ANALYSES OF SELECTED CLIMATIC FACTORS IMPORTANT TO AGRICULTURE IN NORTHERN MANITOBA AND SASKATCHEWAN: RADIATION AND TEMPERATURE

by

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A thesis presented to the Faculty
of Graduate Studies
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ABSTRACT

This study is a first step towards investigating the climatic potential for agriculture in an area where more intensive cultivation and an extension of the arable area are possible. The study area consists of a rectangular zone in the northern agricultural areas of Manitoba and Saskatchewan, stretching from 52° - 55°N. and 101° - 110°W.

An assessment of the agricultural climate of the area is made using 11 meteorological stations as reference points. Integration of the data available from these sites along with estimation procedures has enabled most climatic variables of a thermal nature to be treated. Directly measured variables include global radiation, sunshine duration and air temperature. Estimates have been made of net radiation and for arctic front locations. Agrometeorological factors, which have been shown to be of operational significance, are also considered including spring and autumn frost series, the frost free period and temperature summations.

As each variable is analysed, the data base used is critically assessed and the importance of the variable to crop production outlined.

Results are presented in two sections. One deals with radiation and the other with daylight and temperature. Although

voluminous, the results are far from being a comprehensive survey of the agroclimate of this area.

It is concluded that a great deal more analysis of past weather records, more instrumental recording of variables with agricultural significance and further basic research is required in areas where thermal constraints to agricultural production predominate.

CHAPTER I

INTRODUCTION

(a) Objectives of an agroclimatic study.

In general, agroclimatic studies have tended to move in two directions (Domrös 1974). On the one hand, the effects of climate on crop yields are analysed in order to quantatively evaluate expected yields under given climatic conditions, or to ascertain the reasons for possible damage or loss of yield attributable to the climate. On the other hand the objective, as in the present study, is to relate the climatic conditions of a region to the general climatic requirements of cultivated crops. Climatic potential is assessed in order to identify ways of increasing agricultural productivity. As Cochemé and Franquin (1967, 1) have stated, "Any plan for increasing agricultural production can benefit from such a survey; whether the plan involves intensifying existing cultivations, extending them, introducing new crops or techniques, or improving protection against pests and parasites - whatever the plan may be, the influence of climate cannot be ignored."

Despite the obvious importance of regional agroclimatic studies, the number of major publications in English in this area is limited. Those that are readily available indicate that thermal limitations to agricultural production have been poorly treated. The English language qualification is necessary since 125 agroclimatic handbooks have been published for all agriculturally important provinces, territories and republics of the U.S.S.R. (Sinelshikov 1965). Excluding these, seven agroclimatological surveys deserve particular mention: Agricultural climatologies of the Yass Valley and Katherine Area, N.T. by Slatyer (1960a, b), in the semi-arid and arid zones of the near East (Perrin de Brichambaut and Wallēn 1963), a semi-arid area in Africa south of the Sahara (Cochemē and Franquin 1967), the highlands of Eastern Africa (Brown and Cochemē 1973), Ceylon (Domrös 1974) and England and Wales (Smith 1976).

The two early publications by Slatyer (1960 a,b) are detailed treatments of the agricultural climate of two small areas in Australia. No consideration is given to the climatic requirements of individual crop species. Smith's (1976) study is also exclusively climatic in approach but relates to a much larger and more diverse region. To alleviate this problem, results are presented for smaller agricultural areas and expected local deviations about the mean value are also given.

Comprehensive analyses of both the agricultural climate and the climatic requirements of local crops are presented in the remaining four publications. Of these, three (Perrin de Brichambaut and Wallēn 1963: Cochemē and Franquin 1967: Brown and Cochemē 1973) are interagency projects compiled under the auspices of F.A.O., W.M.O., and U.N.E.S.C.O. Their objective was to assess the possibilities of increasing agricultural productivity in the selected regions. Similarily, Domrös (1974) attempts to devise an agroclimatic potential land classification and zoning of Ceylon according to the crops under investigation.

Attention is drawn to the fact that in only three publications (Brown and Cochemé 1973: Domrös 1974: Smith 1976) is reference made to the possibility of low temperatures being a factor in limiting crop growth potential and, in the first two of these cases, this is clearly an altitudinal rather than a latitudinal constraint. In England and Wales thermal constraints result from a combination of both elevation and latitude. It is evident, therefore, that considerably more attention is required in areas where thermal constraints upon agricultural production, rather than moisture constraints, pose the major problem - a view shared by McKendrick (1976). One such area is the secondary agricultural frontier (Prescott 1965) of Northern Manitoba and Saskatchewan. As Laut (1973, 73) states:

> "Comparison of mean May to September precipitation with potential evapotranspiration suggests that the northern agricultural areas of the Prairie Provinces receive adequate summer precipitation for cropping activities in most years and lack of soil moisture should not be a widespread environmental restriction on agriculture.
>
> However energy receipts tend to be minimal for the satisfactory production of a number of cereal grain crops. Therefore it is necessary to examine such measures of energy availability for plant growth as are available."

The objective of the present study is to examine selected climatic factors important to agriculture in Northern Manitoba and Saskatchewan.

Within Manitoba and Saskatchewan, work on the climate in relation to agriculture has not been entirely ignored. In Manitoba Shaykewich (1974) has mapped mean values of several climatic parameters of agricultural significance for the area south of Dauphin (51^{o} 06' N) and, in Saskatchewan, Frost (1972) has examined the area south of 51^{o} 30' N. Also in Saskatchewan, McKay *et al* (1967) have presented a general analysis of temperature and moisture conditions in relation to agriculture using stations with variable record length. Air temperatures and temperature sums are the only thermal variables discussed in any detail in this publication.

Several earlier geographical studies (e.g. Taylor 1957: Bennett 1959) have investigated the climatic limitations of more northerly areas. However, these works have sought to demarcate absolute limits to cultivation through a single index such as temperature rather than to evaluate the climate as a resource base for agriculture. Such indices have been important in agricultural planning policy since the days of the first pioneers (Dunbar 1973) but the severe limitations of a markedly deterministic approach are obvious. The present study makes no attempt to define precise limits to cultivation.

(b) Study area and data base

The area selected for the study included the majority of the agricultural area in the north which had not been included in previous studies, as well as areas which may have agricultural potential in the future. That more northern areas still have considerable agricultural potential appears to be in little doubt. "It is estimated that there are still about 16.2 million hectares that are capable of development for agricultural use. Over one half of this acreage may be found included in or adjacent to the areas that are now being farmed. The largest zone for future development is in the forested area of the presently occupied farms in Manitoba, Saskatchewan, Alberta, British Columbia and in the adjacent area of Yukon and N.W.T." (Agriculture Canada 1977). Beacom (1974) has estimated that 1.2 million hectares of potentially good to fair arable land exist in Northern Saskatchewan and perhaps half this figure in Manitoba. A broad latitudinal zone, from 52°N to 55°N, was adopted in order to include the majority of this area and in response to the fact that several of the climatic parameters investigated have a direct or indirect reliance upon latitude. In Manitoba, agricultural potential within this zone, but to the east of 101° longitude, is severely limited by both climate and soils so this area was omitted from the study leaving a rectangular area extending from 52° - 55°N and 101° - 110°W. The area is shown in Figure 1.1.

Meteorological observations are currently made at numerous sites within the study area. The observations and measurements made at these sites generally conform with internationally agreed regulations regarding instruments, their usage, and their exposure.

In keeping with general practice a period of 30 years was chosen for analysis. Since climate is continually changing the most recent period for which data were available was considered to be the most appropriate. This period was 1947-1976. However, by adopting the standard time period and rejecting those stations which did not exist throughout this period, or which varied in location, the number of sites from which data were collected diminished to 11; nine in Saskatchewan and two in Manitoba. The locations of each of these stations and the records used in this study are listed in Table 1.1; locations are also shown in Figure 1.1. Although locational descriptions and site histories are not readily available for Canadian meteorological stations (Catchpole and Ponce 1976) it is not thought that locational or instrumental changes have led to significant inhomogeneity of the data base since, at the level of analysis attempted here, small changes in site are unlikely to be of significance.

In general, meteorological stations are sited in order to present a representative sample of the type of area in which they are located. Nevertheless, with such a small number of stations in a relatively large study area it would be unwise to assume that 11 stations adequately represent the whole area. For this reason the use of mapping procedures to represent the data was considered inappropriate.

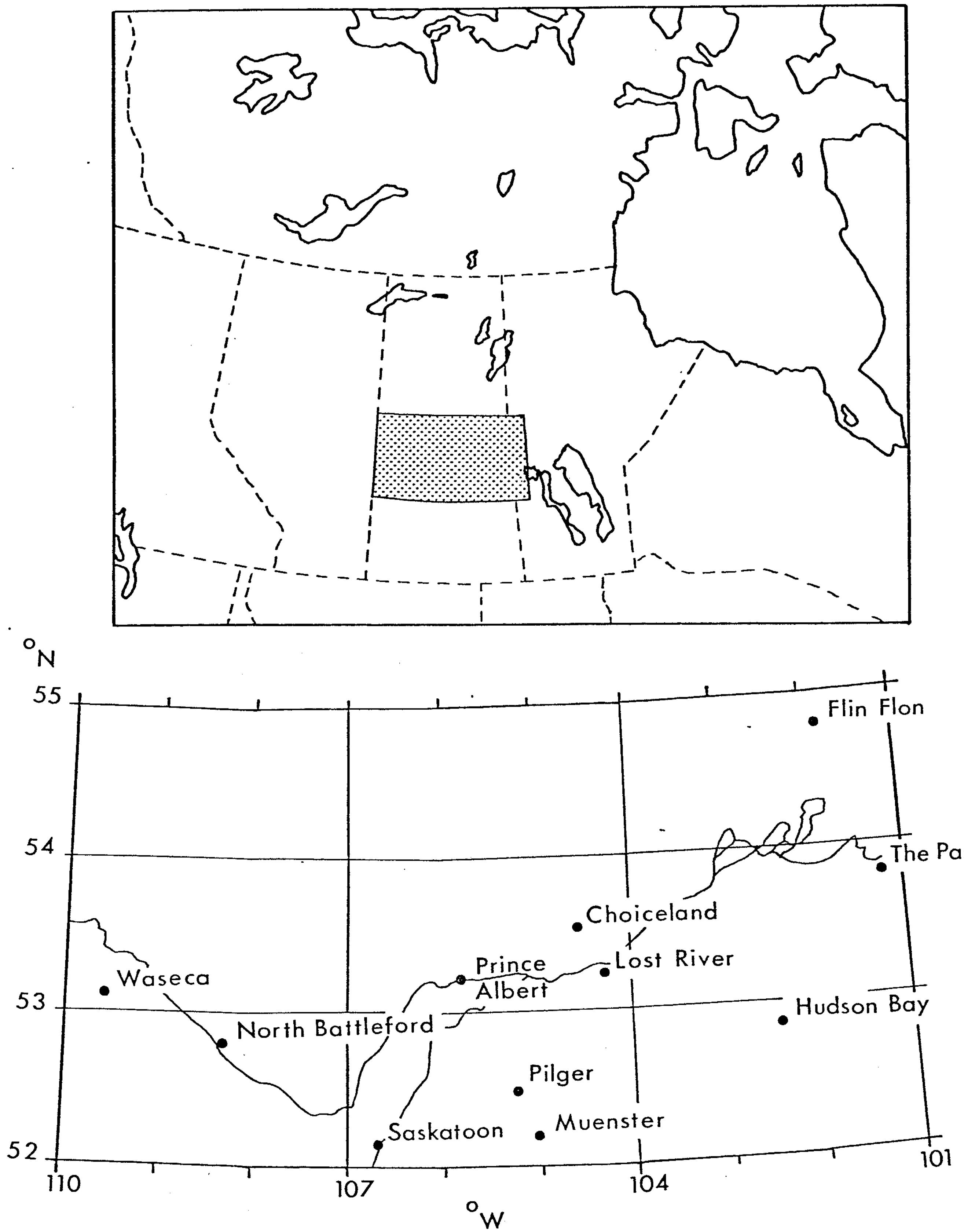


Fig. 1.1 Location of the study area and sites of meteorological stations used in this study.

TABLE 1.1: MAJOR STATIONS USED IN STUDY

STATION	LOCATION ^{o}N	^{o}W	ELEV. (M)	DATES USED	T	S	R
THE PAS A.	53^{58}	101^{06}	273	1947/1-1949/10	X		
				1949/11-1972/7	X	X	
				1972/7-1976/12	X	X	X
FLIN FLON	54^{46}	101^{31}	335	1947/1-1976/12	X		
CHOICELAND	53^{30}	104^{29}	442	1948/12-1976/12	X		
HUDSON BAY	52^{52}	102^{24}	372	1947/1-1976/12	X		
LOST RIVER	53^{17}	104^{15}	387	1947/1-1947/6	X		
	53^{17}	104^{19}	387	1947/6-1976/12	X		
NORTH BATTLEFORD A.	52^{46}	108^{15}	548	1947/1-1975/1	X		
				1975/2-1976/12	X	X	
MUENSTER	52^{12}	105^{00}	576	1947/1-1959/12	X		
				1960/10-1976/12	X		
PILGER	52^{25}	105^{09}	544	1947/1-1976/12	X		
PRINCE ALBERT A.	53^{13}	105^{41}	431	1947/1-1976/12	X	X	
SASKATOON A.	52^{10}	106^{41}	501	1947/1-1976/12	X		
WASECA	53^{08}	109^{24}	648	1947/1-1951/7	X		
				1951/12-1976/12	X		

A - AIRPORT
T - TEMPERATURE
S - SUNSHINE
R - RADIATION

(c) Plan of thesis

Following the introduction, the climatic factors treated in this thesis fall naturally into two distinct sections. The first (Chapter II) covers aspects of the radiation balance within the study area. Under (a) Background relationships, the reader is introduced to the basic principles involved in radiation receipt and the portion available for photosynthetic processes. This is followed by a more detailed treatment of solar, global and net radiation and sunshine duration under the heading (b) Specific topics.

The second section (Chapter III) considers daylength variations over the study area and the temperature conditions at each of the 11 stations. Daylength variations are presented here, in preference to Chapter II, since the duration of the light period operates in conjunction with temperature in stimulating plant development. Plant growth, on the other hand, is affected by the intensity of the light and this is the main theme of Chapter II. Daylength is treated first and the discussion then examines monthly mean daily maximum, monthly mean daily minimum and monthly mean daily air temperatures. This leads by logical progression to a consideration of temperature sums, $0^{\circ}C$ frost dates in spring and autumn, and the frost free period.

Also included in this chapter is a preliminary assessment of the relationship between cold air advection over the study area and the location of the arctic front. While frontal locations influence many climatic parameters, in this instance only temperatures are being considered so this topic is best dealt with in Chapter III.

CHAPTER II

RADIATION

(a) Background relationships

(i) The receipt of solar radiation

Radiation is a fundamental component in the energy balances of the atmosphere and the earth's surface. All bodies above a temperature of absolute zero emit radiant energy in the form of electromagnetic waves. Incessant molecular motion is the source of this thermal radiation when, as a result of interactions between molecules, part of their energy is transformed into radiation. Conversely, radiation can be absorbed by molecules and converted into kinetic and potential energy, thereby raising the temperature of the body. The emission and absorption of thermal radiation are governed by the temperature and the nature of the emitting or absorbing substance (Van Wijk and Scholte Ubing 1963,62).

The sun, which is the ultimate source of practically all of the energy used on the earth for physical and biological processes, has a surface temperature of about $6000^{\circ}K$, emits approximately 98% of its radiation in the wavelength range 0.25 - 4.0 microns(μ) and, by Wien's Law, has a wavelength of maximum emission at 0.483 μ . On the other hand, the earth, with a mean surface temperature of about $300^{\circ}K$, emits radiation in the range

3-80 μ and, again by Wien's Law, has a wavelength of maximum emission at 9.66 μ . Since the spectral range for the sun and earth are almost mutually exclusive, the former source is said to emit shortwave or solar radiation while the latter is a source of longwave or terrestrial radiation.

The rate at which radiation energy falls on a unit area of a plane surface is the radiant flux density or irradiance and is distinquished from the corresponding irradiation. The latter is the time integral of the irradiance or the amount of energy received by a given area in a specific time interval.

The total energy flux on a surface normal to the sun's rays is about 1400 Wm^{-2}. This value, the so-called solar constant, was measured in rocket experiments (Laue and Drummond 1968) and is somewhat larger than the value of 1353 Wm^{-2} used in the Smithsonian Meteorological Tables (List 1966). It is clear that this value is not in fact constant and is subject to slight variations due to the variable distance between the earth and the sun and also to changes in solar activity.

On a horizontal surface at the top of the atmosphere the radiation intensity (I_A) is proportional to cos Θ , where the zenith angle Θ is the angle between the incident solar rays and the direction normal to the surface. Hence:

$$I_A = I_o \cos \Theta \qquad (1)$$

where I_o is the solar constant. The zenith angle depends upon the

geographical latitude (Φ), the sun's declination (δ). and the solar hour angle (H; H=0 at solar noon). Therefore I_A can be computed as follows: $I_A = I_o \left[\sin\Phi \sin\delta + \cos\Phi \cos\delta \cos H \right] D^{-2}$ (2)
where D^{-2} is a correctional term for the eliptical nature of the earth's orbit such that:

$$D^{-2} = 1 + 0.0335 \cos (6.28 \text{ d}/365) \qquad (3)$$

where d is the day of the year and (6.28 d/365) is an angle in radians.

Equation (1) is only valid for positive values of cos Θ . The interval of time that cos Θ is positive is the length of day and when the right hand side is negative $I_A = 0$. Annual fluctuations in day length result from changes in the sun's declination δ . For the northern hemisphere the value of δ reaches a minimum (-23.4^{o}) on December 22nd, a maximum ($+23.4^{o}$) on June 21st and, at the equinoxes, it is zero. Finally, in order to obtain the total radiant energy received over a given period I_A must be integrated with respect to time over the period in question.

On a horizontal surface at the earth-atmosphere interface the radiation intensity is given by:

$$I_E = I \sin\beta + D \qquad (4)$$

where I_E is the total radiation received; I is the irradiance of the direct beam, entering at solar elevation β ; D is the diffuse irradiance from sky and clouds. The depth of atmosphere traversed by the solar beam is expressed by an air mass number (m). At sea level, m = 1 when the sun is directly overhead (i.e. $\beta = 90^{o}$).

From $\beta = 90^{\circ}$ down to about $\beta = 10^{\circ}$ the path is longer and the relationship $m \approx 1/\sin\beta$ holds. Apart from the effects of solar elevation on the receipt of radiation at the surface there is also the effect of atmospheric attenuation to be considered. Atmospheric attenuation occurs as a result of reflection, scattering and absorption.

Absorption by atmospheric gases and water vapour is wavelength specific. For example, ozone absorption occurs mainly in the ultraviolet region ($0.2 - 0.33\mu$) and to a much smaller extent in the visible band. Absorption in the ultraviolet region is extremely important to biological processes as excess doses of this radiation are lethal.

Scattering is caused by the gas molecules of the atmosphere (Rayleigh scattering), and by large particles such as dust, aerosols etc. (Mie scattering). The former is inversely proportional to the fourth power of the wavelength while the latter is inversely proportional to the wavelength.

Reflection in the atmosphere is principally by clouds but, unlike absorption and scattering, reflection is almost independent of wavelength.

(ii) Photosynthetically Active Radiation

It is clear from the above discussion that when incoming radiation reaches the earth's surface it has not only changed in quantity but may also have changed in spectral quality. Not all wavelengths of shortwave radiation are potentially productive in crop growth processes. The relationship between photosynthesis and incoming shortwave irradiance is best evaluated by consideration of that portion of the shortwave irradiance which is photosynthetically active i.e. photosynthetically active radiation (P.A.R.). Although the energy content of the 0.4 - 0.7 μ range has been shown to be the best measure of the flux of P.A.R. (McCree 1972), due to the problems of instrumentation, it is convenient to define the ratio of P.A.R. to total shortwave irradiance as:

$$\Psi = \int_{0\cdot3}^{0\cdot7} E_\lambda \, d\lambda \Big/ \int_{0\cdot3}^{3\cdot0} E_\lambda \, d\lambda \qquad (5)$$

where $E_\lambda d\lambda$ is an energy content of a wavelength interval $d\lambda$ at λ, with λ in microns(Szeicz 1974). Due to an absence of direct measurements of P.A.R. on a large scale several approximations to the above ratio have been proposed. An early analysis by Moon (1940) obtained a ratio of 0.45 while Yocum et al (1964) have reported that the 0.4 - 0.7 μ spectral range constitutes 47% of the response of an Eppley pyranometer. A variable ratio from 0.47 on clear days to 0.58 in very heavy overcast was obtained in New Zealand by McCree (1966). Variable ratios have also been reported by Britton and Dodd (1976), Szeicz (1974) and Yefimova (1971), the two latter studies opting for an overall mean value of 0.50. Assuming that the ratio of P.A.R. to total shortwave irradiance is 0.50 and confining analysis to the visible spectrum, the quantum intensity of sunlight can be computed as follows (Monteith 1965, 245):

At wavelength λ, the amount of energy per quantum is hc/λ where h is Planck's constant (6.63×10^{-34} Js) and c is the velocity of light (3×10^8 m sec^{-1}). If the energy in a waveband $d\lambda$ is $E_\lambda\, d\lambda$, the number of quanta in this waveband is $E_\lambda\, d\lambda\, /hc$. Integrating for the whole visible spectrum, the number of quanta per unit energy is:

$$1/hc \int_{0\cdot 4}^{0\cdot 7} \bar{\lambda} E_\lambda d\lambda \Big/ \int_{0\cdot 4}^{0\cdot 7} E_\lambda d\lambda = \bar{\lambda}/hc \qquad (6)$$

where $\bar{\lambda}$ is the mean wavelength in the range 0.4 – 0.7 μ weighted by energy. Assuming $\bar{\lambda}$ = 0.553 μ and given that one Einstein is N quanta ($N = 6.02 \times 10^{23}$ is Avagadro's number) then $\bar{\lambda}/hc$ = 4.63 Einsteins J^{-1} or alternatively $hc/\bar{\lambda}$ = 0.217 MJ $Einstein^{-1}$.

Using the results of the above computations and following an approximation to the work of Loomis and Williams (1963), a theoretical maximum yield as a function of incoming radiation can be calculated:

Assume a surface receipt of 20 MJ m^{-2} d^{-1} of incoming energy (a realistic summer value for the study area). This corresponds with approximately 10 MJ m^{-2} d^{-1} of P.A.R. Since one joule of incoming radiation contains 4.61 μ Einsteins, on average, the total quanta for 10 MJ would be 46.1 Einsteins m^{-2}. With a mean visible albedo of 14% (Wang 1963, 81) and an inactive absorption loss of 10%, the remaining quanta available for photosynthesis would be 35.1 Einsteins m^{-2}. Taking the quantum requirement for photosynthesis as 10,then 3.5 moles of carbohydrate (CH_2O) would be produced for every square meter. However, with a respiration loss of one-third of the photosynthetic rate net production of CH_2O would be 2.3 moles m^{-2} or, taking 30 g $mole^{-1}$ CH_2O, this would be 70 g m^{-2}.

If this net productivity represents 15671 J g^{-1} stored in carbon compounds, then 1.1 MJ m^{-2} d^{-1} of shortwave radiation ends up in the biomass. This represents 5.5% of the total shortwave irradiance or about 11% of the energy received as P.A.R. These figures are the same as those given by Hall (1976) who used a different method of computation.

Actual values of net productivity and photosynthetic efficiency are found to be very much lower than the above estimates would suggest (Lemon 1969). Many factors can limit primary productivity and it requires that only one of them be greatly different from the optimum for productivity to decline. It could be argued that the radiation climate of an area is the most important of these factors yet it also tends to receive the least attention. The following sections attempt to rectify the latter for the study area.

(b) Specific topics

(i) Solar radiation at the top of the atmosphere

Solar radiation at normal incidence at the top of the atmosphere may be considered as the gross energy input at the latitude of the study area. Table 2.1, computed from data given in Russelo et al (1974) and Chang (1971), gives mean daily and monthly totals of solar radiation at each of four degrees of latitude for the summer months, as well as at the equator for comparison.

TABLE 2.1: MEAN DAILY AND MONTHLY TOTAL SOLAR RADIATION AT THE TOP OF THE ATMOSPHERE FOR THE SUMMER MONTHS; 52° - 55°N AND AT THE EQUATOR ($MJ\ m^{-2}$).

LATITUDE (N)	MAY	JUNE	JULY	AUG.	SEPT.	MAY-SEPT.
55°						
Daily Mean	38.3	42.1	40.3	33.7	24.4	
Monthly Total	1188.4	1264.3	1250.8	1044.0	733.2	5480.8
54°						
Daily Mean	38.5	42.2	40.5	34.0	24.9	
Monthly Total	1194.2	1265.9	1254.4	1053.4	748.1	5516.0
53°						
Daily Mean	38.7	42.2	40.6	34.3	25.4	
Monthly Total	1200.0	1267.5	1257.9	1062.7	762.7	5550.8
52°						
Daily Mean	38.9	42.3	40.7	34.6	25.9	
Monthly Total	1205.5	1269.0	1261.3	1071.6	777.2	5584.7
0°						
Daily Mean	35.5	34.2	34.6	36.3	37.9	
Monthly Total	1100.0	1025.8	1072.9	1125.6	1138.0	5463.8

In all months, mean daily values increase from north to south in the latitude of the study area. Peak daily values for the study area occur in June where, at 52^{o}N, a value of 42.6 MJ m^{-2} is reached on the 19th. Daily receipts decline rapidly on either side of the peak value. By the end of September at 52^{o}N, energy supply has been reduced by 50%. This decline is more marked at higher latitudes.

Monthly total radiation receipts follow the pattern shown for mean daily values, reaching a maximum in June and declining sharply towards the equinoxes.

May to September totals, which characterise the growing season in the area, are also shown in Table 2.1. Over the five month period gross energy receipts decline slightly from south to north. At 55^{o}N latitude, the summer (May to September) total of 5480.8 MJm^{-2} compares favourably with an equatorial value of 5463.8 MJ m $^{-2}$ over the same period. However, in winter, while the energy supply at 0^{o} latitude remains relatively constant, a reduction by as much as 85% in daily values occurs at 55^{o}N. This serves to illustrate the pronounced seasonality in energy supply experienced at the latitude of the study area.

(ii) Global radiation, measurement and estimation

Of more direct significance for agriculture than solar radiation at the top of the atmosphere is the amount of radiation per unit area reaching a horizontal surface at vegetation height both directly and diffusely, via reflection and scattering, herein refered to as global radiation. Global radiation is important to ecophysiological studies as it is the source of energy used in evapotranspiration and photosynthesis. Accurate measurements of this component of the radiation balance are especially important for planning irrigation projects and when assessing the water requirements and yield of many crops.

Direct measurements of global radiation are still made at comparatively few locations in Manitoba and Saskatchewan (Table 2.2). Of the six stations having radiation records in the two provinces only The Pas Airport maintains current records and lies within the belt from 52^{o} - 55^{o}N. Table 2.3 presents monthly mean global radiation for The Pas A. The pronounced seasonal variation is immediately evident and expected from prior consideration of the solar radiation regime at this latitude. However, peak values do not always occur in June when solar receipts are at a maximum and there is considerable variation for any month from year to year. These factors are due to differential atmospheric attenuation of the direct and diffuse components on a day to day basis.

Global radiation records at The Pas A. are of short duration relative to the optimum of 30 years suggested for climatological purposes (W.M.O. 1960). Nevertheless, on a daily basis, records for this station are considered to be of an adequate length to derive a relationship for estimating global radiation receipts from duration of bright sunshine records; one of the best ways to obtain such an estimate (Stanhill 1965: Bennett 1969).

TABLE 2.2: STATIONS WITH RADIATION RECORDS IN MANITOBA AND SASKATCHEWAN

STATION	LOCATION	RECORD LENGTH	TYPE OF RECORD
Churchill A., Man.	58^{45}N 94^{04}W	1949 - 1961 1964 -	Global Solar Global Solar and net Radiation
The Pas A., Man.	53^{58}N 101^{06}W	1972 -	Global Solar
Winnipeg A., Man.	49^{54}N 97^{14}W	1961 - 1976 -	Global Solar Sky Radiation
Saskatoon NRC, Sask.*	52^{08}N 106^{38}W	1953 - 1967	Global Solar
Bad Lake IDH 102, Sask.	51^{19}N 108^{24}W	1971 -	Global Solar, Reflected Solar and Net Radiation
Swift Current CDA, Sask.	50^{16}N 107^{44}W	1959 -	Global Solar

* No simultaneous bright sunshine records.

