Canada

GEOGRAPHICAL PAPER No. 35

Trends and Factors Affecting Break-up and Freeze-up Dates in the Nelson River Drainage System

D. K. MacKay

GEOGRAPHICAL BRANCH
partment of Mines and
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PREFACE

The Canadian Ice Distribution Survey of the Geographical Branch has been collecting data on conditions of sea, lake and river ice for over a decade. In addition, the Branch has developed a program on glaciology during this period.

The areal variability and rate of progress of river ice formation and disintegration in the Nelson drainage system were discussed in Geographical Paper No. 34. This paper complements the previous study, considering trends and factors affecting river ice condition dates in the same area.

N. L. Nicholson
Director
Geographical Branch

TRENDS AND FACTORS AFFECTING BREAK-UP AND FREEZE-UP DATES IN THE NELSON RIVER DRAINAGE SYSTEM

INTRODUCTION

The Canadian portions of the Nelson and Mississippi drainage basins form a convenient area for the examination of river ice conditions in the Prairie Provinces. This area, covering some 397,710 square miles, is referred to here as the Nelson drainage system.* The Nelson basin proper is formed by the North and South Saskatchewan Rivers, the Assiniboine and Red Rivers, the Winnipeg River system, and a number of smaller streams that flow into Lake Winnipeg and the Nelson River. The largest tributary of the Mississippi River in Canada is the Milk River.

The areal variability and rate of progress of river ice formation and disintegration in the Nelson drainage system was discussed in a previous paper (MacKay,in press). The present study deals with river ice conditions in the Nelson system from two other points of view and is in two parts. The first part is concerned with fluctuations and trends in ice condition dates recorded at a number of observation sites along the major tributaries of the Nelson River while the last part involves a preliminary examination of meteorologic and hydrologic data related to ice formation and disintegration at these sites.

Knowledge of both fluctuations and trends in river ice conditions is very important to the fullest utilization of inland waterways,as they are, to some degree, economically dependent upon the length of the navigation season. At the present time, there is a growing interest in the development and use of a waterway stretching eastward from Edmonton along the North Saskatchewan-Saskatchewan River and down Lake Winnipeg to Selkirk.

Many factors affect the formation and disintegration of river ice. Radiation, cloud cover, winds, vapour pressure, evaporation, precipitation, as well as the basic physiographic characteristics of a drainage area, influence runoff and river ice conditions. In this preliminary study, relationships between air temperatures and dates of ice formation and disintegration as well as between discharge and ice dates are discussed. Emphasis is placed on these relationships for the following reasons:

(1) the range and extent of air temperature and discharge data allows relationships

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*22,155 square miles of local and inland drainage in the Cypress Hills region of Southern Alberta and Saskatchewan are included in the estimate of the area of the Nelson drainage system.

between these factors and ice dates to be examined at a number of locations in the Nelson drainage system

(2) previous studies have correlated various measures of air temperatures with ice formation and disintegration dates in other areas and at specific locations (Mackay, 1961; Burbridge and Lauder, 1957; Shipman, 1938; Shebanov, 1958; Chernoevanenko, 1954)

(3) increasing discharge is an important factor in the mechanical disintegration of a river's ice cover (McMullen, 1961; Currie, 1953).

Knowledge of these relations is of theoretical interest and of practical value to geographers, meteorologists, and hydrologists. Eventually, such information may prove helpful in freeze-up and break-up prediction.

Objectives

The principal objectives of this study are as follows:

(1) to describe and compare fluctuations and trends in dates of ice formation and disintegration and in lengths of ice-free or open season throughout the Nelson drainage system.

(2) to examine the covariability between records of ice condition dates in order to indicate the relative importance of over-all climatic controls and local environmental controls in the processes of ice formation and ice disintegration

(3) to discuss the extent and variability of freezing degree days for a given period prior to the onset of ice conditions affecting discharge

(4) to determine the extent and variability of melting degree days for a given period prior to dates of last-ice affecting discharge

(5) to indicate the relations between summed winter temperatures, ice thickness data, and break-up dates

(6) to illustrate and discuss discharge rates prior to ice disintegration.

Definitions

Certain terms are used in a specific sense in this study. These terms are listed below in alphabetical order.

"control" or "controlling section" - the section or sections of the stream channel below the gauging site which control the stage-discharge relations at the gauging site.

"covariability" - the degree of association between the variance of one variable and the variance of a second variable.

"drainage system" - drainage within an area; it includes more than one drainage basin.

"first-ice" - the first ice affecting the normal stage-discharge relation curve in the fall season.

"last-ice" - the last ice affecting the normal stage-discharge relation curve in the spring season.

"stage-discharge relation" - the relation between the elevation of the water surface at the gauging site and the rate of flow in the river.

"stationary series" - a series without a trend; one with a constant mean and variance.

TRENDS

There are considerable data available from the Nelson drainage basin for the examination of trends in the dates of river ice formation and ice disintegration. Two kinds of data related to river ice conditions may be used: (1) series of freeze-up and break-up observations recorded by various individuals and organizations on a non-professional basis, and (2) hydrologic records of first-ice and last-ice affecting discharge recorded by observers appointed by the Water Resources Branch of the Department of Northern Affairs and National Resources. Hydrologic records are available at a number of locations on the Nelson River system for periods ranging up to 48 years. Freeze-up and break-up observations have been kept at fewer locations but, in some instances, cover longer periods of time. Trends in river ice conditions may thus be compared to changes in other climatic indicators.

There is ample evidence of climatic change in the northern hemisphere during the last 50 to 100 years. Air temperature records from a number of regions indicate a warming trend over the first 3 or 4 decades of this century. For example, Longley (1953) and Crowe (1958) show that these trends are evident in temperature records from Western Canada. In the Canadian Prairies, Longley suggests that the rising trend is more marked in Saskatchewan than in Alberta or Manitoba during this period. The extent to which trends in the length of ice-free season reflect trends in mean annual air temperatures is examined in this paper.

One of the problems involved in the study of the relationships between trends in air temperatures and ice conditions on rivers is the imposition of artificial or man-made disturbances upon the natural variations in climate. The majority of meteorological stations with long-term records are located in urban areas or in close proximity to urban areas. Urban growth which may affect the exposure and environment of the instruments at meteorological stations may induce trends in the observations of air temperatures which may not be reflected in ice condition trends on rivers. Errors in calibration, recording and transcription can also generate minor movements in time series that add to the difficulty of assessing relations between air temperature and ice condition trends.

A. Hydrologic data

Records of ice conditions affecting discharge cover limited time periods. The longest hydrologic records used in this study span a range of 48 years. None of these records are complete; all have a number of observations missing within their ranges. The more complete records are examined and compared for similarities and differences of movement or change with respect to time.

Five-point filtered series of representative station records from major tributary basins in the Nelson drainage system are graphed and included in this paper. A filtered type of series with non-equal weights was chosen over an equally-weighted type to reduce auto-correlation and increase the weight of the central, plotted value. Weights are allotted in the manner illustrated below:

Year 1	Year 2	Year 3	Year 4	Year 5
6%	25%	38%	25%	6%

One characteristic of any five-point series that should be noted is the loss of two values at each end of all sequences of observations. As the records cover relatively short periods, and as a number of observations are missing from records, real values, denoted by x, are plotted for the initial and final two years of each sequence.

(1) Last-ice

A total of 15 filtered series of last-ice records are presented in graphic form of which eight are drawn from the Saskatchewan tributary basin, five from the Assiniboine-Red tributary basin, (one) and two from the Mississippi drainage basin. The records are chosen with a view to presenting as complete an areal picture of the Nelson drainage system as possible. Where a choice is available, the record with the longer sequences of observations is chosen over a record with more observations but less continuity.

Last-ice series from upstream sites are plotted on the graphs of adjacent downstream series to give some visual indication of the degree of covariability between records. On occasion, last-ice series from different tributary basins are illustrated on one graph for the same purpose. A dashed line (----) represents a series from an upstream location and a dotted line (....) represents one from another tributary basin. In some instances, the bases of superimposed series from other tributary basins are adjusted for comparison purposes. Ordinate values of a superimposed series can be read from the graph of the original series.

BREAK-UP AND FREEZE-UP DATES IN THE NELSON DRAINAGE SYSTEM

Visual inspection of last-ice series for Edmonton, Prince Albert, and the Pas (Figures 2 and 3) on the North Saskatchewan-Saskatchewan River suggests the following observations;

(1) Oscillatory movement of records from Edmonton and Prince Albert is in accord during the early years of record. The two series show little agreement from 1935 to the end of record.

(2) Short-term fluctuations at Prince Albert and the Pas are out of phase with the possible exception of the latter years of record.

(3) Last-ice generally occurs later at a downstream site than at an upstream one but, occasionally, the reverse of this situation is true

(4) There is a slight trend towards earlier dates of last-ice from 1920 to the mid-1940's.

Filtered series of last-ice are graphed for five sites located along various parts of the South Saskatchewan system. Three of the sites are located on headwater tributaries and two are situated on the main channel. The International Boundary and Lethbridge sites on the St. Mary River (Figure 4) have last-ice records which show some measure of covariability; oscillations differ in amplitude but are essentially in phase. The St. Mary River is one of the headwater tributaries on which last-ice normally occurs earlier at the downstream site than at the upstream one. The last-ice series from the Bow River at Banff tends to parallel the movement of the series from the International Boundary site on the St. Mary River (Figure 4). A distinct change in the relative time of last-ice at the two stations over the length of record is evidence that the series are out of phase in the mid-1930's where missing observations cause each series to be discontinuous. Series from Saskatoon and Medicine Hat (Figure 5), located along the main channel of the South Saskatchewan, show some agreement in movement but the omission of a number of last-ice dates limits comparisons to a period of approximately 20 years. There is some indication that last-ice series from the South Saskatchewan and its tributaries trend towards earlier dates in the 1920 to mid-1940 period. From the mid-1940's to the end of record, a swing towards later dates of last-ice seems to be developing.

In the Mississippi drainage basin, filtered series of last-ice records (Figure 6) display characteristics that are similar to filtered of records from the South Saskatchewan basin. The swing to earlier last-ice dates through the period 1920 to mid-1940's, and the reversal of swing from the mid-1940's to the end of record is apparent in both records. These series suggest that there is a fairly high degree of covariability between the observations from the two records.

Last-ice series from the Assiniboine-Red basin (Figures 7 and 8) appear more stationary in character than series from western parts of the Nelson drainage system. A faint trend towards earlier dates of last-ice is apparent at Brandon and Headingley,but records from Millwood, Emerson, and Dominion City (Figure 9) give no such indication. Series from Brandon and Headingley appear to swing in unison with the exception of a short period in the mid 1940's. Series from Emerson and Headingley show a measure of covariability with some obvious differences in the period, 1920 to 1932. The series from Dominion City on the Roseau River, a tributary of the Red River, does not fluctuate as greatly as the series from Emerson on the Red, but basic movements follow a similar pattern in the latter half of record.

In order to determine whether some degree of covariability exists between last-ice dates throughout the Nelson drainage system as a whole, the filtered series of last-ice from The Pas is superimposed on series from Banff, Milk River, Saskatoon, and Brandon. Banff and The Pas (Figure 3) show considerable agreement in oscillatory movement. Saskatoon and The Pas (Figure 5) have similar trends if absolute values (x's) are considered. Milk River and The Pas (Figure 5) conform as to basic trend over the range of data. Series from Brandon and The Pas (Figure 7) agree in trend but show considerable disparity in oscillatory movement.

The majority of records from the Nelson drainage system suggest there is a trend towards earlier dates of last-ice in the period from 1920 to the mid-1940's. In most filtered series, a swing to later dates is apparent towards the end of record. Some series, particularly those drawn from the south-eastern part of the Nelson drainage system, fluctuate less markedly than others and appear to be more stationary in character. Fundamental agreement in trend and reasonable levels of agreement in oscillatory movement between last-ice series from most areas of the Nelson system suggests that early ice disintegration on headwater tributaries is an indication that early dates may be expected throughout the Nelson basin. Later-than-normal ice disintegration dates in any tributary basin would suggest that dates may be late in the other tributary basins of the Nelson system. The graphs also indicate that ice disintegration dates at downstream locations are, to some degree, dependent upon upstream dates.

(2) First-ice

Thirteen first-ice records are filtered of which three are drawn from the North Saskatchewan-Saskatchewan, five from the South Saskatchewan, one from the Mississippi, and three from the Assiniboine-

Red River systems. First-ice series from upstream sites are superimposed on graphs of downstream channel sites, and in some instances, a series from one tributary basin is superimposed on a series from another tributary basin. Superimposed first-ice series are differentiated in the same manner employed in treating last-ice series (see p. 4).

First-ice series from Edmonton and The Pas (Figure 10) show marked similarities in movement. The series from Prince Albert which is located between Edmonton and The Pas shows little agreement with series from either of these locations. The reasons for the disagreement between the series from Prince Albert and the series from the other two locations are not obvious. There is no marked trend in first-ice records from the North Saskatchewan-Saskatchewan River, although there is some suggestion that first-ice occurs later towards the end of record.

Filtered series of first-ice dates from locations on the South Saskatchewan River system (Figures 11, 12 and 13) indicate that there is a trend to later dates over the range of record. Oscillatory movement of series from downstream locations compares favorably with movement in upstream series on the St. Mary and the South Saskatchewan over the period 1935 to 1955. There is little agreement between upstream and downstream series on either river prior to 1935.

Brandon, Headingley and Emerson,in the Assiniboine-Red basin, exhibit marked similarities between first-ice records (Figures 14 and 15). Comparisons of first-ice series show that major oscillations are in phase with only minor discrepancies in movement and amplitude. The first-ice series from Milk River on the Milk River tributary of the Mississippi drainage basin shows some measure of covariability with series from the Assiniboine-Red basin (Figure 14). A trend towards earlier dates of first-ice from the beginning of record to the late 1930's is evident in the filtered series from the Assiniboine-Red and the Mississippi basins. The period from the late 1930's to the end of record gives some indication of a swing to later dates of first-ice.

The filtered series from The Pas is superimposed on series from Edmonton, Banff, Medicine Hat, and Milk River. As mentioned previously, the series from Edmonton and The Pas exhibit a comparatively high degree of covariability. Banff and The Pas are markedly similar in movement from 1930 to the end of record. Series from Milk River, Medicine Hat, and The Pas swing in unison from 1940 to 1955 but prior to this period there is little evidence of covariability.

The comparison of first-ice series from different tributary basins suggests that some measure of covariability exists between first-ice records. In fact, the measure of agreement between first-ice series appears to be stronger than the agreement indicated between last-ice series. In other words, climatic controls operating throughout the Nelson basin exhibit greater influence upon dates of first-ice than on dates of last-ice; local environmental factors appear to be of less importance in the determination of first-ice dates.

(3) Ice-free Season

Cumulative percentual deviations (Crowe, 1958; Kraus, 1955) based on the mean length of ice-free season, 1921 to 1950, are computed and graphed for records from 6 stations located in the Nelson drainage system. The cumulative percentual deviation curves are derived from the equation,

$$Y_i = \frac{100}{\overline{X}} \sum_{i=1}^{n} (X_i - \overline{X})$$

where Y_i the cumulated percentual deviation in the year i,

X_i the length of ice-free season in the year i, and

$\overline{X}$ the mean length of ice-free season, 1921 to 1950.

The cumulative percentual deviation curve passes through the origin at the beginning of the year 1921, and at the end of 1950.

Cumulative percentual deviations are used to facilitate comparisons between station records with means that differ over the period, 1921 to 1950. The cumulative percentual deviation curve rises during the years in which the ice-free season is consistently longer than the mean ice-free season, 1921 to 1950. The curve falls during the years in which the ice-free season is consistently shorter than the mean ice-free season, 1921 to 1950. Small yearly changes in the length of ice-free season may only change the slope of the curve without appreciably affecting the general trend (see Crowe 1958, p. 3; Kraus, 1955). In those years in which dates of last-ice conditions are missing, the ice-free season is assumed to be average in length.

