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THE ROYAL METEOROLOGICAL SOCIETY, CANADIAN BRANCH

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# THE ACCURACY OF PRECIPITATION MEASUREMENTS

by

J. P. Bruce and J. G. Potter

In the world of 20th century technology, the demand for meteorological and climatological information has been steadily growing. Many highly useful developments in forecasting techniques, and applied meteorology, have evolved as a result of these demands. However, one item in the meteorologist's portfolio of valuable data has received surprisingly little critical attention from meteorologists themselves. This item is the accuracy and representativeness of precipitation measurements.

It is perhaps natural that we have often taken measurements of rainfall and snowfall largely for granted, for the measurement of precipitation has a long and honourable history as a scientific activity of man. The earliest reference (1) we have to the actual use of a rain gauge is found among the instructions to a government chamberlain in charge of a grain store in India about 300 B.C. It was required that: "In (front of) the store house a bowl with its mouth as wide as an 'Aratni' (18 inches) shall be set up as a rain gauge. According as the rainfall is more or less, the superintendent shall sow the seeds which require either more or less water". You will note that this implies that records were kept.

For as long as men have been concerned with the measurement of precipitation, they have also tried to evaluate the accuracy and representativeness of their measurements. Many of the findings of investigators of the 18th and 19th centuries are of value to-day. A precedent for the historical approach was set by Symons (2) over 90 years ago when he stated, in referring to early rainfall records: "I think them far more reliable than modern ones; for in the 17th and early part of the 18th century to measure the fall of rain was esteemed a serious undertaking only to be accomplished by first-class men. The repeated reference to the height of their gauges, their diameter...and the details frequently given, combine to render it certain that they took every reasonable precaution to secure accuracy."

Modern knowledge of the factors which affect the efficiency of the catch of a rain gauge began when Heberden (3) first mentioned in 1769 the variation of rainfall with height. It was then postulated that electricity was involved in this phenomenon. Bache (4) in 1848, noted the effect of eddy winds upon the catch when gauges were exposed around a tower. Jevons (5) in 1861, published a paper entitled: "On the deficiency of rain in an elevated

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rain gauge, as caused by the wind". In essence, the effect is that the accumulation of precipitation on the ground exceeds what enters the gauge, because the gauge obstructs the air movement, and the vertical component of the air trajectory immediately above the gauge may be large with respect to the settling speed of the rain drops or snow particles, and thus prevent some of the precipitation from entering the orifice. In addition turbulent eddies induced by the wind in the gauge mouth may reduce the catch, and the increased horizontal wind speed over the orifice may result in the transport of small droplets across the opening which would, in undisturbed air flow, fall into the gauge.

After Jevons, various experiments were immediately begun to examine the effect of the wind by changing the size and shape of the orifice and the exposure at different heights above the ground. By 1870 Symons (6) reached the conclusion that the diameter of the gauge is irrelevant over 3 inches and in 1881 (7) presented data to illustrate how the height of the orifice affected the efficiency of the gauge (Table I).

TABLE I

VARIATION OF CATCH WITH HEIGHT (SYMONS, 1870)

| Height above Ground | Inches | | | | Feet | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 | 4 | 6 | 8 | 1 | 1.5 | 2.5 | 5 | 20 |
| Catch as % of that at 1 foot | 105 | 103 | 102 | 101 | 100 | 99.2 | 97.7 | 95.0 | 90.0 |

According to these results, there is enough turbulence around the orifice of a gauge at 1 foot to make our sample accurate only to wihin approximately 5 per cent of the actual rainfall reaching the ground. If the gauge is raised higher, the accuracy of the sample decreases.

Many of the results of these 19th century and other, later, investigations are discussed in Kurtyka's report (8). He has summarized the nature and approximate magnitude of various local sources of error that have been investigated, in the following table.

TABLE II

APPROXIMATE ERRORS IN
PRECIPITATION MEASUREMENTS (KURTYKA 1953)

| | % Error |
|---|---|
| Evaporation | -1.0 |
| Adhesion | -0.5 |
| Color | -0.5 |
| Inclination | -0.5 (approx. 1% per degree of tilt of orifice) |
| Splash | +1.0 |
| Total | -1.5 |
| Exposure | -5.0 to -80.0 |

It appears then that the likely errors are nearly all negative and thus the effect on precipitation totals is cumulative rather than compensating. It is also evident that exposure is by far the most significant factor.

Since the exposure problem is entirely a matter of wind effects on the gauge catch, many studies have been done on catch deficiencies at various wind speeds. A summary of the results of many of these experiments has been given in graphical form by Wilson (9) and is reproduced as Fig. I. His figures apply to the U.S. Weather Bureau standard gauge, and he was not certain in each case of the anemometer heights from which the wind data were obtained. However it is clear from the graph that the effect of wind on the catch of an unshielded gauge is likely very important in rain, and nearly disastrous in snow.

It will be noted that the term "local sources of error" is used above. In a discussion of the accuracy and representativeness of precipitation measurements, some consideration must be given to "non-local errors", that is, the effect of the areal variability of precipitation on the reliability of our samples. Middleton and Spilhaus (10) have vividly illustrated the fact that by means of rain gauges we are able to sample only an extremely small proportion of the precipitation that reaches the ground. They note that if a gauge network density of one 8"-diameter gauge for each 10 sq. miles existed in a particular area (such a network density is very rare in North America), then one gauge orifice's area "is only one-eight-hundred-millionth of that of the region which it is taken to represent".

This is not quite as bad as it sounds, however, as there is a fair degree of uniformity of rainfall over an area even in individual general storms. In the case of isolated showers, there may, of course, be serious errors in areal rainfall estimates due to the inadequate size of our sample. Over a period of time though, the individual storm errors will tend to be compensating, providing local orographic effects are not significant. As local error sources tend to be cumulative, rather than compensating, Middleton and Spilhaus sum up the matter, "It therefore behooves us to make our sample...as accurate as we can, and in particular to keep it free from local sources of error".

Before we turn to suggestions for minimizing local errors, it would be instructive to consider some of the present uses of precipitation figures, and the potential economic value of more reliable data.

Much of the impetus in recent years for investigations and critical appraisal of precipitation measurements has come from hydrologists and hydrometeorologists who are, of course, primary consumers of precipitation data. The hydrological problems in which questions of accuracy of rain and snow observations arise include storm studies for establishing design criteria for river and local drainage structures, annual and seasonal water budget investigations, and streamflow forecasting from weather observations.

When dealing with the water supply and flood problems of a moderate size drainage basin, the volumes of water involved are enormous. For example, suppose gauges indicate an average storm rainfall of 2" over the Upper Thames River Watershed in south-western Ontario. Let us assume that the average error of measurement due to various factors is 5% (a conservative figure). This .10 inch error over the 1,325 sq. mi. watershed represents the astounding volume of 2.3 billion gallons of water. This amount of water would supply the population of the City of London for at least 6 months.

The importance of accurate precipitation measurements in water supply planning is thus readily apparent. In flood situations, the possible errors in rainfall measurement may make the difference between a serious flood or just high river levels. In designing dams, bridges and other river structures, accurate rainfall records at times of historic severe floods, are essential to make judicious decisions on the river flows the structures should be designed to accommodate.

The importance to the hydrologist of reliable snow water content observations is difficult to over-rate, in this country. Such organizations as the Ontario Hydro-Electric Power Commission, Shawinigan Pulp and Paper Co., and the Ontario Department of Planning and Development spend considerable sums of money each year to obtain measurements of the water equivalent of the snow accumulated on the ground before spring break-up in order to forecast flood flows and water supply volumes.

In land use planning, persistent errors in seasonal precipitation totals may lead to false ideas about the capability, or lack of it, of a given area to support a particular crop.

In attempting to assess the water balance of barren areas such as the Arctic, a critical appraisal of precipitation data has led to much concern. For example, Black (9) has suggested that the precipitation at Barrow, Alaska may be "two to four times as great as recorded".

In planning city sewer systems, and highway and airport drainage, accurate and reliable rainfall intensity data are a prerequisite to economical design.

The list could go on for several pages, and a much more complete account of the engineering use of rainfall data has been given by Jens (11). However, the examples do serve to indicate the great economic importance of precipitation measurements which accurately indicate actual quantities of water reaching the ground.

Two specific examples of the hydrometeorological problems which depend upon reliable and accurate precipitation methods may be in order.

Some doubts have arisen recently regarding the catch reliability of the Malton gauge in connection with flood forecasting in the Toronto area. The Malton observations are relied on heavily by the flood warning organization of the Metropolitan Toronto area, as it is a 24-hour station with paid staff in continual attendance. Thus any possible local inaccuracy in the Malton catch may have serious consequences.

In a preliminary investigation of this matter, isohyetal maps were drawn for 15 storm occurences in the Toronto area, using data from all climatological stations but Malton. The rainfall that would have been expected at Malton judging from the observations at surrounding stations was estimated for each storm from the isohyetal map. These figures were compared with observed Malton rainfall data. The precipitation that would have been expected at Malton from observations at surrounding stations exceeded the observed by an average of 18%. To see if such an effect was observable in yearly rainfall totals, those for Malton and the three nearest surrounding stations, Brampton, Woodbridge and Islington, were compared. For the 5 years 1951 to 1955 Malton rainfall averaged 25.90" and the mean of the other 3 stations averaged 28.07", 8.4% greater than the Malton figure. Malton averaged less than each of the 3 for the 5 years. Although the above figures are not conclusive, they tend to indicate that some agency is at work reducing the catch of the Malton gauge. It may be orography, or a rain shadow effect due to a building, but the most likely culprit is the effect of exposure. It has been suggested that the Malton gauge may be subject to high winds due to a funnelling effect particularly in south-easterly circulations, and what is more alarming, is that from our information, it seems likely that the Malton gauge is more sheltered than most of those at airport sites.

It is suspected from streamflow observations in the Toronto area, that the precipitation figures reported at the time of storm "Hazel", may be as much as 18% too low, due to the strong winds which accompanied the rainfall. Yet "Hazel", as observed, is being adopted more and more frequently in southern Ontario as a "design storm" for costly hydraulic structures.

In summary, the hydrologist, hydrometeorologist and many other consumers of precipitation data place great emphasis on the need for representativeness and accuracy, as they are interested in quantitative figures accurate in an absolute rather than in a comparative sense. The nature of some of their requirements are as follows:

(1) a greater raingauge network density and the use of weather radar to ensure accurate estimates of volumes of rainwater reaching the ground,

(2) more rainfall intensity measurements, particularly during winter when heavy rainfalls often produce floods, and most tipping-bucket gauges are not in use,

(3) closer attention paid to the siting and possible shielding of gauges to reduce the effect of exposure on gauge catch, as well as a

greater knowledge of the catch efficiency of the M.S.C. standard gauge at various wind speeds and in different exposures,

(4) measurements of the water content of newly fallen snow, and of the snow accumulated on the ground.

Some of these requirements can be met, in areas of hydrologic concern, by establishment of auxiliary networks. For example the Conservation Branch of the Ontario Department of Planning and Development has installed some 40 plastic wedge-shaped gauges to obtain special readings during storm and flood periods for flood forecasting. These are cheap, very easy to read and accurate. Huff (12) has tested them against U.S. Weather Bureau standard gauges with very satisfactory results, and preliminary results of testing against M.S.C. standard gauges are very encouraging.

This agency has also had established a number of recording precipitation gauges. These are of the weighing type and thus are year-round instruments which, while not quite as sensitive as the tipping-bucket gauge, are capable of measuring winter rainfall intensities, and snow water content, as the precipitation occurs. They are equipped with Alter wind shields to ensure as reliable as possible catches of snow and rain.

However, a number of these requirements must be met by the Meteorological Service as standard procedures and instrumentation are affected. To indicate how the necessary changes might be introduced we should examine more carefully the question of the accuracy of our present observing methods.

Apparently our present gauge was not always used in Canada. In a publication (13) of monthly rainfall for Toronto for 1840-41-42 the following footnote appears: "The receiving surface of the anemometer rain gauge was 9 feet above the ground". We have not been able to discover to whom the considerable credit for designing and adopting the present gauge should be given. Its adoption must have been almost concurrent with the work of Symons and it took advantage of all the knowledge available at that time. The following table (III) indicates that the effect of wind on the catch of the Canadian gauge, with its low exposure height, should be as small or smaller than on any other standard gauge presently in use. The work of Denison (14) in testing the M.S.C. gauge against the U.S. Weather Bureau gauge would tend to bear this out.

TABLE III

COMPARISON OF INTERNATIONAL STANDARD GAUGES

| Country | Type Gauge | Diameter (Inches) | Height of Orifice (Inches) |
|---|---|---|---|
| Canada | M.S.C. | 3.57 | 12 |
| England | M.O. pattern | 8 | 12 |
| England | Snowdon | 5 | 12 |
| Australia | 8-inch type | 8 | 12 |
| France | Tonnelot | 8.88 | 28.3 |
| Austria | Kostlivy | 9.93 | 30.3 |
| United States | U.S. Weather Bureau Standard | 8 | 31 ± |
| France | Scientific Association | 8.88 | 39.4 |
| China | Board | 7.91 | 39.4 |
| South Africa | 5-inch type | 5 | 48 |
| Holland | DeBilt | 8.88 | 59.1 |
| Germany | Hellmann | 6.28 | 59.1 |
| Sweden | Swedish | 14.06 | 59.1 |
| Russia | Russian | 9.93 | 78.8 |

The question arises concerning why other standard gauges differ so radically that they appear to neglect the effect of the wind. The answer likely lies in the custom of measuring only rain in the gauge in Canada, while most other gauges are precipitation gauges, for measuring both snow and rain.

Instructions concerning the siting of the Canadian gauge and the methods of measuring precipitation as described by Kingston (15) in 1878 are almost identical to those currently in use.

Since 1878 we have extended our network of rain gauges throughout the prairies and northward into the Arctic. Our primary network more recently has seen many moves from town to airport locations. In 1878 the chief problem in exposure at any observatory or schoolyard would be to keep the gauge away from buildings or trees. Kingston likely had this in mind in his instructions for a "well exposed" gauge and we apparently continued to worry about this problem without considering the problem of over-exposure. The effect of the wind on our gauge in a naturally sheltered yard in 1878 would not be comparable to that on the same gauge today at an open airport site surrounded by tarmac and possibly mounted on a post or the Stevenson screen, for a variety of plausible reasons. The wind speed at the gauge orifice, even at 1 foot, under these circumstances is likely sufficient to make the catch deficiency in our sample as great or greater than that suggested in Table I.

