AN URBAN IMPACT MODEL FOR CHANGES IN THE LENGTH OF THE FROST FREE SEASON AT SELECTED CANADIAN STATIONS

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Abstract. A study of long term temperature data for fourteen Canadian cities showed that the length of the annual frost free season has increased by average of 7 days since 1940. Change in individual stations ranged from 26 to −17 days resulting in significant shifts in the mean probable dates for the first and the last frost of the season at most stations. No similar trend was shown in three non-urban control stations. Three urban factors: heat island effect, enhanced cloud cover and the rate of population growth – together accounted for 80% of the explained variance in the phenomenon. A multiple regression model was developed to describe the relationship between the change in the season and the urban factors. It is shown that for any appreciable gains to be made in the length of the season at reasonably predictable changes in temperature, such changes in temperature should be accompanied by a modest increase in cloud cover.

1. Introduction

The length of the annual frost free season defined here as the number of days in which the minimum temperature continuously exceeds the freezing point, is a major factor in agriculture in farming areas. Its average determines, in part, the type of crop which a given climate can support while its variability can affect the quality of the yearly harvest. Thus any significant long term changes in the quality of the season, especially in those countries where the growing season is short, are seen as having far reaching implication for agriculture and other areas of the environment associated with it. Recent public debates in Canada, for example, drew attention to the potentially detrimental impact of urban sprawl on arable land (Bryant and Greaves, 1978; Bryant, 1981). Ignored in the debate was the equally potential benefits of higher urban temperatures including a probable increase in the length of the frost free season. For cities in particular and the adjoining areas downwind in general, an increase in the season's length could affect the quality of small scale farming (gardening) done in cities, park ecology, water balance, the depth of frost penetration and other areas of the environment. It is helpful, therefore, to identify any changes in the characteristics of the season so as to purposefully take advantage of any improvements which might occur.

In addition, cities are prime sources for gases such as CO_2, N_2O and chlorofluorocarbons (CF_2CL_2 and $CFCL_3$) widely regarded as factors in the anticipated global warming (Carbon Dioxide Assessment Committee, 1983). Since warming is already occurring in urban areas, the possible impact of enhanced temperatures on other climatic variables could be inferred from models developed in cities.

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The tendency towards a longer frost free season in many parts of Canada was established in separate studies (Nkemdirim, 1981; Nkemdirim and Venkatesan, 1984). The latter study speculated on a number of possible causes for the discrepancy but arrived at no firm conclusions. This present study is an attempt to correlate the changes observed in the length of the season with readily accessible environmental and population data. Hopefully, a relationship established from that association could be used for the assessment of the amount and the direction of change in locations other than those included in the sample as well as serve as a device for the estimation of the future behaviour of the climate variable.

The study is based on records of daily minimum and mean temperatures taken at several stations across Canada between 1880 and 1970 (CMS, 1971). Based on the discontinuity contained in the time series of the mean decadal length of the frost free season around the third and the fourth decades of this century (Section 5), the data were separated into two groups, a pre-1940 and a post-1940 set. The difference in the mean length of the season between the two periods was then examined for possible predictive connections with trends in the mean temperature recorded at the stations as well as with other factors associated with urban growth.

2. Data Base

Seventeen stations were used in the study. Their choice was determined by three factors, namely; (a) spatial coverage, (b) population representativeness, and (c) the length of usable meteorological data.

The sample included at least one station from each province except Nova Scotia and the Territories. Together the locations cover most of the more densely settled parts of the country. The distribution of stations is predominantly west to east. A north-south selection is in evidence especially in central and eastern Canada (Figure 1).

The population of the cities and towns in the sample is listed in Table I. It ranges from over two million in Toronto and Montreal to a few thousands in Charlottetown, Prince George and Penticton.

Stations in Charlottetown, Lethbridge (Canadian Agricultural Station) and Penticton, all with comparable long term meteorological data, were added to the study because of their rural location outside smaller towns. They provide an external control to the experiment since the decision on the influence of urbanisation on the change in the length of the season was based in part on the discrepancy between the trend observed in the urban and the control groups.

The major features of the meteorological database are shown in Table I. All stations had at least 59 yr of usable temperature data by 1970. Many of the records date back to the 1880's.

Several meteorological stations were relocated at different times during the period of record (Table II). In all cases, the data were adjusted to compensate for any change in temperature arising from relocation. The record was adjusted to the new site.

The practice in almost every case involved a change from an inner city site to airports

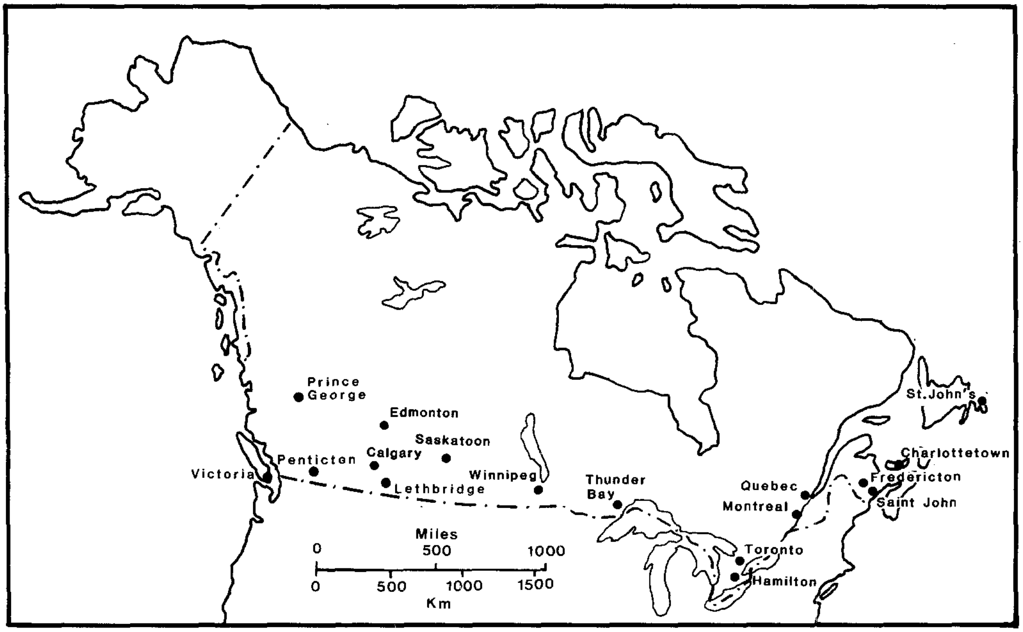


Fig. 1. Location of stations used in the study.

located at the edge of the city. Since inner cities are normally warmer than the outskirts (Landsberg, 1956; Chandler, 1966; Changnon, 1975) warming after relocation cannot be attributed to a change in site. On the contrary, relocation appears to have reduced the degree of warming experienced at a station. Edmonton, Montreal, St. John, Toronto and Victoria, five stations which remained in the inner city throughout the period of record produced the largest increases in temperature (Table V) experienced between the pre-1940 and the post-1940 periods.