Records are selected from stations that give some representation to the varying physical conditions that are found in the major physiographic regions of the Nelson drainage system. No record is included from the Canadian Shield portion because records from Shield gauging sites lack the required length and continuity. The location of stations with respect to physiographic boundaries is shown on Figure 1.

Figures 16 and 17 indicate that the length of ice-free season at each of the six stations differs considerably from year to year. The curves, with the exception of the one representing Brandon's record, are basically valley-shaped. This suggests that the trend is towards longer ice-free seasons in the latter years of records. At Banff, Edmonton, and The Pas, the ice-free season is generally shorter than average in the period 1921 to the early 1930's; the season is generally longer than average at these stations from the early 1930's to the end of record. At Saskatoon, the ice-free season tends to remain shorter than average until the 1940's and then swings to a longer-than-average ice-free season in the latter portion of the record. The curve for Lethbridge is basically W-shaped which indicates there are two periods of shorter-than-average ice-free season and two periods of longer-than-average ice-free season. The curve for Brandon suggests the ice-free season is neither longer nor shorter than the mean for more than four years in a row. As the length fluctuates fairly widely with no tendency to remain consistently shorter or longer than the mean, the ice-free season at Brandon may be regarded as more stationary in character than those at the other locations.

(4) Mean Annual Air Temperatures and the Ice-free Season

Cumulative percentual deviations from the mean ice-free season and from mean annual air temperatures, 1921 to 1950, are illustrated in Figure 18 for three locations in the Nelson basin. The graphs do not indicate that either positive or negative deviations from mean annual air temperatures and lengths of ice-free season are in any measure synchronous. However, trends in the deviations from the mean annual air temperatures, 1921 to 1950, show marked similarities at the three locations. If air temperature trends are basically similar across the breadth of the Nelson basin as records from Edmonton, Saskatoon, and Brandon indicate, there is little reason to expect that the use of air temperatures from upstream locations would improve the levels of agreement illustrated in the graphs.

Figure 19 shows movements in mean annual air temperatures (absolute values) at Prince Albert superimposed on the filtered series of open season (break-up to freeze-up) for the same location. The two series show little agreement in oscillatory movement. The comparison at Prince Albert points to the same conclusion reached following the examination of cumulative percentual deviations: namely, that varying lengths of open or ice-free season cannot be directly related to changes in mean annual air temperatures.

B. Freeze-up and Break-up Data

A few locations in the Nelson basin have longer freeze-up and break-up records than first-ice and last-ice records. Edmonton, Prince Albert, Winnipeg, and Selkirk have break-up records that are 60 to 80 years long. Of the four stations mentioned, only Edmonton and Prince Albert have freeze-up records of similar lengths. These records are filtered and graphed in the same manner used in treating records of ice conditions affecting discharge.

Break-up records from Edmonton and Prince Albert are continuous throughout their individual ranges. The freeze-up record from Prince Albert is the only series of freeze-up observations that is continuous throughout its range. Edmonton's record of freeze-up has a number of gaps, and graphical methods of comparison with other records are of questionable value. Both freeze-up and break-up records from Winnipeg have gaps of fourteen years, from 1893 to 1907. Break-up observations are missing at Selkirk for the period 1916 to 1920 inclusive.

(1) Break-up Records

Break-up records from Edmonton and Prince Albert (Figure 20) show marked similarities in oscillatory movement. All major oscillations are in phase apart from some obvious differences in amplitude. Some minor variations in swing are apparent but the records are essentially in agreement throughout their comparable ranges. The measure of agreement tends to substantiate the accuracy of break-up observations taken at each location. It also demonstrates the dependency of downstream break-up dates upon the time of ice disintegration upstream.

There is an obvious trend towards earlier break-up at Edmonton and Prince Albert. The basic trend supports conclusions reached following the examination of trends in last-ice observations at the same locations.

Break-up records at Winnipeg and Selkirk (Figure 21) show some agreement where comparable data is available. The general oscillatory movements are in accord from 1929 to the end of record. There is some disagreement in the 1922 to 1928 period but a graphic comparison of records from the Red River with those from the North Saskatchewan River shows that Selkirk's record is in almost complete agreement with the records from Edmonton and Prince Albert during this period (Figure 20). In fact, throughout its entire range, the filtered series from Selkirk has a sufficient level of agreement with the series from Edmonton and Prince Albert to suggest that Winnipeg's record in the period 1922 to 1928 is anomalous. Student's "t" test of the difference between means of 10-year periods indicates that the 1921 to 1930 period of Winnipeg's record differs significantly from subsequent periods. This tends to corroborate the results obtained by graphic comparisons. Table 1 shows the "t" values obtained.

TABLE I

Difference Between Means of 10-year
Break-up Periods at Winnipeg

Note: If $t > 2.88$, the difference is significant at the 1 per cent level
If $t < 2.88$, the difference is not significant at the 1 per cent level

	"t" values			
	1921-30	1931-40	1941-50	1951-60
1921-30	-			
1931-40	5.71	-		
1941-50	3.66	1.96	-	
1951-60	5.89	0.32	1.94	-

The covariability between break-up records from Edmonton, Prince Albert, and Selkirk is measured by Pearson's product-moment method of correlation. The correspondence between paired break-up dates is listed in matrix form in Table II. The results suggest that there is a considerable degree of covariation between break-up dates across the full width of the Great Plains physiographic region. The degree of covariability substantiates conclusions reached following the examination of last-ice records. The values obtained are statistically significant at the 1 per cent level. Moreover, the results illustrate quantitatively the greater degree of dependency between records from stations located on the same river than between records from sites in separate tributary basins.

TABLE II

Covariability Between Paired Break-up Dates

Note: There are 51 pairs; the same years are used in determining each value. All values are significant at the 1 per cent level.

	Edmonton	Prince Albert	Selkirk
EDMONTON	-		
PRINCE ALBERT	.729	-	
SELKIRK	.468	.480	

(2) Freeze-up Records

The freeze-up series from Prince Albert is superimposed on that from Winnipeg (Figure 22) and a visual comparison suggests there is a reasonable level of agreement in oscillatory movement between the two series with the exception of the period, 1922 to 1928. The period of disagreement is the same one in which the break-up series from Winnipeg disagrees with the Selkirk, Edmonton, and Prince Albert series.

Both freeze-up series indicate there are two dominant movements over the range 1900 to 1958. A faint trend towards earlier freeze-up is noticeable from 1900 to 1935; the trend is towards later freeze-up dates from 1935 to 1958. First-ice series from the Assiniboine-Red basin have similar incipient trends although first-ice series from other locations in the Nelson drainage system are not necessarily in accord with these findings.

(3) Open Season

The only long, continuous record of open season that is available in the Nelson basin is from Prince Albert; the record from Edmonton is interrupted for extensive periods (Figure 23). A dashed line joining absolute values of open season in the major interrupted period at Edmonton may be used as a rough guide to the oscillatory movement within this period. Swings in the series at Edmonton and Prince Albert tend to parallel each other. At Prince Albert, the length of open season is decreasing from 1912 to 1928; from 1928 to 1958, the length of open season is increasing.

ICE FORMATION AND ICE DISINTEGRATION

Water flowing in a river is affected by varying climatic conditions encountered along its path of flow. Therefore, the formation of ice at any given point on a river is dependent on both the local environmental conditions and the conditions that exist upstream. Similarly, the disintegration of a river's ice cover depends not only upon the environmental conditions affecting the ice cover at an observation site but on upstream conditions as well.

One method used to relate upstream air temperatures to freeze-up is to estimate the rate of progress of a given mass of water down a river and to determine the air temperatures affecting it along its flow path. Flow-travel times in conjunction with air temperatures from enroute weather stations have been used to estimate freeze-up on the Mackenzie River (Mackay, 1961). Hydrographic data of flow velocities in rivers of the Nelson basin are not available to the writer and estimation of theoretical mean velocities is beyond the scope of this paper. The examination of freeze-up in this study is primarily limited to the extent and variability of freezing degree days occurring prior to the onset of ice conditions at six sites in the Nelson basin.

The disintegration of a river's ice cover in the spring is a complex process. Over-all increases in the sum of direct and diffused radiation received in spring months are reflected in the upward trend of air temperatures. Above freezing temperatures occurring at an observation site will cause the river's ice cover to become pitted and structurally weakened. In the upstream drainage areas, above freezing temperatures increase run-off and flow rates in the tributaries and main channel of the river system. If upstream conditions produce sufficient run-off to lift and crack the ice cover, break-up and complete ice disintegration may be expected to proceed rapidly. Measures of local thawing intensities (cumulated degree days) and hydrographs of discharge prior to ice disintegration will be examined.

Another condition affecting the time of ice disintegration on a river is the thickness of the ice cover. Ice thickness is dependent upon factors such as radiation, air temperatures, time and depth of snow cover, current speeds and turbidity, and so on. Ice thickness data is limited in extent. Observations covering sixteen years are available for the Assiniboine River at Brandon, but data from other river stations in the Nelson basin are limited to 1 or 2 years. In any event, the ice thickness determined by borings at one location may not necessarily be a good estimate of the thickness of a river's ice cover. The under-surface of the ice cover will vary considerably depending upon such factors as the position of the main flow channels, the rates of flow, and the variability in the depth of the snow cover.

Summing winter temperatures is one method of estimating the severity of winters and the thickness of the ice cover. This method, however, does not take into account the development of a snow cover and its limiting effects on ice growth. Variability in the depth of the snow cover on the ice surface caused by winds drifting the snow, and differences in the snowfall regimes at locations in the Nelson basin, are complicating factors. Relations between summed winter temperatures and dates of ice disintegration are examined in this study. Summed winter temperatures should be more representative of ice cover thickness at locations where snowfall is relatively light. The seasonal fall of snow is less at Brandon and Saskatoon than at the other four locations dealt with in this study.

Measurements of the accumulated snow cover on the ground are taken at a number of meteorological stations in the Nelson basin on the morning of the last day of each month. Such data are of limited value in the determination of ice thickness for a number of reasons. For example, snow depths measured on the last day of the month are not necessarily characteristic of the month as a whole. Freezing intensities will vary during the course of each month and, therefore, a continuous or daily record of snow cover is necessary to determine with ant degree of accuracy the relations between snow cover and ice thickness. A second problem is that snow measurements taken in comparatively drift-free areas do not necessarily reflect snow conditions on a river's wind-blown ice surface. Snow cover data were examined early in the study and discarded for the reasons outlined above.

This study is primarily concerned with the period 1921 to 1950.

A. Freezing Degree Days Prior to Ice Formation, 1921 to 1950

A freezing degree day is considered to be equivalent to 1° Fahrenheit below the freezing temperature of 32°. Therefore, a mean daily temperature of 20°F is the equivalent of 12 freezing degree days, and a mean daily temperature of 0°F is equal to 32 freezing degree days. The average number of freezing degree days are cumulated over a 10-day period prior to first-ice affecting discharge, 1921 to 1950. The results are listed in Table III for six locations in the Nelson basin.

TABLE III

Average Number of Cumulated Freezing Degree Days Prior to First-ice, 1921-1950

	Days Prior to First-Ice Affecting Discharge										
STATION	10	9	8	7	6	5	4	3	2	1	0
BANFF	-	-	-	2.2	4.8	5.1	8.6	15.9	25.2	36.8	52.9
EDMONTON	-	-	-	-	-	-	-	-	4.3	12.2	22.4
LETHBRIDGE	-	-	-	-	-	-	-	-	-	0.6	7.0
SASKATOON	-	-	-	-	-	-	1.0	4.9	12.9	24.2	36.1
BRANDON	-	-	1.0	2.2	3.9	6.1	10.5	16.4	22.8	30.6	39.4
THE PAS	2.0	5.5	8.9	12.6	16.9	23.5	32.9	42.7	53.7	64.3	75.8

The greatest number of freezing degree days occur at The Pas and at Banff in the 10-day period prior to first-ice affecting discharge. At Banff, it is possible that a steep gradient and consequent high rate of flow require the presence of fairly low local air temperatures before a sufficient amount of ice to affect discharge is formed on site or in the control section. At The Pas, it may be assumed that the influx of warmer water into the North Saskatchewan-Saskatchewan River system from the South Saskatchewan

River requires that local temperatures be below the freezing point for some length of time prior to the formation of ice affecting discharge. At both locations, however, first-ice dates have been reported in years when local mean daily temperatures were above the freezing point. Ice carried downriver from some distance upstream and the formation of ice in sheltered areas under minimum daily temperature conditions, may explain these dates.

The least number of freezing degree days in the 10-day period prior to first-ice affecting discharge occurs at Lethbridge and at Edmonton. The rivers are deeply entrenched at both these locations which suggests that local air temperatures may not be characteristic of temperatures in contact with the free water surface. The St. Mary River, in the Lethbridge area, is entrenched approximately 250 feet below the rolling prairie countryside. Its sharp-walled valley is ideal for the pooling of cool air and, therefore, early morning temperatures at the river's surface may fall well below those recorded at Lethbridge airport. The same situation may prevail at Edmonton where the North Saskatchewan flows at an elevation of approximately 150 feet below the height at which air temperatures are recorded.

The years in which above freezing temperatures occurred on the dates when first-ice affecting discharge was recorded are listed in Table IV.

An examination of Table IV suggests the following:

(1) above freezing temperatures occurred on first-ice dates most frequently at Edmonton and Lethbridge. This suggests that local air temperature observations are less characteristic of temperatures at the free water surface at these locations than at the other locations examined.

(2) with few exceptions, minimum air temperatures are below the freezing point on frist-ice dates. In most cases, the 10-day period prior to first-ice had a majority of days with minimum temperatures below 32°F. Ice formation and accretion in sheltered areas under such temperature conditions may be an important factor in the development of ice conditions affecting discharge.

(3) the extreme variability of air temperature conditions in the 10-day period prior to first-ice is illustrated by the differences between the 10-day mean air temperatures. The degree of variability indicates that any given set of air temperatures at the observation site does not necessarily give rise to ice conditions affecting discharge. In order to relate local air temperatures to the formation of first-ice some knowledge of water temperatures seems necessary.

d

The number of days on which mean daily temperatures are below 32°F prior to first-ice dates differs markedly from year to year at each location. The average day on which mean daily temperatures reached the freezing point prior to the onset of ice conditions (based on the period, 1921 to 1950) at each site is indicated in Table V. The differences between the average length of the freezing period prior to

TABLE IV

Years when Mean Daily Air Temperature was above Freezing
On date of First-Ice Affecting Discharge, 1921 to 1950

STATION	YEAR	Air Temp. on Firt-Ice Date			In 10-day Period Prior to First-Ice	
		Max.	Min.	Mean	Mean Air Temp.	Number of days Min. Air Temp. 32°F
BANFF	1941	43	24	33.5	19.8	10
	1939	43	33	38	39.4	6
	1938	39	30	34.5	26.2	10
EDMONTON	1949	55	19	37	35.0	9
	1944	46	20	33	28.3	10
	1943	49	24	36.5	35.6	9
	1941	45	21	33	37.4	7
	1937	42	27	34.5	37.2	9
	1930	41	32	36.5	42.5	4
	1923	46	29	37.5	32.2	10
LETHBRIDGE	1941	52	28	40	28.6	9
	1936	57	37	47	37.8	9
	1934	42	30	36	34.0	8
	1933	56	38	47	39.4	7
	1930	50	17	33.5	41.4	6
	1929	40	29	34.5	41.0	7
	1924	51	21	36	43.4	6
SASKATOON	1946	50	21	35.5	34.1	10
	1941	64	35	49.5	47.8	6
	1934	49	27	38	30.0	10
	1930	42	30	36	44.2	3
BRANDON	1941	57	26	41.5	30.2	9
	1940	44	30	37	12.8	10
	1936	60	31	45.5	25.2	9
THE PAS	1939	50	22	36	27.3	10
	1936	48	36	42	14.8	10
	1929	42	30	36	27.5	10
	1923	48	32	40	29.7	8

first-ice at the six locations makes it impractical to compute a measure of the variability over a standard 10-day period. Each location must be considered separately. Standard deviations of degree days for the freezing period at each location are listed in Table V. In all but one instance, the standard deviations exceed the expected number of freezing degree days prior to first-ice. The extreme variability indicates the impracticability of relating local air temperature records to first-ice dates without some knowledge of water temperatures.