Gauges should then be exposed at sites with some natural shelter whenever possible. When none is available, artificial sheltering is necessary. Methods employed to overcome this difficulty are of two main types. First, since we are trying to catch a sample of the rain at the ground, why not dig a pit for the gauge and have the orifice at ground level? The pit must be large enough to get away from splashing into the gauge. Then, there are difficulties with drainage and the filling of the pit with snow. A model suggested by Koschmeider (16) uses a brush mat and honeycombed grid to cover the pit. This cuts down turbulence in the pit and makes it possible for the observer to get to the gauge easily. An English modification (17), to get away from the drainage problem, is to place the gauge on the ground and build a circular turf wall around the gauge. This wall should be as high as the orifice, 5 feet in diameter, with the outer slope being 15°, and having a turf cover to prevent splashing.

In countries where snow as well as rain is measured in the gauge, shielding of gauges is usually accomplished by some modification of the inverted cone shield originally invented by Nipher (18) in 1878 or by an Alter shield (19). Air below the level of the gauge orifice is deflected downward by the shield and the flow across the gauge mouth left relatively undisturbed. The present Canadian snow gauge (20) undergoing field trial, has a modified Nipher shield and might be used also to measure rain. Before adopting it for this purpose it may need the further modification of a fine wire mesh above the rim of the shield to break up those drops which might cause splashing into the inner container.

To make the best use of all the above experimental data, the following suggestions to improve rainfall measurements should be considered. Where there is some natural shielding the gauges should all be exposed at the prescribed height. Exceptions should not be tolerated. There may be as many as 50% of M.S.C. gauges which are exposed now at heights greater than 1 foot. If an over-exposed site must be used, and this applies to a majority of sites at airports in the prairies and in the Arctic, consideration should be given to adopting some method of artificial shielding. In addition, field testing of the quantitative effect of winds of various speeds on the catch of the unshielded M.S.C. standard gauge, should be encouraged.

In considering the data required on that part of our precipitation which falls as snow, there are really two measurements we must make, the depth of the freshly fallen snow in inches, and its water equivalent. Only 3 countries are presently keeping records of the depth of the freshly fallen snow in inches, Canada, U.S.A. and West Germany (since 1945). The instrument put in the observers' hands to carry out this observation is perhaps the simplest of all - a ruler.

The difficulties under which this observation of the depth must be carried out to give us reliable data are seemingly insurmountable. They begin when the snow is not uniformly distributed unless it falls in calm conditions. The depth of snow also changes rapidly with time due to melting or to the breakdown of the crystal structure due to wind action, gravity, etc. Thus two sets of equally conscientious observations made at the same site, one at six hourly intervals and one at 24 hourly intervals will yield quite different data. An ideal site for making such observations would be a small clearing in a forest or orchard. Since observers cannot all be re-located at these ideal sites, the following aids should be made available to them for measuring snow depth: 1. A sheet of plywood covered with white flannel to give an even reference surface for measuring and to reduce melting which occurs on the ground at temperatures near 32F. 2. At primary stations where the site is over-exposed, a Nipher shielded snow gauge with a container designed in such a way that the observer can measure the depth of the accumulated snow in the container. In these ways the public requirement for reasonably accurate snow depth measurements could be provided. However, for most scientific and engineering purposes the emphasis should be shifted to direct measurements of the snow's water equivalent.

The Canadian method of using the factor 0.1 to convert the depth of snow in inches to its water equivalent is unique. Errors in the resulting data are due to the difficulties we have already enumerated for measuring the depth in inches, as well as the error in the fact that 0.1 is an unreliable factor for all parts of Canada, and for individual snowstorms. Currie (21) suggests that an average ratio of 0.083 would be more accurate for the snowfall at Saskatoon, while indications are that a greater error occurs in the data from the Arctic. In one snow storm in southern Ontario on April 5, 1957, reliable measurements indicated that the wet snow had a water equivalent of 0.14 and for individual storms during two winter months at Ottawa it varied from 0.02 to 0.13. Thus the use of the factor 0.1 results in an error of approximately 20% in some monthly and seasonal precipitation amounts and even greater errors in estimating the water production of individual storms. In the dry areas of the Prairie where moisture is critical and our data are subjected to exhaustive statistical studies, the error introduced in the total annual precipitation would be approximately 6% based on the ratio suggested by Currie.

The only reference to be found for adopting our present method is described by Kingston (15): "A long series of experiments made under the former director of the Toronto Observatory (General Lefroy), led to the conclusion that ten inches of snow is equivalent on the average to one inch of water. It is not affirmed that this holds true in every case, as the snow varies in density." In the next paragraph Kingston gives a second method of ascertaining the water equivalent by means of a "snow gauge" which was really a sampling tube 12 inches long with cross section equal in area to the mouth of the rain gauge. After a sample was obtained it was melted and measured as rain.

The Meteorological Branch has a shielded snow gauge whose efficiency was studied in wind tunnel tests and which has undergone a lengthy field trial. The latter has indicated that it should be mounted on an adjustable stand. Great care need also be taken in choosing a site to be free from extreme drifting as some have been covered with drifts and others filled by snow blowers. If this gauge were issued to all first order stations to measure the water equivalent of snow directly, it would also be necessary to adopt a comparable method for the 1400 other stations manned by climatological observers to retain consistency. It may be financially and physically impossible to install a gauge for each of these. A suitable alternative in the form of a simple sampling tube by means of which a sample, or samples, representative of the snowfall could be lifted, and the water equivalent determined by melting or weighing, should be developed and supplied to all observers. This alternate method, with a conscientious observer, could give the more accurate results. Huddleston (22) after 7 years experiments in England noted that: "In snow, every kind of rain gauge, whether it be bare or sheltered by artificial means, becomes utterly unreliable. - The only sound procedure --- is to take a 'cheese' of the snow off the ground at some place where it seems to be of average depth and melt it at your leisure." Efficiency of shielded gauges in snow is usually claimed to be about 90% with winds of 8-15 mph but decreases rapidly with increasing wind speed. However, efficiencies of unshielded gauges in catching snow at wind speeds of 8-15 mph but decreases rapidly with increasing wind speed. However, efficiencies of unshielded gauges in catching snow at wind speeds of 8-15 mph are about 60% (see Fig.I). Thus, even at stations equipped with shielded snow gauges, it would be desirable to use the sampling method as a check against the gauge observation.

In conclusion, the Meteorological Service of Canada has apparently made no change in the official methods of measuring precipitation since 1878.

The application of precipitation data to hydrologic, agricultural, building design and other problems is placing an increasingly great economic value on accurate precipitation data. Those who must make engineering and agricultural decisions based on this data should be made aware of its limitations. In considering possible improvements of standard measurement methods, adoption of the outlined suggestions would take advantage of the investigations which have been carried on during the last 80 years, and would also change observing practices to conform with those recommended by the World Meteorological Organization (23).

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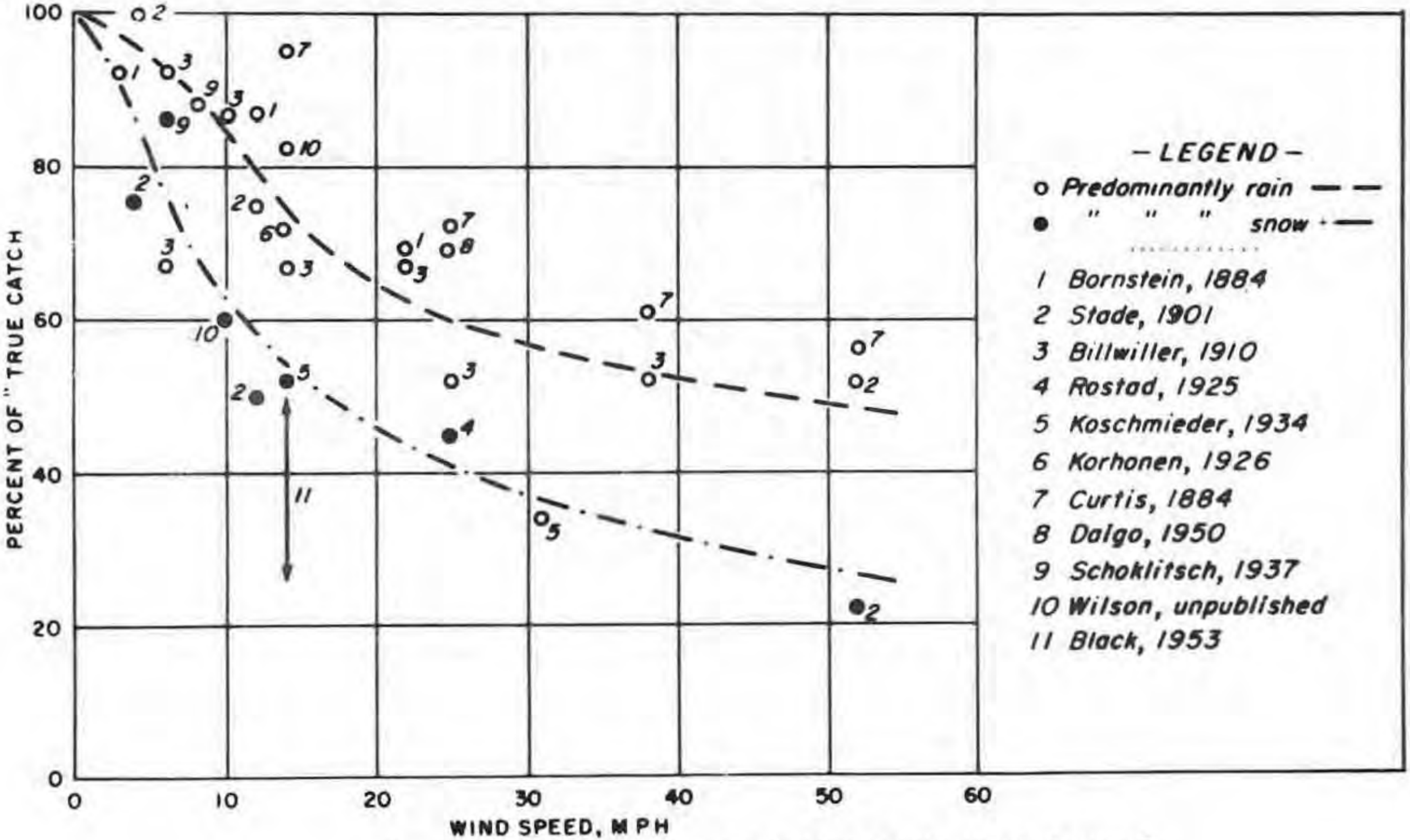
FIG I (AFTER WILSON)




-General relation of precipitation catch to wind speed

# A PRELIMINARY INVESTIGATION INTO BREAK-UP AND FREEZE-UP CONDITIONS IN CANADA*

by
F. E. Burbidge and J. R. Lauder

## ABSTRACT

Information on the ice conditions on rivers and lakes in Canada is tabulated. Maps are drawn showing the average dates of break-up and freeze-up. A study of the meteorological conditions prior to break-up and freeze-up is made to determine the critical number of days of thawing and freezing that are required to produce these changes. It is hoped that a more detailed study can be made when new information and more years of records of the ice conditions have been obtained.

## 1. INTRODUCTION

1.1 The dates of break-up and freeze-up of the inland and coastal waters of Canada are of vital concern to certain transportation interests. River navigation has been used since the days of the early explorers, and in later years the frozen rivers and lakes were used as bridges by many types of land traffic. More recently, the most popular method of transportation in the North has been the light aircraft, which uses floats for summer operations and skis during the winter. Thus a considerable amount of information has already been gathered on this topic, and the purpose of this study is to collect all the available data, and, at the same time, determine if any method can be derived whereby forecasts of the date of occurrence of the seasonal changes can be made.

1.2 It has been very difficult to arrive at any universal definitions of the terms "Break-up" and "Freeze-up". In most cases "Break-up" is considered to be the date when the ice moves in a river, or clears from the shores of a lake, and this was the definition accepted and applied herein. "Freeze-up" can be defined as the date when ice forms and begins to grow, but may sometimes be listed as the time when skim ice or slush ice first forms. In the opposite extreme, some observers do not believe that the "Freeze-up" is

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official until the ice is thick enough to walk on with safety. In this study all three definitions of "Freeze-up" are considered, but in the preparation of maps, the date of first ice formation has been used.

1.3 As several excellent reports have been published by the U.S. Navy Hydrographic Office on the formation and growth of sea and fresh ice, (1), (2), (3), this topic has not been considered. Dates of the opening and closing of certain Arctic seaports have been included to make the survey complete, but no attempt has been made to evaluate ice conditions in the larger bodies of salt water which surround the islands of the Arctic archipelago.

Reports by C. N. Forward on ice conditions in the Gulf of St. Lawrence and along the Hudson Bay Route have appeared in the Geographical Bulletin (4), (5).

1.4 No attempt was made to include a survey of ice on the Great Lakes, as a report by W. W. Oak (6) already covers this subject.

## 2. DATA AVAILABLE

2.1 The largest source of current information was the "Directory of Hinterland Aerodromes" (7) first published by the RCAF in 1949, and amended yearly thereafter. This gives "average" dates of freeze-up and break-up for a great number of Canadian stations. The information was originally obtained in a survey, made in 1946-47, of all points in Canada where ice or water aircraft landings were made. Unfortunately, in some cases the information was either vague or was based on only one or two years of record. Thus it cannot be classed as reliable. A second source was an unpublished paper by W. T. R. Allen, "Dates of Break-up and Freeze-up of Rivers and Lakes in Canada" (8) which contains data for a limited number of stations for the period 1950 to 1954. While this information is reliable, it is in many cases not given for the full five-year period, and in several instances covers only one or two years.

2.2 While these two sources have supplied the bulk of the data used, a good deal of information on various points was obtained from other sources. Notably, the Northern Transportation Company supplied valuable data on the Mackenzie River watershed, and Canadian Pacific Airlines gave some exact information on the lakes in Northern Alberta and the N.W.T.

2.3 In all, information from some 360 stations has been tabulated and used in the preparation of the maps shown as Figures 2 and 5. Of the records on file, only a very small percentage can be considered to be highly reliable, with the information covering periods of 10 to 40 years. The great majority of the data was rated as fair, where 3 to 9 years of records were available. Approximately 10% of the data was rated as poor, because the coverage might be only for a single year, or the data could not be checked.

# 3. THE BREAK-UP

## 3.1 Process of Break-up in Lakes

### 3.1.1 Melting of Lake Ice

Lakes are very slow in clearing of ice since most of the ice must be cleared by the gradual process of melting. With the exception of a few lakes that happen to have a wide river down which the ice can be disgorged, the thawing temperatures in the Spring must overcome the latent heat of fusion of ice. The melting of snow on the shores and run-off from the surrounding land usually creates a narrow shore break although in some cases there is considerable flooding of water over the top of the lake ice. This shore break usually occurs at the same time as the rivers break up.

As the melting of the snow and ice proceeds the lake ice becomes covered with slush and water from the melting snow chich has covered the ice during the winter. The lake ice becomes candled and porous, loses its tensile strength and is easily shattered into fragments and finally is dissolved.