The discrepancy in the size of the increase in mean temperature between relocated and non-relocated stations provides a measure of internal control in the experiment since it appears to indicate the differential impact of urbanisation on temperature and the change in the length of the season.

3. Distribution of the Mean and Variability of the Frost Free Season

The longest seasons are experienced on the west and the east coasts. In the interior, the length of the season generally increases from west to east (Table II). Inland, variability tends to increase westwards. Meridional differences exist but are muted in the sample.

The length of the season is linearly related to the mean daily temperature (Figure 2). The correlation coefficient between the two variables is 0.77 which indicates that mean temperature is the single major determining factor in the spatial variation of the length of the season.

A regression of the mean season length of mean daily temperature produced the equa-

TABLE I: Stations used, Population ('000)(1) and record length of Meteorological data (2)

	Station		Dates of Record	No. of yrs. of useable record
1.	Victoria, B.C.	(195.8)	1898–1970	73
2.	Prince George, B.C.	(33.1)	1912–1970	59
3.	Penticton, B.C.	(18.1)	1907–1970	65
4.	Calgary, Alta.	(403.3)	1883–1970	88
5.	Edmonton, Alta.	(438.1)	1885–1970	86
6.	Lethbridge (CDA), Alta.		1908–1970	64
7.	Saskatoon, Sask.	(126.4)	1892–1894, 1900–1910, 1911–1970	74
8.	Winnipeg, Man.	(540.3)	1881–1970	90
9.	Thunder Bay, Ont.	(112.1)	1881–1970	90
10.	Hamilton, Ont.	(498.5)	1881–1887, 1898–1905, 1907–1929, 1938–1970	71
11.	Toronto, Ont.	(2628.0)	1881–1970	90
12.	Montreal, Que.	(2743.2)	1881–1970	90
13.	Quebec City, Que.	(480.5)	1881–1970	90
14.	Fredericton, N.B.	(24.2)	1881–1970	90
15.	St. John, N.B.	(106.7)	1881–1970	90
16.	Charlottetown, PEI	(19.1)	1881–1886, 1889–1970	88
17.	St. John's, NFL	(131.8)	1881–1970	90

Relocated to Airports:	Calgary (1931, 1939), Saskatoon (1941), Winnipeg (1938), Thunder Bay (1940), Quebec City (1943), Charlottetown (1943), Penticton (1941), Prince George (1942).
Relocated within the City:	Hamilton (1940), Edmonton (1937).
Not Relocated:	Toronto, Montreal, St. John, Victoria, Lethbridge (C.D.A.)

(1) Population (in brackets) are for 1971. Source: 1971 Census of Canada, Statistics Canada, Catalogue 92–702, Vol. 1, 1973.

(2) Source: Canadian Meteorological Service, Daily Climatological Data, 1971.

tion:

$$LLF = 95.9 + 13.09\ Tm \qquad (1)$$

where the quantities to the left and right of the equation are the mean length of the frost free season and mean daily temperature respectively.

The correlation coefficient between the length of the season at any two locations was moderate to weak. Rarely did coefficients attain 0.5. In general, the correlation between events at any two stations was a decreasing function of the distance separating them. This absence of a strong spatial autocorrelation was also underscored by the sharp break in the spatial variance spectrum at about 10^3 km (Figure 3).

The low correlations could have two implications. Firstly, they suggest the presence of significant local elements in the forcing mechanism. Secondly, they indicate that the number of stations required to map the length of the frost free season with reasonable

TABLE II: Frost free season – mean length, variability and probable dates.

Station (1)	Mean (2)	CV (%)(3)	Mean probable dates[a]	
			Last frost (4)	First frost (5)
Victoria, B.C.	273	16	3/7	12/1
Prince George, B.C.	72	37	6/14	8/26
Penticton, B.C.	148	11	5/8	10/5
Lethbridge, (C.D.A.) Alta.	115	15	5/20	9/15
Calgary, Alta.	110	18	5/25	9/12
Edmonton, Alta.	117	14	5/13	9/12
Saskatoon, Sask.	114	18	5/23	9/15
Winnipeg, Man.	121	11	5/14	9/21
Thunder Bay, Ont.	117	15	5/23	9/19
Hamilton, Ont.	188	17	4/24	10/22
Toronto, Ont.	183	11	4/24	10/22
Montreal, Que.	184	15	4/22	10/23
Quebec City, Que.	154	11	5/7	10/8
Fredericton, N.B.	207	12	4/9	11/4
St. John, N.B.	222	13	4/6	11/13
Charlottetown, PEI	166	13	5/8	10/23
St. John's, NFL	176	7	5/1	10/20

[a] There is 50% probability that the frost event will occur on or before the mean probable date. Dates based on the complete record. The current situation may be obtained from Fig. 6 for the non control group.

accuracy should be large. Pittock (1975) noted that there is an upper limit for the number of independent observations required to specify the spatial distribution of a climatic variable. But for those variables which exhibit low spatial correlation, the number of such observations must be larger than for spatially correlated phenomenon to achieve the same result.

4. Comparison between Trends in Urban and Control Stations

The length of the season for each year for three stations – Toronto, Edmonton and Victoria selected because of their inner city location – throughout the study period was averaged and plotted against time. A similar plot was made for the average of the three stations in the control group (Figure 4). A trend line was fitted to each of the series by least square and the significance of the trend line calculated ($\alpha = 0.05$). The upward trend in the urban group was highly significant ($\alpha = 0.40$) while there was no statistically significant trend in the control series.

5. Decade-to-Decade Means and Variability

Most elements of climate show day-to-day, seasonal, and year-to-year variation which are larger than the variation in longer-term mean values. While shorter-term variability on synoptic time scales are not usually indicative of climatic aberation, longer-term variability,

