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THE INTERRELATIONSHIP OF LAKE ICE AND CLIMATE IN CENTRAL CANADA

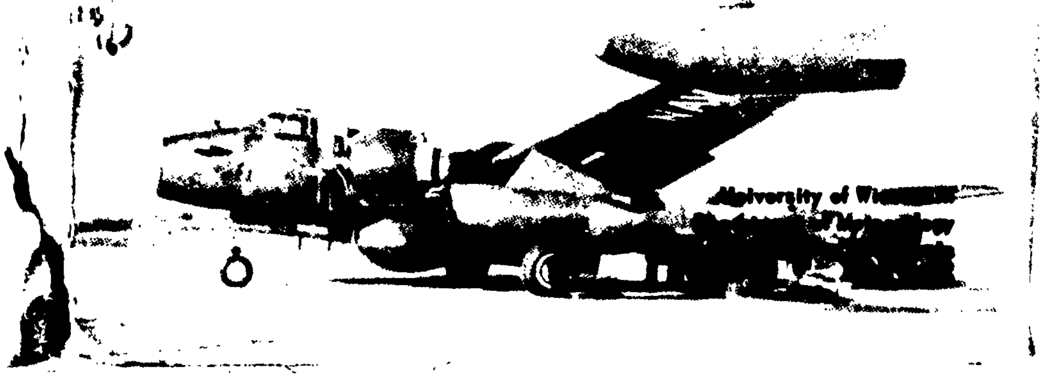
Yellowknife

BREAKUP 1964
Flt. #5

Churchill

James D. McFadden

BREAKUP 1963
Flt. #5



THE INTERRELATIONSHIP OF LAKE ICE AND CLIMATE IN CENTRAL CANADA

by

James D. McFadden

Technical Report #20

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ABSTRACT

An aerial reconnaissance of lake ice conditions in the Shield region of central Canada west of Hudson Bay, and northeastern Minnesota and Wisconsin was conducted during the periods of lake freeze-up 1961 and 1963 and lake break-up 1963 and 1964 using a P2V patrol aircraft provided by the United States Navy. Albedo measurements of the surface were also made during these flights. The data from these surveys were compared with climatic data of the region, and the following interrelationships were found.

Observations of the freezing of lakes showed that between the area of all frozen lakes and the area of all open lakes there is a transition zone. The southern boundary of this zone is determined by the freezing of the shallowest lakes and the northern boundary by the freezing of the deepest lakes. The width of this zone and the directional trend and movement of its boundaries showed a recognizable pattern from year to year for the same region. These patterns reflect and are apparently related to the climatic singularity "Indian Summer".

The patterns of ice break-up for 1963 and 1964 could not be directly compared because different areas were investigated, but the transition zone was observed to be narrower and better defined in the northwest section of the study area, indicating that the climatic boundaries are also more distinct toward the northwest. This agrees with the more sharply defined vegetative boundaries found in this region.

Comparison of lake freezing dates with running mean air temperatures shows that there is good agreement between the freezing date of deep lakes and a 40-day running mean air temperature of 0°C., and a fair agreement between freezing dates of shallow lakes and a 3-day mean air temperature of 0°C. The agreement between thawing dates and mean air temperature is relatively poor.

Aerial measurements show that there is very little horizontal variation in the albedo of the tundra in the summer when lakes are free of ice and in the winter when they are frozen and the region is snow covered. Large horizontal variations of albedo occur in the tundra when lakes are frozen but there is no snow, and in the boreal forest region when the lakes are frozen and snow covered.

The rapid disappearance of the snow from the tundra observed in 1963 produced a sudden increase of 600 percent in the amount of absorbed radiation at the surface. A heat budget estimate for the tundra land surface after the snow had disappeared indicates that the sensible heat transfer to the atmosphere was sufficient to heat the lower 1,000 meters of air at a rate of 1.6°C. per day, a figure that agrees quite well with actual observations.

The freezing of lakes does not appear to be dependent on the presence of a particular type of air mass. Sufficiently cold air temperatures to freeze all lakes can be present in an air mass of polar origin, or in an air mass of Pacific origin that has been modified over an extensive snow surface.

Because the freezing date of a lake is dependent on its mean depth, the relative depths of a group of lakes can be estimated from the sequence of their freezing dates.

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I. INTRODUCTION

Freezing and thawing are two important events in the annual heat cycle of a lake which visually indicate its response to climate. Therefore the dates of freezing and thawing of a lake should be useful as an indicator of the type of climate that existed in the region of that lake prior to freeze-up and thaw-out for a period of time, the length of which is dependent on the size and depth of a lake. By selecting an area with a high concentration of lakes of many different sizes and many different depths for visual observation, it should be possible to obtain a regional picture of the climate of that area from the observed freezing and thawing pattern of the lakes. The areal pattern of freeze-up or break-up, for example, may give us information about the movement and modification of air masses, or it may be possible to estimate the mean depths of lakes by comparing their freezing or thawing dates with those of lakes with known mean depths.

In order to use the distribution of lake ice to analyze climate of a particular region, one must know which climatic factors are related to the freezing and thawing of lakes. The major goal of this study is to map the freezing and thawing of lakes in a particular region and to relate certain aspects of climate to these events. A second objective, which is actually a corollary to the primary objective, is to evaluate the effects of the morphology of lakes on their response to climate, and, after determining these effects, to examine the possibility of estimating mean depths of lakes remotely.

The majority of investigations involving the interrelationship of lakes and climate have dealt with single lakes or, at most, lakes within a single region. To obtain a large scale regional picture of this interrelationship it was necessary to use aerial reconnaissance and remote sensing techniques. Since the detailed information that can be gathered when dealing with a single lake cannot be obtained in a regional study, the observations reported here must necessarily be more general in nature.

II. LITERATURE REVIEW

As already mentioned, there has been extensive work done on the interrelationship of lakes and climate through the studies of heat balance of individual lakes, both ice-free and ice-covered. Probably the most extensive body of literature available on this subject may be found written in the Russian language, none of which, as far as this author knows, has been translated into English. Fortunately, however, there is a sufficiently large volume of literature in English on this subject, and adequate summaries of this literature may be found in Hutchinson (1957), Bunge and Bryson (1956), Dutton and Bryson (1960), and Scott (1964). The SIPRE (now CRREL) bibliographies with abstracts on snow, ice, and permafrost are excellent sources for the literature on this subject.

Scott (1964) has done an excellent study on a group of lakes in Vilas and Dane Counties in Wisconsin. He investigated the heat balance of these lakes beginning just prior to freeze-up, going through the ice-covered period, and ending with break-up. The main emphasis was directed to the ice-covered period with the ultimate goal of determining the role of lakes in studies of climate. Toward this end, Scott observed that the most important lake factors which serve as climatic indicators are maximum ice thickness and the freezing and thawing dates, and that they are good indicators provided morphometric factors are taken into account.

The literature dealing with the freezing and thawing dates of lakes and the relationship of climate to these dates on a regional basis is rather limited. Fobes (1945) was first to touch on the subject in his investigation of the ice clearing dates of Maine lakes. He studied the long term variability of the opening dates of four lakes and then, based on four-year records of 51 lakes, drew a map depicting the opening of these lakes from the coastal sections northward. From a climatic point of view he points out, without giving any supporting evidence, that air temperature is the most important factor controlling the opening of the lakes. He also concludes that wind, sunshine, and the physical factors of the lakes are also significant to a certain degree.

Fobes (1948) re-examined the variability of ice-clearing dates in Maine and added an analysis of New Hampshire lakes to his investigation. This paper discusses only the variability of the extremes of ice-clearing dates and does not touch on the relationship of these dates with climate.

The investigation most closely approaching the author's was done by Burbidge and Lauder (1957). They tabulated information on ice conditions on lakes and rivers over a number of years from data received from the RCAF and then drew maps showing the average dates of break-up and freeze-up in Canada. A study of meteorological conditions prior to freeze-up and break-up was made, and these events were then related to mean temperature, degree days, and freezing indices (cumulative degree-days below freezing). With regard to mean temperature, they concluded that there was a direct relationship between mean air temperature and date of break-up, indicating that this was the controlling feature for this event. In relationship to freeze-up the correlation was not as evident. No firm correlation between either degree days or freezing indices and freezing and thawing could be found.

In contrast to the findings of Burbidge and Lauder, MacKay (1961) in his study of the freeze-up and break-up of the lower Mackenzie River concluded that both freezing and thawing dates could be correlated significantly with air temperature without regard to other factors such as snow cover. He also pointed out that accumulated degree-days are not significantly related to freeze-up or break-up on the Mackenzie River.

From a four year study of ice conditions on the Great Lakes, Richards (1964) concluded that the degree day concept was very useful. He obtained good correlations between degree days and the extent of ice cover on these lakes.

As pertains directly to this study a report by Ragotzkie and McFadden (1962) gave the preliminary results of an attempt to more accurately map the freezing pattern of lakes in central Canada. Much of the information presented in that paper will be included and expanded upon in this dissertation.

III. METHODS

A. Region of Study

For this type of study certain geographical features covering broad areas are desirable. First, low relief of the entire region is essential so that the influence of climate on lake freezing and thawing dates will not be complicated by elevation effects. With low relief it is possible to observe the movement of air masses which are unaffected by major topographic barriers such as mountains and to relate modifications of these air masses to surface factors such as lake ice or snow cover.

Second, it is essential that there be a high concentration of lakes of many different sizes, shapes, and depths covering the entire region. Scott (1964) concluded that because their thermal properties are well known, these homogeneous landscape features are important in climatic studies particularly in regions where meteorological stations are sparsely located.

The region selected for this study was the north-central portion of the North American continent from northern Wisconsin to the Arctic Ocean. The area of observation covered the Districts of Mackenzie and Keewatin, northern Saskatchewan Manitoba, and western Ontario. Figure 1 is a base map of this region. In addition to containing the features mentioned above, its accessibility by aircraft permitted the scheduling of observation flights for any time period desired.

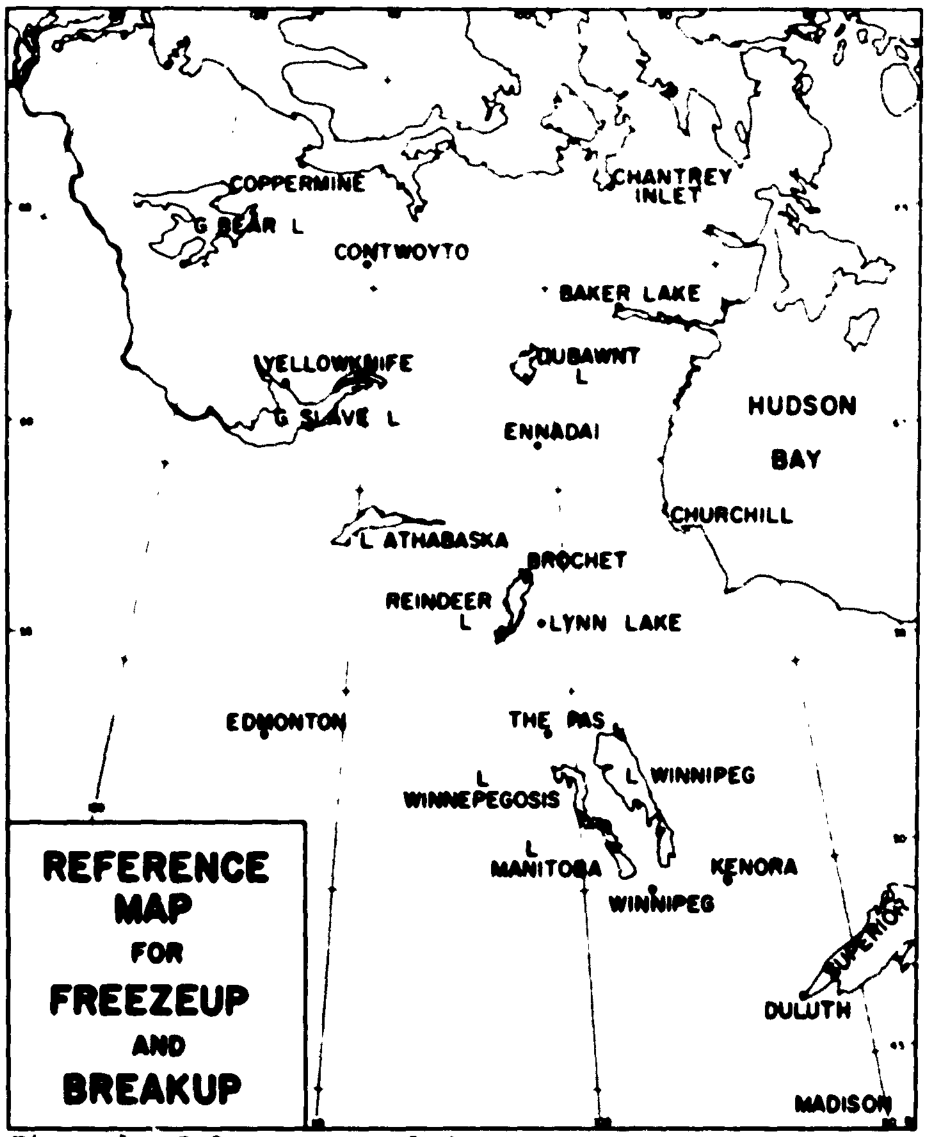


Figure 1. Reference map of the study area showing the location of the larger lakes and meteorological stations mentioned throughout the text.

Of particular interest is the geological structure and the natural vegetation of central Canada and the north-central U. S. Almost the entire observation area lies within the Canadian Shield region. The Shield is predominantly pre-Cambrian in age, although some remnant Paleozoics may be found, and is composed mostly of granites, gneisses, and quartzites. Pleistocene glaciation has stripped off the softer, overlying sediments, exposing the much older impermeable rock.

Because the area is underlain by these impermeable rocks, it has been impossible in the relatively short time since the waning of the last ice sheet for a well-developed drainage system to form. Precipitation that falls onto the surface cannot seep into the ground, and as a result gathers in the many depressions that occur throughout the region. Precipitation exceeds evaporation in this region, so surface water abounds in lakes of all sizes and shapes, muskegs, bogs, and rivers with very irregular courses. From 10 to 20 percent of the land surface is covered by the lakes.

Natural vegetation must play an important role in this study particularly because of the consequence of the "trees or no trees" effect on albedo. These major vegetative regions are delimited for the purposes of this investigation: the tundra or barrens, devoid of trees and other high-standing vegetation; the boreal forest, dominated by conifers such as spruce, tamarack, and jack-pine and with a sprinkling of broadleaf deciduous trees such as aspen, poplar, and birch; and the northern hardwood-conifer forest and farmland mixture with its cultivated fields and wooded areas of mostly deciduous trees.

B. Data Collection

1. Lake Ice Distribution

The platform used for this aerial reconnaissance was a U. S. Navy P2V Neptune patrol aircraft (Fig. 2) which, along with a crew, was provided by the Service Test Division of the Naval Air Test Center, Patuxent River, Maryland, through the Office of Naval Research. This aircraft is useful because of its long range and its multi-engine reliability over the vast uninhabited terrain of northern Canada. Of particular

FIGURE 2. U. S. Navy P2V patrol aircraft used for ice reconnaissance flights.

importance is the plexiglass nose of the plane from which an observer can have an unobstructed view of the terrain in front, below, and to the sides of him. The P2V was normally manned by three observers and eight crew members during each flight. Each observer had specific duties relating to various experiments being performed aboard the aircraft.

Lake ice information was obtained by both visual and photographic means. Three different types of cameras were used to obtain the photographic coverage, each serving a specific purpose. A Polaroid Automatic 100 camera was used to obtain black and white pictures of the terrain and sky at various places along the flight track. These pictures were very useful in the post-flight analysis of the data and for the more efficient planning of the next flight. A Nikkorex Zoom 35 camera was used to obtain color transparencies of ice, terrain, and sky conditions at intervals during each flight. These photographs were used to help document the visual records.

The most useful photographic tool was the time lapse movie camera mounted in the plexiglass nose of the aircraft. The camera was a Bolex 16mm movie camera modified for time lapse operation by Mr. Claude Rönne of the Woods Hole Oceanographic Institution. It was operated at 2 frames per second, which at an airspeed of 200 miles per hour made possible about 35 minutes or 116 miles continuous coverage per

100 foot roll of film. By projecting this film at 16 frames per second the viewer has the sensation of traveling at eight times the real speed of the aircraft or about 1600 miles per hour. Despite the apparent speed, the continuity of the picture is excellent, and by using a projector with an adequate heat filter the film can be stopped for detailed study of a particular frame. A continuous photographic record of the significant portions of each flight was obtained with this camera for use in the detailed analysis of the lake ice distribution.

Visual observations were also made from the plexiglass nose of the aircraft. Ice conditions were entered directly on maps, and interesting terrain features, snow cover, and general weather conditions were recorded in a log book and on tape over the intercom system of the plane. The observer also served as photographer and kept an accurate log of the location of the aircraft at the start and end of each roll of movie film and when a 35mm or Polaroid snapshot was taken.

The maps used were the National Topographic Series of Canada and the Sectional Aeronautical Charts for the United States. Both series have a scale of 8 miles to the inch and show good detail of lakes. Prior to each flight the track to be followed was laid out carefully on two complete sets of maps, one set for the pilot and one set for the observer. On the observer's maps were recorded the ice condition and amount on each lake observed, the deviation of the flight path from the original track, and numbered check marks which, after being simultaneously marked on all recording devices, could be used to accurately locate an event on any of the instrument records.

Ideally, observational flights were conducted at 1000 feet above the terrain although low stratus clouds or snow at times forced the aircraft below this level in order to maintain visual observation with the ground. Visual navigation was maintained at all times by the pilot. The navigator, who could not see outside the plane, carried on dead reckoning or radio navigation with occasional position reports from the pilot. If the observer, while changing film or writing in the log book, lost his position, he would reorient himself with information obtained from the pilot. If the weather deteriorated to the point of losing visual contact with the ground, as it occasionally did, heading and altitude (1000 feet) were maintained until visual contact was reestablished.

2. Albedo

Incident and reflected shortwave radiation used to compute albedo, were measured by two Kipp & Zonen solarimeters mounted on the upper and lower surfaces of the fuselage on the aft section of the aircraft. Both sensors were mounted level for flight. The construction of the upper and lower surfaces of the fuselage is essentially uninterrupted except for the vertical stabilizer, thus providing both sensors with almost completely unobstructed fields of view. The shading effect of the tail was negligible except when it came between the top sensor and the sun. In these cases the measurements were disregarded.

These solarimeters give an output proportional to the incident short wave radiation of about 8 mv per ly/min. The outputs were recorded on a Minneapolis-Honeywell Brown 12-point recorder. Each of the outputs from the top and bottom sensors recorded alternately on this recorder every two seconds. On the most recent flights these outputs were also recorded on magnetic tape on two of the channels of an eight channel Precision Instrument #6100 tape recorder having a speed of 3.75 inches per second.

3. Seiche Measurements

For the study of the relationship of lake morphology, in particular mean depths of lakes, and climate, it was necessary to obtain ground measurements of actual mean depths and to compare these measurements with the estimated mean depths obtained from the ice phenology data. The actual mean depth of a lake can be computed from depths obtained from a series of soundings over the entire lake made from a boat, or it can be estimated from the period of the lake's [illegible] ie with the use of Merian's formula (see Stewart, 1964). The seiche method was used because of the ease in transporting the measuring equipment and because most of the lakes were accessible only by an aircraft equipped with floats. During the summer of 1963, seiche measurements were made on several lakes between The Pas, Manitoba, and

Lynn Lake, Manitoba, with a water level recording instrument designed and described by Stewart (1964). This instrument was an electrical conductivity device and consisted of a plexiglass tube about 10 inches in length with two parallel silver wires inside and running the length of the tube. The changing water level produced a change in electrical resistance which in turn was measured as the imbalance of a wheatstone bridge circuit. The tube was stoppered at both ends and had several small holes which could be opened or closed to permit damping of short waves.

C. Data Processing

1. Lake Ice Distribution

As has been noted by Burbidge and Lauder (1957), the lack of a "universal" definition for either freeze-up or break-up has made it difficult to map these events and, even more so, to relate them to climate. Because the main purpose of this paper is to map lake ice distribution and to relate freezing and thawing to climate, the following explanation regarding freeze-up and break-up terms is presented.

During the period when lakes are freezing or thawing in this region, there is a line north of which all lakes are frozen and a second line south of which all lakes are open. Between these two lines is a region with some open, some frozen, and some partly frozen or thawed lakes which was named the transition zone. During freeze-up the northern line marked the boundary between this transition zone and the region where all lakes, with the exception of those listed below, were 100 percent frozen. This line is called the deep lake freeze line. The southern line, in this case, was marked at the location where the smallest lakes indicated on the sectional charts were frozen and south of which all indicated lakes were open. This line is called the shallow lake freeze line.(Lakes whose diameters are less than approximately 0.5 miles are not mapped.) During the break-up the ice conditions for the northern and southern lines were opposite to those of freeze-up, and these lines are called deep and shallow lake thaw lines.

The exact mean depths of the lakes that formed the shallow lake line and the deep lake line in all locations were unknown. Some estimate as to the range of mean depths for these different size lakes could be made from observations of the freeze-up of lakes in an area where mean depths of several lakes had been determined. A mean depth range of from slightly less than 1 meter to 3 meters appeared to be a realistic estimate for those lakes forming the shallow lake line. There are some lakes in the region having mean depths between 10 and 15 meters. These lakes would definitely be part of the deep lake line, but other lakes with mean depths of about 6.5 meters were observed to form part of the deep lake line in certain areas. A mean depth range of 6.5 meters to 10 meters appeared to be a realistic estimate for the deep lakes, with lakes having mean depths of about 15 meters being the largest lakes considered in this study.

Because of their large areal size, some lakes throughout the region of investigation were not considered as good "indicator" lakes. By this we mean that their response time to climate was so much greater than all of the other lakes that they appeared as large anomalies in the overall pattern. These lakes and their provincial locations are given in Table 1.