TABLE V

Standard Deviations of Cumulated Degree days Prior to First-Ice

(Computed for average freezing periods,
1921 to 1950; including first-ice dates)

STATION	Average Freezing Period (in days)	Standard Deviations (in degree days)
BANFF	8	65
EDMONTON	4	49
LETHBRIDGE	3	18
SASKATOON	6	69
BRANDON	9	65
THE PAS	11	75

B. Melting Degree Days Prior to Last-ice

Above-freezing temperatures occur at an observation site for various periods of time prior to ice disintegration. In some years, freeze-thaw cycles may begin two months or more in advance of break-up. In the latter stages of the winter phase, the cycles are usually diurnal with thawing periods gradually increasing in length as incursions of Pacific maritime weather systems become more frequent during the spring phase. The number and intensity of freeze-thaw cycles are an important factor in river ice disintegration due to the effect of such cycles upon the strength of an ice cover.

The melting degree day concept does not deal adequately with the problem of freeze-thaw cycles nor with yearly variations in snow cover depths on a river's ice surface. However, it does indicate local thaw intensities prior to ice disintegration. The number of melting degree days in any one day equals the number of degrees the mean daily temperature is above the freezing point. In other words, a mean daily temperature of 40 degrees Fahrenheit is equivalent to 8 melting degree days; a 50 degree mean daily temperature equals 18 melting degree days, and so on. The average number of melting degree days cumulated over the 10-day period prior to last-ice dates, 1921 to 1950, is listed in Table VI, for 6 locations in the Nelson basin.

Some locations exhibit marked differences in the average number of melting degree days occurring over the 10-day period prior to last-ice dates. The smallest accumulations of melting degree days occur at Banff and Lethbridge. In the Banff area, a steep river gradient may inhibit the formation of

TABLE VI

Average Number of Cumulated Melting Degree Days Prior to Last-ice, 1921-1950

STATION	10	9	8	7	6	5	4	3	2	1	0
BANFF	-	-	-	-	-	-	-	2.2	2.8	4.1	4.1
EDMONTON	3.7	10.0	17.2	23.9	32.8	42.5	53.9	65.2	76.4	87.9	98.6
LETHBRIDGE	-	-	-	-	1.6	2.2	4.9	7.6	8.1	9.5	10.3
SASKATOON	-	-	-	1.2	2.4	4.0	5.5	10.0	17.9	28.8	38.8
BRANDON	-	-	-	0.4	3.5	6.1	9.8	15.9	22.9	29.9	36.4
THE PAS	1.4	3.3	6.8	11.2	15.7	21.1	26.7	34.3	41.3	47.7	55.9

a thick ice cover; at Lethbridge, the chinook effect and the resultant high number and intensity of freeze-thaw cycles may hinder ice cover development. Thus, break-up on the St. Mary River near Lethbridge, and on the Bow River at Banff may occur with relatively small changes in climatic conditions.

The largest average number of melting degree days occur at Edmonton. Although mean winter temperatures indicate that the ice cover on the North Saskatchewan at Edmonton would not be as thick as the ice cover on the South Saskatchewan at Saskatoon or on the Assiniboine at Brandon, break-up is later at Edmonton. Comparisons of temperature regimes (Figure 24) at these locations shows that the late occurrence of break-up at Edmonton provides an explanation for the greater average number of accumulated melting degree days. However, the reasons for late break-up at Edmonton are less obvious. The proximity of Edmonton's location to the glacier and snow-fed headwaters of the North Saskatchewan suggests that the amelioration of water temperatures by air temperatures during the open season is limited by the flow-travel distance. If water temperatures in the fall are lower at Edmonton than at the other 2 locations, the change to the winter phase would proceed more rapidly. As,in fact, freeze-up is generally earlier at Edmonton, the longer closed season would permit greater ice accretion and, thus, delay ice disintegration in the spring.

The years in which last-ice dates, 1921 to 1950, occurred under freezing conditions at 6 locations in the Nelson basin are listed in Table VII. In most instances, maximum air temperatures are above the freezing point on last-ice dates. The 10-day periods prior to last-ice dates exhibit marked variability in mean 10-day air temperatures and in the number of days that mean daily air temperatures are above 32°F. The variability of air temperature conditions prior to last-ice indicates the importance that other factors, such as discharge, play in the process of ice cover disintegration. Standard deviations of air temperatures in degrees Fahrenheit and in degree days for the 10-day period preceding last-ice are listed in Table VIII.

TABLE VII

Years when Mean Daily Air Temperature was below Freezing
On date of Last-ice Affecting Discharge, 1921 to 1950

STATION	YEAR	Air Temp. on Last-ice Date			In 10-day Period Prior to Last-ice	
		Max. °F	Min. °F	Mean. °F	Mean Air Temp. °F	Number of Days Mean Daily Air Temp. 32°F
BANFF	1950	38	15	26.5	25.7	0
	1949	37	23	30.0	31.4	6
	1948	39	17	28.0	18.7	0
	1946	36	8	22.0	29.2	3
	1945	35	3	19.0	33.2	6
	1942	24	6	15.0	26.3	2
	1940	29	12	20.5	34.8	7
	1939	33	11	22.0	41.8	7
	1935	17	- 4	6.5	18.5	0
	1932	26	-14	6.0	11.0	1
EDMONTON	1934	38	25	31.5	42.4	10
	1927	34	6	20.0	33.7	6
LETHBRIDGE	1940	43	20	31.5	37.0	7
	1930	35	18	26.5	26.1	3
	1927	42	15	28.5	31.6	6
	1926	36	16	26.0	20.2	0
	1924	38	21	29.5	28.0	2
	1923	40	23	31.5	35.0	6
	1921	13	12	12.5	9.9	2
SASKATOON	1947	37	22	29.5	26.2	1
	1945	48	14	31.0	33.1	6
	1939	33	23	28.0	31.0	4
	1933	38	25	31.5	32.0	4
BRANDON	1946	36	26	31.0	39.1	8
	1945	37	22	29.5	32.5	6
	1942	33	29	31.0	27.0	1
	1935	22	17	19.5	35.0	6
	1933	29	22	25.5	34.1	7
	1931	40	23	31.5	39.9	8
	1928	25	21	23.0	27.8	2
THE PAS	1948	48	25	31.5	36.9	8
	1934	27	10	18.5	32.4	4
	1931	36	19	27.5	41.6	8

TABLE VIII

Standard Deviations of Mean Air Temperatures
and Cumulated Degree Days

(Computed for 10-day periods prior to last-ice, 1921 to 1950)

STATION	Standard Deviations Air Temperature (°F)	Degree Days
BANFF	6.7	67
EDMONTON	4.3	43
LETHBRIDGE	7.1	71
SASKATOON	5.0	50
BRANDON	5.3	53
THE PAS	4.9	49

C. Summed Winter Temperatures, Ice Thicknesses, and Ice Disintegration Dates

Maximum ice thicknesses on the Assiniboine River at Brandon have been measured and recorded for the 16-year period, 1943 to 1958 (Canada, Department of Transport, CIR-3195 ICE-4, Oct. 1961). A comparison of maximum ice thickness data and break-up dates at Brandon (Figure 25) suggests that there is some measure of correlation but the relationship is not statistically significant. Similar results results were obtained with comparisons between ice thicknesses at Brandon and local winter temperatures summed over various periods. Break-up dates and last-ice dates at Edmonton and at Saskatoon were plotted against local winter temperatures summed over the periods from freeze-up to break-up, first-ice to last-ice, and November to March inclusive. Results indicate that summed local winter temperatures are unreliable guides to dates of ice disintegration.

D. River Discharge and Ice Disintegration

Each of the major tributary basins of the Nelson system cover vast areas which have manifold physical and climatic differences. The problem of assessing the influence of individual physical and climatic factors upon river ice disintegration in such areas is an extremely difficult task. As stated previously, ice disintegration at any given point on a river is dependent not only upon local environmental conditions but on those existing in the upstream portions of the drainage basin as well. One element in the disintegration of a river's ice cover which measures the aggregate effects of the varying environmental conditions that exist upstream is river discharge.

Increasing discharge is a dynamic factor in the mechanical disintegration of a river's ice cover. Although the process of ice disintegration is not necessarily dependent upon significant increases in discharge, the rates at the seven locations examined generally increased three to five-fold in the period ranging from seven to fifteen days immediately prior to ice disintegration. In cases where last-ice dates have occurred without a rapid increase in discharge immediately prior to the event, an inspection of the records usually shows marked fluctuations have materially weakened the ice cover to the extent that local environmental conditions can give rise to break-up. Cases in which no rapid increase in discharge rates preceded ice disintegration occur in approximately 10 per cent of the years under examination.

Mean discharge rates prior to last-ice dates, 1921 to 1950, are computed for seven gauging stations located in the Great Plains physiographic region. Discharge records from two stations in the headwater's area of the South Saskatchewan River, Lethbridge and Banff, were examined and discarded for two reasons: following first, these locations show minimal stability of flow rates from year to year, and, second, the extreme irregularly in discharge rates prior to last-ice suggests that the representation of these conditions by averages would be meaningless.

Mean discharge rates in the immediate period prior to last-ice dates are illustrated in Figure 26 for two locations on the North Saskatchewan, two on the South Saskatchewan, two on the Assiniboine, and one on the Saskatchewan River. The hydrographs show that the rates of increase in the six day period prior to last-ice are approximately the same at all stations except The Pas, in spite of the fact that discharge rates differ markedly on the various tributaries. The time of the initial upswing varies from 7 to 11 days prior to dates of last-ice at stations on the North Saskatchewan, South Saskatchewan, and Assiniboine Rivers. A lesser rate of increase spread over a longer period is indicated at The Pas on the Saskatchewan River.

Following ice disintegration, discharge continues to rise for a period of one day at Saskatoon and two days at Edmonton before a drop is noticeable. Mean discharge rates at the other locations show a tendency to drop or level off immediately following the date of last-ice. Whether dates of ice conditions from which the dates of last-ice are extracted are inclusive at all locations is difficult to ascertain from gauging records. Thus, differences in the rates of discharge following last-ice dates may be negligible or, possibly greater than they appear to be in Figure 26.

SUMMARY AND CONCLUSIONS

The study of trends in river ice conditions at a number of locations in the Nelson drainage system is based predominantly on filtered series of ice formation and disintegration dates, and on cumulative percentual deviations from the mean ice-free season, 1921 to 1950. Visual inspection of the graphs leads to the following conclusions:

(1) The majority of last-ice records indicate a trend towards earlier dates of last-ice from 1920 to the mid-1940's. A swing towards later dates is indicated in the latter years of record. Series from the Assiniboine-Red basin are more stationary in character than series from the other major tributary basins.

(2) First-ice series do not indicate any marked secular movement. Most records show a swing to later first-ice dates in the latter years of record. The Assiniboine-Red records swing to earlier dates from the beginning of record to the late 1930's.

(3) The covariability between first-ice records appears to be greater than the covariability between last-ice records. This implies that fundamental climatic controls and weather systems operating throughout the Nelson basin exert a greater measurable influence upon dates of first-ice than on dates of last-ice. The weather conditinns that induce break-up in the headwaters of the North and South Saskatchewan Rivers are extremely variable. As ice disintegration dates at downstream locations are in some measure dependent upon dates of ice disintegration at upstream sites, the variability of break-up dates on the headwaters could be a factor in limiting the covariability between last-ice records throughout the basin.

(4) Cumulative percentual deviations from the mean length of ice-free season, 1921 to 1950, show that the ice-free season was shorter than average from 1921 to the early 1930's and longer than average in the latter half of record at most locations in the Nelson basin. The filtered series of open season at Prince Albert exhibits similar movements.

(5) Variations in the length of open or ice-free season cannot be directly related to variations in mean annual air temperatures.

The preliminary examination of climatic and hydrologic factors affecting river ice formation and disintegration suggests the following conclusions:

(1) Local air temperatures in the 10-day period prior to the onset of ice conditions are extremely variable. On occasion, mean temperatures indicate thawing conditions when first-ice dates are reported. Some possible explanations are:

  (i) pooling of cool air due to river entrenchment may mean that local air temperature observations are not characteristic of conditions at the free water surface;

  (ii) ice formed during the local minimum air temperature conditions may be sufficient to affect the normal stage-discharge relation curve, and cause first-ice dates to be reported;

  (iii) ice formed under freezing intensities upstream, or in tributaries, may float down in sufficient quantities to cause first-ice dates to be reported;

(iv) data inaccuracies due to misinterpretation of the stage-discharge relation curve or transcriptional errors may influence results.

(2) Cumulated melting degree days prior to ice disintegration provide little or no indication of the onset of ice disintegration at the sites examined. Last-ice may occur under local thawing or freezing conditions. Due to the averaging process, the computation of melting degree days from mean daily temperatures does not consider the effect of diurnal freeze-thaw cycles on the structural strength of an ice cover. The number and intensity of freeze-thaw cycles is an important factor in the determination of dates of ice disintegration.

(3) There is some indication of a stochastic relationship between maximum ice thickness data and break-up dates recorded at Brandon, on the Assiniboine River. Comparisons of summed winter temperatures and maximum ice thickness at Brandon yield similar results. However, neither of these relationships is statistically significant.

(4) River discharge appears to be the most important single measurable factor involved in the process of ice disintegration. Records from seven Great Plains locations show that marked increases in discharge precedes ice disintegration dates in 9 out of 10 cases. Rates of discharge increase 3 to 5 times in the 10-day period prior to last-ice dates. However, headwater stations in the Rocky Mountains and Foothills regions exhibit considerable variability in discharge rates prior to last-ice dates and statements made regarding increases in discharge do not apply in these regions.

A knowledge of water temperatures in conjunction with flow-travel times would be of great value in explaining ice formation dates. Although air temperatures affecting east-flowing streams crossing the Great Plains are relatively uniform due to minimal latitudinal effect and the dominant westerly circulation, environmental conditions affecting water temperatures in mountainous headwater areas are extremely variable. Thus, water temperature data from streams crossing the area of transition between the Rocky Mountain Foothill and Great Plains Region would seem a prerequisite to the accurate estimation of downstream ice formation dates from air temperatures and flow-travel times.

River discharge is a reliable guide to environmental conditions existing upstream prior to ice disintegration. However, break-up prediction is also dependent upon such local environmental conditions as the strength and thickness of the river's ice cover. Accurate estimation of these factors without more information related to snow cover conditions is extremely difficult. When adequate snow cover data are available, reasonable estimates of ice disintegration dates would appear to be possible.