TABLE 2.3: MONTHLY MEAN GLOBAL RADIATION AT THE PAS A. (MJ m^{-2} d^{-1})

YEAR	JAN.	FEB.	MAR.	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1972	M	M	M	M	M	M	M	16.80	10.47	6.28	2.51	2.85
1973	3.39	7.00	11.93	16.93	22.83	17.47	20.24	18.39	12.70	5.82	2.85	2.64
1974	3.73	7.21	12.61	19.96	17.60	22.00	20.66	16.34	10.64	6.95	3.35	2.14
1975	2.93	7.16	13.87	17.60	18.56	19.44	21.28	15.50	10.35	6.87	3.64	2.51
1976	2.97	7.04	13.28	18.06	22.71	19.27	22.08	18.14	13.41	NA	NA	NA

M - Period before observations began

NA - Not available at time of analysis

Bright sunshine data is treated more fully in Section (b) (iv).

The first proposal of such a relationship came from Ångström (1924), whose equation took the general form:

$$Q = Qo\ (a + b\ n/N) \qquad (7)$$

Where Q is the actual receipt of incoming, direct and diffuse, shortwave radiation; Qo is the total solar radiation received on a horizontal surface at ground level with clear skies; n is the number of hours of bright sunshine (bright being undefined) and N is the daylength in hours. The constants a and b vary according to season and location. Ångström (1924), for example, obtained the values a = 0.25, b = 0.75 for weekly readings at Stockholm, while Fritz and MacDonald (1949) have used the values a = 0.35, b = 0.61 in the United States. Several workers have found this form of the equation most useful (Kimball and Hand 1936: Hamon *et al* 1954: Ganesan 1970: Dogniaux 1974) but most studies have incorporated the modified format where Qo is replaced by Q_A, the total radiation received at the top of the atmosphere (Angot's value). The use of Q_A facilitates comparison between stations and, unlike Qo, values of Q_A are available in tables. In this case the equation is expressed as:

$$Q = Q_A\ (a + b\ n/N) \qquad (8)$$

Since the computed values of the constants a and b vary widely between stations, numerous studies of their values have been undertaken (see Linacre 1967, 73-76: Chang 1971, 22-23). Values obtained in other Canadian studies are given in Table 2.4.

TABLE 2.4: CANADIAN ESTIMATES OF THE RELATIONSHIP BETWEEN GLOBAL RADIATION AND HOURS OF BRIGHT SUNSHINE

SOURCE	LOCATION	'a' VALUE	'b' VALUE	CORR. COEFF.
Mateer (1955)*	6 Stations	0.35	0.68	0.93
Baier and Robertson (1965)**	Ottawa/Edmonton	0.25	0.62	0.92
Driedger and Catchpole (1970)+	Winnipeg	0.23 - 0.51	0.41 - 0.76	0.84
Selirio *et al* (1971)++	Guelph	0.23	0.57	0.92
Present Study	The Pas A.	0.26	0.50	0.90

* Using summer monthly means and the original Angstrom equation

** 856 daily observations during the growing season.

+ Daily values 1950 - 1967, using original Angstrom equation.

++ 400 daily observations from four seasons with a sample of 20 per season for five years.

The Pas Airport climatological station, located at latitude 53°58' N, longitude 101° 06' W, at an elevation of 273 meters above M.S.L., was the recording site of all global radiation and bright sunshine data used in this analysis. Data collected in the Canadian climatological station network is published by the Atmospheric Environment Service, Environment Canada (previously the Meteorological Branch of the Canadian Department of Transport) in the form of monthly summaries. From these summaries, daily values of Q and n were obtained for the period 16th July 1972 to 31st September 1976. Q values are measured by a Kipp pyranometer while bright sunshine is measured by a Campbell-Stokes sunshine recorder. Daily values of Q_A and N were obtained from Russelo et al (1974), a source which eliminates the need for graphic interpolation between points and therefore has advantages over the more commonly used Smithsonian Meteorological Tables (List 1966). In total, 1445 usable observation pairs were available. Missing Q values occur when the instrument is being recalibrated or when obstruction of the recording surface reduces significantly the number of hourly recordings. When a small part of a day has no record the daily total is estimated and the entry is marked as such in the monthly summary. Very few daily sunshine recordings were missing save for the absence of published values in June 1975.

Flexibility in the analysis of the data was achieved using program BMDPIR of the Biomedical (BMDP) package series (Dixon 1975). This simple regression program facilitated computation of regression equations on an all-data, annual, monthly and, for the summer months, 10 day basis. Early examination of the graphic output given by the program revealed that outliers were not associated with estimated radiation values. The inclusion of estimates in all subsequent analyses was therefore considered to be appropriate.

The constants derived in the analysis of the relationship between Q/Q_A and n/N are given for an annual and all-data basis in Table 2.5. Surprisingly little variation in either constant occurs from year to year and each year analysed approximates well with the mean annual values. This would tend to indicate that a general value for a and b can be obtained from a small number of years of data at any site with appropriate records.

Several modifications to Equation 8 have been proposed to improve the significance of the statistical relationship. In a dry monsoonal environment, Fitzpatrick and Stern (1965) found that the exclusion of values where n/N = 0 and a hyperbolic relationship gave a better fit for their data. However, as can be seen from Table 2.5, the computation of a second mean annual regression equation which excluded values where n/N = 0 did not improve the estimate of the relationship and a hyperbolic relationship was deemed to be inappropriate in this case.

Using data from two British stations Collingbourne (1976) has shown that the use of a polynomial curve does not add useful extra precision when composed with a linear regression line, a conclusion also reached by de Vries (in de Boer 1961, 539). Glover and McCulloch (1958 a,b) analysed daily observations from seven stations for periods ranging from two to nine years. While values

TABLE 2.5: ANNUAL AND MEAN ANNUAL VALUES OF THE CONSTANTS IN THE RELATIONSHIP $Q = Q_A\ (a+b\ ^n/N)$ FOR THE PAS A., 1972 - 1976

YEAR	NO. OF OBSERVATIONS	CONSTANTS a	b	TURBIDITY a+b=t	CORR. COEFF.	STD. ERROR OF ESTIMATE
1972	160	0.236	0.503	0.739	0.918	0.072
1973	351	0.270	0.497	0.767	0.902	0.082
1974	346	0.263	0.498	0.761	0.874	0.089
1975	324	0.264	0.500	0.764	0.910	0.077
1976	264	0.267	0.495	0.762	0.920	0.065
1972 - 76*	1445	0.262	0.500	0.762	0.903	0.079
1972 - 76+	1193	0.285	0.467	0.752	0.879	0.071

* All data included

\+ Values where $^n/N = 0$ omitted

of b were essentially constant from station to station, they found that a varied with latitude, Φ . They proposed an equation:

$$Q/Q_A = 0.29 \cos \Phi + 0.52\, n/N \qquad (9)$$

This equation has not been widely accepted. Nor has a proposal by Swartman and Ogunlade (1967) to incorporate a humidity parameter.

Returning to Table 2.4, the mean annual values obtained in the present study can be compared with those from other Canadian analyses. Although it would appear at first that the results differ greatly, this is probably due to differences in the data base and the method of analysis used. Mateer (1955) used the original Ångström equation and summer monthly means for radiation and sunshine data. The analysis undertaken by Driedger (1969, 61-62) suggests that the use of monthly means for universal application is open to doubt. Baier and Robertson (1965) used daily observations but for the growing season only. Driedger and Catchpole (1970) found that variations in a and b could be described as parabolic over the period of a year and that the least squares estimators of the parameters a and b could be assessed for any five day period.

The method used by Selirio _et al_ (1971) most closely approximates to the present analysis and also gives the closest results. The variation in coefficient values which still exists emphasises the need for station by station analysis of the global radiation, sunshine duration relationship whenever adequate records are available.

On a monthly basis (Table 2.6) it would appear that there is a seasonal fluctuation in the a and b values for The Pas A. as noted by Driedger (1969) for Winnipeg. This apparent trend is confirmed in Figure 2.1, where a pronounced annual cycle and inverse relationship between the constants is evident. The a value depends upon the level of diffuse radiation which, in turn, is directly related to cloud and/or snow cover. This is exemplified in spring when multiple reflection between snow cover and cloud base declines and there is a corresponding decline in the value of a. With a complete cloud cover the ratio n/N will equal zero and the value of a will indicate Q/Q_A. Such a position is hypothetical however as n/N = 0, although occuring frequently as a daily value, does not exist as a monthly mean. According to Davies (1965, 362) the value a, "... is to be regarded strictly as an index of the general displacement of the scatter with reference to the ordinate from month to month."

The slope of the regression equation, b, is related to the attenuation of direct radiation and is apparently also an index of the latitudinal gradient in the solar radiation, sunshine duration relationship (Davies 1965). However, the mean annual value of b = 0.500 appears low when compared to results obtained from other stations of similar latitude (Linacre 1967, 75-78). This may be due to the continental location of The Pas A.

By setting n/N = 1 an index of turbidity (t) can be obtained. Turbidity is defined as any condition of the atmosphere which reduces its transparency to radiation and is a measure of the total aerosol

TABLE 2.6: MONTHLY VALUES OF THE CONSTANTS IN THE RELATIONSHIP $Q = Q_A$ (a+b n/N) FOR THE PAS A., 1972 - 1976

MONTH	NO. OF OBSERVATIONS	CONSTANTS a	b	TURBIDITY t=a+b	CORR. COEFF.	STD. ERROR OF ESTIMATE
Jan.	121	0.318	0.460	0.778	0.915	0.068
Feb.	104	0.387	0.375	0.762	0.917	0.051
Mar.	118	0.391	0.427	0.818	0.931	0.052
April	116	0.277	0.542	0.819	0.940	0.064
May	119	0.227	0.550	0.777	0.940	0.064
June	84	0.185	0.557	0.742	0.944	0.065
July	139	0.199	0.534	0.733	0.944	0.054
Aug.	151	0.207	0.517	0.724	0.945	0.053
Sept.	142	0.185	0.605	0.790	0.965	0.052
Oct.	121	0.208	0.522	0.730	0.920	0.073
Nov.	113	0.243	0.475	0.718	0.913	0.065
Dec.	117	0.302	0.449	0.751	0.884	0.079

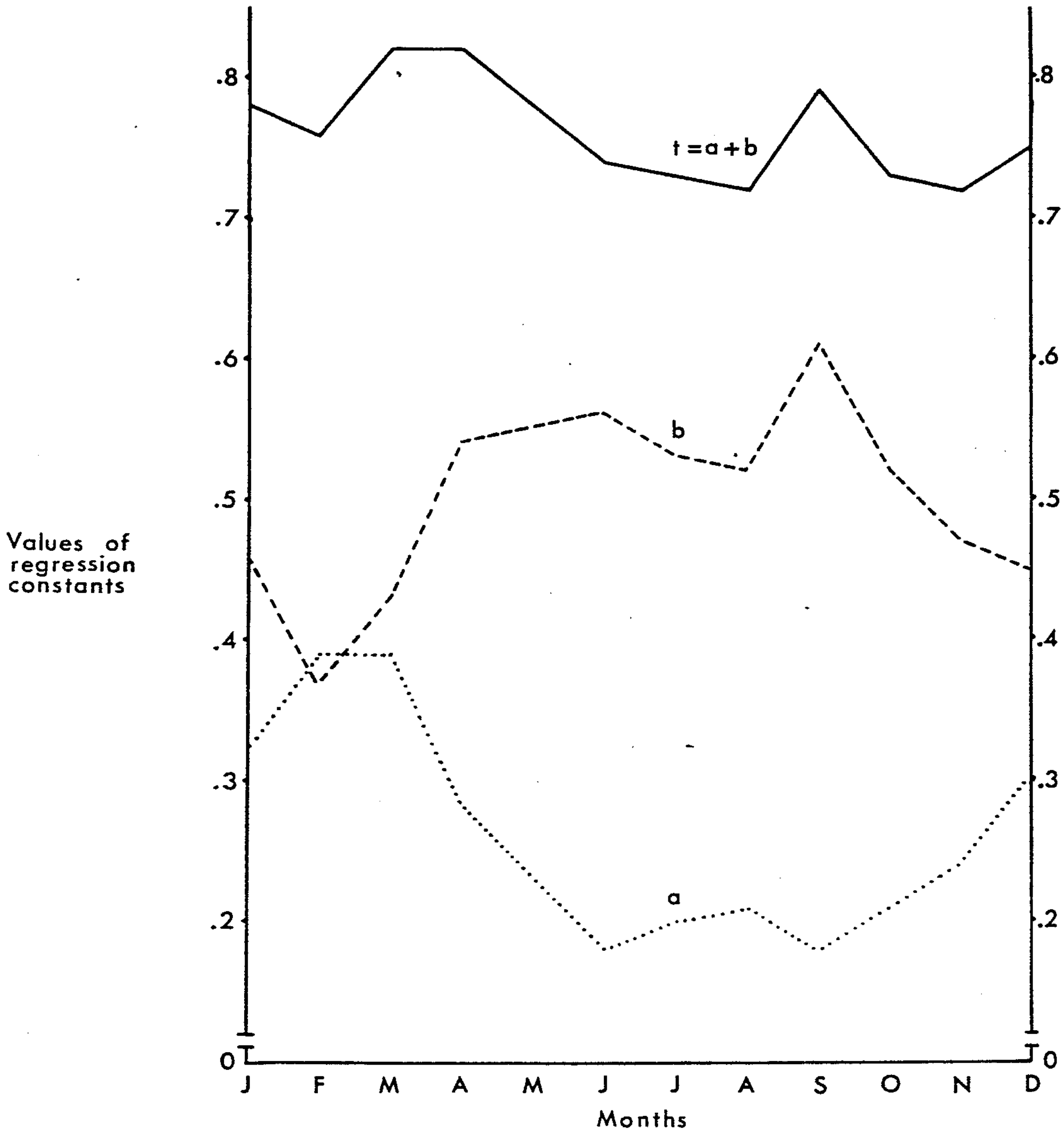


Fig. 2.1 Annual variation of regression constants a and b linking global radiation and sunshine duration (for daily totals) at The Pas A, 1972-1976, t=a+b.

in a column of atmosphere, the term usually applying to a cloud-free portion of the atmosphere. Seasonal variations in monthly t values (Figure 2.1) may be apparent rather than real. Peak t values in spring and autumn may be the result of increased atmospheric transmission but it is not obvious why this should occur at these times. While it is difficult to be conclusive about variability in monthly t values, it is clear that stability characterises annual values (Table 2.5). For the data as a whole t = 0.762 was obtained which, although considerably lower than the value of 0.87 obtained by Baier and Robertson (1965), agrees well with both Selirio et al (1971); who derived a value of t = 0.77 for Guelph, and Ångström (1957) who found an average value of t = 0.75. In this case n/N = 1 is also hypothetical, not only as a monthly mean but also on a daily basis since the Campbell - Stokes sunshine recorder has a variable lower threshold recording level which, on average, is 130 Wm^{-2}. This in fact means that the sunshine recorder fails to register bright sunshine when the sun's elevation above the horizon is less than about 3^{o} which constitutes a considerable portion of the day during winter months. It is possible to correct daylength values to take this fact into account.

In addition, 10 day values for a and b have been calculated and the results are presented in Table 2.7. Comparably high correlation coefficients with those obtained for monthly groupings would appear to justify computations for the shorter period. As expected, a and b values fluctuate around those obtained from monthly groupings.

TABLE 2.7: 10 DAY VALUES OF THE CONSTANTS IN THE RELATIONSHIP $Q = Q_A$ (a+b n/N) FOR THE PAS A. (SUMMER MONTHS ONLY), 1972 - 1976.

PERIOD	NO. OF OBSERVATIONS	CONSTANTS a	b	TURBIDITY t=a+b	CORR. COEFF.	STD. ERROR OF ESTIMATE
May						
1-10	37	0.267	0.505	0.772	0.948	0.057
11-20	40	0.212	0.588	0.800	0.945	0.067
21-31	42	0.206	0.556	0.762	0.940	0.063
June						
1-10	29	0.220	0.512	0.732	0.917	0.068
11-20	26	0.153	0.581	0.734	0.941	0.074
21-30	29	0.163	0.597	0.760	0.975	0.046
July						
1-10	40	0.160	0.576	0.736	0.948	0.048
11-20	45	0.223	0.504	0.727	0.928	0.065
21-31	54	0.192	0.552	0.744	0.961	0.046
Aug.						
1-10	48	0.235	0.494	0.729	0.901	0.065
11-20	48	0.210	0.507	0.717	0.969	0.042
21-31	55	0.186	0.539	0.725	0.958	0.049
Sept.						
1-10	49	0.187	0.590	0.777	0.977	0.042
11-20	43	0.171	0.626	0.797	0.962	0.058
21-30	50	0.193	0.604	0.797	0.959	0.055

TABLE 2.8: MONTHLY GLOBAL RADIATION ESTIMATES FOR PRINCE ALBERT A. AND ACTUAL MEASUREMENTS AT THE PAS A. (MJ m^{-2} d^{-1})

MONTH	Q_A	$^n/N$ RATIO (30 YR. AVG.)	GLOBAL RADIATION EST.	THE PAS A. MEASURED
Jan.	7.49	0.365	3.64	3.26
Feb.	13.03	0.429	7.14	7.12
Mar.	21.58	0.453	12.61	12.83
April	31.10	0.520	17.38	18.13
May	38.79	0.541	20.35	20.50
June	42.25	0.520	20.05	19.70
July	40.58	0.598	21.03	20.88
Aug.	34.28	0.597	17.68	17.00
Sept.	25.42	0.545	13.08	11.59
Oct.	16.24	0.441	7.12	6.51
Nov.	9.17	0.312	3.59	3.05
Dec.	6.11	0.297	2.66	2.51

Q_A - solar radiation on a horizontal surface at the top of the atmosphere at 53°N.

n - hours of bright sunshine

N - daylength

Given a sufficiently long period of data, variations in a and b can be studied as a function of time for shorter periods as in the work of Driedger (1969).

In order to illustrate application of the estimation procedure, sunshine records for Prince Albert A. have been used (see also Sec. (b) (iv)). The results of the computations along with 30 year n/N ratios and Q_A values for 53^{o}N are shown in Table 2.8. The annual cycle of values closely approximates recorded values for The Pas A. Relatively high global radiation values are attained from April to August but not all of this energy will be available for crop growth. In April a significant proportion will be consumed in snow melt, evaporation and soil heat flux so the remaining energy available for warming the air and for photosynthesis will be considerably reduced. Clearly the net energy available for each of these processes is of fundamental importance. It is to this component of the radiation balance, net radiation, that attention is now turned.

(iii) The estimation of net radiation

Net radiation can be defined as the difference between the downward flux of shortwave global radiation and longwave sky radiation, on the one hand, and the reflected shortwave radiation plus outgoing terrestrial radiation, on the other (e.g. Rosenberg 1974, 32). This can be expressed algebraically as:

$$Q_N = Q - \alpha Q + R_{L\downarrow} - R_{L\uparrow} \quad (10)$$

Where Q_N is the net radiation; Q is global radiation; α is the reflection coefficient (shortwave albedo); $R_{L\downarrow}$ and $R_{L\uparrow}$ are the incoming and outgoing longwave radiation respectively.

The longwave components, which are extremely difficult to measure, are often combined to:

$$R_L = R_{L\uparrow} - R_{L\downarrow} \qquad (11)$$

where R_L is the effective outgoing longwave radiation. Combining equations 10 and 11 we obtain:

$$Q_N = (1 - \alpha)\ Q - R_L \qquad (12)$$

In the absence of site measurements an example of the magnitude of the net radiation component in the daily energy balance is appropriate and one is given in Table 2.9. Almost 60% of the global radiation reaching the surface is available as net radiation and, although the portions into which this net energy will be divided varies appreciably under different situations, actual values measured over a barley crop under clear, dry, summer conditions in England are also given. Long et al (1964) also showed that the value for expenditure in heating the air was positive during the middle of the day (air gaining heat) and negative in early morning and late afternoon (air supplying heat). The daily total was -1.09 MJ m^{-2}, i.e. the air supplied heat to the crop.

Of the two stations recording net radiation in Manitoba and Saskatchewan (Table 2.2), neither lies within the area of interest and one station, Churchill A., lies a considerable distance outside the current and potential agricultural area. This shortage of net radiation data is partially attributable to the fact that direct instrumental measurements of net radiation is even more difficult to achieve than with global radiation. Available evidence (Latimer 1963: Boyd and Reynolds 1963: Holmes

TABLE 2.9: THE DAILY RADIATION BALANCE MEASURED OVER A BARLEY CROP: ROTHAMSTED JULY 23rd 1963 (ADAPTED FROM LONG *et al* 1964)

INCOME	$MJ\ m^{-2} d^{-1}$
Incoming energy at top of atmosphere	39.91
Global radiation at surface	20.57
Loss by reflection	4.90
Loss by reradiation	3.39
Net radiation income	12.28 *
USE AT SURFACE	
Expenditure as evaporation	12.19
"Expenditure" in heating air	- 1.09
Expenditure in heating soil	1.17
	12.27 *

* Difference due to rounding errors in conversion.

and Watson 1967) tends to confirm the assertion that a satisfactory and widely acceptable instrument for measuring net radiation has yet to be designed (F.A.O. et al 1967, 180). A significant proportion of published data on net radiation continues to be from sporadic observations in conjunction with specific experimental work. This widespread shortage of net radiation data has prompted the derivation of several equations which attempt to estimate net radiation from more readily available climatic data, as well as relationships expressing net radiation as a linear function of global radiation.

Of the empirical formulae, the Penman equation is probably the best known (Penman 1948, 139). Assuming a constant albedo, the solution of this formula requires data on global radiation, bright sunshine duration, air temperature and humidity. Penman's equation reads:

$$Q_N = (1-\alpha)Q - \sigma T_K^{\,4}(0.56-0.008e_a^{\,½})\ (0.1+0.9\ n/N) \qquad (13)$$

where σ is Stefan-Boltzmann's constant (4.93×10^{-9} MJ m^{-2} d^{-1}); T_K the screen temperature in degrees Kelvin (^{o}C + 273); e_a is the screen vapour pressure (Pa).

The four variables required to solve this equation are not available for many climatological stations. By making appropriate assumptions, Linacre (1968:1969) has attempted to deal with this problem by deriving a series of expressions for net radiation with increasing simplicity of estimation but apparently without severe loss of accuracy. Four of the ten expressions derived by Linacre (1969, 61-63) are given below:

$$Q_N = (1-\alpha)Q - 16x10^{-4}\ (0.2+0.8\ n/N)\ (100-T) \qquad (14)$$

$$Q_N = (1-\alpha)Q_A\ (a+bn/N) - 16x10^{-4}(0.2+0.8\ n/N)\left[100+0.006h - Q_A\ (a+bn/N)\ (100-1.2A)\right] \qquad (15)$$

$$Q_N = (1-\alpha)Q - 16x10^{-4}\left[100-Q(102-1.2A+0.006h)\right](0.8Q/bQ_A + 0.2-0.8a/b) \qquad (16)$$

$$Q_N = \frac{(1-\alpha)(T+0.006h)}{102-1.2A} - 32x10^{-5}\ (100-T)\left[1-4a/b + \frac{4(T+0.006h)}{bQ_A(102-1.2A)}\right] \qquad (17)$$

where each symbol is as previously stated and T is the screen temperature (^{o}C); h is the altitude (m); and A is the altitude in degrees. Values of Q and Q_A must be in cal cm^{-2} min^{-1}.

Again, assuming a constant albedo, equation 14 has three variables (global radiation, bright sunshine, temperature) while the remaining expressions each involve only one climatic variable (bright sunshine, global radiation and temperature respectively).

The choice of a value for the reflection coefficient, α, is open to considerable debate. Shortwave albedo varies with the season, with the nature of the ground cover, and with the time of day.

Marked asymmetry is a characteristic of the diurnal distribution of reflection coefficient values (Nkemdirim 1972). Nkemdirim (1973, 233) stresses that, "The dependence of albedo on zenith angle has been widely recognised but the dependence of the values on period of day has not received the attention it deserves in the literature." However, for present purposes, the adoption of average values is justified by the scale of analysis and the lack of site measurements.

From measurements over a variety of crop surfaces Monteith (1959) has shown that α is close to 0.25 when a complete vegetative cover is present. Similar values have been reported in subsequent work by the same author (Monteith and Szeicz 1961: 1962) as well as by Fritschen (1967) in Arizona and Idso et al (1969) in Minnesota. However, Graham and King (1961) have reported much lower values in Ontario as have Fitzpatrick and Stern (1965) in a dry monsoonal area and Decker (1966) in Missouri.

Kung et al (1964) have made airborne measurements of shortwave albedo from northern Mexico to above the Arctic Circle in Canada. They found that during the summer season values of α were about 0.18 with little variation from north to south. In winter, on the other hand, when a snow cover was present, the meridional profile of shortwave albedo values was markedly skewed. The presence or absence of snow determines the greatest variations of albedo and best illustrates the effect of the surface reflection coefficient on net radiation. McFadden and Ragotzkie (1967) used measured changes in shortwave albedo to estimate sensible heat transfer to the atmosphere during the period of rapid snow disappearance over central Canada in the spring of 1963. Values of shortwave albedo recorded for the summer months were very similar to those quoted for Kung et al (1964).

Judging from the above studies a summer monthly mean reflection coefficient value of 0.20 would appear to be realistic for the study area. This value was found by Linacre (1969, 67-68) to reduce to zero the bias resulting from the use of equation 14 with weekly mean data.

The alternative to empirical formulae, which use other climatic data for estimating net radiation, is the derivation of a relationship between net radiation and global radiation. Fleischer (1953) was the first to recognise such a relationship but its implementation may be attributed to Monteith and Szeicz (1961). The development of this approach involves the definitive radiation balance equation (equation 12) and two linear approximations:

$$Q_N = cQ - d \qquad (18)$$

$$Q_N = c^1 (1-\alpha) Q - d^1 \qquad (19)$$

where c and c^1 are regression coefficients and d and d^1 are constants. Values for c and d have been derived for several locations (see Chang 1971, 37: Rosenberg 1974, 37). Given the importance of shortwave albedo in determining net radiation, it may appear obvious to assume that equation 19, which includes a reflection coefficient term, would produce a better regression of net radiation on global radiation than equation 18 which does not include such a term. Apparently this is not the case. Both Fritschen (1967) and Idso (1968) have questioned the value of incorporating a shortwave albedo term in the predictor while Davies and Buttimor (1969, 373) in an analysis of data from Simcoe, southern Ontario assert that, "...there is no advantage to incorporating albedo in the linear relationship between net and net shortwave radiation." In an earlier paper, Davies (1967) amalgamated data from 14 globally distributed meteorological and research stations, including six from Canada, to obtain an overall regression equation:

$$Q_N = 0.617\ Q - 1.01\ (MJ\ m^{-2}\ d^{-1}) \qquad (20)$$

An extremely high correlation coefficient was obtained (r=0.99) despite the range in types of cover and climate experienced at each of the stations. The constant d was found to increase when the negative values of net radiation recorded at night were included but the coefficient c was virtually independent of the period of integration.

In order to obtain a working estimate of net radiation for the study area six of the above equations (equations 13, 14, 15, 16, 17, 20) have been evaluated using daily data from The Pas A. The results (Table 2.10a) are presented as monthly mean values in MJ $m^{-2}d^{-1}$. Table 2.10b lists the variables involved in each estimation procedure.

In the absence of site measurements for comparison it is difficult to make precise statements about the relative merits of each of the methods used to estimate net radiation. However, some general observations can be made.

Equation 17, which uses only temperature as a variable, gives results which are very much higher than those of the other equations. In a comparison between his estimation procedures and measured net radiation values Linacre (1969, 64) states that equation 17, "...is the least accurate in almost every case ...". This large positive deviation results from using the approximation:

$$T = Q(102-1.2A) - 0.006h \qquad (21)$$

TABLE 2.10a: COMPARISONS OF SUMMER MONTHLY ESTIMATES OF NET RADIATION FOR THE PAS A. 1972 - 1976 ($MJ\ m^{-2}\ d^{-1}$)

MONTH	PENMAN EQ. 13	LINACRE EQ. 14	LINACRE EQ. 15	LINACRE EQ. 16	LINACRE EQ. 17	DAVIES EQ. 20
May	9.89	10.74	10.80	10.86	8.75	11.64
June	10.68	11.04	10.20	10.62	14.06	11.16
July	10.62	11.22	10.98	10.86	16.83	11.89
Aug.	7.90	8.33	7.84	7.84	13.64	9.47
Sept.	4.04	4.34	4.04	4.04	6.03	6.15

TABLE 2.10b: VARIABLES INVOLVED IN EACH ESTIMATION PROCEDURE

EQ. NO.	VARIABLES USED			
13	Q	n	T	ea
14	Q	n	T	
15		n		
16	Q			
17			T	
20	Q			

Q - global radiation   T - air temperature

n - daily bright sunshine e_a - vapour pressure which does not allow for the lag between temperature and the annual radiation changes.