TABLE 1

LAKES CONSIDERED AS ANOMALOUS IN THIS INVESTIGATION

Lake	Province or District
Great Bear	Mackenzie
Great Slave	Mackenzie
Baker	Keewatin
Dubawnt	Keewatin
Nueltin	Keewatin and Manitoba
Reindeer	Saskatchewan and Manitoba
Southern Indian	Manitoba
Athabaska	Alberta and Saskatchewan
Winnipegosis and Manitoba	Manitoba
Winnipeg	Manitoba
Wollaston	Saskatchewan

To locate the transition zone and its boundaries and to map the migration of this zone during the freezing and thawing seasons, it was necessary to analyze the ice maps, 16mm movies, 35mm slides, and polaroid pictures from each flight using the following procedure.

Using the maps, with the amount and condition of ice on each observed lake marked on them, as a guide, the 16mm movies were projected using the start-stop projector. A comparison of the information on the map with the movies was made to assure that the boundaries of the transition zone were located correctly. The still photographs, which as a rule were taken to either side of the flight path, were used in conjunction with the maps and movies to provide more detail in the analysis. Because each flight crossed the transition zone boundaries in at least two different locations and because flight tracks were repeated at least twice during each operation, it was possible to map both the location and the migration of the transition zone during the observational period. All distances were reported in nautical miles.

2. Albedo

The albedo records from each flight were analyzed in much the same manner as the ice maps. The record of each flight was first stratified according to terrain type, snow cover, time of day, and cloud cover as recorded by the movies, still pictures, and notes of existing conditions made at frequent intervals by the observer during each flight. After sectioning of the record was complete, values of the upper and lower solarimeters were read at 3/4-minute intervals within each section. Albedo in percent, which is the ratio of reflected to incident solar radiation times 100, was computed for the individual readings. The mean, standard deviation, and relative variance (coefficient of variability) for the albedo of each section were also computed.

3. Seiche Data

Seiche records were subjected to power spectrum analysis to determine the primary seiche period for each of the lakes sampled. For each record a sampling interval of much less than half of the shortest wave period was selected. The data taken from the records were punched on IBM cards, and a variance spectrum analysis for each was made using the CDC 1604 computer. The program used was that of Hutchins (1963), the output of which included lag number, frequency, period, normalized spectrum (percentage of total variance at each frequency), auto-covariance function, and the natural log of the normalized spectrum. After determining the primary seiche period for each lake, the mean depth of the lake was computed using Merian's formula (Stewart, 1964).

4. Mean Temperature Records

Daily maximum and minimum temperatures for selected Canadian stations were obtained from the Meteorological Branch of the Department of Transport, Canada, for use in calculating running mean temperatures (R. M. T.). These data were punched on IBM cards, and, using an IBM 1620 computer, running mean temperatures were computed for each station for 3, 5, 10, 15, 20, 30, and 40 days. For example, the 10 day R. M. T. for November 12 would be the mean of the mean temperature for that day plus the mean temperature for each of the preceding nine days, viz.,

$$\frac{\bar{T}\text{ Nov. }12 + \bar{T}\text{ Nov. }11 + \ldots + \bar{T}\text{ Nov. }3}{10} \qquad (1)$$

These computed temperatures were then compared with the lake ice distribution in a manner that will be described in a later chapter.

5. Radiosonde Data

In preparation for the air mass studies, radiosonde data were gathered for selected stations and dates during the observational periods from the Monthly Bulletin of Canadian Radiosonde Data (1961-1963). Only the data from the surface to the 500 millibar height were used. From these data, potential temperature and mixing ratio for each height were computed and plotted on Rossby diagrams. This information was used for part of the air mass-lake ice comparison study.

IV. LAKE ICE DISTRIBUTION

A. Freeze up

The results of lake ice distribution from both Freeze-up 1961 and 1963 are grouped together and discussed in this section, and the results from Breakup 1963 and 1964 will be discussed in the following section.

On 24 and 26 October 1961, the dates of the first lake ice reconnaissance flights into central Canada, the freezing or transition zone was south of Churchill and well into the boreal forest as shown in Figure 3. Subsequent flights from W nnipeg, Manitoba, and Madison, Wisconsin, revealed lake ice d utions as shown in Figures 3 and 4.

Transition zone widths were measured along several longitudes for various observational dates, and rates of migration of both the deep and shallow lake lines along 98°W. and 94°W. longitude were computed. These data are given in Tables 2 and 3, and the widths are shown graphically in Figure 5.

After analyzing the data and reporting the results from Freezeup 1961 (Ragotzkie and McFadden, 1962), Project Freezeup 1963 was planned to observe the freezing of lakes from the Arctic Ocean south to Wisconsin and to ascertain whether there was a year to year similarity in the overall lake freezing pattern of the region. This plan called for beginning the operation in the middle of September and continuing to the middle of November. The distribution of lake ice during the 1963 observational period is shown in Figures 6 - 9, and the transition zone widths and rates of migration are presented in Tables 4 and 5 and Figure 10.

When the lake ice distribution was first mapped on 24 and 26 October 1961, the transition zone was narrower than at any other time during this observational period. Also it widened toward the west. Between these dates and 5 November, the freezing zone advanced southward, widening at approximately the same rate along all longitudes within the study area. Between 5 and 9 November the zone continued to advance. The rate of migration of the shallow lake line was much greater along the eastern flank of the area so that by 9 November the transition zone had widened toward the east, the reverse of the situation on 5 November and earlier.

When the transition zone was first observed in the tundra on 26 September 1963, the zone was over 260 miles in width along 100° W. longitude and slightly wider toward the east. Between 26 September and 20 October, it advanced southward and narrowed to less than one-half this width. This narrowing was due to the slowing down and erratic movement of the shallow lake freeze line during this interval.

The distribution of lake ice after 20 October 1963 can be compared with the 1961 distribution in order to ascertain if the freeze-up patterns

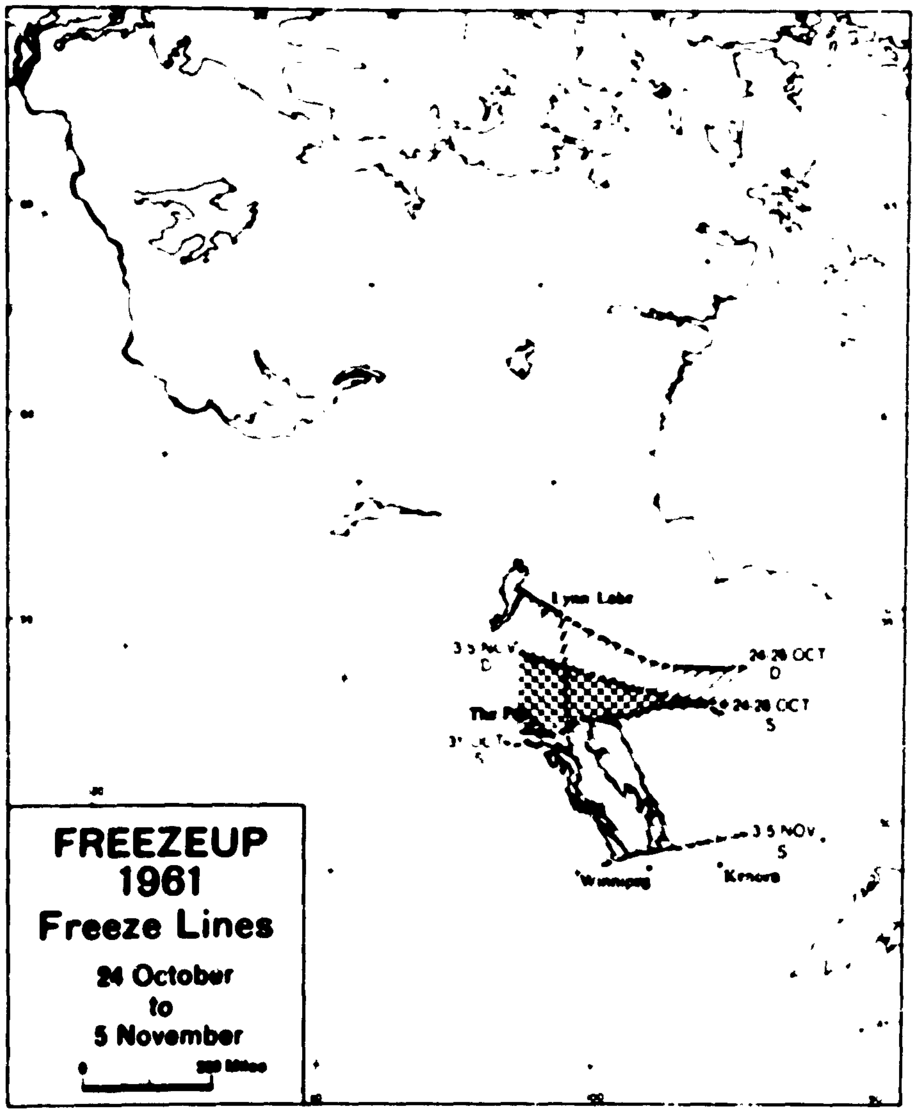


Figure 3. Lake ice distribution for 24-26 October and 3-5 November. Hatched areas are transition zones between shallow (S) and deep (D) lake freeze lines.

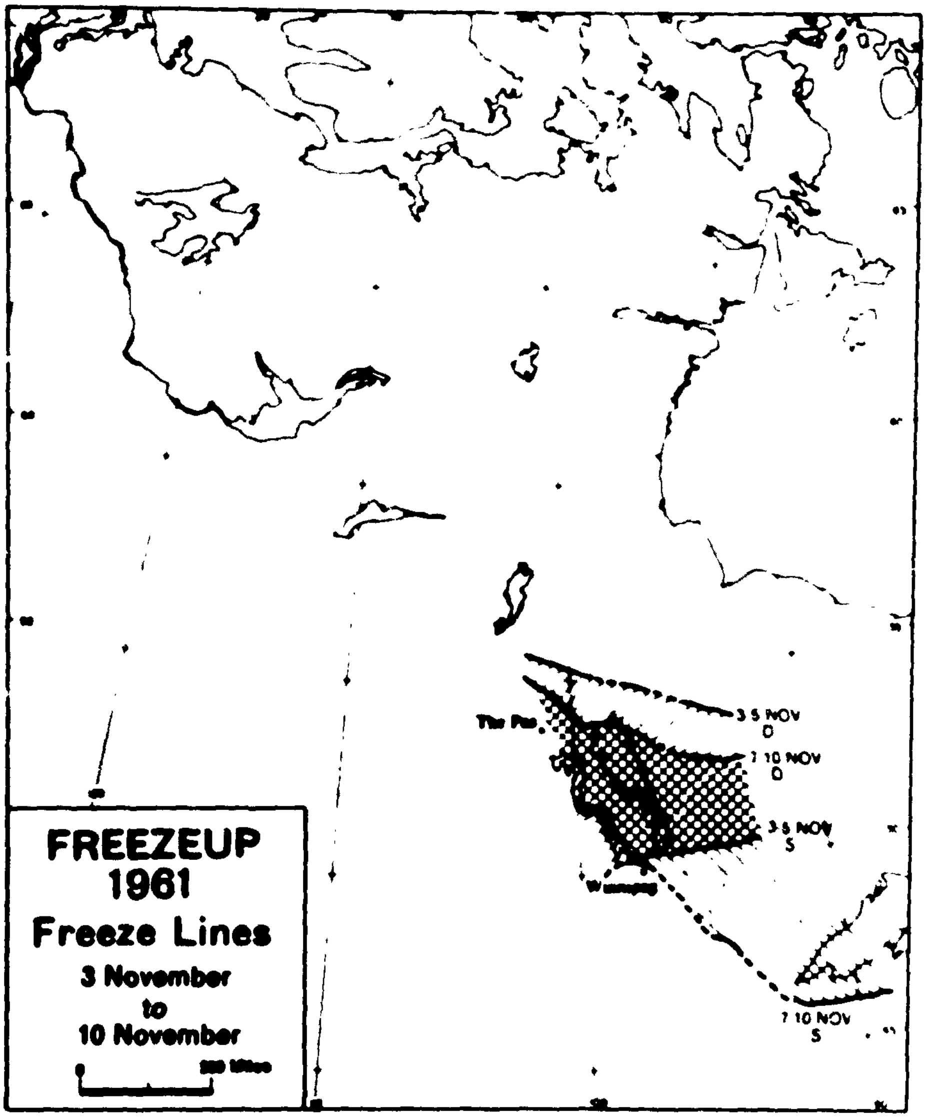


Figure 4. Lake ice distribution for 3-5 and 7-10 November. Hatched areas are transition zones between shallow (S) and deep (D) lake freeze lines.

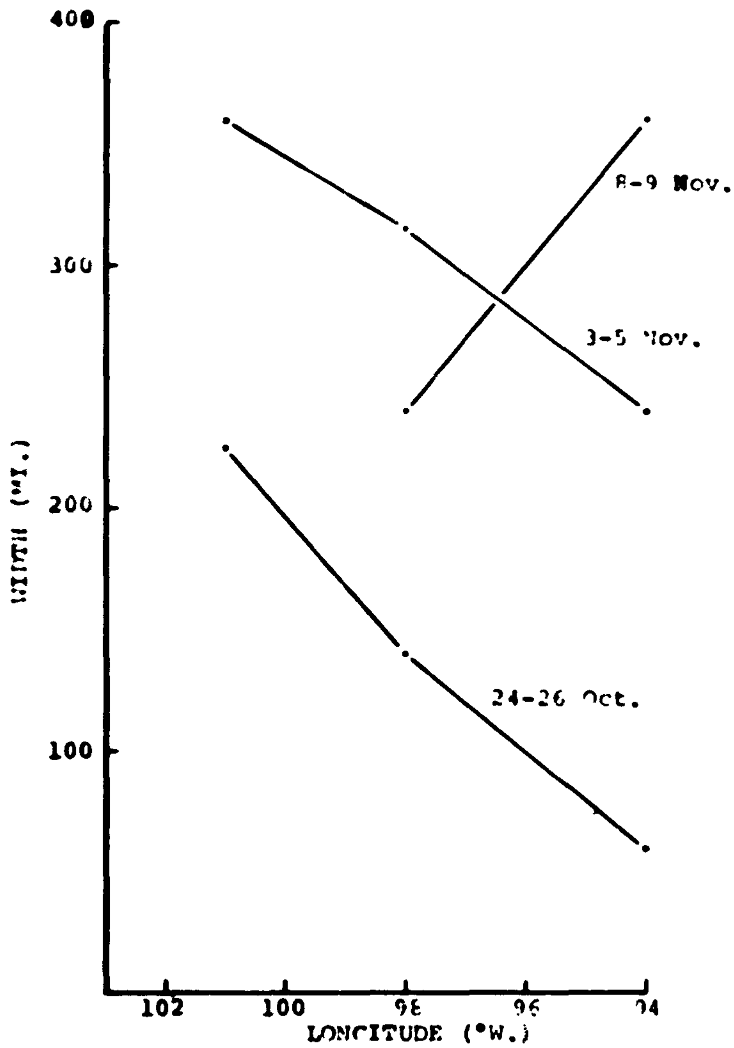


Figure 5. Transition zone widths for indicated dates during freezeup 1961.

TABLE 2

TRANSITION ZONE WIDTHS, FREEZEUP 1961

Date	Western Sector Width (n. mi.)	Western Sector Longitude ° W.	Eastern Sector Width (n. mi.)	Eastern Sector Longitude ° W.
24 Oct	225	101	-	-
26 Oct	140	98	60	94
3 Nov	360	101	-	-
5 Nov	315	98	240	94
9 Nov	240	98	360	94

TABLE 3

AVERAGE RATES OF MOVEMENT IN MI/DAY OF FREEZE LINES, FREEZEUP 1961

Date	98°W. Deep	98°W. Shallow	94°W. Deep	94°W. Shallow
26 Oct to 5 Nov	7.0	24.5	6.0	24.0
5 Nov to 9 Nov	25.0	3.0	20.0	51.0

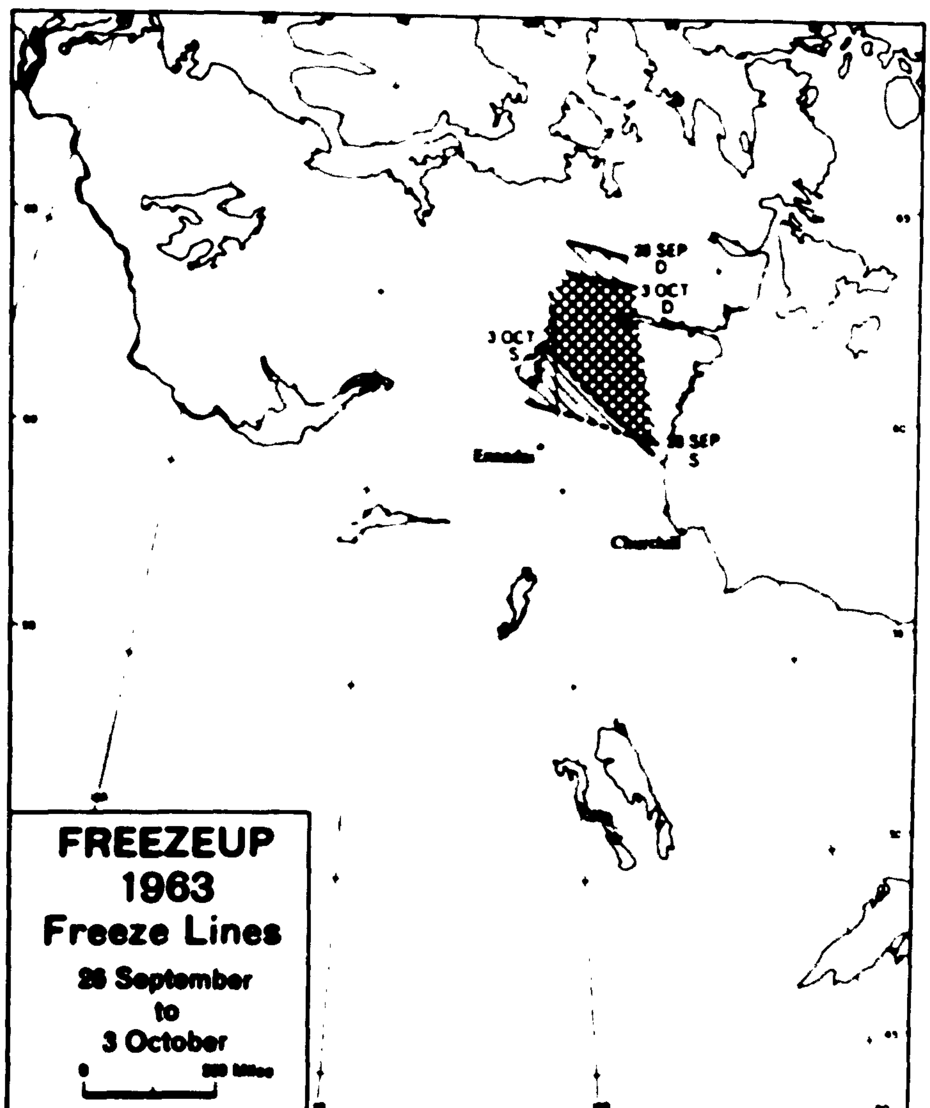


Figure 6. Lake ice distribution for 26 September and 3 October. Hatched areas are transition zones between shallow (S) and deep (D) lake freeze lines.

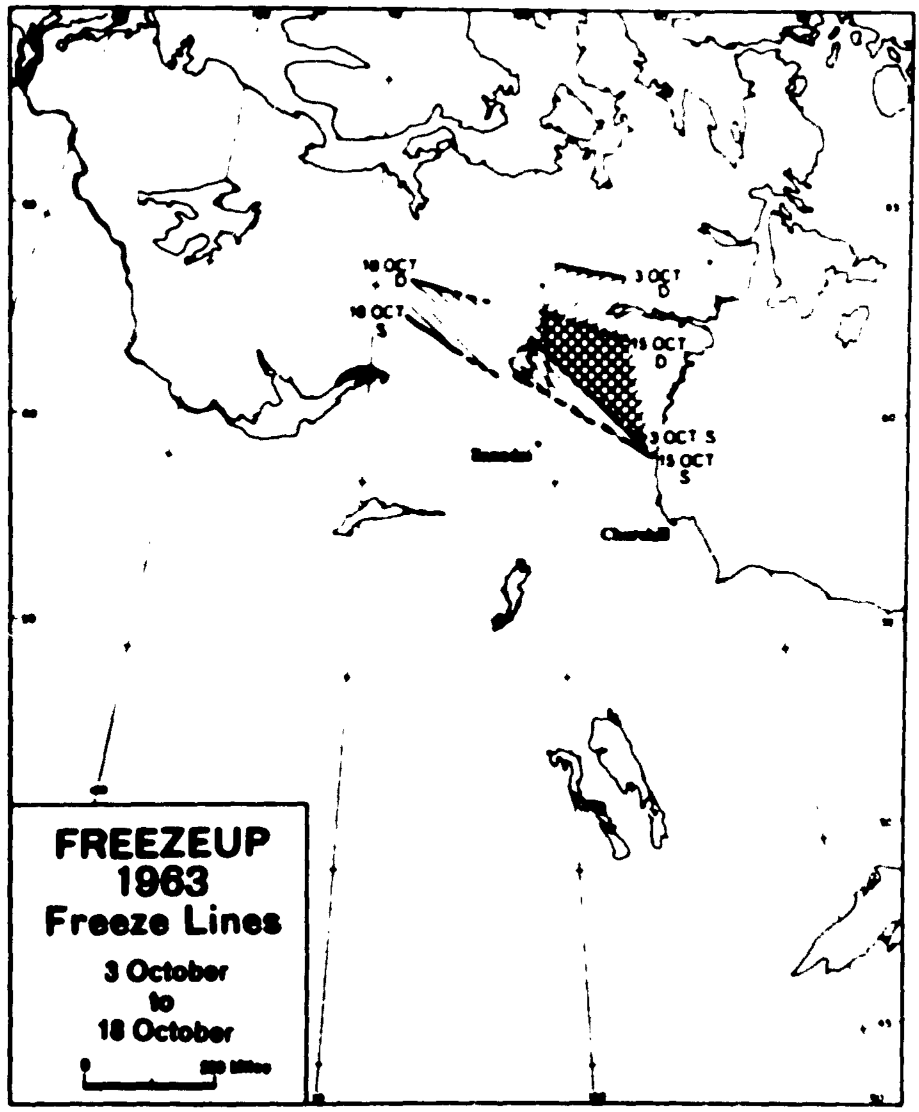


Figure 7. Lake ice distribution for 3, 15, and 18 October. Hatched areas are transition zones between shallow (S) and deep (D) lake freeze lines.