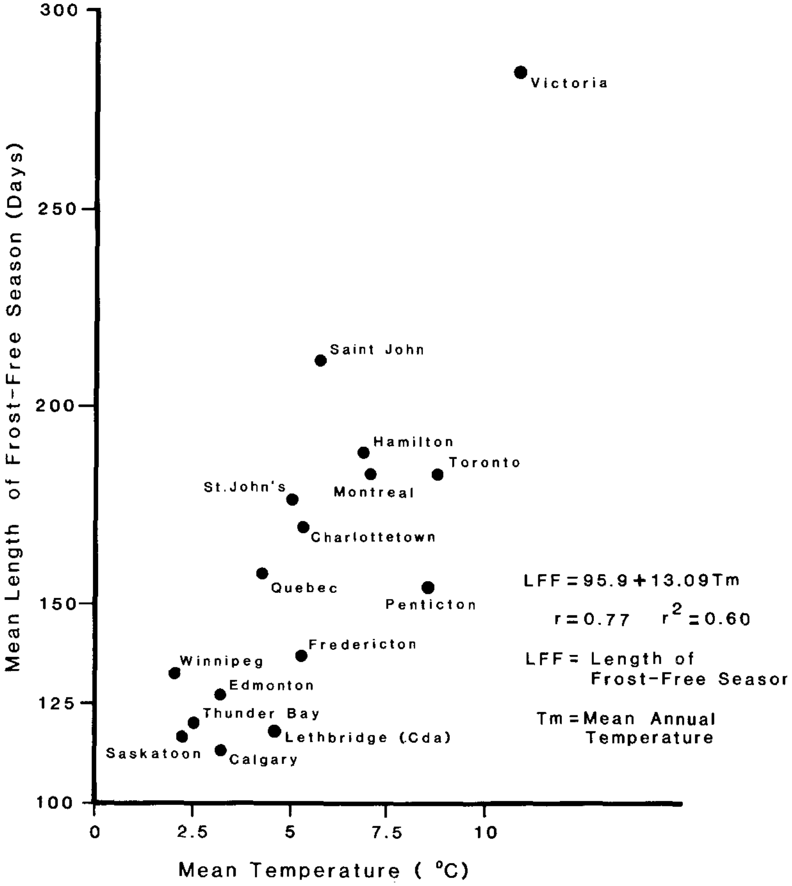


Fig. 2. Relationship between mean daily temperature and the length of the season.

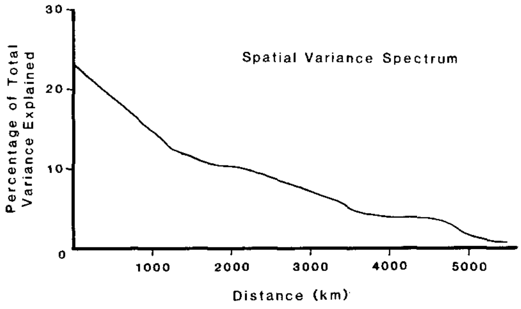


Fig. 3. The spatial variance spectrum of frost free seasons.

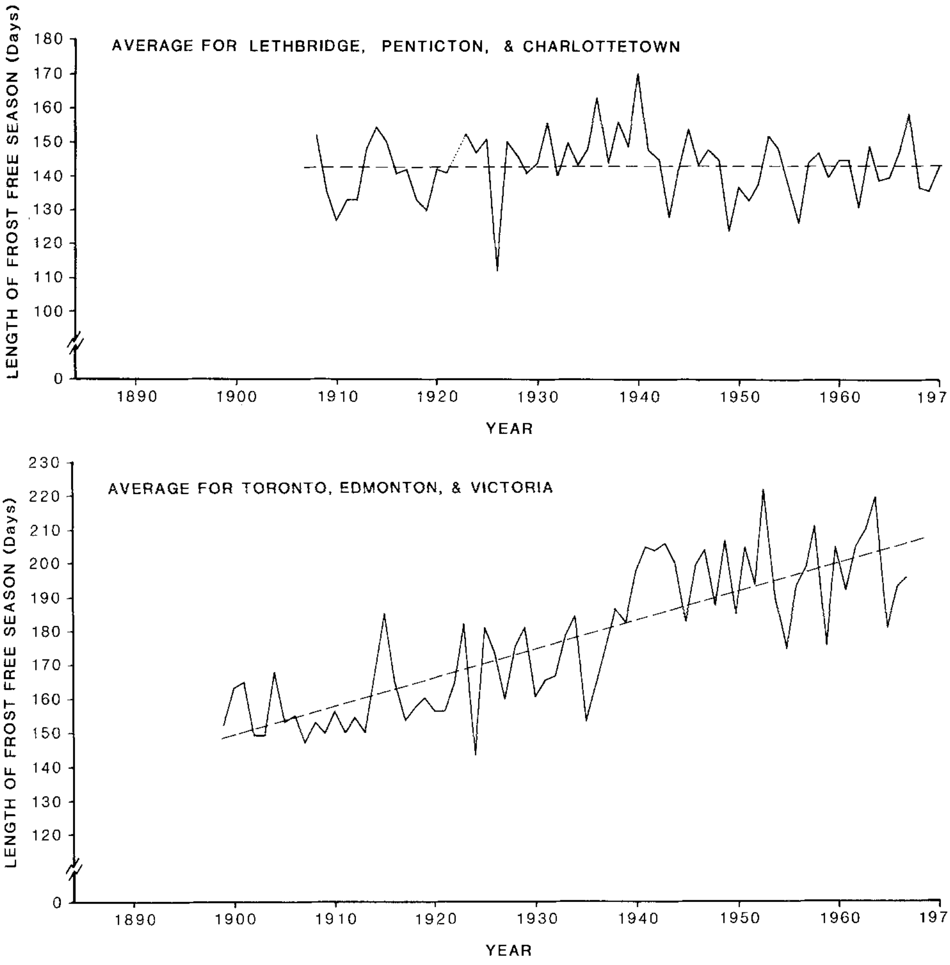


Fig. 4. Trends in the mean length of the season for 'control' and 'urban' groups.

for example, on a decade-to-decade time scale may be symptomatic of a significant change in climate (Chico and Sellers, 1979).

The mean variability of the length of the frost free season for all stations is observed to be fairly stable from decade to decade (Figure 5). It has fluctuated around a variance of 200 days since the beginning of records. However, there were two decades of higher variability. The first occurred between 1901 and 1910, and the second in the decade centered on 1945.

The significance of the higher than normal variance observed during the two decades is not clear at present and needs looking into. However, we wish to point out that while the large variability of 1901–1910 coincided with the shortest mean frost free season in the sample, the variability of 1940–1950 marked the beginning of a trend towards longer seasons (Table III).

Mass curves are used to test data for internal consistency (Kohler, 1949). A cumulative

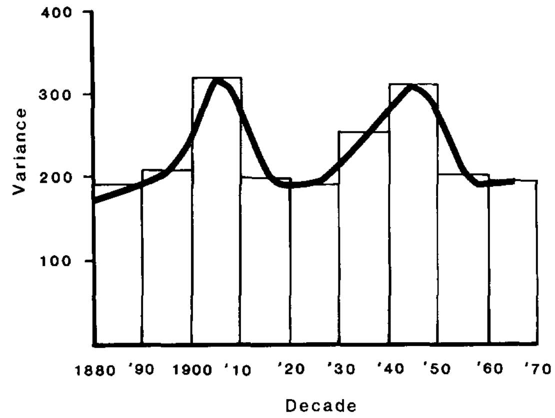


Fig. 5. Decade-to-decade variability.

plot of a stationary annual series yields a straight line. Breaks in the mass curve, where they are statistically significant, are normally indicative of a change in the character of the variable.

