS (FEET)

The diurnal effects of solar radiation heating are the single most important factor responsible for the inversion decay. It is expected that the diurnal effects would cause the decay of the inversion in the 35-200 feet layer; but analysis detected that this effect is less influential in the deeper 35-810 feet layer (see Ch. 4, Section 4.2.2). Enquiry should therefore be focussed on accounting for the decay of the 35-810 feet layer inversion one hour after the 35-200 feet layer.

Radiative heating of the lower atmosphere was aided by the gentle winds. This arises as the air stayed longer in contact with the radiatively heat surface. A heat reservoir was quickly built up at the surface because large amounts of sunshine were received on several days in the presence of a warm airflow. It is only when temperature differences occur that heat flow arises. Since the vertical temperature gradient showed large temperature differences in the early portion of the decay period, heat flow was thus directed downwards. Convective coupling of the lower air layer with the higher occurred around 1200 hours; the decay time of the inversion in the 35-810 feet layer. Goff and Hudson (1972, p. 20) found at central Oklahoma that the boundary layer and the free atmosphere are not coupled until 5.5 hours after sunrise, or around noon.

5.4.3 Summary

In general Cluster 8 inversions are restrictive in character. They occurred in the latter part of February, developed at a particular time (1800 hours), were of similar duration, and decayed in the heat gain period.

Cyclonic circulations of warm Pacific and Gulf air excluded Arctic air from the weather making scene during the period of Cluster 8 inversions. As warm air streams cross a cold surface they transfer heat to the surface. It seems reasonable to suspect a relation between advective processes and the inversion development and decay structures. The surface however, is heated not only through the agency of atmospheric advection, but also through direct solar radiation. Analysis determined that the daily rhythm of radiative heating and cooling is the important cause of the development and decay of 35-200 feet layer inversions.

When these inversions are studied in the deeper 35-810 feet layer, their behaviour is effected more by advection. However when sunshine duration is high over several days, a heat reservoir is quickly built up at the surface. Coupling of the lower atmosphere with the higher occurs around noon. The 35-810 feet layer inversion is then destroyed by the diurnal effects of radiation heating complemented by atmospheric advection.

CHAPTER VI

Summary of Results and the Implications Regarding Air Pollution Potential

6.1 Radiative Clusters

Variation in inversion structure arises from variation in weather process. The important factor that controls the structure of inversions in Cluster 2 is the cyclical component of diurnal temperature variation which is a function of solar radiation heating. The structure of the 35-200 feet layer inversions follow a daily rhythm -- developing with initial cooling through loss of longwave radiation and decaying after several hours of heating.

These inversions are associated with anticyclonic circulations of cold, clear Arctic air (cA). Under such synoptic systems, the associated higher 35-810 feet layer inversions very likely respond to the process of subsidence, rather than radiation. With decline of the sun angle, very little cooling is required to convert the subsidence inversion aloft to a surface-based inversion.

Analysis detected that the 35-810 feet layer inversions are maintained for the duration of the anticyclonic system. On an average, they are maintained for 45 hours.

The single most important factor causing their complete destruction is an exchange in air mass with contrasting properties.

Because of their subsidence inversions and gentle winds, anticyclones are conducive to high concentrations of pollutants at low levels, especially in winter when radiational inversion reinforces this inversion (Williamson, 1973). A double inversion with lower, radiation and upper, subsidence inversions, can cause extremely heavy accumulation of air pollutants (Stringer, 1972).

The diurnal rhythmic behaviour of the lower layer inversions facilitates the establishment of positive lapse rates for brief periods notably around noon. This means that the effective depth of the mixing layer is increased to 200 feet diurnally. Although this development is brief, it allows greater ventilation so that air pollutants can be dispersed and diluted more readily. It is important to realize, however, that during this time the higher inversion acts as a lid to hold the pollutants within the mixing layer. The air in this mixing layer becomes incorporated in the inversion when the high subsidence inversion base descends close to the ground at night and restricts the depth of the underlying mixing layer.

When attention turns to clusters that are increasingly different from the distinct radiative Cluster 2, the structure of inversions and related weather processes increase in complexity. The cyclical component due to solar heating becomes less noticeable as it is progressively dominated by other meteorological elements.