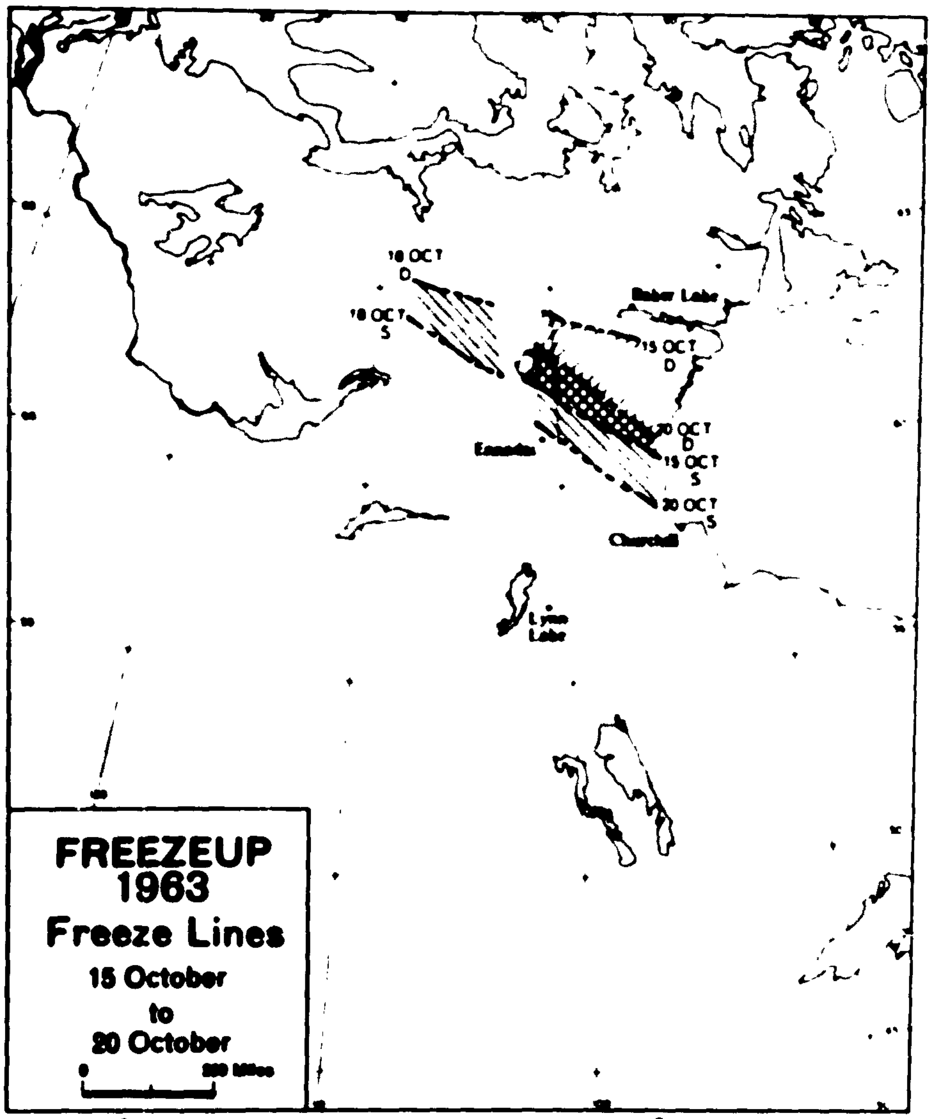


Figure 8. Lake ice distribution for 15. 18, and 20 October. Hatched areas are transition zones between shallow (S) and deep (D) lake freeze lines.

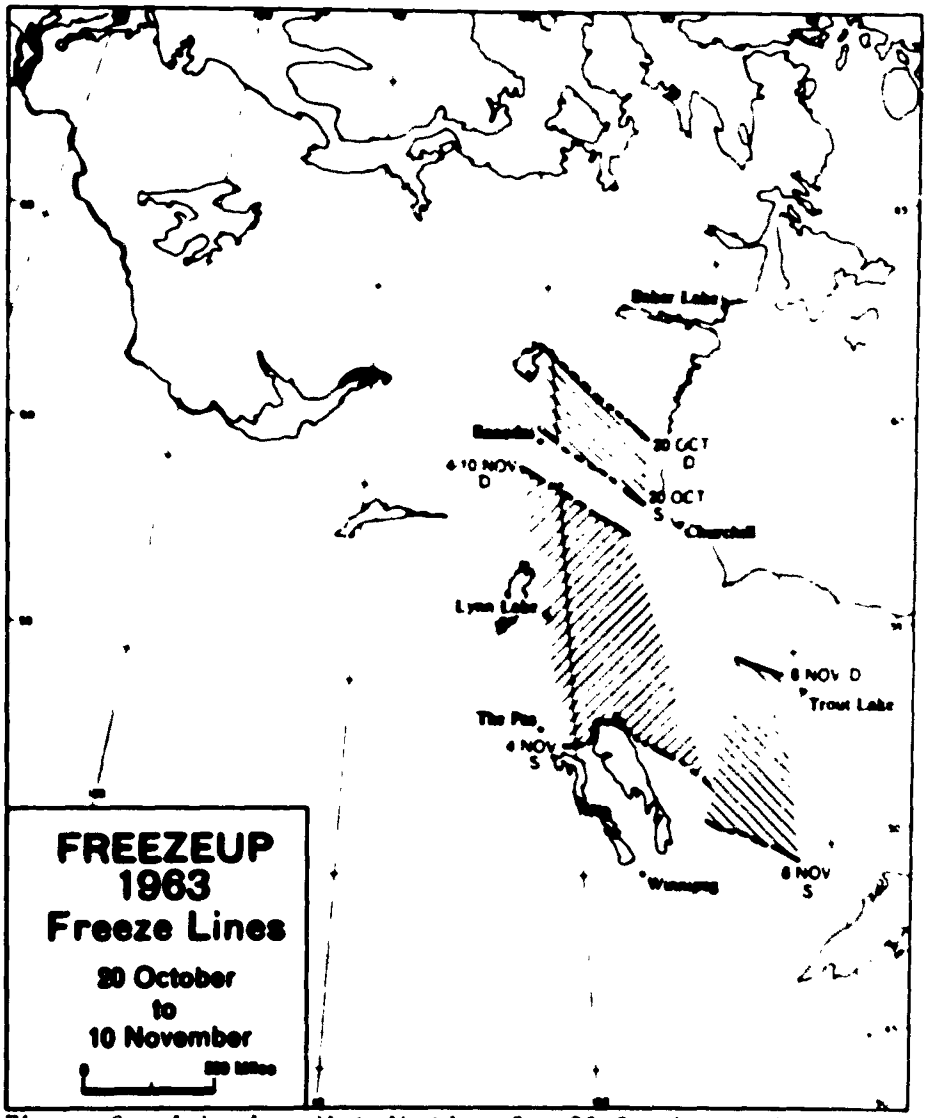


Figure 9. Lake ice distribution for 20 October and 4, 6, and 10 November. Hatched areas are transition zones between shallow (S) and deep (D) lake freeze lines.

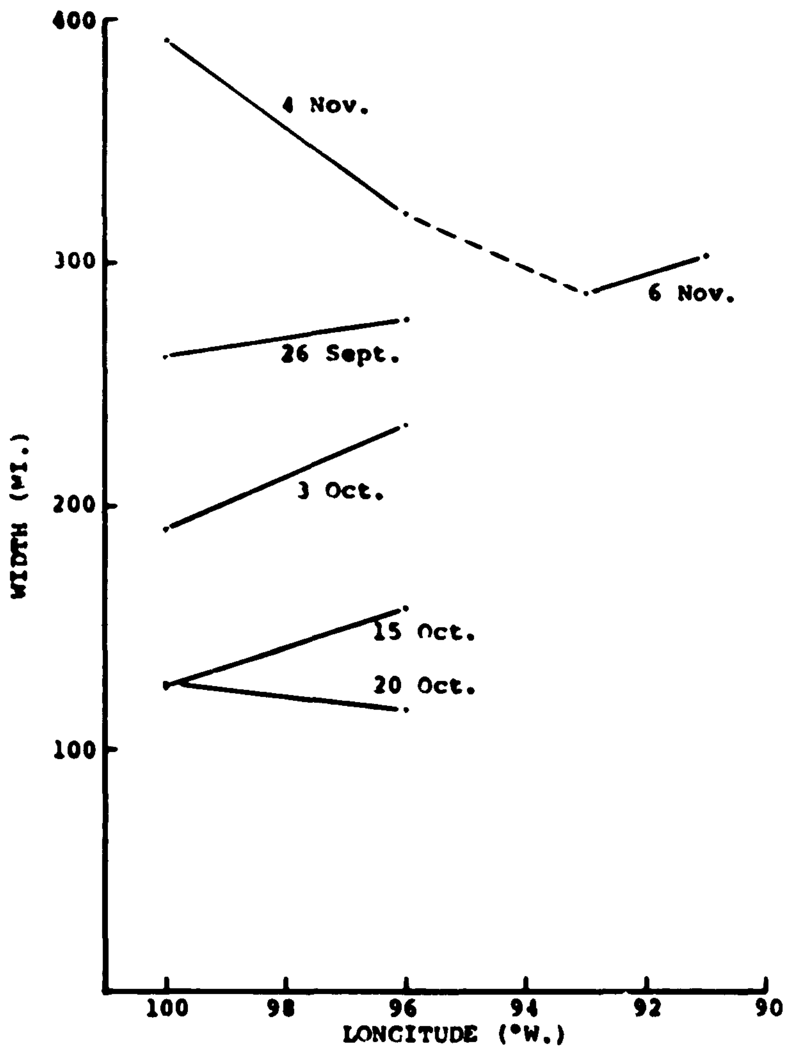


Figure 10. Transition zone widths for indicated dates during Freezeup 1963.

TABLE 4

TRANSITION ZONE WIDTHS, FREEZEUP 1963

Date	Western Sector		Eastern Sector	
	Width (n. mi.)	Longitude ° W.	Width (n. mi)	Longitude ° W.
26 Sept	262	100	277	96
3 Oct	191	100	234	96
15 Oct	126	100	158	96
18 Oct	52	108	91	105
20 Oct	127	100	117	96
4 Nov	391	100	320	96
6 Nov	288	93	303	91

TABLE 5

AVERAGE RATES OF MOVEMENT IN MI/DAY OF FREEZE LINES, FREEZEUP 1963

Date	100° W.		96° W.	
	Deep	Shallow	Deep	Shallow
26 Sept to 3 Oct	7.3	-11.4	6.1	0
3 Oct to 15 Oct	6.0	5.6	7.7	1.8
15 Oct to 20 Oct	13.4	13.6	26.4	17.2
20 Oct to 4 Nov	13.3	30.9	12.4	25.9

are similar for the two years. The width of the zone was narrower at this time than at any other time in either year. The zone was also wider along the western flank on both occasions. However, in 1963 the narrower transition zone stage occurred about 225 miles north of the 1961 position.

The pattern of freezing after 20 October 1963 was very similar to the pattern observed in 1961 after 24 and 26 October: a general widening of the zone occurring between this date and 4 November and a rapid advance of the shallow lake line in the eastern sector after 4 November.

The results obtained on the distribution of lake ice during the autumn freeze-up period suggest that the annual pattern of freezing remains fairly constant even though certain events that take place during this period occur at slightly different times and in slightly different locations from one year to the next. This pattern appears to be a reflection of the two phases of "Indian Summer" described by Bryson and Lahey (1958). The following is taken directly from their paper (pp. 32-33) relating their conclusions pertaining to this event.

> "The rapidly rising zonal index about the 20th of September ... ends the September rains and ushers in "Indian Summer." With the more meridional flow of early September, moist tropical air from the Gulf of Mexico enters the storms and frontal systems of the upper Midwest, but as the zonal flow increases the source of warm air shifts more to the west, and it is drawn from the southwestern desert area after the 20th of September. This change is evident in the resultant surface flow charts for September and October ... as well as in the mean 500 mb flow.
>
> "...the 16th of October (on the average) ushers in a second phase of Indian Summer characterized by a rapid southward shift

> of the polar frontal zone. While the mid-United States remains generally dry during this period the probability of snow rapidly rises, as outlined by Wahl (1954). It appears from the data presented here and on the five-day normal charts that this second phase of Indian Summer is one in which the mid-latitude anticyclones change to cooler air masses at the surface.
>
> "Indian Summer and typical autumn synoptic patterns end quickly about the first of November as true continental polar outbreaks and the storms of early winter begin."

It is suggested that the observed narrowing of the transition zone in the last week of September, 1963, and the widening of the zone after the third week in October in both 1961 and 1963 are directly related to the two phases of Indian Summer described above. Specifically, the 80 mile northward retreat of the shallow lake freeze line along 100° W. longitude between 26 September and 3 October 1963 correlates very well with the initial phase of Indian Summer, which begins in the upper Midwest after 20 September. The second phase of Indian Summer is reflected in the much faster rate of southward movement of both freeze lines after 15 October 1963. The true continental Polar outbreaks that mark the end to this singularity probably accounted for the high rate of movement of the shallow lake freeze line observed in the early part of November in both 1961 and 1963.

B. Break-up

The observational periods for the two years covered different areas: Breakup 1963 covered the same area as Freezeup 1963, and Breakup 1964 included generally the region from 105° W. to 115° W. longitude. This plan was followed in order to gain knowledge of the

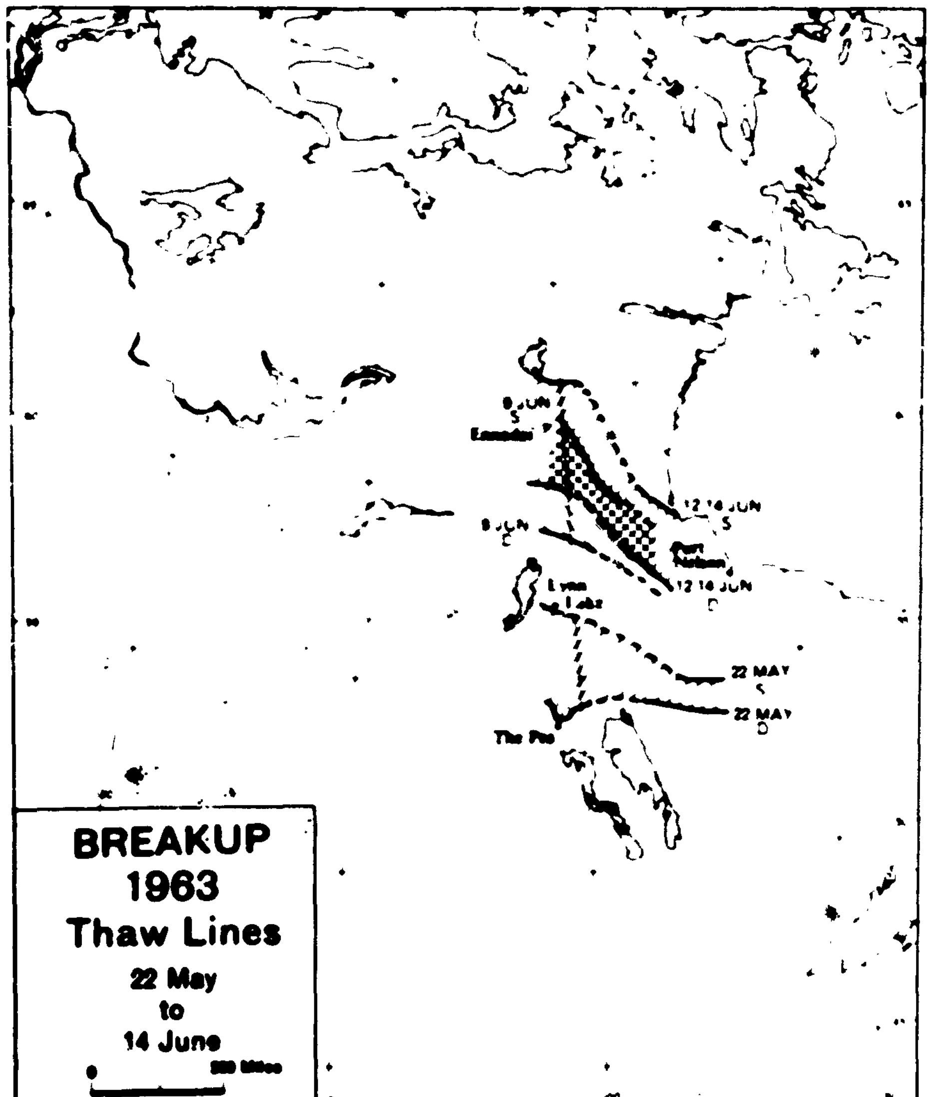


Figure 11. Lake ice distribution for 22 May, 9 June, and 12-14 June. Hatched areas are transition zones between shallow (S) and deep (D) lake thaw lines.

pattern of thawing over the entire region of central Canada.

Ice reconnaissance flights in 1963 commenced on 22 May and ended on 1 July. A total of seven flights were made during this period, and the observed lake ice distributions are shown on the maps in Figures 11 - 13. The measured thawing zone widths and calculated migration rates are presented in Tables 6 and 7 and Figure 14.

Several features of the northward progression of the transition zone are of interest. On 22 May the zone was narrower on the east, but as it retreated northward its width along 96° W. increased steadily, and it became wider along this longitude than along 101° W. due to the fairly uniform acceleration of the shallow lake line. Conversely, on the western side of the area the unsteady movement of the shallow lake line resulted in sharp variations in the zone width.

From data obtained on the flights of 29 June and 18 October 1963, it was apparent that the transition zone, be it freezing or thawing, decreased in width and became more sharply defined west of 100° W. longitude. Breakup 1964 was planned primarily to investigate this apparent trend in northwestern Canada.

All flights with the exception of the first, which originated in Winnipeg, Manitoba, were made from Yellowknife, N.W.T. The distribution of lake ice during this period is shown in Figures 15 and 16. The measured break-up zone widths and calculated migration rates of the ice lines are presented in Tables 8 and 9.

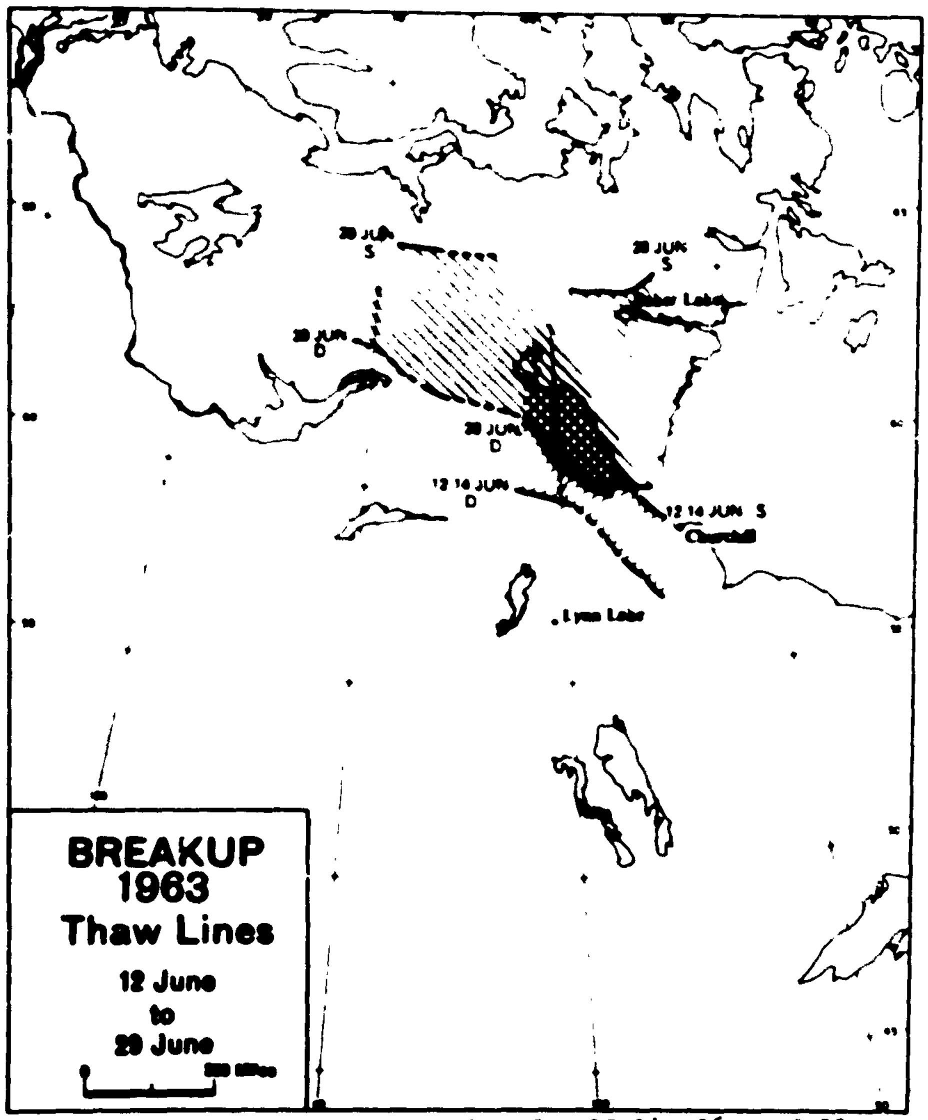


Figure 12. Lake ice distribution for 12-14, 26, and 29 June. Hatched areas are transition zones between shallow (S) and deep (D) lake thaw lines.