A mass curve of decadal means revealed internal homogeneity in the data at most stations up to 1940 (Figure 6). But in 1940 statistically significant breaks appeared at eleven stations. In eight of the nine, the change in slope marked a trend towards longer seasons (Group A, Table VI). In one station it represented reduced values (Group B). There was no statistically meaningful trend in the remaining four stations (Group C). Four mass curves drawn from each of the three groups are shown in Figure 5.

The break in 1940 does not suggest a one-year shift in the length of the season. Rather it indicated as noted previously the entrenchment of a change which began gradually and non-uniformly in the preceding decades. 1940 is therefore used here as a convenient point for the demarcation of a modern era.

The stations in Group A are distinguished by at least one of the following factors – a significant manufacturing and processing industrial base (Marshall, 1981), a large urban population or a strong urban growth rate (Table II). Between 1940 and 1970, the average annual growth in those cities exceeded 3%. Cities in the remaining groups are mainly service centres with lower population growth.

These observations on decadal means have three implications. Firstly, they confirm the existence of significant shifts in the nature of the season over the time period examined. Secondly, they show that the change was not uniformly applied over the affected areas and thirdly, the internal consistency exhibited by the data before and after the break in the mass curve for the affected cities indicates that relocation did not affect the *trend* in the data since the timing of relocation was not synchronized.

6. Shifts in the Mean Probable Dates for the Start and the End of the Frost Free Season

The S-curves in Figure 7 show the distribution of the probable dates for the commencement and the end of the frost free season for all 14 locations. Curve 1 is the pre-1940 dis-

TABLE III: Mean Length of the annual frost free season by decades

Decade	Calgary	Rank	Edmonton	Rank	Saskatoon	Rank	Winnipeg	Rank	Thunder Bay	Rank	Hamilton	Rank	Toronto	Rank	Montreal	Rank	Quebec City	Rank	Fredericton	Rank	St. John	Rank	Victoria	Rank	Prince George	Rank	St. John's	Rank
1881–1890	101	8	103	7	N/A		112	9	112	7	INC	–	163	9	171	9	152	8	202	7	213	7	–	–	–	–	162	8
1891–1900	99	9	119	4	N/A		113	8	128	2	INC	–	171	7	182	5	153	6	205	5	215	4	–	–	–	–	159	9
1901–1910	102	7	102	8	99	6	118	7	118	5	INC	–	169	8	174	8	155	5	200	9	215	4	239	7	–	–	177	4
1911–1920	106	6	108	6	117	4	128	3	125	3	INC	–	173	6	181	6	153	6	207	4	214	5	252	6	71	5	180	2
1921–1930	107	5	102	8	120	1	131	1	133	1	180	–	175	5	180	7	163	2	201	8	212	7	282	3	57	6	173	7
1931–1940	124	1	112	5	118	2	124	5	124	4	INC	–	181	4	183	3	159	4	204	6	224	3	275	5	74	2	174	6
1941–1950	111	4	122	3	108	5	119	6	101	9	189	–	193	3	183	3	164	1	208	6	233	1	288	2	71	4	176	5
1951–1960	120	2	143	1	118	2	129	2	105	8	187	–	194	2	193	1	160	3	214	1	229	2	276	4	72	3	186	1
1961–1970	117	3	140	2	114	4	125	4	113	6	176	–	197	1	190	2	138	8	210	2	230	3	290	1	88	1	179	3

N/A = Not Available.

INC = Incomplete

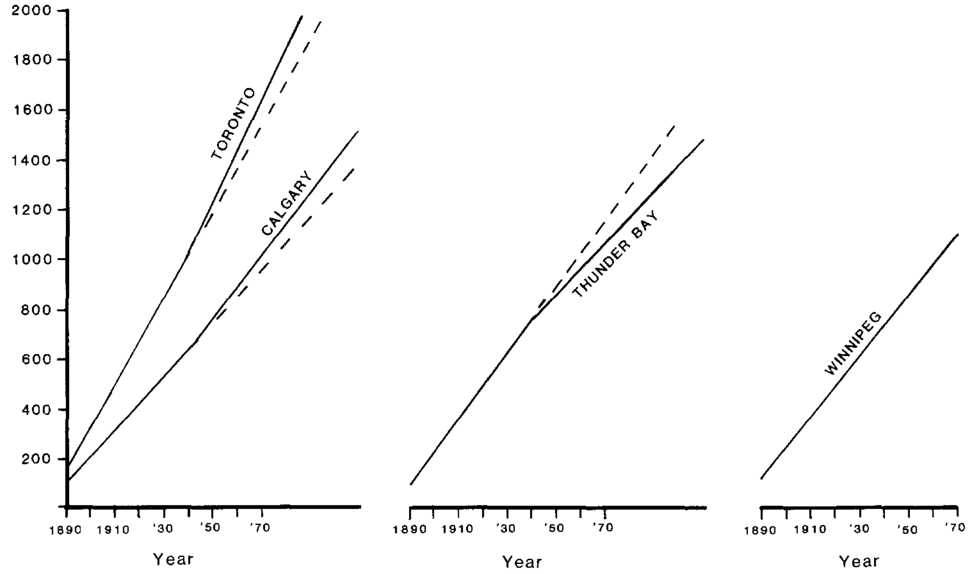


Fig. 6. Mass curves of annual frost free season series.