Cluster 4 inversions may be identified as being of radiative and nocturnal origin on the basis of their structural behaviour. The sun initially heats the ground and it is mainly from the ground that the atmosphere is heated. The inversions in the 35-200 feet layer generally develop and decay first, and the processes are observed with a lag of up to 3 hours in the 35-810 feet layer.

The development structure of these inversions is the integrated result of the diurnal effects, the time snowfall ends, and the character of the wind speed profile. Their development is favoured when cool north-westerly air under the control of an anticyclonic system replace warm and moist air, so that, snow flurries end and sky obscurity lowers. The earlier in the day this phenomena occurs, the earlier Cluster 4 inversions develop in the nocturnal period. Once the lower inversion is established, vertical propogation of the inversion surface to the deeper 35-810 feet layer depends on the wind speed profile. With increased speed shear, the vertical propogation by turbulent transfer is accelerated.

The most important factor responsible for the decay of the inversions in the lowest 810 feet is a change in airflow type in which cooler air is replaced by a cyclonic circulation of warmer air. If this process is complemented by direct solar heating, the decay of the inversions in both layers is simultaneous. If not, the decay structure depends principally on the time airflow interchange is effected.

Cluster 4 inversions usually develop and decay earlier in the 35-200 feet layer than in the 35-810 feet layer. In neither of these layers does the duration of the inversion exceed 20 hours, presumably because synoptic systems with dissimilar airflows change fairly rapidly. Positive lapses lasting more than 5 hours occur before and after Cluster 4 inversions. These two features together indicate that the hazard of potential air pollution accumulation is not great. It is instructive to note that this inversion type occurs most frequently in winter in the Winnipeg area.

The results of this analysis justified the identification of Cluster 7 inversions as transitional between the radiative and advective cluster groups. Consequently, it was comparatively difficult to assess the weather processes related to the development and decay of these inversions. This is because such processes as radiation and advection act seperately or collectively to control these inversions.

When the advective process is operating, the 35-810 feet layer inversions develop before and decay after the 35-200 feet layer inversions. These inversions are frequently connected with weak cyclonic circulations of warm Maritime Polar air. When the lower inversions develop and decay before their higher layer counterparts, the diurnal effects of solar heating are more influential. However, since this process is less significant in higher portions of the boundary layer, advective influences play a critical role in the structure of the higher layer inversions. Irrespective of the weather process, a one hour lag is required for the development process to extend to either the lower or the higher layer.

Postive lapses lasting an average of 10 hours, precede and follow Cluster 7 inversions which have a duration of less than 20 hours. When the lower layer inversion develops first, pollution accumulation is greater as the depth of the mixing layer is reduced earlier. However, because of their brevity and their alternation with positive lapses, these inversions are not conducive to a high concentration of air pollutants.

In sum, the structural behaviour of inversions in the distinct radiative Cluster 2 is conducive to the highest air pollution accumulation hazard. Care should therefore be exercised in the emission of pollutants in the atmosphere when the weather scene is dominated by an anticyclonic system associated with the circulation of cold, clear Arctic air. In the presence of such a system, the time best suited to the emission of pollutants is around noon when the scale of the effective mixing layer is increased to 200 feet for a limited period.

6.2 Advective Clusters

The structures of the inversions in the advective clusters are significantly related to the irregular component of diurnal temperature variation. This component arises from the effects of advective heating and cooling induced by air mass movement. In particular the passage of a front usually causes large shifts in temperature. The dynamic nature of the irregular component provokes complexities with respect to the structure of these inversions and related weather processes.

Even Cluster 1, the distinctively advective cluster, demonstrates a composite structure. This cluster is composed of two structure classes -- inversions lasting not less than 30 hours behaved differently to those maintained for shorter periods. Although they are both largely generated by atmospheric advection, when solar radiative heating and nocturnal cooling are effective, diurnally rhythmic behaviour is observed in the 35-200 feet layer.