Despite the claim by Davies (1967, 115) that, "They (linear relationships between net and global radiation) are preferable to the empirical formulae in common use which are very rough approximations at best ...," the use of equation 20 also appears to give rather high results especially in May and September. It was previously stated that shortwave albedo is very important in determining net radiation. Yet equation 20 fails to take changing albedo into account at all. This omission would be of particular importance in spring and autumn when a low sun angle would combine with the possibility of a snow cover to considerably reduce the net radiation value. The high correlation found in Davies's study may be due to the short period of record used from each station or, perhaps, the use of monthly rather than daily mean values. Of more fundamental importance are the general shortcomings of this approach which have been outlined by Gay (1971). Clearly there exists a need for a detailed study of methods of estimating net radiation in the northern Prairies, with particular emphasis upon the role of albedo in spring and autumn.

It has been argued that equations 17 and 20 are likely to give poor estimates of net radiation but there is no evidence to indicate which of the remaining four equations gives the optimal estimate of net radiation. Since the values provided by equations 15 and 16 are so similar it was decided to take only one of these two (equation 15) along with equations 13 and 14 to provide 10 day net

TABLE 2.11: 10-DAY ESTIMATES OF NET RADIATION FOR THE PAS A., 1972 - 1976 (MJ $m^{-2}d^{-1}$)

MONTH/PERIOD		PENMAN EQ. 13	LINACRE EQ. 14	LINACRE EQ. 15
May	1-10	9.83	10.26	10.32
	11-20	10.08	10.80	11.04
	21-31	9.77	11.52	11.52
June	1-10	9.77	9.65	9.35
	11-20	10.68	11.04	10.32
	21-30	11.28	12.13	10.98
July	1-10	11.64	12.37	11.95
	11-20	10.86	11.22	10.86
	21-31	10.14	10.62	10.26
Aug.	1-10	9.41	10.08	9.77
	11-20	7.84	8.27	7.72
	21-31	6.64	6.82	6.40
Sept.	1-10	4.89	5.55	4.95
	11-20	4.22	4.40	3.74
	21-30	3.02	3.08	2.90

radiation estimates for the May to September period. The results of these computations are shown in Table 2.11. Of particular interest is the low estimate of Q_N for the first ten days in June. This was largely due to the very low solar radiation value for this period which has, in turn, reduced the net radiation value.

Again the results are very similar for the shorter time period. This, of course, does not validate these estimates but, in the absence of site measurements which are always preferable to estimates, the values of net radiation given in Tables 2.10a and 2.11 may be useful in further agroclimatic studies.

(iv) Sunshine Duration

It has already been pointed out that, due to expense and difficulty of maintenance, few stations in Manitoba and Saskatchewan record global and net radiation. In the absence of more sophisticated equipment, the simplest measure of radiation is achieved by recording sunshine and, as already indicated, bright sunshine can be used to estimate global radiation.

The Campbell-Stokes sunshine recorder is the standard instrument used for measuring hours of bright sunshine at Canadian stations. This instrument uses a glass sphere to focus direct global radiation on to a specially treated card. If the radiation intensity is sufficient to cause a perceptible discolouration of the card (i.e. the card is burnt) bright sunshine is said to have been recorded. Provided that the instrument has an unobstructed exposure during daylight hours and that correct adjustments have been made for latitude, level and azimuth acceptable records are

TABLE 2.12: STATIONS CURRENTLY RECORDING DAILY BRIGHT SUNSHINE WITHIN THE STUDY AREA (ENVIRONMENT CANADA 1976)

STATION	LAT.	LONG.	ELEVATION	STARTING DATES
Melfort C.D.A., Sask.	52^{49}	104^{36}	480 m.	1937/10 -
Nipawin, Sask.	53^{20}	104^{00}	374 m.	1973/8 -
N. Battleford A., Sask.	52^{46}	108^{15}	547 m.	1975/2 -
Prince Albert A., Sask.	53^{13}	105^{41}	431 m.	1940/9 -
Saskatoon S.R.C., Sask.	52^{09}	106^{36}	497 m.	1948/1 -
Scott C.D.A., Sask.	52^{32}	108^{50}	660 m.	1930/1 -
Pasquia Project P.F.R.A., Man.	53^{43}	101^{35}	262 m.	1974/8 -
The Pas A., Man.	53^{58}	101^{06}	273 m.	1949/11 -

obtainable, but they may be difficult to interpret in periods of intermittent sunshine (H.M.S.O. 1969, 147-150). Since these instruments are relatively cheap and simple to use they are more numerous than other radiation recorders. Of the eight stations currently recording bright sunshine, five have records beginning before 1950 while the remaining three have only recently been established (Table 2.12). Locationally the stations are poorly distributed. Seven of the eight stations lie between 104^{o}-109^{o}W and no station lies between 54^{o}-55^{o}N throughout the longitudinal extent of the study area.

Monthly averages and annual totals, 1941-1970, were obtained from Yorke and Kendall (1972) for the five stations with long periods of record. For two of these stations, Prince Albert A. and The Pas A., records were collected in the form of actual monthly totals for 1947-1976 and 1949-1976 respectively. This allowed a more detailed analysis of sunshine data for these two stations.

In Table 2.13 the last column gives the average annual totals of sunshine duration for the five principal recording stations. From these figures it can be noted that the duration of sunshine over the area is subject to considerable fluctuations. The highest value is for Saskatoon with 2403 h. and a sharp gradient exists between this station and Melfort with only 2058 h.

Summer season (May to September) totals are also shown in Table 2.13. At four of the five stations the summer period receives 58-59% of the annual total, while at Scott the percentage is slightly higher at 60.8%. Again, therefore, the highest May to September means

TABLE 2.13: MEAN MONTHLY, SEASONAL AND ANNUAL DURATION OF BRIGHT SUNSHINE AT FIVE STUDY AREA LOCATIONS

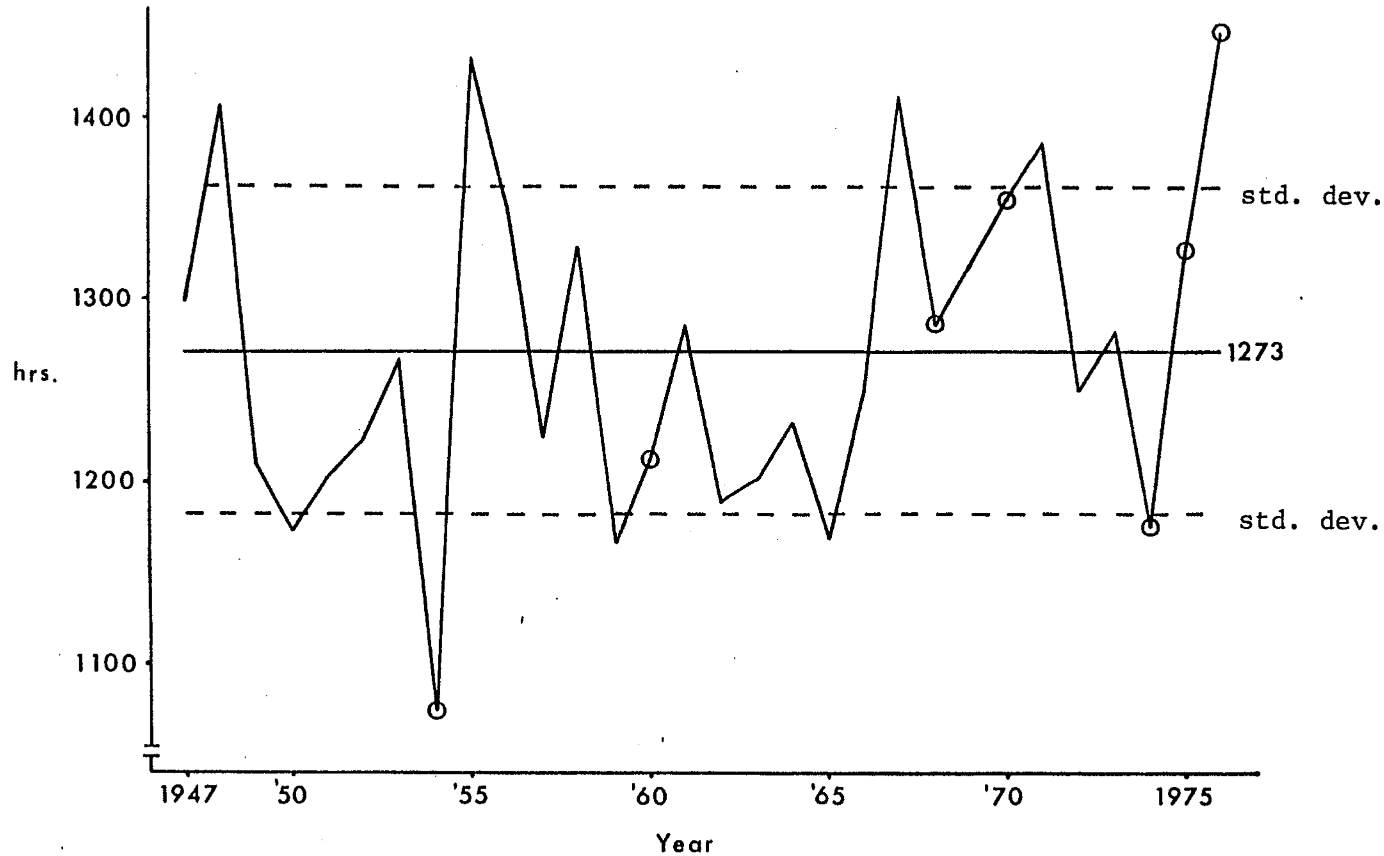
		J	F	M	A	M	J	J	A	S	O	N	D	MAY-SEPT.	JAN.-DEC.
Melfort C.D.A.	(1)	98	117	159	199	242	243	296	255	163	144	75	67	1199	2058
Prince Albert A.	(1)	94	115	168	212	259	258	303	269	170	143	80	72	1259	2143
	(2)	92	119	166	218	265	262	303	271	172	144	80	69	1273	2161
Saskatoon S.R.C.	(1)	99	129	192	225	279	280	341	294	207	175	98	84	1401	2403
Scott C.D.A.	(1)	85	113	151	209	273	269	326	275	181	150	84	62	1324	2178
The Pas A.	(1)	103	129	172	217	277	263	301	246	147	120	63	70	1234	2108
	(3)	102	131	176	221	276	266	300	260	160	120	63	72	1262	2148

(1) Yorke and Kendall (1972) using variable data base up to 1970.

(2) Present study using data from 1947 to 1976.

(3) Present study using data from 1949 to 1976.

Fig. 2.2 Duration of bright sunshine, May - September at Prince Albert A, 1947 - 1976.



O - in those years some data were missing and the values are estimated.

are experienced at Saskatoon and the lowest at Melfort (1401 h. and 1199 h. respectively). Pronounced interannual variability exists in both annual and seasonal sunshine totals. This point can be verified by refering to Figure 2.2 which shows year to year fluctuations in May to September totals of sunshine at Prince Albert A. between 1947-1976.

As values were absent for one month in seven of the years, estimates were made using overall monthly means as a substitute. Assuming a normal distribution for summer season totals, the mean and the standard deviation are also shown. With a standard deviation of 90 h. it can be expected that in four years out of five years the May to September total will be in the range of 1158 h. to 1388 h.

The remainder of Table 2.13 gives the average number of sunshine hours observed in each month. July values are always highest while the minimum occurs in either November or December. The greatest annual range of sunshine duration, represented by the largest difference between the sunniest and least sunny month, occurs at Scott with a range of 264 h. For all the stations this represents an amplitude of seasonal variation of 75-80% and largely determines the pronounced seasonality in radiation receipts already noted.

Also of interest is a comparison of the results of Yorke and Kendall (1972) with those of the present study (Table 2.13). At Prince Albert A. the results are very similar, the greatest deviation occuring in December when a 4.1% deficit is noted in the up-dated values. However, other variations at Prince Albert A. are so small that either set of data could be considered representative. In the case of The Pas A.

TABLE 2.14: MEAN DAILY DURATION OF BRIGHT SUNSHINE PER MONTH, SEASON AND YEAR AT FIVE STUDY AREA LOCATIONS

		J	F	M	A	M	J	J	A	S	O	N	D	M-S	J-D
Melfort C.D.A.	(1)	3.2	4.2	5.1	6.6	7.8	8.1	9.5	8.2	5.4	4.6	2.5	2.2	7.8	5.6
Prince Albert A.	(1)	3.0	4.1	5.4	7.1	8.3	8.6	9.8	8.7	5.7	4.6	2.7	2.3	8.2	5.9
	(2)	3.0	4.2	5.4	7.3	8.6	8.7	9.8	8.7	5.7	4.7	2.7	2.3	8.3	5.9
Saskatoon S.R.C.	(1)	3.2	4.6	6.2	7.5	9.0	9.3	11.0	9.5	6.9	5.6	3.3	2.7	9.2	6.6
Scott C.D.A.	(1)	2.7	4.0	4.9	7.0	8.8	9.0	10.5	8.9	6.0	4.8	2.8	2.0	8.6	6.0
The Pas A.	(1)	3.3	4.6	5.5	7.2	8.9	8.8	9.7	7.9	4.9	3.9	2.1	2.3	8.1	5.8
	(3)	3.3	4.7	5.7	7.4	8.9	8.9	9.7	8.4	5.3	3.9	2.1	2.3	8.2	5.9

(1) Adapted from Yorke and Kendall (1972) using variable data base up to 1970.

(2) Present study using data from 1947 to 1976.

(3) Present study using data from 1949 to 1976.

M-S May to September

J-D January to December

Fig. 2.3 Seasonal variations in sunshine duration, on a monthly basis, at Saskatoon S.R.C.

Monthly sunshine totals (frequency polygon), daily sunshine averages by months (histogram); 1948-1970.

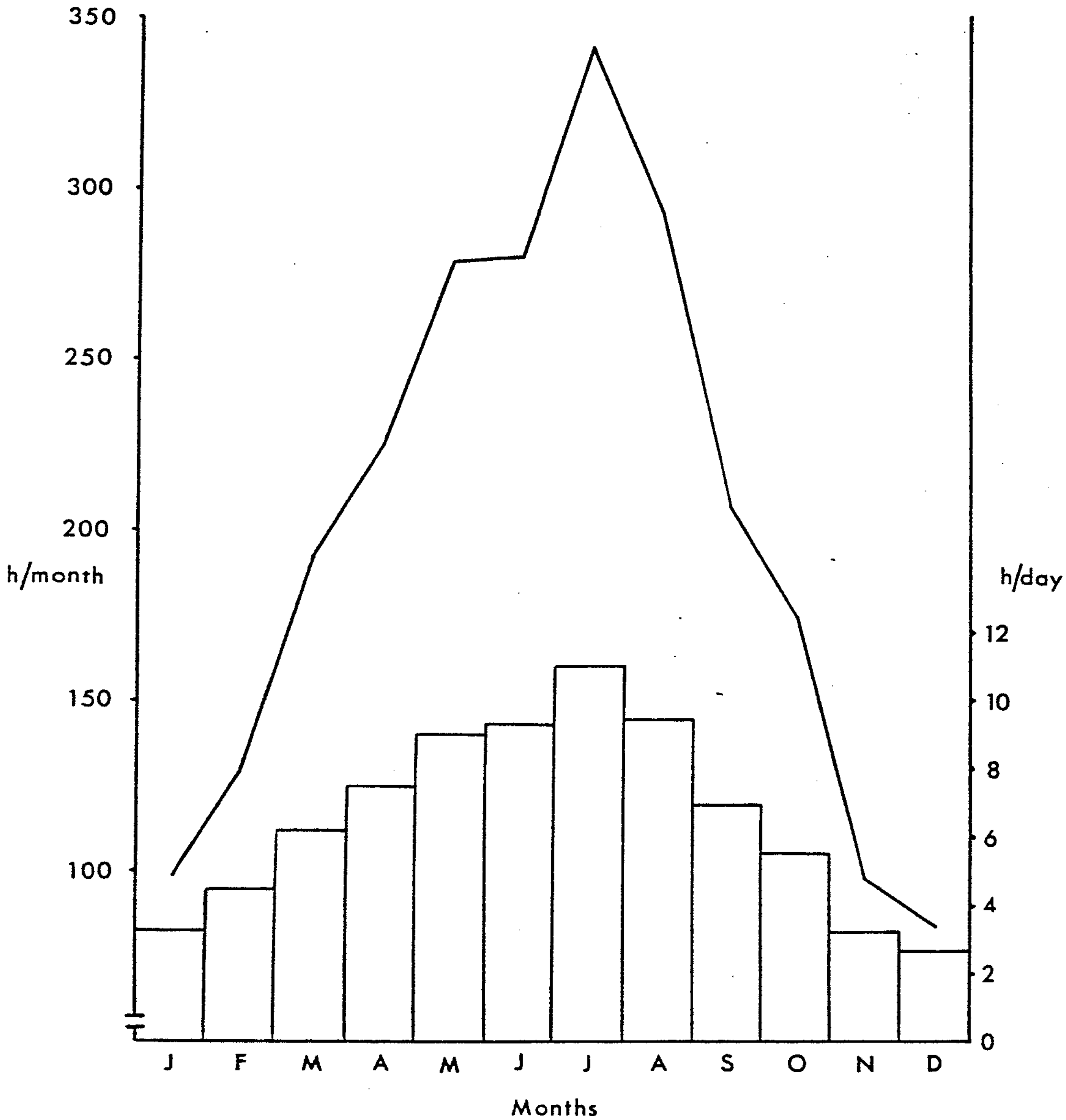
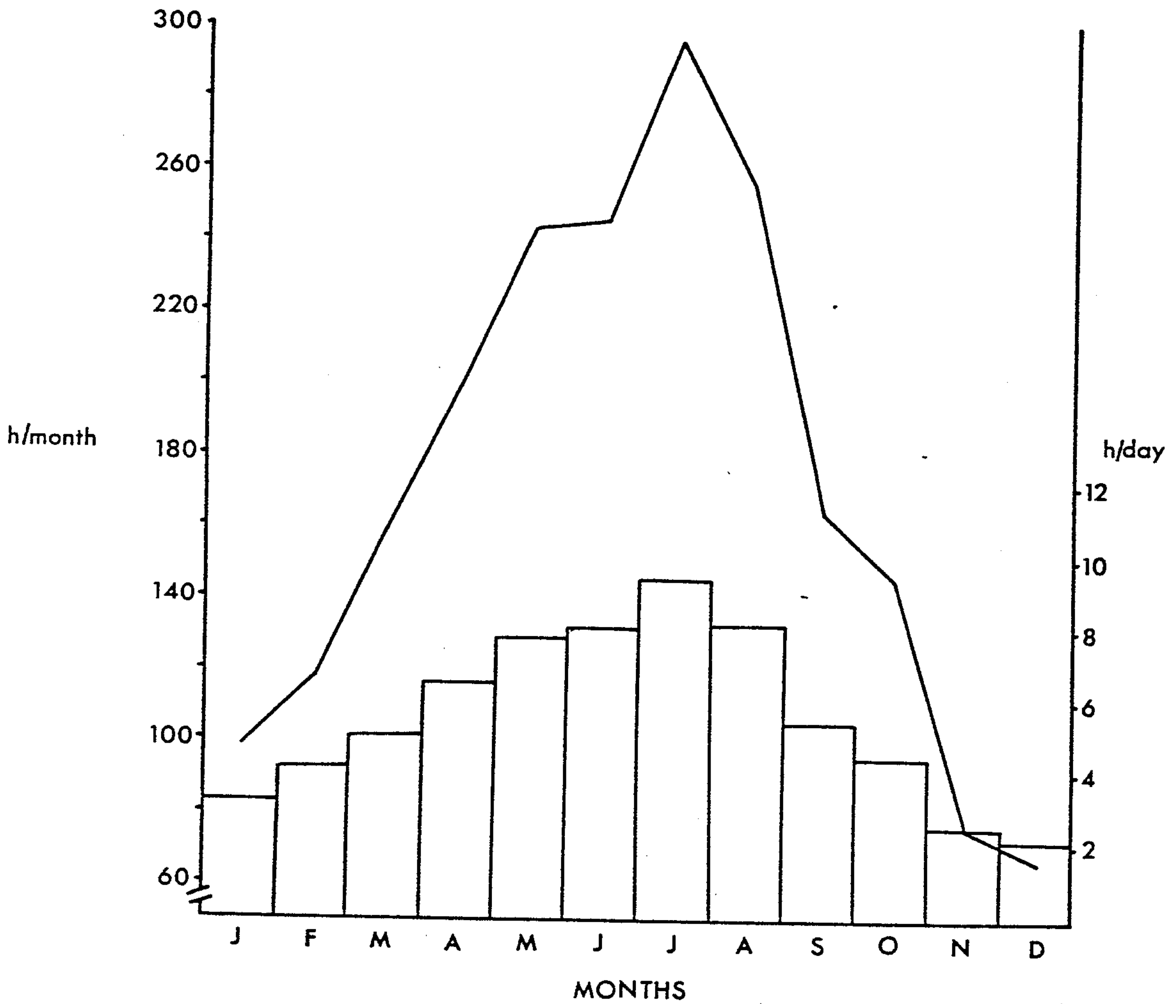


Fig. 2.4 Seasonal variations in sunshine duration, on a monthly basis, at Melfort C.D.A.

Monthly sunshine totals (frequency polygon), daily sunshine averages by months (histogram); 1941-1970.



the differences are somewhat larger with the up-dated values showing an excess of 8.8% in September and 5.7% in August. While Yorke and Kendall's data cover 21 years of record for The Pas A., the present study utilises 27 years so the figures given by the latter should be prefered in this case.

In June, global and net radiation values were slightly less than might be expected from purely astronomical considerations and this is also true for bright sunshine values. This is evident from both the mean monthly total figures (Table 2.13) and derived daily values which compensate for the varying number of days in each month (Table 2.14). As a graphic illustration of this point attention is drawn to Figures 2.3 and 2.4 which plot, for Saskatoon and Melfort respectively, the appropriate data from the preceding tables.

Since bright sunshine is inversely related to cloud cover, low daily and monthly values of bright sunshine in June must be the direct result of increased cloud cover. This is confirmed by the work of Longley (1972, 64-65) which shows that, throughout the Prairies, cloud cover peaks in June before declining sharply in July. During the spring months (March to May), the boundary zone between cold Arctic air, which has covered the Prairies for most of the winter, and warmer air to the south is displaced northwards. Low pressure or storm centres frequently form along this boundary bringing widespread precipitation to the Prairies. Increased cloud cover between May and June is compensated by increased daylength so that May and June sunshine figures are highly alike in most areas. Sunshine again increases in July as the decrease in cloud cover,

TABLE 2.15: OBSERVED MEDIAN, QUARTILE VALUES AND 10-YEAR EXTREMES OF SUNSHINE FOR MAY TO SEPTEMBER AT:

(a) THE PAS A. (1949-1976)

MONTH	1 in 10 CLOUDIEST	LOWER QUARTILE	MEDIAN	UPPER QUARTILE	1 in 10 SUNNIEST
May	230	248	273.5	304	322
June	201	231	264	305	315
July	256	278	299	323	332
August	211	236	262	285	293
Sept.	123	133.5	161.5	184	212

(b) PRINCE ALBERT A. (1947-1976)

MONTH	1 in 10 CLOUDIEST	LOWER QUARTILE	MEDIAN	UPPER QUARTILE	1 in 10 SUNNIEST
May	225	244	264	284	338
June	203	219	262	303	316
July	259	283	296	325	351
August	208	236	277.5	296	325
Sept.	127	150	172	198.5	217

(All values in hours)

(a) The Pas A. (1949-1976)

(b) Prince Albert A. (1947-1976)

Fig. 2.5 Monthly percentage ratio of actual to possible hours of bright sunshine at (a) The Pas A. and (b) Prince Albert A.

associated with a change from widespread to localised storm tracks, more than compensates for decreasing daylength.

Interannual variability in monthly sunshine totals can be inferred from Table 2.15 which, using quartile values and one in ten probabilities, indicates the range of values to be expected. Variation about the median occurs from month to month at each station as well as between stations. The interquartile range, which gives an indication of the spread of the distribution, is smaller for The Pas A. in June and August than at Prince Albert A. while the reverse is true for May. Both the interquartile range and the difference between the expected 10 year extremes are very similar for these two stations in September. This indicates a similar distribution of sunshine totals.

Finally, the effect of daylength in controlling sunshine hours at more northerly latitudes cannot be ignored. In order to illustrate the effect of variable daylength, Figures 2.5a and 2.5b plot monthly sunshine as a percentage of the theoretical maximum. The values shown will tend to underestimate actual values during the winter months when the sun is at a low angle above the horizon. It can be recalled that the Campbell-Stokes recorder has a mean lower threshold recording level of 130 Wm^{-2}. This value varies between 90 Wm^{-2} and 260 Wm^{-2} depending upon the moisture content of the card or the presence of dew or rime on the sphere. Nevertheless the pattern of annual change in the ratio of actual to possible sunshine follows the pattern established previously for other components of the radiation regime.

CHAPTER III

DAYLIGHT AND TEMPERATURE

(a) Daylength

Shortwave radiation provides the energy necessary for photosynthesis and hence plant growth. This process depends upon the intensity of the light as well as other environmental factors. Plant development is also affected by the duration of the light period which results in physiological changes upon which initiation of the flowering period depends. The length of the daily exposure to light is called the photoperiod and the plant's developmental response to a photoperiod is termed photoperiodism. So low is the light requirement for photoperiodic response that, strictly speaking, civil twilight - the time interval between sunrise or sunset and the time when the upper limit of the sun is 6^{o} below the horizon - should be added to daylength in the calculation of photoperiod. The duration of twilight varies seasonally and latitudinally as does daylength being as much as two hours in June at the latitude of the study area. Table 3.1 lists, for May to September, the daily mean and monthly totals of daylight hours at 52^{o} - 55^{o}N. and at the equator for comparison. Both the monthly and seasonal averages are higher for the study area than at the equator,despite the absence of twilight time in the figures. The seasonal pattern of change is a reflection of the one

TABLE 3.1: DAILY MEAN AND MONTHLY TOTAL HOURS OF DAYLIGHT DURING THE SUMMER MONTHS AT 52°-55°N AND AT THE EQUATOR (ADAPTED FROM CHANG 1971, 19-21)

LATITUDE (N)	MAY	JUNE	JULY	AUG.	SEPT.	MAY-SEPT.
55°						
Daily Mean	16.1	17.3	16.7	14.9	12.7	15.6
Monthly Total	500.6	518.0	518.2	462.4	382.0	2381.2
54°						
Daily Mean	16.0	17.0	16.5	14.8	12.7	15.4
Monthly Total	495.5	511.5	512.5	458.8	381.0	2359.3
53°						
Daily Mean	15.8	16.8	16.3	14.7	12.7	15.3
Monthly Total	490.8	505.0	506.9	455.7	380.5	2338.9
52°						
Daily Mean	15.7	16.6	16.2	14.6	12.7	15.2
Monthly Total	486.2	499.0	501.7	452.6	380.0	2319.5
0°						
Daily Mean	12.1	12.1	12.1	12.4	12.1	12.1
Monthly Total	375.6	363.5	375.6	373.5	363.5	1851.7

shown for solar radiation at the top of the atmosphere (Sec. 2.b.1). Decline in daylength towards the equinoxes is marked. By September 25th. at 55^{o}N. daylength is 12.1 hours, equal to the mean value for this month at the equator and in mid-winter daylength declines to 41% of its maximum value in June.

Four categories of plants can be identified according to their photoperiodic requirements for floral initiation i.e. long-day, short-day, intermediate and day-neutral (Garner and Allard 1920: Allard 1938). Long-day plants require a daylength of 14-16 hours while short-day plants need less than 8-10 hours. Intermediates demand 12-14 hours and are inhibited in reproduction by daylengths shorter or longer than this period. Day-neutral plants can flower irrespective of the period of illumination. From Table 3.1 it can be seen that species demanding a lengthy photoperiod are likely to give the best results in the study area. Species which favour a longer photoperiod include spring barley, fescue, oats, ryegrass and spring wheat.

The interaction of photoperiod with other environmental factors, especially temperature, in affecting plant development cannot be ignored. Within a species a particular variety may differ in its photoperiodic requirements and hence in the temperature sums necessary for a particular developmental stage to be reached. By way of illustration, Table 3.2 shows the varying temperature sums necessary to meet the requirements of wheat varieties with differing photoperiodic thresholds. Variety S-801 appears to be indifferent to the photoperiod while Marquis and Thatcher demand long periods of

TABLE 3.2: VARYING DEGREE OF PRECOCITY OF WHEATS SOWN AT DIFFERENT PLACES IN AMERICA WITH DIFFERENT PHOTOPERIODS AT THE TIME OF HEADING (PASCALE 1972a, 90).