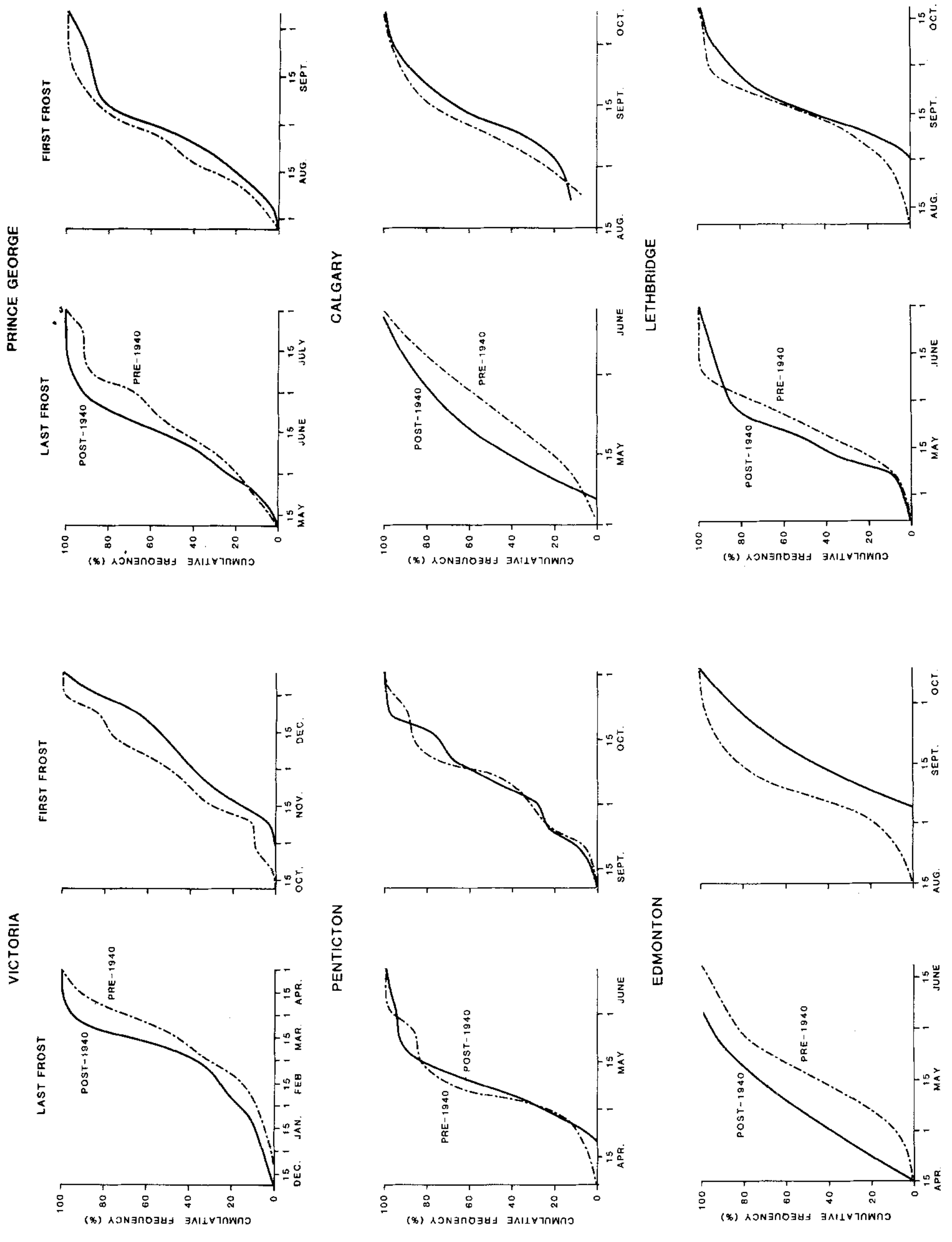
tribution and curve 2 its post-1940 equivalent. It is convenient to discuss them in terms of the groups shown in Table VI.

Group A Stations: All stations showed significant gains in the length of the season (Table V). The average increase is almost two weeks long (13.6 days). The mean probable dates for the fall frost was delayed about 8 days while the mean probable date for the spring frost advanced 6 days.

Group B Stations: Thunder Bay is the only station in this group. The loss was 16 days. The fall frost advanced 11 days while the spring event arrived 6 days later than the mean probable date established in period 1.

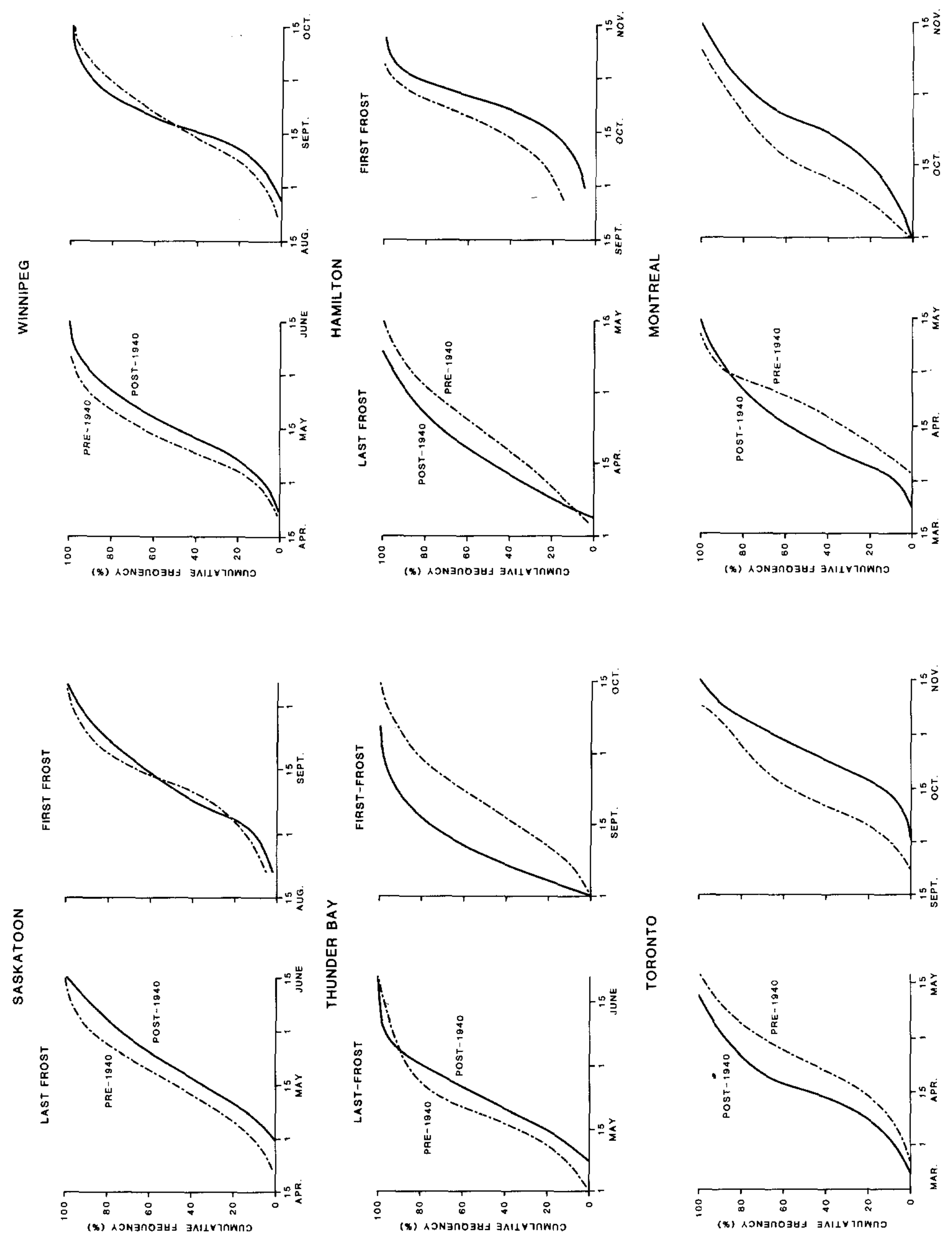
Group C Stations: Taken together, the changes in this group were not statistically significant. However, in all four stations the last spring frost occurred later in the year. The average delay was about five days. The shift in the probable dates for the fall frost were mixed. Multiple crossovers occurred in many of the S-curves. As a general rule, early frost appeared to arrive a little earlier. Late frost arrived later. However, these later shifts were asymmetric. The gain in the timing of late frosts in the fall was greater than the loss resulting from early frost.