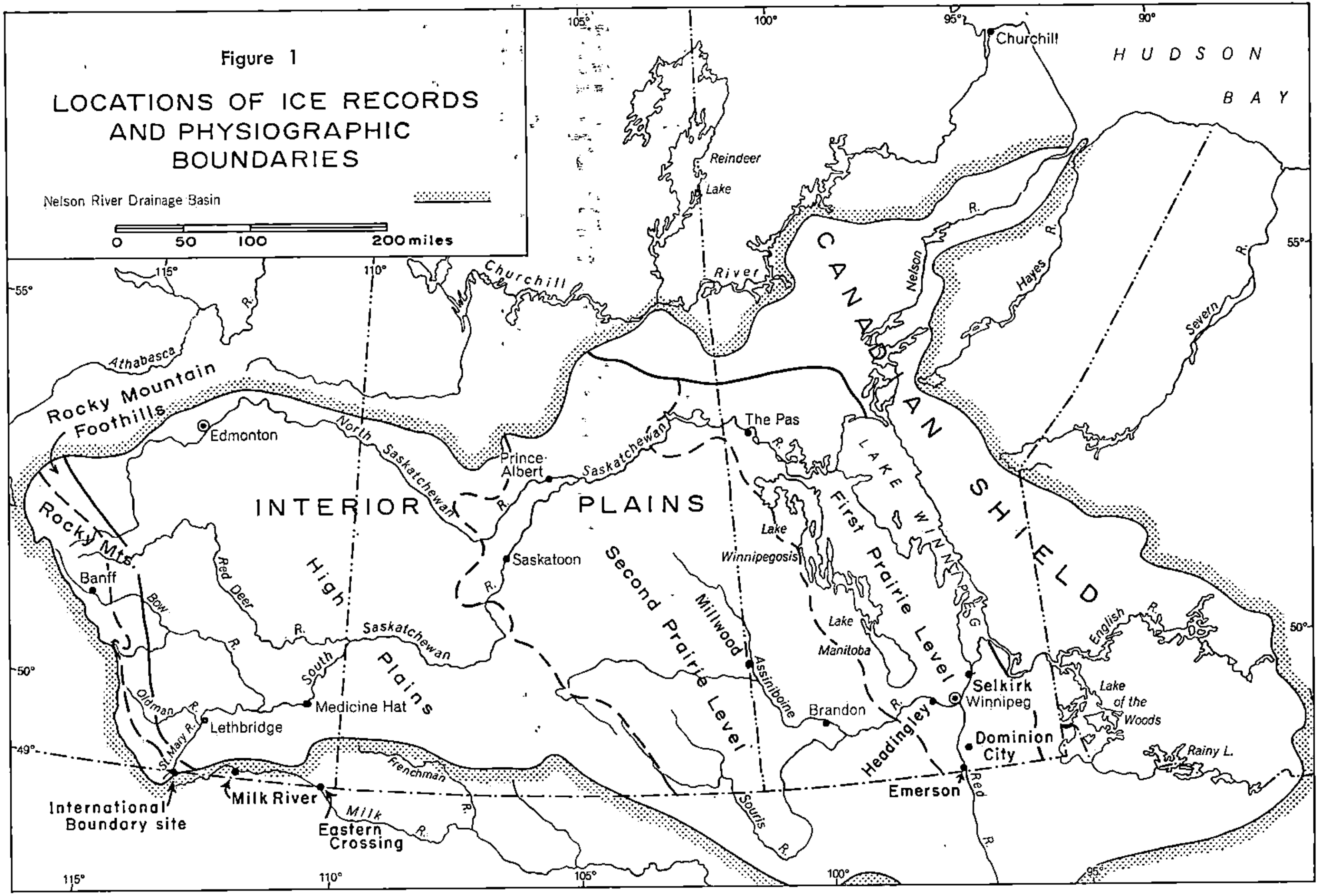


Figure 1

LOCATIONS OF ICE RECORDS AND PHYSIOGRAPHIC BOUNDARIES

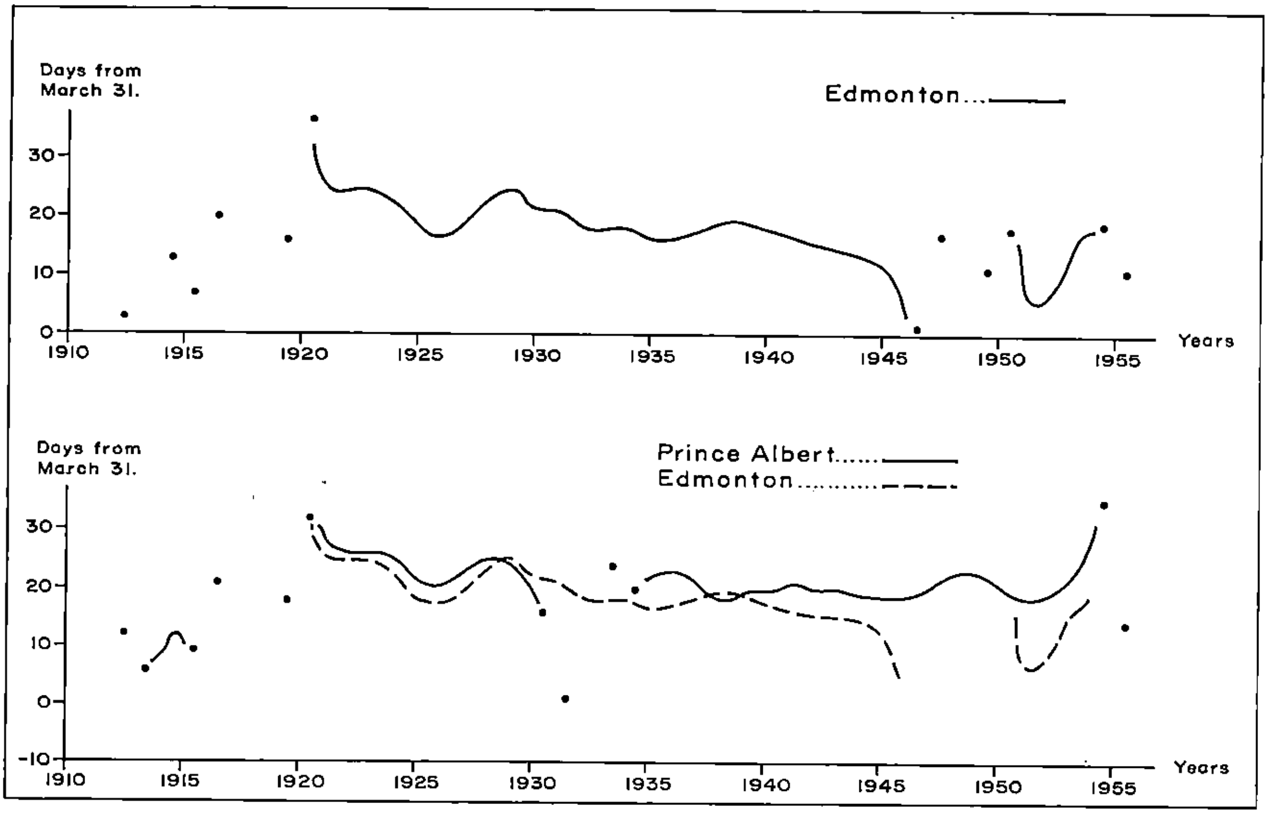


FIGURE 2. 5-point filtered series of last-ice.

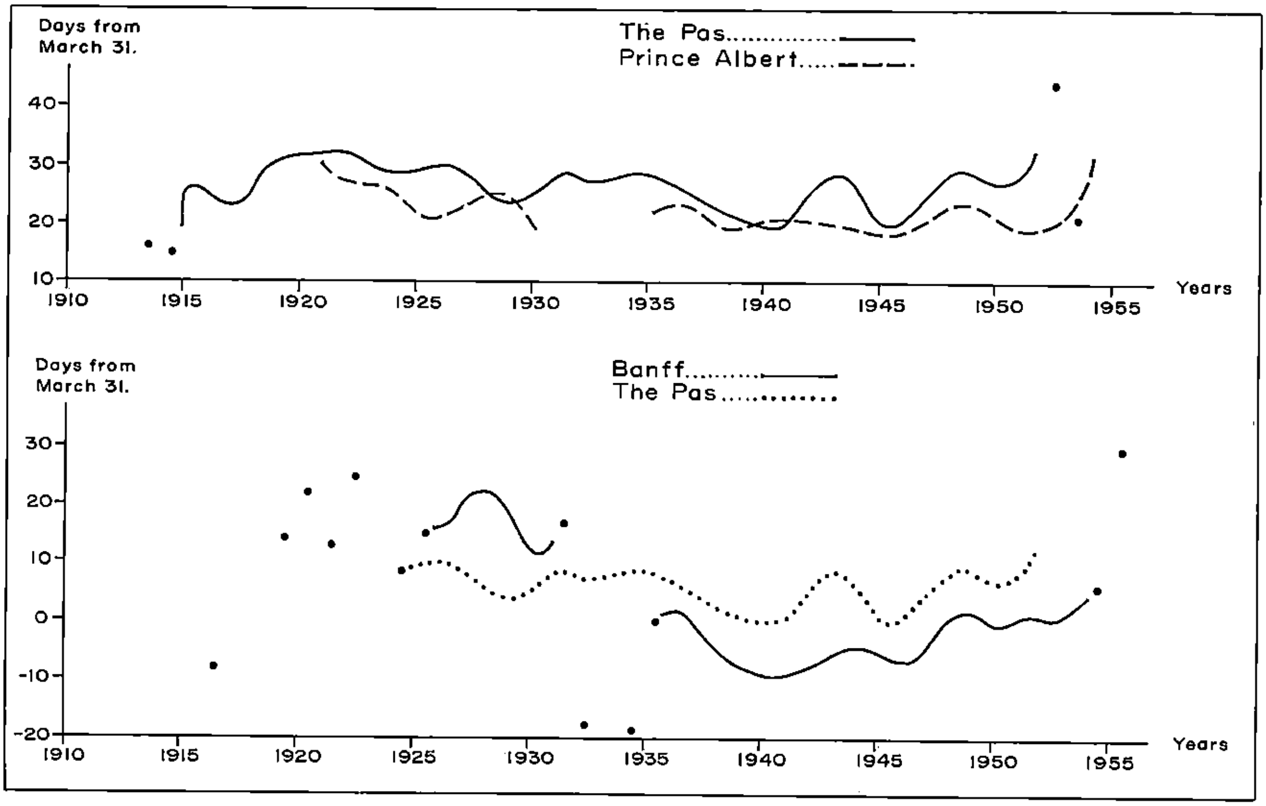


FIGURE 3. 5-point filtered series of last-ice.

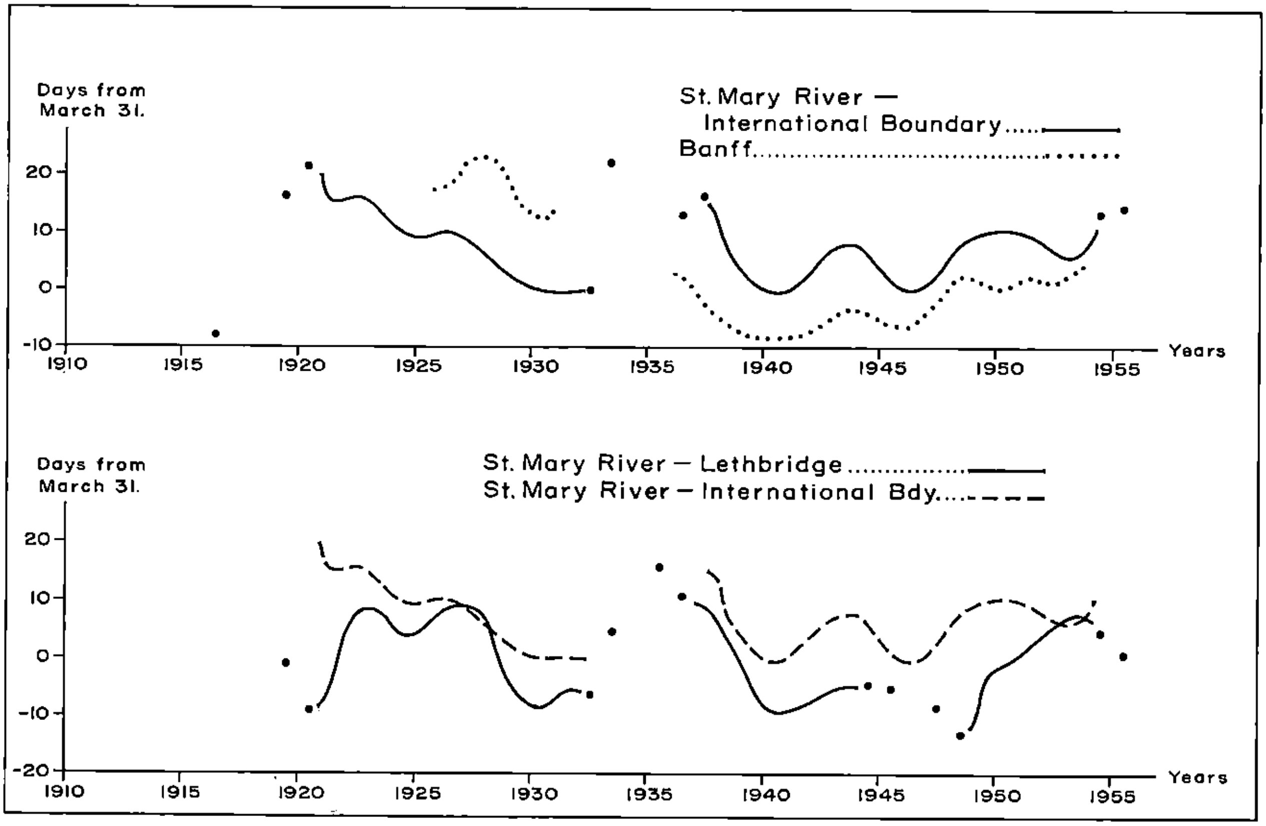


FIGURE 4. 5-point filtered series of last-ice.

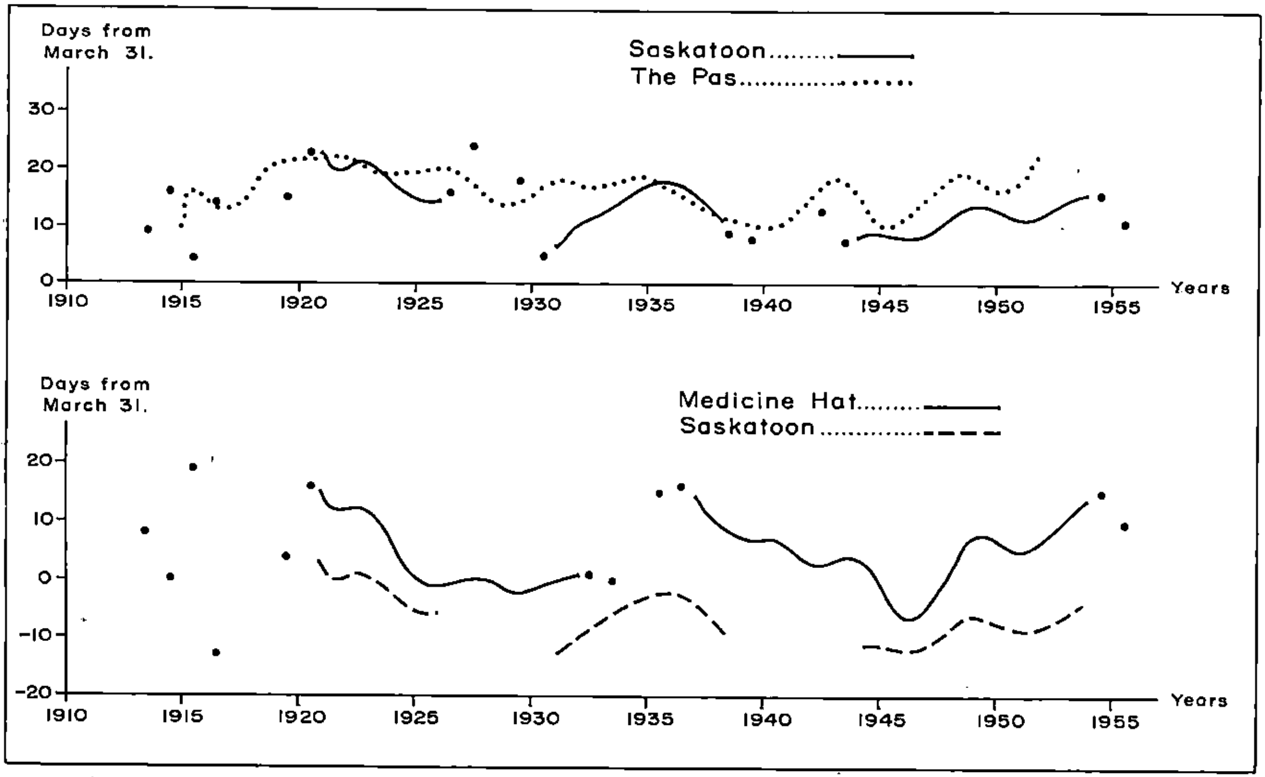


FIGURE 5. 5-point filtered series of last-ice.