### 3.1.2 Effects of winds

Once the lake ice is floating free of the shore, the wind becomes important in driving the ice away from one shore and packing it against the opposite shore. Once the ice has become candled, a strong wind hastens the clearing of the ice by crushing it. However in doing so it usually piles rafts it on the windward shore.

### 3.1.3 Size of Lakes

The size and depth of a lake has an important bearing on the time of ice break-up. The ice on small lakes melts much sooner than on large deep lakes. The flood of slightly warmer run-off water from surrounding land has a relatively high volume in the case of small lakes and the lake water temperature is raised much more quickly.

### 3.1.4 Effect of Snow Cover

A heavy snow cover on top of the lake ice delays the melting of the ice since considerable heat is required to melt this snow. In a year of heavy snowfall the delay has been estimated at about two weeks. No definite figures are available since there are many complicating factors.

The thickness of the ice is another important factor and this depends on the severity of the winter and also on the amount of snow and the time of occurrence of the snowfall; for example, a heavy snowfall, if it occurs right after freeze-up, will insulate the ice and result in less total thickness of the ice in the Spring.

A quantitative graphical evaluation of the blanketing effect of snow cover has been made by E. B. Calloway (1). From his graph (using several meteorological parameters including an initial ice thickness of 6 inches, an air temperature of $-4^{\circ}F$, and a wind speed of 10 miles per hour,) the following data have been computed to illustrate the insulating effect of snow.

To add 4 inches of ice with no snow cover takes approximately 2 days
To add 4 inches of ice with 4 inches of snow cover takes approx. 8 days
To add 4 inches of ice with 8 inches of snow cover takes approx. 14 days
To add 4 inches of ice with 12 inches of snow cover takes approx. 20 days
To add 4 inches of ice with 20 inches of snow cover takes approx. 32 days
To add 20 inches of ice with no snow cover takes approximately 18 days
To add 20 inches of ice with 4 inches of snow cover takes approx. 48 days

## 3.2 Process of Break-up in Rivers

### 3.2.1 Melting of River Ice

The break-up of ice in rivers is much earlier than in lakes because only a portion of the ice has to be melted. Only enough melting is required to create a break in the ice along the shores. Then the flood of run-off water from the surrounding land increases the water volume of the river, creating a lifting force on the ice and also results in a greater surface area on which the ice can float downstream.

### 3.2.2 Water Pressure

The current in the river exerts a considerable pressure on the ice and helps break the ice free from the land. This pressure, plus the increased river volume, plus the melting of the ice, combine to break the ice and float it downstream.

### 3.2.3 Ice Jams

Different configurations and local factors along a river valley result in different places having break-up at slightly different times. Various restrictions in the course of the river result in bottlenecks which delay the breaking of the ice so that the river ice tends to break up in sections. These bottlenecks are also the usual places for ice jams to form and they delay the clearing of the ice floes. The tremendous pressure of the ice and water plus the flooding, usually forces the ice through the bottleneck within a few days. Large chunks of ice are frequently left stranded on the shores but the river is usually clear of ice within one or two weeks of the time of break-up.

## 3.3 Duration of the Break-up Period

3.3.1 Lakes

As would be expected, large lakes take a longer period to become completely ice-free than do small lakes. Lake Atlin, for example, clears in 4 to 6 days, once the ice has broken, whereas such lakes as Athabaska, Great Slave and Great Bear may require six weeks before all the ice disappears.

3.3.2 Rivers

Investigations were made to determine the length of time required for river ice to break, once melting had begun. At Edmonton, the North Saskatchewan River ice requires 12 to 18 days with the mean daily temperatures above freezing before the ice moves out of the river. The Mackenzie River at Fort Good Hope and Aklavik seems to require about the same period of time, as does the Coppermine River at its mouth, the Klondike River at Dawson City, and the Hay River at its mouth. Figure 1 (a) shows a graphical comparison of the long-term daily mean temperatures for Edmonton with the date of break-up. Figure 1 (b) to (g) graphically illustrates the temperatures at Edmonton prior to break-up for the years 1951 to 1956. The degree-days of thawing have been computed on these charts and the average figure for Edmonton is 77 degree-days prior to break-up.

3.3.3 Rivers compared to Lakes

As indicated above, the process of break-up in a river differs from that in a lake. Thus there is a considerable difference in time, when comparison is made between rivers and lakes in the same geographical area. The variation may run as much as six weeks, and normally is 3 to 4 weeks. At Edmonton, in 1956, the river cleared on April 14th, yet nearby lakes were not ice-free until May 19th. Earlier years' records for the Edmonton area show variations of from two weeks to a month. Data from White River, Ontario, indicate that three weeks is the normal time delay between the ice moving out of the river and from lakes in the vicinity. The break-up date for a river usually coincides with the occurrence of a break in the ice along the shore of a lake in the same area and this date has been used as the time of break-up. The average date of the complete clearance of ice has been recorded in the case of some of the larger lakes.

3.4 Fresh Water Ice vs Sea Ice

3.4.1 There are some ten stations where the occurrence of break-up of both fresh and sea ice are reported. Nearly all these points are located on the sea at the mouths of rivers, so in addition to comparing fresh and salt water, the comparison is between moving fresh water and the ocean. The sea ice is normally later to disintegrate, being about one month later than the fresh water ice; e.g., at Fort Chimo the fresh ice disappears about June 1st while the sea ice remains until July 1st. At Hebron harbour the fresh ice goes on May 15th and the sea ice on June 15th.

## 3.5 Relationship with Mean Temperature

3.5.1 Figure 2 shows the average dates of break-up for lakes and rivers in Canada. To prepare this chart, dates of break-up for the 360 stations covered in the survey were plotted and isopleths drawn for half-month intervals. It was necessary to do a considerable amount of smoothing of the isopleths to obtain the results as shown. In addition, the 32 degree isotherms for the spring months are drawn on the chart. These must be considered as approximate. The April isotherm is taken from a map in the "Climatological Atlas of Canada" (9) but the others were obtained from temperature maps prepared locally.

3.5.2 From the chart, it can be readily seen that a direct relationship exists between mean temperature and date of break-up. It is difficult to define the exact period of time required for the temperature conditions to take effect, and it is true that this period will vary from year to year. In addition, the weight which should be given to other factors such as snow cover, pressure of water in a stream, etc., has yet to be calculated. However, the close relationship between isopleths and isotherms would indicate that the controlling feature is the temperature.

3.5.3 In the hope that monthly deviations from normal could be utilized, a study was made of ten widely scattered stations. The date of break-up was compared to the mean temperature for the month prior to the occurrence, and in some cases the two-month period prior to break-up was investigated. The results indicated that the trend was in the right direction, but were far from being conclusive; for example, at Peace River the break-up was very late when April's monthly mean was 13 degrees F. below normal and it was early when April was 8 degrees above normal. But it was "average" with April mean temperatures 5 degrees above normal, 4 degrees below normal, and when no difference from normal was noted. Fort Nelson was late with April 17 degrees below normal, but was even later with April 15 degrees below normal, yet was "average" when April and March showed 5 and 8 degrees respectively above normal. In other years, the March and April temperatures were close to the normals, and the break-up occurred on the average date. These cases would indicate that the monthly period is too long for any exact correlation to be found.

3.5.4 Long-term records for Edmonton (1881-1955) show that the average date on which the daily mean climbs above freezing is April 2nd. The average date of break-up of the North Saskatchewan River at Edmonton is April 17th, fifteen days later. Studies of individual years indicate that a consistent 15-day period of temperatures above freezing results in break-up. Thus it would seem that this period of time is the one which should be considered in attempting to forecast the break-up. In the same manner, the break-up of the Klondike, Coppermine, Mackenzie and Hay Rivers was checked. Here again the period was found to be approximately two weeks.

3.5.5 Shipman (10) investigating the Mississippi River at Davenport, Iowa, considered the three-day average temperature prior to break-up. He found it to be 39.7 degrees. At Edmonton the mean temperature for the same three-day period is 40.1 degrees, very close to Shipman's figure. However, his study considered only the temperatures for two days before opening, one day before opening, and on the opening day, and it would appear that for rivers in Canada a considerably longer period of time must be used if temperatures are to be related to break-up.

3.6 Relationship with Degree-Days and Freezing Indices

3.6.1 Degree-days of melting prior to break-up were computed for Edmonton and the long-time average came to 77 degree days. Comparing the degree days for individual years on the charts in Figure 1 shows that only a few years were close to the long-time average and that large deviations frequently occur. Degree-days computations should give a better indication of melting conditions than just using the number of days of thawing; however there are several complicating factors. Short periods of freezing and thawing are difficult to deal with since the refreezing may more than overcome the effects of thawing periods. In some cases run-off water flooding over the top of the ice, then freezing, may increase the ice thickness. The severity of the winter and the snow depth also complicate the break-up.

3.6.2 Freezing indices (the cumulative degree-days of below freezing air temperatures) are a measure of the severity of the winter season. The thickness of ice that grows during the winter is related to the freezing index. Our lines of equal break-up were compared to the map of "Freezing Indices for Canada" by E. B Wilkins and W. C. Dujay (11) but the correlation did not appear to be as good as with the 32°F. isotherm.

As indicated in para. 3.1.4 above, the thickness of ice that develops during a winter depends not only on the severity of the winter but also on the snow depth and the time of occurrence of the snowfall. It is quite possible to have a small ice thickness in a severely cold winter if a heavy snowfall occurred right after freeze-up and insulated the ice during the winter. Further studies will have to be made to determine the relationships between these factors.

4. THE FREEZE-UP

4.1 The Process of Freeze-up in Lakes and Rivers

4.1.1 Freezing Temperatures

During the Fall season there is a gradual loss of the residual summer heat. By the time that the mean daily temperature drops below 32°F. most of the residual heat from shallow bodies of water has been lost so that skim ice forms immediately. There is practically no lag in the formation of ice on very shallow lakes and sloughs and within a day or two they are covered with skim ice.

4.1.2 Loss of Residual Heat

In the case of deeper lakes and rivers there is a considerable lag in the formation of a sheet of ice. The large volume of water that has been heated to great depths steadily loses its residual heat but the flux of heat upward prevents the formation of ice. The loss of heat finally reaches the point where the temperature of the surface water drops below 32°F. and ice forms. The shore ice (that had formed earlier) builds out and the deepest part of the lake is usually the last to freeze over. Winds help in freezing the water due to the rapid removal of the residual heat and also the increased evaporation from the surface. Strong winds, however, tend to break the ice that forms and prevent a sheet of skim ice from forming.

4.1.3 Currents

A strong current in a river or lake also delays the formation of a sheet of ice. The time lag in freezing varies from only a few days to the extreme case of some waterfalls that remain open throughout the winter.

4.2 Duration of the Freeze-up Period

4.2.1 Lakes

As indicated above the size and depth of a lake will affect the duration of the freeze-up. However, when lakes are compared with rivers in the same area it would be logical to assume that the lakes would be the first to freeze. The only station with reliable information on this matter is White River, Ont., and here the small lakes do freeze some three weeks prior to the river. Aircraft reports over large lakes like Great Bear Lake and Great Slave Lake indicate some open water is still visible six weeks to two months after freeze-up.

4.2.2 Rivers

The length of time from the first appearance of skim ice on rivers to the time of solid freeze-over varies from two to six weeks. Latitude does not seem to have any marked effect on the length of time required. Edmonton shows an average of 15 days from the time skim ice is first reported until the river is ice bound. Fort Nelson, Coppermine, Fort Good Hope and Arctic Red River all show a similar period. It is of interest to note that while the reports indicate that growth of the ice requires 15 days or longer, the actual formation of the ice takes only 1 to 3 days. Figure 3 (a) shows a graphical representation of the long-term daily mean temperatures prior to the freeze-up for Edmonton. Figure 3 (b) to (g) shows the daily mean temperatures prior to freeze-up for the years 1951 to 1955. It should be noted that at Edmonton the skim ice forms just as soon as the daily mean falls to 32 degrees F. Figures for freeze-up at Athabaska show the date when "crossing on foot" was possible, and it is evident that some 20 to 25 days are required with the temperatures below the freezing point, before the ice is strong enough to bear the weight of a man. Figure 4 (a) shows the long-term daily mean temperature prior to freeze-up for Athabaska. Figure 4 (b) to (n) shows the daily mean temperatures prior to freeze-up from broken records 1931 to 1952.

4.3 Fresh Water Ice vs Sea Ice

4.3.1 As with the break-up, there are some ten Canadian stations reporting the formation of both sea ice and fresh water ice. The sea ice, as would be expected, is the latest to form, being approximately one month later than the fresh water ice in the same vicinity. Eskimo Point gives the formation of fresh water ice on September 15th, with the sea ice on October 15th. Mingan shows fresh water ice on November 1st, and sea ice on December 1st.

4.4 Relationship with Mean Temperature

4.4.1 Figure 5 shows the average dates of freeze-up for points in Canada. As with Figure 2, this was prepared from the data for all the 360 stations covered in the survey. Again, the isopleths and isotherms must be considered as only approximate.

4.4.2 The relationship between isopleths and mean temperatures is not as evident as in the case of break-up. Across southern Canada the pattern is quite good, but the correlation is badly disrupted by Hudson Bay and the large lakes in northwestern Canada. Possibly another difficulty arises from the fact that no firm definition of freeze-up can be used, so that the actual date reported will vary from one station to the next. Further complications arise from the fact that the size and depth of each lake will cause great variations in freeze-up time.

4.4.3 In attempting to forecast the freeze-up, the first essential seems to be the time when the mean temperature will reach the freezing point. Following this, the temperatures for a few weeks must also be estimated, as 20 to 30 days are required before the ice can be used as a bridge. Fort Nelson freeze-up records show that the time with mean readings below 32°F. prior to freeze-up ranges from 5 to 24 days, and is, on the average, 14 days. Watson Lake shows an average of only 8 days. Thus any attempt to relate the freeze-up to prevailing air temperatures will involve a study of the temperatures for one to two weeks after the time the mean drops to 32°F.

4.5 Relationship with Degree-Days

4.5.1 Degree days of freezing can be used quite readily for the growth of ice since the loss of heat from the water can be handled through heat equations (1). However these equations require knowledge of the temperatures at various depths and such soundings are not available at the present time.

4.5.2 An attempt was made to calculate the number of degree days required to ensure sufficient ice before "crossing on foot" could be made on the Athabaska River. No definite relationship could be found. This was probably due to the fact that vastly different ice thicknesses were being considered, plus other complicating factors such as snow insulation. It would appear that from the information now available, no firm relationship can be found between freezing degree-days and freeze-up times.