The Thunder Bay situation is anomalous because it is clearly out of step with the rest of the data. The city is large enough for the occurrence of a well defined urban heat island by the criteria established in Oke (1973). The only plausible explanation for the station's aberrant behaviour appears to lie in the possibility that the difference in topoclimate between the old and the new site was not fully compensated for by the correction made to the temperature data following relocation from Port Arthur to the International Airport.



7. Related Factors

The length of the frost free season is a function of climate. It is a full year at sea-level in the tropics decreasing polewards to smaller fractions of a year. To that extent, the variable is an expression of mean daily temperature. But mean temperature alone does not completely determine the length of the season because the latter could be changed if the



mean temperature is maintained at a fixed level by increasing the range.

Other atmospheric variables such as clouds, water vapour, particulates, and gases such as CO_2 and NO_X are believed to play a significant role in determining the range of temperature (Weller *et al.*, 1983) and by implication the length of the frost free season. It follows, therefore, that the presence of clouds and radiatively active gases in increased amounts could contribute to a major change in the nature of the season. It is for these

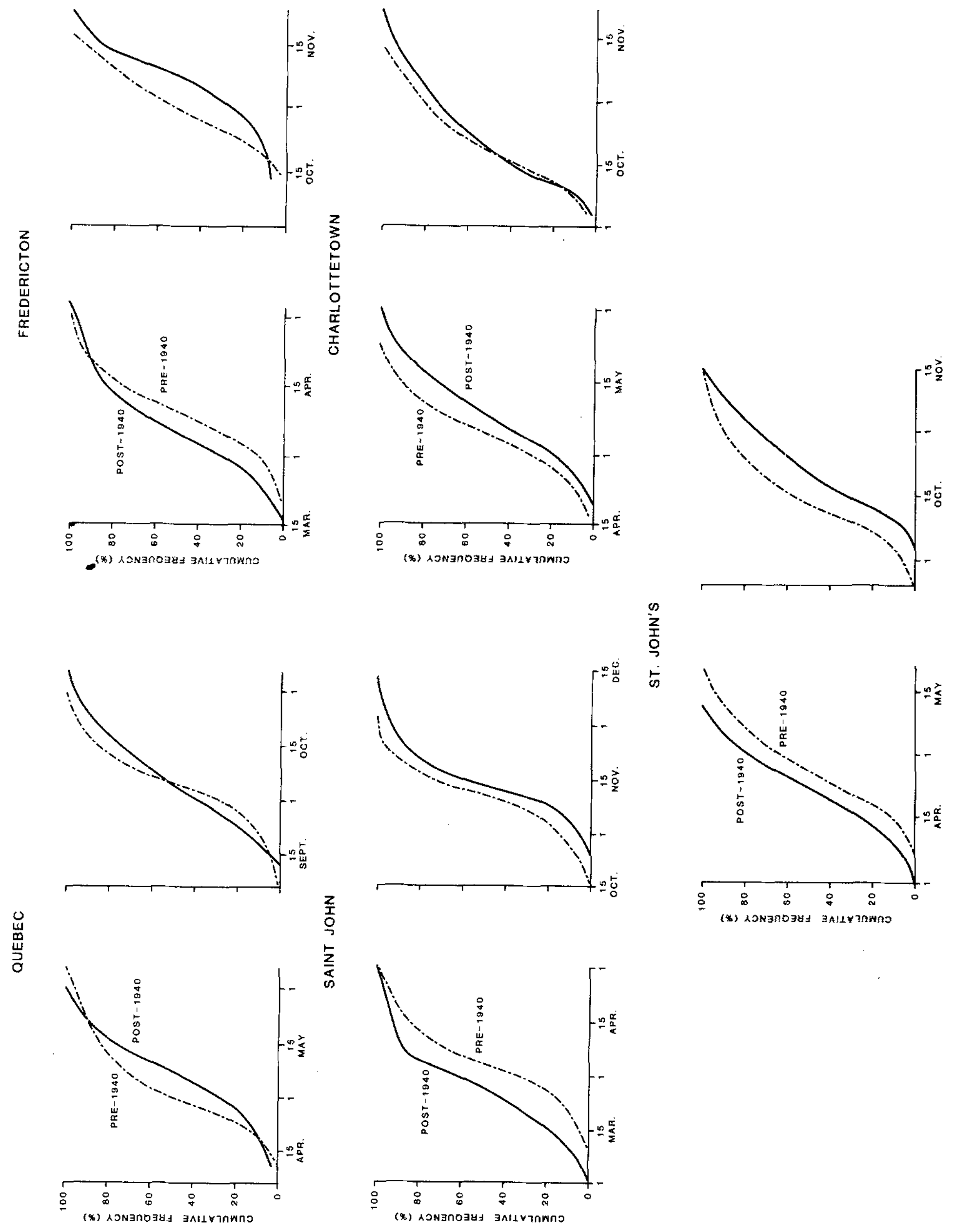


Fig. 7. S-curves of probable dates for the first and last frost of the season.

reasons that the search for an explanation for the longer season was begun by correlating the size of the change in the season with differences in mean temperature and mean cloudiness between the pre-1940 and post-1940 periods together with the mean population growth rate between 1940 and 1970 in the cities in the sample. These urban factors are

TABLE IV: Classification of stations by change type

Group A	Group B	Group C
Victoria		
Calgary		
Edmonton		Saskatoon
Hamilton		Winnipeg
Toronto	Thunder Bay	
Montreal		Quebec City
Fredericton		
St. John		
St. John's		
Prince George		

believed to represent some of the local elements responsible for the low spatial autocorrelation discussed in Section 3.

(i) *Temperature change:* In light of the strength of the relationship between mean temperature and the average length of the season discussed in Section 2, a systematic change in mean temperature could induce a similar change in the length of the season.

Period 2 was warmer than period 1 at all stations except Thunder Bay (Table V). The average increase was 0.53 °C. The largest gains were made at those stations which remained in the inner city (Montreal, Toronto, Edmonton and St. John). Stations which relocated at airports showed smaller increases.