Typically the development of these inversions are related to the advection of warm Maritime Polar westerly air under the control of cyclonic circulations (usually Alberta low). These inversions develop in the 35-200 feet layer due to basal chilling of the warm air stream as it crosses over the cold winter continental surface. A lag of up to 3 hours is required for the development process to extend to the deeper 35-810 feet layer. This time lag depends on the rate and depth of cooling of the overlying air and is a function of the wind speed and temperature profiles.

Usually these inversions decay simultaneously in both layers in the early morning during which time the increase in speed of lower atmosphere advection is favoured. Potential instability is thus probably generated. The mechanism causing its release is slow vertical motion induced through differential temperature advection associated with change in synoptic circulations.

As these inversions are related to the dynamic action of long-lasting synoptic systems, they are intense, persistent inversions. The inversions lasting not less than 30 hours are especially conducive to high pollution concentration. It is worth emphasizing however, that strong winds are characteristic of Cluster 1 inversions. Thus, although the effective depth of the mixing layer is not subject to temporary daytime increase when the advective process is operating, yet it is possible for air pollutants to be horizontally dispersed by the strong winds.

A striking feature of Cluster 3 is the diurnal variability of the time of inversion development and decay. In general, this arises because the inversions are related to frontal disturbances which can occur at any time of the day or night. Nevertheless, these inversions are also related to the diurnal effects of radiation heating.

When the weather scene is influenced by anticyloni-cally controlled cool north-westerly air, Cluster 3 inversions develop early in the nocturnal period. In such circumstances, inversions are structured in accordance with the basic principle of solar heating. The 35-200 feet layer inversions develop first, and less than 3 hours later convective processes lift the inversion surface to the 35-810 feet layer. In instances where frontal activity is encountered, the inversions in both layers develop simultaneously and this occurrence usually takes place late in the nocturnal period.

The decay of Cluster 3 inversions is largely a function of frontal passage. The occurrence of this phenomena is composite in character as it arises through a variety of weather patterns at any time of the day or night. Nevertheless, a common synoptic condition accompanying frontal activity at decay time is the presence of snowfall. The inversions in both layers decay at the same time when snowfall commences.

These inversions are associated with rapidly changing weather and, consequently, they are short-lived. In view of this, and the long period of positive lapses that alternate with these inversions, the hazard of air pollution accumulation is minimal. Williamson (1973, p. 159) reported that, unfortunately, little is known about the importance of frontal inversion for local air pollution because it is poorly documented due to its transient nature. Strong winds and turbulence induced by rapid pressure changes in a front usually encourage good horizontal ventilation to compensate for the limited vertical mixing layer.

Cluster 8 inversions are associated with cyclonic circulations of warm Pacific and Gulf air. The inversion behaviour results from an interplay of the irregular component of atmospheric advection with the cyclical component of solar heating. The lower 35-200 feet layer inversions respond to the latter component, while the former is more influential in the deeper 35-810 feet layer.

Thus the higher layer inversion behaviour is not diurnally cyclic.

A heat reservoir is quickly built up at the surface if near maximum possible total sunshine is received on several successive days. This condition, in the presence of advective influences, induces coupling of the lower atmosphere with the higher around noon. The higher layer inversion then decays one hour after the lower layer inversion.

One of the two components in the process of inversion formation aids in reducing the hazard of high air pollution accumulation. The cyclical component produces an increase in the depth of the underlying mixing layer as positive lapse rates are established in the lower 200 feet for 6 hours. The risk of pollution accumulation is reduced as more pollutants can be dispersed and diluted in a larger vertical depth.

Inversions in Cluster 1 are conducive to the greatest concentration of potential air pollutants. If solar heating is absent or negligible, the depth of the effective mixing layer is not increased during the inversion period. A critical feature however, is the strong winds associated with these inversions which can aid in the horizontal dispersion of air pollutants. This is a necessary, though not sufficient, factor in alleviating the hazard of air pollution accumulation.

6.3 General Conclusions

This thesis has investigated the development and decay structures of winter inversions not less than 10 hours in the lowest 810 feet near Winnipeg. It seemed desirable to perform a climatological survey of this kind on two major counts: a) the temporal distribution of inversions, especially in the transitional periods corresponding to sunrise and sunset, warrants further investigation; b) the relationship of lapse rates to synoptic systems, especially for particular areas, is not adequately understood.

a) The first question was successfully investigated using a fundamental model based on the diurnal cyclical component of solar radiation heating. The core feature of the model is the times of the day relative to sunrise and sunset, when the surface layer is adjusting to the addition of and loss of solar radiant energy.