## 5. NAVIGATION ON THE MACKENZIE RIVER WATER SYSTEM

5.1 Of all the transportation operations in the North, possibly that most closely related to the freeze-up and break-up is navigation on the Mackenzie River, its tributaries, and the adjoining lakes. The Northern Transportation Company, due to greatly increased commitments, now operates to the absolute maximum of the shipping season. As soon as the ice clears at Waterways, traffic starts down the river, and in the Fall the Company will allow its boats and barges to be "frozen in" at points down river rather than lose one final cargo.

5.2 Records on the opening of the shipping season have been kept by the Company over a 15-year period. Dates of the last departures from various points are available for 10 years. From these it is possible to compute the average lenth of the navigation season for various points on this inland water route. This information is given below:

| STATION | Opening of Navigation | Closing of Navigation | Average duration of the Shipping Season |
|---|---|---|---|
| Waterways, Alta. | Apr 25 | Oct 20 | 178 days |
| Ft. Fitzgerald, Alta | May 15 | Oct 20 | 158 days |
| Goldfields, Sask. | June 6 | Oct 20 | 136 days |
| Yellowknife, N.W.T. | June 16 | Oct 15 | 121 days |
| Norman Wells, N.W.T. | June 22 | Oct 15 | 115 days |
| Aklavik, N.W.T. | June 30 | Oct 15 | 107 days |
| Port Radium, N.W.T. | July 17 | Oct 15 | 90 days |

5.3 It is of interest to note that while the break-up moves progressively northward and down the river, the freeze-up occurs more or less simultaneously along the river.

## 6. TIME BETWEEN BREAK-UP AND FREEZE-UP

By combining the maps for average break-up and average freeze-up, Figures 2 and 5, (using a gridding process) a chart was prepared showing the length of time between these occurrences. This chart is shown as Figure 6. It gives an approximation of the length of the navigation season on the various waterways of Canada. However, it should be noted that errors due to smoothing or insufficient data in the original charts may be compounded in this chart.

## 7. CONCLUSIONS

### 7.1 Break-up and Freeze-up Maps

The average dates of break-up and freeze-up are given on the maps Fig. 2 and 5. It must be stressed that these are average dates and large deviations may be expected in any one year.

## 7.2 Break-up

### 7.2.1 Temperature Extremes

Abnormal weather during any one year can cause a delay or advance in the time of break-up. Exceptionally warm weather in the Spring can advance the time of break-up by approximately one month. Similarly an extremely long cold Spring can delay the break-up by about one month from the average date.

### 7.2.2 Thawing Temperatures Prior to Break-up

Once the mean daily temperature has climbed above $32^{\circ}F.$, it usually requires 15 days of thawing to cause the break-up in rivers. At Emonton 77 degree-days of thawing are required prior to break-up.

### 7.2.3 Lake Ice

Lakes require a much longer period to become clear of ice than rivers. The time required to melt the ice is directly related to the size and depth of the lake. The thickness of the lake ice depends on the snowfall, the time of occurrence of the snowfall, and on the severity of the winter.

### 7.2.4 Other Factors

Short periods of thawing, the depth of snow and the thickness of the ice all complicate the length of time required in determining the break-up.

## 7.3 Freeze-up

### 7.3.1 Yearly Temperature Variations

The onset of freezing temperatures in the Fall varies from one year to the next. This variation in the temperatures will cause the main deviation from the average time of freeze-up as shown on the maps.

### 7.3.2 The Time of Freeze-up

The date of freeze-up is not nearly as definite as the date of break-up. This is partly due to the lack of universal definition of the term 'freeze-up'. In addition, the river currents and the size and depth of lakes are of such major importance that it is almost impossible to draw lines of equal freeze-up dates.

### 7.3.3 Duration of Freeze-up

Skim ice forms along the shore and on small lakes once the mean temperature drops below $32^{\circ}F$. Consequently a map showing the $32^{\circ}F$. isotherm is excellent for the formation of this type of ice. For freeze-up conditions of a sheet of ice thick enough to walk on, the number of days below freezing weather that are required varies directly with the river current and the size and depth of the lake. Both the 32°F. isotherm and the average date of freeze-up are shown on the freeze-up maps.

## 8. RECOMMENDATIONS FOR FURTHER STUDY

As soon as more date are available on the dates of break-up and freeze-up, the mean maps will have to be reviewed and a more complete study of the ice conditions can be made. A research laboratory for the study of ice conditions and a more detailed and extensive ice observation program would greatly increase our knowledge in this field. Theoretical formulae have already been developed (1) for the growth of ice, the insulating effects of snow cover, and other meteorological factors, and these should be tested under Canadian winter conditions.

## 9. ACKNOWLEDGMENTS

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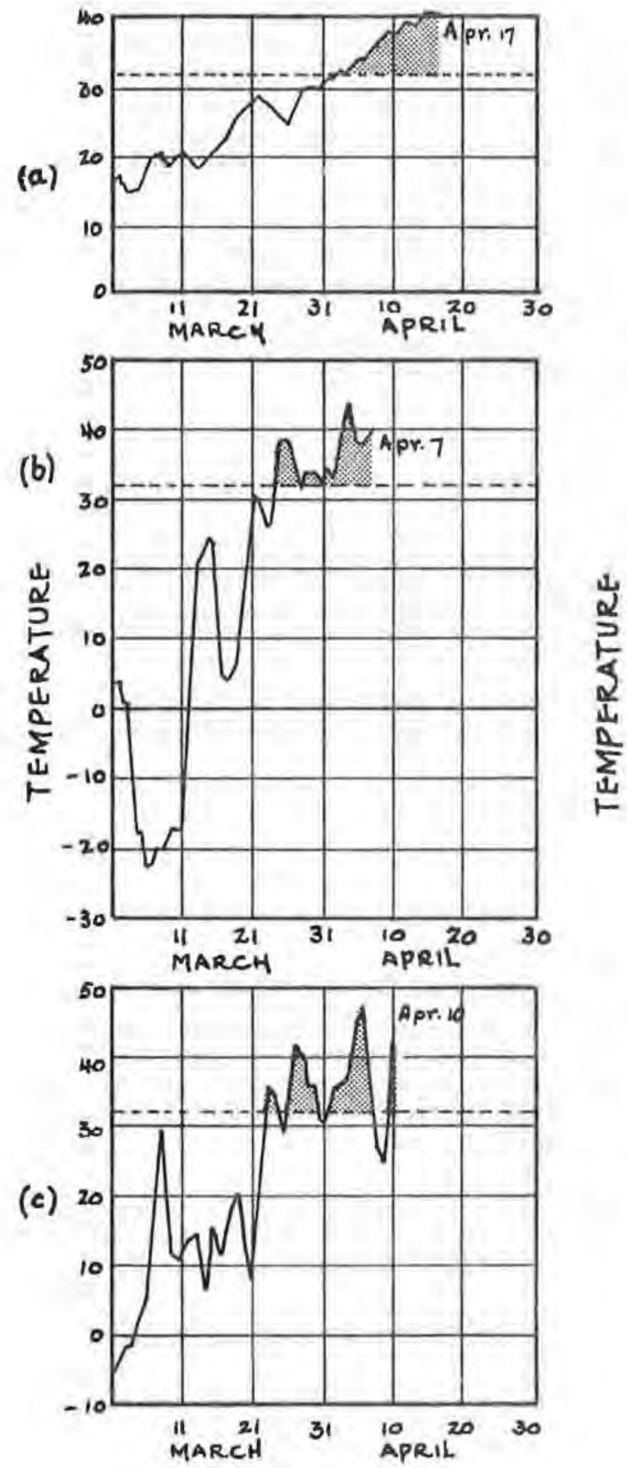
BREAK-UP OF THE NORTH SASKATCHEWAN RIVER AT THE EDMONTON POWER PLANT

Mean daily temperatures for Edmonton from March 1st to date of Break-up




LONG TERM. Mean Temperatures 1881-1955 and break-up dates 1883-1956. Number of days prior to break-up with mean temperatures above freezing is 15.

From April 2nd, a total of 77 degree-days of melting are required on the average.

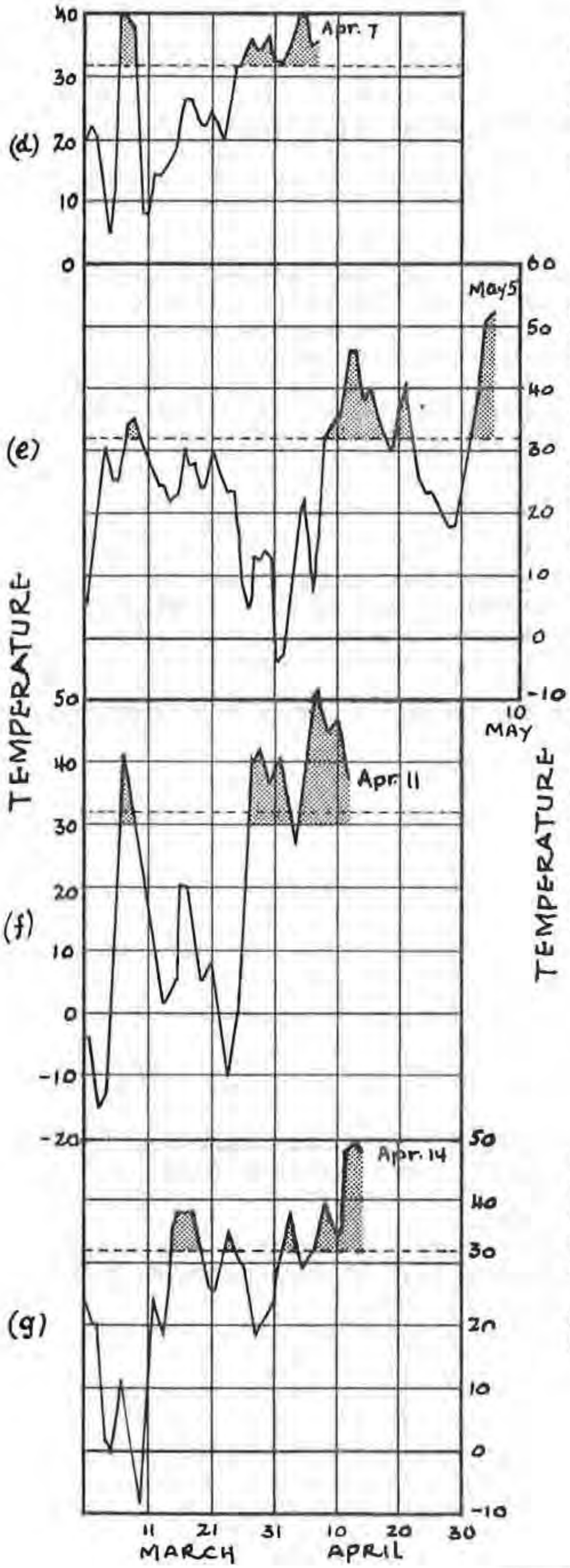
1951. March much below the normal but 15 consecutive days with above freezing temperatures, beginning on March 23rd, resulted in an early break-up.

From March 23rd, 75 degree-days of melting.

1952. March temperatures close to normal. 14 days of melting prior to break-up.

From March 22nd, 69 positive degree-days of melting, less 10 negative degree-days, gives a net of 59.

Figure 1




1953. March considerably above normal. Total days of melting 14. An early break-up following 12 consecutive days with temperatures above 32 F.

From March 26th, 38 degree-days of melting.

1954. Early March above normal but late March and first half April much below normal. 18 days of melting altogether before break-up. This was the second latest break-up on record at Edmonton. Latest was May 6th, 1909.

From April 8, total of 104 positive degree-days, less a total of 72 negative, gives a net of 32. Ice must have been ready to break on April 22nd, but cold spell caused it to reform.

1955. Late March temperatures below normal. However 14 days of melting at end March and early April gave a relatively early break-up.

From March 28th, positive total 133, less negative of 4, gives 127 degree-days of melting.

1956. Early March far below normal, as was the entire winter of 1955-56. Latter half of March above normal, combined with melting in early April to give a break-up very close to the average date.

From April 2nd, 69 positive degree-days, less 4 negative, with net of 65 degree-days of melting.

Figure 1 (cont'd).