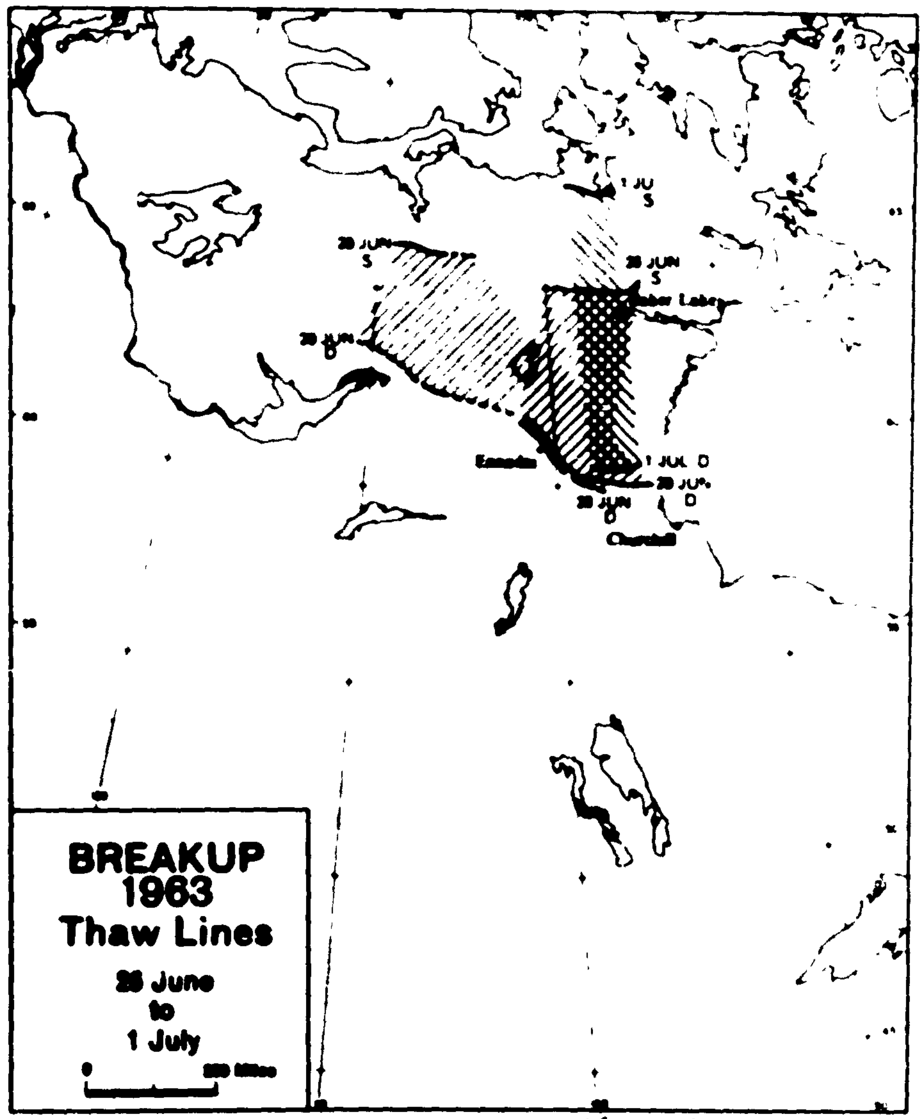


Figure 13. Lake ice distribution for 26 and 29 June, and 1 July. Hatched areas are transition zones between shallow (S) and deep (D) lake thaw lines.

TABLE 6.

TRANSITION ZONE WIDTHS, BREAKUP 1963

Date	Western Sector Width (n. mi.)	Western Sector Longitude ° W.	Eastern Sector Width (n. mi.)	Eastern Sector Longitude ° W.
22 May	166	101	111	99
			45	96
9 Jun	198	101	108	99
			108	96
12 Jun	-	-	126	96
14 Jun	161	101	182	99
26 Jun	220 (est.)	101	288	99
			308	96
29 Jun	166	109	-	-
1 Jul	363 (est.)	101	414	96
	390 (est.)	100		

TABLE 7.

AVERAGE RATES OF MOVEMENT IN MI/DAY OF THAW LINES, BREAKUP 1963

Date	101° W. Deep	101° W. Shallow	96° W. Deep	96° W. Shallow
22 May to 9 Jun	15.7	17.5	9.6	12.8
9 Jun to 12-14 Jun	14.4	7.2	7.7	13.3
12-14 Jun to 26 Jun	7.4	12.5	11.0	22.6
26 Jun to 1 Jul	3.6	30.4	6.2	29.8

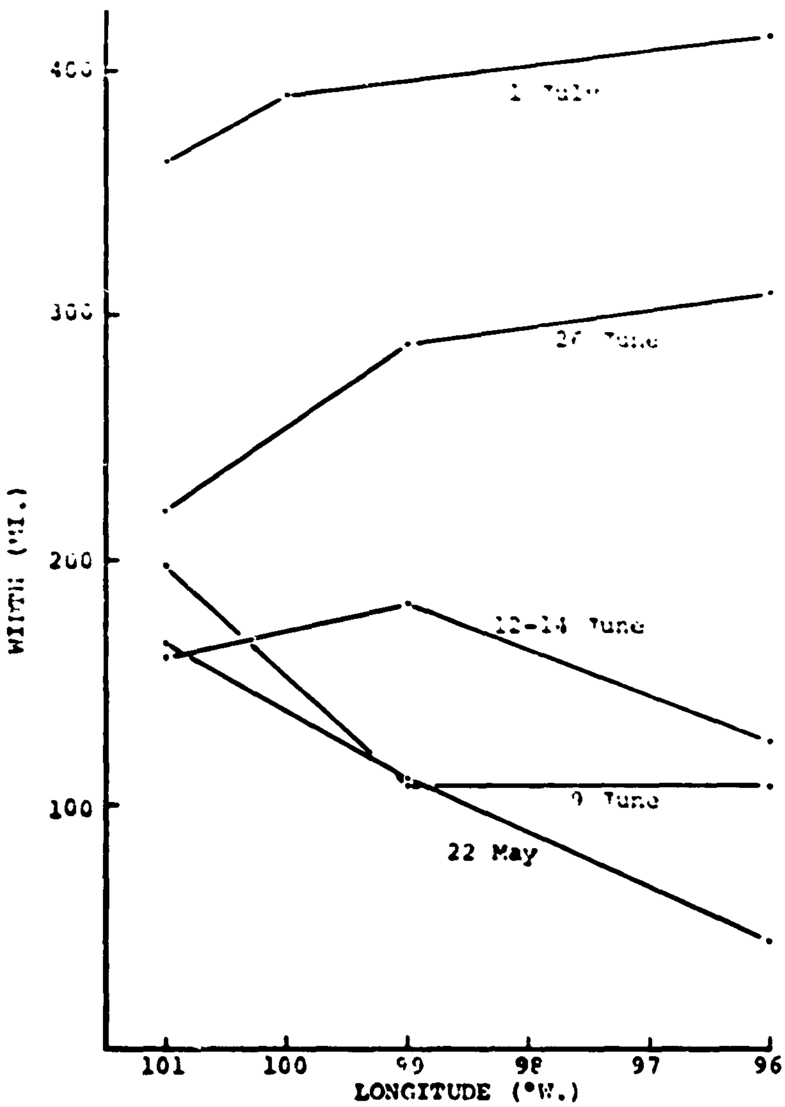


Figure 14. Transition zone widths for indicated dates during Breakup 1965.

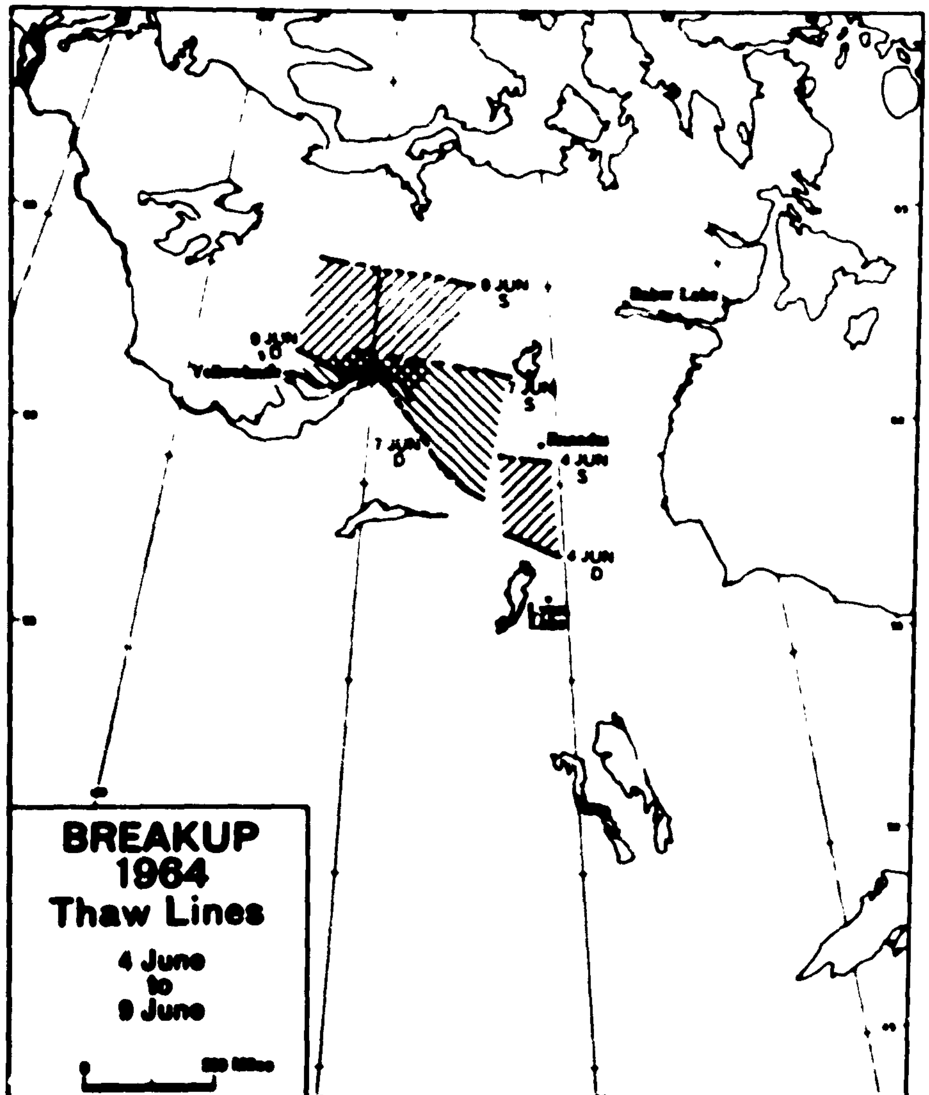


Figure 15. Lake ice distribution for 4, 7, and 9 June. Hatched areas are transition zones between shallow (S) and deep (D) lake thaw lines.

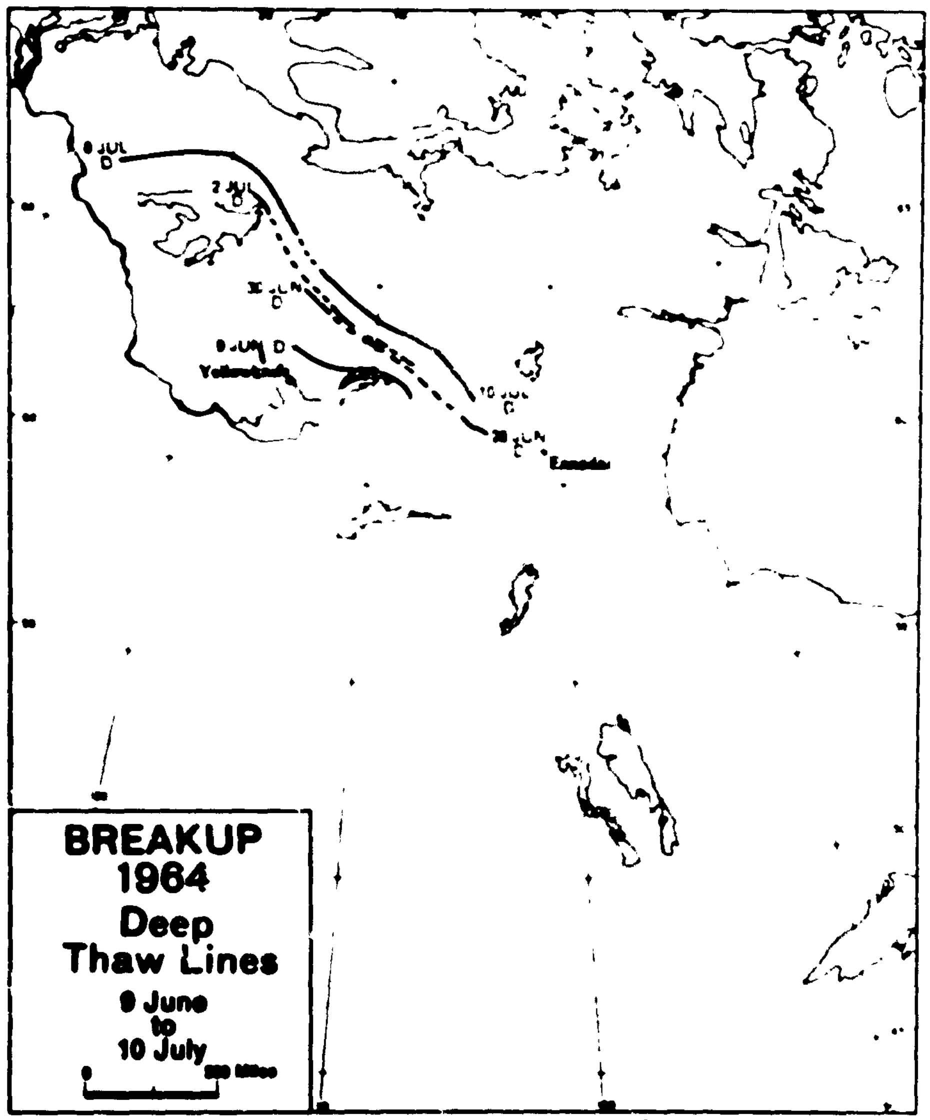


Figure 16. Deep lake thaw lines for 9, 26, and 30 June and 2, 8, and 10 July.

TABLE 8

TRANSITION ZONE WIDTHS, BREAKUP 1964

Date	Western Sector Width (n. mi.)	Western Sector Longitude ° W.	Eastern Sector Width (n. mi.)	Eastern Sector Longitude ° W.
4 June	118 (est)	103	127	102
			135	101
7 June	63	113	197	104
			208 (est)	103
9 June	153	113	165	108.5

TABLE 9

AVERAGE RATES OF MOVEMENT IN MI/DAY OF THAW LINES
BREAKUP 1964

	113° W.		108.5° W.		103° W.	
Date	Deep	Shallow	Deep	Shallow	Deep	Shallow
4 Jun to 7 Jun	-	-	-	-	12.3	42.7
7 Jun to 9 Jun	18.5	64.0	-	-	-	-
9 Jun to 28 Jun	-		1.5		-	
9 Jun to 30 Jun	4.0		-		-	
28 Jun to 30 Jun	-		6.0		-	
30 Jun to 2 Jul	4.5		-		-	
2 Jul to 10 Jul	4.3		-		-	
30 Jun to 10 Jul	-		3.7		-	

Although the break-up of lakes in 1964 was characterized by the rapid northward movement of the shallow lake line to the arctic coast, between 9 and 28 June, some interesting results were obtained both before and after this interval. While the width of the transition zone was still measurable in early June, it was observed that the zone narrowed westward of the previous area of study. For example, on 7 June the width decreased from an estimated 208 miles along 103° W. longitude to 63 miles along 113° W. longitude.

One of the most striking features of the transition zone observed during Breakup 1964 was its sharp southern boundary or deep lake thaw line in the region west of 105° W. longitude and in particular north of Great Slave Lake. Ice cover increased from zero at the line to over 50 percent only 20 miles north of the line. It was originally thought that this sharp boundary was a result of a certain amount of uniformity of mean depths for the lakes in this region. Later discussions concerning the vegetation of the region brought out the fact that the vegetative boundaries were much more sharply defined in this region also (Larsen, 1965b). This would suggest that the sharp ice boundary is in some way climatically induced, but any conclusions regarding this must await further study.

It was mentioned in an earlier chapter that only those lakes large enough to be mapped on the topographic map series used were considered.

Thus the shallow lake thaw line is not indicative of the ice conditions on the shallowest or smallest lakes in the tundra. It should be noted that only one flight in either break-up operation, 9 June 1964, resulted in the observation of a region of completely frozen lakes. Two such areas were observed on this flight, both lying along a line from Takiyuak Lake (66° 25' N, 113° W) to Macalpine Lake (66° 40' N, 103° W). The area of completely frozen lakes coincided with the area of 100 percent snow cover in both cases.

A third interesting observation made during Breakup 1964 concerned the effect the ice covered Great Slave Lake had on the position of the deep lake thaw line on 7 and 9 June. East of Great Slave Lake this line trended northwest-southeast in the usual manner, but north of the large ice covered body of water the trend direction was not maintained. It is suggested that northward moving warm air is modified as it moves across Great Slave Lake so as to retard the thawing of lakes immediately north of it and to destroy the NW-SE trend. It should be noted that this trend had been re-established along the entire line by the end of June after the disappearance of ice from Great Slave Lake.

The longitudinal extent of the observations of the deep lake line was extended during this operation because of the close proximity of Yellowknife to the study area. The best coverage was obtained on the flights of 8 and 10 July. During these flights the deep lake line was intersected a total of nine times between 103° W. and 127° W. longitude (Figure 20).

A brief comparison of freeze-up and break-up patterns shows some interesting features. The general trend direction of both freeze and thaw lines is northwest-southeast. This is significant in that it agrees with the trend of vegetative zones and boundaries, such as the tree line. This would seem to indicate that the same climatic factors are to some extent responsible for both patterns.

Another similarity observed was the narrowing of the transition zone in the northwest portion of the study area. This agrees with findings that some vegetative zones also narrow to the northwest.

Differences were observed in the rate of movement of the deep lake freeze and thaw lines. During freeze-up the rate of movement was initially slow but increased later in the fall. The rate of movement of the deep lake thaw line, on the other hand, was faster initially and slower later.

It was also noted that freeze-up followed the seasons more closely than did break-up. The coming of winter in a particular area coincided with the freezing of the lakes, but summer had come and the snow had disappeared quite some time before all of the ice had melted on the deep lakes.

V. COMPARISON OF LAKE FREEZING AND THAWING DATES WITH AIR TEMPERATURE DATA

The hypothesis that a lake integrates the air temperature over a period of time was first proposed in a quantitative form by Dutton and Bryson (1960) and later by Scott (1964). Although earlier investigators, such as Halbfass (1905) and Birge (1915), recognized that lakes reacted to changes in climate, Dutton and Bryson, in their study of heat fluxes in Lake Mendota, were first to establish quantitatively that a lake integrates the climate over a certain period of time. Scott, in his study of a group of Wisconsin lakes, showed quantitatively that this integration period is a function of the size and depth of the lake.

Since the freezing and thawing of a lake are easily observable thermal events in the annual heat cycle of a lake, they might be useful as indices of the mean temperature of the atmosphere for some period of time preceding the event.

Before proceeding to a comparison of lake ice and air temperatures a brief review of the freezing and thawing processes of lakes is presented in order to lay a foundation for a following hypothesis. Scott (1964) made an extensive study of these processes on a group of lakes in Wisconsin, and the following explanation is a general summary of his observations.

In late autumn lakes cool rapidly by a transfer of sensible and latent heat to the atmosphere with the deep lakes losing heat more rapidly than the shallow lakes. Just prior to freeze-up, when the net radiation becomes negative, there is some cooling by radiation. The amount of heat loss by this process is considerably less than by sensible and latent heat transfer. When the mean water temperature decreases to between 0° and 3.5°C, the lake freezes. After freezing, the dominant mode of heat loss is by radiation.

Scott also found that the ice-melt or wastage period, which is the interval between maximum ice thickness and break-up is characterized by both radiation gain and transfer of sensible and latent heat from the air to the ice. Once the snow cover has disappeared from the ice surface an obvious greenhouse effect occurs. Roughly 60 to 75 percent of the effective solar radiation at the ice surface is transmitted through the ice and is absorbed by and heats the water. Conduction of heat from the water to the ice causes melting at the bottom of the ice, and transfer of sensible and latent heat from the warmer air above results in wastage at the upper surface of the ice. The amount of heat available for melting the ice from below is a function of the size and depth of the lake. Radiation may account for approximately 25 percent of the ice wastage from the lower surface in deep lakes and up to 50 percent of the wastage in shallow lakes.

The effects of wind on the closing and opening of lakes were not studied by Scott although an implied relationship was made in his consideration of the relation between fetch and the mean temperature of the lake at closing. Because of the areal scale of this study these effects will be omitted here also, except for one example to be presented later in this chapter. It is important to note, however, that wind does play a role in both the closing and opening of lakes, tending to hold the lake open in the autumn and often causing rapid and sometimes destructive "blow-outs" in the spring.

From this brief account it is evident that sensible and latent heat transfer processes are important for the cooling of the water preceding freeze-up and the ice-wastage preceding break-up, with radiation sharing up to equal importance for the ice wastage period only. The dependence of freezing and thawing on air temperatures, then, is apparent, and it should be possible to show to what degree this relationship exists for both shallow and deep lakes.

If the date of one of these thermal events is noted for a given lake, it should be possible to determine for that date a preceding time period for which a selected mean air temperature exists. This time period will be called the thermal time constant, and the purpose of this chapter is to describe the results of the lake ice - air temperature comparisons which were made in order to determine the time constants for the deep and shallow lakes.

A climatological application of such a thermal relationship would be: if the freezing or thawing dates of a group of different size lakes are observed at a particular location, then estimates of mean air temperatures for various time periods preceding the events can be made for this location. If the observations were extended to a large region, then the mean air temperature over the entire region for various time periods could be determined. Conversely, if mean air temperature data from climatological stations were available, an observer could determine the dates of freezing or thawing of lakes of various sizes and depths throughout the region.

A. Freeze-up

The dominant process involved in the closing of lakes is sensible and latent heat transfer to the atmosphere. The relationship between the preceding mean air temperatures and freezing dates for shallow and deep lakes is presented for a number of stations in the study area in Figs. 17-26 and Table 10. The daily running mean air temperature values for 3 and 40-days were selected by inspection from the 3, 5, 10, 15, 20, 30, and 40-day period runs because these intervals provided the best fits with the observed lake freezing dates. The dates of freezing listed for each station in Table 10 were determined by interpolation except for those stations starred.