LOCATION	LATITUDE	DATE OF SOWING	SUM OF TEMPS. ABOVE 0°C DURING THE SUB PERIOD SPROUTING-HEADING (1)	(2)	(3)	(4)	(5)
Maracay (Venezuela)	10° 14'N	10.1.62	1323	817	742	-	-
Pelotas (Brazil)	31° 45'S	30.6.60	1258	-	-	-	-
Buenos Aires (Argentina)	34° 35'S	21.7.62	1117	1140	815	1314	1321
Ottawa (Canada)	45° 24'N	17.5.62	740	860	-	753	774
Beaverlodge (Canada)	55° 13'N	10.5.62	686	708	-	654	645

(1) Sinvalocho M.A.
(2) Pergamino Gaboto
(3) S-801
(4) Marquis
(5) Thatcher

daylight. All the varieties increase their growth rate with a lengthening of the photoperiod except Pergamino Gaboto which is indifferent to the shorter days experienced at Maracay. Daylength is the variable which makes Thatcher a late developer at Buenos Aires and an early variety at Beaverlodge while the reverse is true for Sinvalocho M.A.

Because of the interaction between daylength and temperature sums the use of combined bioclimatic indices which incorporate both elements has received some attention (Nuttonson 1955). This topic will be dealt with in greater detail later (Sec. 3.c).

Also important in relation to photoperiod and temperature are the effects on development of chilling (vernalisation). Most biennials will fail to flower if they have not experienced a period of low temperatures irrespective of the photoperiod.

The effects of temperature on plant growth warrant greater attention and it is to a more detailed examination of the seasonal temperature regime in the study area that attention is now turned.

(b) Monthly mean daily maximum temperatures, monthly mean daily minimum temperatures and monthly mean daily air temperatures.

Plant growth activity is essentially restricted to temperatures between $0^{\circ}C$ and $60^{\circ}C$ where the lower value is the freezing point of water and the upper value is the temperature level of denaturation of proteins. Within this temperature range a wide variety of cultivated species exists. However, it is apparent from specificity in location that some species are adapted to low, moderate or high temperatures. Over the past few decades the work of plant breeders has, to some extent, mitigated against thermal constraints. Nevertheless, temperature is still of fundamental importance for plant growth and development.

For each species there is a lower and upper temperature level beyond which damage or death occurs via the destruction of tissues, regardless of other environmental factors. Between these extremes of temperature and the points at which growth begins or ceases the plant remains at rest, without visible external changes. Beginning at the lower growth threshold plant growth increases with temperature until a temperature is reached at which there is the greatest increase in dry matter production per unit time. This is known as the optimal temperature. Above the optimum there is a successive reduction in growth rate until the upper growth threshold is reached, at which time growth ceases. The lower and upper growth thresholds and the optimum temperature are collectively named the cardinal temperatures. Attempts to delimit fixed cardinal temperatures have met with little success. The physiological complexity of the plant may preclude the definition of precise cardinal points since each physiological process may differ in its thermal requirements and therefore have different temperature thresholds. For example, it is known that the optimum temperature for photosynthesis is lower than that for respiration. As early as 1903 Pfeffer realised that, "... the cardinal points can never be determined with more than approximate accuracy, since their position is related to the external conditions, the duration of exposure, the age of the plant and its previous treatment" (Bierhuizen 1973, 89).

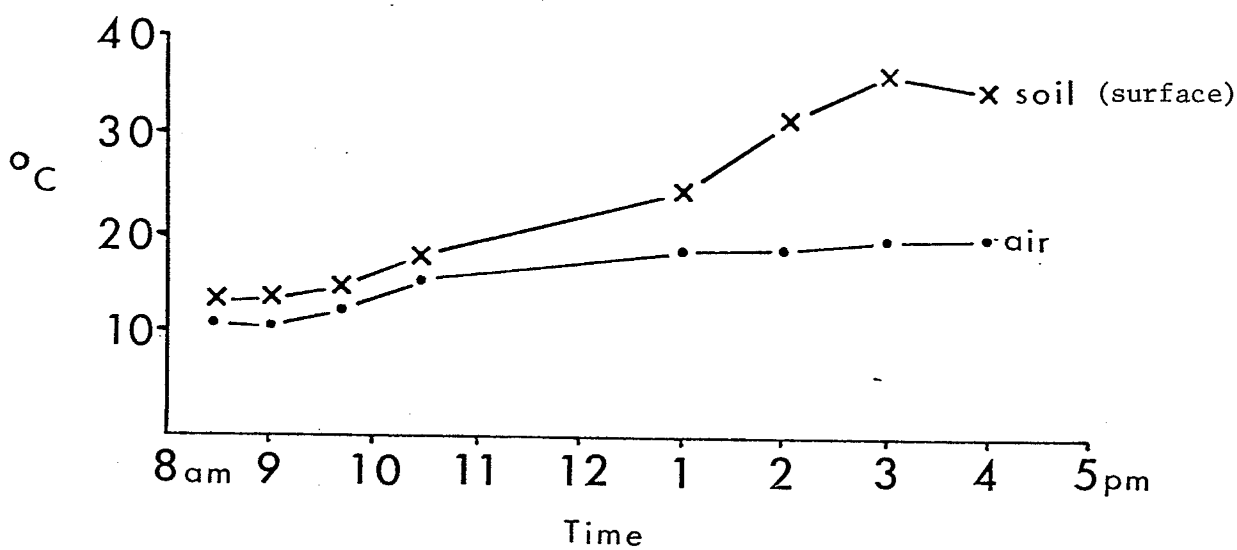
This statement suggests that cardinal temperatures also vary within a species for each of the three major developmental stages i.e. germination, vegetative growth and reproduction. For some species a temperature of $0^{o}C$ may be required before germination will begin while the same temperature at the reproductive stage may be lethal.

Despite barriers to precise determination, approximate cardinal temperatures are available for many crops. Chang (1968, 75) reports that crops such as oats, rye, wheat and barley have a lower threshold at $0\text{-}5^{o}C$, an optimum range from $25\text{-}31^{o}C$ and an upper threshold of $31\text{-}37^{o}C$. Cardinal temperatures for other crops have been presented by Wang (1963,104) and Bierhuizen (1973, 90).

Air temperature is normally measured by mercury or alcohol containing thermometers housed in Stevenson screens with the bulb approximately 1.2 meters above a short grass surface. The screen is designed so as to shield the instruments from global and terrestrial radiation without seriously impeding free ventilation. It is pertinent to consider to what extent recordings taken under the above conditions are representative of temperatures actually experienced by a field crop.

Wang (1963, 211) reports that during clear, calm nights the air temperature in the shelter is lower than the air temperature outside, while on clear, calm days, it is higher. Apparently the temperatures experienced inside and outside the screen are similar only on days which are windy and cloudy, wind acting as a natural aspirator. Temperatures also vary in the vertical plane. During the day lapse conditions are normally such that temperature decreases

Fig. 3.1 Soil and air temperature measurements at Flin Flon, 27th August 1975.



(H.B.M.S. et.al. 1977, Fig. 12a)

with height. Figure 3.1 gives soil and air temperatures recorded on a calm, sunny day at Flin Flon. The temperature difference ranged from 2-16^{o}C and throughout the day soil temperatures were above air temperatures. However, in a situation where sensible heat advection is occuring this may not be true and a positive lapse rate (inversion) may occur. Inversions are much more common at night when, due to rapid radiational cooling of ground and crop surfaces, air temperature increases with height. Witterstein (Geiger 1965, 100) analysed the difference between screen and grass (5 cm. level) minima and found a median difference of 2.6^{o} C on clear and 0.75 ^{o}C on overcast nights. Therefore screen temperatures tend to underestimate the range of temperature conditions experienced closer to the ground surface. This point should be kept in mind throughout the following discussion.

Temperature recordings are made at all 11 of the stations analysed in this section although not all stations record with equal frequency. At the four airport stations (The Pas A., North Battleford A., Saskatoon A., Prince Albert A.) dry bulb temperatures have been taken hourly for most or all of the period 1947-1976. This was also true for Hudson Bay until 1974 when the number of recordings per day was reduced from 24 to 4 (every six hours from 0000Z). For all 11 stations maximum and minimum temperatures are recorded daily. The monthly weather summaries in which all recordings are published contain daily maximum, minimum and daily mean temperatures along with computed monthly means. Throughout the period of analysis entries have been made in degrees Fahrenheit so this scale was used in the computations to reduce the time required for conversions. The results are nevertheless given in degrees Celsius in all cases. Collection of data was confined to the published monthly means for each of the three parameters over the 30 year period and the data were punched on to computer cards. It would be extremely tedious to list every descriptive statistic obtained from the output. However, as a measure of central tendency, the means and, as a measure of dispersion, the standard deviations for every month at each station are given in Appendix 2. The monthly mean daily maximum and monthly mean daily minimum temperatures are defined as the means of the individual daily maximum and minimum temperatures, respectively, in each month. The monthly mean daily air temperature is the average of the daily means in each month. The annual range of temperature is the difference between the monthly means of the warmest and coldest months.

Seasonal temperature characteristics for the area are strongly influenced by the annual course of solar income and by the advection of warm and cold air through the mechanism of the general circulation. In the absence of any temperature -moderating maritime influence the area has a marked continental temperature regime. This can be demonstrated by the use of Conrad's (1946) continentality index (k) which takes the form:

$$k = (1.7A/\sin(\phi + 10^{\circ})) - 14 \qquad (22)$$

where A is the annual range of temperature in $^{\circ}$C and ϕ is the latitude angle. In the use of this type of index it is the relative magnitude of the values obtained which is important. A lower value of about zero is obtained for the oceanic regime of Thornhavn in the Faeroes and an upper value of about 100 for the extremely continental climate

TABLE 3.3: VALUES OF CONRAD'S CONTINENTALITY INDEX (k) FOR 11 STUDY AREA LOCATIONS

STATION	k	STATION	k
The Pas A.	62.7	Prince Albert A.	60.1
Flin Flon	62.4	Saskatoon A.	58.6
Muenster	59.2	Choiceland	60.1
N. Battleford A.	56.9	Lost River	60.1
Waseca	54.6	Hudson Bay	59.6
Pilger	59.0		

of Verschojansk in Siberia. Using the data in Appendix 2 the solution to equation 22 for each station is given in Table 3.3. Spatially, the values have a tendency to increase in an easterly and a southerly direction but the difference in relative values is small. This, of course, is a reflection of the close similarity between monthly mean daily temperatures at each station. In winter the lowest January means are experienced by The Pas A. (-22.8°C), Flin Flon (-22.5°C) and Choiceland (-22.1°C) while the highest monthly means are for Saskatoon A. (-19.3°C), Waseca (-19.3°C) and North Battleford A. (-18.9°C) giving an overall range in monthly means of 3.9°C. However, of great importance during the winter months is the expected deviation from year to year in this overall mean as indicated by the standard deviation. In no case is the standard deviation of January means less than $\pm$ 3.5°C and it goes as high as $\pm$5°C at two of the stations. Assuming a normal distribution it is possible to infer that in 68% of cases at North Battleford A., for example, the mean January temperature will lie between -14.0°C and -23.8°C. Therefore, during winter, the mean is a poor representation of the group as a whole. This conclusion can be compared with the corresponding position for the summer (May to September) months.

The coolest July means are at Choiceland (16.9°C), Waseca (16.9°C) and Hudson Bay (17.3°C) while the highest are at North Battleford A. (18.2°C), Flin Flon (18.2°C) and Saskatoon (18.5°C). The range of means in this case is considerably smaller (1.6°C), as is the range of standard deviations (1.2°-1.4°C). So the inference this time is that in 68% of cases the mean July temperature at North

Battleford A. will lie in the range 16.9°-19.4°C. Since a similar narrow range of means and standard deviations applies for all of the summer months at each station, the mean can be said to give an adequate measure of the group as a whole for these months. It seems unnecessary therefore, to list additional statistical characteristics for every station during these months. However, to give an indication of the expected spread around the central value, data from two stations may be of interest. Table 3.4 lists some characteristics of summer monthly mean temperatures at Prince Albert A. and North Battleford A. Entries in this table are self explanatory.

What has been said about monthly mean daily temperatures can be repeated for the monthly mean daily maximum and monthly mean daily minimum temperatures i.e. the mean value is not representative of the group in winter but in summer these values are broadly representative.

Monthly mean daily maximum and minimum temperatures can also be used to estimate the diurnal range of temperature (thermoperiodicity). Thermoperiodicity is an important parameter for an agrometeorological assessment of the temperature conditions and resources in a region especially in relation to net photosynthesis. The two main physiological processes involved in plant growth are photosynthesis and respiration. Photosynthesis proceeds mainly under daylight temperature conditions and the higher those temperatures are, up to a certain point, the greater the amount of dry matter produced. Respiration, on the other hand, is a continuous 24 hour process and a low night time temperature will reduce respiratory losses. Therefore, the best

TABLE 3.4: SOME CHARACTERISTICS OF MEAN MONTHLY TEMPERATURES IN SUMMER AT (a) PRINCE ALBERT A. (b) NORTH BATTLEFORD A. (^{o}C)

(a)	MAY	JUNE	JULY	AUG.	SEPT.
Mean	9.7	14.6	17.5	16.2	10.0
Standard Deviation	1.3	1.3	1.2	1.4	2.0
Quartile Range	2.0	1.2	1.6	2.1	2.1
Extreme Range	5.5	5.3	5.5	5.2	9.2
Lowest	6.2	12.3	14.8	13.6	5.3
Q_1	8.9	13.8	16.8	15.1	9.1
Median	9.8	14.4	17.3	16.3	10.0
Q_3	10.9	15.0	18.4	17.2	11.1
Highest	11.7	17.6	20.3	18.8	14.4

(b)	MAY	JUNE	JULY	AUG.	SEPT.
Mean	10.9	15.4	18.2	17.1	11.1
Standard Deviation	1.5	1.4	1.2	1.6	2.1
Quartile Range	2.0	1.3	1.4	2.5	2.4
Extreme Range	5.5	6.3	5.7	6.2	9.5
Lowest	7.8	12.7	15.2	14.1	6.0
Q_1	10.0	14.7	17.7	15.9	9.8
Median	10.7	15.4	18.0	17.5	11.2
Q_3	12.0	15.9	19.1	18.4	12.2
Highest	13.3	19.0	20.9	20.3	15.5

TABLE 3.5a: PERCENTAGE CORRECTION FACTORS USED TO ESTIMATE THERMOPERIODICITY USING MONTHLY MEAN DAILY MAXIMUM - MINIMUM TEMPERATURE RANGE (CROWE 1971, 65)

^{0}N MONTH	J	F	M	A	M	J	J	A	S	O	N	D
5 5	40	55	70	75	80	80	80	80	75	70	50	30
5 0	55	75	75	80	85	85	85	85	80	75	65	50

TABLE 3.5b: ESTIMATES OF THERMOPERIODICITY FOR THE SUMMER MONTHS AT FLIN FLON, 1947-1976

MONTH	MAXIMUM-MINIMUM RANGE	THERMOPERIODICITY ESTIMATE
May	11.6^{o}C	9.3^{o}C
June	10.2	8.1
July	10.4	8.3
August	10.1	8.1
September	8.5	6.4

conditions for some plants exist when there is a combination of a high day time temperature and a low night time temperature i.e. with a large diurnal temperature range. It would appear to be a simple matter to subtract the monthly mean daily maximum and minimum temperatures to obtain an average monthly estimate of the thermoperiodicity for the area. However, Crowe (1971, 63) points out that this method, "... can never give too small a range but almost everywhere it yields values in excess of the variation which we are endeavouring to assess." He goes on to say, "The 'error' involved is a purely statistical one; it is introduced when these values are averaged out over a month ..." (Crowe 1971, 64). It is possible to apply an empirical correction factor which varies according to latitude. Crowe (1971, 65) presents the reduction values at 5^{o} latitude intervals in the northern hemisphere and those of greatest relevance to the present study are given in Table 3.5a. It is now a relatively simple matter to apply these corrections to any of the 11 stations. The resulting values for the summer months at Flin Flon (54^{o} 46'N) are given in Table 3.5b.

(c) Temperature sums

In the previous section the discussion of the influence of temperature on plants was largely confined to the effects that variations in temperature have on plant growth. However, the overall development of some plants is also closely related to temperature.

The original notion of plants having an accumulated temperature requirement to reach a given stage of maturity was published by Reaumur in 1735. He summed mean daily air temperatures for April, May and June and noted that this sum was virtually constant for the development of any plant from year to year. Subsequent work led to a wide assortment of other indices (see Thornthwaite and Mather 1954: Wang 1960: Robertson 1968: 1973 for reviews of this work) which can all be considered a sub-group of general temperature efficiency indices (see Klages 1942, 238-265). Of all these indices the calculation of temperature sums is carried out with the greatest ease and the application of this index has drawn wide attention.

Two types of temperature summations can be identified (Todorov and Pali-Shikhulu 1974, 72). Firstly, active temperature summations consider the whole temperature above the lower growth threshold. If the latter were $6^{o}C$ then a mean daily temperature of $15^{o}C$ would give an active sum of 15^{o} since the mean is above the lower threshold. Any temperature below the threshold is considered equal to zero. Secondly, effective temperature summations consider temperatures above the lower cardinal growth temperature relative to this threshold. In this case temperatures below the threshold are assumed equal to the threshold. For example, if the minimum cardinal growth temperature, also referredto as the base temperature, for a given crop is $6^{o}C$ and the mean temperature on a given day is again $15^{o}C$, the temperature sum or degree days for that day is $15^{o}-6^{o}=9^{o}$. Expressing effective temperature summations (TS) in equation form we have:

$$TS = \sum_{P}^{M} (T - To) \qquad (23)$$

where T is the mean daily air temperature; To is the base temperature and the summation is made from the date of planting (P) to the date of maturity (M). Although values of TS are normally assessed for the whole growth period (P to M), the major interphase periods may also be computed. Apart from temperature summation or degree day a variety of terms have been proposed to describe the above summation. Many of these terms include the words 'heat' or 'thermal'. However, Smith (1967, 276) points out that, "Temperature is not and never can be, a measure of heat, although it is clearly a manifestation of its effect. In continental areas there is often a high correlation between air temperature and net energy, but the use of temperature as an expression of radiant energy without corroborative evidence is to be deprecated."

Clearly, if no daily temperatures lie below the base temperature then equation 23 becomes:

$$TS = t\ (Tm - To) \qquad (24)$$

where t is the number of days and Tm is the mean temperature for the period t. Using this relationship in conjunction with field trials it should be possible to plot T against the reciprocal value of t, giving a linear relationship from which the two unknowns (TS the slope and To the intercept) can be calculated. The regression equation takes the form:

$$Tm = TS\ {}^{1}/t + To \qquad (25)$$

Equation 25 is only one of several ways in which the base temperature for various crop species has been evaluated (Arnold 1959). This method apparently gives results comparable with those obtained using the coefficient of variation method (Nuttonson 1955) but has been criticised by Robertson (1968). In computing degree day data in North America the base temperature is normally taken as $5.6^{o}C$ (Williams and MacKay 1970) but for individual species the value used may range from $4.4^{o}C$ for peas to $10^{o}C$ for corn (Holmes and Robertson 1959).

Use of equation 24 gives satisfactory results so long as the base temperature does not fall between the maximum and minimum temperatures. In such a case equation 24 underestimates the true degree day value. Several methods have been proposed to overcome this problem (Arnold 1960: Lindsey and Newman 1956) and comprehensive tables using the Lindsey and Newman method, where required, have been given by Williams and MacKay (1970).

Values of degree day normals are tedious to compile and may be difficult to obtain. However, it is possible, using an approximation procedure, to estimate degree day normals for monthly periods using mean monthly temperatures and standard deviations of mean monthly temperatures. This relationship, first derived by Thom (1954) and reitterated in relation to crop growth by Holmes and Robertson (1959) takes the form:

$$TS = t \left[(\bar{T}m - To) + L \vartheta \sqrt{t} \right] \qquad (26)$$

where TS, t and To are as before and $\bar{T}m$ is the mean monthly temperature; ϑ is the standard deviation of the mean monthly temperature and L is a coefficient of propotionality obtained from a table in which it is entered with a value of $H = (\bar{T}m - To)/\vartheta\sqrt{t}$. The table is given in Thom (1954, 5).

Equation 26 was used to calculate degree day normals for five summer months at all eleven stations using the temperature means

TABLE 3.6a: SUMMER MONTHLY AND SEASONAL ESTIMATES OF DEGREE DAYS AT ELEVEN STUDY AREA LOCATION 1947-1976 (DAY-DEGREES CENTIGRADE)

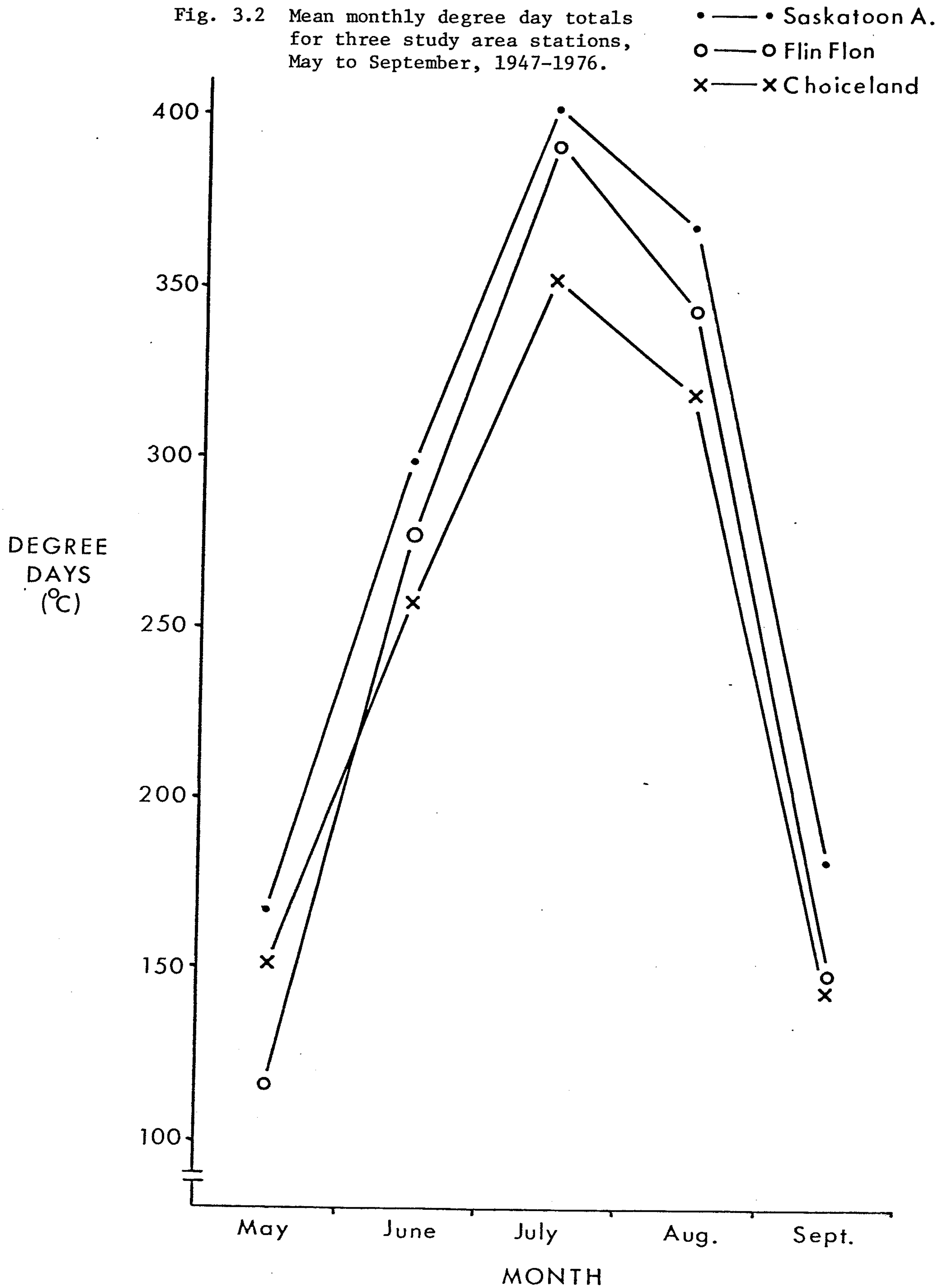
STATION	MAY	JUNE	JULY	AUG.	SEPT.	MAY-SEPT.
The Pas A.	94	263	379	336	147	1225*
Flin Flon	116	277	391	344	147	1275
Muenster	150	280	375	349	162	1317
N. Battleford A.	169	296	391	356	179	1392
Waseca	150	259	353	314	154	1230
Pilger	164	287	383	355	180	1369
Prince Albert A.	137	270	370	329	153	1259
Saskatoon A.	167	299	402	368	181	1417
Choiceland	151	257	352	319	143	1223
Lost River	137	269	366	323	147	1242
Hudson Bay	124	267	366	325	143	1225

* Totals may not equal sum of months due to rounding.

TABLE 3.6b: AVERAGE SUMMER MONTHLY AND SEASONAL DEGREE DAYS AT FLIN FLON 1965-1974 (H.B.M.S. et al 1977)

MONTH	MAY	JUNE	JULY	AUG.	SEPT.	MAY-SEPT.
Degree day value	122	278	378	358	139	1275

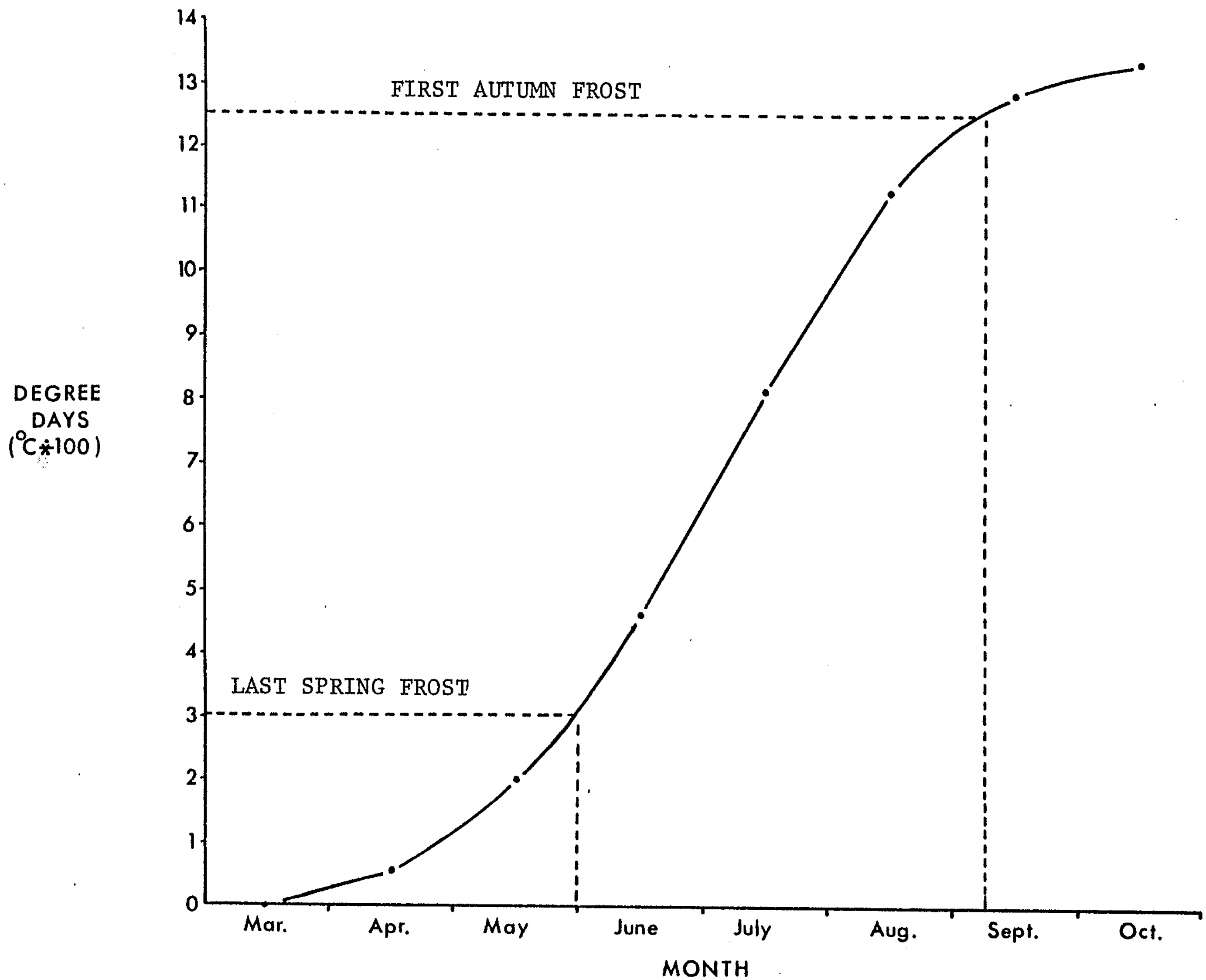
Fig. 3.2 Mean monthly degree day totals for three study area stations, May to September, 1947-1976.



and standard deviations given in Appendix 2. All calculations are based on a 5.6^{o}C threshold temperature and the results are given in Table 3.6a.