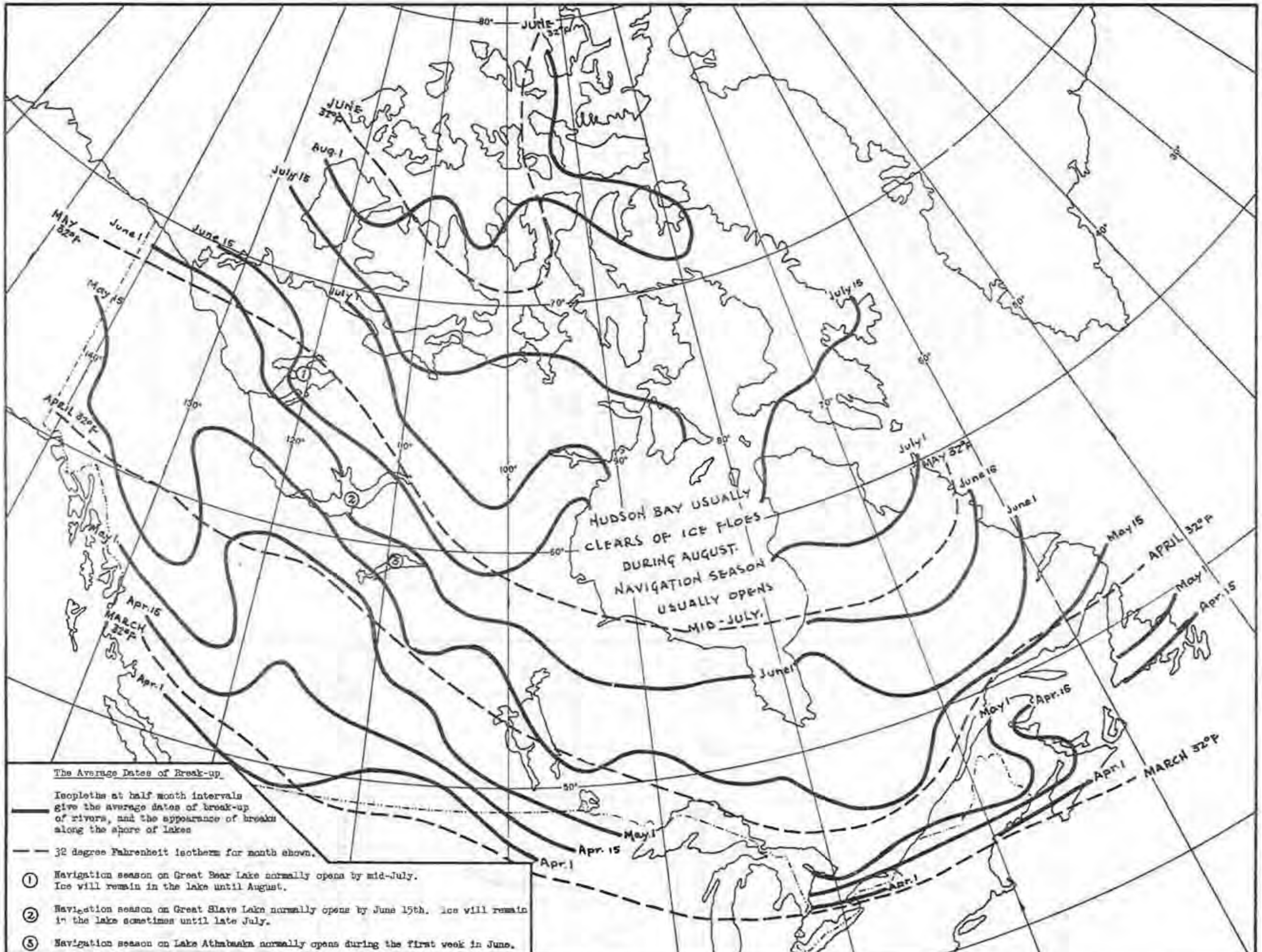
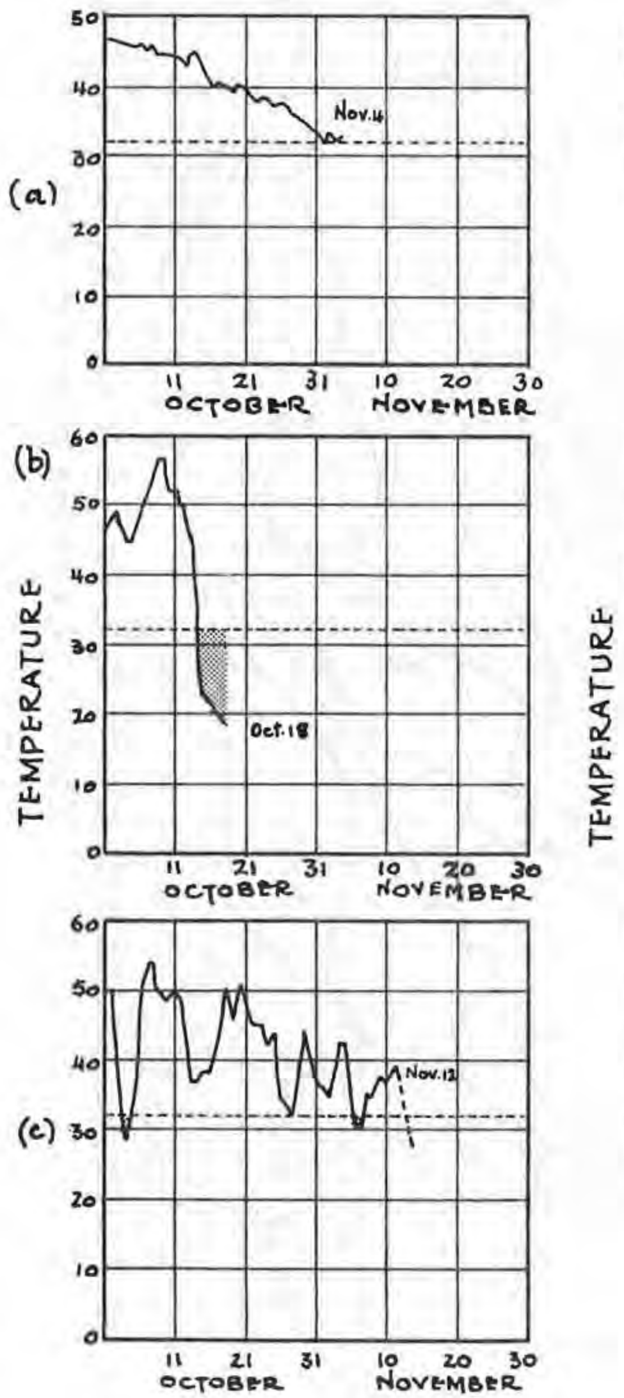



**Figure 2. The Average Dates of Break-up**

FREEZE-UP (FIRST FORMATION OF SKIM ICE) ON NORTH SASKATCHEWAN RIVER AT EDMONTON POWER PLANT

Mean daily temperatures for Edmonton from October 1st to date of skim ice formation

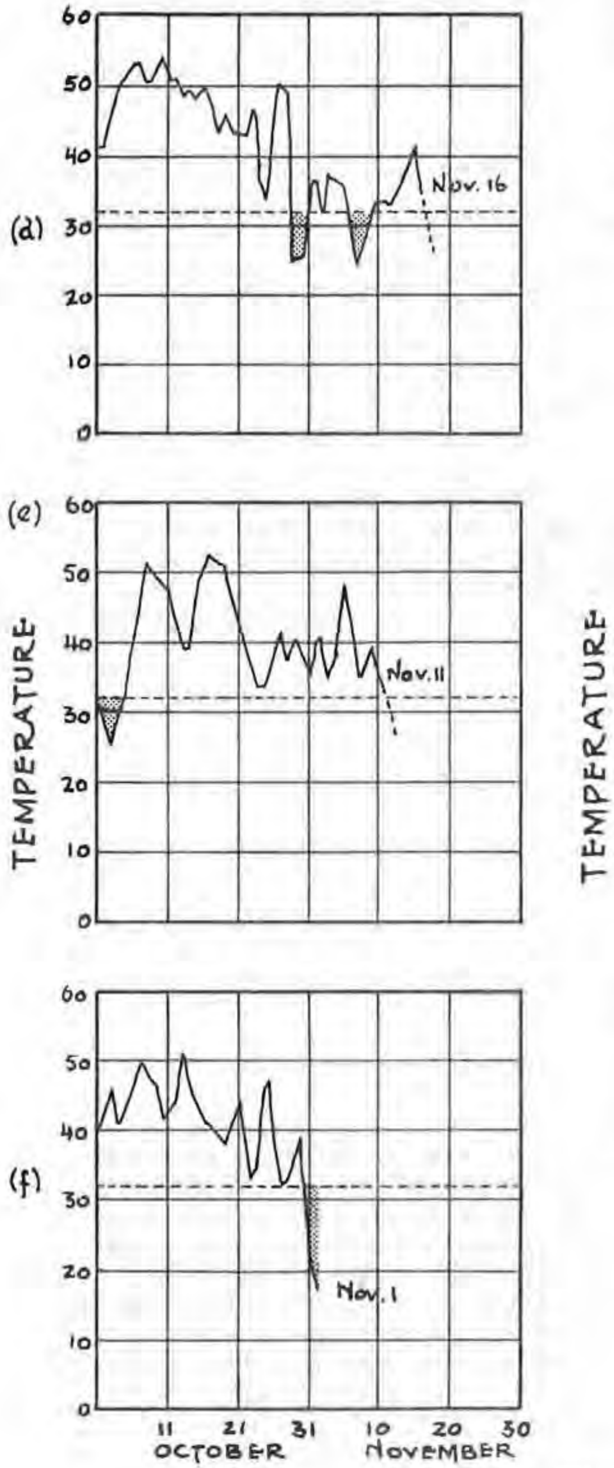



LONG TERM. Mean Temperatures 1881-1955 and average date of skim ice formation 1928-1955. Thin ice forms as soon as mean daily temperature falls to the freezing point. The mean daily minimum temperature (not shown) is actually below freezing from October 15th onward. Thus, for 21 days prior to skim ice formation there will be night-time freezing.

1951. The earliest formation of skim ice on record in the 24 years used. The first ten days of October had above normal temperatures, but on the 14th the mean fell below freezing and remained so for most of the rest of the month. After four days of freezing temperatures, skim ice formed.

1952. Temperature for October and early November well above normal, and the skim ice formation was a week later than the average. Skim ice formed while the daily mean was still above the freezing point. However, the overnight minimum had been below 32 degrees F. for eight days prior to the date of skim ice formation.

Figure 3




1953. The latest formation of skim ice in the 24 years of record. October and early November temperatures are erratic, but much above normal. Again the skim ice formed before the mean daily temperature dropped to 32 deg. F. However, prior to formation there were two periods with freezing temperatures, and the minimums had been below freezing for 17 days. (Since Oct. 29th, except for Nov. 5th and 15th).

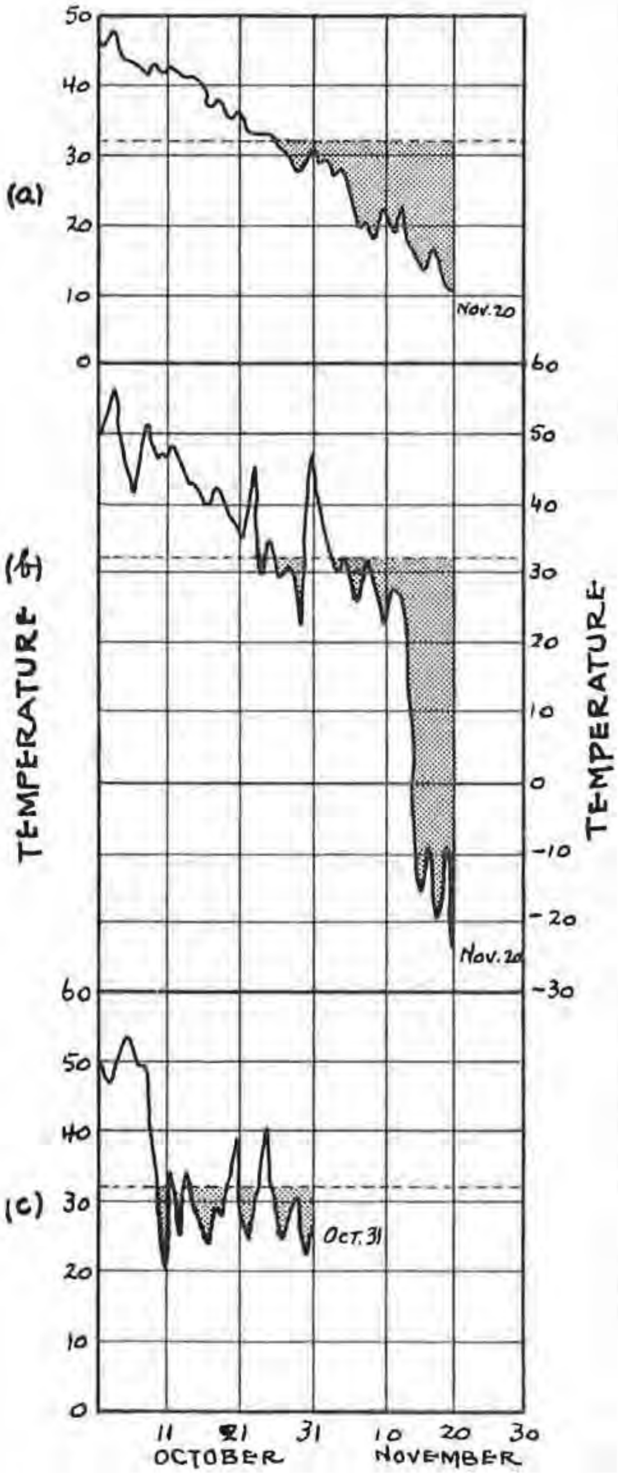
1954. Above normal in October and slightly above in November, with the skim ice formation a week later than average.m The ice began to form form just as soon as the mean dropped to 32 deg. There had been eight days with minimums below freezing when ice formed.

1955. This can be considered as a "normal" year. October temperatures were close to the long term averages. There were two days with the mean below freezing when the skim ice formed, and there had been nine days with minimums below 32 deg. F. since October 17th.

Figure 3 (cont'd)

FREEZE-UP (CROSSING OVER ICE MADE ON FOOT) ON ATHABASKA RIVER AT TOWN OF ATHABASKA

Mean daily temperatures for Athabaska from October 1st to time of crossing on foot




LONG TERM. Daily mean temperatures for 14 years for Athabaska from broken years of records 1931 to 1952. Average date of "crossing on foot" taken from the same years as are the temperatures. Twenty-five days of sub-freezing temperatures required before ice will carry the weight of a man. If it is assumed that skim ice forms four days after temperature drops below freezing, then ice growth requires 21 days.

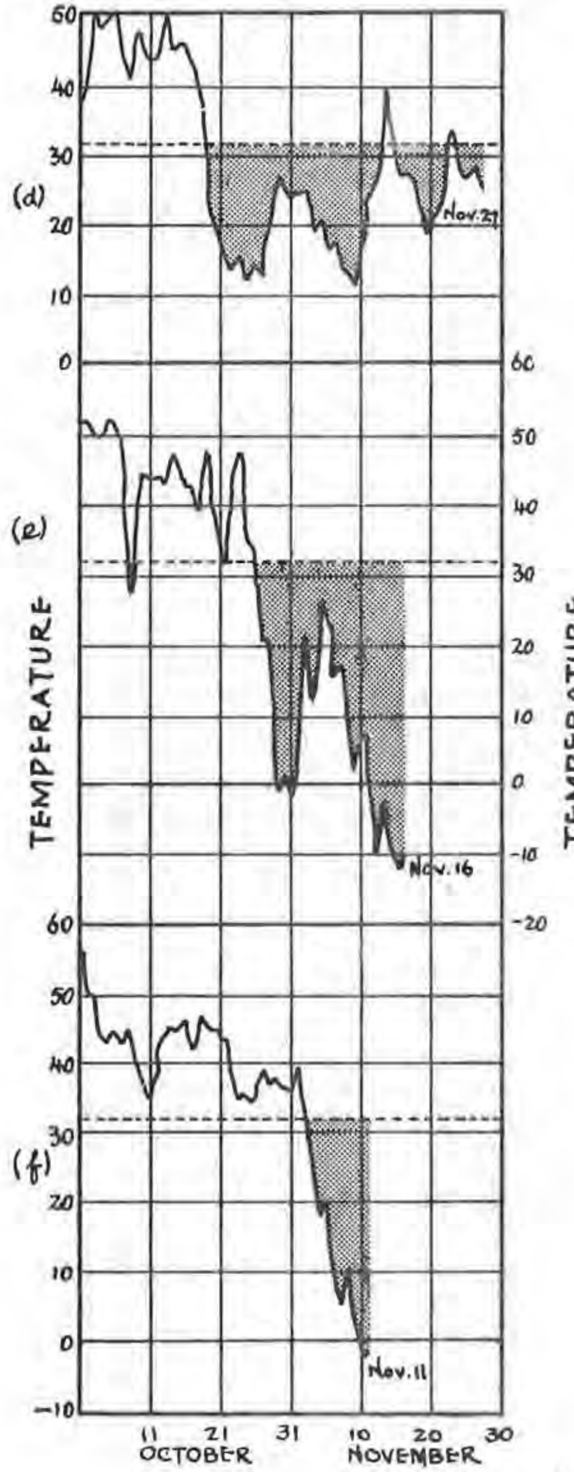
1931 An "average" year. Twenty-three days with temperatures below 32 deg. prior to the time of crossing on foot.

