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GEOGRAPHICAL PAPER No. 34

River-ice Conditions in the Nelson River Drainage System

D. K. MacKay

GEOGRAPHICAL BRANCH
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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 more than a decade. In addition the Branch has developed a program of glaciology during this period.

This paper is related to both of these programs. It forms part of a study of ice conditions in the Canadian Prairies section of the Nelson River drainage system. It is a statistical treatment of break-up and freeze-up data in which hydrological and meteorological observations are related to river-ice conditions. The areal variability and rate of progress of ice formation and disintegration are analysed and mapped.

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RIVER-ICE CONDITIONS IN THE NELSON RIVER DRAINAGE SYSTEM

ABSTRACT: Hydrological and meteorological observations related to ice conditions on rivers in the Nelson drainage system are compared statistically to determine the measure of agreement between paired sets of data. Results show a high degree of positive correlation; mean differences are limited in magnitude.

Dates of first-ice and last-ice affecting discharge are used to map the areal variability of both ice formation and ice disintegration; maps of mean dates for 10-year periods and the entire period 1921-1950 are included in this paper. In addition, maps illustrating the mean length of the ice-free season as well as the standard deviations of first-ice and last-ice are incorporated in the study.

The progress of ice formation and ice disintegration was checked latitudinally and along the major tributaries of the Nelson River using the Wilcoxon matched-pairs signed-ranks test. Results indicate that first appearance of ice affecting discharge generally follows the expected north-to-south pattern; no systematic progression along tributaries in either an upstream or a downstream direction is apparent from test results. On each major tributary tested the ice-cover disintegration begins at some point on the upper reaches and progresses in a downstream direction. Latitudinal progess follows the expected south-to-north pattern with one obvious exception, the southeasterly-flowing portion of the Assiniboine River opposes the established trend.

RESUME: L'auteur compare, avec l'aide de la statistique, les observations hydrologiques et météorologiques et l'état des glaces sur les rivières du bassin hydrographique de la rivière Nelson. Il espère ainsi déterminer le degré de concordance qui existe entre des séries appariées de données. Les résultats démontrent que le degré de concordance positive est élevé tandis que les écarts moyens ont une valeur restreinte.

Pour mettre en plan la variabilité distributive de la formation et de la désintégration de la glace, l'auteur se sert des dates de la première et de la dernière glace qui influent sur le débit des cours d'eau; l'étude renferme des cartes qui indiquent les dates moyennes par périodes de 10 ans et pour l'ensemble des années 1921-1950. D'autres cartes illustrent la longueur moyenne de la saison durant laquelle les rivières sont libres de glace de même que la longueur normale de la saison qui s'étend de la première à la dernière glace.

Pour vérifier la marche de la formation et de la désintégration de la glace sur les principaux affluents de la rivière Nelson, tant en largeur qu'en longueur, l'auteur utilise la méthode de Wilcoxon. Les résultats obtenus permettent de conclure que la première glace qui influe sur le débit se forme en général dans la direction nord-sud prévue. Ils ne montrent aucune avance méthodique de la glace le long des affluents, soit vers l'amont soit vers l'aval. Cependant, les essais ont révélé que, sur chaque grand affluent, la désintégration de la glace commence à un endroit donné du cours supérieur et progresse vers l'aval. Dans le sens de la largeur, la désintégration de la glace suit une direction générale nord-sud prévue, mais tel n'est pas le cas dans le tronçon où la rivière Assiniboine coule en direction du sud-est.

INTRODUCTION

The Nelson River and its tributaries form one of the great drainage basins of North America with an area of approximately 414,000 square miles. Riverine arteries stretch eastward and northward from the headwaters of the Bow River in the Rocky Mountains to the mouth of the Nelson River in Hudson Bay, a distance of 1,740 miles. One branch from Lake Winnipeg runs east 450 miles to the Steep Rock area of Ontario, while the Red River stretches more than 500 miles south to its headwaters in North Dakota. The basin extremities are bounded on the west by the Great Rocky Mountain Divide, on the north by the Mackenzie and Churchill drainage, on the east by the Hudson Bay drainage system and the St. Lawrence drainage, and on the south by the Mississippi River basin.

In Canada, the Nelson River system drains approximately 375,550 square miles; this area includes most of the valuable agricultural land in the Prairie Provinces. The southern Canadian Prairies, however, are not wholly drained by the Nelson River system (Figure 1), for the Mississippi River system drains 22,155 square miles of Canadian territory.* The Canadian portions of the Mississippi and Nelson drainage basins bounded by the International Boundary and the extremities of the Nelson basin form the focus of this study. The combined areas of these two systems, hereafter referred to as the Nelson drainage system, extend over some 397,710 square miles of Central Canada (Thomas, 1956, 1958).

In all parts of the Nelson drainage system, the climate is severe enough to cause ice conditions in rivers and lakes for a variable period of time during the winter season. Knowledge of these ice conditions is of both practical and theoretical importance to individuals and groups in such fields as geography, agriculture, forestry, hydrologic engineering, and meteorology.

Objectives

The major objectives of this study are as follows:

(1) to correlate two kinds of data, (a) hydrologic data of ice conditions affecting discharge (Water Resources Papers, 1912-) and (b) historical records of freeze-up and break-up recorded by various individuals and organizations on a non-professional basis;

(2) to extend freeze-up and break-up records and to increase the coverage in certain areas;

(3) to determine the areal progress of river ice-formation and ice disintegration in the Nelson drainage system; and

(4) to examine the progress of ice formation and ice disintegration on individual tributaries of the Nelson River.

Definitions

Some expressions used in this paper have different connotations. To avoid ambiguities, these expressions are defined below in the specific sense in which they apply to this study. Meanings of terms that are related to hydrologic data are those of the Water Resources Papers published by the Department of Northern Affairs and National Resources. The terms are listed alphabetically:

"between variability": - the variability between two series of observations

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

"drainage system":- the drainage within an area; it involves more than one river drainage

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*Local and inland drainage in the Cypress Hills region of southern Alberta and Saskatchewan are included in the 22,155 square miles.

basin

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

"integrative climatic element":- one which results from a combination of simple climatic elements

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

"river drainage basin":- a region bounded by other basins; it includes the whole of the catchment area

"river system":- the river, its tributaries, and collecting basins

"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 over a given period of time

"within variability":- variability within a series of observations rather than between two series of observations

Notation

The notation used in this paper is listed below.

T	test value of the Wilcoxon matched-pairs signed-ranks test
$T_{.05}$, $T_{.01}$	5 per cent and 1 per cent significance levels for the Wilcoxon matched-pairs signed-ranks test
z	Fisher's "z" transformation, i.e. $z \approx 1.15 \log_{10} \frac{(1+r)}{(1-r)}$
r	sample correlation coefficient
$r_{.05}$, $r_{.01}$	5 per cent and 1 per cent significance levels for the sample correlation coefficient
E	index of predictive efficiency, i.e., $E = 100$ per cent $(1-K)$ where $K=\sqrt{1-r^2}$, the coefficient of alienation
X_i	independent variable
Y_i	dependent variable

FREEZE-UP AND BREAK-UP DATA

A lack of data has placed limitations on the study of freeze-up and break-up in many river basins. This lack is particularly noticeable along rivers which have not been utilized as primary arteries of transportation and communication. On the other hand, where rivers have been used as waterways and where the open-water season has been of some importance to the welfare of communities, a considerable amount of freeze-up and break-up data has been recorded. For example, fairly extensive records of freeze-up and break-up are available for a waterway as important as the Mackenzie River but the major tributaries of the Nelson River have not been widely used for navigation and, consequently, do not have the same measure of data coverage as the Mackenzie.

Many of the rivers and streams that form part of the vast Nelson River system flow through the major populated, productive regions of the Canadian Prairies. Early settlement in these regions did not depend on the use of rivers as waterways. With land routes forming the primary means of communication and transportation, settlers showed little interest in recording dates of freeze-up and break-up. As a result, few long-term records or, for that matter, few records of any length, are presently available for the examination of these phenomena in this river system. In fact, within the entire Canadian area of the basin, published reports list only 20 stations recording formal dates of freeze-up and break-up. Records from these stations vary considerably in length, cover different periods, and lack uniformity in definitions of freeze-up and break-up. This collection of data, as it stands, is not comprehensive enough to warrant an examination of the areal aspects of these phenomena in the Nelson drainage system, and data must be derived or extracted from additional sources.

Hydrologic Data

Hydrologic data (Canada, Department of Northern Affairs & National Resources, Water Resources Papers, 1912 -) dealing with ice conditions in rivers and streams may be used to chart the progress of freezing and thawing of rivers and to broaden the general understanding of these processes. Ice conditions are reported at gauging stations when the relation of the elevation of the water surface to the discharge is affected by ice. This stage-discharge relation can be affected by various types of ice and varying amounts of ice cover. An increase in stage caused by the formation of ice or the grounding of ice blocks in the stream channel on site or in the sections downstream controlling the stage-discharge relation may result in ice conditions being reported. The control sections are formed by natural or in some cases, artificial weirs which may act as barriers to the free passage of ice blocks. If the passage of ice is obstructed in the controlling section, or sections, a change in the stage will occur at the gauging site.

The extent of hydrologic data related to ice conditions affecting discharge in the Nelson, Mississippi, and Athabasca River drainage basins is indicated in Tables I and II. The distribution of stations with 10 or more years of first-ice and last-ice dates is noted in Figures 1 and 2, respectively. In some instances locational dots represent more than one gauging station. Athabasca River records were used as aids in mapping mean dates of ice conditions.

TABLE I

FIRST-ICE RECORDS

Drainage Basin	Stations with: 10 or more Years of Record	20 or more Years of Record	30 or more Years of Record
Nelson River	50	29	18
Mississippi River	4	1	1
Athabasca River	3	2	0
Total	57	32	19

TABLE II

LAST-ICE RECORDS

Drainage Basin	Stations with: 10 or more Years of Record	20 or more Years of Record	30 or more Years of Record
Nelson River	79	44	24
Mississippi River	28	12	5
Athabasca River	3	2	0
Total	110	58	29

At some point early in the winter season, formation of river ice will cause the stage-discharge relation curve to deviate from its normal path. In hydrologic records, the point of deviation is recorded as the date of first-ice affecting discharge and no subsequent change in physical conditions can alter the date of occurrence. Unlike first-ice dates, freeze-up dates are subject to change if climatic or hydrologic conditions following the initial formation of ice cause the ice to disappear and reform at a later date.

In the spring, the disintegration of the main ice cover at the gauging station may or may not result in the final date of ice conditions affecting discharge being recorded. Jamming of ice at some point downstream may cause the water level to rise to the extent that ice conditions affecting discharge may again be reported by the observing officer. In contrast to dates of last-ice, break-up dates are not susceptible to change if the phenomenon is defined as the initial movement of ice downstream in the spring season (Mackay, 1961, p. 1121). If an alternative definition, which implies complete clearance of ice, is used to define break-up, then a movement of isolated ice pans from upstream past the observation site could cause a change in the date of break-up.

From previous statements, it seems clear that all four sets of data are composed of complex variables lacking precise definition. It is also clear that initial and final stages of ice conditions affecting discharge are related fundamentally to freeze-up and break-up. Any combination of climatological elements that creates optimum conditions for first-ice will create optimum conditions for freeze-up if those conditions are sustained for a reasonable length of time. A similar statement may be made regarding the relationship between break-up and last-ice. If sets of data are paired in sense, and a one-to-one time relationship is set up between the observations, the differences may be tested for their significance using appropriate statistical methods.

Data Available for Comparisons

Four locations in the Saskatchewan tributary basin and one location in the Assiniboine tributary basin have corresponding records of ice conditions which may be extracted from meteorologic and hydrologic reports. It should be emphasized that the locations are general ones and that the observation sites may or may not be the same for each type of data. Possible differences in record due to the site factor are not considered here; the sites are assumed to be identical for testing purposes. The number of years in which corresponding observations from paired sets of data are recorded at each location is listed in Table III.

TABLE III

NUMBER OF PAIRS OF CORRESPONDING OBSERVATIONS

Location	River	Comparable Years of Record Break-up & Last-ice	Freeze-up & First-ice
Edmonton	Saskatchewan	35	27
Prince Albert	Saskatchewan	38	37
Saskatoon	Saskatchewan	14	None
The Pas	Saskatchewan	19	None
Brandon	Assiniboine	13	12

In southern parts of the Nelson basin, no corresponding observations of ice conditions recorded at specific locations other than Brandon are available from published sources of data. In the interests of increased coverage, data from three locations in close proximity to each other are examined to ascertain the extent of existing relationships. Headingley, on the Assiniboine River, lies 12 miles west of the junction of the Assiniboine and Red Rivers at Winnipeg; Selkirk, on the Red River, is situated 23 miles downstream from Winnipeg. Dates of first-ice and last-ice at Headingley are compared with dates of freeze-up and break-up at Winnipeg; break-up at Selkirk is compared with break-up at Winnipeg and with last-ice at Headingley.

COMPARISON OF DATA

A. Break-up and Last-ice

Means and mean differences of break-up and of last-ice are listed in Tables IV and V for 10-year periods and for total length of the periods covered by the data. Break-up at Edmonton, Prince Albert, and Winnipeg refers to dates on which the water was clear of ice; break-up at Saskatoon, Selkirk, and The Pas refers to dates of initial movement of ice downstream. Break-up at Brandon (i) refers to initial ice movement, and Brandon (ii) refers to complete clearance of ice.

There are 106 matched pairs of observations in the sets of data recorded at the four locations in the Saskatchewan tributary basin. The over all average indicates that break-up occurs 2 days earlier than last-ice. The largest discrepancy between any matched pair of observations is 20 days. This difference

TABLE IV

MEANS AND MEAN DIFFERENCES BETWEEN DATES OF BREAK-UP AND LAST-ICE

Location	River	Period	Mean Dates Break-up	 Last-ice	Omissions in Period	Mean Difference in Days	Earlier Phenomena
Edmonton	N. Saskatchewan	1916-25	Apr. 20	Apr. 23	2	3	Break-up
		1926-35	" 17	" 20	0	3	" "
		1936-45	" 14	" 16	2	2	" "
		1946-55	" 14	" 11	2	3	Last-ice
		1915-55	" 16	" 17	6	1	Break-up
Prince Albert	N. Saskatchewan	1916-25	Apr. 21	Apr. 24	2	3	Break-up
		1926-35	" 20	" 20	1	0	" "
		1936-45	" 18	" 20	0	2	" "
		1946-55	" 18	" 21	0	3	" "
		1915-55	" 19	" 21	3	2	" "
Saskatoon	S. Saskatchewan	1946-55	Apr. 10	Apr. 13	0	3	Break-up
		1942-55	" 9	" 12	0	3	" "
The Pas	Saskatchewan	1936-45	Apr. 29	Apr. 28	1	1	Last-ice
		1946-55	" 24	" 26	0	2	" "
		1936-55	" 26	" 27	1	1	" "
Brandon (i)	Assiniboine	1946-55	Apr. 12	Apr. 13	0	1	Break-up
		1943-55	" 10	" 13	0	3	" "
Brandon (ii)	Assiniboine	1946-55	Apr. 19	Apr. 13	0	6	Last-ice
		1943-55	" 18	" 13	0	5	" "

TABLE V

MEANS AND MEAN DIFFERENCES BETWEEN DATES OF BREAK-UP AND LAST-ICE WINNIPEG, HEADINGLEY, AND SELKIRK

WINNIPEG Break-up	HEADINGLEY Last-ice	Years	Omissions	Mean Differences in Days	Earlier Phenomena
Apr. 3	Apr. 18	1916-25	1	15	Break-up
" 6	" 18	1926-35	0	12	" "
" 10	" 16	1936-45	0	6	" "
" 12	" 15	1946-55	0	3	" "
" 8	" 16	Total Record		8	" "

SELKIRK Break-up	HEADINGLEY Last-ice	Years	Omissions	Mean Differences in Days	Earlier Phenomena
Apr. 14	Apr. 18	1926-35	0	4	Break-up
" 14	" 16	1936-45	0	2	" "
" 11	" 15	1946-55	0	4	" "
" 14	" 16	Total Record		2	" "

SELKIRK Break-up	WINNIPEG Break-up	Years	Omissions	Mean Differences in Days	Earlier Phenomena
Apr. 14	Apr. 6	1926-35	0	8	N/A
" 14	" 6	1936-45	0	4	"
" 11	" 12	1946-55	0	1	"
" 14	" 8	Total Record		6	"

was recorded in observations taken at Saskatoon in 1946. In the Assiniboine-Red tributary basin, the computation of a grand mean difference is meaningless because of the distances separating observation sites. The greatest difference between paired observation was 32 days which separated break-up at Winnipeg and last-ice at Headingley in 1922.

Mean differences may be greatly distorted by extreme values. Large differences between paired observations can arise from a combination of physical factors or, possibly, from an error in recording or transcribing the day or month in which one or the other of the observations took place. The occurrence of such an error could conceivably result in a nil mean difference if the direction or sign of the difference caused by the error is opposed to the norm. The Wilcoxon matched-pairs signed-ranks test (Siegel, 1956, pp. 78-83) was used to avoid such problems.