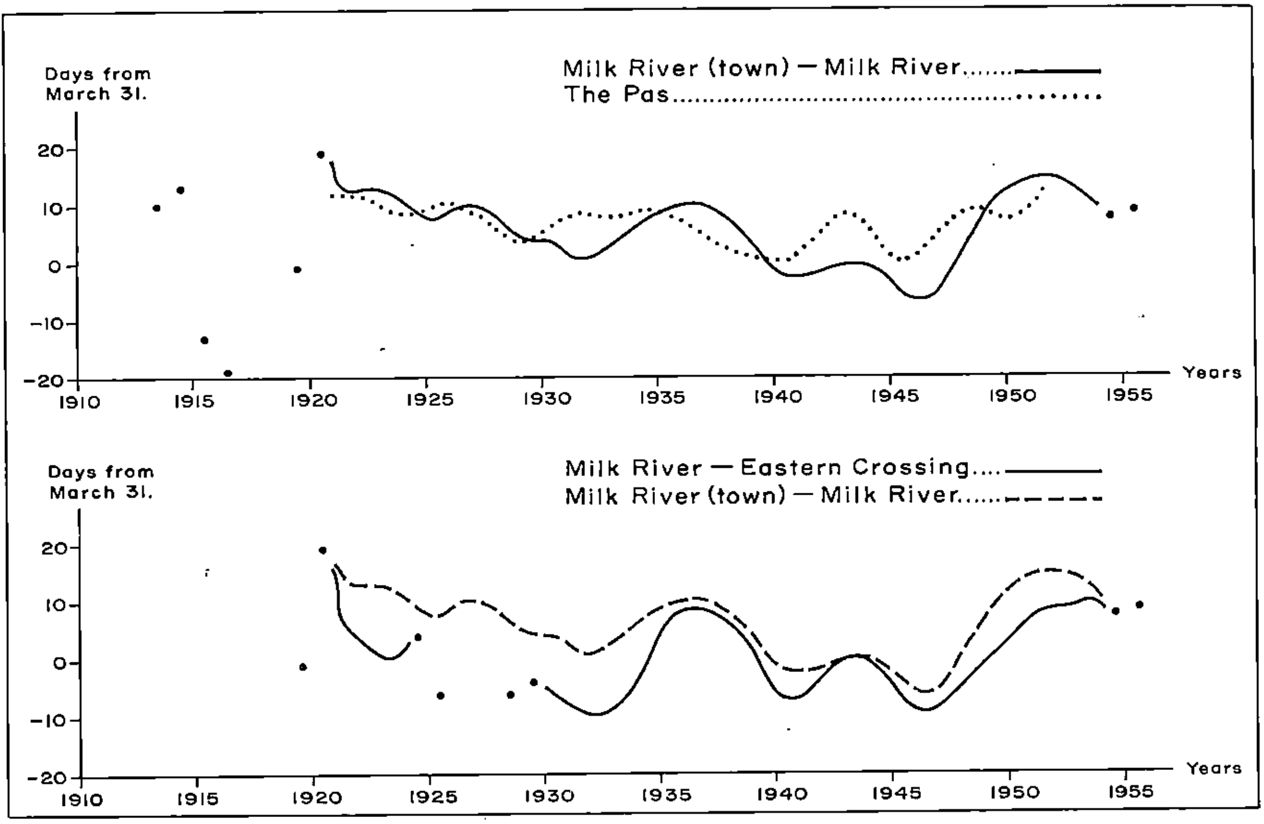


FIGURE 6. 5-point filtered series of last-ice.

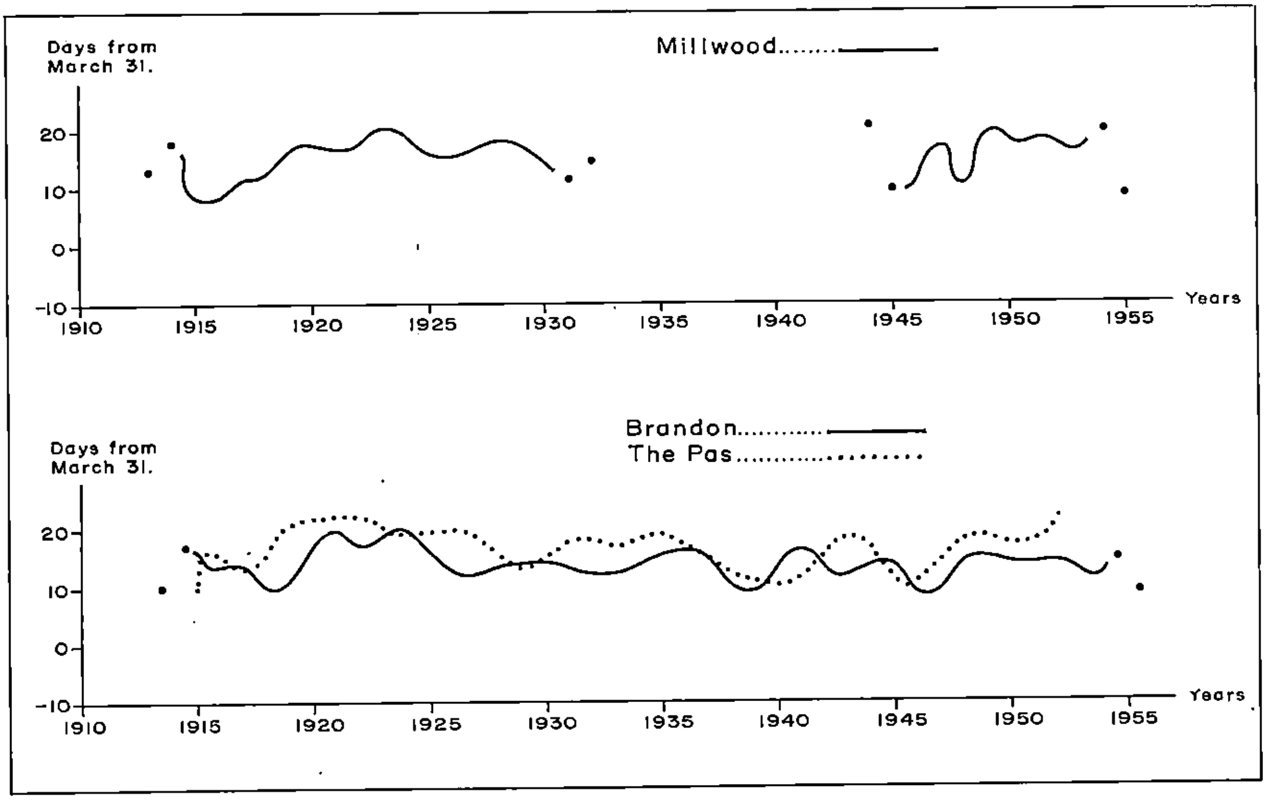


FIGURE 7. 5-point filtered series of last-ice.

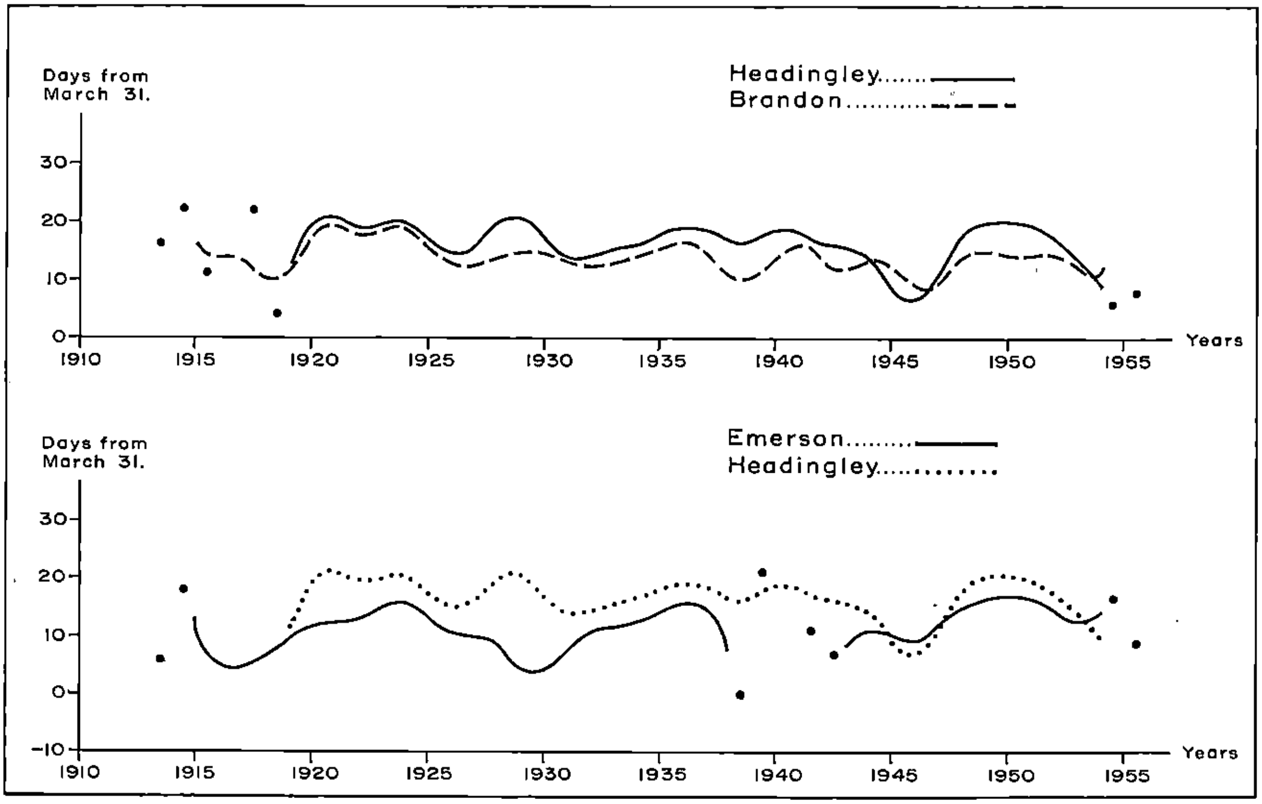


FIGURE 8. 5-point filtered series of last-ice.

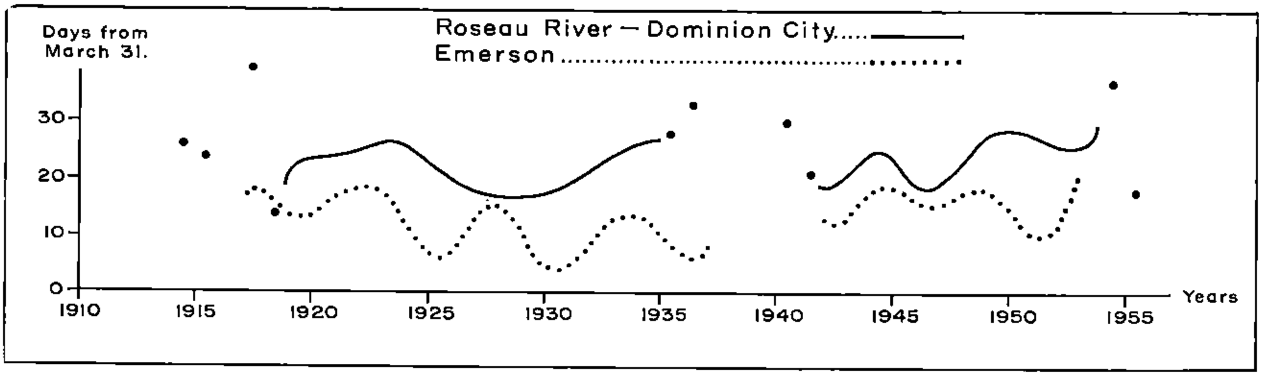


FIGURE 9. 5-point filtered series of last-ice.

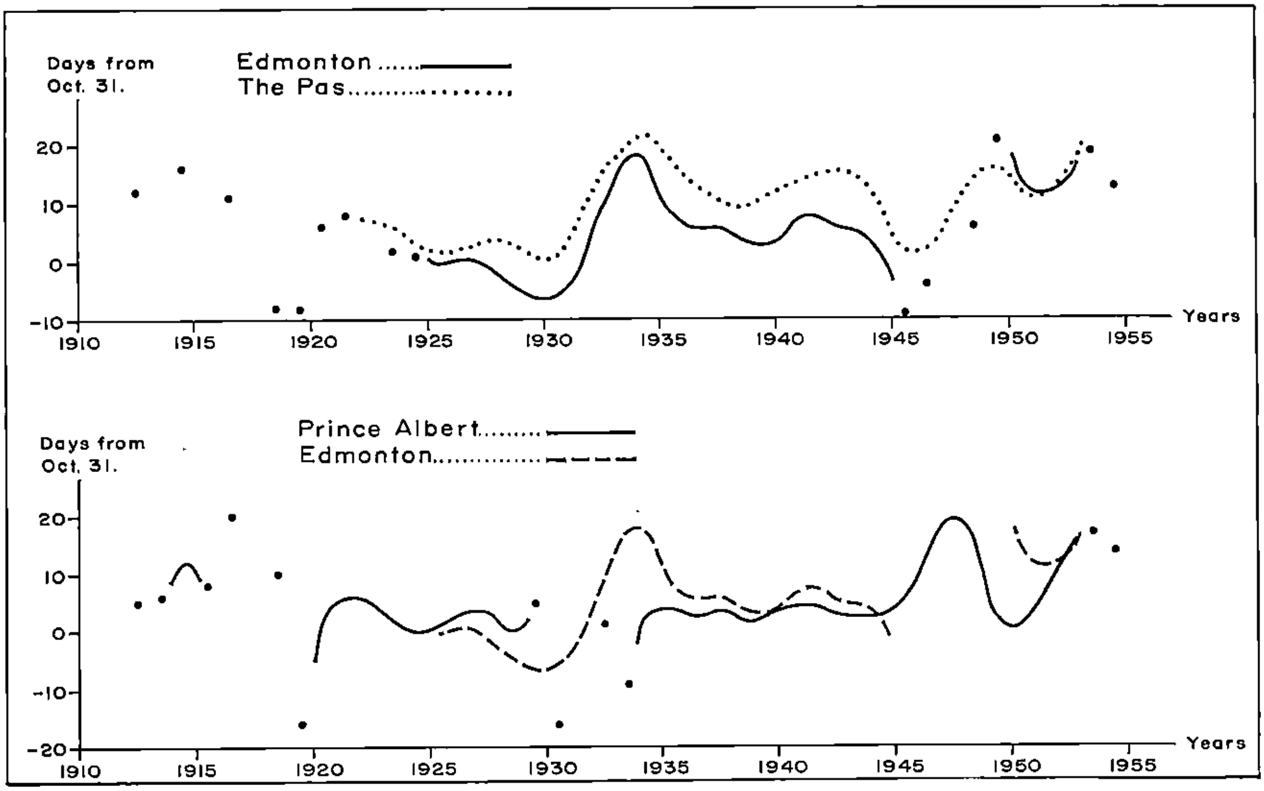


FIGURE 10. 5-point filtered series of first-ice.