1932. The earliest case in 22 years where the crossing on foot has been recorded. (Broken years of record since 1918). From October 9th onward the temperatures are below normal, and there are a total of 17 days with the mean daily readings below freezing. However, the day degrees of frost is not high, and it is difficult to account for this unusually early freeze-up, especially if compared with the years 1933 and 1935.

Figure 4

FREEZE-UP (CROSSING OVER ICE MADE ON FOOT) ON ATHABASKA RIVER AT TOWN OF ATHABASKA

Mean daily temperatures for Athabaska from October 1st to time of crossing on foot

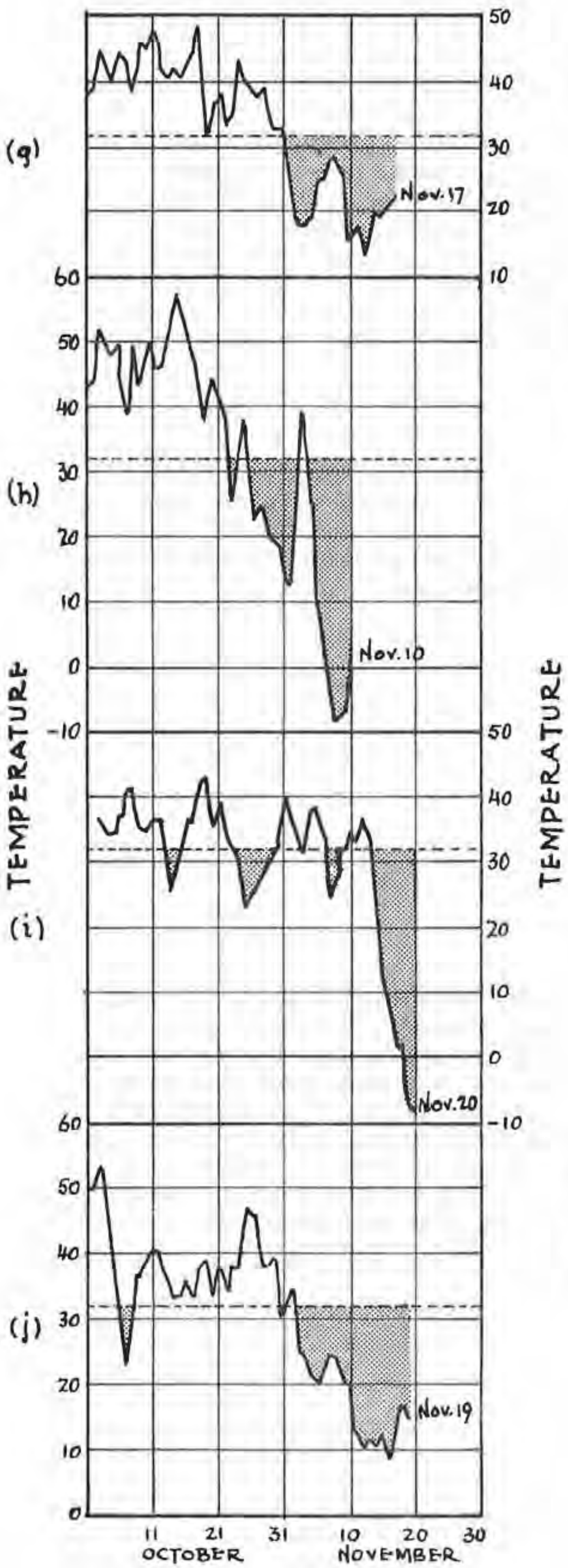



1933. Above normal temperatures in early October, slightly below normal in late October and early November; then slightly above normal in late November. Result is that freeze-up about a week later than the average. There were 37 days in all with sub-freezing temperatures prior to the date of first crossing on foot.

1935. October close to normal. November also quite near to normal, with the time of first crossing near the average. There were 24 days with temperatures below 32 deg. prior to November 16th.

1940. October temperatures above the long term normals. However, very cold in the first part of November, with the result that crossing on foot made some nine days before the average date. Only 9 days with sub-freezing temperatures before the ice was strong enough to bear the weight of a man. Here the day degrees would probably be close to the long term average.

Figure 4 (cont'd)



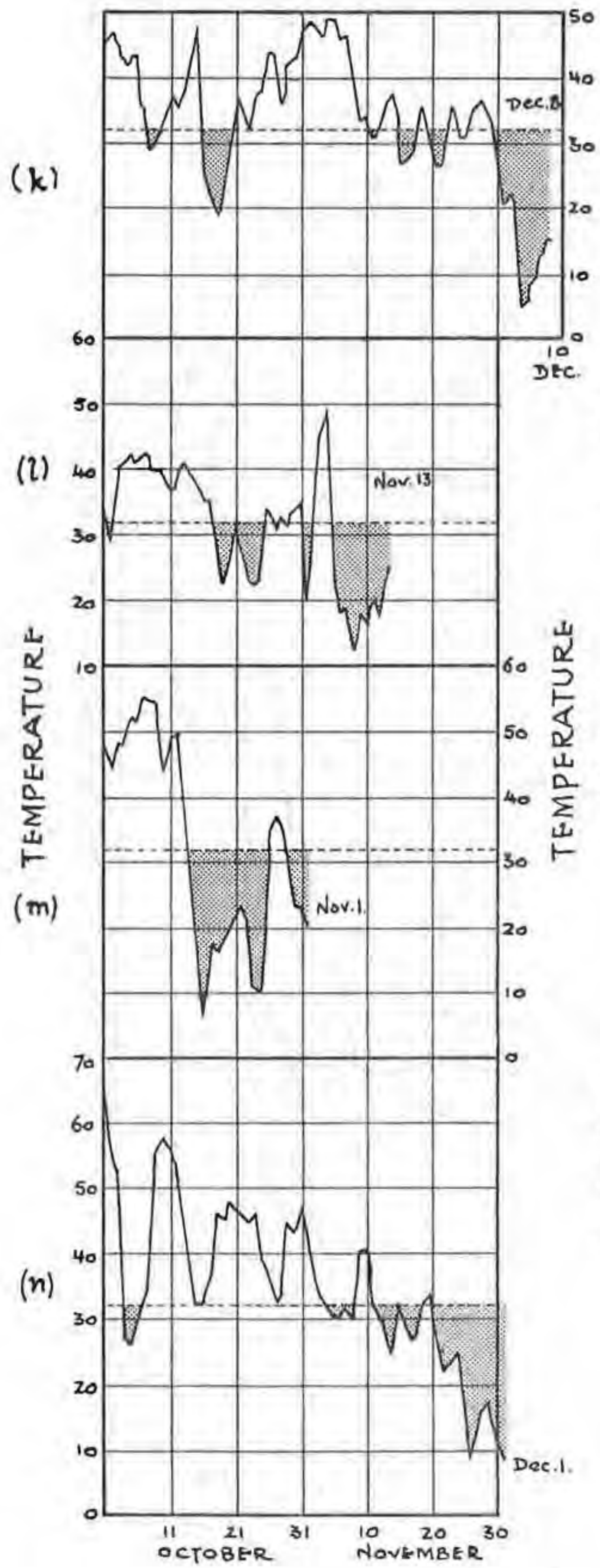

1944. An "average" year, with late October temperatures slightly higher than normal. Crossing on foot made following seventeen consecutive days of sub-freezing temperatures.

1945. First twenty-one days of October above normal, and from then on the temperatures well below normal. Freeze-up ten days early after there had been 17 days with the temperature below 32 deg. F, of which three days averaged below zero.

1946. Temperatures erratic during October and slightly below normal. First half of November above normal but very cold after the 15th. Crossing on foot made on the "average" date, after a total of twenty-two intermittent days with the mean temperature 32 degrees or colder.

1947. October slightly below normal and November very close to the normal. Result is that crossing on foot made on nearly the average date. Twenty-four days all told with sub-freezing temperatures prior to November 19th.

Figure 4 (cont'd)




1949. The latest case in the 22 years of record. October temperatures close to normal but November very much above normal, so that crossing on foot not made until December 8th. By this date what appears to be the average amount of day degrees of frost have accumulated. In all there were 27 days with sub-freezing temperatures, if those in October, November and December are considered.

1950. Temperatures in October and November close to normal, with the freeze-up about one week early. Twenty-one days with below freezing temperatures prior to time of first crossing on foot.

1951. Latter half of October was much below normal, with the result that the second earliest foot crossing was recorded. A total of 16 days with the mean temperature below 32 degrees prior to November 1st.

1952. October and November temperatures are erratic but for both months are well above normal. The freeze-up was eleven days later than the average. There was a total of 28 days with the temperature less than 32 degrees in the two months prior to the time of first crossing on foot.

Figure 4 (cont'd)

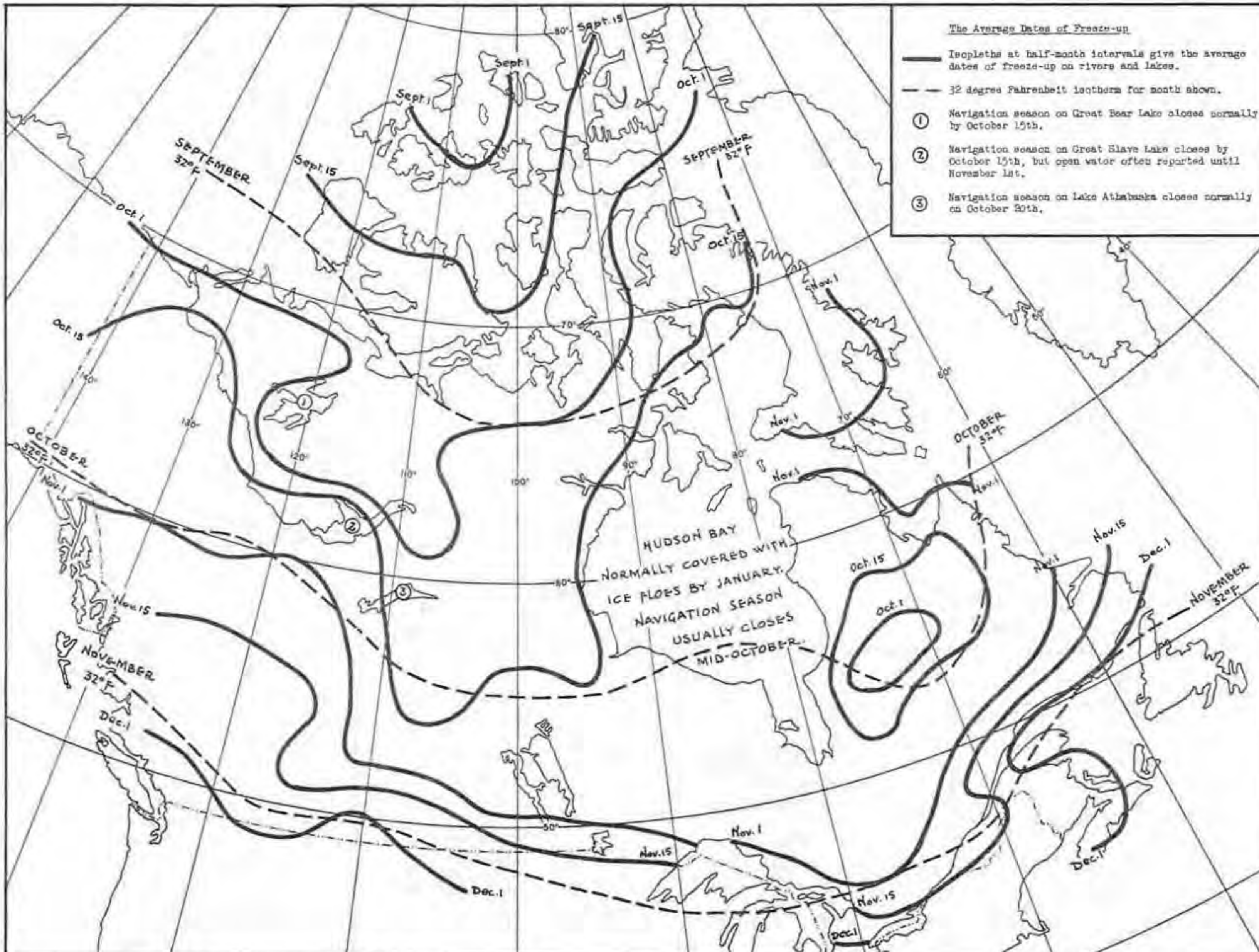



Figure 5. The Average Dates of Freeze-up.

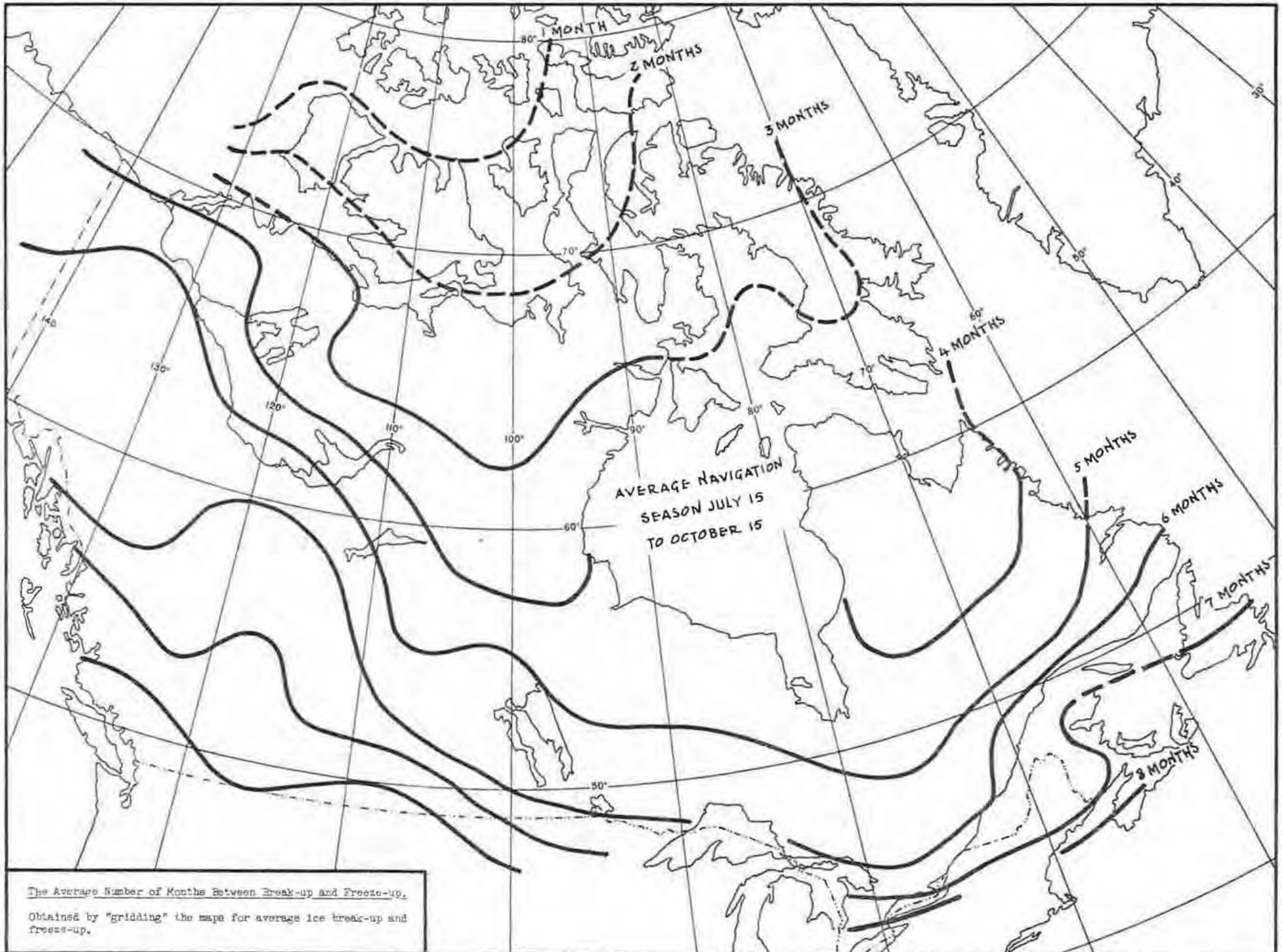



Figure 6. The Average Number of Months Between Break-up and Freeze-up.