There is very good agreement (less than two days difference) between the freezing dates of deep lakes and the date the 40-day mean air temperature falls to 0° C for all stations except Madison, Wisconsin. It is suggested that the 3-day error that appeared in 1961 and

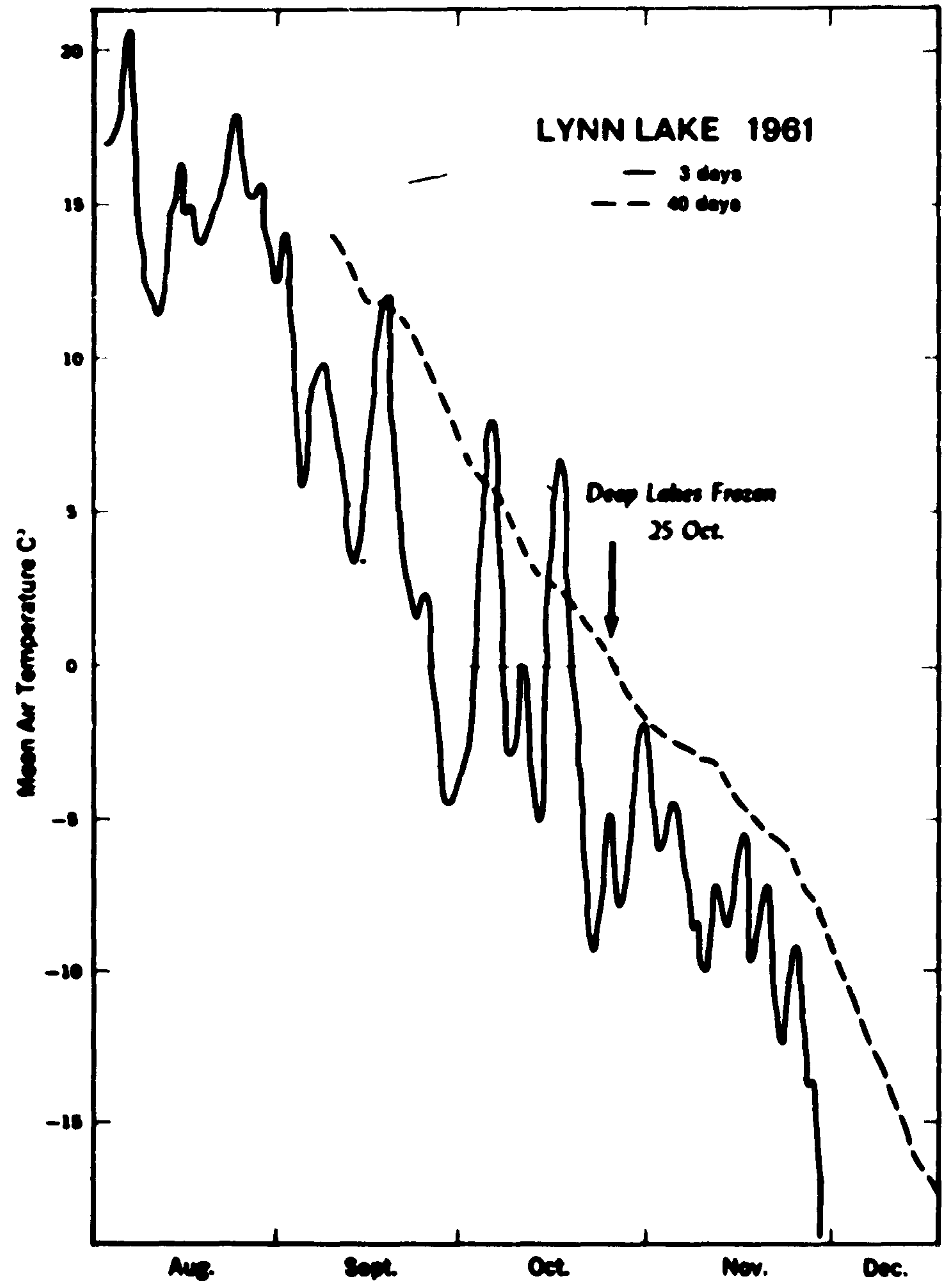


Figure 17. Comparison of freeze dates and the 3-day and 40-day running mean air temperatures at Lynn Lake, Manitoba for 1961.

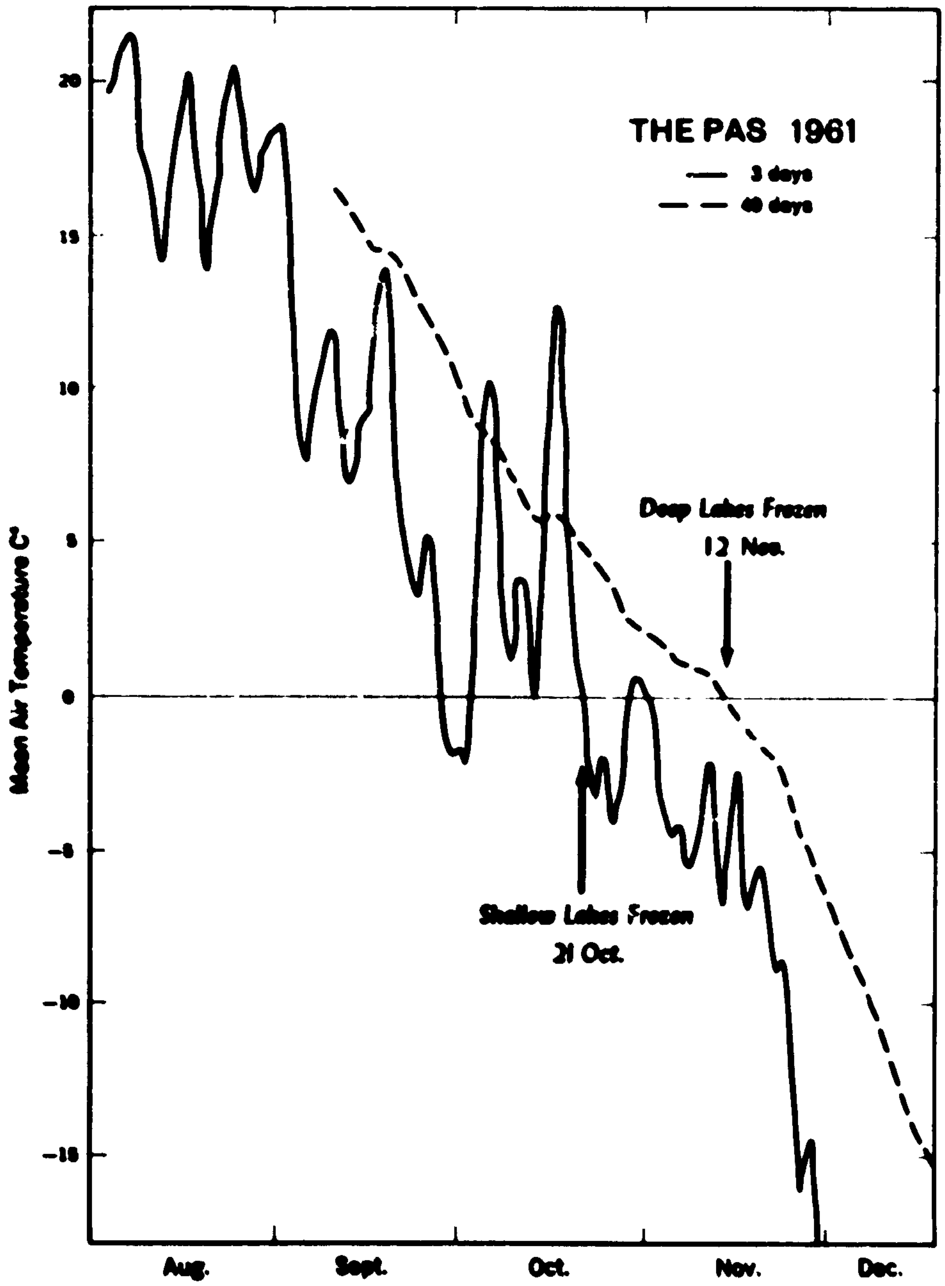


Figure 18. Comparison of freeze dates and the 3-day and 40-day running mean air temperatures at The Pas, Manitoba for 1961.

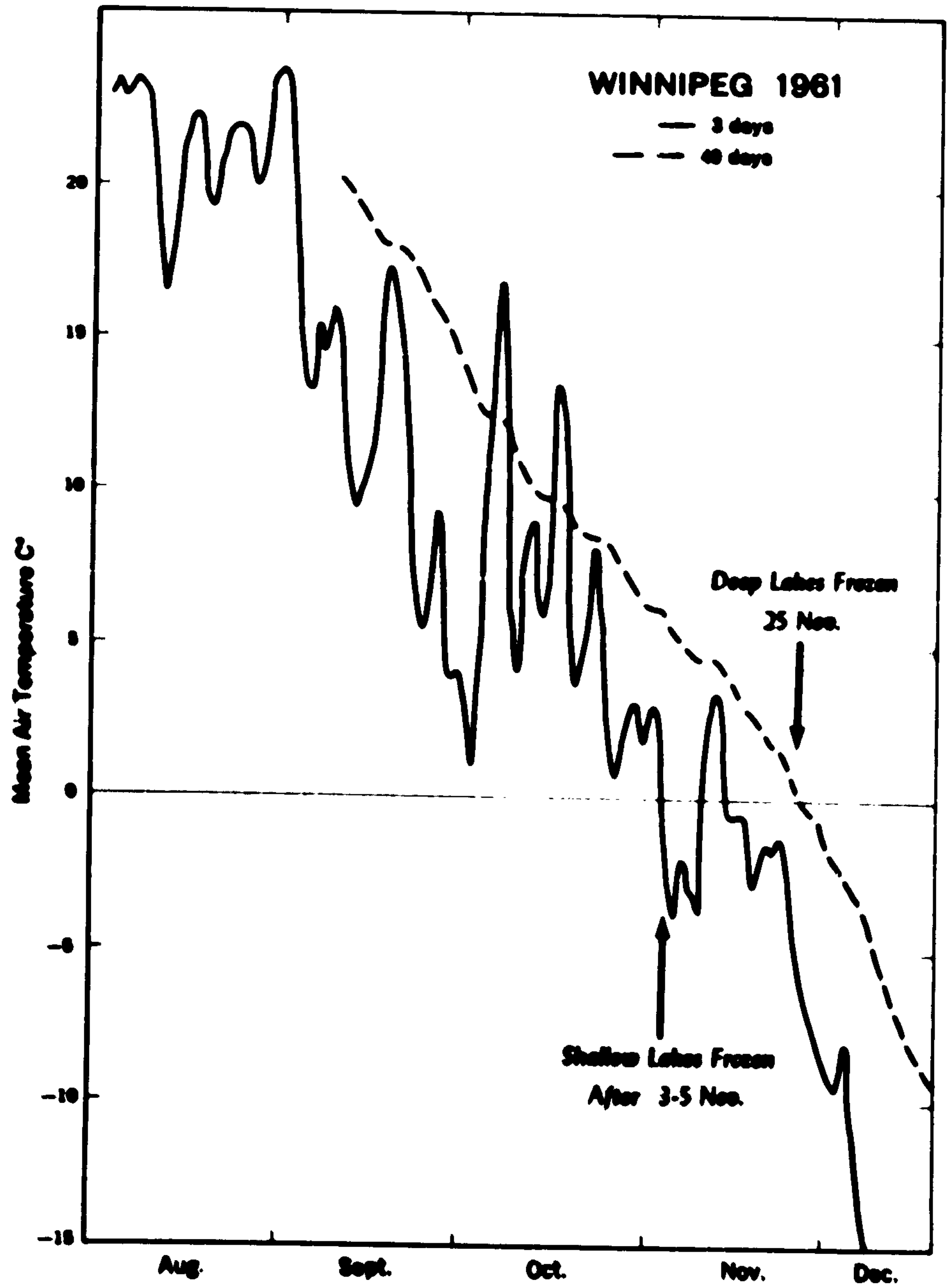


Figure 19. Comparison of freeze dates and the 3-day and 40-day running mean air temperatures at Winnipeg, Manitoba for 1961.

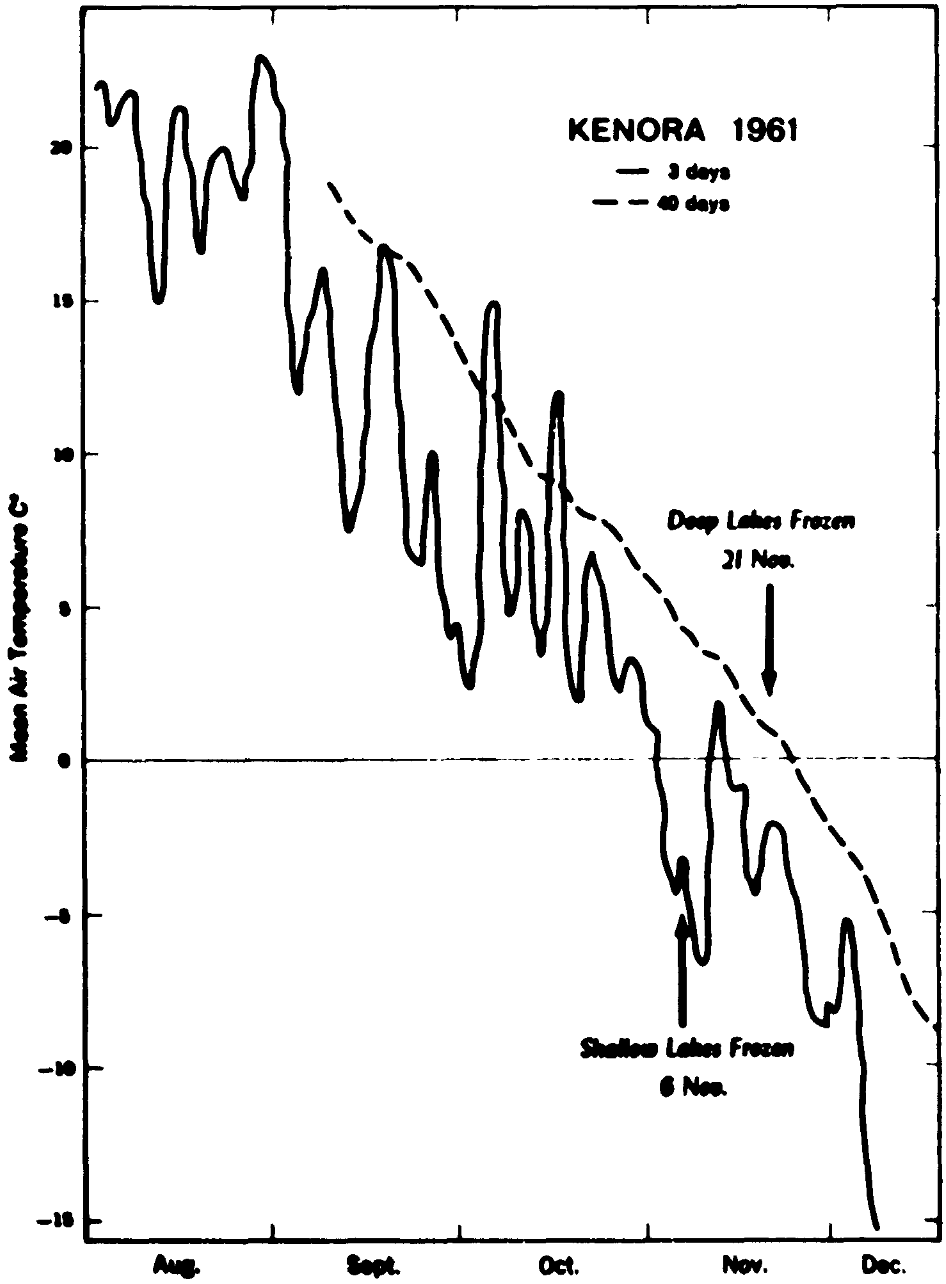


Figure 20. Comparison of freeze dates and the 3-day and 40-day running mean air temperatures at Kenora, Ontario for 1961.

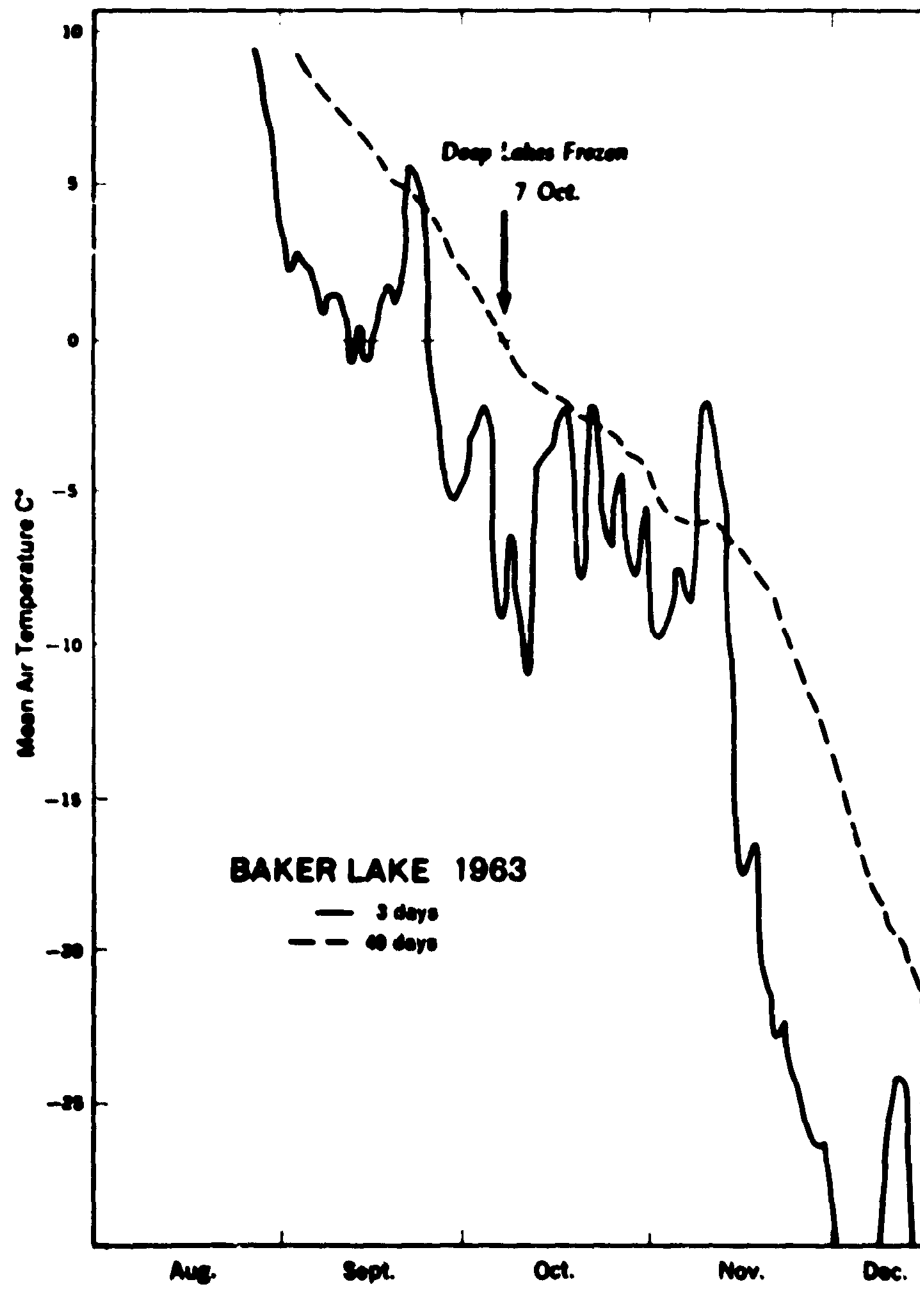


Figure 21. Comparison of freeze dates and the 3-day and 40-day running mean air temperatures at Baker Lake, N.W.T. for 1963.

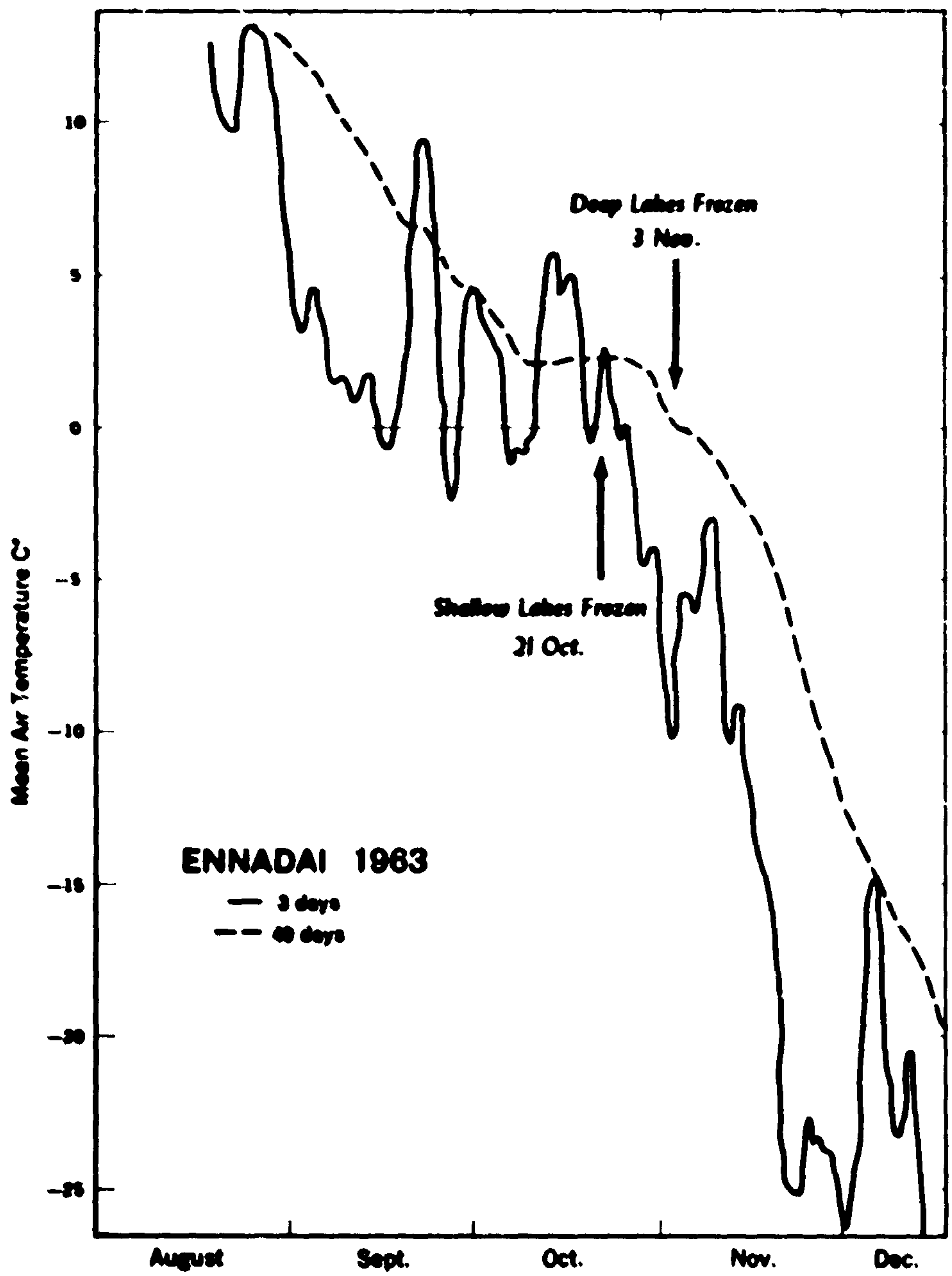


Figure 22. Comparison of freeze dates and the 3-day and 40-day running mean air temperatures at Ennadai, N.W.T. for 1963.