The first point to note is that each station displays the same relative order in monthly totals. July always has the highest values followed by August then June, with May and September being lower and very similar. This point is illustrated graphically for three stations in Figure 3.2. Seasonal totals (May to September) are also given in Table 3.6a. Saskatoon A. has the highest value of 1417 degree days while the lowest, at Choiceland is 1223 degree days, a difference of 18%. Spatially the values decrease in all directions away from Saskatoon, the only increase being at Flin Flon with an apparently anomalous total of 1275 degree days. It was possible to check both the validity of the value given for Flin Flon and the relative accuracy of the estimation procedure in general using the results of a study undertaken locally (H.B.M.S. et al 1977). This study computed monthly values of degree days from May to September using daily mean temperatures over the period 1965-1974. The same base temperature was used and the results (using graphic interpolation) are presented in Table 3.6b. Comparing these results with the estimates for Flin Flon (Table 3.6a) it can be seen that they are very similar. The largest individual monthly difference is 6% in September. These small differences may be due to inaccuracy in interpretation of the graph. Only the May to September total was available without graphic interpolation and in this case the results are identical at 1275 degree days. It can be concluded, therefore, that the Flin Flon values

Fig. 3.3 Average seasonal accumulation of degree days for Waseca, 1947-1976.



are a valid estimate and that the estimation procedure in general gives values which would be obtained using daily temperatures. However, this does not imply that the temperature recordings taken at the Flin Flon site are representative of the area in general. Only in a comparison with records taken close-by, at Flin Flon Airport, for example, could a hypothesis of non-representation be tested.

So far only monthly values have been considered, but daily averages can be obtained by plotting mean daily values on the mid-day of each month, and joining the points. Daily values can then be read directly from the graph. Of more value, perhaps, than individual daily values or monthly means would be estimates of degree days over any given period during the warm season. This is made possible by plotting cumulative monthly totals, as in Figure 3.3 for Waseca. By reading off the expected degree day accumulations by 31st. May (mean date of last spring frost) and 8th. September (mean date of first autumn frost), the normal frost free period accumulation can be derived by subtraction (950 degree days). Using the standard deviations of the frost dates, the degree of variability in accumulations can be estimated. It should also be noted that in the period planting to emergence soil temperatures are often used in place of air temperatures.

From the discussion so far it might be deduced that the use of degree days for predicting plant development is the best method available. This is not the case since the method suffers from several major faults (Wang 1960: Robertson 1968:1973: Pascale 1972b). These deficiencies can be considered under six major headings:

(1) The effects of temperature vary for many species from one phenological stage to the next. Degree day summations fail to take this into account by implying, for example, that a cool spring followed by a warm summer is the same as a warm spring followed by a cool summer. Work at Vollebekk in Norway by Strand (reported in Smith 1967) over the period 1940-1951 and involving trials with 49 barley varieties showed that in all cases the highest yields followed cool spring conditions. Therefore, degree days do not provide an accurate assessment of the yield of such crops.

(2) The base temperature from which effective temperature accumulation starts is not constant and varies during the life cycle of the plant. The base temperature for tomatoes has been given as 15°C (Holmes and Robertson 1959) but the lower threshold varies as each phase of development procedes (Wang 1963, 350). Only occassionally is the adverse effect of temperatures above the optimum taken into account (Bilbro 1963 in Pascale 1972c) and although this is not a serious omission at higher latitudes for a whole season, detrimental effects of high temperatures may occur on individual days.

(3) Neither the varying of lower thresholds nor the adjustment of upper thresholds improve the correlation between degree day totals and rate of development (Thornthwaite 1952 in Wang 1960, 787). This is also true when summations are made over growing periods of various lengths (Wang 1960).

(4) The principle of cardinal points suggests that plant response with respect to temperature is not linear over the entire temperature range, especially near the upper and lower threshold

temperatures. To overcome this problem, use of an exponential index is sometimes suggested (Klages 1942, 243) based on the van't Hoff Arrhenius principle. A temperature coefficient can be defined as the ratio of a rate of reaction at a given temperature to its rate at a temperature $10^{o}C$ higher and is designated by the symbol Q_{10}. Since, in general, metabolic processes give a value of $Q_{10} = 2.0$, use of an exponential index is assumed to be justified. The obvious fault with this method is that temperatures above the optimum are ascribed an increasingly high efficiency when, in fact, these temperatures may be detrimental to the development rate.

(5) As indicated previously, the temperature records used in computing degree day values are not necessarily representative of the environment within which growth and development take place. More research is needed into models which relate air temperature to "effective crop temperature" such as the one devised by Robertson (1953 in Robertson 1973).

(6) Finally, and most importantly, temperature is not the only variable influencing plant development. Ideally the effects of planting date, soil characteristics (type, temperature and moisture content), plant population density, light intensity, diurnal temperature changes, global radiation, wind, daylength and weather variability should all be taken into consideration. Attempts have been made to overcome some of these deficiencies by the use of combined indices.

Chen (1973), for example, has incorporated Monte Carlo simulation techniques to develop a stochastic model which will account for weather variability in predicting temperature summations. The stochastic model developed was:

$$TS = \sum_{1}^{t} \left[T \quad (\mu , \vartheta) - To \right] \qquad (27)$$

where T (μ , ϑ) is the random daily average temperature; μ and ϑ are the mean and standard deviation of the month, respectively.

Daylength has been incorporated as an important variable in the work of Nuttonson (1948). His photothermal concept can be expressed as:

$$PTU = D \sum_{P}^{M} (T - To) \qquad (28)$$

where PTU is the number of photo-thermal units and D is the average daylength. Nuttonson found that this equation gave values which were more constant from station to station than temperature sums alone.

Both photoperiod and diurnal temperature changes have been taken into account in Robertson's (1968) biometeorological time scale. The basic model can be expressed:

$$r = dM/dt = F_1 \ (D) . \ F_2 \ (T) \qquad (29)$$

where r is the average rate of maturity (M) per unit of time (t) and $F_1(D)$, $F_2(T)$ are appropriate non-linear functions of photoperiod and day and night temperatures respectively. The degree of maturity cannot be observed numerically and so was given a stochastic value of one for each phenological period i.e. from one phenological stage S_1, to another S_2. Therefore, integrating equation 29 over time leads to:

$$\int_{S_1}^{S_2} r dt = M = \int_{S_1}^{S_2} F_1 \ (D) . \ F_2 \ (T) \ dt = 1 \qquad (30)$$

The final form of the expression for which coefficients were evaluated was:

$$1 = \sum_{S_1}^{S_2} \Big[\left\{ a_1 \ (D - a_o) + a_2 \ (D - a_o)^2 \right\} - \left\{ b_1 \ (T \max - b_o) \right.$$

$$+ b_2 (T\max - b_o)^2 + C_1 (T\min - b_o) + C_2 (T\min - b_o)^2 \Big\}\Big] \quad (31)$$

where T max and T min are the daily maximum and minimum temperatures respectively and a_o, a_1, a_2, b_o, b_1, b_2, c_1, C_2 are coefficients to be evaluated.

This model is a definite improvement over earlier work and has been used to estimate those locations on the Prairies at which Marquis wheat can be expected to reach maturity (Williams 1969: 1971). It was estimated that wheat would ripen at all locations tested in Manitoba and Saskatchewan. South of 53°N the period from planting to ripe stage exceeded 100 days at only about 2% of the locations while north of 53°N in Saskatchewan the duration was less than 98 days at about half the points (Williams 1971, 6-7).

In response to the poor results obtained when degree days are used to predict soybean development (Major et al 1975a) a model similar to that of Robertson's has been devised for this crop (Major et al 1975 b).

A major assumption of all temperature based models is that a close relationship exists between radiation and temperature. However, Chang and Root (1975) have analysed monthly data from 442 stations in seven climatic regimes defined according to the Köppen classification. The correlations were poor especially in A and E climates. Therefore, there would appear to be a need for models which incorporate both radiation and temperature, such as the solar thermal model developed by Caprio (1974) for lilacs. Meanwhile the simple degree day system will continue to be used, "... because of its value in satisfying practical needs, rather than for its accuracy or theoretical soundness"

(Wang 1960, 786). This is evident from the recent update of Holmes and Robertson's 1959 publication (Edey 1977). As Smith (1967, 277) points out, "The surprising feature is that so much information can be obtained by using such a simple parameter ...".

(d) Last spring frost, first autumn frost and the frost free period.

As the temperature drops below the lower threshold for active growth there comes a point at which irrepairable damage occurs in the plant cells. The extent of damage depends not only upon the actual temperature reached, but also upon the duration of the cold period and the rapidity with which the cold point is reached. For example, a short period of chilling may not cause any damage while one which lasts throughout a night may be much more serious. Also, several days of near freezing temperatures may harden plants and prevent serious damage. On the other hand, damage occurs when ice crystals form within the plant or the plant itself freezes. Therefore, rapid cooling, which can result in large ice crystal formation, is more destructive. For this reason, the term freeze is often prefered to frost. In the present discussion freeze will refer to any low temperature which is potentially detrimental to plant growth and frost will refer to a screen temperature of $0^{o}C$ or below. Problems of interpreting the latter with respect to actual crop conditions have already been discussed (Sec. 3.b).

In northern areas lethal minimum temperatures are obviously of considerable importance in limiting plant growth. The temperature level at which freeze damage occurs is species specific and also depends upon the stage of development. Ventskevich (1961, 138-139) lists the resistance of selected crops to low temperatures in different developmental phases. Those crops showing the highest resistance include spring wheat, oats and barley which can tolerate temperatures of -7^{o} to $-10^{o}C$ during germination, -1^{o} to $-2^{o}C$ during flowering and -2^{o} to $-4^{o}C$ during fruiting. Slightly less resistance is offered by flax with values of -5^{o} to $-7^{o}C$, -2^{o} to -3^{o} C and -2^{o} to $-4^{o}C$ for each of the three developmental phases. It should be noted that these data (also presented in Rosenberg 1974, 267) give no account of the plant's growth history, degree of toughening or duration of low temperature conditions.

Despite the problems of specifying freeze temperatures adequately, the occurence of $0^{o}C$ at screen level is generally considered as an appropriate temperature at which analysis can begin. There are two main reasons for this:

(1) Prolonged periods of time with temperatures at $0^{o}C$ or below is regarded as harmful to most plant tissues involved in vegetative activity.

(2) The physical change of state, water to ice, occurs at this temperature.

Therefore the last and first dates at which this temperature occurs during the year, limit the period of time in which most temperate crops can safely vegetate.

For each of the 11 stations the dates on which the last frost in spring and the first frost in autumn occured were derived for the 30 year period 1947-1976. These dates were changed into days of the year, allowances being made for leap years, and the resulting values were used to compute the length of the frost free period. In some cases the number of frost events recorded was less than 30 due to deficiencies in the data base. These data were punched onto computer cards in order that descriptive statistics of the frost series could be obtained.

Previous work in Iowa (Thom and Shaw 1958) has shown that freeze date series are randomly and normally distributed. This suggests that the sample mean and variance are jointly sufficient for estimating the frost distribution function. In order to verify the normality hypothesis for frost dates and for the frost free period in the study area, use was made of the skewness and kurtosis measures given in the BMDP P2D package program printout. Pronounced skewness indicates that a distribution is affected by extreme values while kurtosis gives a measure of the flatness (longtailedness) of the distribution curve. The standard errors of the estimates of these two moments are given by $(6/N)^{\frac{1}{2}}$ and $(24/N)^{\frac{1}{2}}$ respectively, where N is the sample size. Using this information, 90% and 95% confidence intervals were computed for these statistics for the required range of N values. In nearly every case the hypothesis of normality was verified so the mean and standard deviation can be said to give an adequate measure of the frost series and frost free period. For two stations, however, the hypothesis of normality could be rejected for at least one of the frost series on both the skewness and kurtosis measures at the 95% confidence level. In these cases Hampel's estimate of central location is given. This estimate reduces the weights assigned to extreme observations and it

TABLE 3.7: FROST STATISTICS FOR 11 STUDY AREA LOCATIONS (DATES ARE GIVEN AS DAYS OF THE YEAR).

STATION	DATE OF LAST SPRING FROST MEAN	DATE OF LAST SPRING FROST STD.DEV.	DATE OF FIRST AUTUMN FROST MEAN	DATE OF FIRST AUTUMN FROST STD.DEV.	FROST FREE PERIOD (DAYS) MEAN	FROST FREE PERIOD (DAYS) STD.DEV.
The Pas A.	148	9	262	10	114	12
Flin Flon	144	10	263	9	120	13
Muenster	147	14	253	12	107	20
North Battleford A.	140	11	259	10	118	16
Waseca	151	13	251	12	100	19
Pilger	150	12	258	9	108	15
Prince Albert A.	155	11	248	12	93	13
Saskatoon A.	145	11	257	11	112	15
Choiceland	155	17	249	12	93	21
Lost River *	154		250		95	
Hudson Bay *	152		253		101	

* Hampel's estimate of location (Andrews et al 1972)

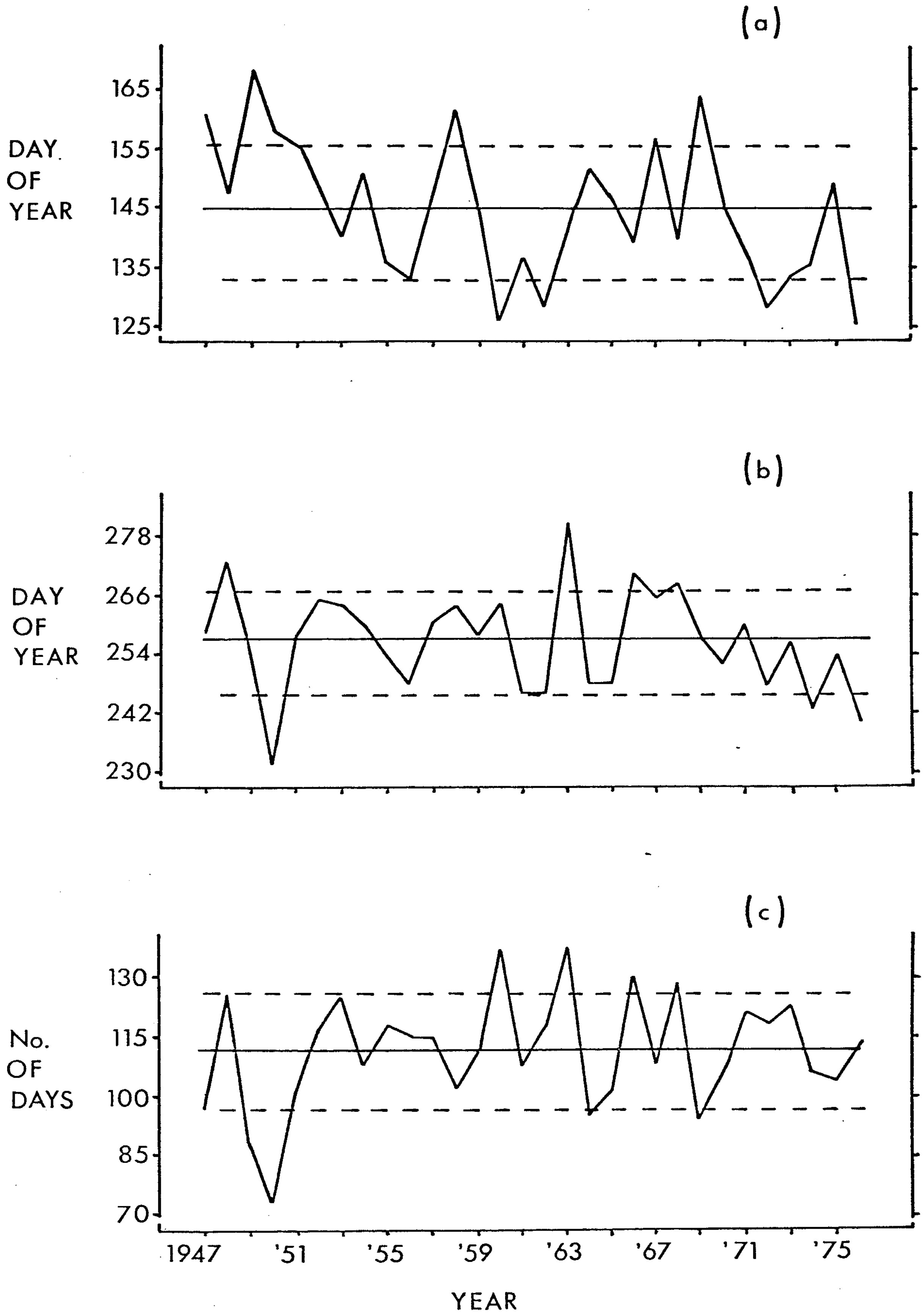


Fig. 3.4 Dates of the (a) last spring frost and (b) first autumn frost, and length of the (c) frost free period at Saskatoon A., 1947-1976.

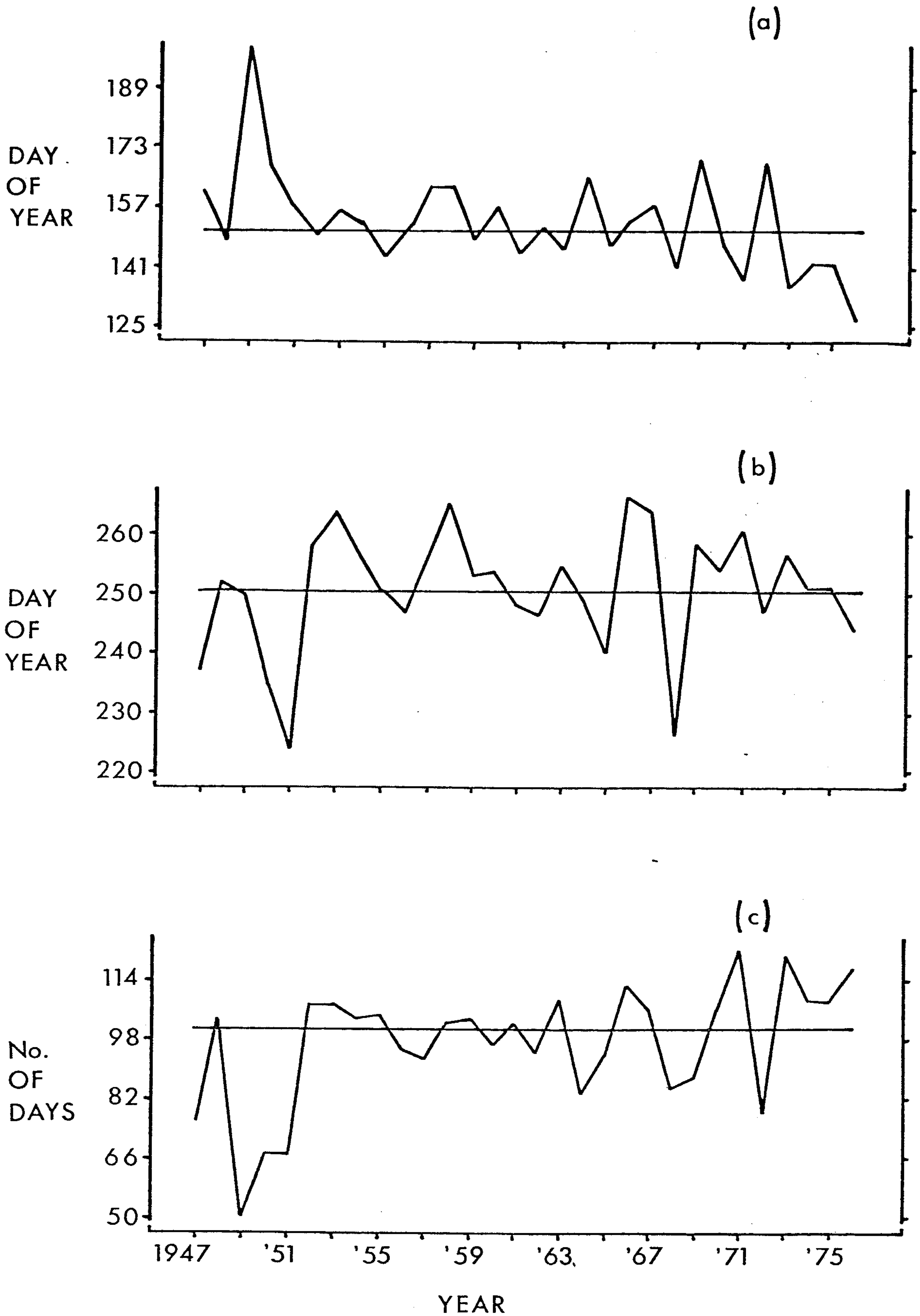


Fig. 3.5 Dates of the (a) last spring frost and (b) first autumn frost, and length of the (c) frost free period at Hudson Bay, 1947-1976.

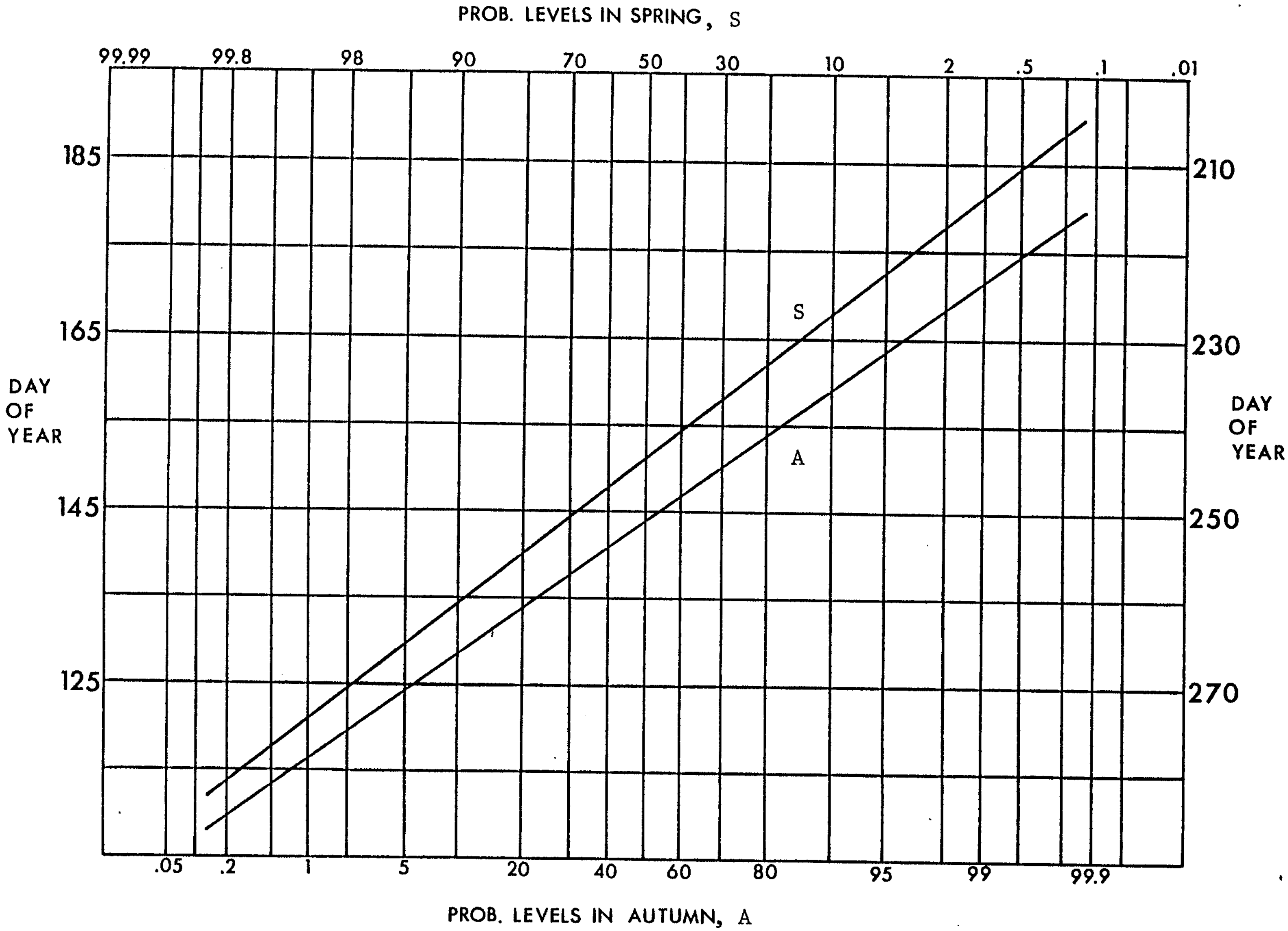
is a robust estimate in the sense that the statistical variability of the measure is never much greater than that of the mean and the median, but is considerably less for long-tailed symmetric parent distributions (Andrews et al 1972)

It is clear from the high standard deviations of the frost measures given in Table 3.7, coupled with the independence of the values of consecutive years, that inter-annual variability of each frost measure will be high. This is illustrated by Figures 3.4 and 3.5 which plot annual values for each of the three frost measures. Also shown are the mean and standard deviation of each measure for Saskatoon A. and Hampel's estimate of location for Hudson Bay.

For the nine stations which have normally distributed data, it is possible to estimate the probabilities that the last spring or first autumn frost will occur on or after specified dates. This can be done using normal probability paper by plotting the mean at 50% and the means plus or minus two standard deviations at 2.275% and 97.725% respectively. This procedure has been followed for Waseca and the result is presented in Figure 3.6. In spring, for example, there is a 15% chance that a frost will occur after June 14th (day 165).

It has also been shown that the dates of the occurence of the last spring and first autumn frosts are independent of one another (Thom and Shaw 1958). This enables a specified length of growing season to be calculated. By way of illustration dates of last spring and first autumn frosts were correlated using BMDP P8D for Saskatoon A. and The Pas A. Results gave correlation

Fig. 3.6 Probability plot of the frost hazard in spring and autumn at Waseca.