The period 1940 to 1960 was marked by reduced mean temperatures in the Northern Hemisphere (Mitchell, 1963; Chico and Sellers, 1979). Although data presented by Phillips

TABLE V: Data on urban factors used in the study

Station	ΔFFL	ΔTm	ΔPOP(%)	ΔCL(0.00)
Victoria	9	0.7	2.7	0.06
Prince George	10	0.7	4.9	0.02
Calgary	10	0.16	5.9	0.11
Edmonton	26	0.70	5.2	0.08
Saskatoon	− 1	0.20	4.4	0.06
Winnipeg	1	0.44	1.9	0.003
Thunder Bay	−17	−0.05	1.9	–
Hamilton	10	0.20	3.0	0.21
Toronto	18	0.97	4.0	0.10
Montreal	11	1.17	3.0	0.06
Quebec City	− 1	0.5	2.7	0.01
Fredericton	6	0.79	2.0	0.03
St. John	14	1.1	1.3	0.04
Charlottetown	− 2	0.3	1.6	–
St. John's	10	0.39	2.5	0.05

ΔFFL is the difference in the mean length of the frost free season (days) between periods 2 and 1.
ΔTm is the difference in mean daily temperature between periods 2 and 1 (°C).
ΔPOP is the mean annual population growth rate from 1940–1970 (%).
ΔCL is the difference in cloud cover between periods 2 and 1 (decimal fraction).

(1982) appear to suggest that reduced temperatures were not as evident in southern Canada as they might have been elsewhere in the hemisphere, no study indicates that Canada was immune from the global trend. In addition, the mean temperature change between the two periods was a statistically insignificant –.012 °C (α=.05) within the control group. In light of the urban growth which occurred in the second period (Robinson, 1971) and the corresponding high energy consumption rate associated with the growth (Fowler, 1972), the distribution of the net increase in temperature between relocated and non-relocated stations, and the lack of a significant trend in the length of the season among the control stations, it is suggested that the positive temperature anomalies reported here were due mainly with urbanisation.

Temperature change correlated well with the increase in the length of the season (Table VIII). The correlation coefficient was 0.63 or an explained variance of 40%.

(ii) *Cloudiness:* A feature of advancing urbanisation is an increase in mean cloud cover (Changnon, 1977). Machta and Carpenter (1971) reported a general growth in cloudiness in North America which they attributed to human activities. Clouds are more frequent in urban areas because of the large amounts of hygroscopic condensation nuclei emitted into the atmosphere through anthropogenic processes practised in cities. These nuclei are known to encourage condensation and subsequent cloud formation at relative humidities as low as 75%. Huff (1975) reported a lower cloud base in the Chicago area, the result of a raised mean dew point temperature induced by urbanisation.

Clouds absorb outgoing terrestrial radiation and in return re-emit longwave radiation to the surface. The net effect of this heat exchange is to reduce the cooling rate. Consequently, an increase in mean cloud cover should reinforce the atmospheric greenhouse and affect the length of the season. The Carbon Dioxide Assessment Committee (1983) concluded that none of the known potential feedback mechanisms such as an increase in low or middle clouds, can be expected to vitiate the anticipated warming. Indeed the indication is that they could enhance it.

There was a general increase of cloud cover at all stations except Winnipeg. The increase ranged from 21% (0.21) in Hamilton to –3% in Winnipeg. The increase at most stations was almost monotomic (Nkemdirim, 1981).

The correlation coefficient between the change in mean cloud cover and the change in the mean length of the season was 0.584 (Table VI). The low correlation between temper-

TABLE VI: Correlation between urban factors and changes in the length of the frost free season

	ΔFFL	ΔTm	ΔCL	ΔPOP
ΔFFL	1			
ΔTm	634	1		
ΔCL	584	0.018	1	
ΔPOP	469	0.107	0.522	1

ature and cloud change (0.02) was unexpected.

(iii) *Other Urban factors:* The reinforcing of an atmospheric greenhouse in a city atmosphere is not a function of an increased cloud cover only. Urban areas are major sources of radiatively active gases and particulates mainly because of the massive burning of fossil fuel which occurs in them. Hubbert (1973) showed that energy conversion through the combined use of coal and oil increased dramatically since 1940. Fowler (1972) noted that the rate of energy production, and by implication its environmental impact, exceeded the rate of population growth in the last 40 yr. However, energy use and population were strongly correlated.

The lack of long term data on radiatively active gases and particulates for most of the cities in the sample precluded their use in the study. However, because of the correlations noted in the preceding paragraph it was felt that the rate of population growth could be used as a substitute variable designed to measure the impact on the climate of the city of the other environmental factors not explicitly expressed in direct measurements.

The use of population as a surrogate variable in studies of urban climate is not new. Bogolepow (1928) showed that urban-rural temperature differential increased with population size. Oke and Hannel (1968) described the intensity of an urban heat island in term of the logarithm of population while Nkemdirim and Truch (1978) showed that the size of the heat island in one city increased proportionally with its population.

Between 1940 and 1970, population within the sample increased at an average annual rate of 3.2%. There appears to be a direct relationship between the rate of growth and the change in the length of the season. Cities such as Edmonton, Calgary and Toronto where some of the highest growth rates occurred made very impressive gains in the length of the season (Table V). The correlation coefficient between the two variables was 0.47 ($r^2 = 0.22$).

Correlation between total population and the change in the length of the season was not statistically significant ($\alpha = 0.5$). A similar attempt in which the absolute increase in population over the two periods was used yielded a lower ($r = 0.3$) though statistically significant coefficient (Nkemdirim and Venkatesan, 1983).

8. An Urban Impact Model

The results of the analyses were used to develop a multiple regression model to describe the interaction among the four variables. The linear form yielded the smallest mean square error and was consequently adopted. The equation was:

$$\mathrm{FFL} = 18.19\ \Delta\mathrm{Tm} + 2.416\ \Delta\ \mathrm{POP} + 71.83\ \Delta\mathrm{CL} - 14.45,$$

where ΔFFL is the change in the length of the frost free season between period 1 and 2 in days, Δ POP is the mean rate of population growth in percent from 1940 to 1970, and ΔCL is the change in cloud cover between the two periods in decimal fraction.

A two tailed Student's *t* distribution with 11 degrees of freedom was used to test the three regression coefficients for statistical significance. Based on the null hypothesis $H_0{:}B_j = 0$ and the alternative $H_1{:}B_j > 0$ and $t_{\alpha.025}, H_0$ was rejected in all cases in favour of H_1. The 95% confidence interval $B_j \pm t_{0.25} S\sqrt{C_{jj}}$ was within 20% of the estimate B_j for all k parameters based on the sample size. B_j is the beta coefficient in the regression model, S is the variance estimator and C is an element in the inverse of the variance–covariance matrix of the variables.

The coefficient of multiple correlation between the dependent variable and the group of independent variables was 0.89 which represents an explanation of 80%.