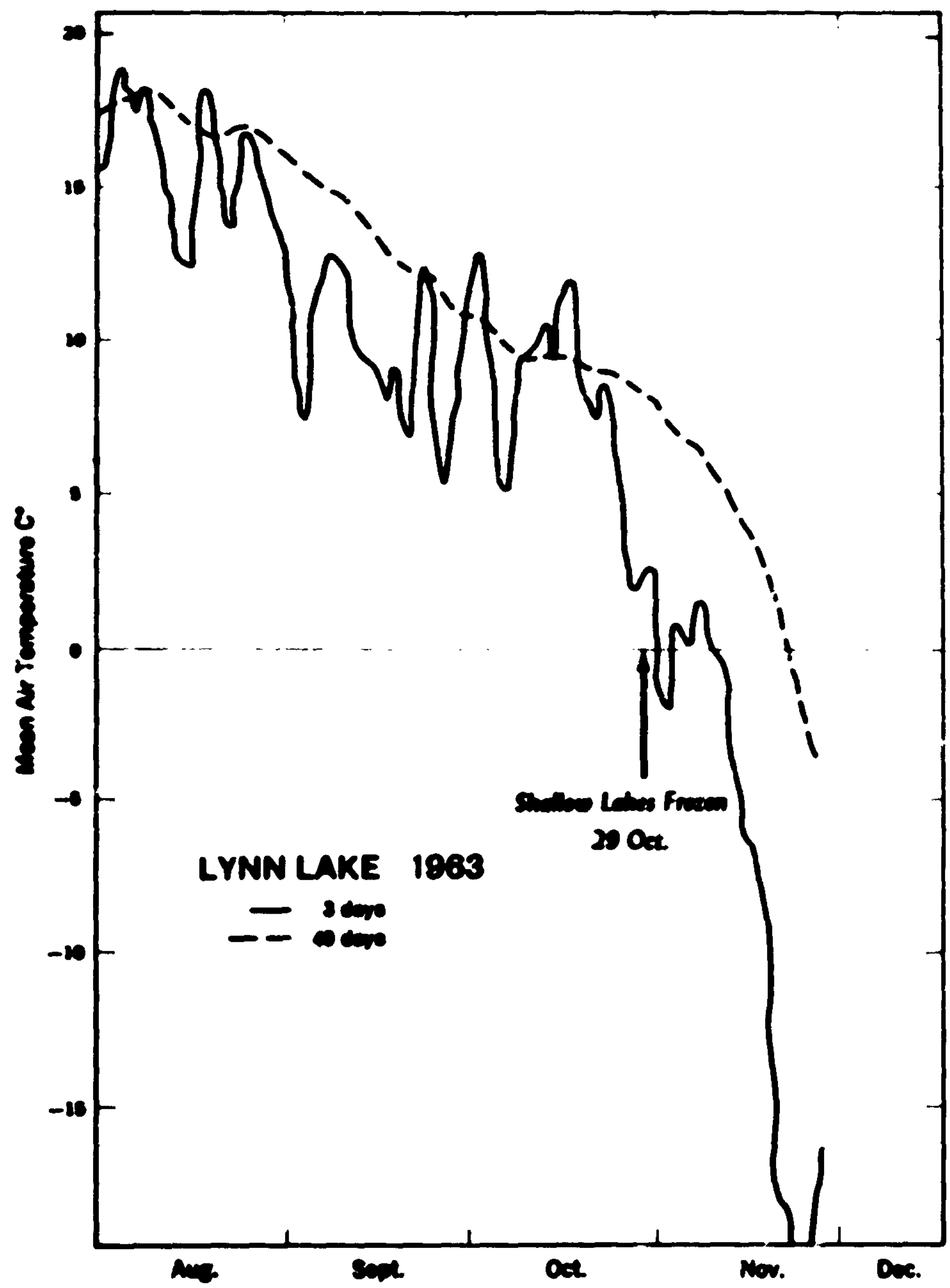


Figure 23. Comparison of freeze dates and the 3-day and 40-day running mean air temperatures at Lynn Lake, Manitoba for 1963.

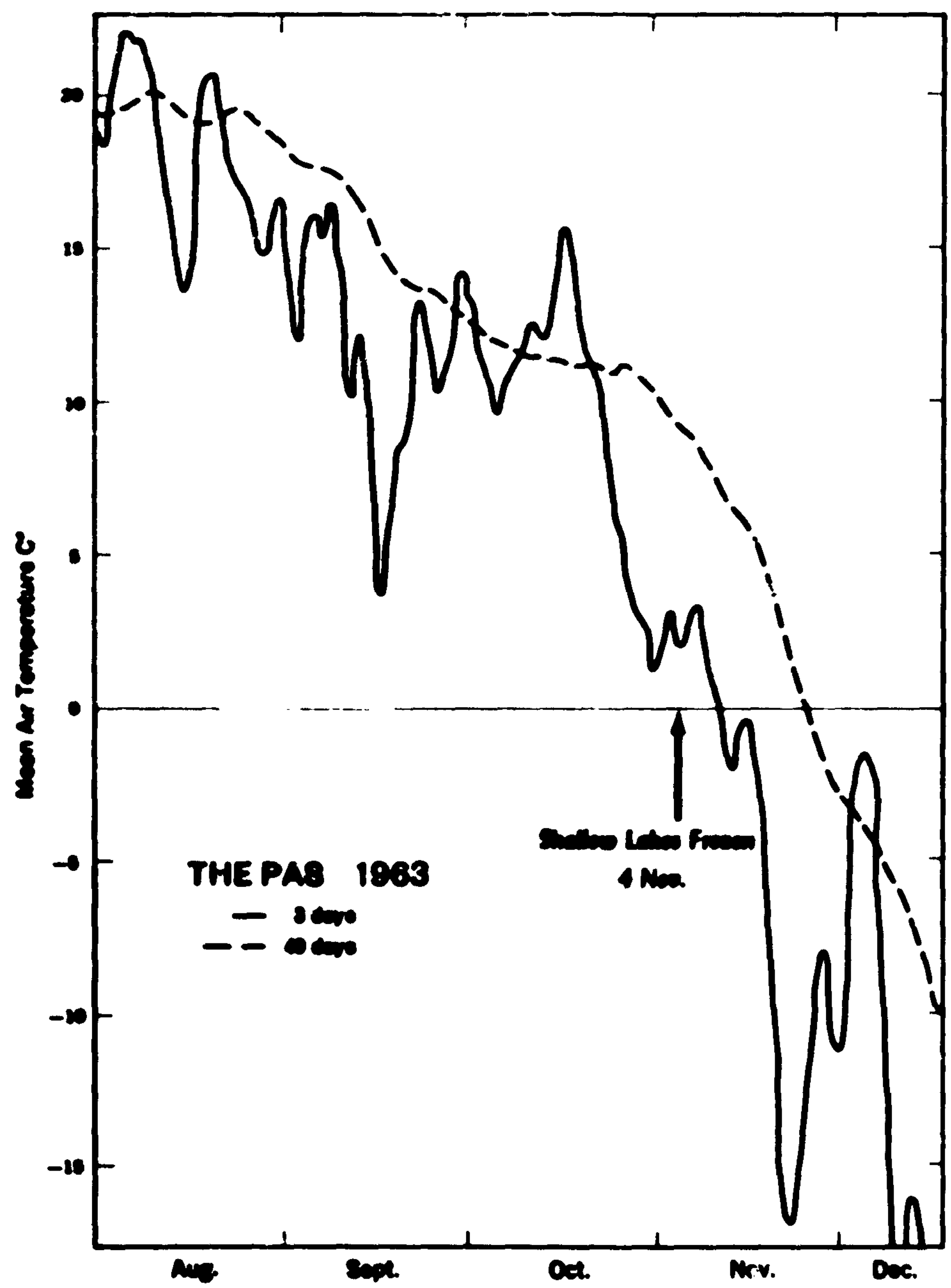


Figure 24. Comparison of freeze dates and the 3-day and 40-day running mean air temperatures at The Pas, Manitoba for 1963.

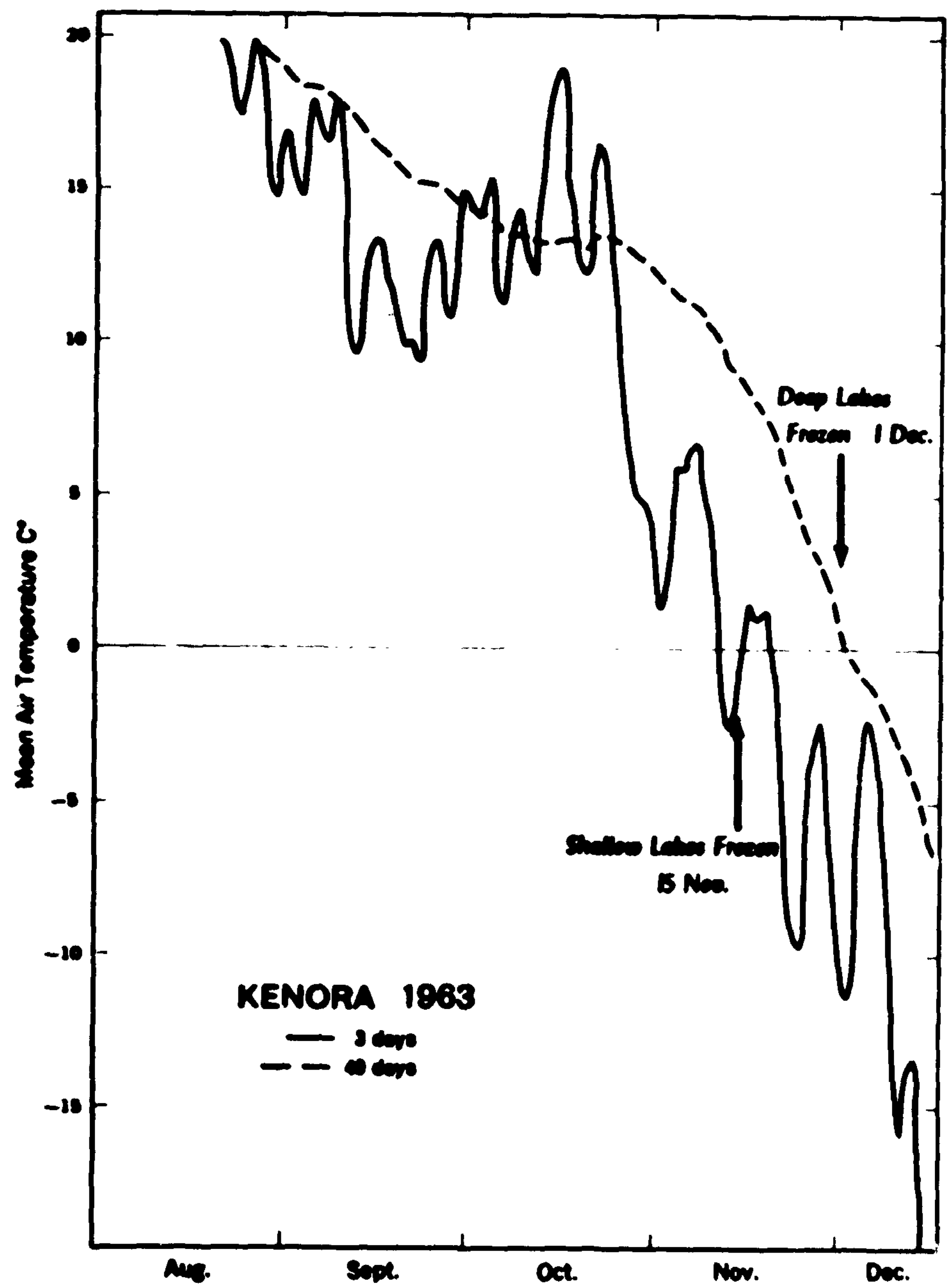


Figure 25. Comparison of freeze dates and the 3-day and 40-day running mean air temperatures at Kenora, Ontario for 1963.

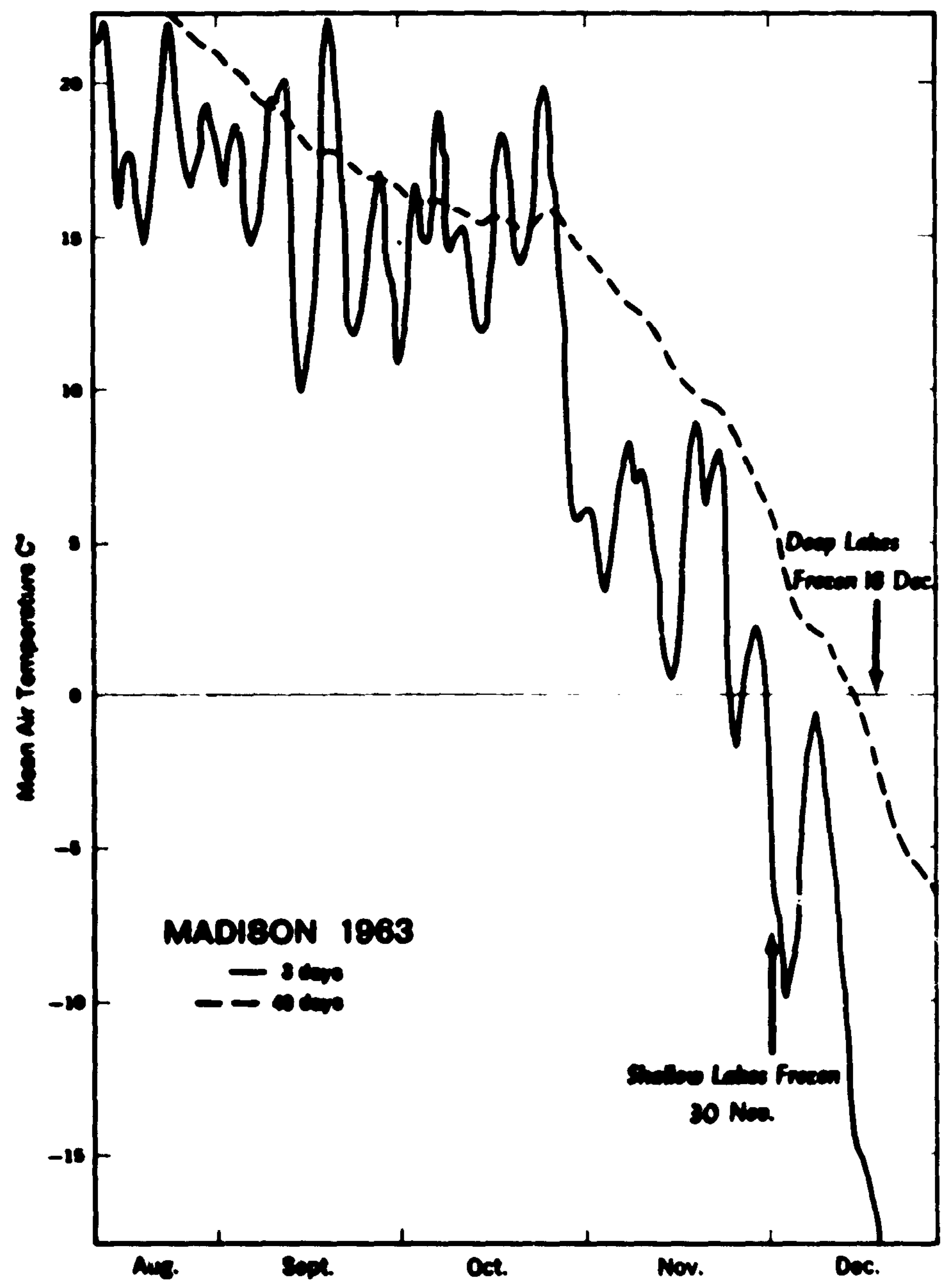


Figure 26. Comparison of freeze dates and the 3-day and 40-day running mean air temperatures at Madison, Wisconsin for 1963.

TABLE 10

COMPARISON OF FREEZE DATES AND MEAN AIR TEMPERATURE

Station	Year	DEEP LAKES			SHALLOW LAKES		
		Freeze Date	40-day mean air T(°C)	Days lead(+) or lag (-) of freeze-up vs. 40-day (0°C)	Freeze Date	3-day mean air T(°C)	Days lead (+) or lag (-) of freeze-up vs. 3-day 0°C
Lynn Lake	1961	25 Oct	-0.5	<- 1	-	-	-
The Pas	1961	12 Nov*	0.0	0	21 Oct	-0.4	< - 1
Winnipeg	1961	25 Nov	-0.1	<- 1	3 Nov	-1.3	< - 1
Kenora	1961	21 Nov	+0.7	+ 2	6 Nov	-3.1	< - 4
Madison	1961	16 Dec**	-1.7	- 3	-	-	-
Baker Lake	1963	7 Oct	0.0	0	-	-	-
Ennadai	1963	3 Nov	-0.2	<- 1	21 Oct	0.0	0
Lynn Lake	1963	20 Nov**	+1.2	+ 1	29 Oct	+1.9	+ 3
The Pas	1963	-	-	-	4 Nov	+2.0	+ 7
Kenora	1963	1 Dec	+0.9	+ 1	15 Nov	-0.3	- 3
Madison	1963	18 Dec**	-2.2	- 3	30 Nov**	-1.1	<- 1

*Freezing date obtained by extrapolation
**Freezing line observed at station location

1963 at Madison, a station where the passage of the deep lake line was observed, was due to the non-representativeness of the air temperature data collected at Truax Field just north of the city. This recording station is located in an area surrounded by hills which aid the collection and retention of pockets of cold air during periods of strong radiational cooling, thus leading to lower nocturnal minimum air temperatures.

Shallower lakes are more nearly in equilibrium with the atmosphere than deeper lakes. Thus the integration period for climatic data becomes drastically reduced. Oscillations of the 3-day mean air temperature above and below 0°C may occur several times at any one station before it falls below this level for the remainder of the autumn season. Because of these fluctuations it might be expected that shallow lake freeze dates are less precisely related to mean air temperature. The results of the comparison of the freezing of shallow lakes with the 3-day mean air temperature shown in Table 10 bear this out.

For shallow lakes it is suggested that there are two contributing factors to the increased variation. Interpolation and extrapolation of ice lines based on average rates of movement introduce errors because shallow lakes may freeze, thaw, and then refreeze one or more times before final freeze-up. This means that the southern freeze line may have oscillated north and south between observational periods. Also, linear interpolation is an oversimplification since we know by observation that the shallow line moves unevenly.

Difference in mean depths of the shallower lakes from one region to another may also be another factor contributing to the discrepancies in computed versus observed freeze dates. The shallowest lakes may freeze after a single day average of 0°C or below or even an overnight low below freezing. Such was probably the case for the estimation of the shallow lake freeze date for The Pas in 1963. Skim ice was observed on some small and apparently very shallow lakes along the Saskatchewan River, 30 miles SSE of The Pas Airport, early on the morning of 4 November. It is possible that this ice was only temporary, and that these shallow lakes froze again at some later date. Grace Lake at The Pas, which is known to have a mean depth of one meter, was still unfrozen on this date.

Figures 17-26, which show the 3 and 40-day running mean air temperature curves and deep and shallow lake freeze dates for different stations, also show the overall trend of decreasing temperatures during the autumn season. A conspicuous feature of this trend is "Indian Summer," which was referred to in Chapter IV. A comparison of temperature trends for 1961 and 1963 shows the greater influence this singularity played on the climate of central Canada in 1963.

In 1961 (Figures 17-20), Indian Summer was reflected in the 3-day running mean temperature curve at all four stations by two or three sharp rises in temperature beginning in the first few days of October. The effect was much more pronounced at Winnipeg than at Lynn Lake. The

40-day running mean curve does not appear to reflect this singularity during this period as would be expected considering the short duration of the temperature rises.

Indian Summer is an outstanding feature of the autumn temperature trend in 1963 at all stations, even as far north as Baker Lake. So prominent was this singularity in 1963 that it even showed up markedly in the 40-day running mean curve. At northern stations, Indian Summer appeared as a plateau on the temperature graphs, but at Madison the effect was so strong that it appeared as a continuation of the mid-August warm trend (Figures 21-26). The stronger influence on the lake ice distribution induced by this singularity in 1963 was clearly reflected in the more northerly position of the transition zone at the time of its minimum width.

B. Break-up

Before comparison tests were made between mean air temperature and break-up dates it was suspected that the dominance of two processes, radiation, and sensible and latent heat transfer, would produce somewhat different results from those obtained in the freeze-up comparisons. The same time periods were used for break-up comparisons after it was observed from freeze-up comparisons and from inspection of similar time period runs for break-up that the 3-day and 40-day means were the best air temperature time constants. The results of this analysis are shown in Figures 27-36 and Table 11.