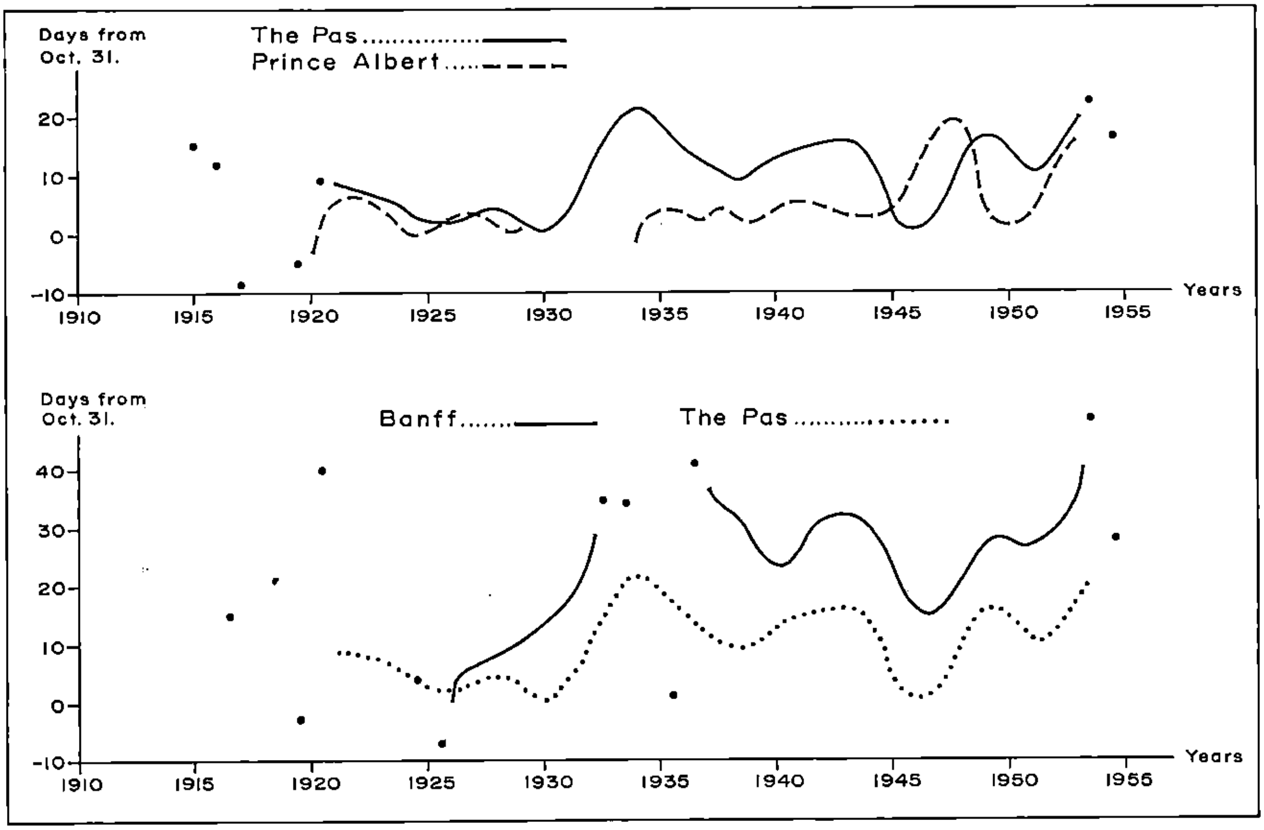


FIGURE 11. 5-point filtered series of first-ice.

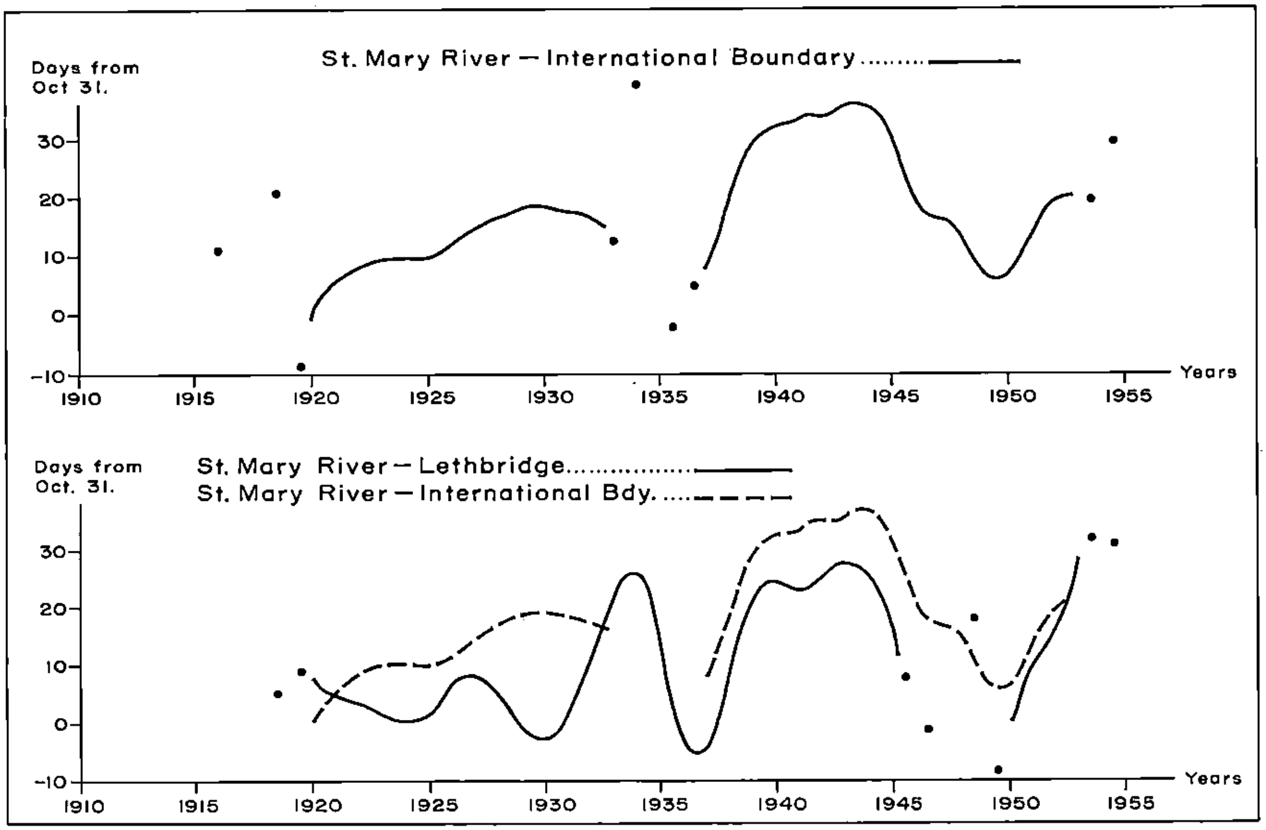


FIGURE 12. 5-point filtered series of first-ice.

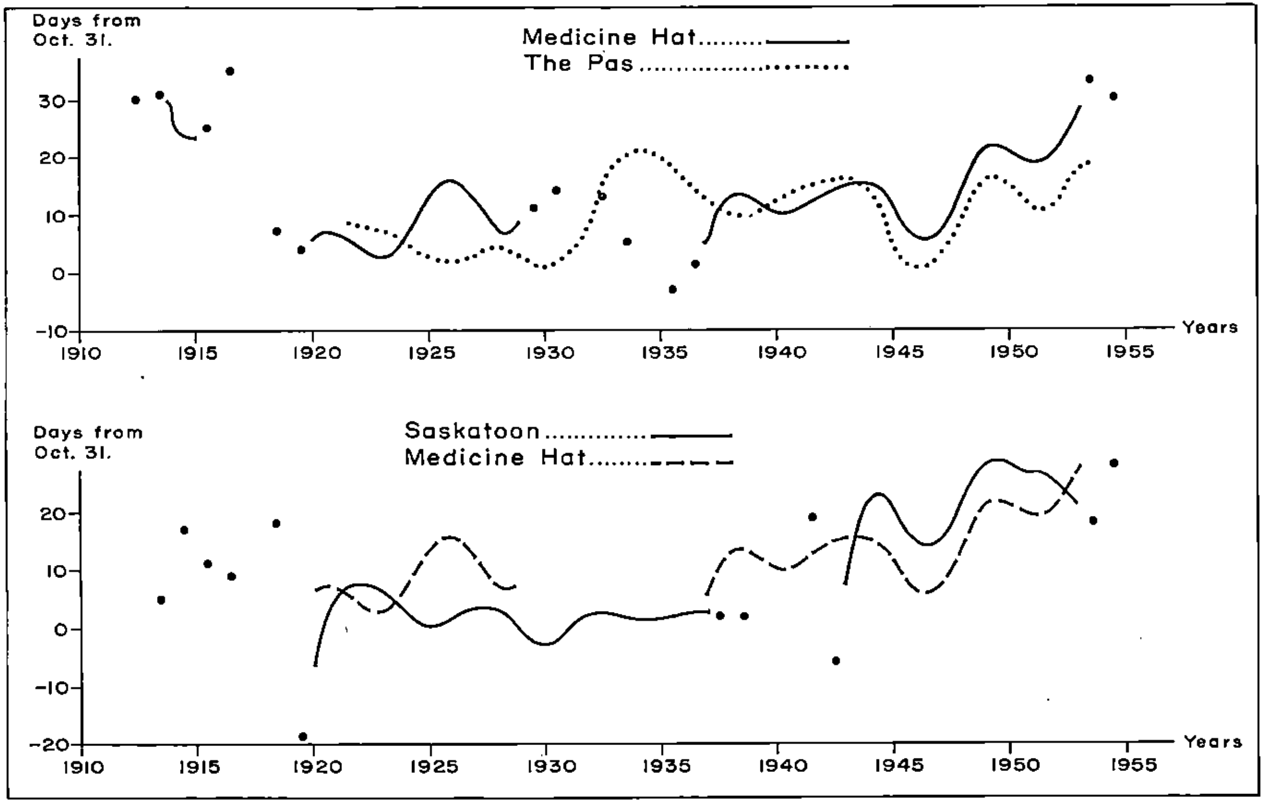


FIGURE 13. 5-point filtered series of first-ice.

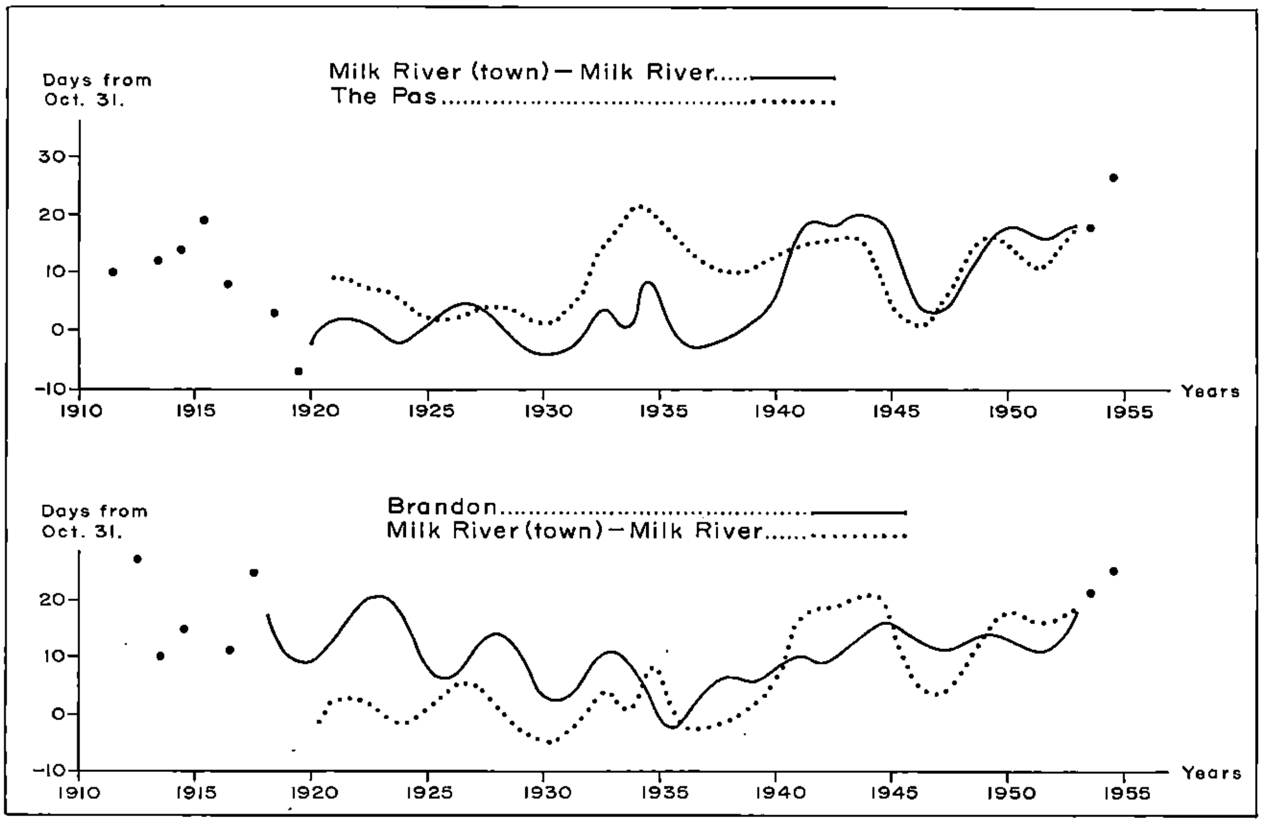


FIGURE 14. 5-point filtered series of first-ice.

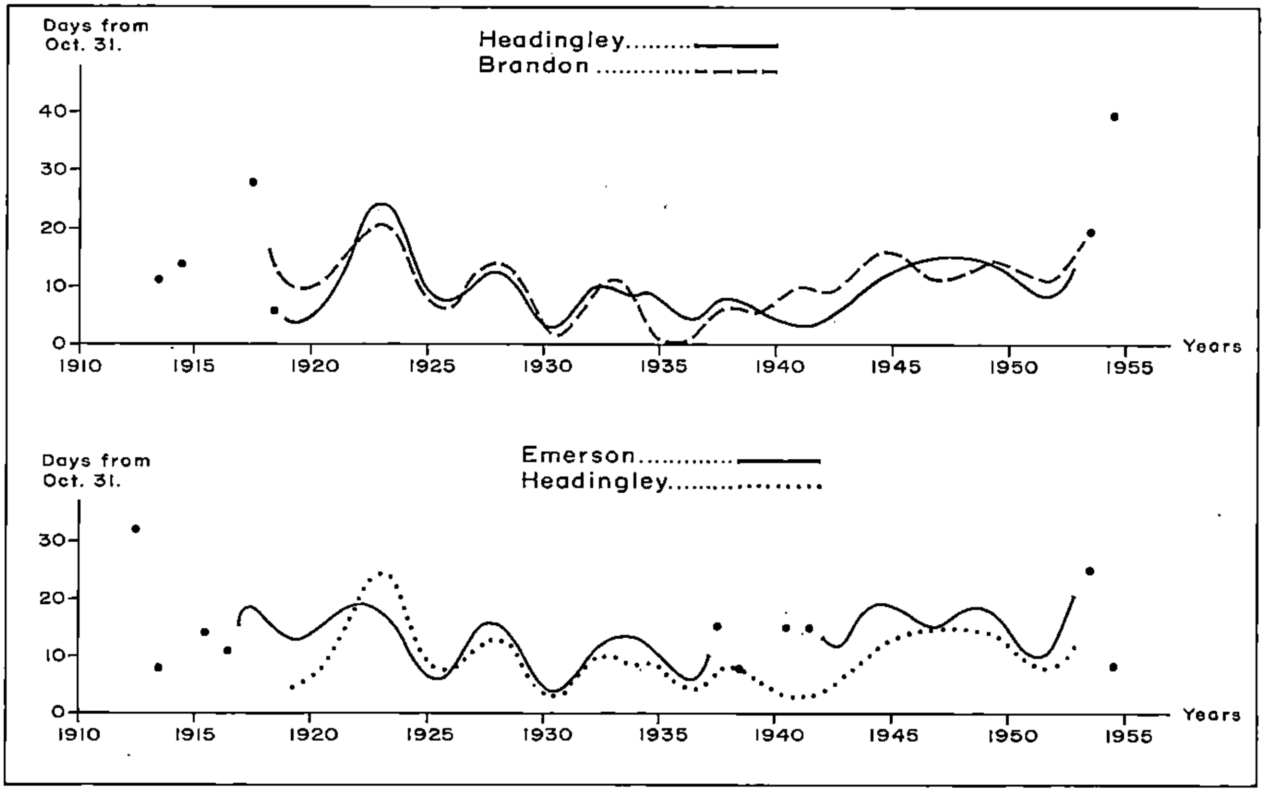


FIGURE 15. 5-point filtered series of first-ice.