The Wilcoxon matched-pairs signed-ranks test is non-parametric; unlike standard statistical tests of rank, it determines the significance of the magnitude as well as the direction of the difference between paired sets of data. However, this test is most effective when it is used to compare sets of data of a fairly high degree of known accuracy; with data that may include the occasional error of some magnitude; the sensitivity of the test is such that a reasonable approach must be adopted in interpreting the results. The significance of the differences between records of break-up and last-ice are listed in Table VI.

TABLE VI

VALUES OF THE WILCOXON MATCHED-PAIRS SIGNED-RANKS TEST

Location	N	T	$T_{.01}$	$T_{.05}$	Significance of Differences
Edmonton (a)	30	-1.40	2.58	1.96	Not significant
(b)	23	42	55	73	Sig. at 1 per cent level
Prince Albert	36	-4.61	2.58	1.96	Sig. at 1 per cent level
The Pas	19	62	38	46	Not significant
Saskatoon	12	12	10	14	Sig. at 5 per cent level
Brandon (i)	10	11	3	8	Not significant
Brandon (ii)	12	2.5	7	14	Sig. at 1 per cent level

The null hypothesis that no difference exists between break-up and last-ice can be accepted at Edmonton (a), Brandon (i), and The Pas. The rejection of the null hypothesis at Edmonton (b) is caused by the omission of the last 9-paired observations from the record.

In Table VI, 7 rather than 9 paired observations are omitted at Edmonton (b) because the initial step in the application of the Wilcoxon matched-pairs signed-ranks test is to drop all paired observations with equal scores (i.e. dates) from the analysis. Hence, Table VI indicates the number of pairs subjected to the test and not the number of pairs of corresponding observations in the records at each location (see Table III).

At Brandon, a change in the definition of break-up from initial movement of ice (i) to complete clearance of ice (ii) results in rejection of the null hypothesis suggesting that dates of last-ice affecting discharge at this station are more closely related in time to first dates of break-up than to second dates of break-up. Mean break-up dates corroborate these results (Table IV).

Test results of records at Saskatoon and Edmonton are border-line cases and it is best to regard these results with some reservations. This particularly applies in tests which involve limited numbers of paired observations and where those observations may incorporate errors of one kind or another.

It is obvious from testing the disparity between last-ice and break-up records that significant differences exist at some locations. However, it is also apparent from the computation of mean differences (Table IV) that the time disparity is relatively insignificant. The discrepancies between paired observations at Headingley, Winnipeg, and Selkirk were not subjected to Wilcoxon's test because of the distances separating the observation sites.

The degree of relationship between break-up and last-ice at each location was measured by the product-moment correlation coefficient. Individual values of "r" and a pooled estimate of "r" for the locations in the Saskatchewan tributary basin are listed in Table VII. The pooled estimate was derived by using Fisher's "z" transformation.

TABLE VII

VALUES OF SAMPLE CORRELATION COEFFICIENTS
(Saskatchewan Tributary Basin)

Location	r	$r_{.05}$	$r_{.01}$	Significance
Edmonton	.574	.324	.418	Sig. at 1 per cent level
Prince Albert	.905	.314	.403	Sig. at 1 per cent level
Saskatoon	.737	.497	.623	Sig. at 1 per cent level
The Pas	.929	.433	.549	Sig. at 1 per cent level
Pooled Estimate	.825	.190	.250	Sig. at 1 per cent level

The "r" values indicate that a stochastic relationship exists between break-up and last-ice in the Saskatchewan tributary basin. The measure of positive correlation is highly significant when it is considered that break-up dates recorded by various individuals and organizations at one location have differed in some years by as much as two weeks (Mackay, 1961). The general index of predictive efficiency E, is 43.5 per cent although individual values of the index run from 18.1 per cent at Edmonton to 63 per cent at The Pas. These index values indicate that the problem of estimating any particular value of one phenomenon from a given value of the other phenomenon is a difficult one.

In the Assiniboine-Red tributary basin, Brandon is the sole location with records of break-up and last-ice. Results at Brandon are in accord with the results obtained in the Saskatchewan basin. Correlations of last-ice dates with first dates of break-up (r .792), and last-ice dates with second dates of break-up (r .826) are significant at the 1 per cent level. The indices of predictive efficiency are 39 per cent and 44 per cent, respectively.

Correlations measuring relationships between records of ice disintegration from Headingley, Winnipeg, and Selkirk in the Assiniboine-Red tributary basin are placed in matrix form (Table VIII) to facilitate comparisons.

TABLE VIII

MATRIX OF SAMPLE CORRELATION COEFFICIENTS

	Headingley Last-ice	Winnipeg Break-up	Selkirk Break-up
Headingley Last-ice			
Winnipeg Break-up	.469		
Selkirk Break-up	.718	.341	

The relatively high measure of agreement between last-ice at Headingley and break-up at Selkirk as compared to the less tenuous relationship apparently existing between break-up at Winnipeg and comparable phenomena at the other locations indicates that break-up at Winnipeg is somewhat of an anomaly. This could arise from the interplay of such factors as differences in break-up criteria, transcription errors, warming effect of sewage, and so on.

Estimates of the regression of last-ice on break-up are noted on the scatter diagrams (Figures 3, 4, 5, 6 and 7) used to illustrate the relationship between the two phenomena at each location. Break-up is regarded as the independent variable because this event, in most instances, occurs prior to last-ice.

In view of the limited amount of data available for comparison purposes and the occurrence of occasional extreme differences between paired observations, the use of median values of differences seems most appropriate for purposes of adjustment, if adjustment is considered desirable or necessary. Median values of differences are as follows: 4 days at Edmonton, 2 days at Prince Albert, 2 days at Saskatoon, 2 days at The Pas, and 2 days at Brandon. The median value of the difference between break-up and last-ice for the 5 records combined is 2 days.

B. Freeze-up and First-ice

Table IX lists means and mean differences between first-ice and freeze-up for 10-year periods and the whole period of record at each station. Freeze-up at Edmonton refers to the initial formation of ice; freeze-up at Prince Albert is defined as the time the river was completely frozen over at the observation site. Freeze-up dates at Brandon are recorded for both the initial formation of ice (i) and complete freeze-over (ii).

TABLE IX

MEANS AND MEAN DIFFERENCES BETWEEN DATES OF FIRST-ICE AND OF FREEZE-UP

Location & Period	Mean Dates Freeze-up	Mean Dates First-ice	Mean Difference in Days	Omissions	Earlier Phenomena
EDMONTON					
1926-35	Nov. 2	Oct. 29	4	2	First-ice
1936-45	" 4	Nov. 4	0	2	" "
1946-55	" 3	" 13	10	3	Freeze-up
1915-55	" 3	" 4	1	14	" "
PRINCE ALBERT					
1916-25	Nov. 10	Nov. 4	6	1	First-ice
1926-35	" 14	" 1	13	1	" "
1936-45	" 9	" 4	5	1	" "
1946-55	" 17	" 12	5	1	" "
BRANDON (i)					
1946-55	Nov. 12	Nov. 15	3	1	Freeze-up
1943-55	" 9	" 15	6	1	" "
BRANDON (ii)					
1946-55	Nov. 23	Nov. 15	8	1	First-ice
1943-55	" 21	" 15	6	1	" "

At Edmonton the definition of freeze-up in use is such that this event generally occurs before first-ice affecting discharge is recorded at the gauging station. At Prince Albert, results are considerably different; mean dates indicate that first-ice is observed 7 days earlier than freeze-up as defined at that station. At Brandon, dates of first-ice affecting discharge are generally later than first freeze-up dates but earlier than second freeze-up dates. Differences in definitions of freeze-up make it unreasonable to compute an over all mean for this phenomenon, and, thus, to determine a grand mean difference between freeze-up and first-ice.

The Wilcoxon matched-pairs signed-ranks test was used to test the magnitude and direction of the difference between freeze-up and first-ice. This test indicates that no difference exists between freeze-up and first-ice at Edmonton; at Prince Albert, however, dates of first-ice are earlier than dates of freeze-up. Results at Brandon indicate that there is no difference between dates of first-ice affecting discharge and first freeze-up dates, but second freeze-up dates are significantly later than first-ice affecting discharge. Intuitively, it would seem that dates of first-ice affecting discharge and dates of freeze-up defined as first formation of ice are more comparable than dates of complete freeze-over and dates of first-ice affecting discharge. Results of Wilcoxon's test add weight to this statement despite the great 'within variability' exhibited by both sets of data at each location.

Scattergrams illustrating the relationship between freeze-up and first-ice at Edmonton, Prince Albert, and Brandon are included in the text as Figures 8, 9, and 10. Plotted values that deviate strongly from the mean of either variable have been noted on the scattergrams according to the year of their occurrence. At Edmonton (Figure 8) it is quite obvious that a very few values play a major role in markedly lowering the degree of positive correlation. In those years in which a marked difference between the dates of freeze-up and first-ice have been noted, it is possible that recording of either phenomenon might be in error. However, the date of first-ice affecting discharge in the year 1933 is more than three standard deviations from the mean dates of first-ice for the period 1921 to 1950. It seems reasonable to assume that the date of first-ice in 1933 might be an observational or transcriptional error. At Prince Albert (Figure 9) the scattergram indicates that a few large discrepancies between dates of first-ice and freeze-up have greatly reduced the measure of positive correlation. The plotted value for the year 1947 is 3.4 standard deviations from the mean date of first-ice and may be assumed to be in error. Some of the other years that are noted, may also incorporate errors of one kind or another in the recorded dates of one or both phenomena. At Brandon (Figure 10), the disparity between first-ice and freeze-up dates in the year 1944 has greatly reduced the measure of agreement between the two sets of data.

TABLE X

VALUES OF SAMPLE CORRELATION COEFFICIENTS

LOCATION	n	r	$r_{.05}$	$r_{.01}$	Significance
EDMONTON	27	.547	.367	.470	Sig. at 1 per cent level
PRINCE ALBERT	35	.416	.325	.418	Sig. at 5 per cent level
BRANDON (First Dates)	12	.616	.532	.661	Sig. at 5 per cent level
BRANDON (Second Dates)	12	.427	.532	.661	Not significant

The product-moment correlation coefficient was used to measure the relationship between freeze-up and first-ice at Edmonton, Prince Albert, and Brandon. The measure of correlation between second dates of freeze-up and dates of first-ice affecting discharge at Brandon is the sole value of all the values obtained in 2-variable correlation of break-up with last-ice dates and freeze-up with first-ice dates that is not significant at the 5 per cent level. However, if the year 1944 is omitted from the period of record, the coefficient of correlation (r .710) is significant at the 1 per cent level. The computed value of the correlation coefficient between first dates of freeze-up and dates of first-ice affecting discharge (r .850) also becomes significant at the 1 per cent level.

In the Assiniboine-Red tributary basin, no specific location other than Brandon has records of freeze-up and of first-ice affecting discharge covering comparable periods of sufficient length to justify measurement of the degree of relationship that exists between the two phenomena. In order to illustrate that some measure of agreement does exist between dates of freeze-up and first-ice at other locations, the record of first-ice at Headingley was compared with the record of freeze-up at Winnipeg. The sample value (r .565) of the coefficient of correlation is significant at the 1 per cent level.

The comparisons of data show that differences between dates of freeze-up and first-ice are considerably larger than differences between dates of break-up and last-ice. All four 10-year mean differences at Prince Albert and at least one 10-year mean difference at Edmonton and one at Brandon support such a conclusion. However, the apparent differences in the working definitions of freeze-up may magnify the discrepancies between freeze-up and first-ice to a greater extent than differences in the working definitions of break-up enlarge the discrepancies between break-up and last-ice.

In the majority of cases, the 'within variability' in freeze-up and first-ice records exceeds the 'within variability' in break-up and last-ice records. The standard deviations of first-ice and last-ice partially bear this out (Figure 16 and Figure 22). There is also a greater 'between variability' which is reflected in the lower measures of positive correlation between freeze-up and first-ice than between break-up and last-ice at both Edmonton and Prince Albert.

MAPS

Mean first-ice and last-ice dates are plotted for stations recording 4 or less omissions in each 10-year period under consideration. Those stations with 2 to 4 omissions in each 10-year period are used as reference points only when no other information is available in the immediate area. In areas where clustered mean dates differ in value, the most representative (i.e. modal or, if necessary, mean) value is used as a reference for plotting. Isopleths of mean dates for 10-year periods appear as Figures 11, 12, 13, and 14 for first-ice conditions, and as Figures 17, 18, 19 and 20 for last-ice conditions.

Means (Figures 15 and 21) and standard deviations (Figures 16 and 22) of first-ice and last-ice for the period 1921 to 1950, are mapped and included in this paper. A map of the mean length of ice-free season (Figure 23) is also included for the period 1921 to 1950. Averages of climatic observations based on this period are generally regarded as "normals" (Meteorological Branch, CIR-3208 CLI-19, 3 Jun 59, p. 1).

Station records covering the period 1921 to 1950 are limited in number; 26 stations have records of last-ice observations with fewer than 6 omissions in the period, and 22 stations have records of first-ice observations with the same characteristic. As no obvious progression of standard deviations or mean dates of first-ice, 1921 to 1950, is apparent within the Nelson drainage system, dot intensities are used to overcome the spurious impression of abrupt transition that may be created through the use of cross-hatching.

Isopleths of mean first-ice dates for 10-year periods (Figure 11, 12, 13 and 14) bow south in the west central area of the Nelson drainage system with some moderation of this tendency apparent in the period 1946 to 1955 (Figure 14). The period 1946 to 1955 also indicates a marked shift in the time of ice formation to later dates throughout most areas of the Nelson drainage system. Variations exhibited by the isopleths of first-ice in the 10-year periods are modified by the process of averaging to produce a less complicated pattern for the period 1921 to 1950 (Figure 15).

In contrast to isopleths of mean first-ice dates for 10-year periods, isopleths of last-ice dates for 10-year periods (Figures 17, 18, 19, and 20) bow north in the west central part of the Nelson drainage system. This tendency is modified to some degree when the over-all period, 1921 to 1950,(Figure 21) is considered. A visual comparison of isopleths of mean last-ice dates, 1921 to 1950, with isotherms of mean monthly temperatures for March, May (Currie, 1953), and April (Kendrew and Currie, 1955) suggests that dates of last-ice and air temperatures may be correlated. The orientation of isopleths of mean last-ice dates, 1921 to 1950, and isotherms of mean monthly temperatures for spring months is substantially the same, northwest to southeast.

The mean length of ice-free season, 1921 to 1950, (Figure 23) varies from 232 days in the southwest corner of the Nelson drainage basin to 196 days in the northeast sector between Prince Albert and The Pas. Rates of change in the mean length of ice-free season differ substantially from area to area. A rapid decrease in length occurs from west to east in the transitional zone between the Rocky Mountains and the Great Plains physiographic regions. A minimal rate of decrease occurs northward from the International Boundary to the upper reaches of the Assiniboine River in the central section of the Nelson drainage system.

PROGRESS OF LAST-ICE

Dates of last-ice were examined to see if any progressive upstream or downstream sequence of final ice conditions was evident along the major tributaries of the Nelson River system. Differences between records of adjacent stations along each major tributary were tested with Wilcoxon's matched-pairs signed-ranks test. A basic 10-year period was used for purposes of comparison in each tributary basin, although, in some instances, the length of the period was adjusted to compensate for omissions in record and to maintain the number of observations at 10 for each test.

A 5 per cent significance level was used as criterion for acceptance or rejection of the hypothesis of no difference between dates of last-ice. If acceptance of the null hypothesis was caused by an extreme difference between one pair of observations, a further year of record was compared to either substantiate or negate previous results.

The expected progress of ice cover disintegration in northward-flowing rivers suggests that open-water areas will initially appear in the upper reaches and spread downstream until the river becomes ice-free. Destruction of the ice cover most likely occurs in downstream surges rather than by any continuous process of disintegration (Burbridge and Lauder, 1957). Snow melt and spring rains swell the river in its upper reaches and increase the pressure beneath the ice surface, forcing the ice to rise, after which cracks appear, and the ice cover breaks up. The ice blocks then move downriver until jamming requires the process to repeat itself.

An examination of the tributaries of the Nelson River should show the effect of river orientation on the progress of last-ice. The North Saskatchewan River is predominantly a west-to-east flowing river throughout its entire length; the South Saskatchewan flows northeasterly to its junction with the North Saskatchewan, 30 miles past Prince Albert; the Assiniboine flows southeasterly until it crosses the Manitoba-Saskatchewan border where it turns southward as far as the Virden area and then eastward to its junction with the Red River at Winnipeg. A major westward-flowing tributary, the Winnipeg River, cannot be examined for progress of last-ice because the data available are too limited for this purpose. Progress of last-ice along the North Saskatchewan, the South Saskatchewan, and the Assiniboine Rivers is listed in Table XI. Locations of gauging sites used to chart the progress of last-ice are shown in Figure 24.