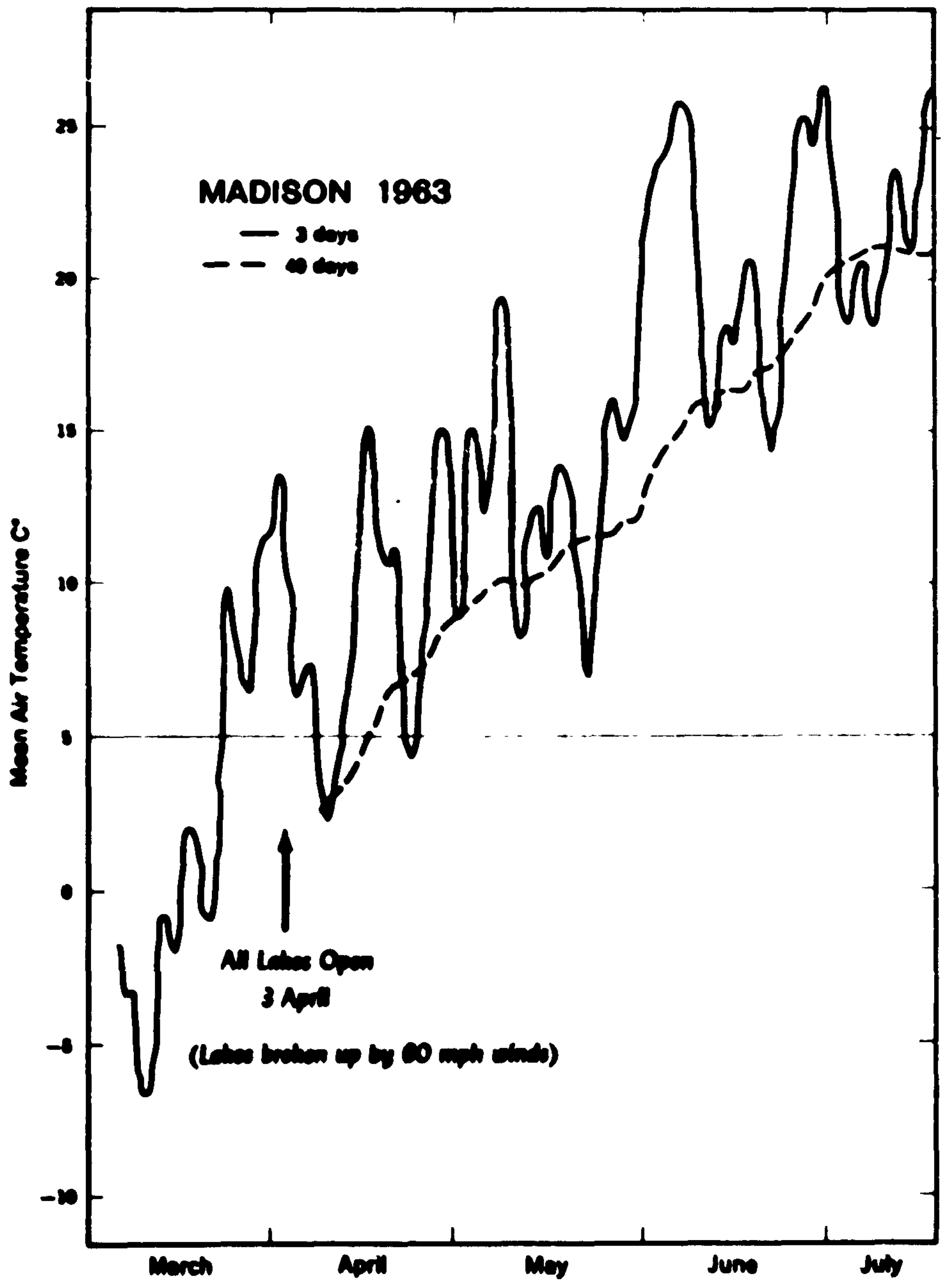


Figure 27. Comparison of opening dates and the 3-day and 40-day running mean air temperatures at Madison, Wisconsin for 1963.

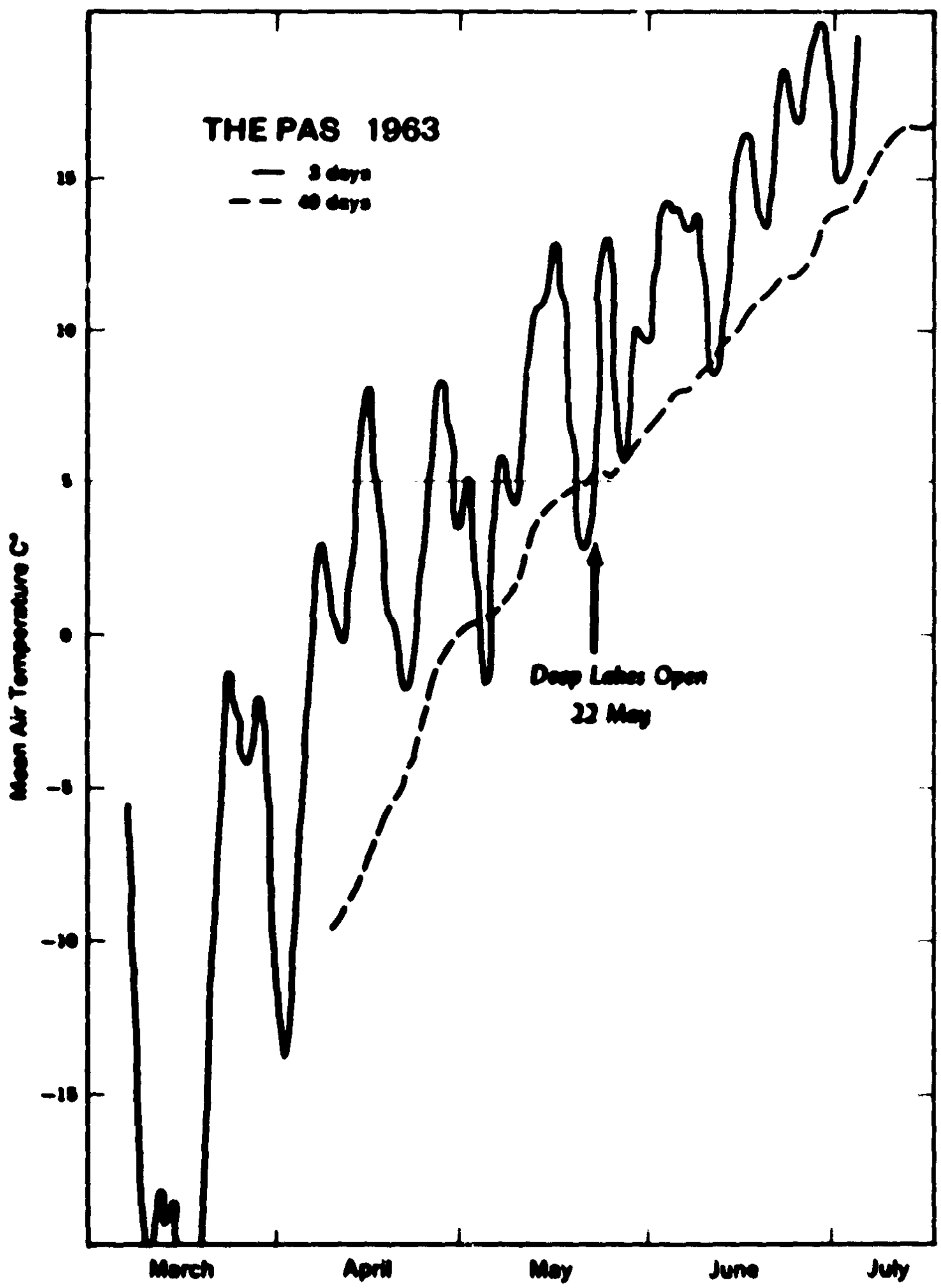


Figure 28. Comparison of opening dates and the 3-day and 40-day running mean air temperatures at The Pas, Manitoba for 1963.

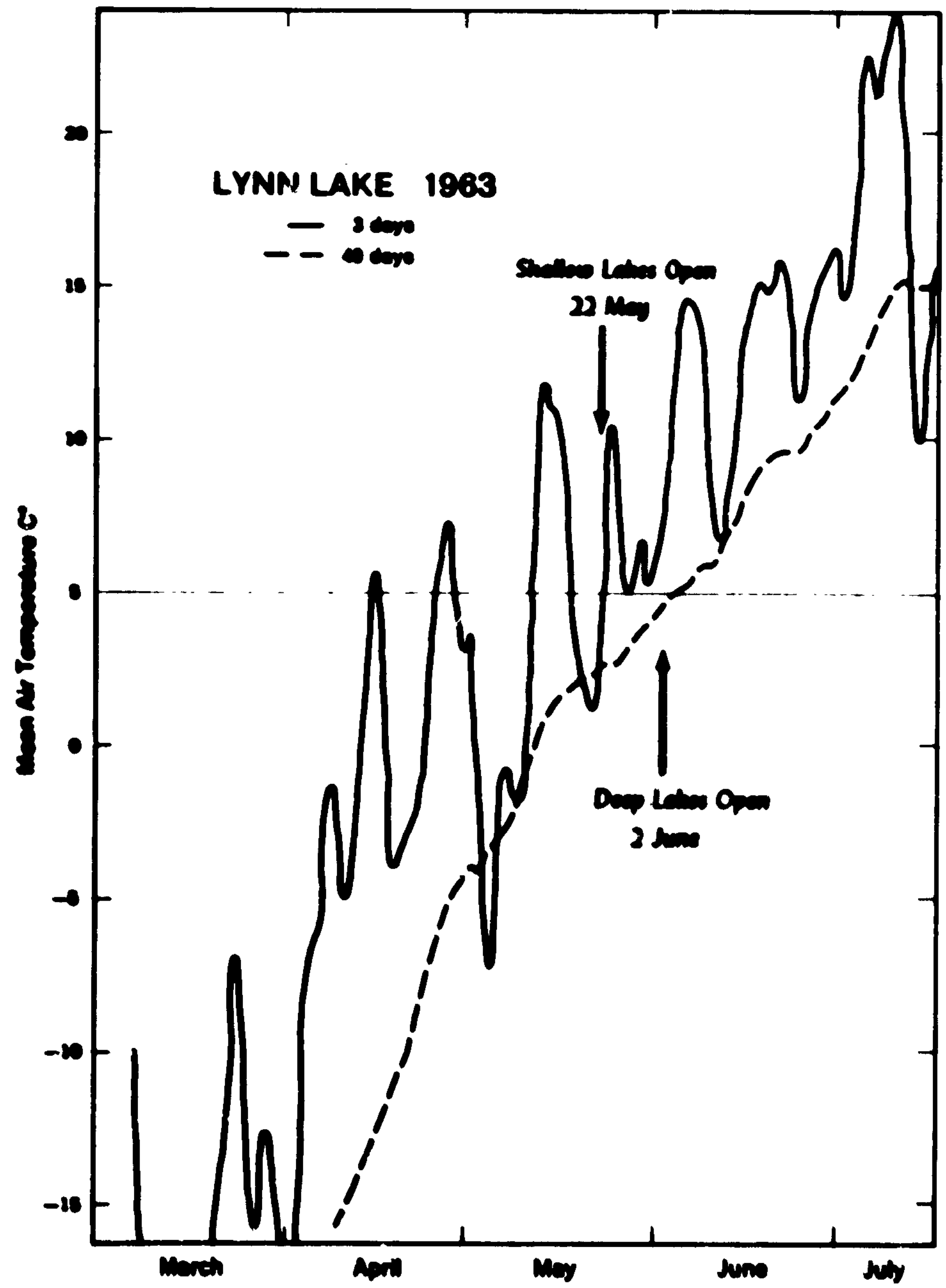


Figure 29. Comparison of opening dates and the 3-day and 40-day running mean air temperatures at Lynn Lake, Manitoba for 1963.

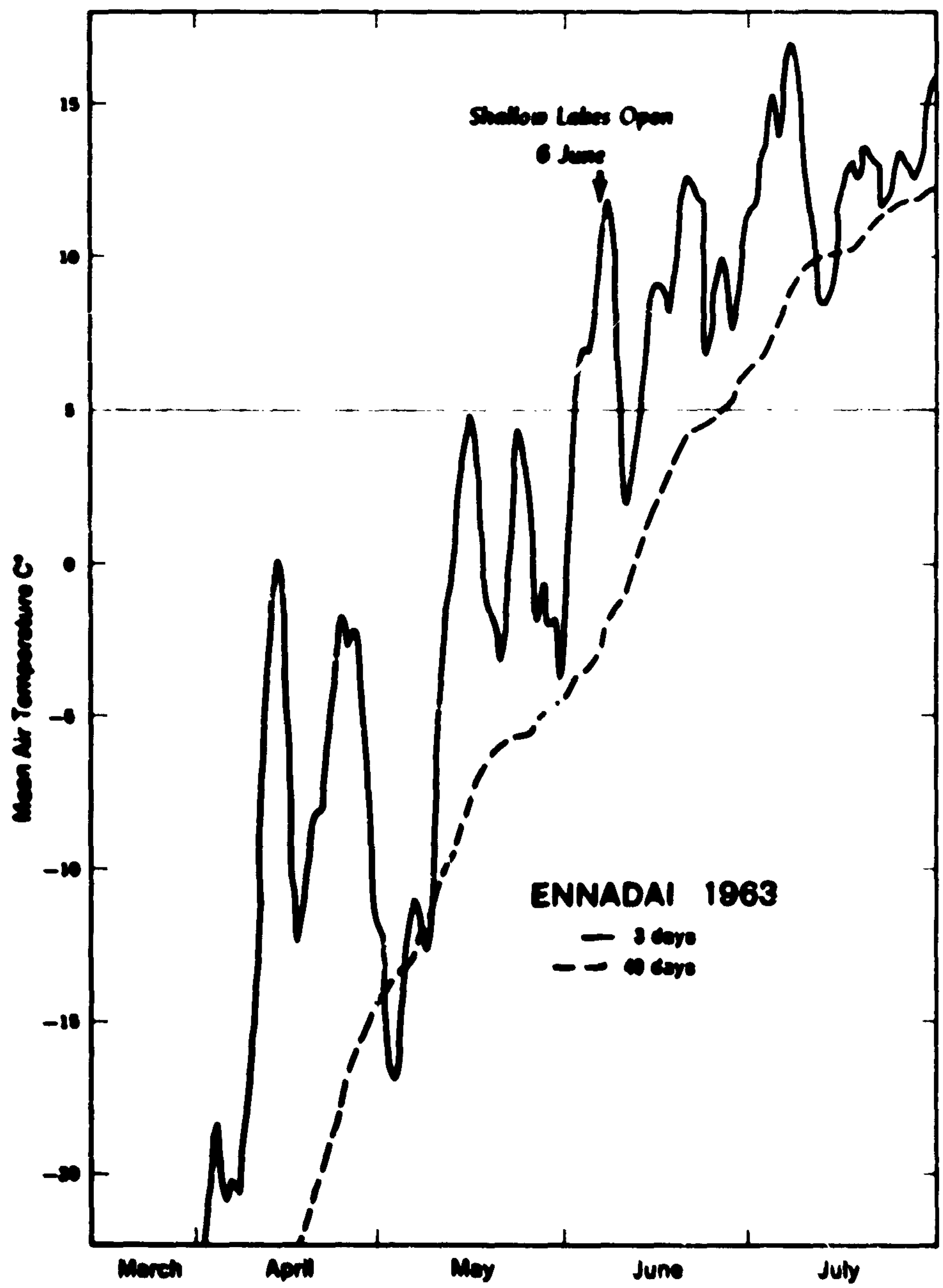


Figure 30. Comparison of opening dates and the 3-day and 40-day running mean air temperatures at Ennadai, N.W.T. for 1963.

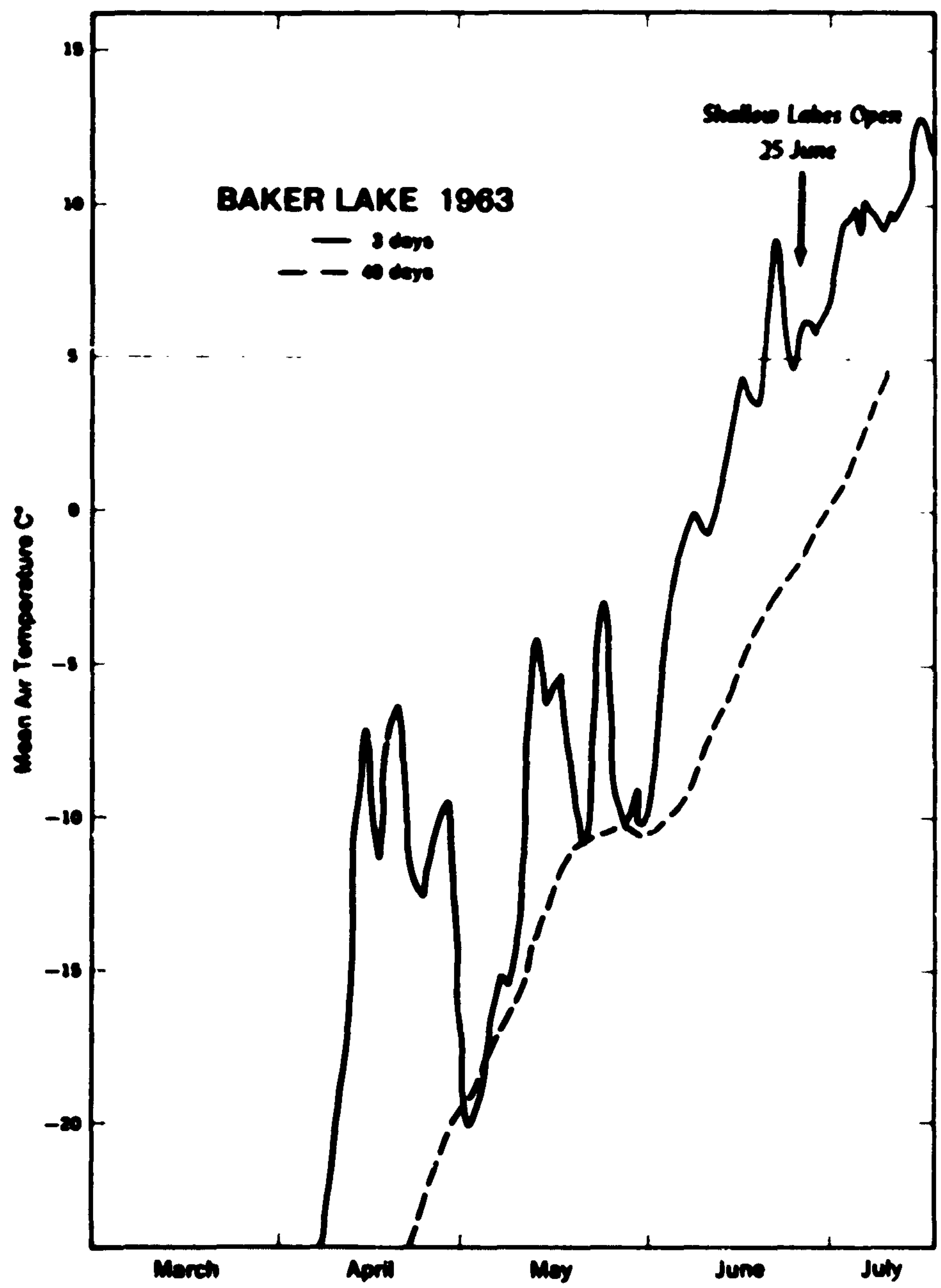


Figure 31. Comparison of opening dates and the 3-day and 40-day running mean air temperatures at Baker Lake, N.W.T. for 1963.

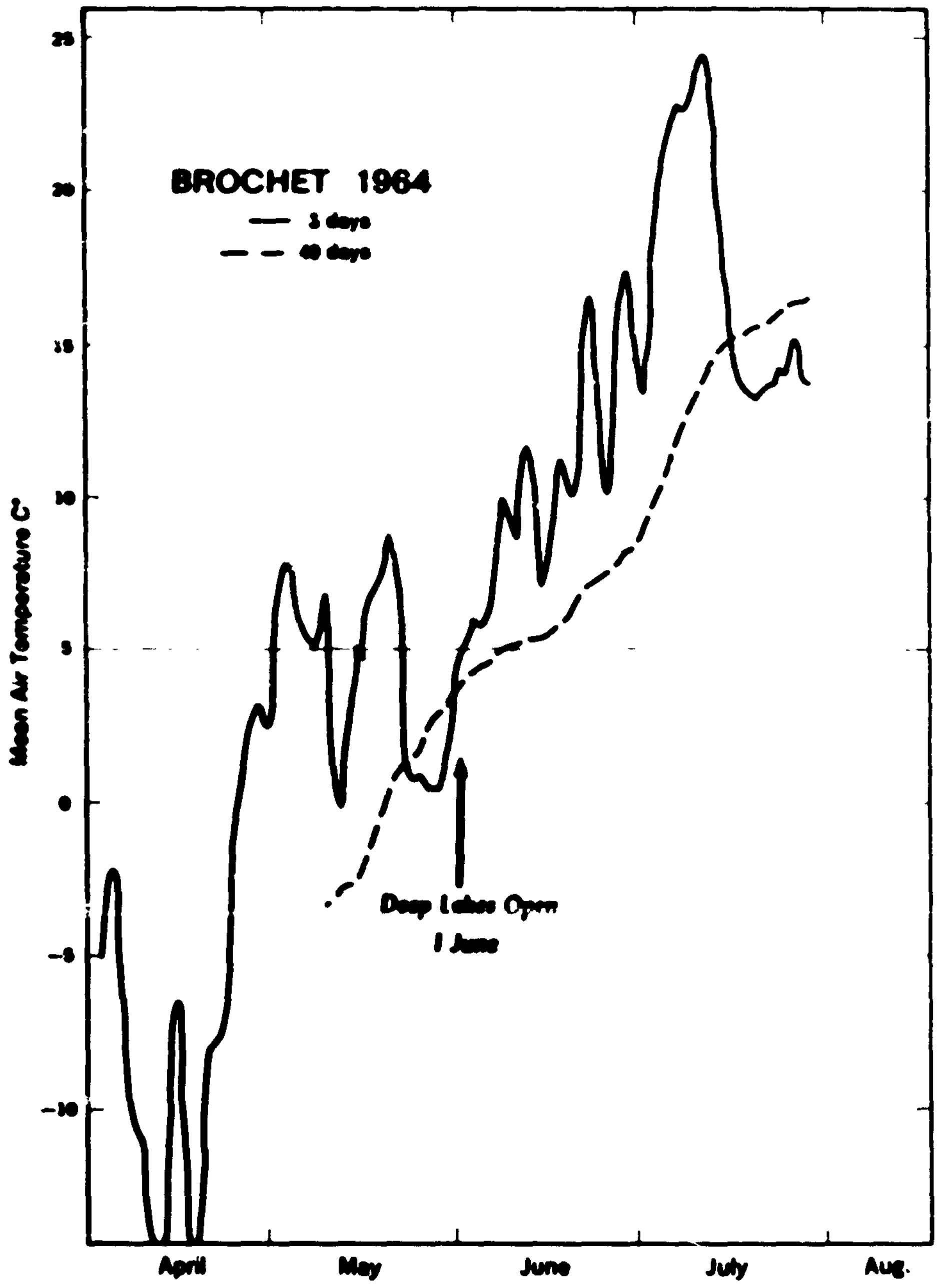


Figure 32. Comparison of opening dates and the 3-day and 40-day running mean air temperatures at Brochet, Manitoba for 1964.