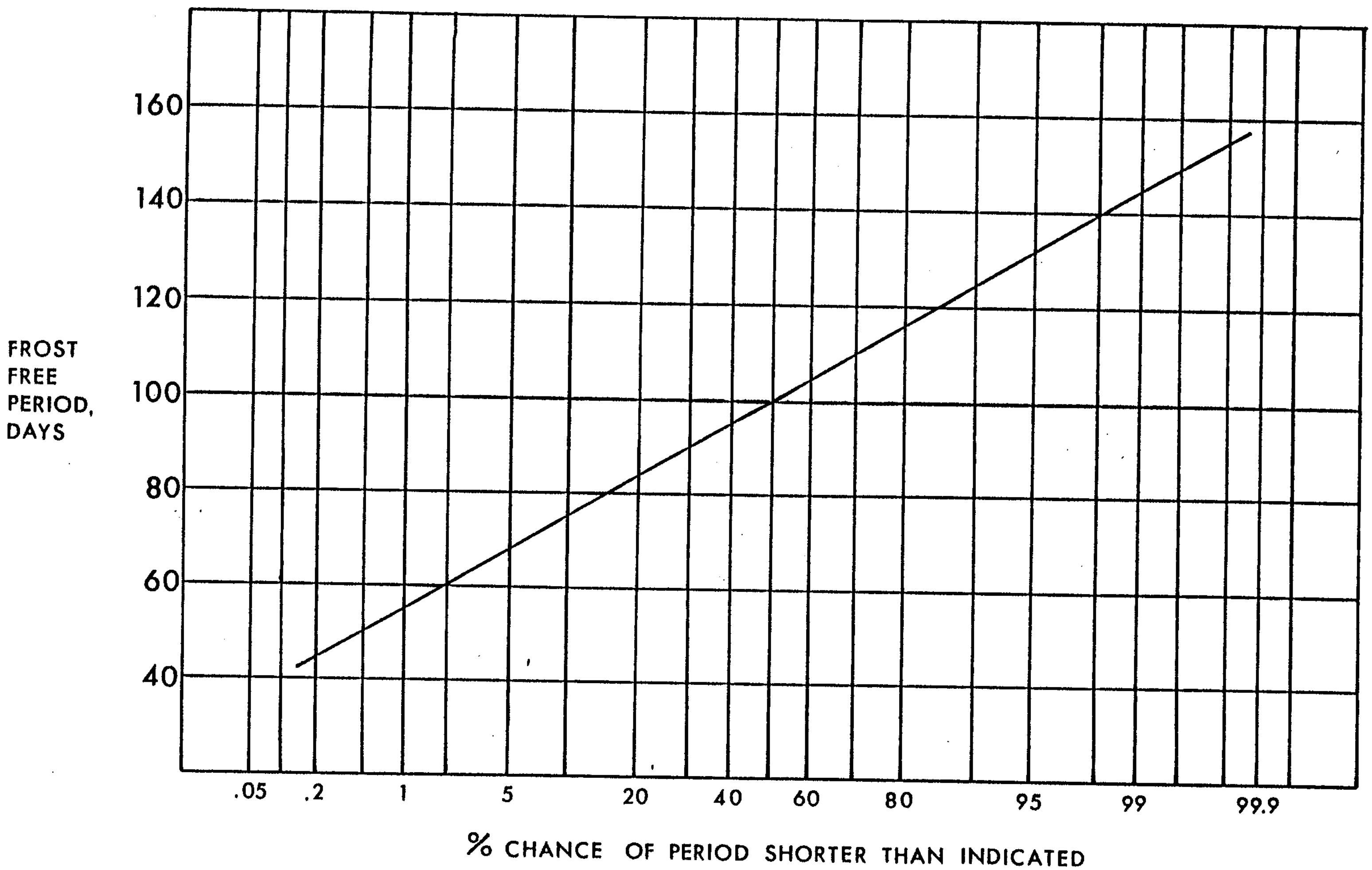


Fig. 3.7 Probability plot of the frost free period at Waseca.

coefficients for the two stations of r=0.15 and r=0.21 respectively. Therefore the mean and standard deviation of the frost free period can be closely approximated by assuming that the mean frost free period is the difference between the spring and autumn means and that the standard deviation of the frost free period is the square root of the spring and autumn frost variances. In fact there is no need to complete these calculations as the actual frost free period means and standard deviations for the nine stations with normally distributed frost series are given in Table 3.7. Again these values can be plotted on normal probability paper, thus allowing the probability of a given length of frost free period to be specified. This has been done for Waseca (Figure 3.7) and it can be seen that there is a 2% chance of the frost free period being less than 60 days

(e) Cold air advection and the Arctic Front

Two main factors determine the temperature of the air at any location:

(1) The balance between incoming and outgoing radiation

(2) Advection or the horizontal transfer of air masses with different temperature characteristics.

This has led Biel (1961) to distinguish between radiation frosts, which occur within homogeneous air masses during clear, calm nights and are characterised by the presence of inversions, and advection frosts which result from large-scale air mass transportation. Rosenberg (1974, 268) however, points out that radiation and advection frost types are not mutually exclusive. Often, the advection of cool, clear dry air will enhance radiational losses from soil and plant surfaces. On the other hand radiational processes contribute to heat exchange during cold air advection.

Since the radiation balance at any place is influenced by such factors as soil type, slope, aspect etc. the occurence of radiation frosts tends to be a localised event. For this reason, frost protection measures are often successful and a large number of methods to achieve this goal are available (W.M.O. 1963). Advection frosts, on the other hand, may occur over many thousands of square kilometers, are not accompanied by low level inversions and protection is not generally feasible. Since many of the crops grown within the study area are resistant to a moderate degree of frost, it is advection frosts which are of considerable significance in limiting crop growth in general.

It is frequently stated that the last spring and first autumn frosts are due to radiational cooling. To verify this assertion Rosenberg and Myers (1962) have undertaken a detailed investigation of radiation and advection frosts in and along the Platte River Valley of Nebraska. They found that 69-93% of last spring frosts and 57-82% of first autumn frosts were of the radiation type. Since protection against damage from radiation frosts is practical, Rosenberg and Myers defined a 'potential growing season' as the number of days between the last spring and the first autumn advection frosts. The mean length of this period was found to be from 15-32 days longer than the frost free period based on a $0^{\circ}C$ shelter minimum temperature definition. Most of this difference was accumulated in spring when the last advection frost preceeded, by as much as 20 days, the last radiation frost. Although protection against damage from radiation frosts is not economically practical in the north, calculation of a 'potential growing season' by assessing the nature and occurence of cold air advection is useful, if it is accepted that the hardy nature of northern crops militates against severe damage by radiational cooling alone.

The dates of last spring and first autumn frost defined by a 0^{o}C screen minimum temperature have already been presented for the study area (Sec. 3.d.). It would also have been interesting to investigate the incidence of advection frosts by recording their dates of occurence in a manner similar to that used by Rosenberg and Myers. Unfortunately temporal and data constraints precluded such a detailed investigation. However, as advection frosts over the study area are normally associated with the presence of Arctic air, it would be of considerable interest to study the southern extent of this air mass during the summer season. Therefore, a preliminary analysis of cold air advection has been undertaken by recording fluctuations in the position of the arctic front - the assumption being that the occurence of advection frosts over the area is related to the movements of this frontal zone.

The arctic front is one component of the four air mass, three front model favoured by Canadian meteorologists in analyses of the baroclinic structure of the atmosphere over North America. The model can be presented as follows:

AIR MASS	FRONT	
CONTINENTAL ARCTIC (cA)		
MARITIME ARCTIC (mA)	(continental) ARCTIC FRONT	(A)
MARITIME POLAR (mP)	MARITIME ARCTIC FRONT	(M)
MARITIME TROPICAL (mT)	POLAR FRONT	(P)

Throughout the winter period cA air dominates both the study area and its environs at all times. The presence of this air mass is evident from extremely low temperatures, negligible mixing ratios and very little cloud cover. Stability in cA air is witnessed by the fact that potential temperatures may increase by well over 20^{o}K from the surface to 700 millibar level, ruling out convective processes (Crowe 1971, 274).

During the summer months the normal source regions for cA air are covered with thawing ice, ice-melt water and cold, muddy land. Therefore the term 'continental' is a misnomer for this season, although it is often retained to indicate that the geographical source region is similar to that of the winter type and all three frontal zones appear on most surface frontal analyses. In reality, cA air during the summer season closely approximates with mA air from the Pacific.

Detailed investigations of the average position of the arctic front and, by implication, the southern extent of cA air, have been undertaken by two authors.

Bryson (1966) used three different techniques to establish mean frontal positions. These techniques were:

(1) Surface air mass trajectories for each 5^{o} latitude and longitude grid intersection in July for the ten years 1945-1951 and 1954-1956.

(2) The resolution of the daily maximum temperature distribution into partial collectives for July 1948-1957.

(3) An analysis of monthly resultant wind streamlines from 1930-1945.

All three methods employ the use of surface data although it is no means clear to what extent the air mass types determined empirically by these methods relate to those of the four air mass, three front model.

Barry (1967) has employed frontal contour charts for the 850 millibar level to determine the position of the arctic front along each 10 degree meridian from 50^{o} to 160^{o} W. Daily positions were recorded at 00 GMT for January, April, July and October in the years 1961-1965. The method involved the use of microfilm records which may be subject to enlargement errors but this was not considered to be significant. Although the results are related to surface vegetation zones, the relationship between the 850 millibar frontal contour and its corresponding surface location was only briefly discussed.

The objective of the present study was to analyse the surface location of the arctic front in relation to the study area using the data available from surface synoptic charts. The method, although similar to the one used by Barry (1967), was originally conceived as an adaption and extension of that employed by Catchpole et al (1977) to assess the poleward extent of mT air at 85^{o}W. Results are presented for summer monthly (May to September) and 10 day groupings and are related to those obtained by Bryson (1966) and Barry (1967).

Synoptic surface charts for western Canada are prepared at Winnipeg International Airport for the purposes of daily weather analysis and forecasting. These charts employ the four air mass, three front model so, when the arctic front can be identified it is recorded.

Charts are prepared every three hours at a scale of 1:10,000,000 using a Polar Stereographic Projection true at 60°N.

A preconstructed latitude, longitude grid overlay was used to determine the meridional location of the arctic front at 3° intervals from 95°W to 110°W (i.e. at 95°, 98°, 101°, 104°, 107°, 110°). Estimations were made to the nearest degree of latitude so results should be within ± 56 km. Data were only estimated from 00 GMT charts although every chart was inspected to obtain an indication of intermediate locational changes of the frontal zone. It was considered desirable to assess the position of the front throughout the period when last spring and first autumn frosts are likely to occur within the study area, as well as the intervening summer period. Therefore locations were estimated from 1st May to 10th October. The most recent year for which records were conveniently available was 1975 and it was hoped that a continuous 10 year period, up to and including this year, would be available. However, much of the data for the summer of 1966 could not be located; charts prior to this year being stored in the Federal Public Archives in Winnipeg and more recent charts remaining at the Winnipeg Airport. For this reason, 1965 was substituted for 1966 and the 10 year period became 1965, 1967-1975. For ease of analysis, each set of daily estimations was punched onto computer cards.

All charts were available for the 10 year period considered but the arctic front was not always present. Two reasons can be advanced to explain the absence of the front over part or all of the survey area. Firstly, in mid summer differentiation of cA air from mA air becomes increasingly difficult and no arctic front may be demarcated. Secondly, in spring and autumn the outbreak of cA air southward may result in a fragmentation of the frontal zone as the characteristics of the cA air are progressively modified (Palmén 1951). An indication of the frequency with which no arctic front was recorded over the survey area is given in Table 3.8. As expected, the arctic front is absent most frequently in mid summer and the table also indicates that the frequency of non-occurence increases from west to east in all months. It is also interesting to note that the front is most frequently present in June, a fact indicative of a highly significant change in the circulation pattern between June and July.

The results of the monthly analysis can be grouped into two sections:

(1) The central tendency and degree of variability in arctic front locations, represented by the median and quartiles respectively. If the assumption is made that, when the arctic front is present, all air lying to the north of it is cA air, then the median and quartiles also indicate levels of cA air frequency. That is, at the lower quartile (Q_1) the cumulative percentage frequency of arctic air occurence is 25%, at the median 50%, and at the upper quartile (Q_3) 75%.

(2) The percentage frequency of arctic front occurence in latitudinal sectors. This method of presentation takes into account the fact that the front is not always present but its occasional absence prevents the estimation of a cumulative percentage frequency.

TABLE 3.8: MONTHLY PERCENTAGE FREQUENCY OF SURFACE ARCTIC FRONT ABSENCE FROM THE SURVEY AREA: 1965, 1967 - 1975.

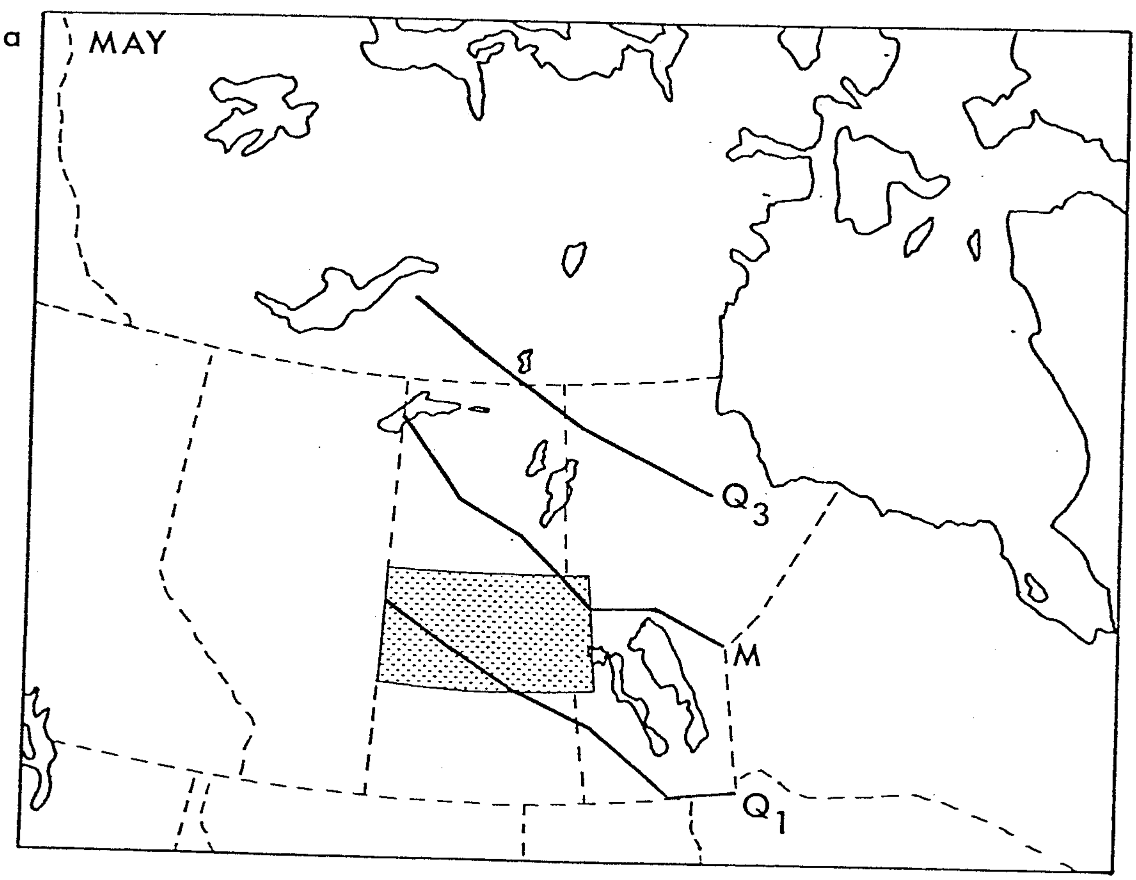
	°W LONGITUDE					
MONTH	110	107	104	101	98	95
May	11.0	13.2	15.2	17.7	20.0	25.5
June	9.3	11.7	13.7	14.3	16.3	16.7
July	35.5	37.4	39.3	39.7	40.6	41.0
Aug.	22.9	25.5	27.7	29.7	31.3	32.6
Sept.	13.7	15.7	18.3	19.0	20.0	22.3

Figures 3.8a to 3.8e show the median locations of the surface arctic front for May to September as well as the quartile ranges. The quartile lines delimit the central 50 per cent of the frequency distribution and this area can be considered as the main frontal zone for each month.

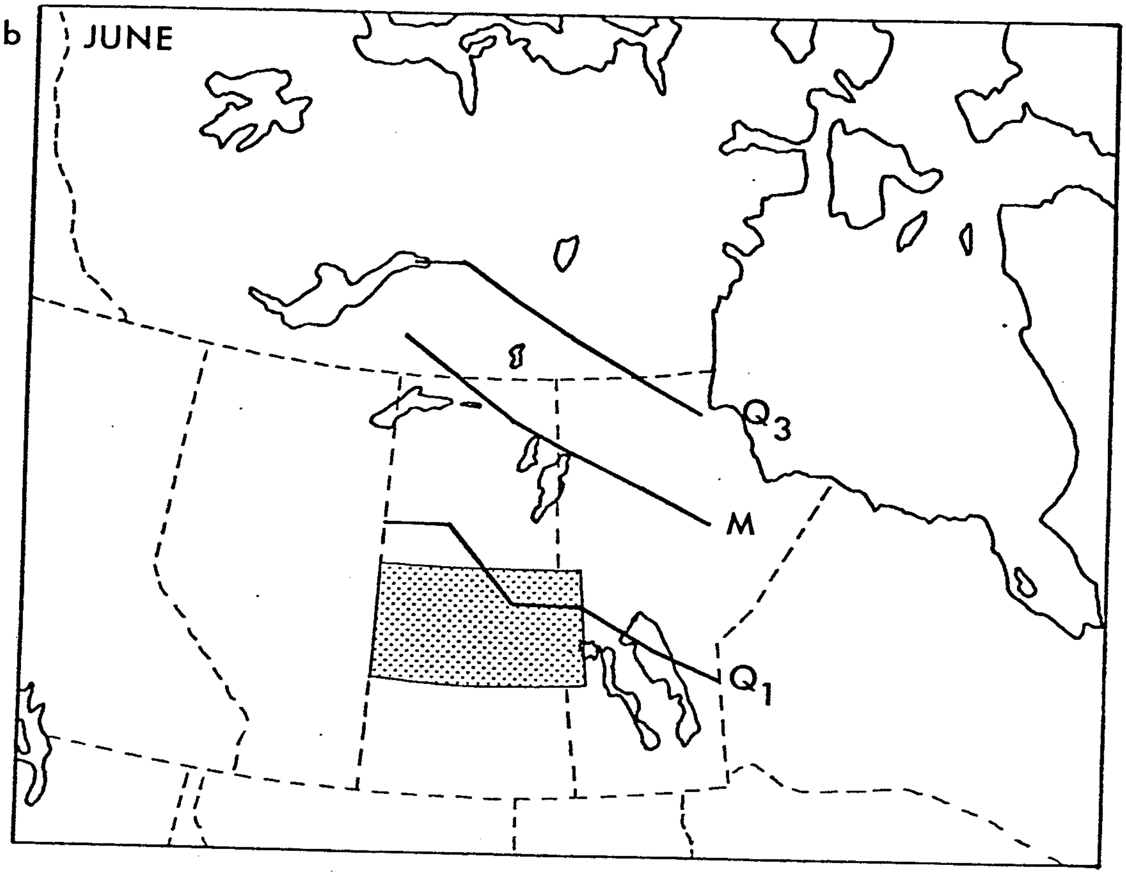
In May (Fig. 3.8a) the frontal zone is well established over most of the study area. The median line starts at 110°W,, 59°N and dips sharply from west to east but there is no indication of increased variability in either direction. By June (Fig. 3.8b) there has been a marked northward shift in the frontal zone. Over the study area the probability of occurence is generally less than 25%. Another northward dislocation occurs between June and July (Fig. 3.8c). During the latter month the frontal zone reaches its most northerly limits. Taking into account the fact that the front may be absent for up to 40% of the time during July it is hardly surprising that frosts are virtually unknown throughout the study area in this month. There is a tendency in both July and August for variability in the frontal zone to increase from west to east, a trend which is absent during the other months. The median frontal location dips southward only slightly from July to August (Fig. 3.8d). However, the southward shift in the lower quartile line is quite marked. This movement of the frontal zone may by reflected in the infrequent, although not insignificant, occurence of first autumn frosts during the latter part of August. By September (Fig. 3.8e) the cycle is complete and the possibility of the arctic front bisecting or lying to the south of the study area again approaches 50 per cent.

Fig. 3.8 Median (M) and quartile (Q) locations of the arctic front between 95°W and 110°W for: (a) May (b) June (c) July (d) August (e) September.

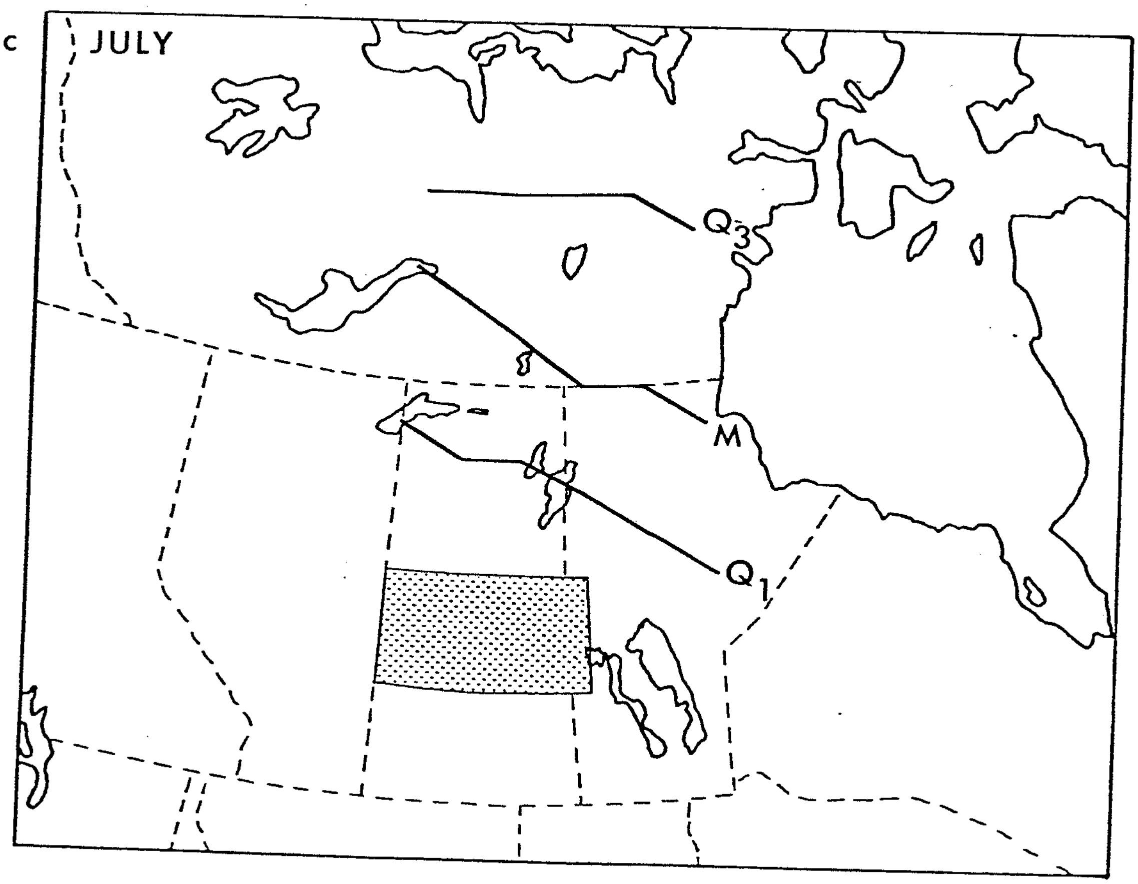
a



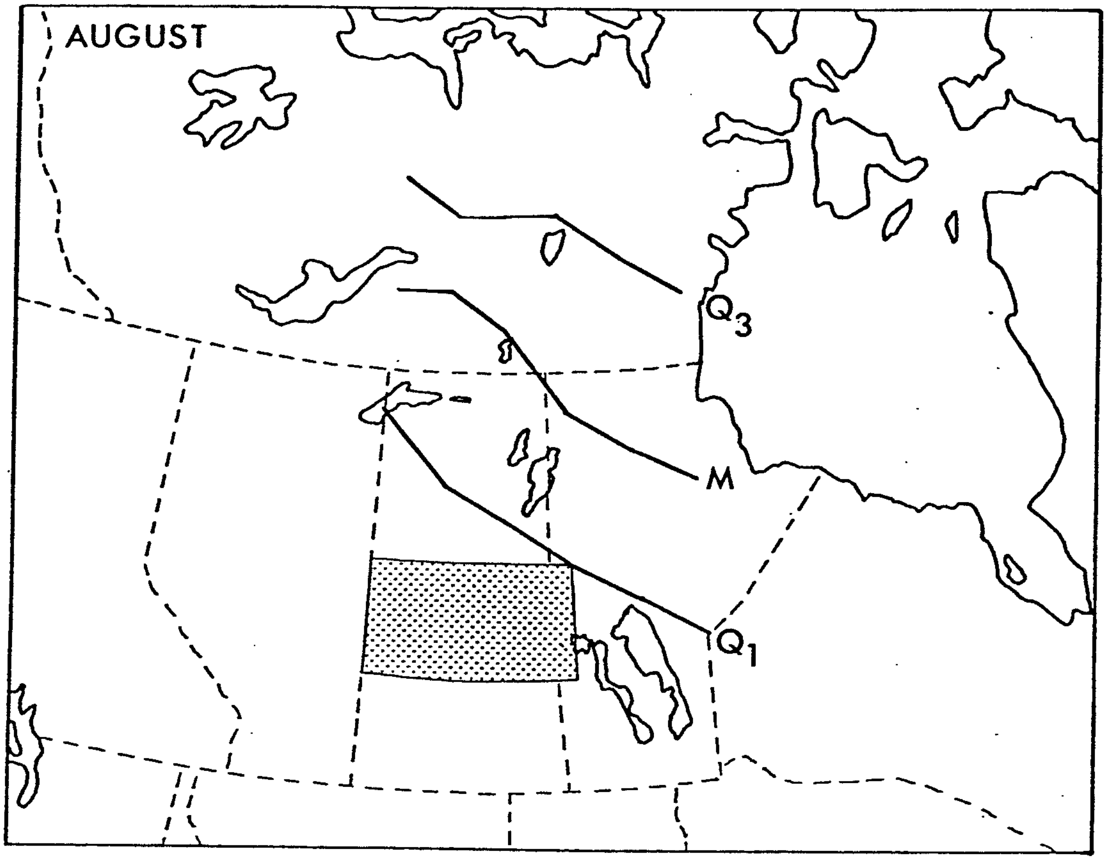
b



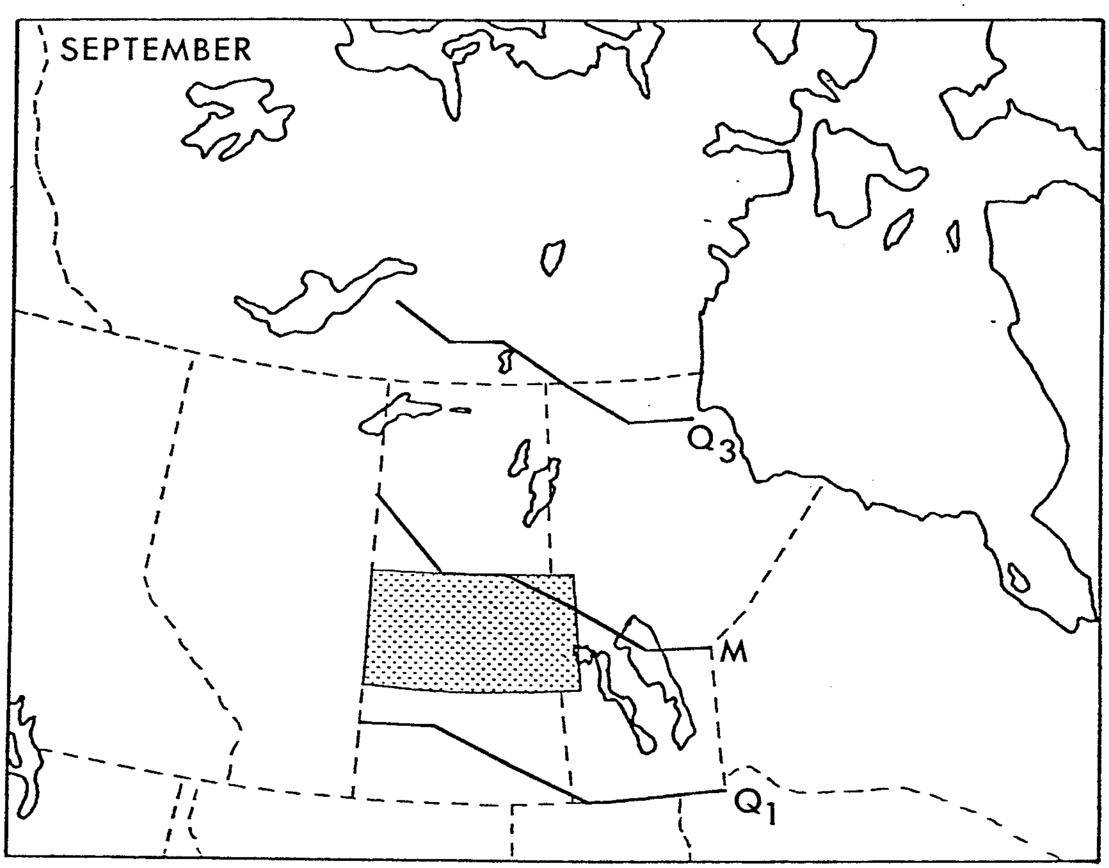
c



d



e



The results presented for May, June, August and September cannot be easily compared with the work of either Bryson (1966) or Barry (1967). Only Bryson considers these months and then only in the case of the method using the streamlines of surface resultant winds. Comparing results from the latter technique with the median arctic frontal positions presented here leads to the conclusion that in July and August both methods give similar locations but in May and June the confluence zones demarcated by Bryson appear far to the south of the median locations presented here and in September to the north.

Only the month of July is incorporated within all three studies. The median position shown for July (Fig. 3.8c) coincides well with the line given by Bryson to represent the modal position of the front between Arctic and Pacific air (Bryson 1966, 235). Comparing the median line with the Arctic air mass frequency distribution presented by Bryson (1966, 230) it can be noted that the median location presented here corresponds well with the 40% Arctic air line given by Bryson but lies to the south of his 50% line. This difference can be attributed to the high frequency of arctic front absence in July. When the front is not present in this month the major reason is the absence of distinguishable cA air. Therefore, the median line, which only represents cases when the front is present, overestimates the southern extent of Arctic air. A similar conclusion can be drawn for August.