The disintegration of ice affecting discharge on the North Saskatchewan, progresses downstream from the head-waters area to the river's junction with the South Saskatchewan. The fact that no significant difference exists between dates of last-ice at Rocky Mountain House and Edmonton and, farther downstream, between dates of the same phenomenon at Frenchman's Butte and Prince Albert tends to substantiate the belief that disintegration of the ice cover occurs in sections.

TABLE XI

LAST-ICE PROGRESS ALONG MAJOR TRIBUTARIES OF THE NELSON RIVER

NOTE: If 'T' > 8, the difference between last-ice dates is not significant

If 'T' < 8, the difference is significant. See Figure 24 for station locations.

A. North Saskatchewan River; base period, 1944-55

Stations Compared	'T'	Significance
Rocky Mountain House-Edmonton	13	Not sig. at 5 per cent level
Edmonton - Frenchman's Butte	0	Sig. at 1 per cent level
Frenchman's Butte - Prince Albert	13	Not sig. at 5 per cent level
Prince Albert - The Pas	0	Sig. at 1 per cent level

(Table XI continued)

B. South Saskatchewan River; base period, 1921-55

Stations Compared	'T'	Significance
Cowley - MacLeod	0	Sig. at 1 per cent level
MacLeod - Lethbridge	22	Not sig. at 5 per cent level
Lethbridge - Medicine Hat	5	Sig. at 5 per cent level
Medicine Hat - Saskatoon	0	Sig. at 1 per cent level
Saskatoon - The Pas	0	Sig. at 1 per cent level

C. Headwater Stations on Easterly - Flowing Streams. Base periods; St. Mary River, 1945-55; Bow River, 1937-46; Athabasca River, 1919-31.

Stations Compared	'T'	Significance
(i) St. Mary's River International Boundary-Lethbridge	0	Sig. at 1 per cent level
(ii) Bow River Banff - Calgary	3	Sig. at 1 per cent level
(iii) Athabasca River Jasper - Entrance	10	Not sig. at 5 per cent level
Entrance - Athabasca	0	Sig. at 1 per cent level

D. Assiniboine River; base period, 1944-55

Stations Compared	'T'	Significance
Sturgis - Kamsack	19	Not sig. at 5 per cent level
Kamsack - Millwood	20	Not sig. at 5 per cent level
Millwood - Brandon	4	Sig. at 5 per cent level
Brandon - Headingley	15	Not sig. at 5 per cent level

E. Mississippi Drainage Basin: Milk River; base period, 1946-55

Stations Compared	'T'	Significance
International Boundary - Milk River	15	Not sig. at 5 per cent level
Milk River - Eastern Crossing	2	Sig. at 1 per cent level

Disintegration of the ice cover on the South Saskatchewan River system begins with head-water tributaries in the southwestern foothills of Alberta. Earliest dates of last-ice occur at the MacLeod and

Lethbridge gauging stations on the Oldman River and at a gauging site on the St. Mary River near Lethbridge. Removal of ice conditions affecting discharge progresses along these tributaries and thence down the South Saskatchewan as the river runs its northeasterly course across the Great Plains. Break-up of the ice cover continues in a downstream direction past the junction of the North and South Saskatchewan, past the gauging station on the main Saskatchewan at The Pas, and on to the river's outlet in Lake Winnipeg.

Dates of last-ice for Cowley on the Oldman River and for the International Boundary gauging site on the St. Mary River are later than dates of last-ice at the downstream stations of MacLeod and Lethbridge. The situation is reversed on the Bow tributary to the north; dates of last-ice at the Banff gauging station are earlier than dates of last-ice at Calgary, some distance downstream. Farther north, on the North Saskatchewan, dates of last-ice at Rocky Mountain House exhibit no significant differences from dates down-river at Edmonton. Similarly, on the Athabasca River still farther north, no significant difference exists between Jasper and Entrance records of last-ice although dates of last-ice at Entrance are earlier than dates of last-ice downstream at Athabasca. Thus, where records of gauging stations along easterly-flowing streams in the Rockies and their foothills can be tested for differences, dates of last-ice are earlier at upstream sites on two occasions, and exhibit no difference between upstream and downstream sites on two occasions.

On the other hand, the upper reaches of two of the South Saskatchewan's headwater tributaries in the southwestern corner of the Nelson drainage basin demonstrate a lateness of last-ice dates affecting discharge. This condition, which is atypical of other easterly-flowing streams rising in the Rockies occurs in an area in which Foehn or Chinook winds may have a considerable effect upon spring run-off. These warm dry winds are heated by compression as they descend the lee side of the Rockies. In the spring they reach their frequency peak and can cause snow and ice to disappear very rapidly. Although some ice and snow is undoubtedly removed through the process of sublimation, some run-off will occur and the melt-water may, in some instances, be sufficient to break open local rivers and streams.

As the Chinook winds are heated on descent at the dry adiabatic lapse rate of 5.5°F per 1,000 feet, differences of a few hundred feet in the elevation of gauging sites can produce a change from freezing conditions at the upstream site to thawing conditions at the downstream one. If these conditions are sustained for a number of hours, and if the Chinooks have a high frequency of occurrence in a given period of time, the cumulative effect may result in break-up occurring initially on the lower reaches of streams.

In the southern foothills of Alberta, the elevation of the Oldman River at Cowley is approximately 1,000 feet above its elevation at Lethbridge; the St. Mary River is some 1,500 feet higher at the International Boundary gauging site than at the Lethbridge site, downstream. Differences between the elevations of upstream and downstream gauging sites of this order could have a considerable influence upon the initial point of break-up.

On the Canadian side of the border, the strength and frequency of Chinooks generally decrease northwards. Calgary is less affected by these winds than Lethbridge, Edmonton less than Calgary, and so on. If Chinooks have an effect upon the disappearance of ice conditions affecting discharge, it would be more pronounced in the southern foothills area and would diminish northwards. Figures 17 to 23 inclusive support such a conclusion.

The Assiniboine River which flows in a southeasterly direction for more than half its length was tested to determine whether ice cover disintegration progresses downstream in a manner similar to the progress of break-up on the North and South Saskatchewan Rivers. Five gauging sites with records suitable for comparisons of last-ice dates are situated on the Assiniboine at fairly even intervals along its length. Results of Wilcoxon's test indicate that ice cover disintegration progresses downstream from Millwood in Manitoba, located near the river's middle reaches, to Headingley, 12 miles west of the junction of the Assiniboine and Red Rivers in Winnipeg. From Millwood to Sturgis in Saskatchewan, an approximate distance of 150 miles up-river, there is no significant time differential in the disintegration of ice conditions affecting discharge. Similar results obtained from testing records for the North and South Saskatchewan Rivers make it reasonable to assume that lack of differences between records can be interpreted as meaning that break-up of the ice cover is not a continuous process but, rather, a spasmodic one with varied-size sections breaking up at irregular intervals. The sections do not break-up in the same order on each tributary examined, but generally speaking, the progress of ice cover disintegration begins on a river's upper reaches and proceeds downstream towards its mouth. At least, this is the case if records tested from gauging sites along the North Saskatchewan, South Saskatchewan, and Assiniboine Rivers are an indication of the progress of ice break-up on other rivers in the Nelson drainage system.

Three series of last-ice records from stations that are latitudinally separated along north-south bands in the west, central, and east sections of the Nelson drainage system were tested for differences.

Figure 24 illustrates the location of each station and Table XII lists the results of Wilcoxon matched-pairs signed-ranks test of the differences. The base period used for testing purposes varied with each section due to the omission of some last-ice dates from a number of station records. The latest 10-paired dates from records are compared in each test.

Ice conditions are expected to remain longer at northern gauging sites than at southern sites during the spring break-up. Isopleths of mean last-ice dates indicate that this is the case. Furthermore, statistical tests of differences tend to substantiate the general south-north pattern of last-ice progress.

In the western section, the record of last-ice at Lethbridge is earlier than other records of last-ice. Each of the other station records tested in the western section is either the same as, or earlier than its nearest northern neighbour. In the central section, records of last-ice exhibit differences between all stations subjected to Wilcoxon's test. The differences substantiate the belief that ice conditions tend to persist for a longer period in spring at the station with the more northerly location. Stations in the east section follow the same general pattern established by stations in the central section with one exception, the two southern most stations, Wawanesa and Tantallon, have records that exhibit no significant difference between them. The same results were obtained from two tests between stations in the west section. It may

TABLE XII

TEST OF DIFFERENCES BETWEEN RECORDS OF LAST-ICE DATES AT LATITUDINALLY-SEPARATED STATIONS

NOTE: If 'T' > 8, the difference between last-ice dates is not significant.

If 'T' < 8, the difference is significant. See Figure 24 for station locations.

'T' VALUES

	St. Mary R. at International Boundary	Oldman R. at Lethbridge	Bow R. at Calgary	Red Deer R. at Red Deer	North Sask. at Edmonton
St. Mary R. at International Boundary					
Oldman R. at Lethbridge	2				
Bow R. at Calgary	8	2.5			
Red Deer R. at Red Deer	6	0	19.		
North Saskatchewan R. at Edmonton	2	0	15.5	5	

(Table XII continued)

B. Central Section: base period, 1924–1940

	Frenchman R. at International Boundary	Swift Current Cr. at Swift Current	S. Sask. R. at Saskatoon	N. Sask. R. at Prince Albert
Frenchman R. at International Boundary				
Swift Current Cr. at Swift Current	2			
S. Saskatchewan R. at Saskatoon	0	0		
N. Saskatchewan R. at Prince Albert	0	0	6	

C. East Section: base period, 1927–55

	Souris R. at Wawanesa	Qu'Appelle R. Tantallon	Swan R. at Swan River	Saskatchewan R. at The Pas
Souris R. at Wawanesa				
Qu'Appelle R. at Tantallon	13.5			
Swan R. at Swan River	4	5		
Saskatchewan River at The Pas	0	0	0	

be assumed that either the removal of ice conditions can be expected to occur concurrently at stations where no statistically significant differences exist or that the acceptance of the hypothesis of no difference is in error. If differences are not statistically significant, it does not mean that real differences between dates of last-ice are non-existent; it means, rather, that on the basis of the results of Wilcoxon's test, real differences are not meaningful from a statistical point of view.

The rate of disappearance of ice conditions affecting discharge varies in different areas of the Nelson drainage system. The disintegration of ice conditions affecting discharge, 1921 to 1950, progresses northward at an average rate of 16 miles per day in the west and central sections, and at an average rate of 22 miles per day in the eastern section. The average rate of progress measured at right angles to isopleth orientation in the central section is approximately 17 miles per day. The minimal average rate of last-ice progress, 4 to 5 miles per day, occurs west to east in the Rocky Mountain and foothills region between

Banff and Calgary.

PROGRESS OF FIRST-ICE

The progress of ice formation in the Nelson drainage system was examined from two points of view. Firstly, records from a number of locations on major tributaries were tested for progressive upstream or downstream development of ice conditions affecting discharge. Secondly, these records, with some omissions and additions, were tested for evidence of a stochastic relationship between latitude and the time of ice formation. Once again, the differences between records were subjected to Wilcoxon's test, in order that both the magnitude and the direction would be taken into consideration. The last 10-paired observations in each base period were used in the test.

Records of first-ice dates from four locations along the North Saskatchewan-Saskatchewan River system were tested and the results infer that no differences exist between them. On the South Saskatchewan River, three widely-separated locations exhibit no differences between their records. Saskatoon, however, the farthest downstream station, does display significantly later dates of first-ice than The Pas, downstream on the main Saskatchewan. Three station records on the Assiniboine River show no significant differences between dates of first-ice formation (See Table XIII).

The procedure used to check the north-to-south progress of ice formation is the same one that was used to examine the progress of ice disintegration from south-to-north. The Nelson drainage system was again arbitrarily divided into a western, a central, and an eastern section, and tests of differences were again conducted between latitudinally-separated stations., although, locations that have recorded first-ice dates are few in number. For example, the central section is limited to a comparison between records of first-ice at Saskatoon and Prince Albert. The results of the tests are listed in Table XIV.

On the basis of available evidence, the western section may be divided, according to tests of the time of initial ice formation affecting discharge, into two latitudinal segments with demarcation falling between Calgary and Red Deer. Test results show that no difference exists either between records from Lethbridge and Calgary or between records from Red Deer and Edmonton. If the station records are assumed to be representative ones, then there is some basis for making the assumption that relative homogeneity, in terms of the time of ice formation, exists in the areas between Lethbridge and Calgary, and between Red Deer and Edmonton. Demarcation may thus be envisaged as zone of indeterminate width

TABLE XIII

FIRST-ICE PROGRESS ALONG MAJOR TRIBUTARIES OF THE NELSON RIVER

NOTE: If 'T' > 8, the difference between first-ice dates is not significant

If 'T' < 8, the difference is significant. See Figure 24 for station locations.

A. North Saskatchewan River; base period, 1921-54

Stations Compared	'T'	Significance
Rocky Mountain House-Edmonton	12.5	Not sig. at 5 per cent level
Edmonton - Prince Albert	18.	Not sig. at 5 per cent level
Prince Albert - The Pas	24.5	Not. sig. at 5 per cent level

B. South Saskatchewan River; base period, 1941-54

Stations Compared	'T'	Significance
Lethbridge - Medicine Hat	21	Not sig. at 5 per cent level
Medicine Hat - Saskatoon	20.5	Not sig. at 5 per cent level
Saskatoon - The Pas	4.5	Sig. at 5 per cent level

C. Assiniboine River; base period, 1925-54

Stations Compared	'T'	Significance
Millwood - Brandon	13.5	Not sig. at 5 per cent level
Brandon - Headingley	25	Not sig. at 5 per cent level

TABLE XIV

TEST OF DIFFERENCES BETWEEN RECORDS OF FIRST-ICE DATES AT LATITUDINALLY - SEPARATED STATIONS

NOTE: If 'T' > 8, the difference between first-ice dates is not significant.

If 'T' < 8, the difference is significant. See Figure 24 for station locations

'T' VALUES

A. Western Section; base period, 1936-45

	St. Mary R. at Lethbridge	Bow R. at Calgary	Red Deer R. at Red Deer	N. Saskatchewan R. at Edmonton
St. Mary R. at Lethbridge				
Bow R. at Calgary	21.5			
Red Deer R. at Red Deer	6	6		
N. Saskatchewan R. at Edmonton	3.5	3	14.5	

(Table XIV continued)

B. Central Section: base period, 1936-45

A test of the two stations with available records, Saskatoon and Prince Albert, suggests that no significant difference exists between them. The 'T' value is 14.5

C. Eastern Section: base period, 1921-31

	Souris R. at Wawanesa	Assiniboine R. at Millwood	Swan R. at Swan River	Saskatchewan R. at The Pas
Souris R. at Wawanesa				
Assiniboine R. at Millwood	23.5			
Swan R. at Swan River	12.5	10		
Saskatchewan R. at The Pas	5	8	11	

separating areas that exhibit differences in the time of initial ice formation affecting discharge.

The central section is devoid of records suitable for comparison purposes south of the Saskatoon gauging station. Saskatoon's record was tested against Prince Albert's and the result indicates no difference exists between them.

In the eastern section, the effects of ice upon discharge are first noticeable at the most northerly station, The Pas. To the south, rivers generally remain unaffected by ice formation until later in the fall season. At first glance, test results do not necessarily convey this impression; the apparent incongruity of Swan River's agreement with the other stations on the time of first-ice development, and The Pas disagreement with stations south of Swan River on the same matter, confuse the issue. Test results reveal, however, that differences between Swan River's record and the other records are border-line cases. In each of these cases, a decrease in the magnitude of the difference between one pair of observations would have resulted in a rejection of the hypothesis of no difference. Mean values for the period of the test bear out the belief that ice formation at Swan River occurs later than the formation of the same phenomenon at The Pas, and earlier than its formation at Millwood. Essentially, the test results support the isopleth map of mean first-ice dates, 1946-55.

Southward progress of ice formation effecting discharge based upon mean dates of first-ice, 1921 to 1950, occurs at a rate of 20 to 25 miles per day in the western and central sections, and at a rate of approximately 100 miles per day in the eastern section. The minimal average rate of first-ice progress, 15 to 20 miles per day, occurs west to east in the transitional zone between the Great Plains and Rocky Mountain physiographic regions.

SUMMARY AND CONCLUSIONS

This study is based chiefly on statistical comparisons of two kinds of data. Hydrologic records of first-ice and last-ice are compared with historical records of freeze-up and break-up. Such comparisons are desirable because records overlap at some locations. The sections which overlap were tested for similarities (Pearson's product-moment correlation coefficient) and for differences (the Wilcoxon's matched-pairs signed-ranks test). The principal conclusions are as follows:

1. Dates of (a) first-ice with freeze-up, and (b) last-ice with break-up can be correlated significantly.
2. Significant differences exist between paired series (see 1.) of observations at some locations. However, the degree of correlation suggests extrapolation from one kind of data to the other is possible.
3. Hydrologic records of first-ice and last-ice may be used to extend historical records of freeze-up and break-up, and to increase the coverage in certain areas.