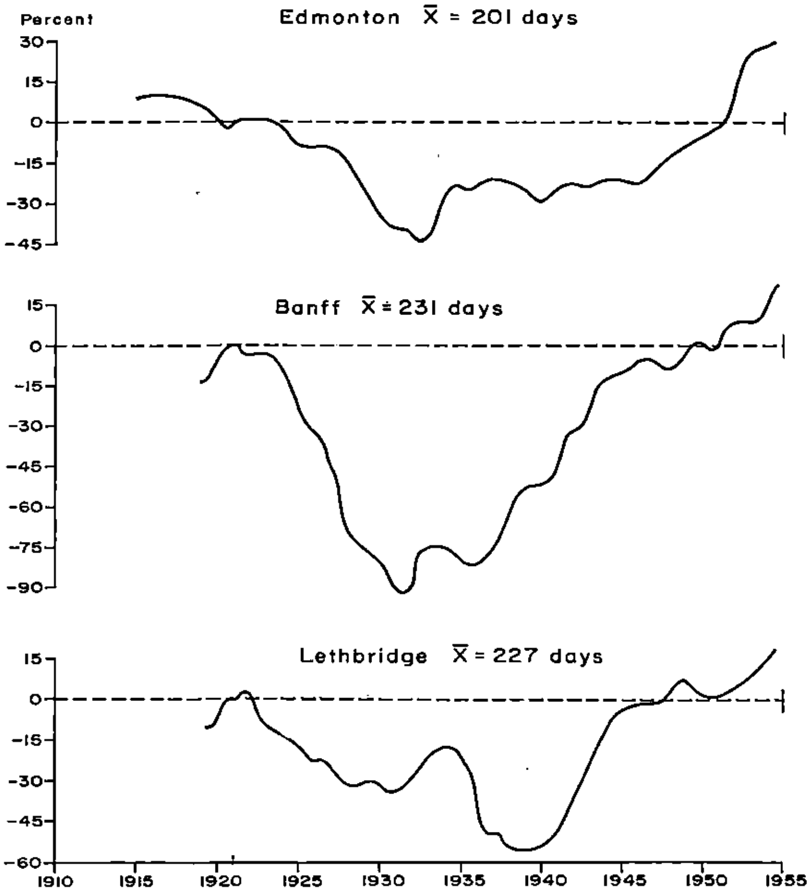


FIGURE 16. Cumulative percentual deviations from the mean ice-free season $(\overline{X})$, 1921 to 1950.

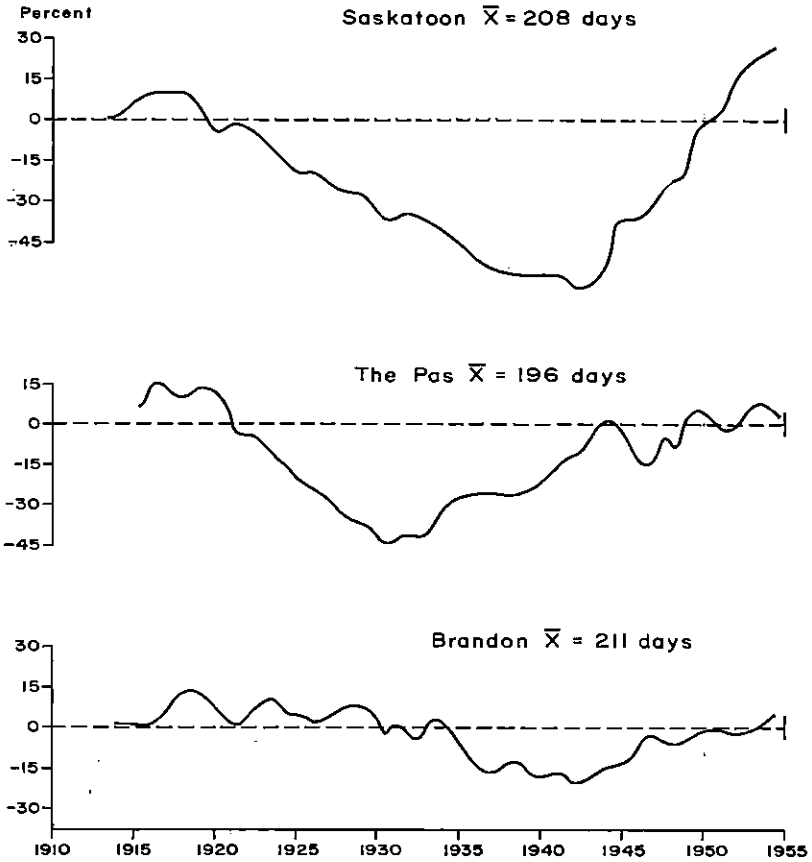
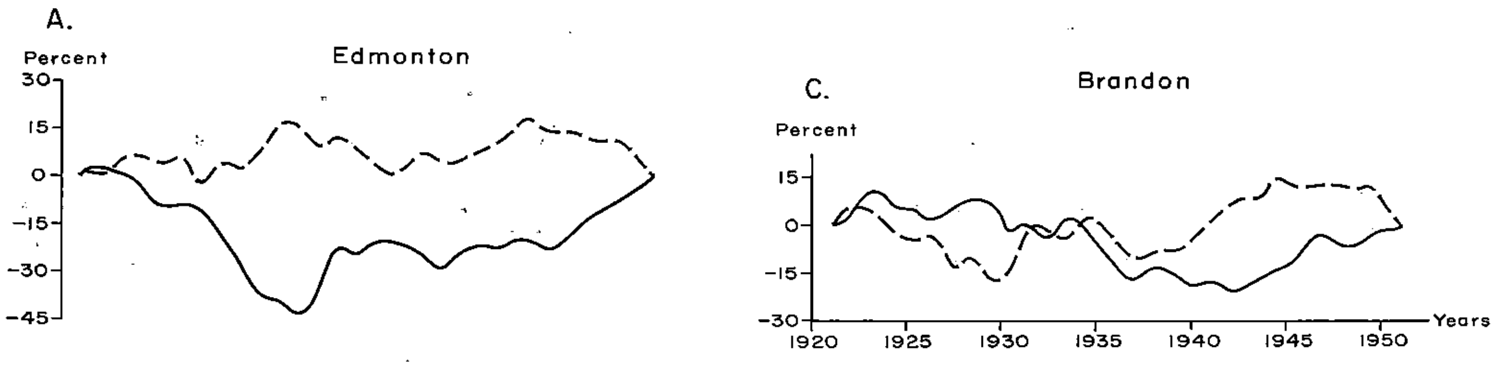
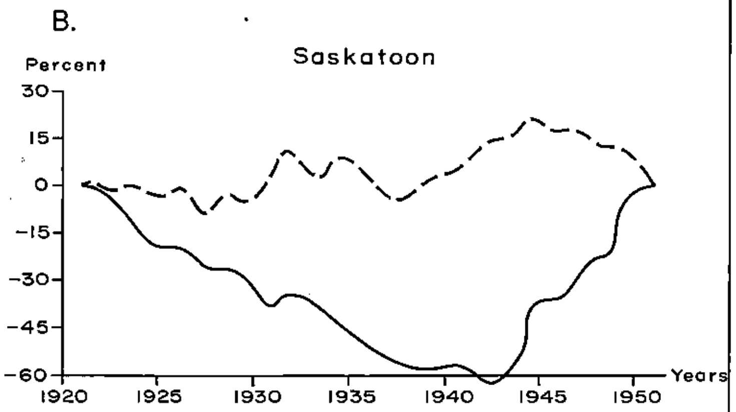


FIGURE 17. Cumulative percentual deviations from the mean ice-free season $(\overline{X})$, 1921 to 1950.





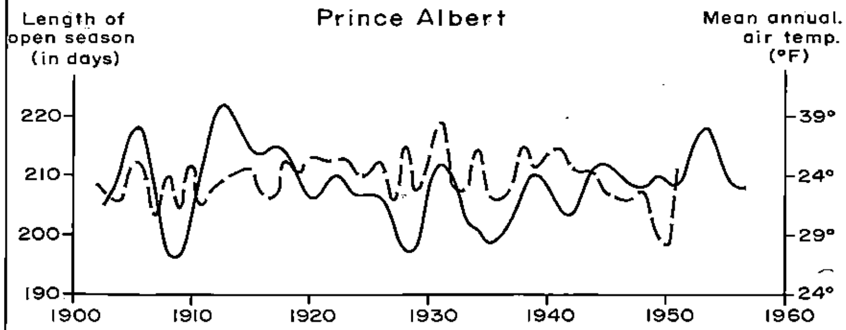


FIGURE 18. A comparison of the cumulative percentual deviations from the mean ice-free season (solid line) and from the mean annual air-temperature (dotted line), 1921 to 1950.

FIGURE 19. A comparison of open season (solid line), and mean annual air-temperature (dotted line).

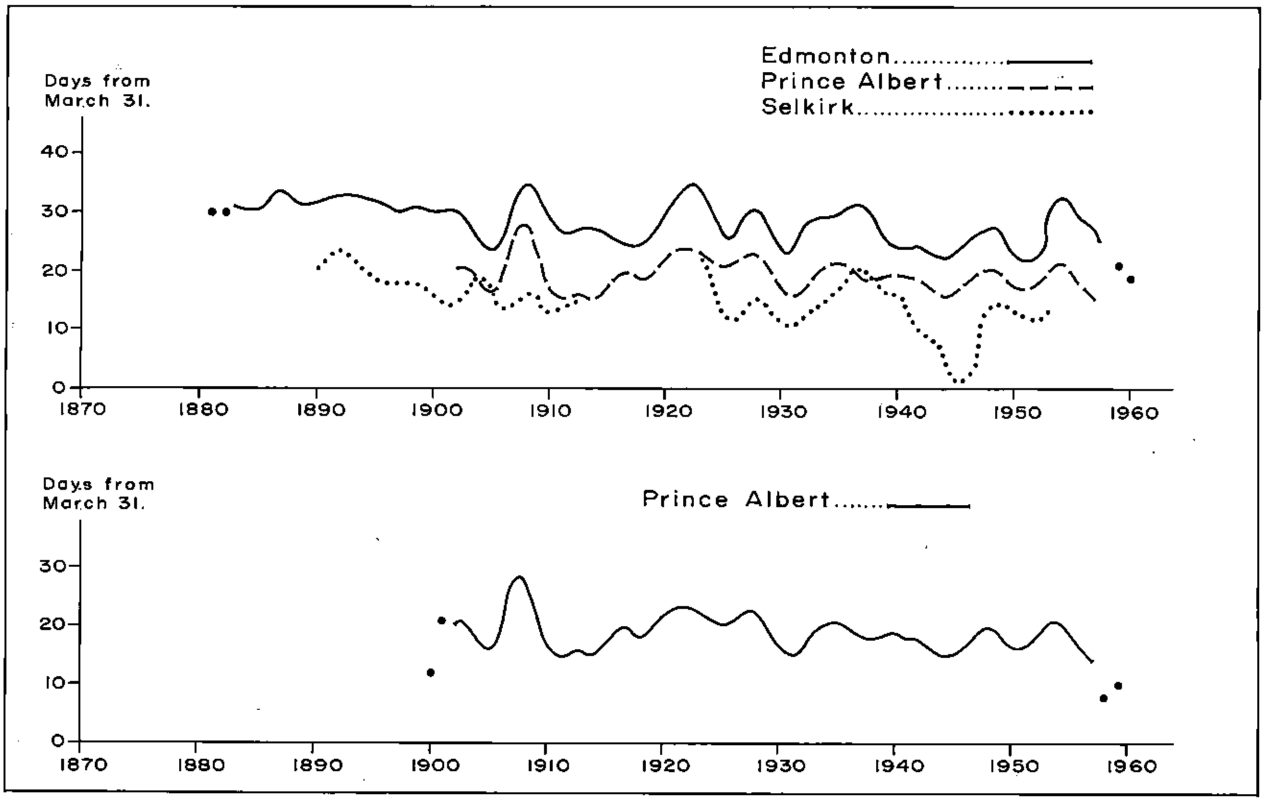


FIGURE 20. 5-point filtered series of break-up.

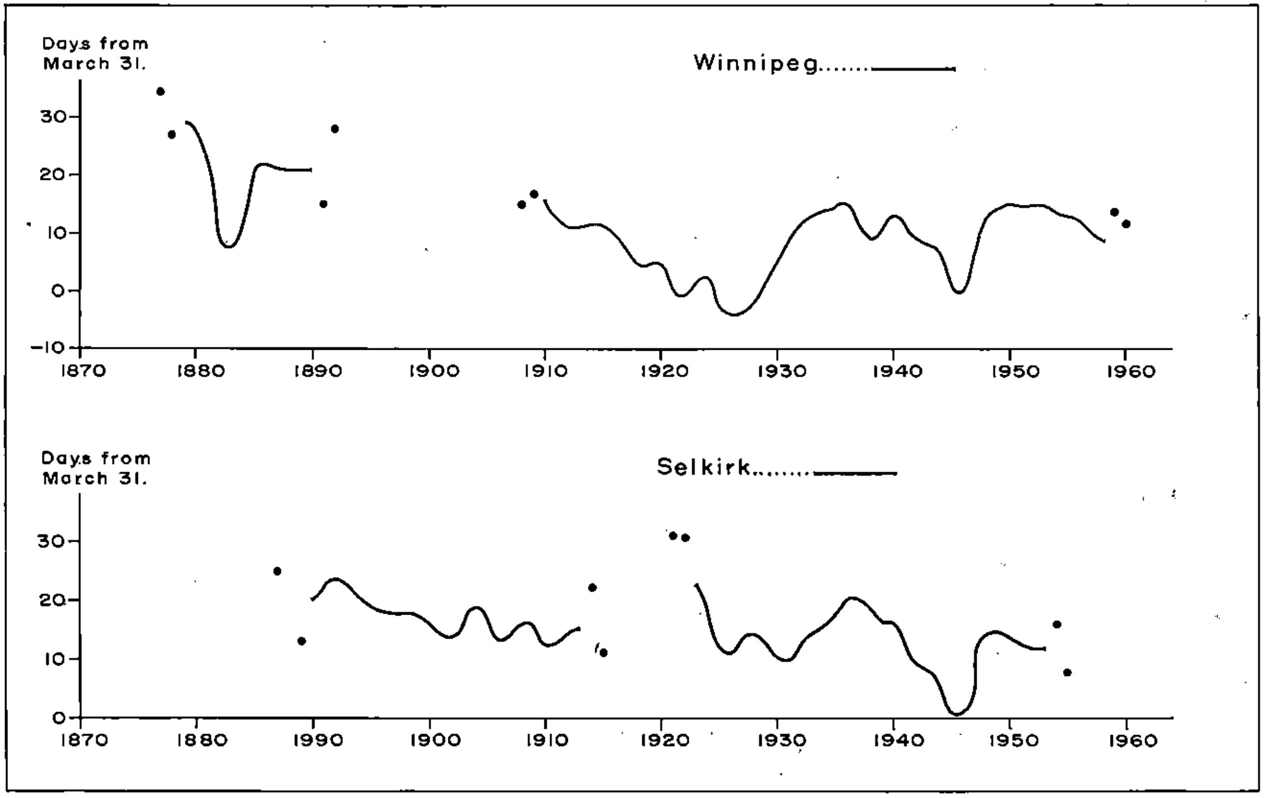


FIGURE 21. 5-point filtered series of break-up.