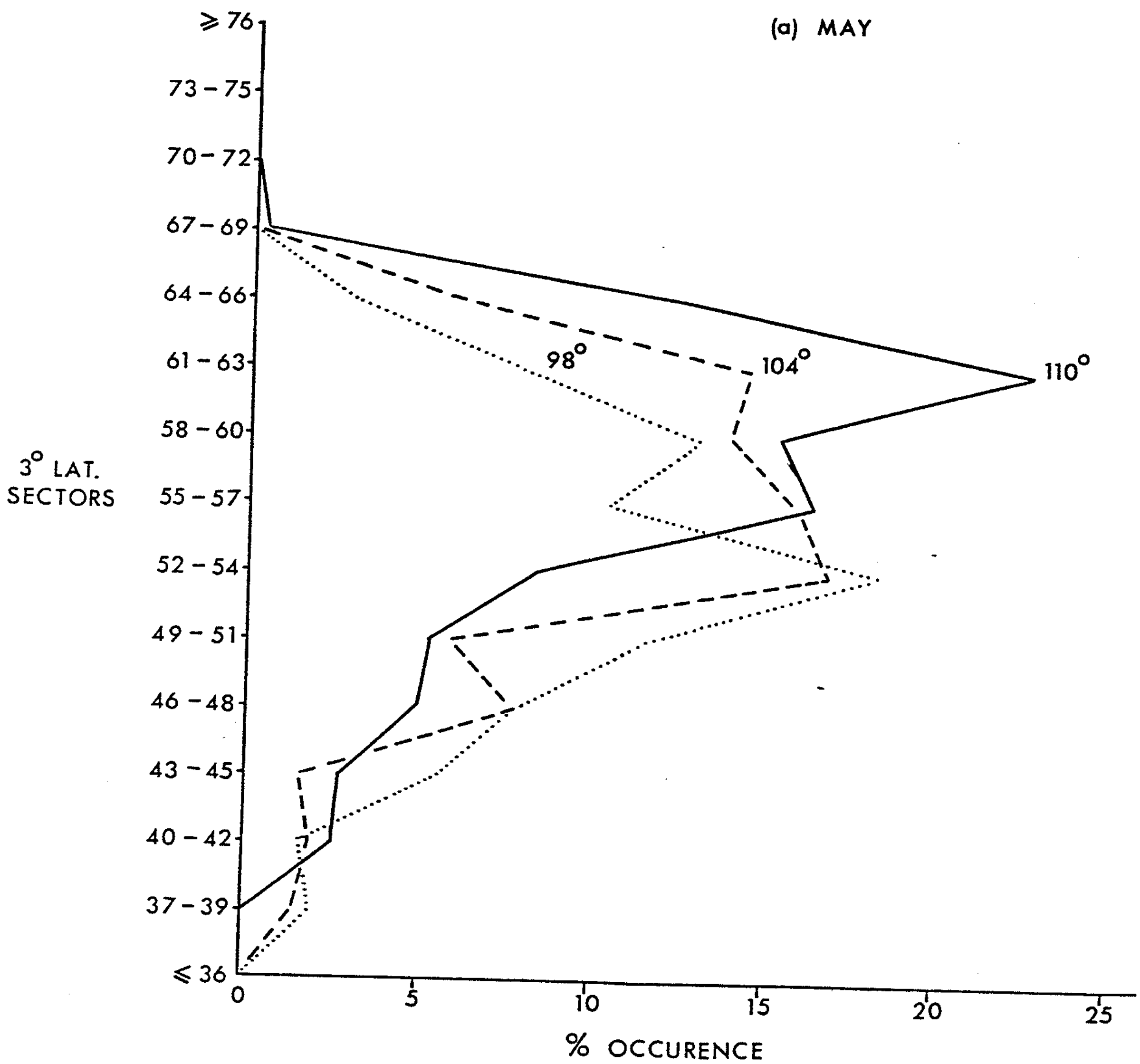
The frontal zone shown in Figure 3.8c can also be compared with the presentation by Barry (1967, 41) for this month. Barry's zone lies approximately 5 degrees northward of the presently estimated position. Apart from differences in the frequency with which the surface and 850 millibar frontal contours are present, this variation is most probably due to two factors. One is that the 850 millibar frontal contour can be expected to lie Poleward of the surface front. The other is the different periods of analysis as well as their length, 1965 being the only year common to both studies. July 1965 was computed independently and it was found that the difference between the two methods was reduced by up to 2 degrees.

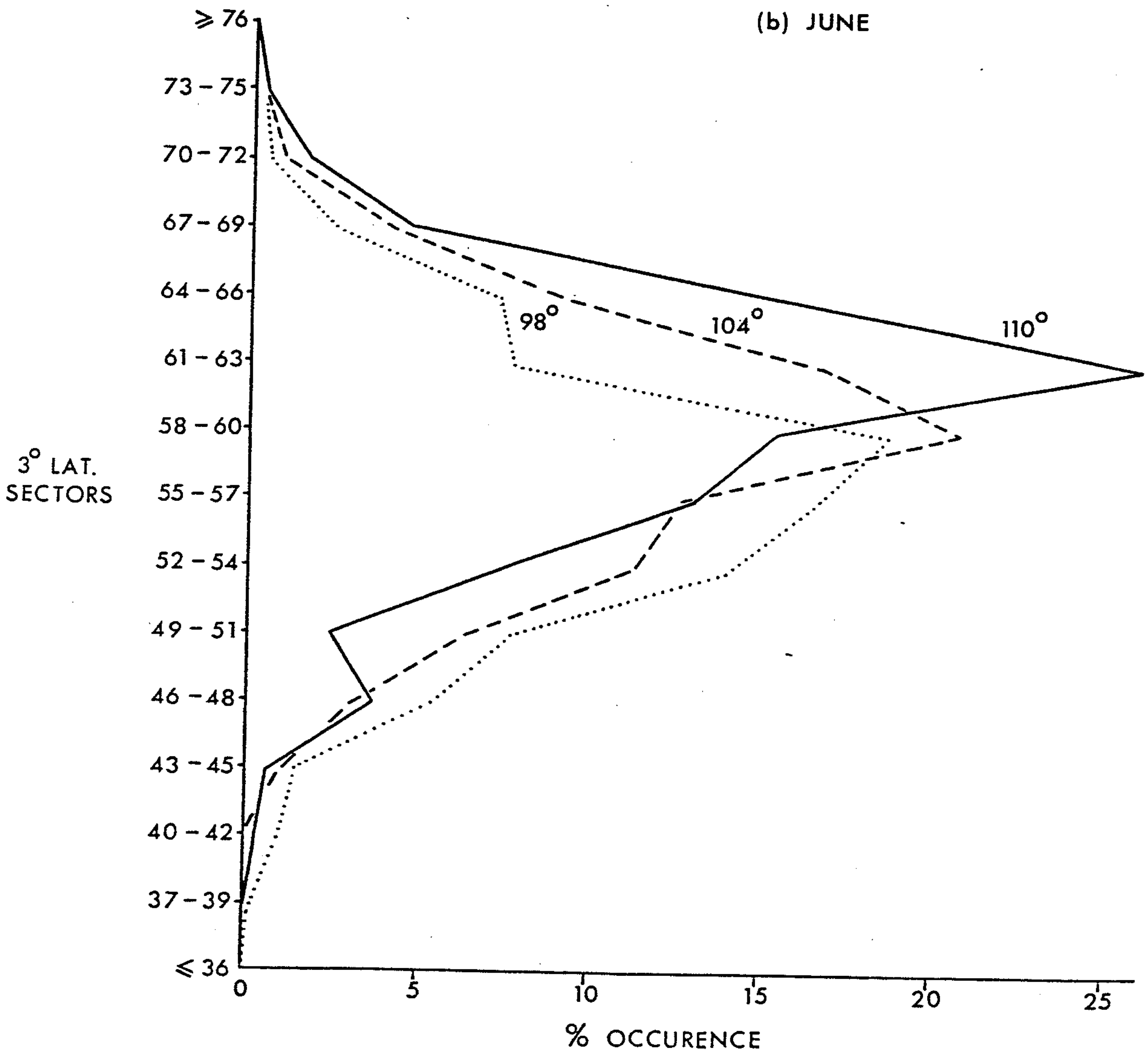
As the above discussion indicates the method of presentation used in Figures 3.8a to 3.8e is suboptimal due to its failure to take into account cases when the arctic front is not present. As a means of overcoming this problem Figures 3.9a to 3.9e have been prepared. For each month the percentage frequencies of arctic front occurences at 98° W, 104°W and 110°W have been plotted against 3° latitudinal sectors. These sectors have been chosen so that the study area corresponds to one sector closely. In this case it is 52°-54° which, recalling that data was recorded to the nearest degree of latitude, in fact represents 51.5° to 54.5°.

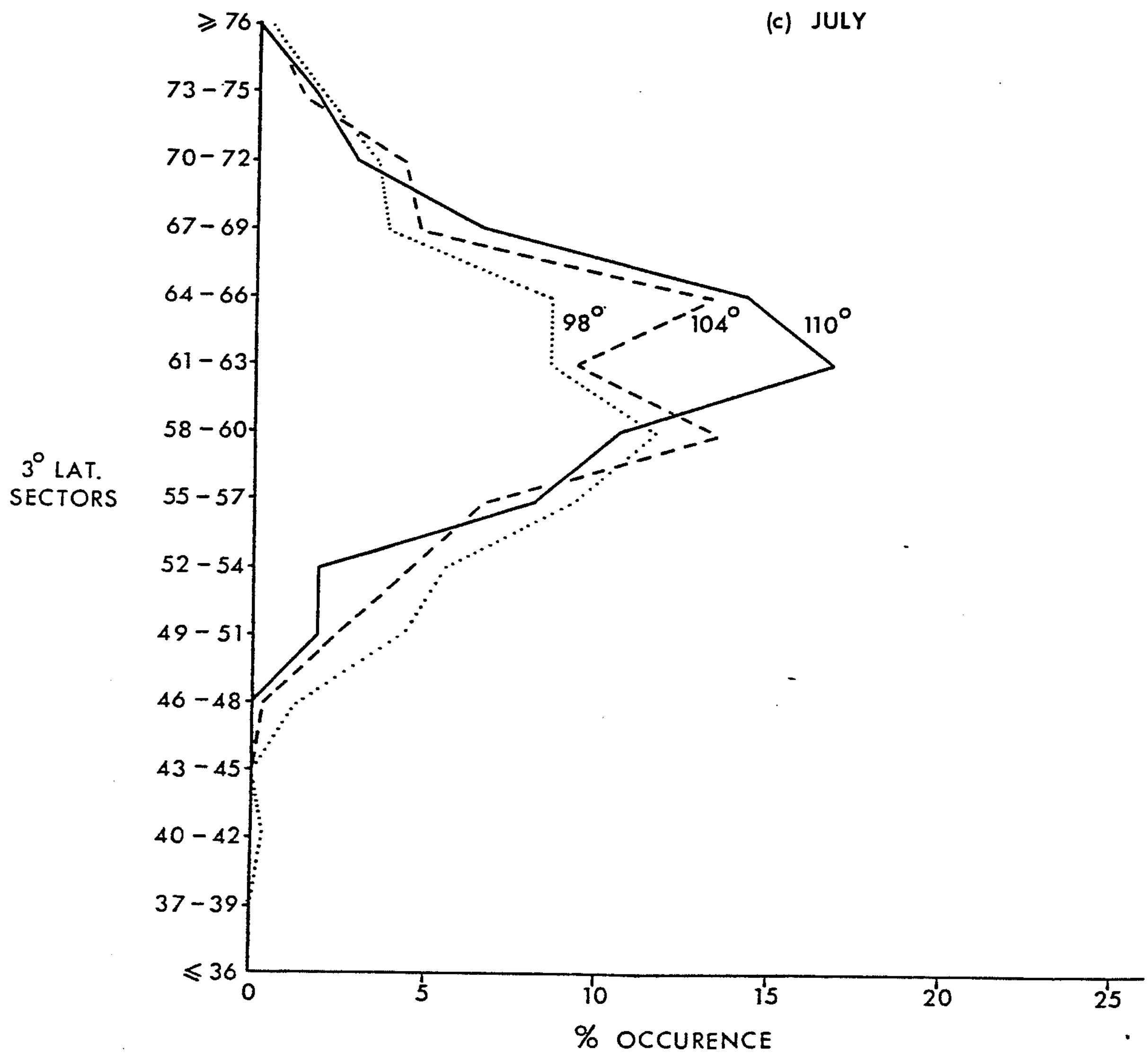
The area enclosed between each curve and the vertical axis represents the total percentage frequency of arctic front occurence during any month. Subtracting this total from 100% gives the percentage frequency of non-occurence (Table 3.8). Therefore, comparing June (Fig. 3.9b) with July (Fig. 3.9c), it is evident that along each meridian the arctic front is absent more often in July than in June. Similar visual comparisons can be made between other months.

As previously stated, the above data were also analysed on

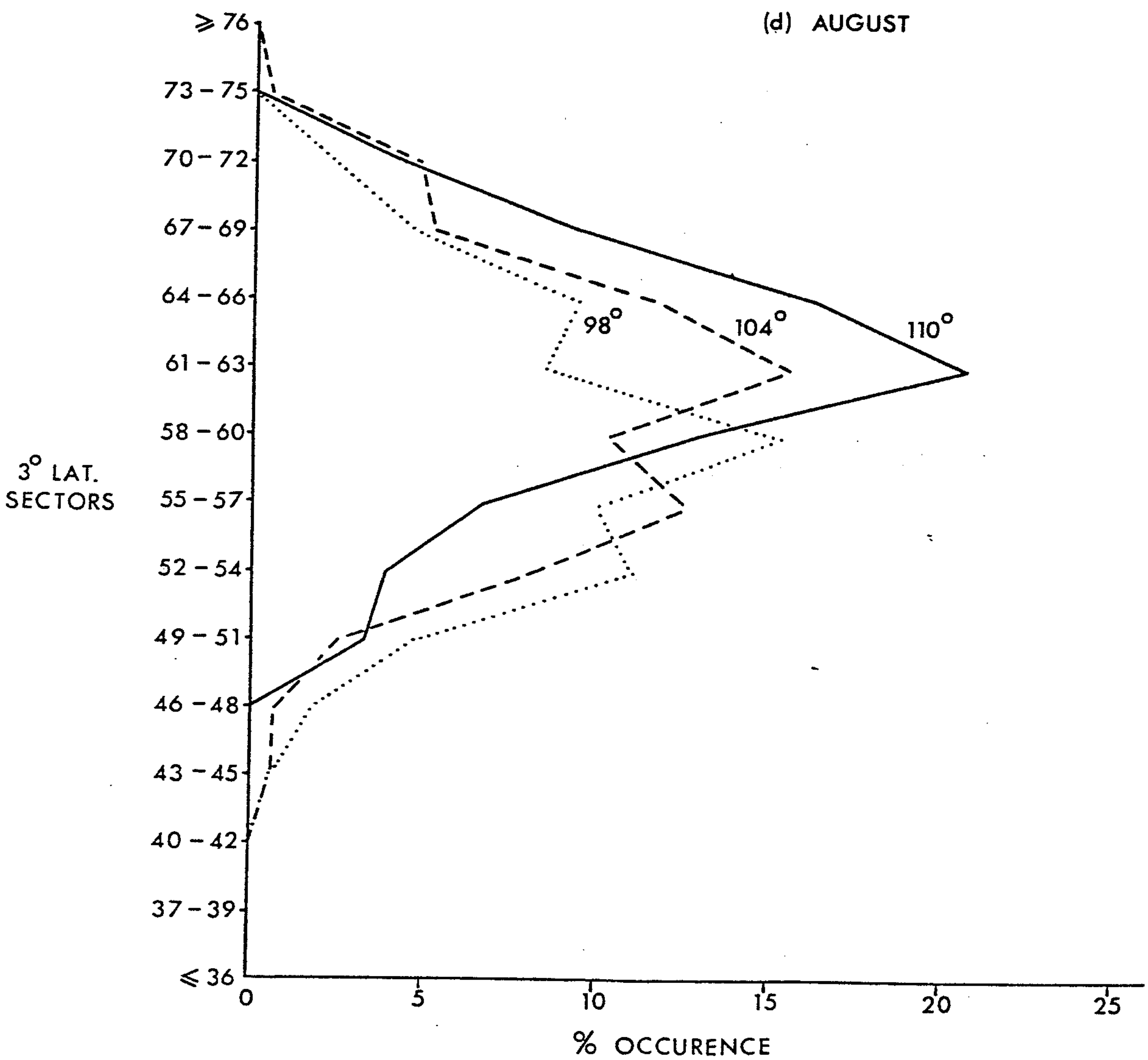
Fig. 3.9 Percentage frequency of arctic front occurence in 3° latitude sectors for 98° W., 104°W., and 110° W. in: (a) May (b) June (c) July (d) August (e) September.




(b) JUNE
≥ 76
73 – 75
70 – 72
67 – 69
64 – 66
61 – 63
58 – 60
55 – 57
52 – 54
49 – 51
46 – 48
43 – 45
40 – 42
37 – 39
≤ 36
3° LAT.
SECTORS
98°
104°
110°
0
5
10
15
20
25
% OCCURENCE



(c) JULY
≥ 76
73 – 75
70 – 72
67 – 69
64 – 66
61 – 63
58 – 60
55 – 57
52 – 54
49 – 51
46 – 48
43 – 45
40 – 42
37 – 39
≤ 36
3° LAT.
SECTORS
98°
104°
110°
0
5
10
15
20
25
% OCCURENCE


(d) AUGUST
≥ 76
73 – 75
70 – 72
67 – 69
64 – 66
61 – 63
58 – 60
55 – 57
52 – 54
49 – 51
46 – 48
43 – 45
40 – 42
37 – 39
≤ 36
3° LAT.
SECTORS
98°
104°
110°
0
5
10
15
20
25
% OCCURENCE

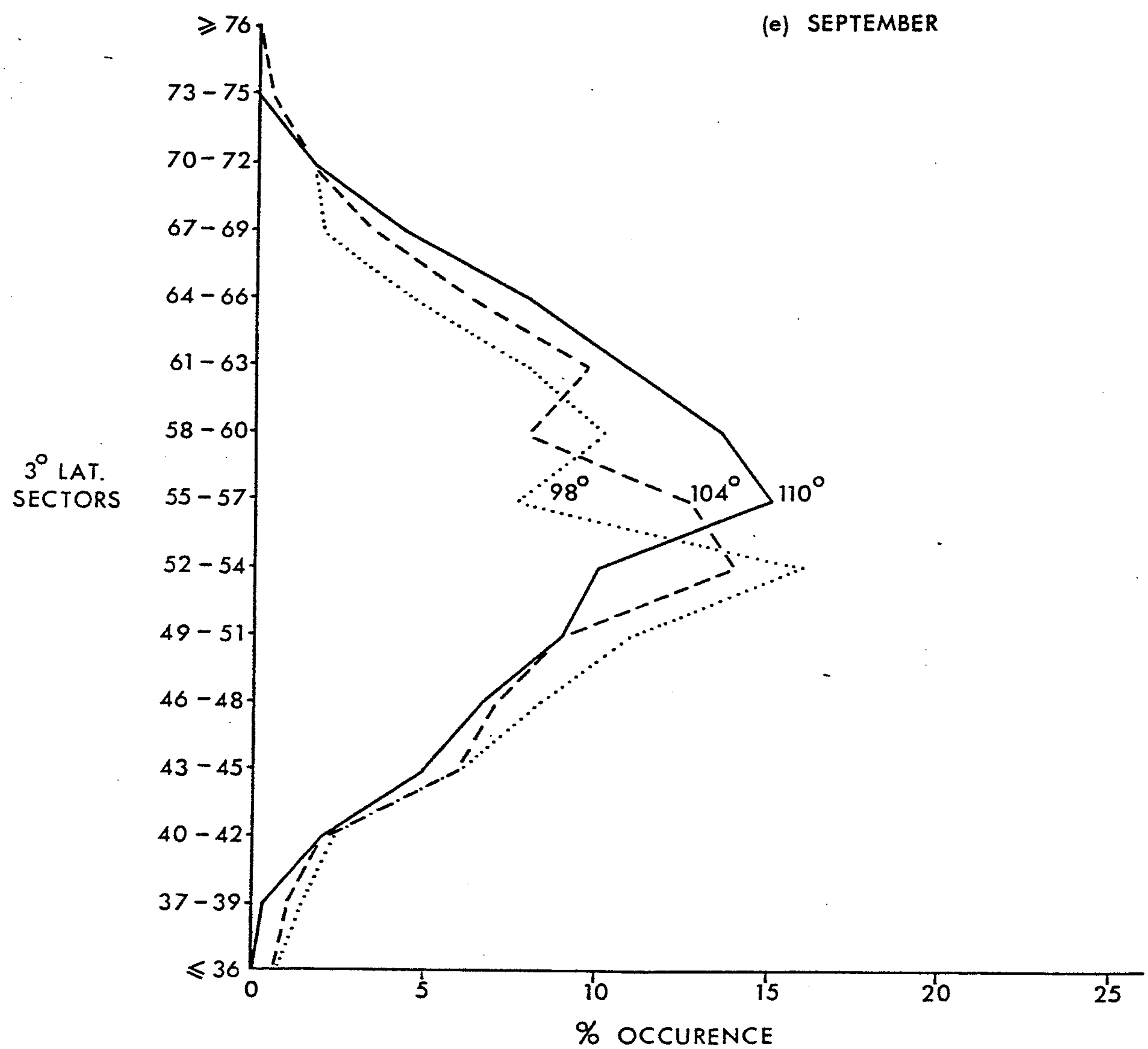
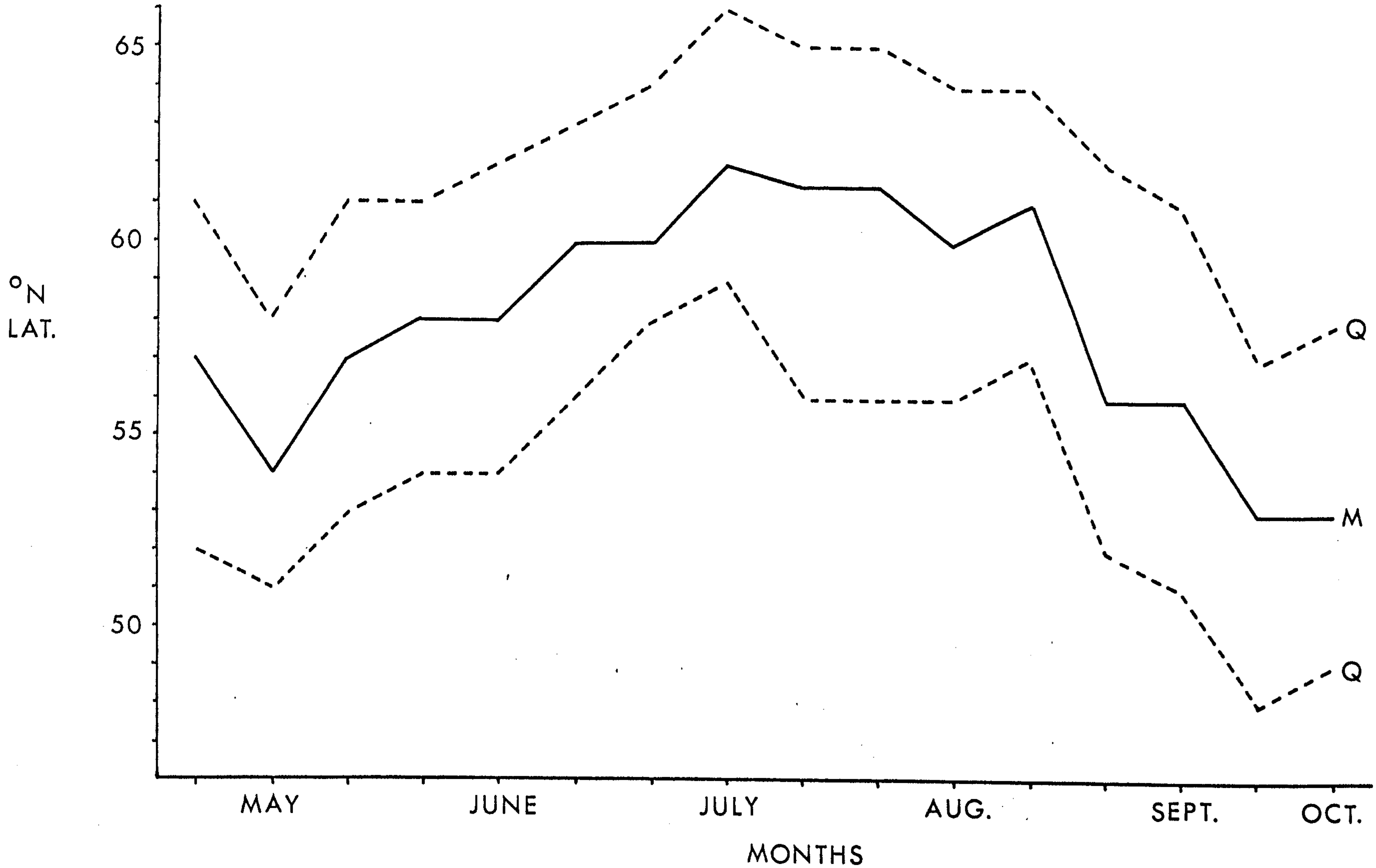

(e) SEPTEMBER
≥ 76
73 – 75
70 – 72
67 – 69
64 – 66
61 – 63
58 – 60
3° LAT.
SECTORS
55 – 57
52 – 54
49 – 51
46 – 48
43 – 45
40 – 42
37 – 39
≤ 36
98°
104°
110°
0
5
10
15
20
25
% OCCURENCE

Fig. 3.10 10 day median (M) and quartile (Q) locations of the arctic front at 104° W. (1965, 1967-1975).



a 10 day basis. To present all of these results in a similar manner to those used for monthly calculations would be impracticable. Nevertheless, Appendix 3 lists, for each 10 day period from 1st May to 10th October, the median and quartile values of the frequency distributions along each of the six meridians. A brief analysis of the 10 day values in relation to those plotted in Figures 3.8a to 3.8e reveals that the higher level of resolution offers a more detailed picture of the trends evident for monthly groupings. In Figure 3.10 the 10 day median and quartile locations of the surface arctic front have been plotted for 104^{o}W. The sharp transition between June and July, noted for monthly groupings, is evident and this change appears to be continuous from mid June to mid July. More marked is the southward shift in the frontal zone occuring in early September indicating that the end of the warm season is more abrupt than its beginning.

This section will conclude by taking a tentative step towards relating the frontal locations to the occurence of last spring and first autumn frosts. This has been achieved by examining and selecting two cases where it would appear that the location of the arctic front had an overwhelming effect upon frost incidence within the study area. Considering first of all a case in spring, attention is drawn to Figure 3.11. In May 1970, 10 of the 11 stations used in this study experienced their last spring frost on one of three days. By plotting the average latitudinal location of the arctic front during this period there is a strong indication that the final spring frost occured as a result of an outbreak of Arctic air. No such relationship exists for the one anomolous station (North Battleford

Fig. 3.11 Average latitudinal position of the arctic front (101^{o} - 110^{o}W) 10th - 31st May 1970.

Numbers relate to the number of stations in the study area having their last spring frost on the date indicated.