A considerable amount of data related to ice conditions affecting discharge is available for the Nelson drainage system. These data were used to describe and to analyse (a) the areal progress of ice formation and ice disintegration in the Nelson drainage system, and (b) the progress of ice formation and ice disintegration along individual tributaries of the Nelson River. The principal conclusions are as follows:

1. In general, isopleths of mean first-ice dates and tests of differences (the Wilcoxon matched-pairs signed-ranks test) between first-ice records from latitudinally-separated stations support the expected north-to-south progress of ice formation. However, variability in the rates of ice formation affecting discharge has significantly altered the direction of progress in some areas. For example, the map of mean first-ice dates, (Figure 15) suggests that ice conditions affecting discharge spread radially, west, south and east, from the area of earliest occurrence in the north central part of the Nelson drainage basin.
2. In general, isopleths of mean last-ice dates and tests of differences (the Wilcoxon matched-pairs signed-ranks test) between last-ice records from latitudinally-separated stations support the expected south-to-north progress of ice disintegration. However, variability in the rates of ice disintegration cause a shift in the direction of last-ice progress in some areas. In the central section of the Nelson drainage system, the progress of last-ice trends from southwest to northeast. The clockwise swing in trend is even more pronounced in the Rocky Mountain foothills physiographic region.
3. Isopleths of last-ice, 1921 to 1950, and isotherms of mean monthly temperatures for March, April, and May, (Currie, 1953) show marked similarities in trends which suggest they can be correlated.
4. Ice formation along those individual tributaries of the Nelson River tested,does not seem to respond to controls other than latitude and continentality.

5. Ice disintegration on those individual tributaries of the Nelson River tested, begins in the upper reaches and progresses in a downstream direction.
6. Chinooks may be a contributary factor in early ice disintegration and in lengthening the mean ice-free season in the southwestern foothills of Alberta.
7. Standard deviations of first-ice and last-ice, 1921-50, indicate that the magnitude of 'within variability' is relatively homogeneous for all station records examined from the Great Plains physiographic region. A marked increase in variability occurs in records from stations situated in the foothills and Rocky Mountain regions.

The basic patterns of isopleth orientation for mean dates of last-ice and mean length of ice-free season covering the period of the climatic norm, 1921-50, are in general agreement with the basic patterns derived by Burbridge and Lauder (1957) in their analyses of freeze-up and break-up data. However, various differences in the time element do exist; these differences are partly explained by the exclusion from this study of data concerning ice formation and ice disintegration on lakes and by certain inconsistancies in the definitions of terms used in basic source data.

On occasion, maps of ice conditions may contradict the progress of ice formation and ice disintegration suggested by statistical tests of the differences. With due respect to the 5 per cent significance levels, it is assumed that the sensitivity of means to extreme values, coupled with the differences in the base periods are responsible for any apparent contradictions.

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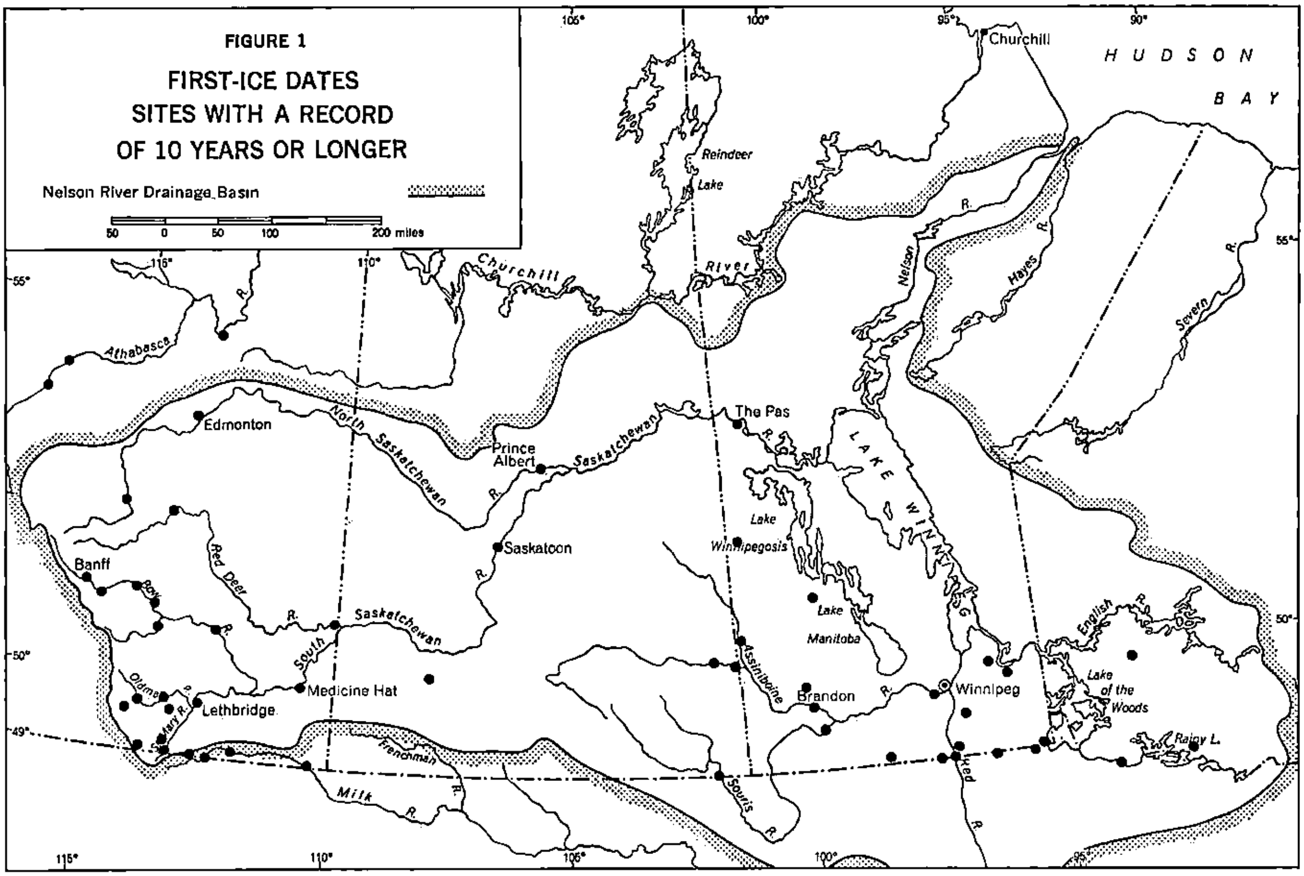