# A NOMOGRAPHIC SOLUTION OF PENMAN'S EQUATION

# FOR THE

# COMPUTION OF EVAPORATION

J. A. Turner

## 1. INTRODUCTION

1.1 Penman (4,5,7) has derived a formula for the calculation of natural evaporation from existing weather records, by combining the two classical approaches, namely energy balance and turbulent transfer, with the results of some of his experiments. His method has been applied with some success to controlled irrigation experiments in England.

The derivation of the formula and a discussion of the underlying physical assumptions have been given by Penman (5) and will not be considered here, except for a cautionary note regarding the general applicability of the formula used for estimating the radiation balance at the earth's surface.

This paper presents a series of nomograms which have been constructed to facilitate the use of Penman's formula for routine computations.

## 2. REVIEW OF PENMAN'S FORMULA

2.1 Penman's method for the estimation of evapo-transpiration involves three steps, as follows:

1. An estimate of the evaporation ($E_o$) that would take place from an extended sheet of open water under the observed climatic conditions.

2. A seasonal correction factor (f) is applied to convert this to the potential evapo-transpiration ($E_t$) that would take place over the area, if it were covered with green vegetation, and if an adequate supply of moisture were available to the roots at all times. ($E_t = f \cdot E_o$).

3. The actual evapo-transpiration may be obtained by the application of a further correction factor (not considered here) dependent on the depth of the rooting of the vegetation under study, which controls the availability of water during rainfall deficient periods.

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Mr. Turner, a specialist in forest meteorology, is seconded from the Meteorological Branch to the Forest Service of the British Columbia Department of Lands and Forests, Victoria, B.C. The paper was presented at the meeting by Mr. C.L. Mateer of Research and Training Division of the Meteorological Branch.

Penman's formula for the computation of $E_o$ is:

$$E_o = \frac{\Delta H + 0.27 E_a}{\Delta + 0.27} \quad \text{mm/day}$$

Where: $\Delta$ is the slope of the saturation vapour pressure curve, in mm (Hg)/$^oF$, at mean air temperature, Ta.
H is the average daily radiation budget, at the earth's surface, converted to evaporation units (mm/day) by dividing cal cm $^{-2}$ day $^{-1}$ by 59.

$$E_a = 0.35\ (e_a - e_d)(1 + U_2 \cdot 10^{-2}) \quad \text{mm/day}$$

$e_a$ is the saturation vapour pressure at the mean air temperature, $T_a$ .

$e_d$ is the saturation vapour pressure at the mean dew point temperature, $T_d$ .

$U_2$ is the average wind speed in miles/day at 2 metres above the ground. If the wind speed at 10 metres is used, an approximate reduction factor of 0.8 may be used to obtain the 2 metre value.

Empirical values of f have been determined for the British Isles as follows:

November to February, inclusive . . . . . . . . . . . . . . . 0.6
March, April, September, October. . . . . . . . . . . . . . . 0.7
May to August inclusive . . . . . . . . . . . . . . . . . . . 0.8
Annual Average . . . . . . . . . . . . . . . . . . . . . . . . 0.75

The theoretical justification for the selection of these values has been discussed by Penman and Schofield (6).

3. DETERMINATION OF THE RADIATION BUDGET

3.1 The radiation budget may be expressed as the difference of the solar and long-wave (terrestrial) radiative components. Because of the paucity of actual observations of one or both of these components, it is frequently necessary to resort to empirical formulae relating these components to other more commonly measured meteorological parameters. According to Penman, the radiation budget, at least for the United Kingdom stations, may be adequately represented by the following empirical equation:

$$H = \frac{Q_E}{59}(1 - r)(0.18 + 0.55S) - \frac{\sigma T_a^4}{59}(0.56 - 0.92\sqrt{e_d})(0.10 + 0.90S)$$

Where:

$Q_E$ is the total solar radiation (cal cm $^{-2}$ day $^{-1}$) that would be received at the earth's surface in the absence of an atmosphere.

r is the albedo of the surface (plane water), taken here to be 0.05.

S is the ratio of actual to total possible hours of bright sunshine.

$\sigma T_a^4$ is the theoretical black body radiation (cal cm$^{-2}$ day $^{-1}$) at mean air temperature, $T_a$ .

If the reader wishes to evaluate climatological values of $E_o$ for stations in North America, he should refer to the work of Fritz and MacDonald (2) for the United States and Mateer (3) for Canada for the solar radiation component. It is further suggested that the relationship between Q and S, as presented in the above-noted papers, is probably somewhat better for North American stations than the one suggested by Penman. In any event, these empirical relations should be used with considerable caution and, in general, their application should be limited to periods of not less than 5-days' duration.

## 4. THE NOMOGRAMS

Computations of average daily evaporation for any particular station may be done quite rapidly by making use of two or more of the nomograms presented here. Each nomogram takes care of the computation in one of the stages indicated below. For practical convenience, the units used on the various scales of the nomograms are not always the same as those used in the original formulae.

Nomogram I. $0.95Q = 0.95\, Q_E\,(0.18 + 0.55S)$

The 0.95Q scale is marked in evaporation units (mm day $^{-1}$). Values of $Q_E$ for any latitude and time of year may be interpolated from Table 132 of the Smithsonian Meteorological Tables (Sixth Revised Edition).

Nomogram Ia. $0.95Q = 0.95\, Q_o\,(0.355 + 0.68S)$

This is an alternative empirical equation which is recommended for use at Canadian locations.

Nomogram II. $N = \sigma T_a^4 \, (0.56 - 0.092\sqrt{e_d}) \, (0.10 + 0.90S)$

In this nomogram, the $e_d$ scale has been labelled directly in terms of the average dew-point temperature and the N scale in evaporation units.

Nomogram III $E_a = 0.35 \, (e_a - e_d) \, (1 + U_2 . 10^{-2})$

In this nomogram, $(e_a - e_d)$ is obtained from an auxiliary nomogram which has scales labelled for $T_a$ and $T_d$. The wind speed ($U_2$) scale is labelled in terms of mph (daily average).

Nomogram IV.

$$E_o = \frac{\Delta H + 0.27 E_a}{\Delta + 0.27}$$

The $\Delta$ scale is labelled directly in units of air-temperature $T_a$. To use this nomogram the point of intersection for values of $T_a$ and H is aligned with $E_a$ to obtain the value $E_o$.

## 5. COMPUTATIONAL TECHNIQUE

The calculation of potential evapo-transpiration may be facilitated by the use of a table similar to Table I, which shows a sample computation for Summerland. The various column headings are self-explanatory. The data tabulated are either observed or have been derived from the appropriate nomogram as indicated. Values of S, the ratio of actual to total possible hours of sunshine, may be derived from data tabulated in Table 171, Smithsonian Meteorological Tables, and in a Meteorological Branch publication (1).

The final result is obtained in units of mm day $^{-1}$ and is the average daily evaporation for the period concerned. To determine the monthly potential evapo-transpiration in inches per month, Penman's factor f, the number of days in the month, and the conversion from mm to inches have been incorporated into a single factor f' which is given in Table 2 for each month of the year.

## 6. ACKNOWLEDGEMENT

It is a pleasure to acknowledge the very considerable assistance given by Mr. Carl Mateer of the Research and Training Division of the Meteorological Branch, who contributed the alternative nomogram Ia for computing the solar radiation component, and who was responsible for the final preparation of the figures.

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TABLE 1

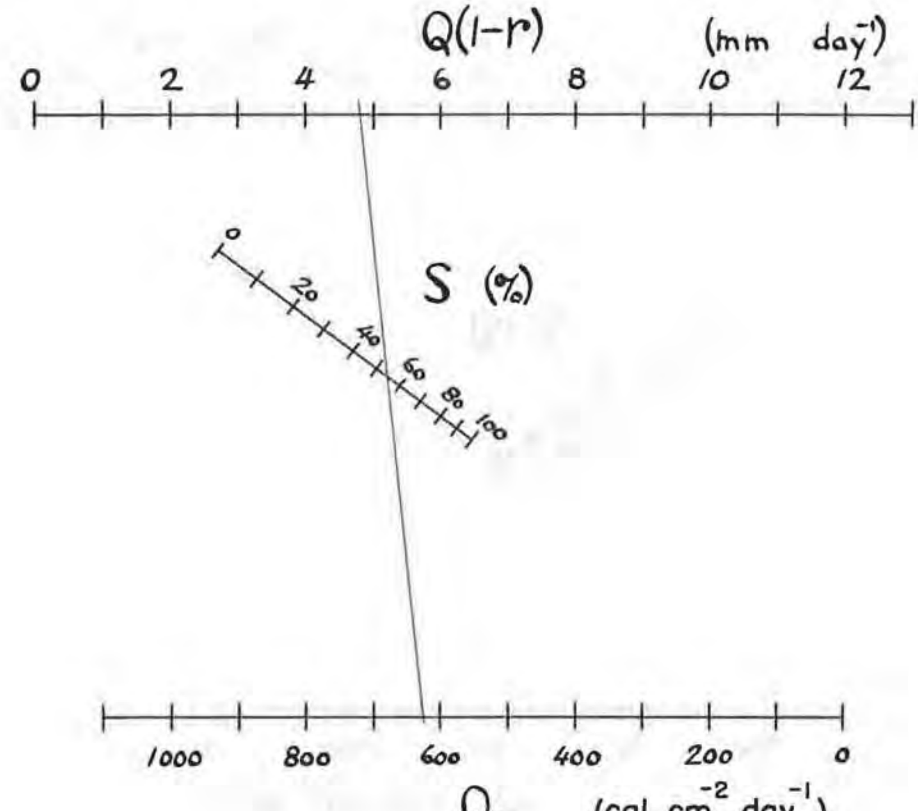
COMPUTATION OF POTENTIAL EVAPO-TRANSPIRATION FOR SUMMERLAND

| | S | $T_a$ | $T_d$ | $U_2$ | $Q_o$ | Q | N | H | $E_a$ | $E_o$ | f' | f'$E_o$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | (1-r) | | | | | | |
| | | | | | Cal | Ia | II | | III | | Table 2 | $E_t$ |
| | | °F | °F | mph | $cm^{2}$ $day^{-1}$ | mm $day^{-1}$ | mm $day^{-1}$ | mm $day^{-1}$ | mm $day^{-1}$ | | | Ins. $Mth^{-1}$ |
| JAN | .20 | 26 | 23 | 6 | 165 | 1.4 | 1.1 | .3 | .3 | .3 | .73 | .2 |
| FEB | .32 | 29 | 28 | 6 | 260 | 2.7 | 1.7 | 1.0 | .2 | .5 | .67 | .3 |
| MAR | .40 | 39 | 27 | 6 | 425 | 4.3 | 2.1 | 2.2 | 2.0 | 2.1 | .86 | 1.8 |
| APR | .48 | 47 | 34 | 6 | 600 | 6.6 | 2.4 | 4.2 | 2.8 | 3.6 | .83 | 3.0 |
| MAY | .50 | 56 | 42 | 6 | 725 | 8.1 | 2.5 | 5.6 | 3.6 | 4.8 | .98 | 4.7 |
| JUN | .51 | 64 | 49 | 6 | 765 | 8.7 | 2.4 | 6.3 | 5.3 | 6.0 | .95 | 5.7 |
| JUL | .64 | 70 | 53 | 7 | 740 | 9.5 | 2.9 | 6.6 | 7.7 | 6.9 | .98 | 6.8 |
| AUG | .63 | 68 | 53 | 6 | 625 | 7.9 | 2.7 | 5.2 | 6.2 | 5.5 | .98 | 5.4 |
| SEP | .54 | 59 | 48 | 6 | 480 | 5.6 | 2.4 | 3.2 | 3.6 | 3.3 | .83 | 2.7 |
| OCT | .42 | 49 | 42 | 6 | 295 | 3.1 | 2.1 | 1.0 | 1.8 | 1.4 | .86 | 1.2 |
| NOV | .22 | 37 | 33 | 6 | 190 | 1.5 | 1.2 | .3 | .6 | .5 | .71 | .4 |
| DEC | .16 | 28 | 28 | 6 | 130 | 1.0 | 1.0 | 0 | 0 | 0 | .73 | 0 |

TABLE 2

Correction factor f' to be multiplied by the monthly mean value of $E_o$ (mm day $^{-1}$) to obtain the potential evapo-transpiration $E_t$ (inches month $^{-1}$)

| Month | Factor f' |
|---|---|
| January | 0.73 |
| February | 0.67 |
| March | 0.86 |
| April | 0.83 |
| May | 0.98 |
| June | 0.95 |
| July | 0.98 |
| August | 0.98 |
| September | 0.83 |
| October | 0.86 |
| November | 0.71 |
| December | 0.73 |