Whereas the three independent variables individually correlated reasonably well with the dependent, internal correlation among them was not large. This outcome was not expected and is not readily explained. However, the lack of strong dependency among the variables appears to indicate that they separately measured different aspects of the urban impact on the change in the length of the frost free season.

Analysis of residuals shows that the model performed best in cities which experienced a high growth rate between 1940 and 1970. Model error was within 15% in Calgary, Toronto and Hamilton. At the other end St. John's was grossly overpredicted (Table VII).

In light of the reasonable precision attained by the model, a variety of scenarios were constructed to simulate the effect of different combinations of the predictor variables on in the length of the frost free season (Table VIII). Row 1 is the average conditions used in

TABLE VII: Predicted and observed changes in the length of the season

Station	Actual	Predicted	Error
Victoria	9	9.12	−0.12
Prince George	10	11.56	−1.56
Calgary	10	10.613	−0.613
Edmonton	26	16.59	9.41
Saskatoon	−1	4.125	−5.125
Winnipeg	1	0.296	0.704
Thunder Bay	−17	−12.929	−4.071
Hamilton	10	11.521	−1.521
Toronto	18	19.859	−1.859
Montreal	11	18.389	−7.389
Quebec City	−1	1.883	−2.883
St. John	14	11.572	2.428
Charlottetown	−2	−6.097	4.097
St. John's	10	2.273	7.727
Fredericton	6	6.905	−0.905

TABLE VIII: Predictions of ΔFFL based on hypothetical changes in urban factors

	ΔTm	ΔPOP	ΔCL	Predicted ΔFFL
1.	0.5	3.19	0.06	6.56
2.	1	–	–	3.74
3.	–	1	–	−12
4.	–	–	0.1	−7.26
5.	1	1	0.1	13.43
6.	2	−0.5	–	21.01
7.	−1	−1	−0.1	−42
8.	–	–	1.0	57.4

this study. The result is within 5% of the observed mean increase in FFL. Row 2 shows that a 1° rise in mean temperature but with no change in population and cloud cover would induce only a modest increase in the length of the season. However, when that rise is accompanied by a 1% population growth rate and a 10% increase in cloud cover, the gain is two weeks. It appears therefore that for any appreciable gains to be made in the length of the season at reasonably predictable changes in temperature, such changes in temperature should be accompanied by a modest increase in cloud cover.

Nkemdirim and Venkatesan (1984) have suggested that there might be a link between solar activity and the length of the frost free season. They noted the significant increase in the peak values of three sunspot cycles over the interval 1935–1965. Dickinson (1975) suggested that solar-related fluctuations in some aspects of cloudiness might connect solar activity to the meteorology of the lower atmosphere. He speculated that this connection might occur through, for example, the effect of cosmic-ray induced ionization on aerosol and cloud condensation nuclei and through that impact on the radiative property of clouds and subsequently on the length of the season.

The frost free season series was examined for possible solar connection. This was done by subtracting the portion of the time series of the length of the frost free season explained by the three urban variables from the historical series and then fitting a power spectrum to the residual series. A similar spectrum was fitted to the time series of sunspot numbers. The two spectra were then compared. The distribution of frequencies in them were markedly different (Figure 8) which led to the conclusion that any connection between solar activity as revealed in sunspots and the length of the frost free season is not proved.

9. Conclusion

Between 1940 and 1970, the mean length of the annual frost free season increased by an average of 7 days in 13 Canadian cities. The gain which ranged from 26 to –17 days in individual cities resulted in significant shifts in the mean probable dates for the first and the last frosts of the season.

The phenomenon appears to be strongly associated with urbanisation. While urban growth in the last forty years might not have outpaced similar growth in the preceding decades, growth during the former was associated with a disproportionate increase in the use of fossil fuels, a more complex urban system and a reinforced urban greenhouse.

The analysis conducted here does not necessarily establish cause. It does, however, provide a basis for the estimation of the change which might be expected to occur in the nature of the frost free season from changes in other environmental quantities. The model of Section 8 is in that sense a predictive and not an explanatory equation. In any event, these results should be seen as another step taken in the search for cause.

There is an emerging concensus among climatologists that we are approaching a climatic change (Revelle, 1982). Because some of the expected qualities of that change are already being experienced in cities, this study is seen as an example of how the city could serve as a laboratory for the assessment of the impact of human intervention on climate.

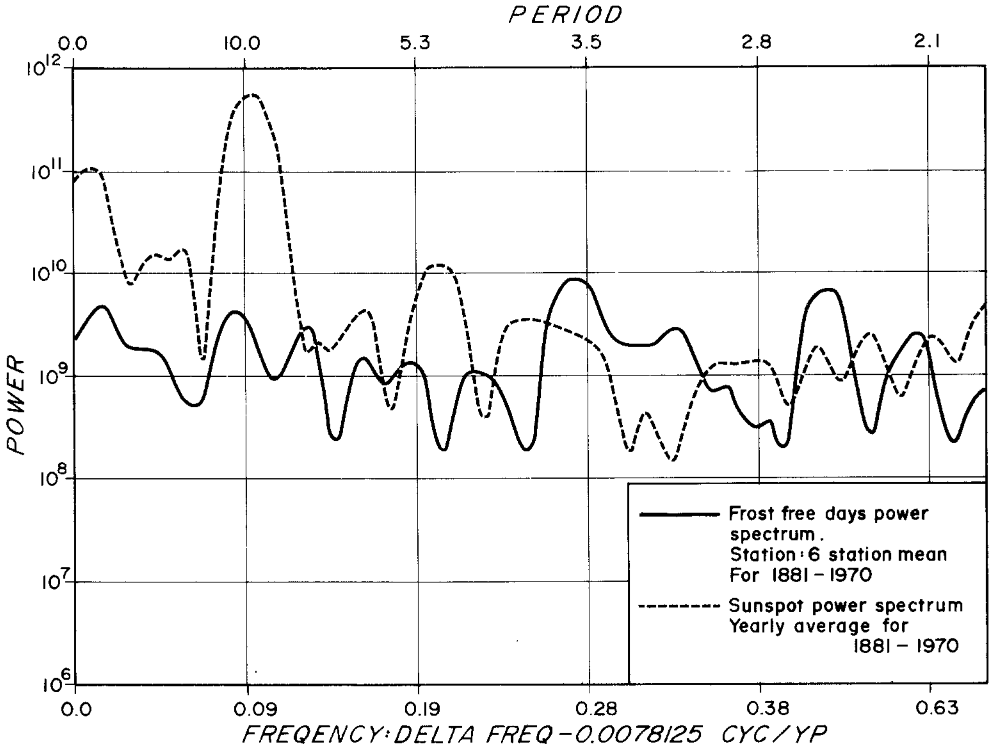


Fig. 8. Power spectra of the length of the frost free season and sunspot number.

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