(i) Virtually all (96 per cent) of the 35-200 feet layer inversions in the winter sampling period developed in the radiative heat loss period from 1500 to 0700 hours. Most developments occurred from 1500 to 1900 hours. At the mean time of sunset (1700 hours) a peak hourly frequency of 30 per cent was observed.

(ii) Though all inversions decayed in the period from 0100 to 1400 hours, a majority of 72 per cent decayed in the radiative heat gain period ffom 0800 to 1400 hours. The peak hourly decay frequency occurred at 1100 hours; that is, 3 hours after the average time of sunrise.

(iii) The model was adjusted by a 2-hour factor to accomodate the temporal distribution of inversions in the deeper 35-810 feet layer.

b) The descriptive analytical approach utilizing selected case studies to investigate the structural behaviour of inversions during development and decay, in relation to weather processes, served to identify some of the relationships of lapse rates to synoptic systems in a continental environment. Since the behaviour of air pollutants is mainly dependent on weather processes, the present work is of practical value in air pollution potential studies.

(i) In winter, Winnipeg may occassionally be subjected to intense and persistent inversions associated with long-lasting synoptic systems. This circumstance, presents the greatest hazard to air pollution accumulation.

Intense advective universions in the lowest 810 feet are connected with warm maritime Polar (mP) westerly air under control of cyclonic systems (usually Alberta low). A feature characteristic of these inversions is strong winds. Even in the presence of low level inversions these winds will aid the horizontal dispersion of air pollutants. Intense inversions of the radiative type are associated with anticyclonic circulations of cold, clear Arctic air (cA) from the north. Though these inversions are associated with light winds, the 35-200 feet layer inversions are subjected to temporary daytime decay around noon. This will facilitate an increase in the depth of the effective mixing layer so that pollutants can be more readily dispersed and diluted.

6.4 Suggestions for Future Research

This field of study is important climatologically but it is seldom considered, and the literature in this field is generally sparse. Its limited scope militates against detailed discussion and definitive conclusions.

Lapse rates vary both spatially and temporally and the acquisition of more detailed information will facilitate their interpretation and understanding. The period of observation and the number of variables used can be expanded. Instead of hourly averages, the use of 10-minute averages would provide a clearer insight into these processes.

The study of the relationship of lapse rate to air masses can be improved by using the methods of synoptic climatology. Inversion data can then be stratified according to types of air masses and synoptic situations. Inversion structures may be studied in a step-wise progression. That is, with the 35-200 feet layer as the initial block, structures can be determined for the 200-400 feet layer, then the 400-600 feet layer, and finally for the 600-810 feet layer.

The main inversion features of intensity, duration and frequency can be integrated with the ascertained structural behaviour of inversions during development and decay. Results may then be used to establish an inversion index that would enable more definitive statements to be made of air pollution potential in the Winnipeg area. It is expected that this will greatly contribute to corrent knowledge of inversion character in a continental environment.

APPENDIX 1

Conversion Tables

All units of measurement used in this study are imperial. That is, temperature is measured in degrees Fahrenheit, wind in miles per hour, and height in feet. This is a result of the fact that the meteorological tower is part of the Canadian micrometeorological tower network which utilized imperial units at the time of observation. Furthermore, due to the difficulty involved and the considerable loss of precision that can result, it seemed inappropriate to convert the units. Conversion tables are provided to facilitate interconversion between the imperial system and the metric system.