FIGURE 1

FIRST-ICE DATES
SITES WITH A RECORD
OF 10 YEARS OR LONGER

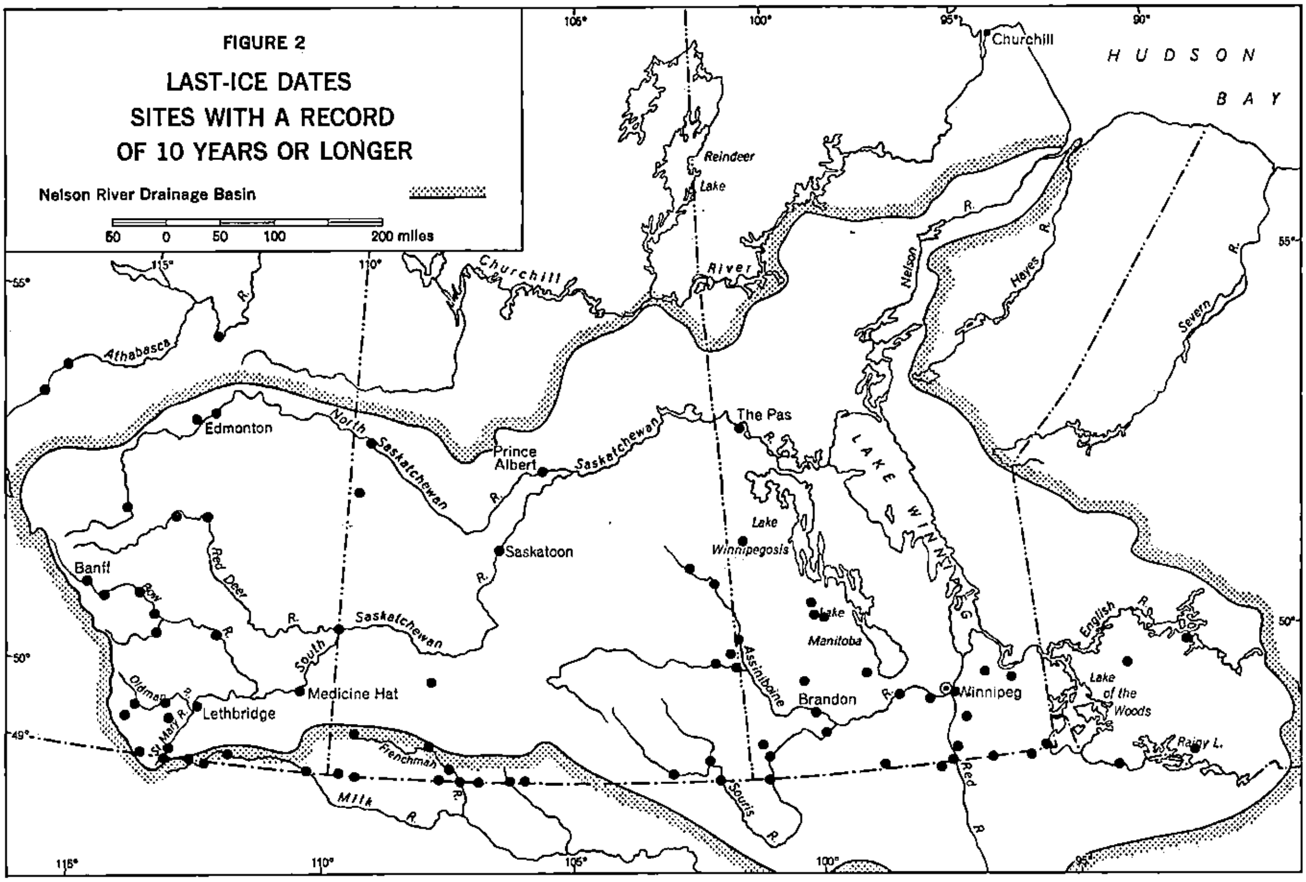


FIGURE 2

LAST-ICE DATES
SITES WITH A RECORD
OF 10 YEARS OR LONGER

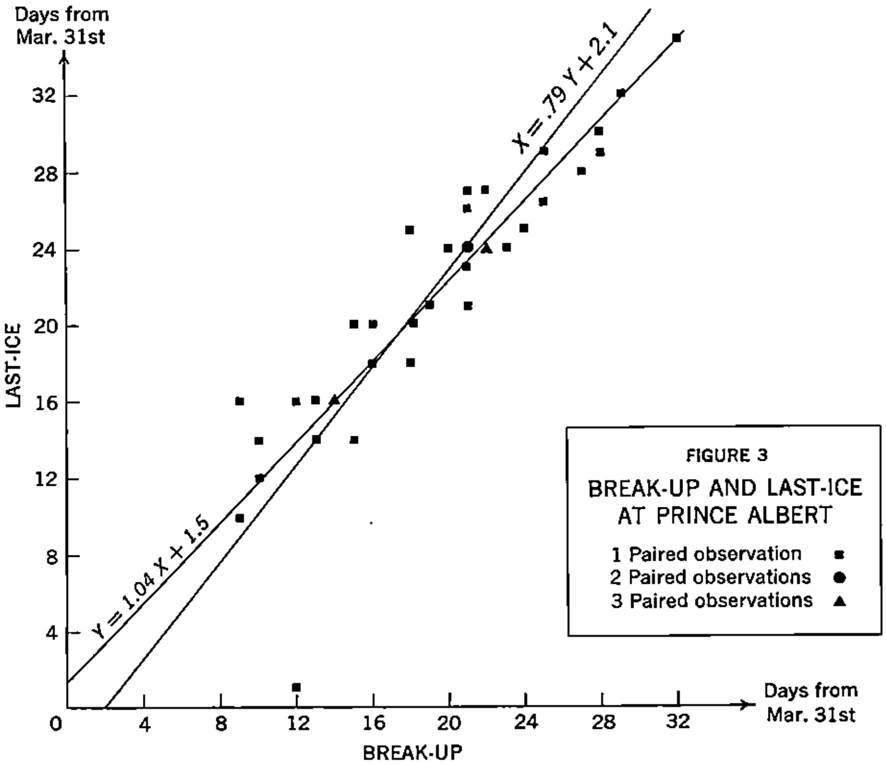


FIGURE 3

BREAK-UP AND LAST-ICE AT PRINCE ALBERT

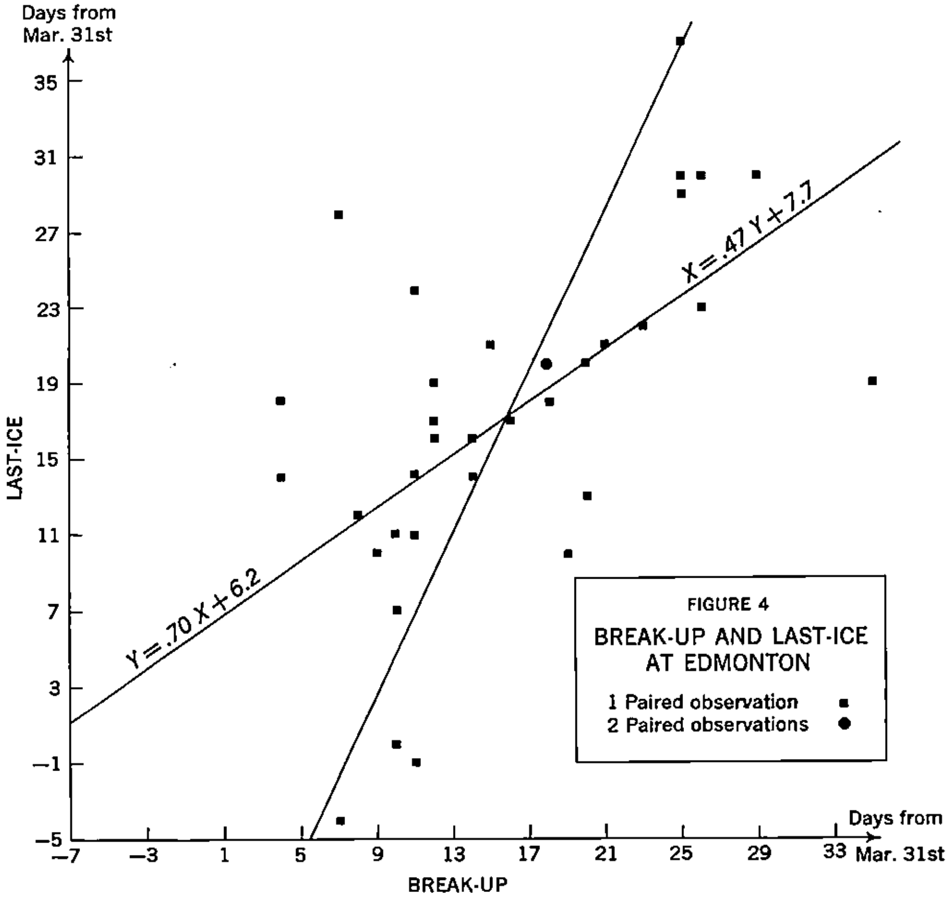


FIGURE 4

BREAK-UP AND LAST-ICE AT EDMONTON

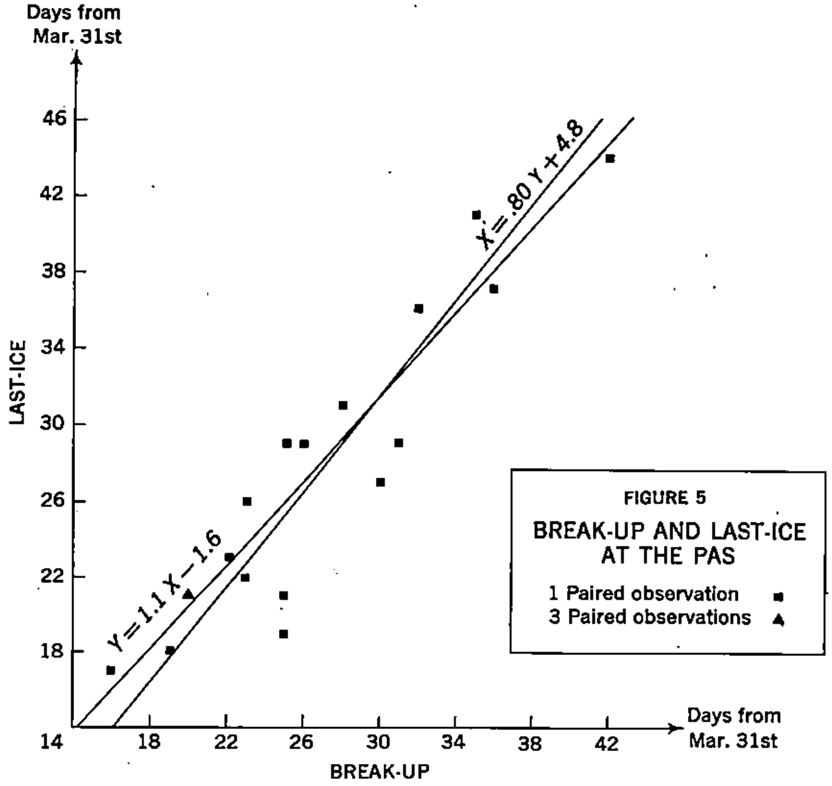


FIGURE 5

BREAK-UP AND LAST-ICE AT THE PAS

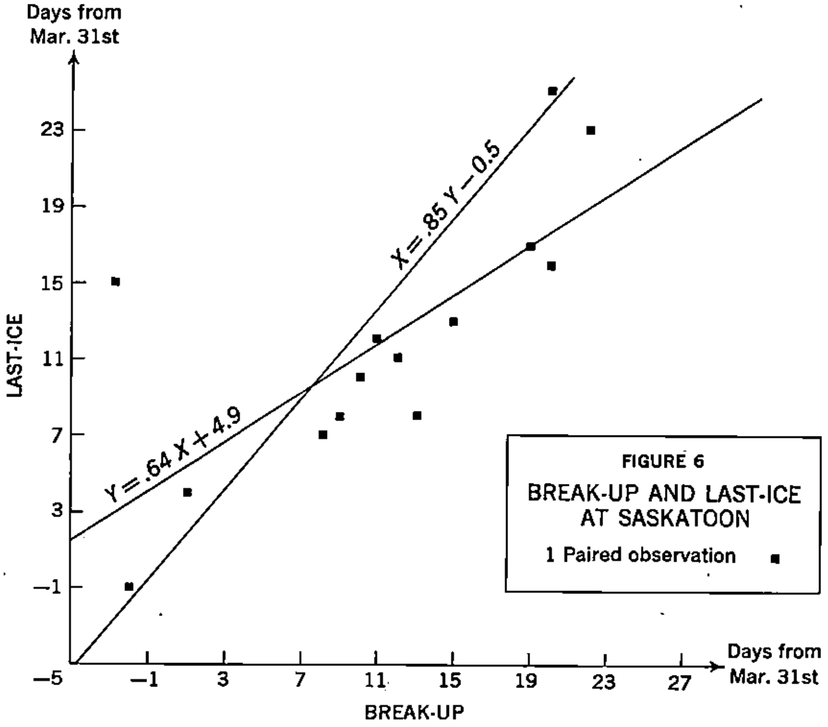


FIGURE 6

BREAK-UP AND LAST-ICE AT SASKATOON