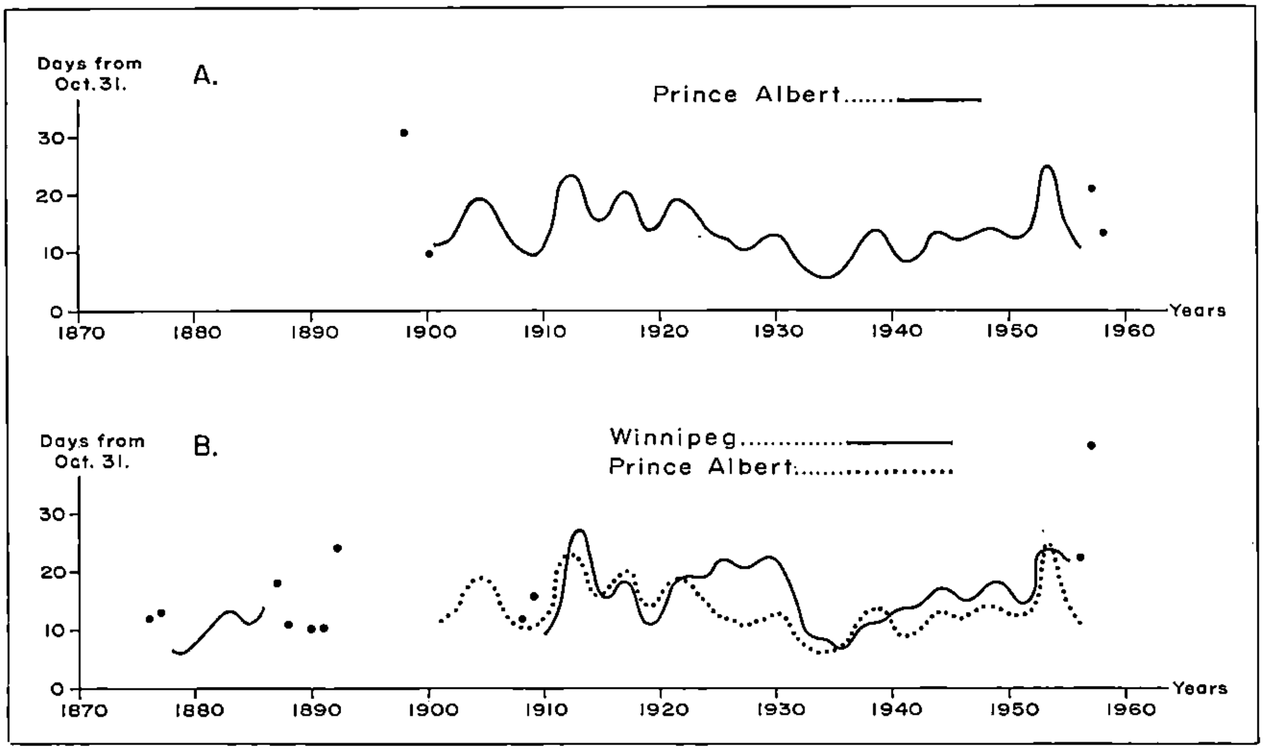


FIGURE 22. 5-point filtered series of freeze-up.

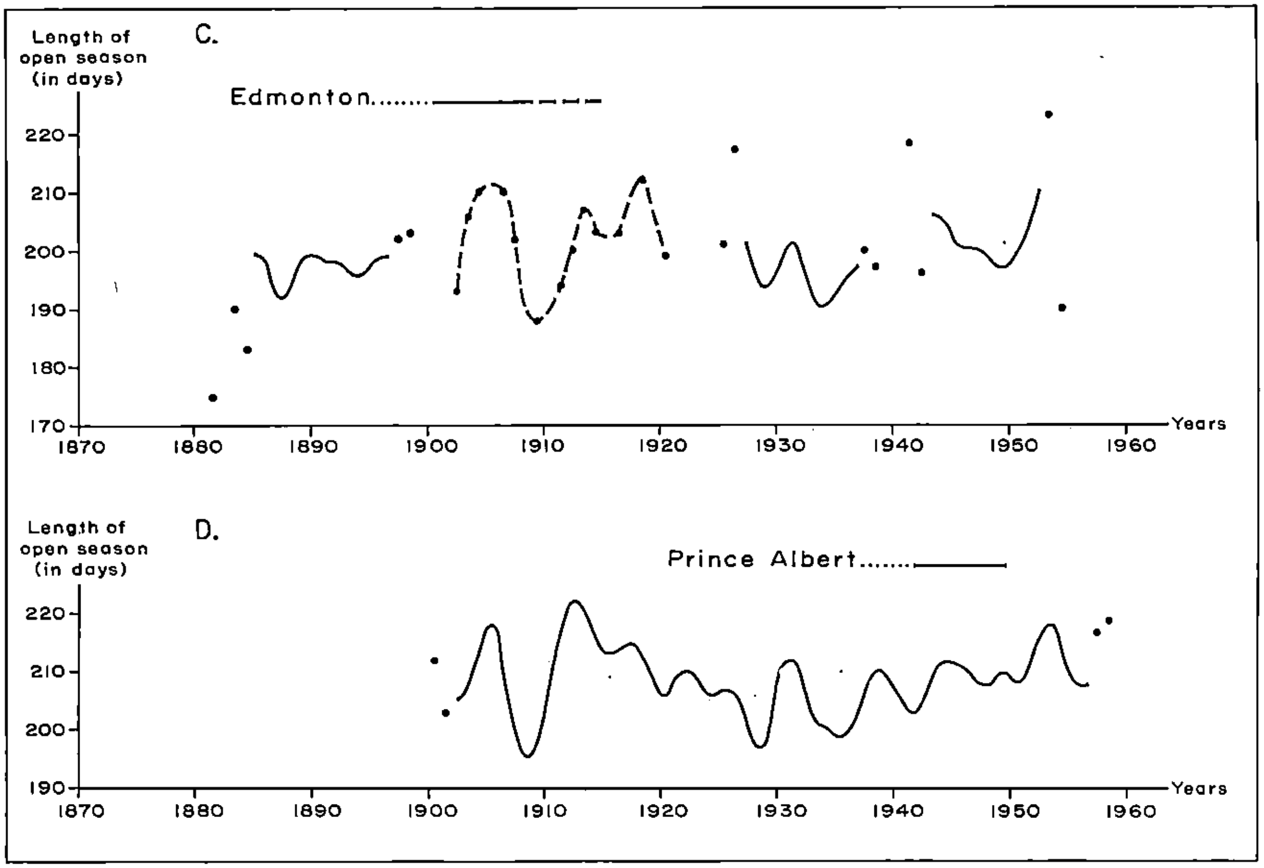


FIGURE 23. 5-point filtered series of freeze-up.

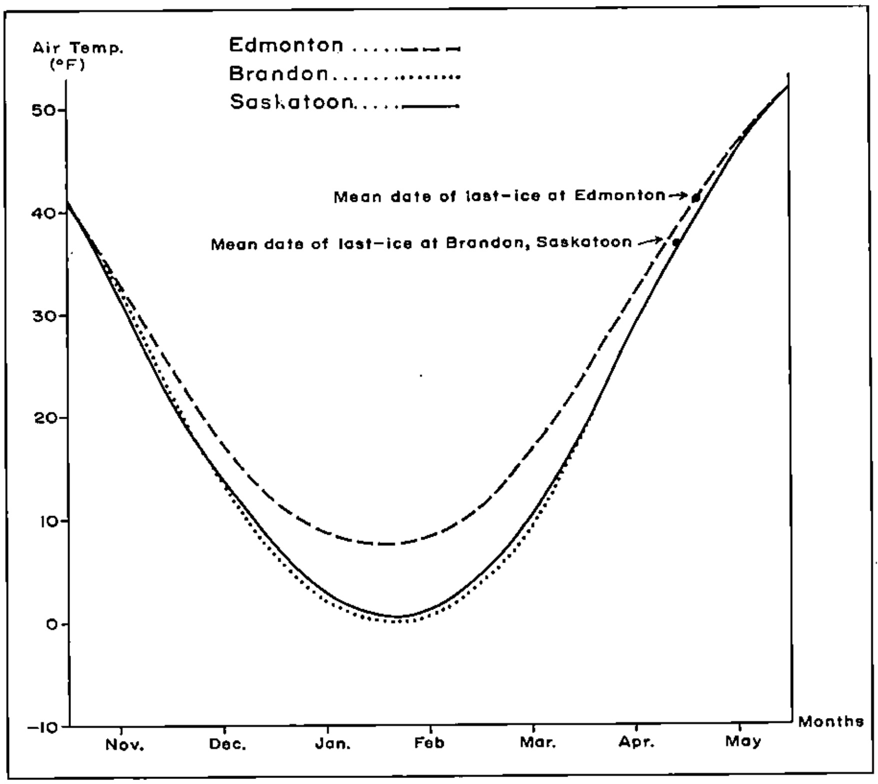


FIGURE 24. Winter air-temperature regimes and mean dates of last-ice, 1921 to 1950.

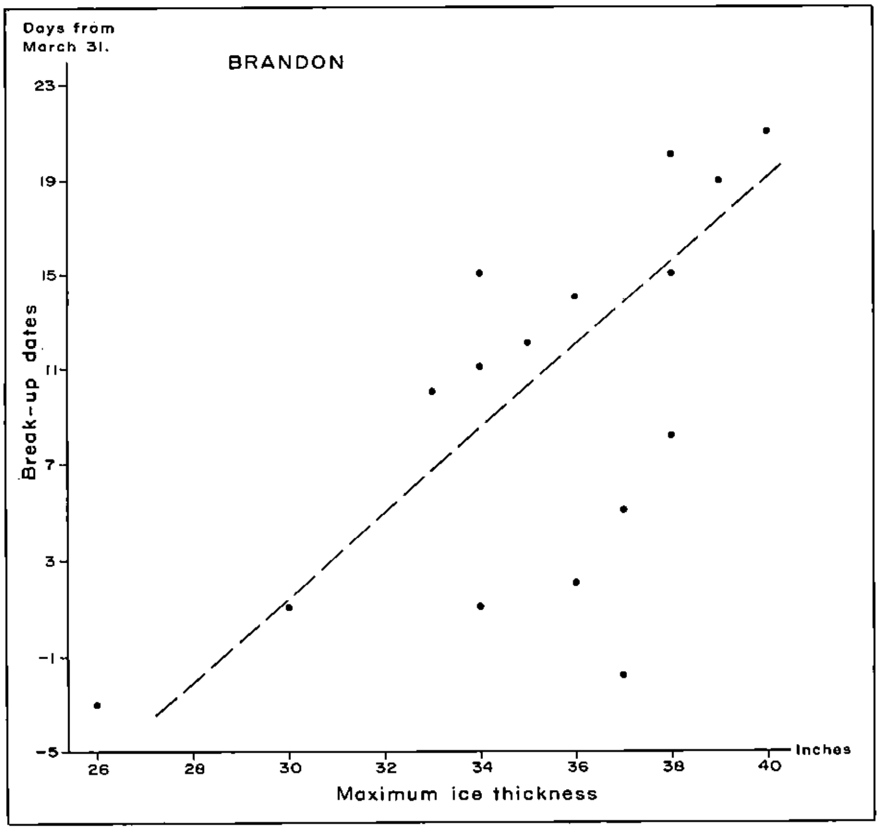


FIGURE 25. Comparison of maximum ice-thicknesses and break-up dates on the Assiniboine River, 1943 to 1958.

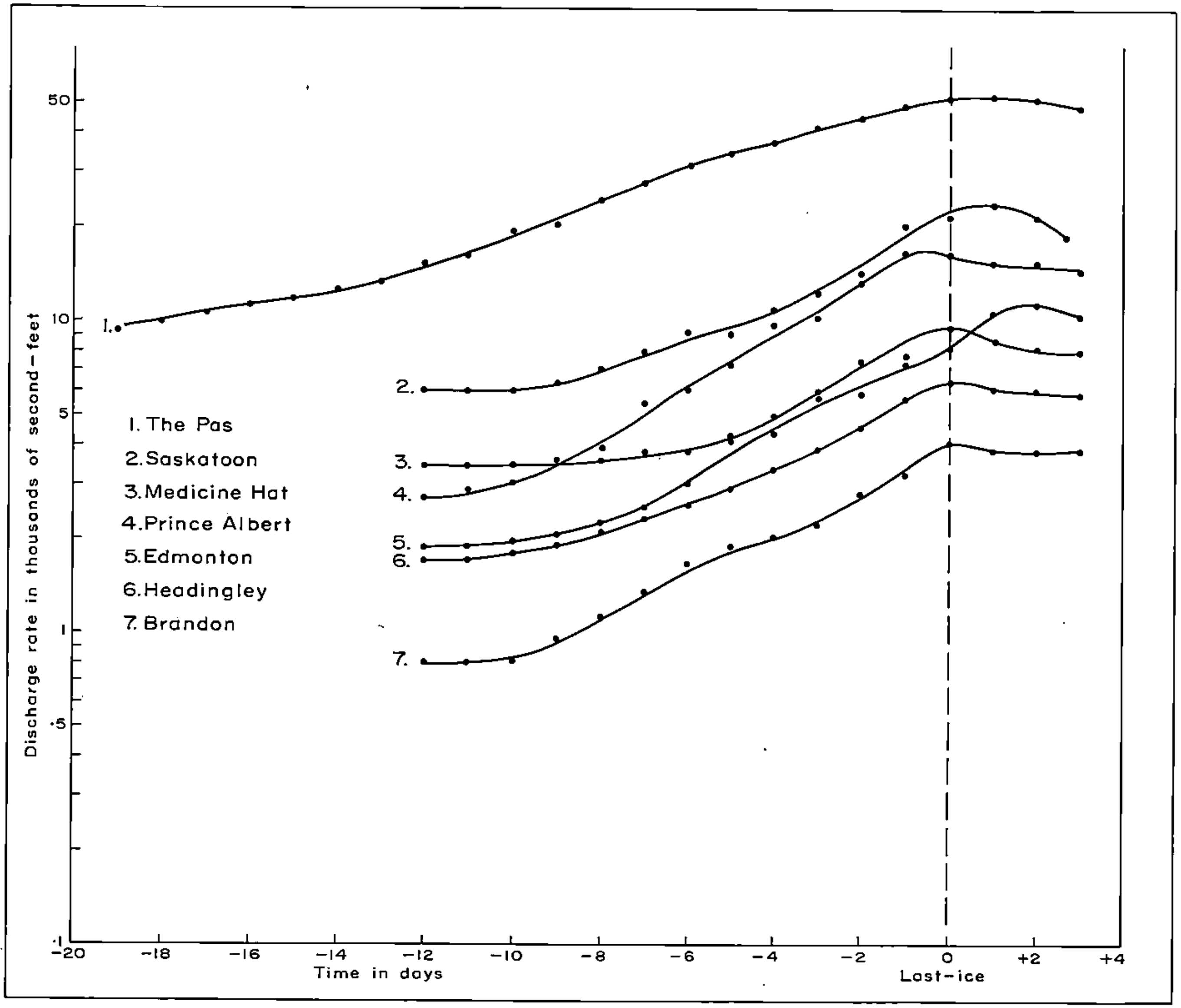


FIGURE 26. Hydrograph of mean discharge rates preceding and following last-ice dates, 1921 to 1950.

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