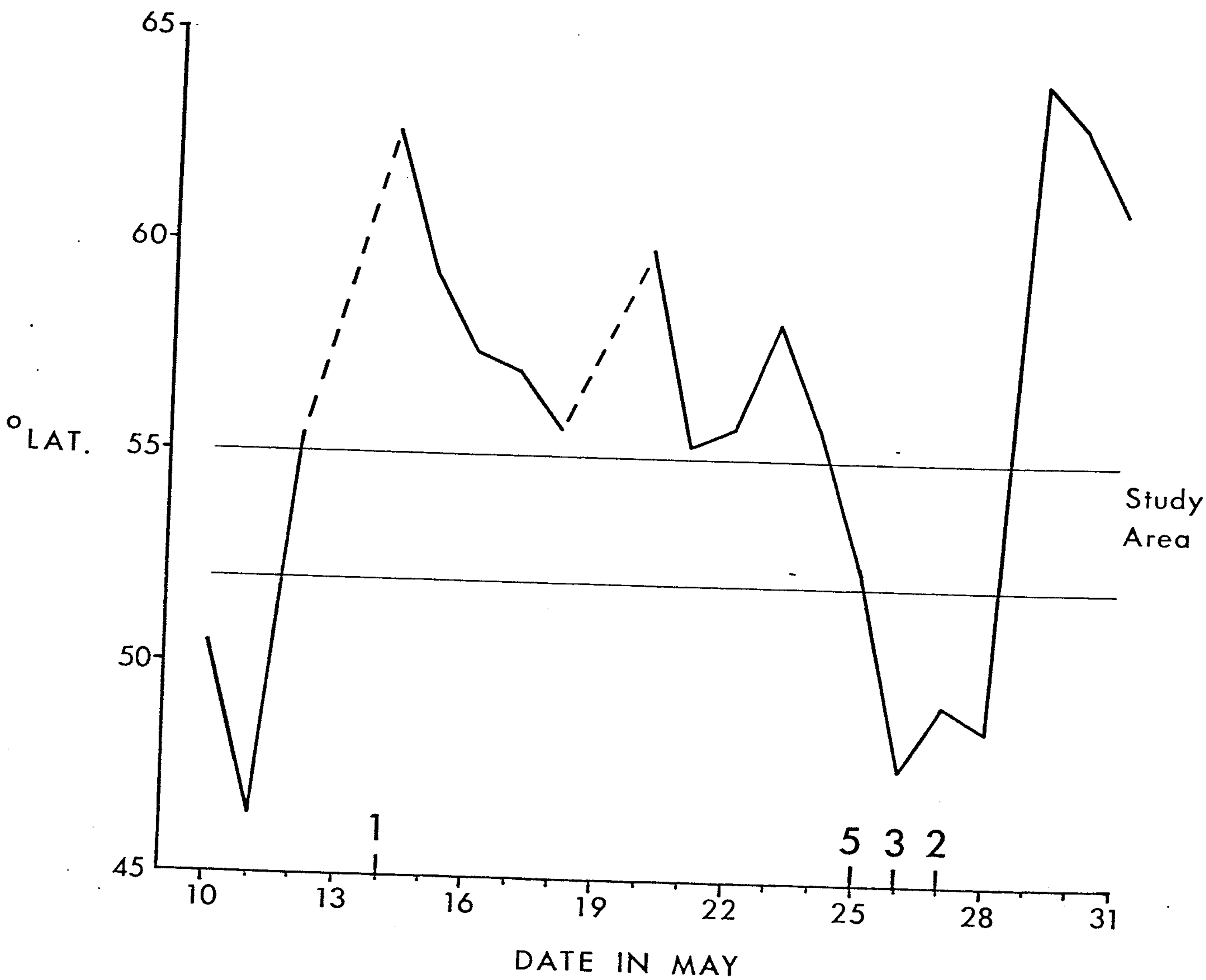
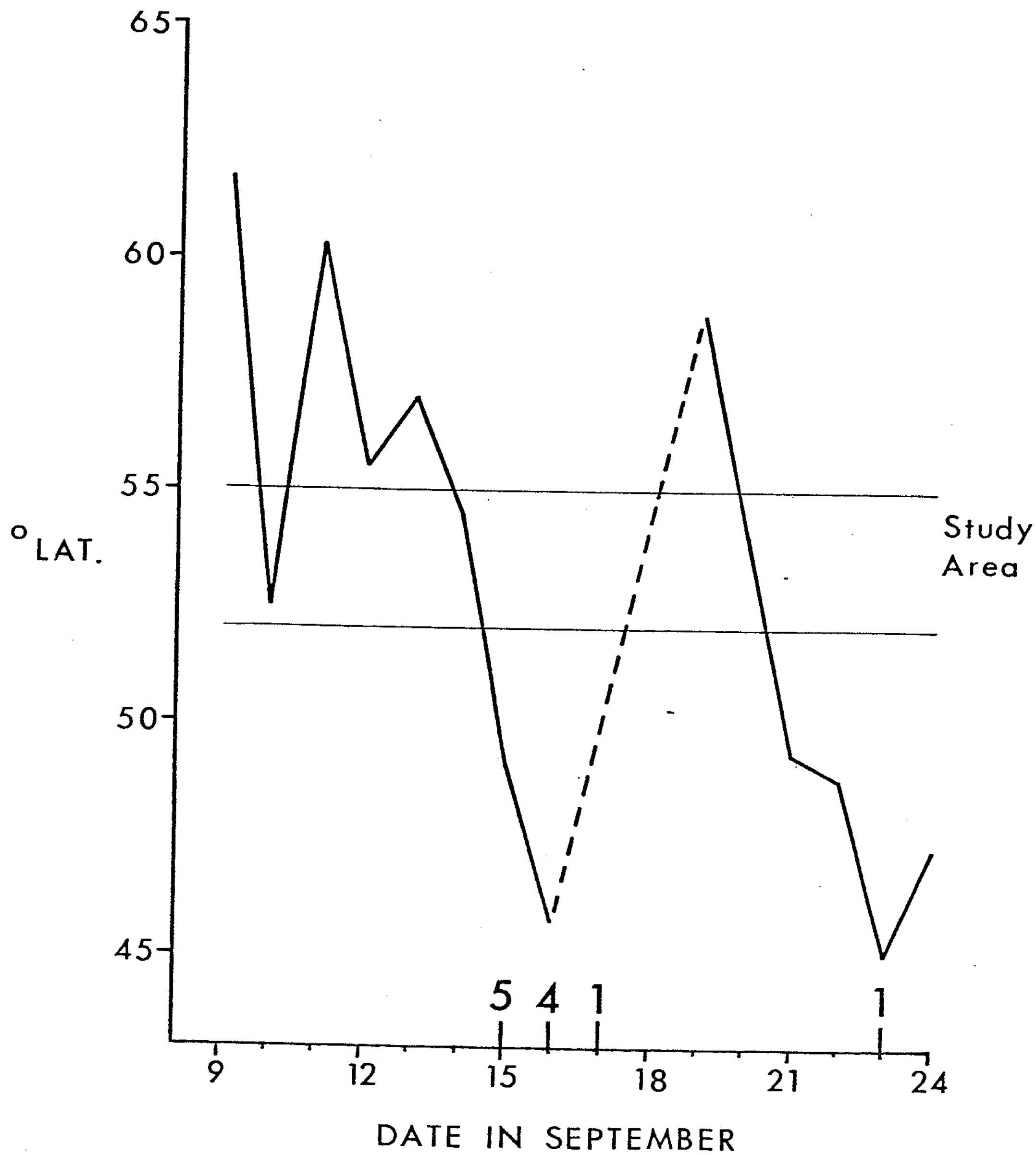


Fig. 3.12 Average latitudinal position of the arctic front (101^{o} - 110^{o}W) 9th - 24th September 1969.

Numbers relate to the number of stations in the study area having their first autumn frost on the date indicated.



A.) which experienced its last spring frost some 11 days earlier, perhaps indicative of a radiation frost.

Turning now to the autumn of 1969 (Fig. 3.12) a very similar pattern emerges. The arctic front moved south over part of the study area on 10th September but no frosts were recorded. However, five days later a much more vigorous southward thrust of the front led to first frost recordings at all but one of the stations (Flin Flon). It was not until the 23rd of September, when yet another southward movement of the front was taking place, that this station recorded its first frost.

These two examples give indications of a relationship between arctic frontal positions and frost occurrences. However, the examples were chosen because most of the frost events were grouped into a few days and were therefore likely to be associated with advectional processes. Nevertheless these examples offer sufficient evidence to warrant a further, more probing, analysis of this topic.

CHAPTER IV

CONCLUDING REMARKS

In the introduction it was noted that there is a paucity of agroclimatic research in areas where thermal rather than moisture constraints pose the most severe limitations to agricultural production. As a preliminary step towards remedying this situation, this thesis has analysed selected climatic factors of importance to agriculture in a high latitude area. The area chosen for study, which lies astride the secondary agricultural frontier in northern Manitoba and Saskatchewan, forms a rectangular zone from 52^{o}-55^{o}N and 101^{o}-110^{o}W. A considerable portion of this zone is already under cultivation and much of the remainder shows promise for future expansion. Therefore, a study of this nature, which is essentially an inventory of thermal resources for agriculture, is of considerable practical significance.

The primary data base for this study included the records of radiation, bright sunshine and air temperature recorded at meteorological stations within the study area as well as surface synoptic charts compiled at Winnipeg International Airport. 11 Stations were chosen for their consistency of location and continuity of records, although not all of the climatic elements were recorded at every station. Radiation records were analysed on a daily basis from 1972 to 1976, bright sunshine and air temperatures on a monthly basis from

1947 - 1976 and synoptic charts on a daily basis (May to October only) for 1965 and 1967 - 75.

Most variables of a thermal nature have been discussed although soil temperature has been omitted. A comprehensive analysis of the latter is being undertaken in many areas of Manitoba by the Manitoba Soil Survey in conjunction with the Department of Soil Science at the University of Manitoba (Mills et al 1974). With respect to those variables which have been analysed in some detail, the following general observations can be reitterated with a view to assessing the possible directions of future research.

At the present time global radiation is only recorded at one study area location - The Pas A. Nevertheless, records from this station are considered to be sufficiently long, if used on a daily basis, to derive a linear relationship between the ratio of global radiation to solar radiation at the top of the atmosphere and the ratio of actual to possible hours of bright sunshine. The constants in this relationship have been evaluated for annual, monthly and 10 day (summer months only) groupings. Values derived for the constants can be used to estimate global radiation at sites where only bright sunshine records are available. Application of the relationship has been demonstrated for Prince Albert A. and the results compared with actual measurements at The Pas A.

Net radiation is not recorded in the study area and the absence of direct measurements forces the use of estimation procedures. Numerous estimation procedures are available but it is far from clear which, if any, offers a completely satisfactory estimate. Six methods were selected and evaluated using data from The Pas A. on a monthly basis from May to September. Comparison of the results with theoretical and observational criticisms of each method led to two estimates being used to evaluate net radiation for 10 day intervals. While the values so obtained may be accurate, the optimal solution is always to use direct measurements and this would involve an extension of the net radiation network to incorporate other areas of Manitoba and Saskatchewan.

Given the importance of sunshine records in estimating global radiation where no recordings of the latter are taken, the available records of bright sunshine have been given close attention. Sunshine recorders are relatively cheap and simple to use so these instruments are, and will continue to be, the most frequently employed radiation instrument in this area. However, although their numbers are adequate in the study area, their distribution is poor. A northward extension of the sunshine recorder network is suggested. With particular attention being paid to data from The Pas A. and Prince Albert A. available records have been analysed on a monthly and seasonal basis. Average monthly ratios of actual to possible hours of bright sunshine have also been computed for these two stations.

Monthly mean daily maximum, monthly mean daily minimum and monthly mean daily air temperatures have been analysed for each of the 11 study area locations. In winter the temperature distributions are platykurtic showing typically large standard deviations, a combined effect of radiative heat losses and advective gains. In summer temperature distributions are more commonly leptokurtic with standard deviations being small. The overall temperature pattern for the study area follows a strong annual cycle typical of a continental location. This severely restricts the time period within which plant growth and development can take place. A preliminary assessment of the length of this period has been achieved by recording the dates of last spring and first autumn frosts at each station for 1947-1976. Both were found to be normally distributed at the majority of stations despite the important role of cold air advection from the north in affecting temperatures near the ground in spring and autumn. For those stations with normally distributed frost series, probabilities of occurence can be estimated using graphic procedures and this has been demonstrated for Waseca. Since low temperatures, apart from 0^{o}C, may be damaging to plants a need exists for a more complete analysis of the freeze series at northern stations. One such series has been produced for Saskatoon (Coligado *et al* 1968). At those stations with normally distributed occurences of last spring and first autumn frost, the frost free period also has a normal distribution. Therefore, the probability of a given length of season can be derived as illustrated in the case of Waseca.

Temperature sums or degree days have been shown to be of operational significance in agricultural planning. Therefore, temperature sums above 5.6^{o}C have been computed for each study are a station on a monthly basis using an estimation procedure. Values so obtained have been related to a similar study using daily data and the results shown to be in close agreement. Despite shortcomings in the use of temperature sums to assess the potential for plant development, a review of alternative procedures reveals that they also contain many deficiencies despite the additional computational effort involved. Considerably more fundamental research into plant growth and development and climatic variables will be required before this problem is fully resolved.

Finally, given the importance of advection frosts in limiting the period available for plant growth within the study area, this topic has been given further consideration. Hypothesising that advection frosts are closely associated with the location of the arctic front, particularily at the beginning and end of the growing season, the location of this front has been assessed for monthly and 10 day periods throughout the summer and its position related to the study area. The monthly median location of the front shows a northward migration in spring and southward in autumn. The higher level of resolution afforded by using 10 day groupings indicates that these changes are not gradual but are sharp transitions. A tentative correlation between frost occurence and arctic front locations looks promising but a great deal of additional work is required on this topic.

The above discussion suggests that potential future research falls into three areas:

(1) An extension in the network of stations recording variables which are poorly distributed or sparsely located i.e. net radiation and sunshine duration.

(2) More in-depth analyses of existing climatic records as well as surface synoptic charts. Parameters such as temperature analysis using daily values would be more satisfactory than monthly

means. Change through time should also be considered and analysed for such variables as freeze series.

(3) Further basic research into the interactions of crops suitable for northern agriculture and climatic variables. This should lead to a better assessment of the cropping potential in marginal climatic areas than presently provided by temperature sums.

APPENDIX 1. S.I. UNITS

Every attempt has been made to use S.I. units throughout. However, in several cases other units are still in common use and, in order to aid the reader who is as yet unfamiliar with S.I. units, the following conversions may be useful. For a comprehensive treatment of S.I. units reference is made to Peach (1970).

Chapter II: The S.I. unit for irradiance is watts per square meter (Wm^{-2}) and this unit gives a value of approximately 1353 Wm^{-2} for the solar constant (see Sec. 2.b.1). Previously the unit used was calorie per minute (cal min^{-1}) and;

$$1 \text{ cal min}^{-1} = 0.0698 \text{ watts}$$

$$1 \text{ cal cm}^{-2} \text{ min}^{-1} = 698 \text{ Wm}^{-2}$$

One calorie per square centimeter is also termed a langley (Ly).

Amount of energy in S.I. units is expressed as the joule and the corresponding unit of irradiation is joules per square meter ($J\ m^{-2}$). An energy rate of one watt lasting for one second amounts to one joule. Since $J\ m^{-2}$ is an extremely small unit, megajoules per square meter are often used instead ($MJ\ m^{-2}$). This latter unit can be converted to other, still widely used units, as follows;

$$1 \text{ MJ m}^{-2} = 278 \text{ Wm}^{-2} = 23.9 \text{ cal cm}^{-2}$$

$$1 \text{ Wm}^{-2} = 0.0036 \text{ MJ m}^{-2} = 0.086 \text{ cal cm}^{-2}$$

$$1 \text{ cal cm}^{-2} = 0.0419 \text{ MJ m}^{-2} = 11.6 \text{ Wm}^{-2}$$

Daylength and sunshine values are both given in hours and tenths.

Chapter III: All air temperatures are given in degrees centigrade (^{o}C). Conversion to degrees Fahrenheit (^{o}F) is as follows;

$$^{o}F = (^{o}C \times 1.8) + 32$$

Temperature sums have traditionally been given in day degrees Fahrenheit and it is only recently that publications have begun to appear using day degrees Centigrade (e.g. Edey 1977). The conversion is:

$$(TS)\ ^{o}F = (TS)\ ^{o}C \times 1.8$$

where TS is the temperature summation or degree day value.

APPENDIX 2

TEMPERATURE SUMMARIES FOR STUDY AREA STATIONS
(all figures in ^{o}C)

THE PAS A.

MONTH	1	2	3	4	5	6
Jan.	-17.9	3.7	-27.6	3.7	-22.8	3.6
Feb.	-12.7	2.9	-24.1	3.5	-18.4	3.1
Mar.	-5.2	2.7	-17.7	3.4	-11.4	3.0
Apr.	5.2	3.2	-6.1	2.7	-0.4	2.9
May	14.2	2.0	1.9	1.4	8.1	1.6
June	20.0	1.7	8.7	1.5	14.3	1.5
July	23.2	1.3	12.3	1.3	17.8	1.2
Aug.	21.7	1.9	11.0	1.2	16.4	1.4
Sept.	14.6	2.3	5.2	1.7	9.9	1.9
Oct.	7.8	2.7	-0.6	1.7	3.6	2.1
Nov.	-3.9	2.7	-11.2	2.9	-7.5	2.8
Dec.	-13.3	3.6	-22.0	4.0	-17.7	3.8

1 Monthly mean daily maximum temperature
2 Standard deviation of 1
3 Monthly mean daily minimum temperature
4 Standard deviation of 3
5 Monthly mean daily temperature
6 Standard deveiation of 5

Annual range of temperature (A.R.T.) = 40.6

FLIN FLON

MONTH	1	2	3	4	5	6
Jan.	-18.4	3.5	-26.6	3.5	-22.5	3.5
Feb.	-12.6	3.0	-22.8	3.2	-17.7	3.1
Mar.	-4.8	2.7	-16.4	3.3	-10.6	2.9
Apr.	5.7	3.1	-5.2	2.7	0.2	2.8
May	14.4	2.0	2.8	1.6	8.6	1.7
June	20.1	1.7	9.9	1.1	14.8	1.5
July	23.3	1.3	12.9	1.2	18.2	1.2
Aug.	21.7	1.9	11.6	1.3	16.7	1.5
Sept.	14.0	2.5	5.5	1.8	9.8	2.1
Oct.	6.8	2.8	-0.2	2.0	3.3	2.3
Nov.	-4.8	2.6	-11.1	3.1	-7.9	2.8
Dec.	-13.9	3.6	-21.3	3.7	-17.6	3.6

A.R.T. = 40.7

MUENSTER

MONTH	]	2	3	4	5	6
Jan.	-I6.0	4.8	-24.9	4.7	-20.4	4.8
Feb.	-II.0	3.4	-2I.2	3.3	-I6.2	3.3
Mar.	-5.I	2.3	-I5.2	3.7	-I0.I	3.4
Apr.	6.8	3.8	-3.4	2.8	I.7	3.2
May	I6.3	2.3	3.7	I.3	I0.0	I.7
June	2I.I	I.9	8.2	2.6	I4.9	I.6
July	24.I	I.8	II.2	3.2	I7.7	I.4
Aug.	23.6	2.6	I0.I	I.2	I6.8	I.7
Sept.	I6.6	2.7	4.4	I.7	I0.5	2.0
Oct.	9.4	3.2	-I.3	I.6	4.I	2.3
Nov.	-2.6	3.5	-I0.4	3.3	-6.5	3.3
Dec.	-II.I	2.8	-I9.2	4.I	-I5.2	4.0

A.R.T. = 38.I

NORTH BATTLEFORD A.

MONTH	1	2	3	4	5	6
Jan.	-14.2	5.1	-23.5	4.8	-18.9	4.9
Feb.	-9.7	3.7	-19.7	3.7	-14.7	3.7
Mar.	-4.0	3.5	-14.0	3.9	-9.0	3.7
Apr.	8.1	3.4	-2.8	2.5	2.7	2.9
May	17.5	1.8	4.3	1.2	10.9	1.5
June	21.6	1.8	9.2	1.2	15.4	1.4
July	24.4	1.7	11.9	0.9	18.2	1.2
Aug.	23.6	2.3	10.6	1.2	17.1	1.6
Sept.	17.2	2.8	4.9	1.7	11.1	2.1
Oct.	10.5	3.0	-1.1	1.4	4.7	2.1
Nov.	-1.4	4.0	-9.8	3.4	-5.6	3.7
Dec.	-9.7	4.3	-18.4	4.3	-14.1	4.2

A.R.T. = 37.1

WASECA

MONTH	1	2	3	4	5	6
Jan.	-14.3	5.2	-23.8	4.9	-19.1	5.0
Feb.	-9.2	3.7	-19.6	3.9	-14.4	3.8
Mar.	-3.3	3.2	-14.4	3.7	-8.9	3.4
Apr.	7.9	3.3	-3.6	2.5	2.2	2.8
May	17.3	1.7	3.2	1.2	10.2	1.3
June	21.0	1.7	7.3	1.5	14.2	1.3
July	23.8	1.8	10.1	1.0	16.9	1.2
Aug.	22.6	2.5	8.7	1.3	15.7	1.7
Sept.	16.5	2.8	3.7	1.6	10.1	2.1
Oct.	9.9	3.0	-1.9	1.5	4.0	2.2
Nov.	-1.9	4.2	-10.7	3.8	-6.3	3.9
Dec.	-9.7	4.5	-18.7	4.5	-14.2	4.5

A.R.T. = 36.0

PILGER

MONTH	1	2	3	4	5	6
Jan.	-15.2	4.9	-25.1	4.5	-20.1	4.8
Feb.	-10.2	3.4	-21.5	3.3	-15.8	3.3
Mar.	-3.9	3.2	-15.6	3.9	-9.8	3.5
Apr.	7.6	3.7	-4.1	2.7	1.8	3.1
May	17.9	2.3	3.2	1.2	10.6	1.6
June	21.9	1.7	8.3	1.5	15.1	1.4
July	24.9	1.9	11.1	1.1	17.9	1.2
Aug.	24.1	2.7	9.9	0.9	17.0	1.7
Sept.	17.8	2.7	4.6	1.4	11.2	1.9
Oct.	10.4	3.1	-1.6	1.5	4.4	2.2
Nov.	-1.9	3.6	-10.7	3.3	-6.3	3.4
Dec.	-10.4	4.1	-19.6	4.2	-15.1	4.1

A.R.T. = 38.1

PRINCE ALBERT A.

MONTH	1	2	3	4	5	6
Jan.	-15.6	4.5	-27.3	4.6	-21.4	4.5
Feb.	-10.3	3.3	-23.7	3.7	-17.0	3.5
Mar.	-3.8	3.0	-17.5	3.8	-10.7	3.4
Apr.	7.7	3.5	-4.6	2.7	1.6	3.0
May	17.2	1.9	2.3	1.1	9.7	1.3
June	21.5	1.6	7.6	1.5	14.6	1.3
July	24.4	1.6	10.6	1.1	17.5	1.2
Aug.	23.2	2.2	9.1	0.9	16.2	1.4
Sept.	16.7	2.6	3.2	1.8	10.0	2.0
Oct.	9.8	2.9	-2.6	1.5	3.6	2.1
Nov.	-2.4	3.5	-11.8	3.6	-7.1	3.4
Dec.	-11.1	4.0	-21.9	4.5	-16.4	4.2

A.R.T. = 38.9

SASKATOON A.

MONTH	1	2	3	4	5	6
Jan.	-14.1	4.9	-24.4	4.9	-19.3	4.8
Feb.	-9.6	3.7	-20.7	3.8	-15.2	3.8
Mar.	-3.6	3.6	-14.6	4.2	-9.1	3.9
Apr.	8.7	3.5	-2.8	2.3	2.9	2.9
May	17.8	1.9	3.8	1.2	10.8	1.4
June	22.2	1.8	8.8	1.4	15.5	1.4
July	25.4	1.9	11.6	1.1	18.5	1.4
Aug.	24.5	2.3	10.3	1.1	17.4	1.6
Sept.	17.9	2.8	4.6	1.5	11.3	2.1
Oct.	11.0	3.0	-1.6	1.5	4.7	2.2
Nov.	-0.9	3.8	-10.4	3.5	-5.7	3.5
Dec.	-9.2	4.1	-19.1	4.3	-14.2	4.2

A.R.T. = 37.8

CHOICELAND

MONTH	1	2	3	4	5	6
Jan.	-16.8	5.2	-27.4	4.8	-22.1	5.0
Feb.	-10.4	3.9	-23.3	3.7	-17.0	3.5
Mar.	-3.6	2.9	-16.7	3.9	-10.2	3.4
Apr.	7.5	4.0	-4.4	3.2	1.6	3.4
May	17.4	2.4	2.4	1.9	9.9	2.0
June	21.4	1.9	6.9	1.9	14.1	1.7
July	24.2	1.4	9.7	1.6	16.9	1.4
Aug.	23.1	2.3	8.7	1.9	15.8	2.0
Sept.	16.9	2.5	2.9	1.7	9.9	1.9
Oct.	8.7	2.9	-2.7	1.4	3.1	1.9
Nov.	-3.5	3.9	-12.0	4.2	-7.8	4.1
Dec.	-11.6	4.7	-20.6	5.0	-16.1	4.8

A.R.T. = 39.0

LOST RIVER

MONTH	1	2	3	4	5	6
Jan.	-15.8	4.2	-27.3	4.3	-21.6	4.2
Feb.	-10.6	3.3	-23.8	3.7	-17.2	3.4
Mar.	-3.8	2.7	-17.9	3.8	-10.8	3.2
Apr.	7.3	3.6	-5.3	2.8	1.1	3.1
May	16.7	2.1	2.1	1.1	9.7	1.4
June	21.7	1.8	7.4	1.6	14.5	1.4
July	24.4	1.8	10.2	1.1	17.4	1.3
Aug.	23.1	2.3	8.8	1.1	15.9	1.5
Sept.	16.6	2.7	3.2	1.6	9.9	1.9
Oct.	9.7	2.9	-2.4	1.4	3.6	2.0
Nov.	-2.8	3.2	-11.8	3.2	-7.3	3.1
Dec.	-11.5	3.9	-21.9	4.3	-16.7	4.1

A.R.T. = 39.0

HUDSON BAY

MONTH	1	2	3	4	5	6
Jan.	-15.6	4.0	-26.8	4.2	-21.2	4.0
Feb.	-10.0	3.2	-23.3	3.5	-16.7	3.3
Mar.	-3.3	2.8	-16.9	3.7	-10.0	3.2
Apr.	7.4	3.4	-5.0	2.4	1.2	2.9
May	16.2	1.9	2.2	1.3	9.2	1.4
June	21.2	1.6	7.6	1.6	14.4	1.4
July	24.2	1.4	10.5	1.3	17.3	1.2
Aug.	22.9	2.2	9.2	1.1	16.1	1.5
Sept.	16.2	2.5	3.4	1.5	9.8	1.9
Oct.	9.3	3.3	-1.8	1.4	3.9	1.9
Nov.	-2.7	3.1	-11.4	2.9	-7.1	2.9
Dec.	-11.2	3.5	-21.3	4.1	-16.3	3.8

A.R.T. = 38.5

Medians and Quartiles of Arctic Front Positions for 10 Day Periods at 110°, 107°, 104°, 101°, 98° and 95°W., 1965, 1967-75.

PERIOD	110°	107°	104°	101°	98°	95°	
May 1-10	63	62	61	60	58	57	Q_3
	59	58	57	54	53	52	Med.
	54	52	52	50	48	48	Q_1
May 11-20	60	59	58	57	56	55	Q_3
	57	55	54	53	53	52	Med.
	54	53	51	51	48	48	Q_1
May 21-31	63	62	61	60	59	58	Q_3
	60	59	57	56	56	55	Med.
	56	54	53	52	51.5	51	Q_1
June 1-10	63	62	61	60	58	57	Q_3
	60	60	58	57	56	56	Med.
	56	55	54	53	52	52	Q_1
June 11-20	63	63	62	61	60	59	Q_3
	60	60	58	57	56	56	Med.
	56	55	54	54	53	52	Q_1
June 21-30	64	64	63	62	62	62	Q_3
	62	61	60	59	58	57	Med.
	58	57	56	55	54	54	Q_1
July 1-10	65	65	64	65	63	62.5	Q_3
	63	61	60	60	59	58	Med
	58	57	58	56	55	54.5	Q_1
July 11-20	65	65	66	66	65	64	Q_3
	63	63	62	61	60	59.5	Med.
	59	59	59	58	57	56	Q_1
July 21-31	65	65	65	65	65	65	Q_3
	62	62	61.5	61	61	61	Med.
	58	58	56	56	55.5	54	Q_1
Aug. 1-10	65	65	65	64	64	64	Q_3
	63	63	61.5	61	59	57	Med.
	60	58	56	58	56	54	Q_1
Aug.11-20	64	64	64	63	62	63	Q_3
	61	60	60	59	59	58	Med.
	58	57	56	55	54	53	Q_1
Aug.21-31	66	65	64	64	63	62	Q_3
	62	62	61	59	58	57	Med.
	60	58	57	55	53	52	Q_1

APPENDIX 3 Cont'd

Sept.1-10	63	63	62	62	61	62	Q_3
	58	58	56	55	54	54	Med.
	53	52	52	50	49	50	Q_1
Sept.11-20	62	61	61	60	60	60	Q_3
	57	56	56	55	54	54	Med.
	53	52	51	51	50	50	Q_1
Sept.21-30	59	58	57	57	56	56	Q_3
	55	54	53	52	52	52	Med.
	49	49	48	47	47	47	Q_1
Oct.1-10	59	59	58	57	55	55	Q_3
	55	54	53	53	52	51.5	Med.
	50	49	49	48	48	47.5	Q_1

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