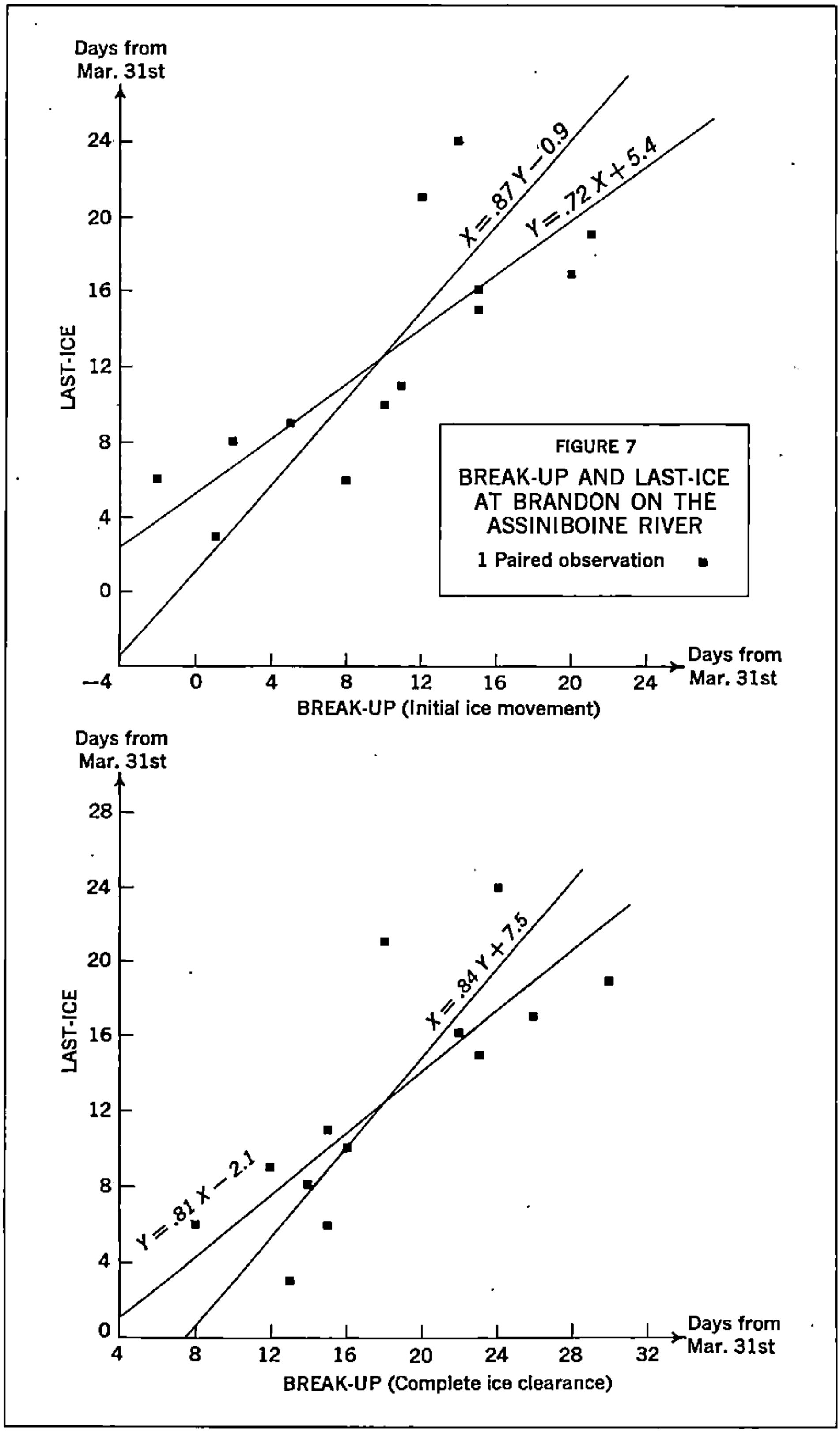


FIGURE 7

BREAK-UP AND LAST-ICE AT BRANDON ON THE ASSINIBOINE RIVER

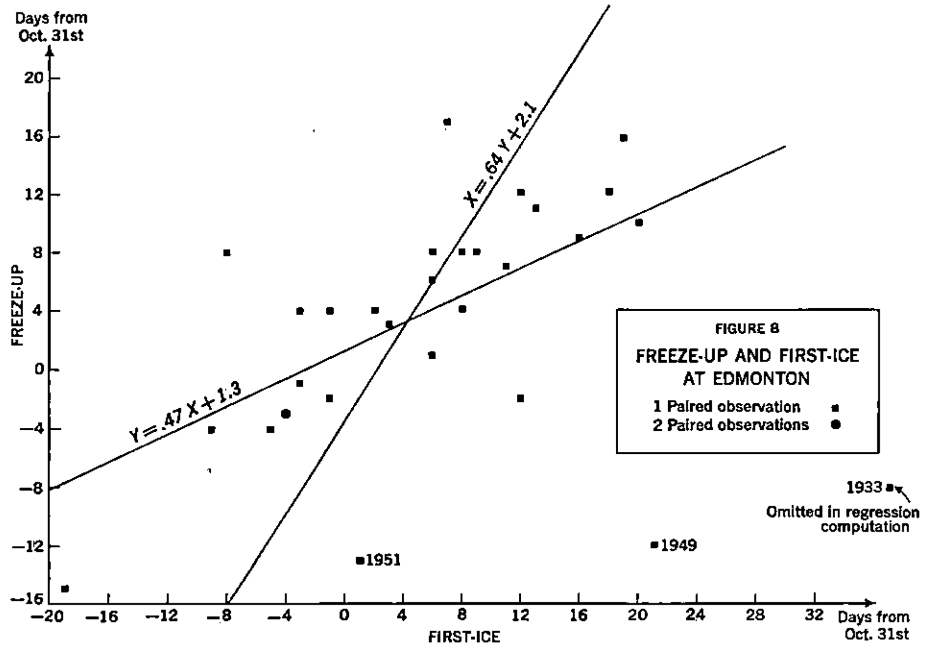


FIGURE 8

FREEZE-UP AND FIRST-ICE AT EDMONTON

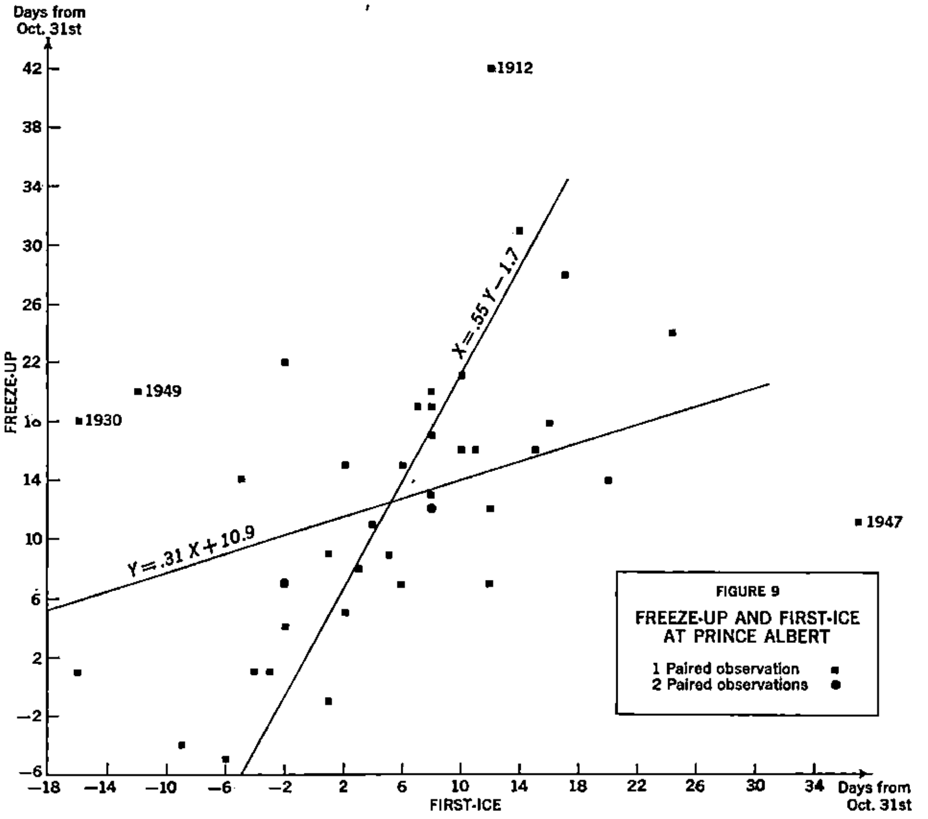


FIGURE 9

FREEZE-UP AND FIRST-ICE AT PRINCE ALBERT

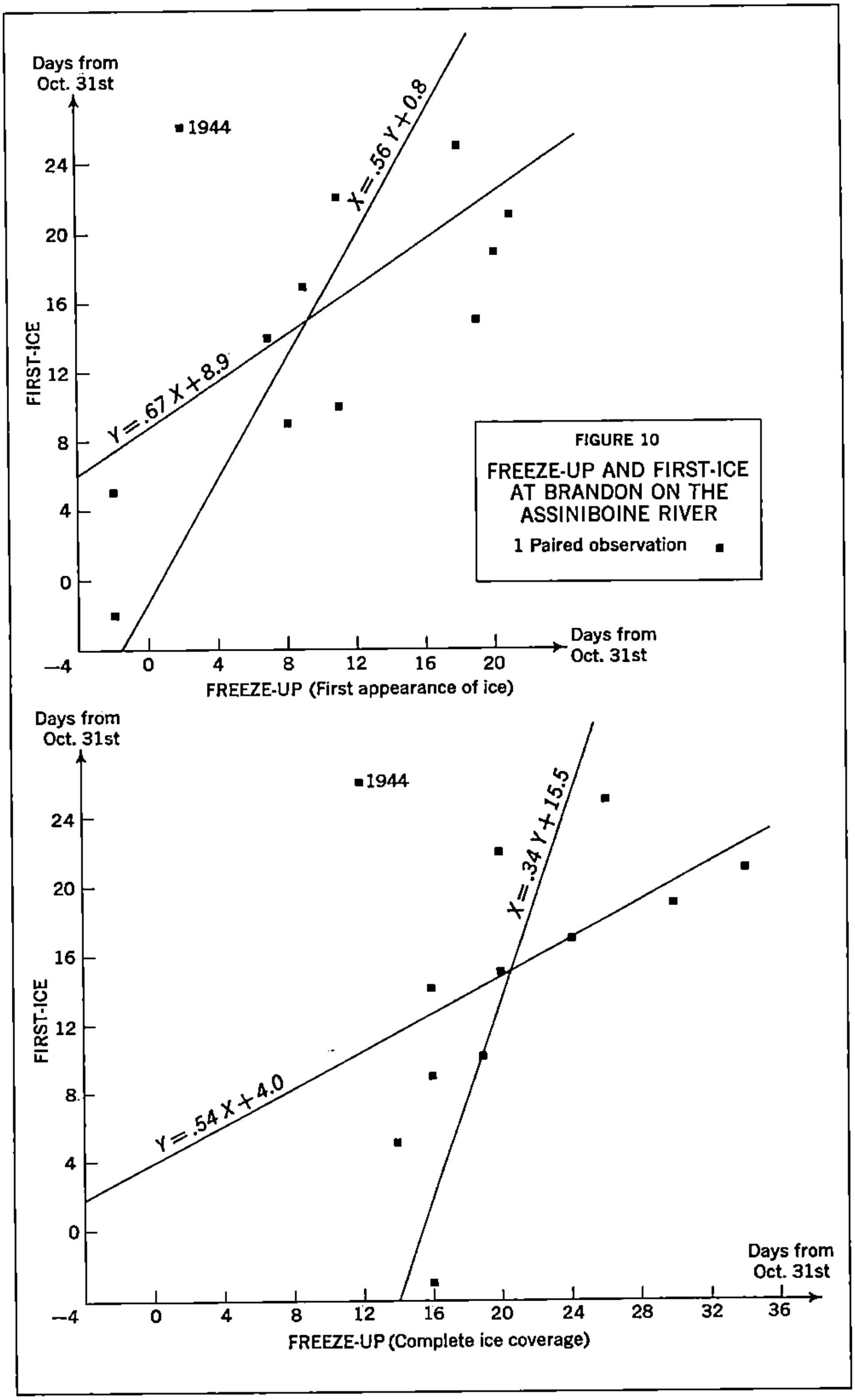


FIGURE 10

FREEZE-UP AND FIRST-ICE AT BRANDON ON THE ASSINIBOINE RIVER

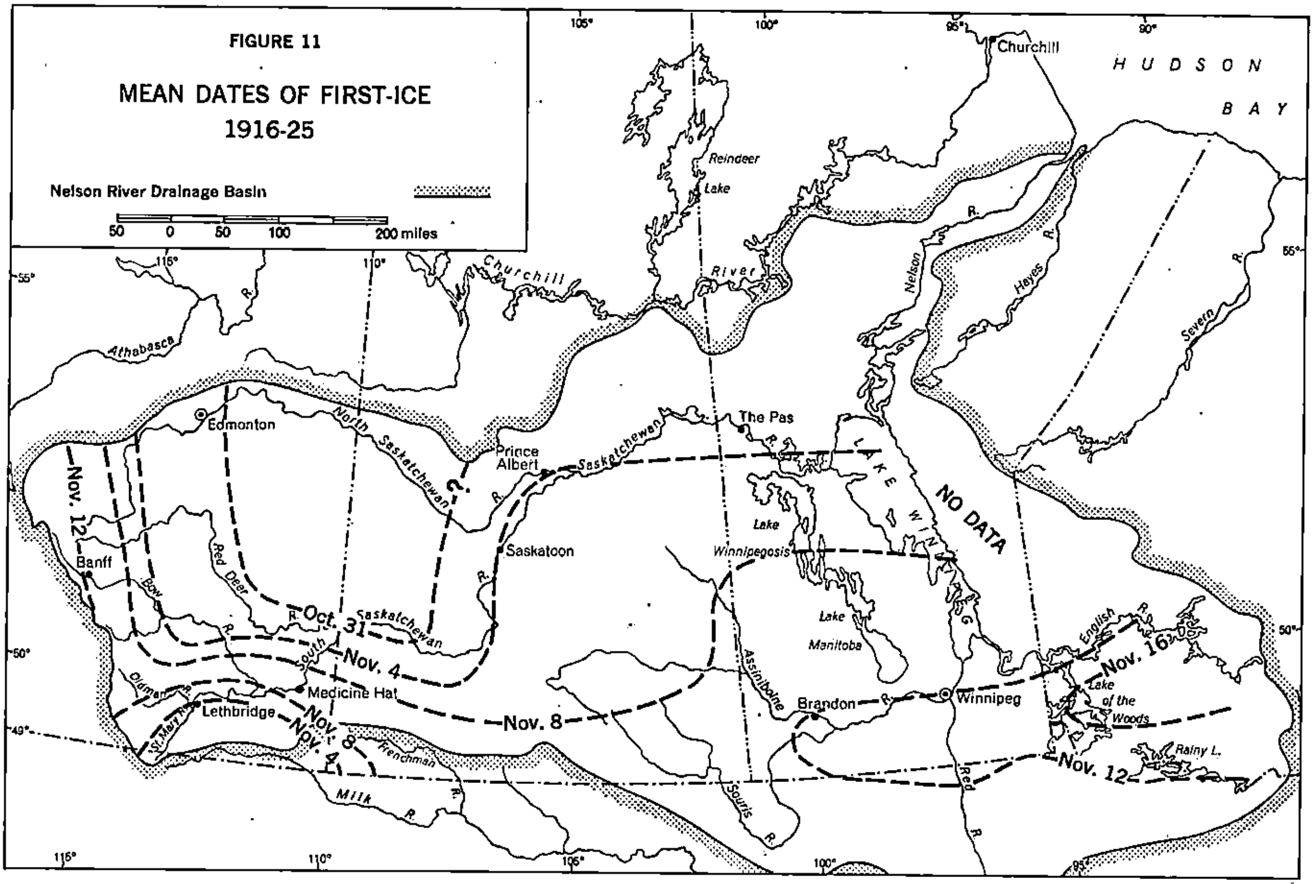


FIGURE 11

MEAN DATES OF FIRST-ICE 1916-25

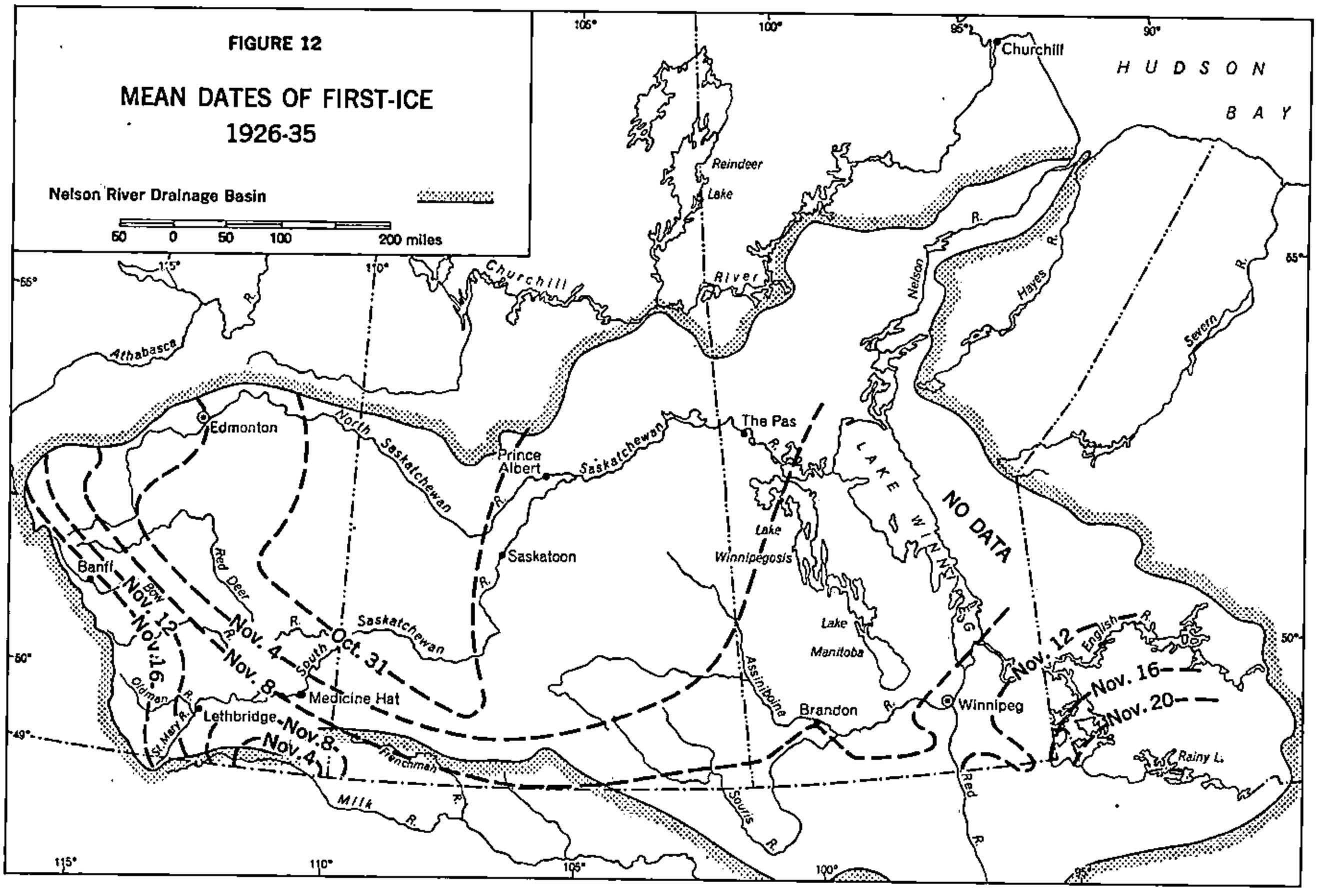


FIGURE 12

MEAN DATES OF FIRST-ICE 1926-35