NOMOGRAM I

$$Q(1-r) = Q_E(.18 + .55\,S)(1-r)$$

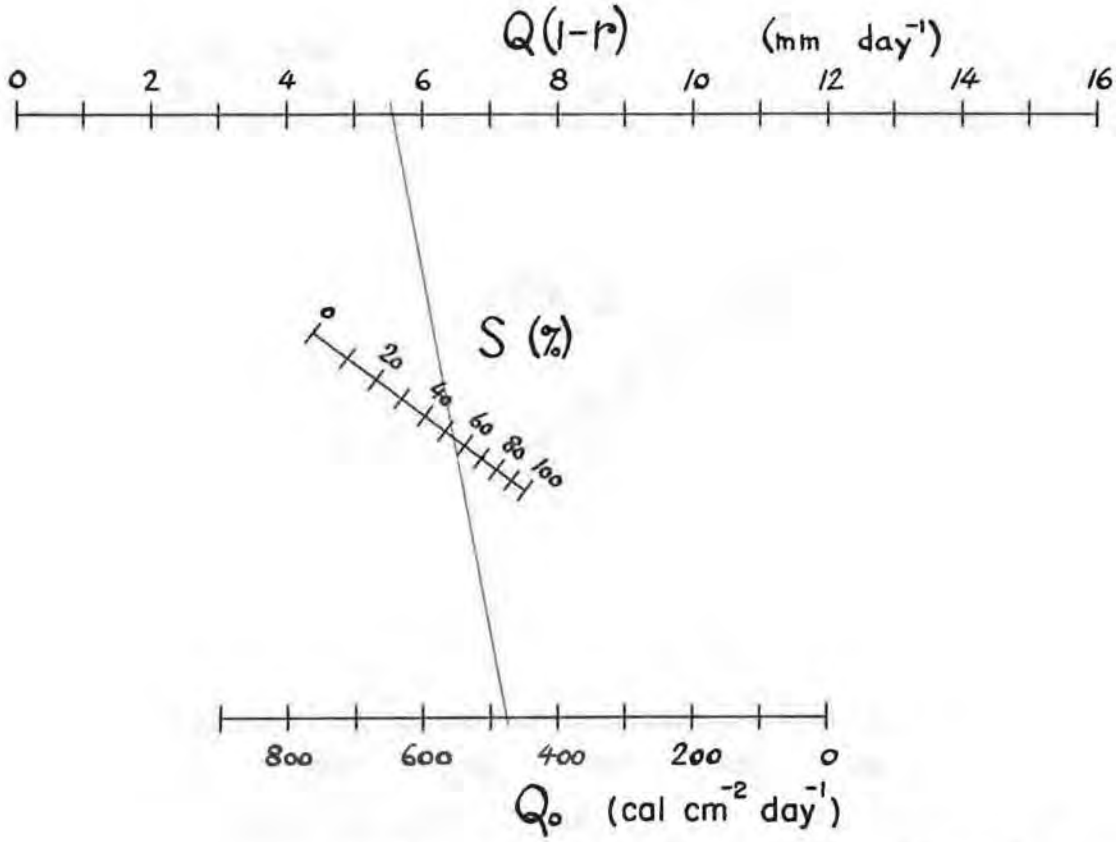
Example:

Summerland, B.C., September.

S = 54%

Q = 615

Q (1-r) = 4.8




NOMOGRAM Ia

$$Q(1-r) = Q_o(.355 + .68S)(1-r)$$

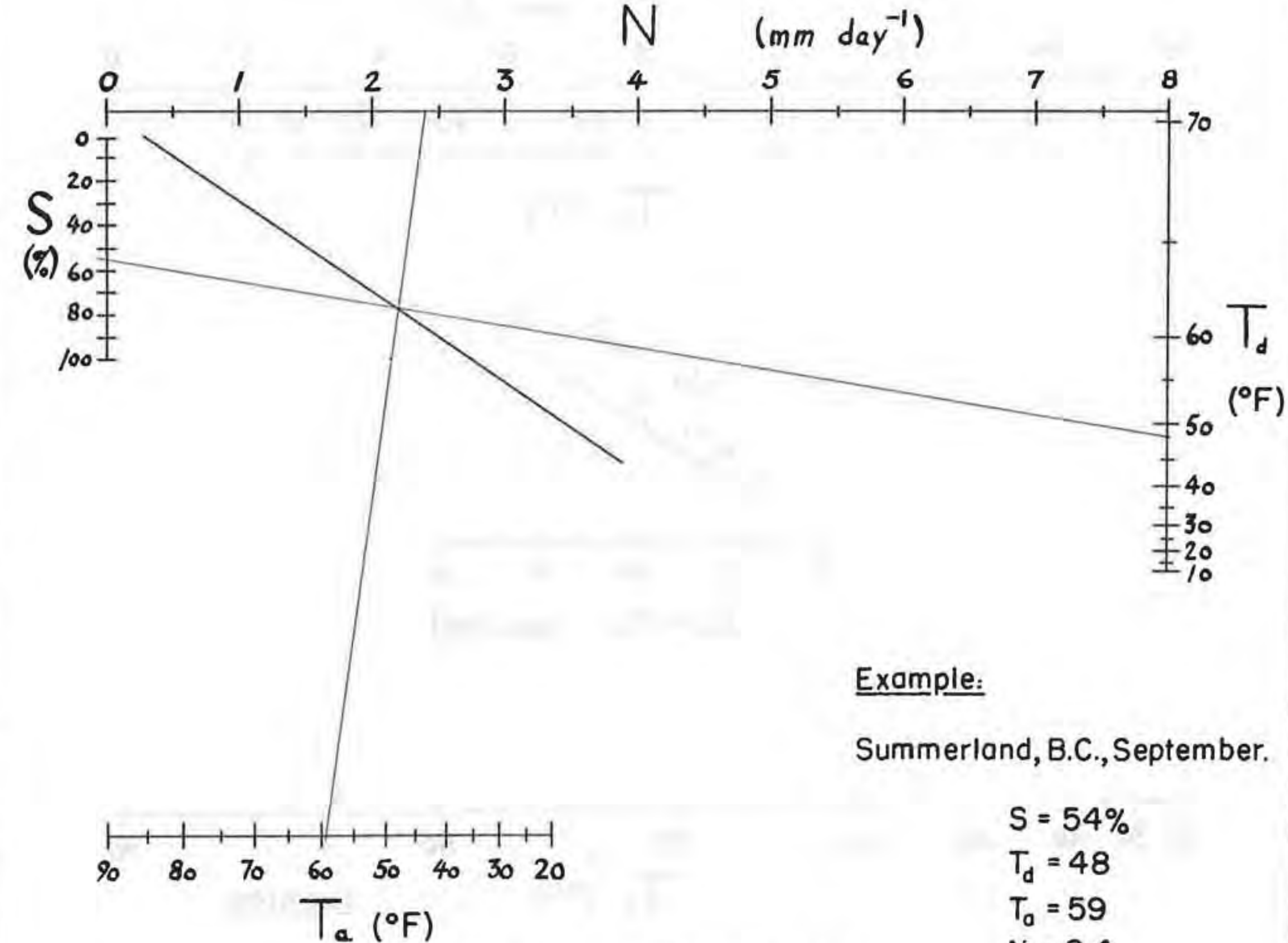
<u>Example:</u>

Summerland, B.C., September.

S = 54%

Q = 480

Q(1-r) = 5.6



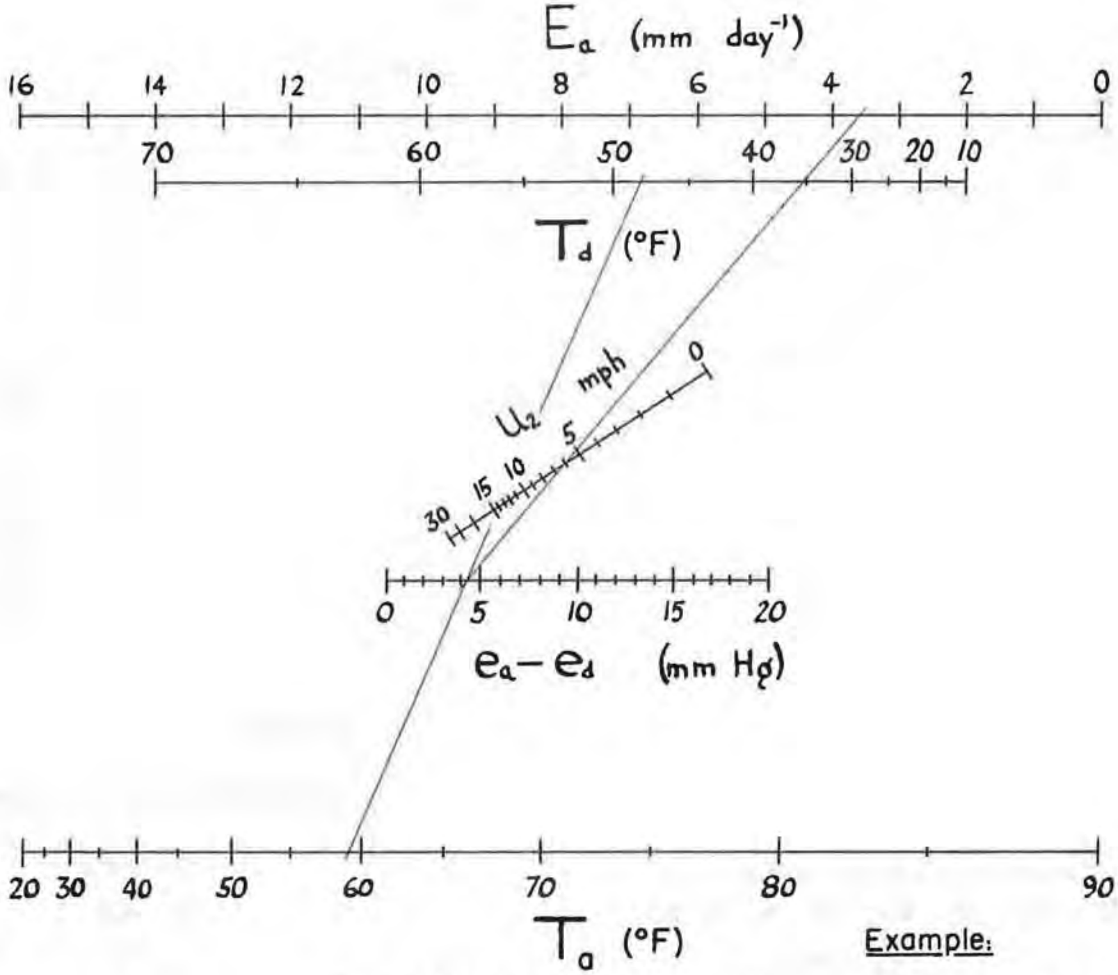

<u>Example:</u>

Summerland, B.C., September.

$S = 54\%$
$T_d = 48$
$T_a = 59$
$N = 2.4$

NOMOGRAM II

$$N = \sigma T_a^4 (.56 - .092\sqrt{e_d})(.10 + .90S)$$




NOMOGRAM III

$$E_a = .35\,(e_a - e_d)\,(1 + 10^{-2} u_2)$$

**Example:**

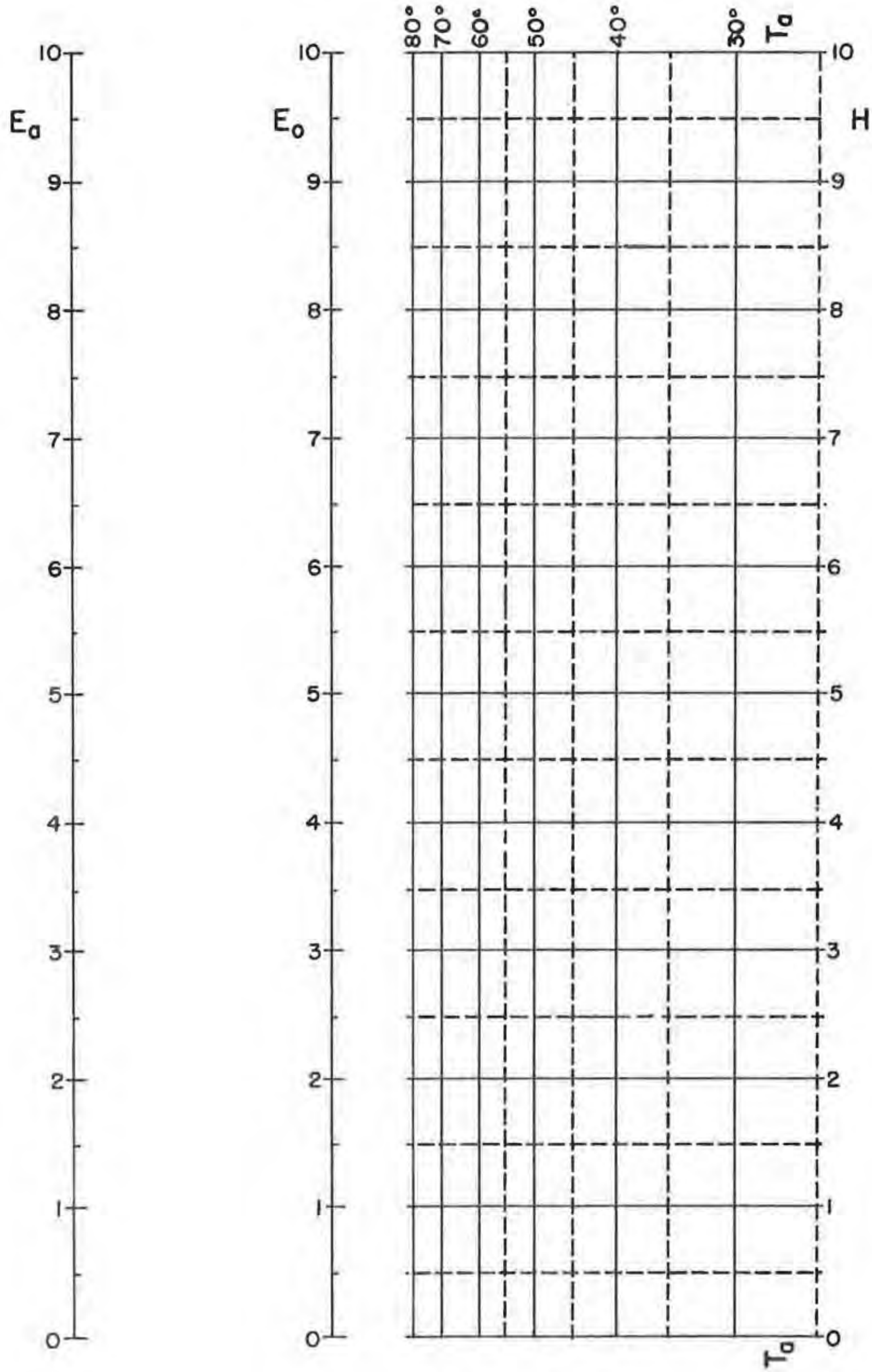
Summerland, B.C., September.

$T_d$ = 48

$T_a$ = 59

$U_2$ = 6

$E_a$ = 3.6




NOMOGRAM IV