Temperature

Temperature in °C = 5/9 (temperature in °F −32°)

Temperature in °F = 9/5 (temperature in °C) +32°

Temperature in °K = temperature in °C + 273.15°

Fahrenheit scale to centigrade

°F	0	1	2	3	4	5	6	7	8	9
-60	-51.1	-51.7	-52.2	-52.8	-53.3	-53.9	-54.4	-55.0	-55.6	-56.1
-50	-45.6	-46.1	-46.7	-47.2	-47.8	-48.3	-48.9	-49.4	-50.0	-50.6
-40	-40.0	-40.6	-41.1	-41.7	-42.2	-42.8	-43.3	-43.9	-44.4	-45.0
-30	-34.4	-35.0	-35.6	-36.1	-36.7	-37.2	-37.8	-38.3	-38.9	-39.4
-20	-28.9	-29.4	-30.0	-30.6	-31.1	-31.7	-32.2	-32.8	-33.3	-33.9
-10	-23.3	-23.9	-24.4	-25.0	-25.6	-26.1	-26.7	-27.2	-27.8	-28.3
- 0	-17.8	-18.3	-18.9	-19.4	-20.0	-20.6	-21.1	-21.7	-22.2	-22.8
+ 0	-17.8	-17.2	-16.7	-16.1	-15.6	-15.0	-14.4	-13.9	-13.3	-12.8
10	-12.2	-11.7	-11.1	-10.6	-10.0	- 9.4	- 8.9	- 8.3	- 7.8	- 7.2
20	- 6.7	- 6.1	- 5.6	- 5.0	- 4.4	- 3.9	- 3.3	- 2.8	- 2.2	- 1.7
30	- 1.1	- 0.6	0.0	0.6	1.1	1.7	2.2	2.8	3.3	3.9
40	4.4	5.0	5.6	6.1	6.7	7.2	7.8	8.3	8.9	9.4
50	10.0	10.6	11.1	11.7	12.2	12.8	13.3	13.9	14.4	15.0
60	15.6	16.1	16.7	172.	17.8	18.3	18.9	19.4	20.0	20.6
70	21.1	21.7	22.2	22.8	23.3	23.9	24.4	25.0	25.6	26.1
80	26.7	27.2	27.8	28.3	28.9	29.4	30.0	30.6	31.1	31.7
90	32.2	32.8	33.3	33.9	34.4	35.0	35.6	36.1	36.7	37.2
100	37.8	38.3	38.9	39.4	40.0	40.6	41.1	41.7	42.2	42.8
110	43.3	43.9	44.4	45.0	45.6	46.1	46.7	47.2	47.8	48.3

Speed

1 meter per second = 3.281 feet per second

1 meter per second = 3.6 kilometers per hour = 2.237 miles per hour

1 kilometer per hour = 0.62 mile per hour

1 knot = 1 nautical mile per hour = 1.151 miles per hour

Conversion of speeds

Knots	mph	m/sec	Knots	mph	m/sec
1	1.2	0.5	60	69.1	30.9
2	2.3	1.0	70	80.6	36.0
3	3.5	1.5	80	92.1	41.2
4	4.6	2.1	90	103.6	46.3
5	5.8	2.6	100	115.2	51.5
6	6.9	3.1	110	126.7	56.6
7	8.1	3.6	120	138.2	61.8
8	9.2	4.1	130	149.7	66.9
9	10.4	4.6	140	161.2	72.1
10	11.5	5.1	150	172.7	77.2
20	23.0	10.3	160	184.2	82.4
30	34.5	15.4	170	195.8	87.5
40	46.1	20.6	180	207.3	92.7
50	57.6	25.7	190	218.8	97.8
			200	230.3	103.0

Length

1 kilometer = 1,000 meters = 0.6214 mile = 3,281 feet

1 meter = 100 centimeters = 1.0936 yards = 3.281 feet = 39.37 inches

1 centimeter = 10 millimeters = 0.3937 inch

1 micron = 10^{-6} meter = 10^{-4} centimeter = 3.937×10^{-5} inch

Conversion of stature miles to nautical miles and kilometers

Statute miles	Nautical miles	Kilometers
1	0.87	1.6
2	1.74	3.2
3	2.60	4.8
4	3.47	6.4
5	4.34	8.0
6	5.21	9.7
7	6.08	11.3
8	6.95	12.9
9	7.82	14.5
10	8.68	16.1
20	17.37	32.2
30	26.05	48.3
40	34.74	64.4
50	43.42	80.5
60	52.10	96.6
70	60.79	112.7
80	69.47	128.7
90	78.16	144.8

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