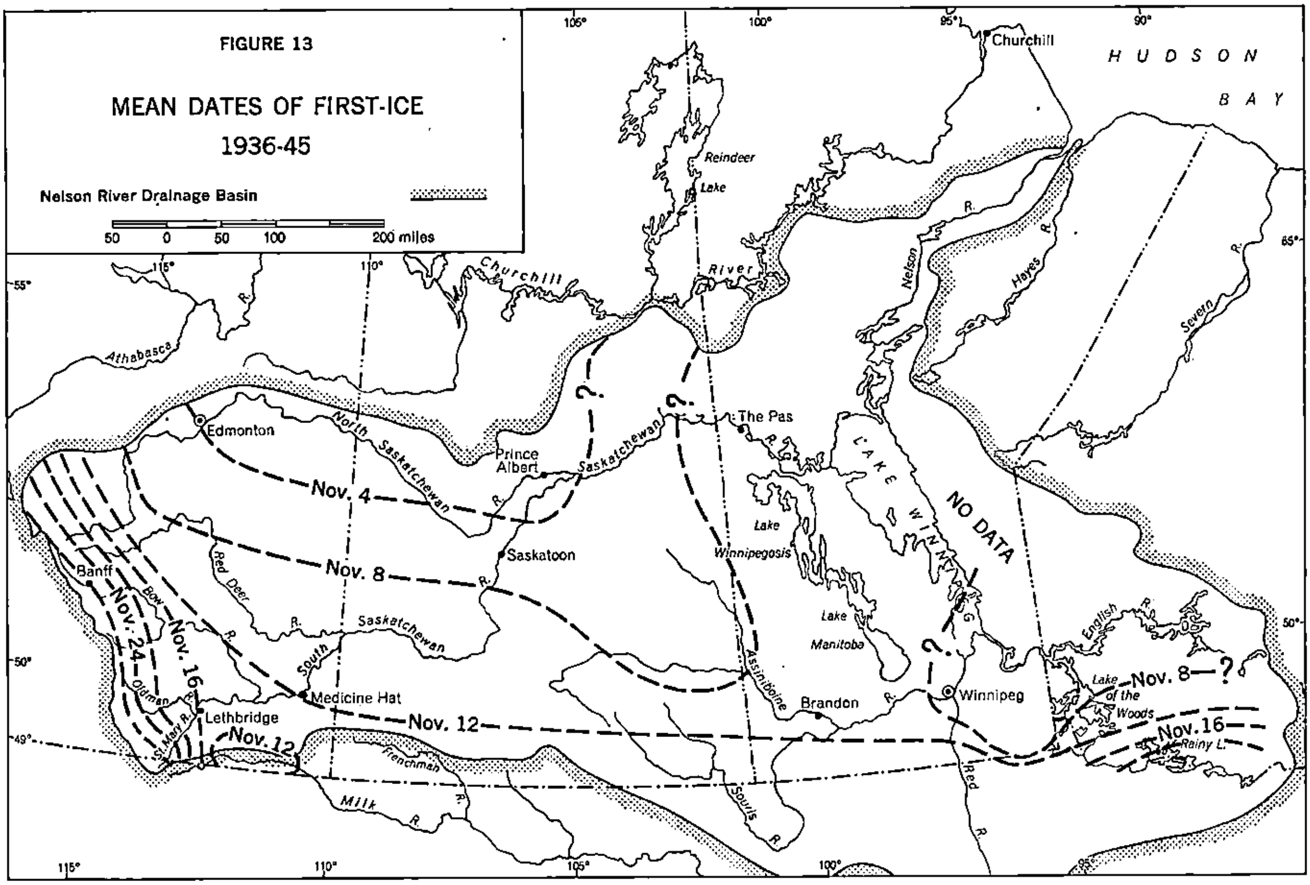


FIGURE 13

MEAN DATES OF FIRST-ICE
1936-45

Nelson River Drainage Basin

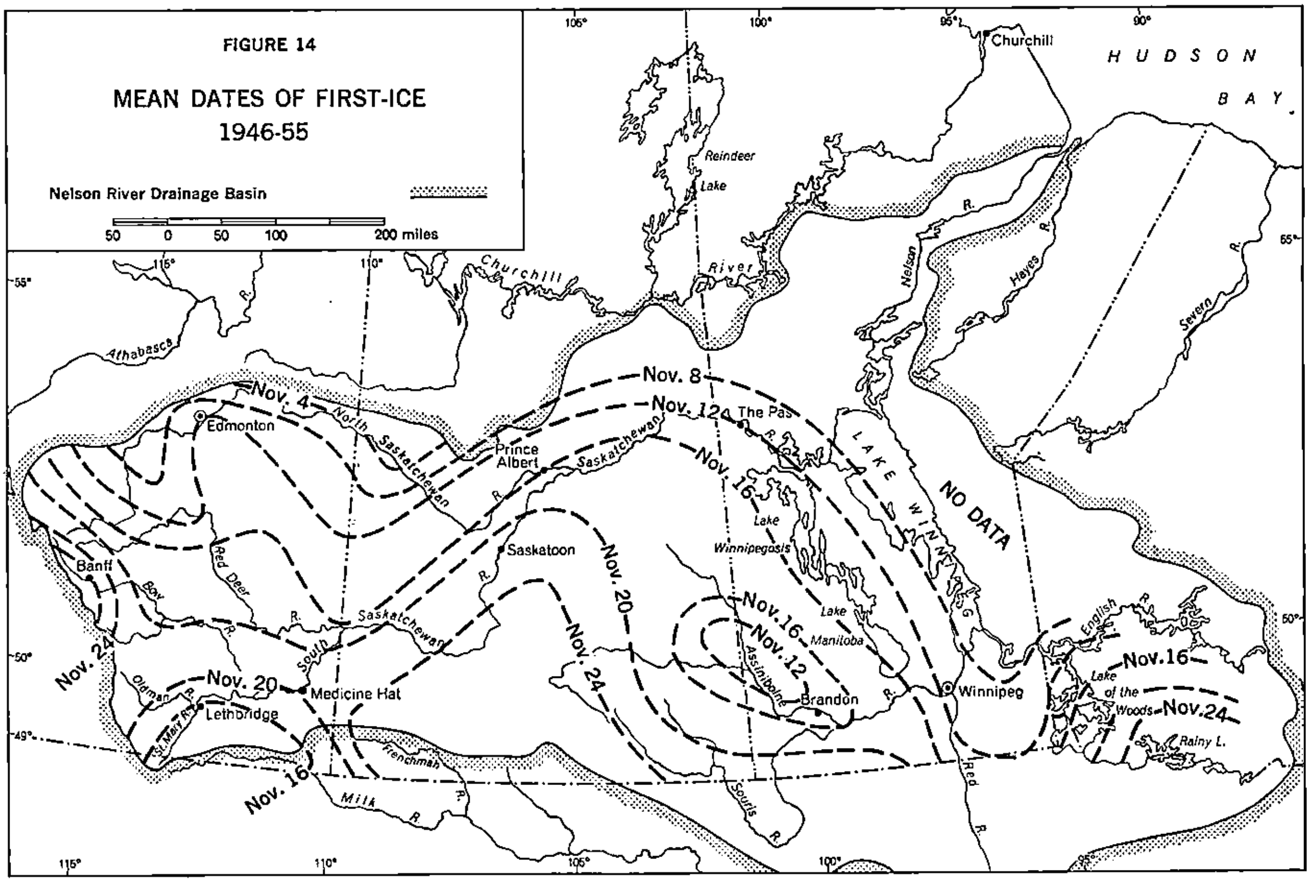


FIGURE 14

MEAN DATES OF FIRST-ICE
1946-55

Nelson River Drainage Basin

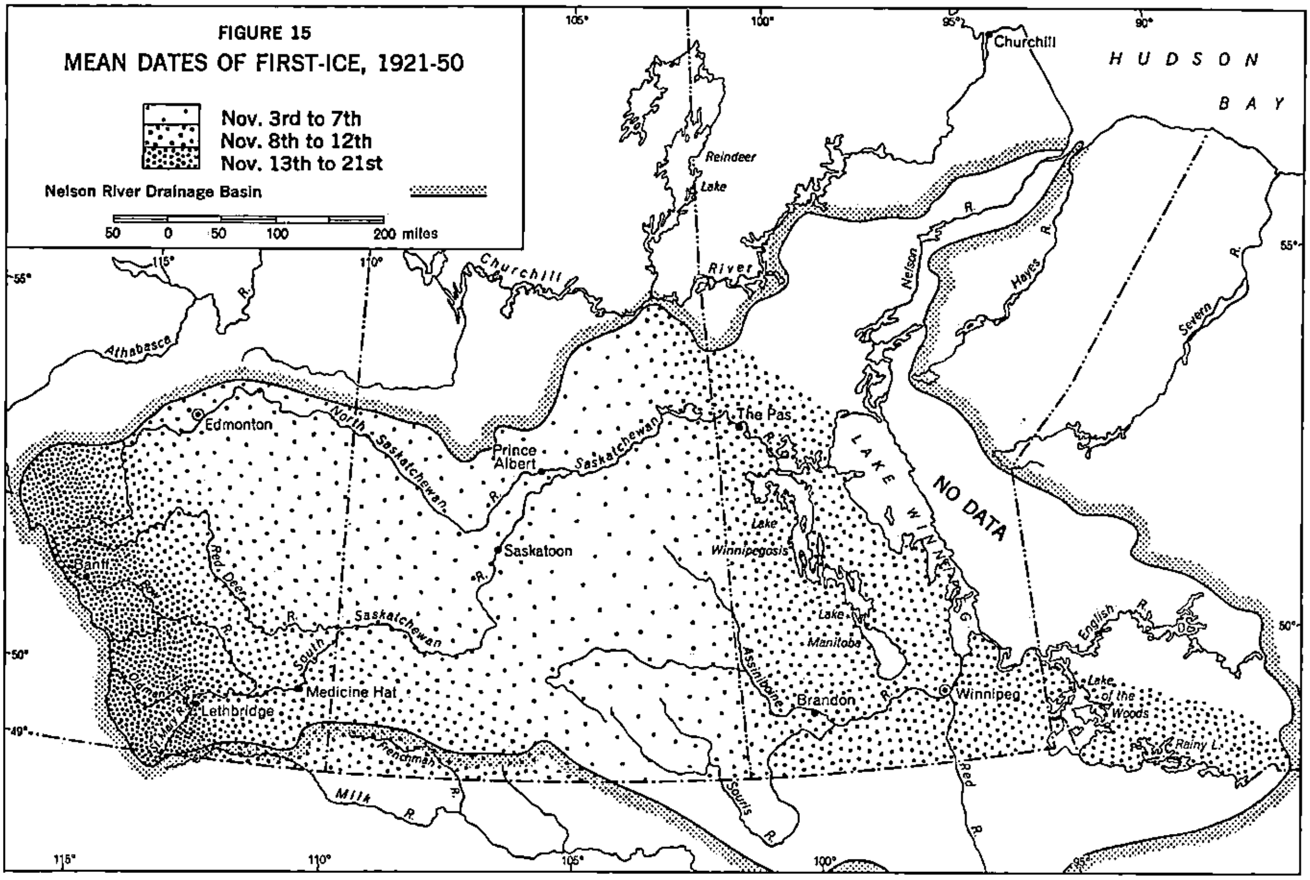


FIGURE 15
MEAN DATES OF FIRST-ICE, 1921-50

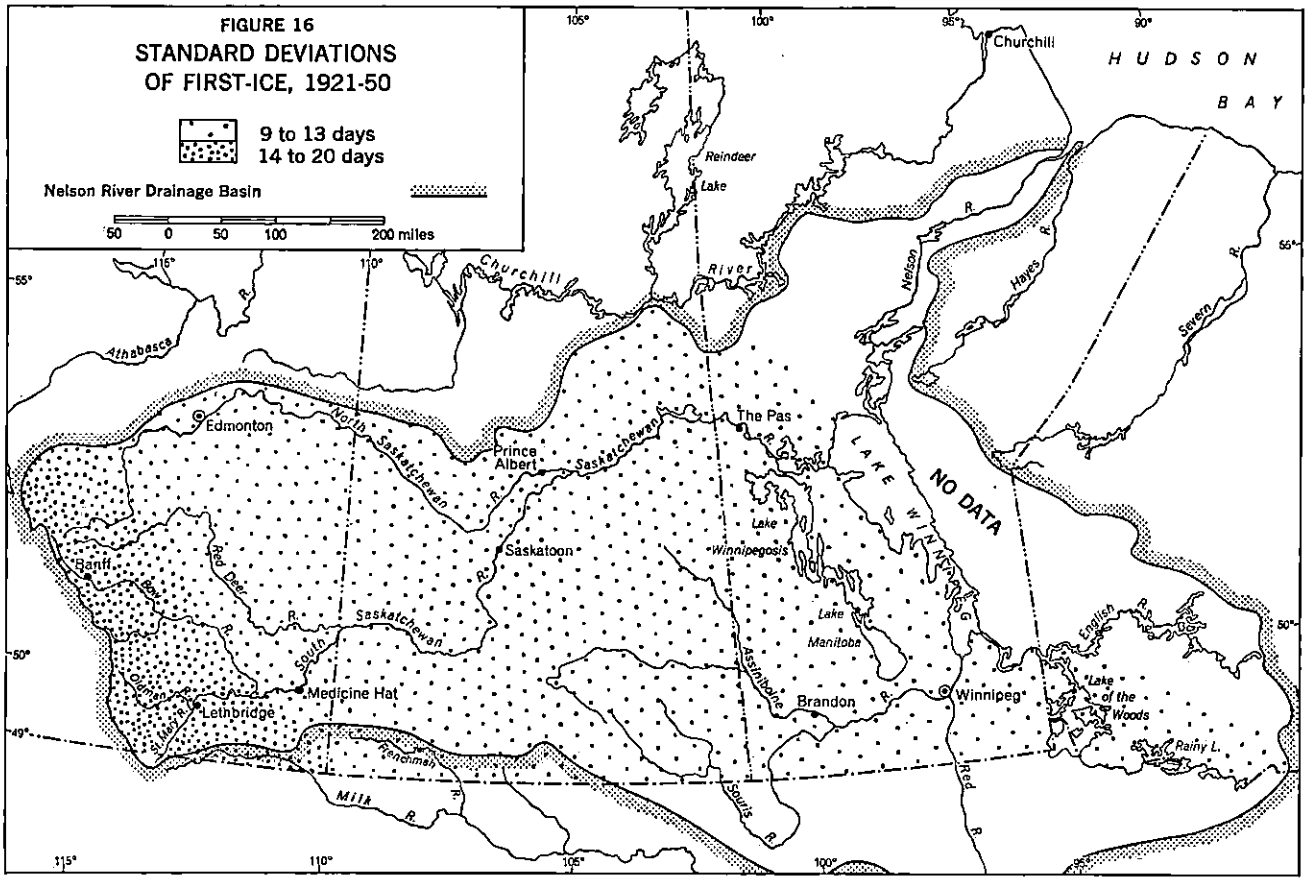


FIGURE 16
STANDARD DEVIATIONS
OF FIRST-ICE, 1921-50

FIGURE 17

MEAN DATES OF LAST-ICE 1916-25

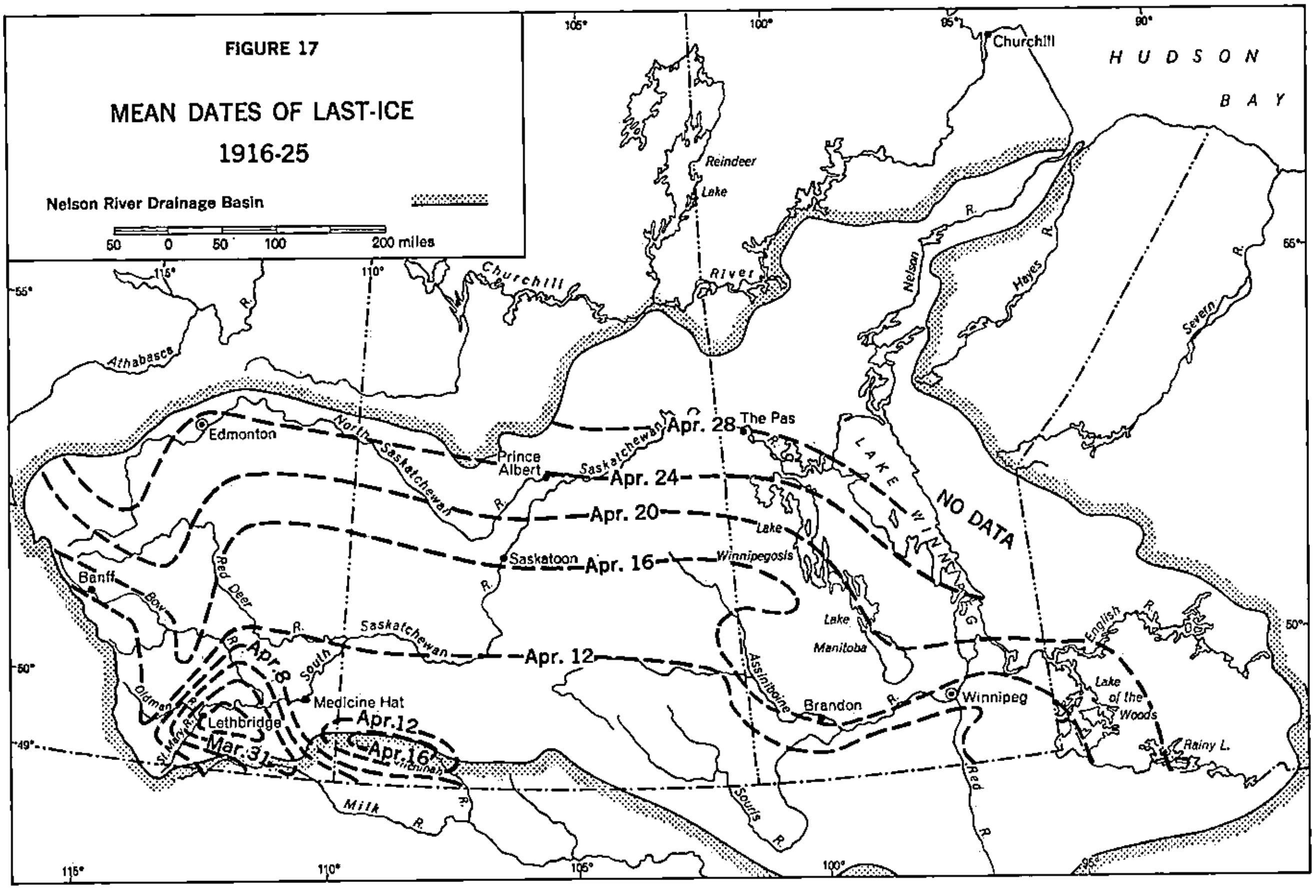
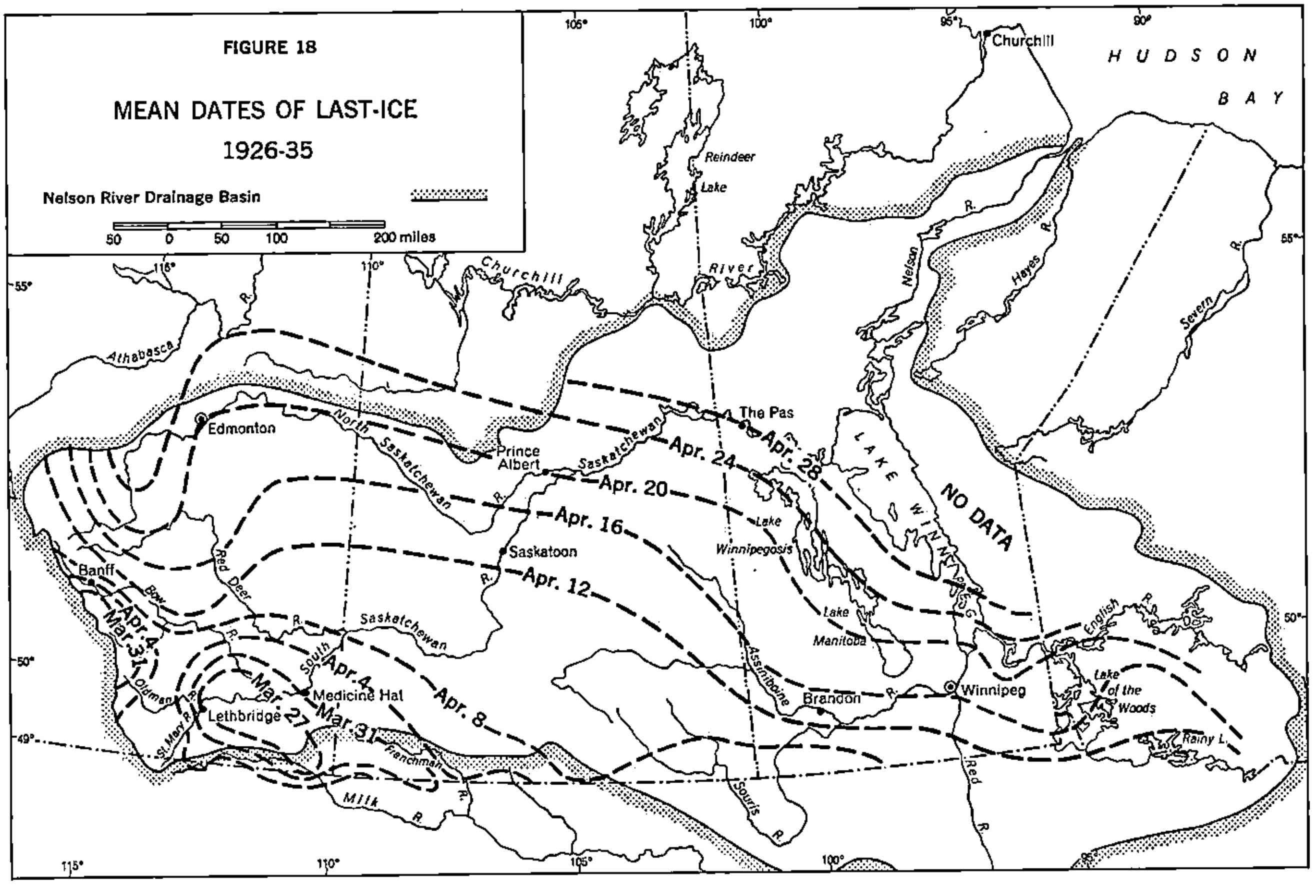


FIGURE 18

MEAN DATES OF LAST-ICE 1926-35



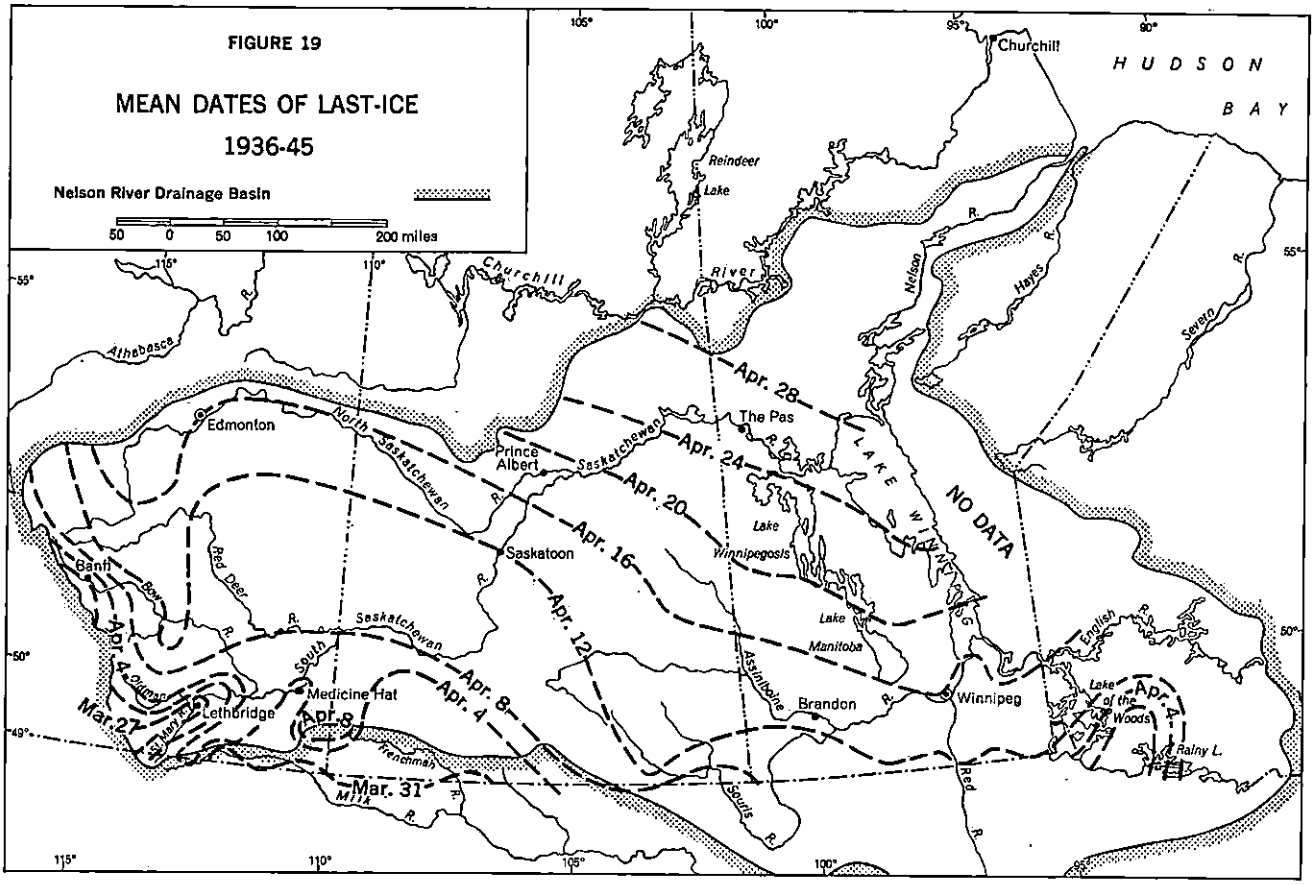


FIGURE 19

MEAN DATES OF LAST-ICE 1936-45

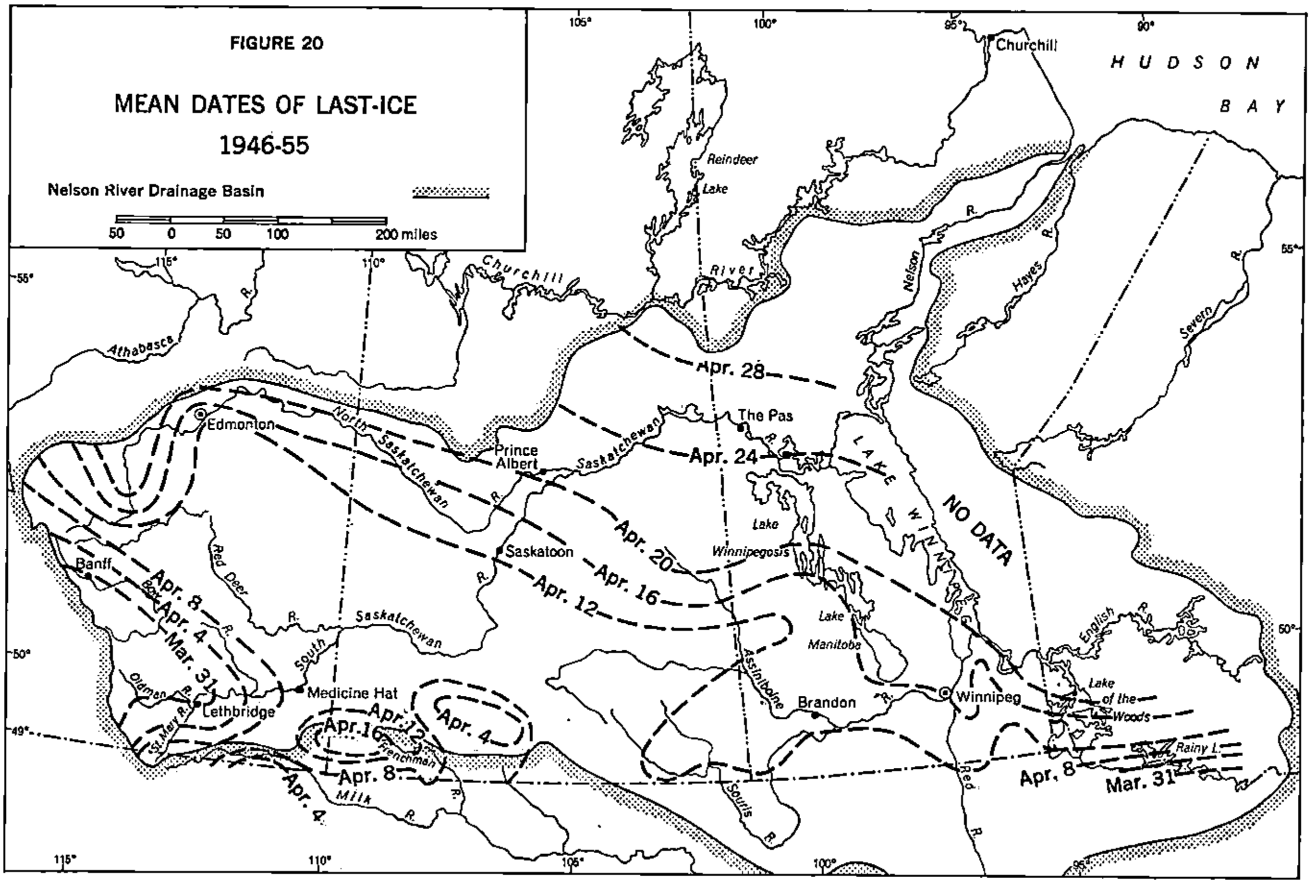


FIGURE 20

MEAN DATES OF LAST-ICE 1946-55

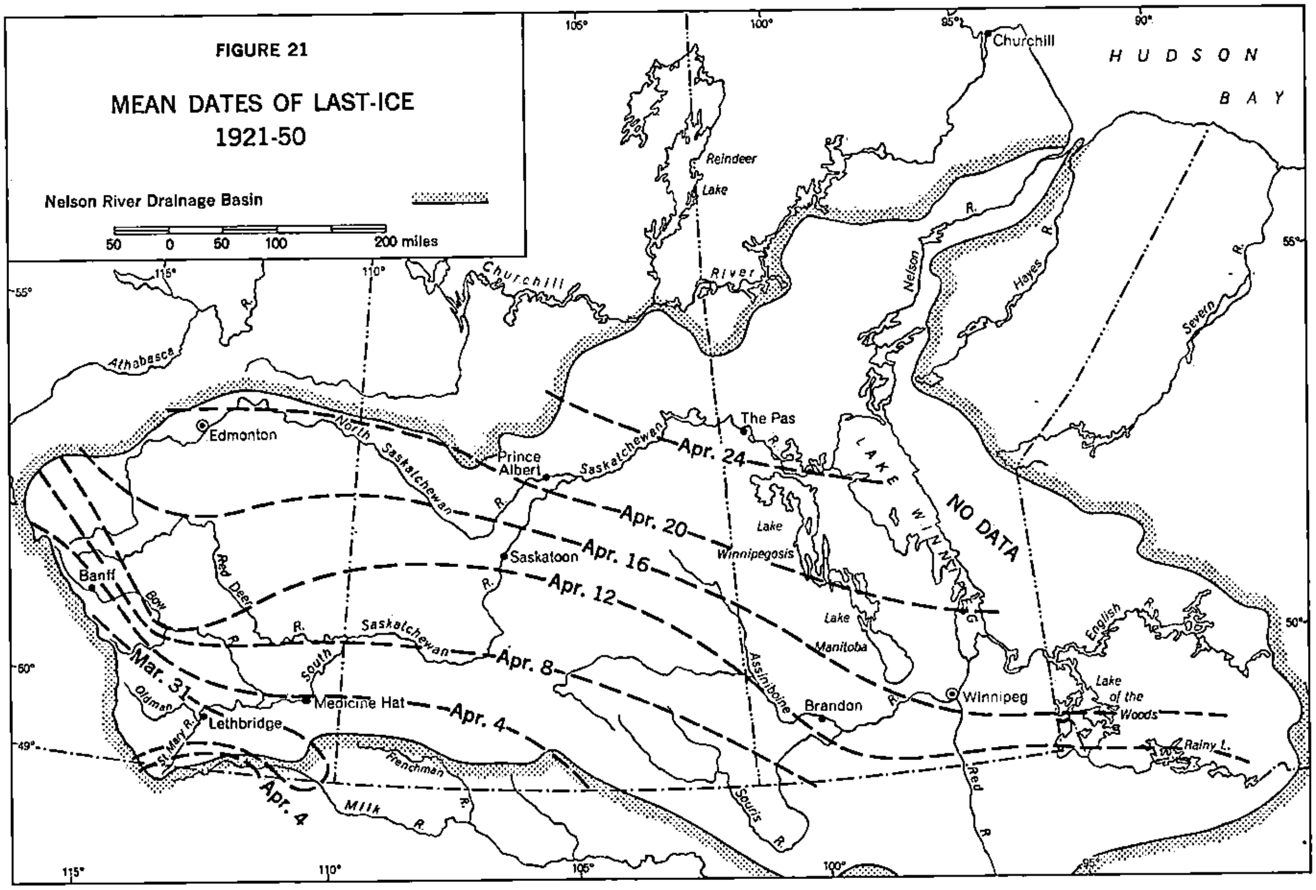


FIGURE 21

MEAN DATES OF LAST-ICE
1921-50

Nelson River Drainage Basin

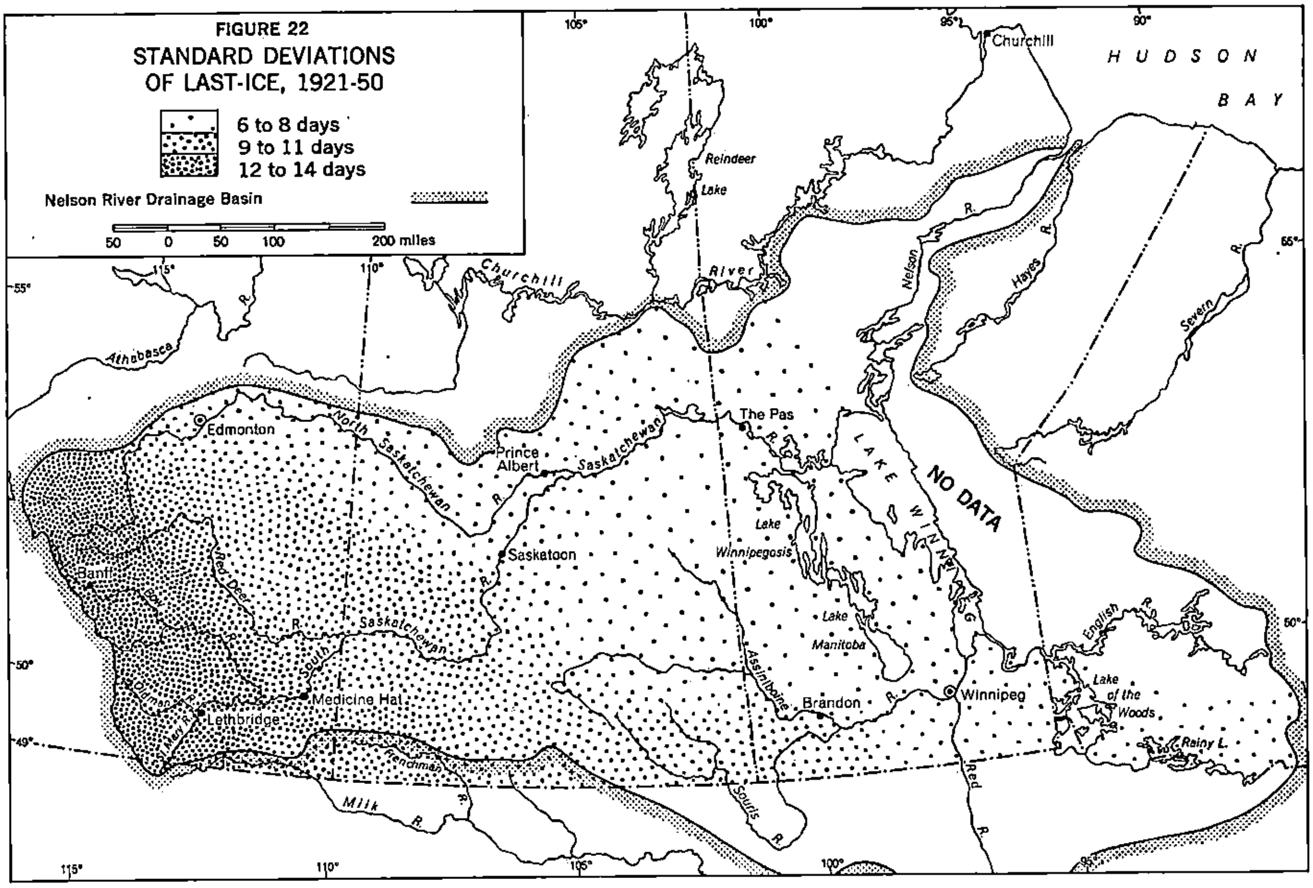


FIGURE 22
STANDARD DEVIATIONS
OF LAST-ICE, 1921-50

- ⁘ 6 to 8 days
- ▒ 9 to 11 days
- ▓ 12 to 14 days

Nelson River Drainage Basin

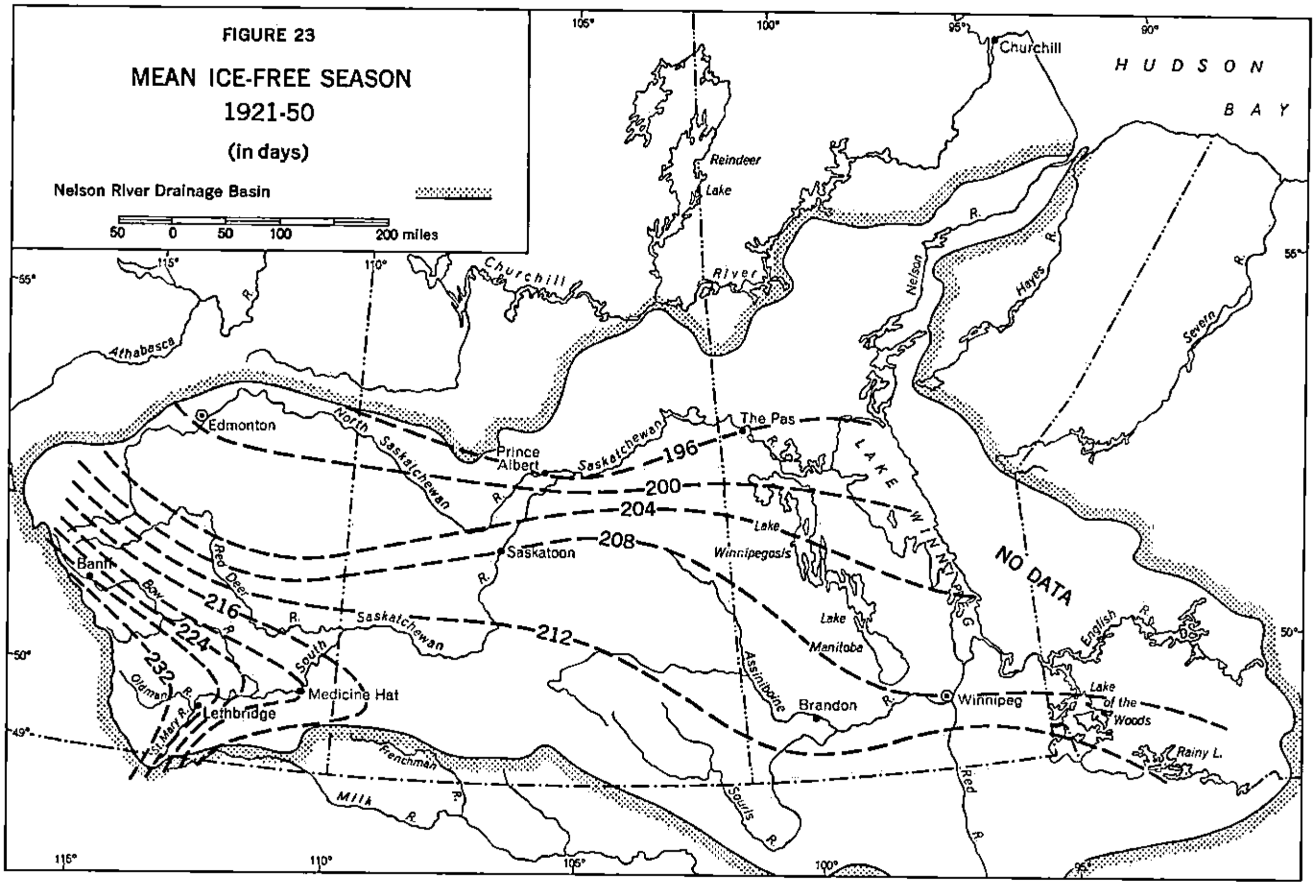


FIGURE 23

MEAN ICE-FREE SEASON 1921-50 (in days)

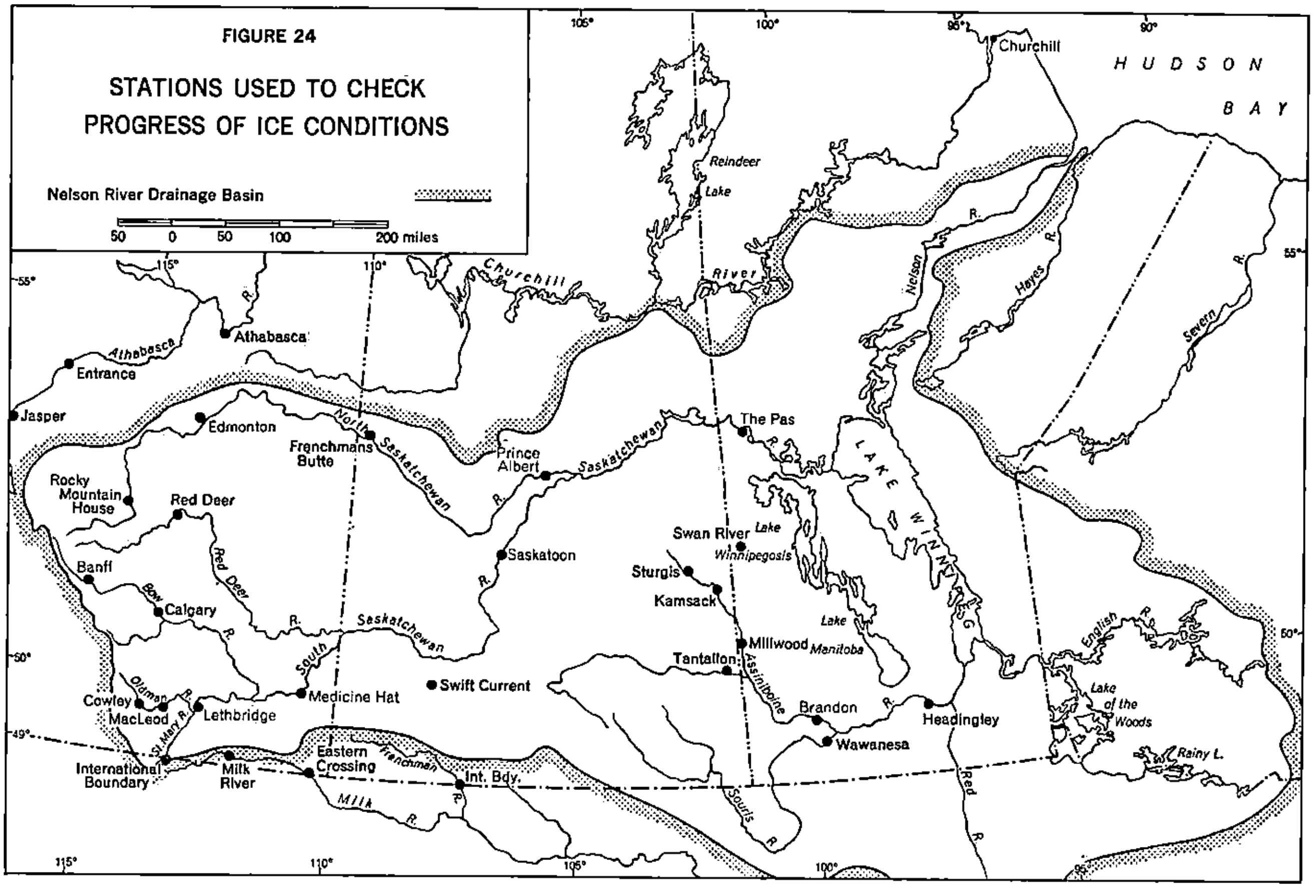


FIGURE 24

STATIONS USED TO CHECK PROGRESS OF ICE CONDITIONS