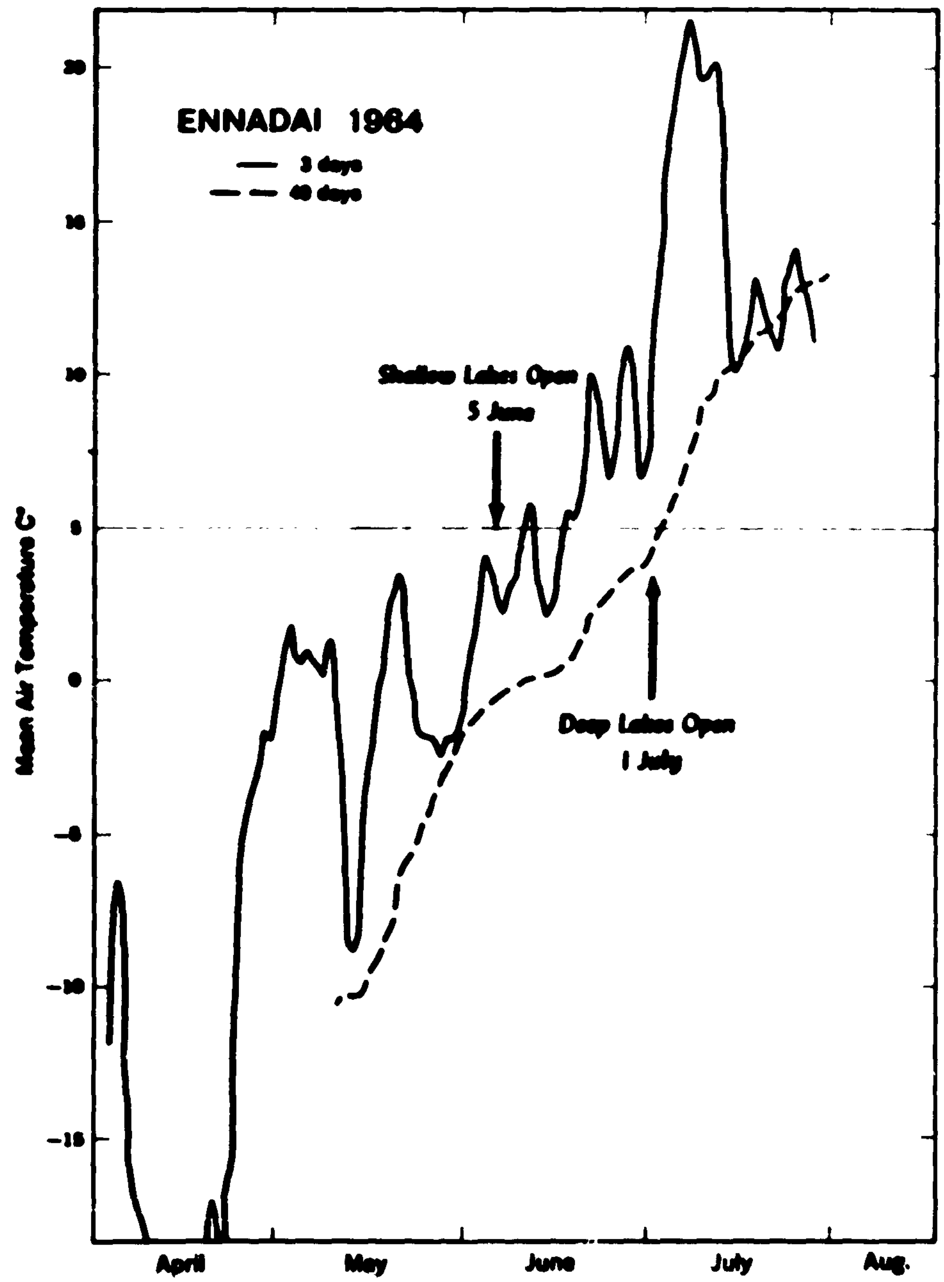


Figure 33. Comparison of opening dates and the 3-day and 40-day running mean air temperatures at Ennadai, N.W.T. for 1964.

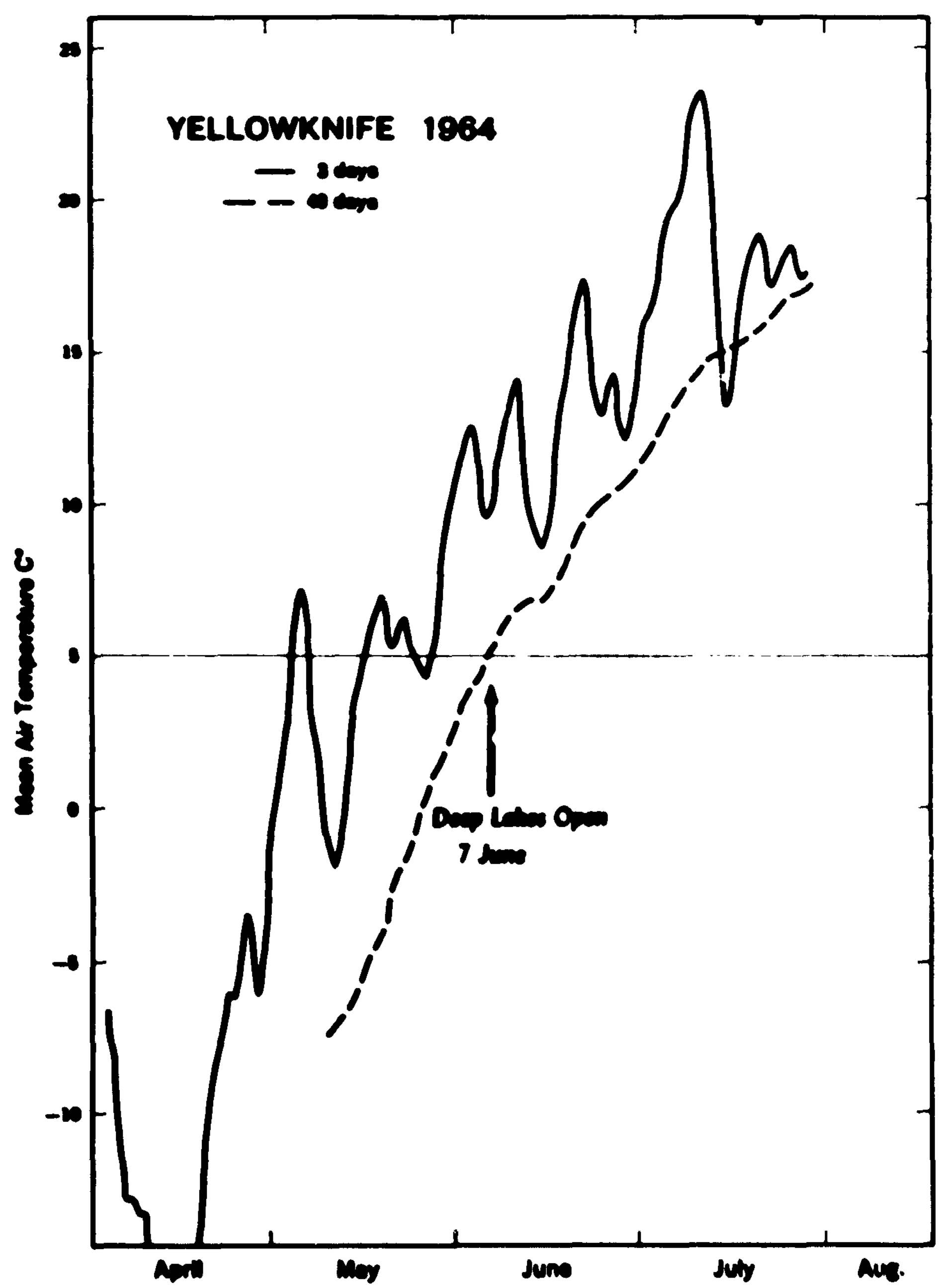


Figure 34. Comparison of opening dates and the 3-day and 40-day running mean air temperatures at Yellowknife, N.W.T. for 1964.

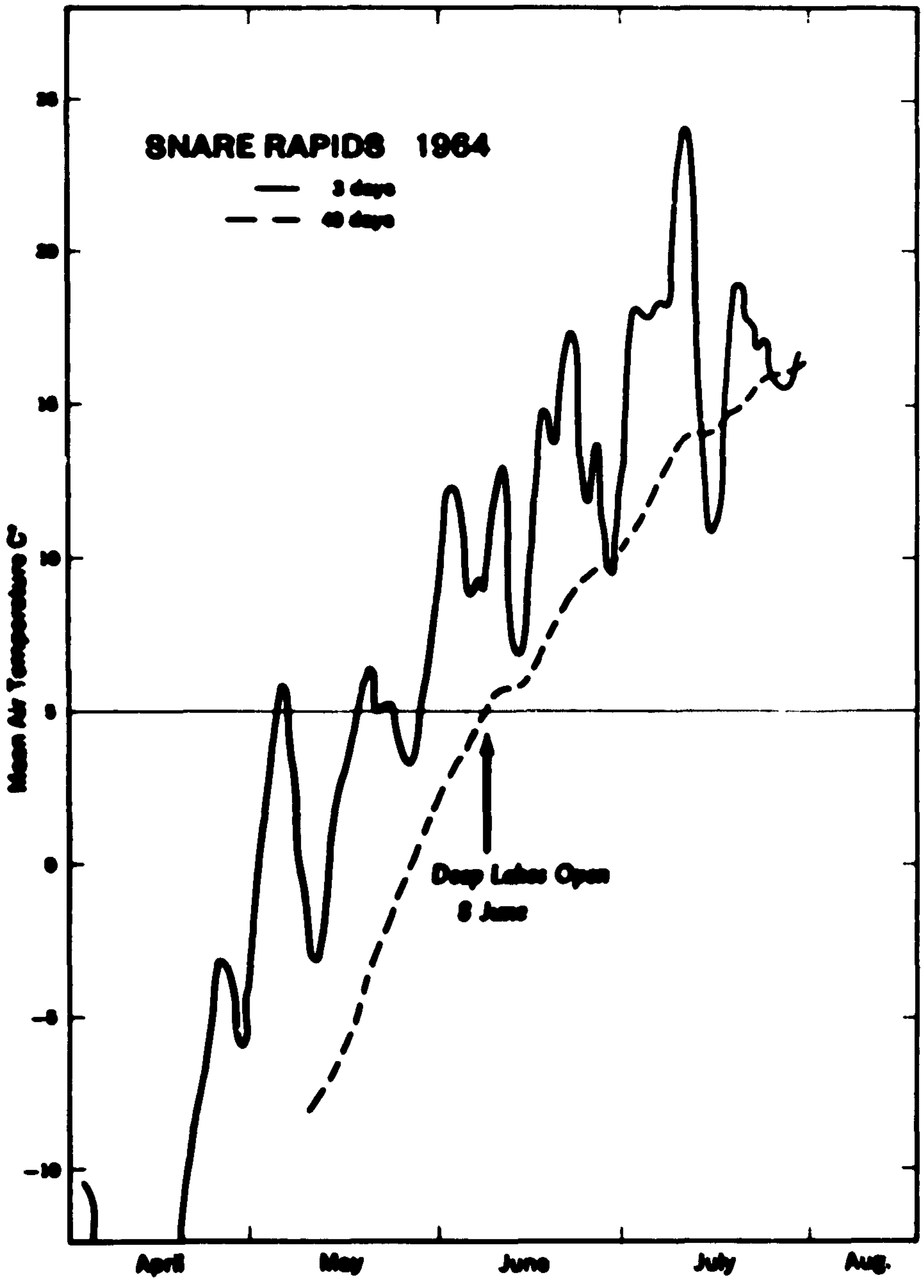


Figure 35. Comparison of opening dates and the 3-day and 40-day running mean air temperatures at Snare Rapids, N.W.T. for 1964.

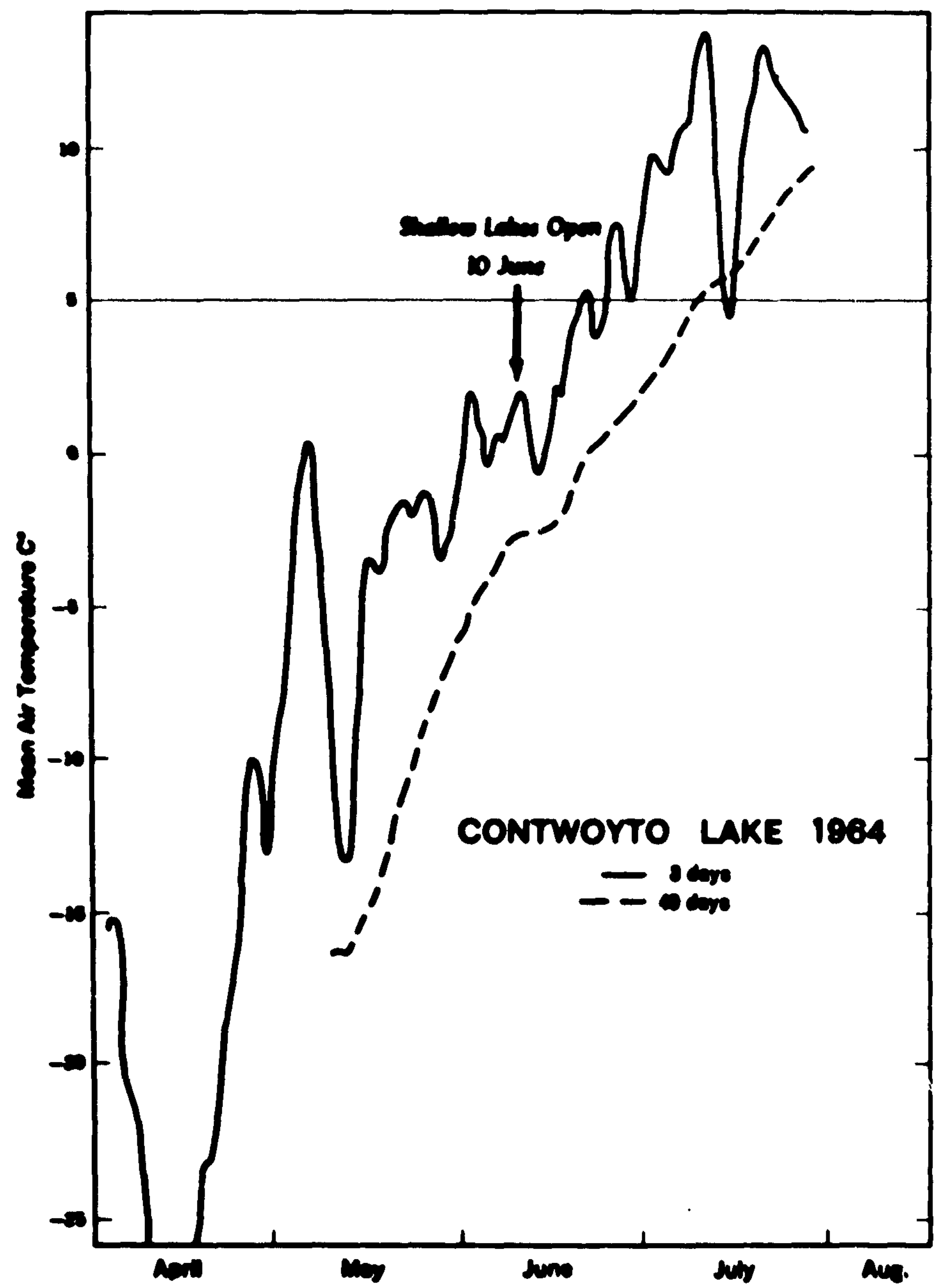


Figure 36. Comparison of opening dates and the 3-day and 40-day running mean air temperatures at Contwoyto, N.W.T. for 1964.

TABLE 11

COMPARISON OF OPENING DATES AND MEAN AIR TEMPERATURE

Station	Year	DEEP LAKES			SHALLOW LAKES		
		Thaw Date	40-day mean air T(°C)	Days lead(+) or lag(-) of break-up vs. 40-day 5 °C	Thaw Date	3-day mean air T(°C)	Days lead(+) or lag(-) of break-up vs. 3-day 5°C.
Madison	1963	3 Apr*	< 3.0	+ 14	3 Apr*	13.3	- 10
The Pas	1963	22 May	4.9	< + 1	-	-	-
Lynn Lake	1963	2 Jun	4.4	+ 3	23 May	6.9	< - 1
Ennadai	1963	24 Jun	4.6	+ 2	6 Jun	10.8	- 4
Baker Lake	1963	-	-	-	25 Jun	5.5	< - 1
Brochet	1964	1 Jun**	3.9	+ 7	-	-	-
Ennadai	1964	1 July	4.3	< + 2	5 Jun	3.4	+ 5
Yellowknife	1964	7 Jun	5.2	< - 1	-	-	-
Snare Rapids	1964	8 Jun	5.1	< - 1	-	-	-
Contwoyto	1964	-	-	-	10 Jun	2.0	+ 10

*Thawing line observed at station location
**Opening date obtained by extrapolation

Examination of the results shows that there is generally good agreement between thaw dates and the running mean air temperature of 4.5 to 5°C for the deep lakes. Processes other than sensible and latent heat transfer, namely radiation and, in at least one case, wind, also play a role in causing break-up. At Madison, Wisconsin, for example, break-up was the result of a severe storm with over 60 m.p.h. winds that struck southern Wisconsin on 3 April and opened all lakes in the region, shallow and deep, on that date (Lettau, K., 1963). Again, it is suggested that interpolation or extrapolation of ice lines may have been responsible for some of the larger variations obse... d in the break-up date comparisons.

Examination of the 3-day mean air temperatures for opening dates of the shallow lakes shows no apparent agreement. This again may be a result of the need for a more critical interpolation and extrapolation of the thaw lines in the case of shallow lakes, or a regional difference in the mean depths of the shallow lakes.

It was pointed out earlier in this chapter that the effect of radiation on the wastage of ice is a function of the size and depth of the lake. Because shallow lakes have much smaller heat capacities than deep lakes, they will have higher water temperatures for a given amount of absorbed radiation. The shallow lakes would therefore have more heat available to melt the ice from below. This would tend to reduce the effectiveness of using mean air temperature as an indicator for break-up, particularly for shallow lakes.

VI. ALBEDO

Surface albedo, which is defined as the ratio of reflected to incident solar radiation at the earth's surface, is important in any climatic study, because that portion of the incident solar radiation that is not reflected by the surface is absorbed and becomes available for heating the lower atmosphere or for evaporating water. The horizontal variations and the seasonal changes of albedo over large areas are important to air mass modification and regional climate studies. These variations and changes can be estimated from aerial albedo measurements. Studies on this subject have been made by such investigators as Fritz (1948), Bauer and Dutton (1960 and 1962), Dutton (1962), and Kung, Bryson, and Lenschow (1964).

Because the subject of this report is the relationship of lake ice and climate, the main emphasis of this section will be on the effects of lakes and snow cover on albedo in the tundra and boreal forest regions of central Canada with the inclusion of albedo values from the northern hardwood-conifer forest and farmland mixture area of the northern U. S. included for comparison purposes. Representative sections from the albedo records obtained on various flights and covering horizontal distances of 15 to 50 miles over these regions were selected, and the mean, standard deviation, relative variance, and range of the albedo for each of these sections are given in Table 12 and shown graphically in Figures 37, 38 and 39. Additional values of

TABLE 12

REPRESENTATIVE ALBEDO VALUES FOR VARIOUS REGIONS

Terrain	Lakes	Snow Cover	Mean (percent)	Std. Dev. (percent)	Range (percent)	Rel. Var. (percent)	Sky
Tundra	frozen	snow	89.0	2.98	84.0-92.0	3.35	Clear
Tundra	frozen	snow	77.7	3.45	70.5-83.2	4.40	Stratus
Tundra	partly frozen	no snow	24.9	8.82	15.2-47.1	35.4	Clear
Tundra	unfrozen	no snow	10.8	1.14	7.9-12.4	10.6	Clear
Tundra	none	no snow	14.8	0.95	13.5-15.6	6.4	Clear
Tundra	none	no snow	14.9	1.14	13.8-16.5	7.7	Clear
Forests	frozen	snow	48.0	1.14	30.3-63.2	23.7	Clear
Forests	frozen	snow	46.9	0.97	37.9-68.2	20.7	Clear
Forests	partly frozen	snow	34.5	8.00	22.7-54.5	23.2	As
Forests	partly frozen	no snow	26.7	3.80	11.1-29.5	14.2	Clear-Hazy
Forests	partly frozen	no snow	16.9	2.00	10.7-20.2	11.9	As
Forests	none	light snow	18.2	3.00	13.0-26.0	16.7	Clear-Hzy
Forests	none	no snow	14.9	2.00	12.7-19.0	13.5	Clear-Hzt
Fields, Woods	none	snow	43.8	4.00	31.2-48.3	9.2	Clear-Hzy
Farms	none	none	22.1	3.8	13.4-26.4	17.2	Clear-Hzy
Farms	none	none	18.9	0.8	17.7-19.7	4.5	Clear-Hzy
Farms, Woods and Bogs	none	none	18.6	2.5	13.5-22.7	13.7	Clear-Hzy
Plowed Fields	none	none	12.3	1.6	11.1-14.2	13.3	Clear-Hzy

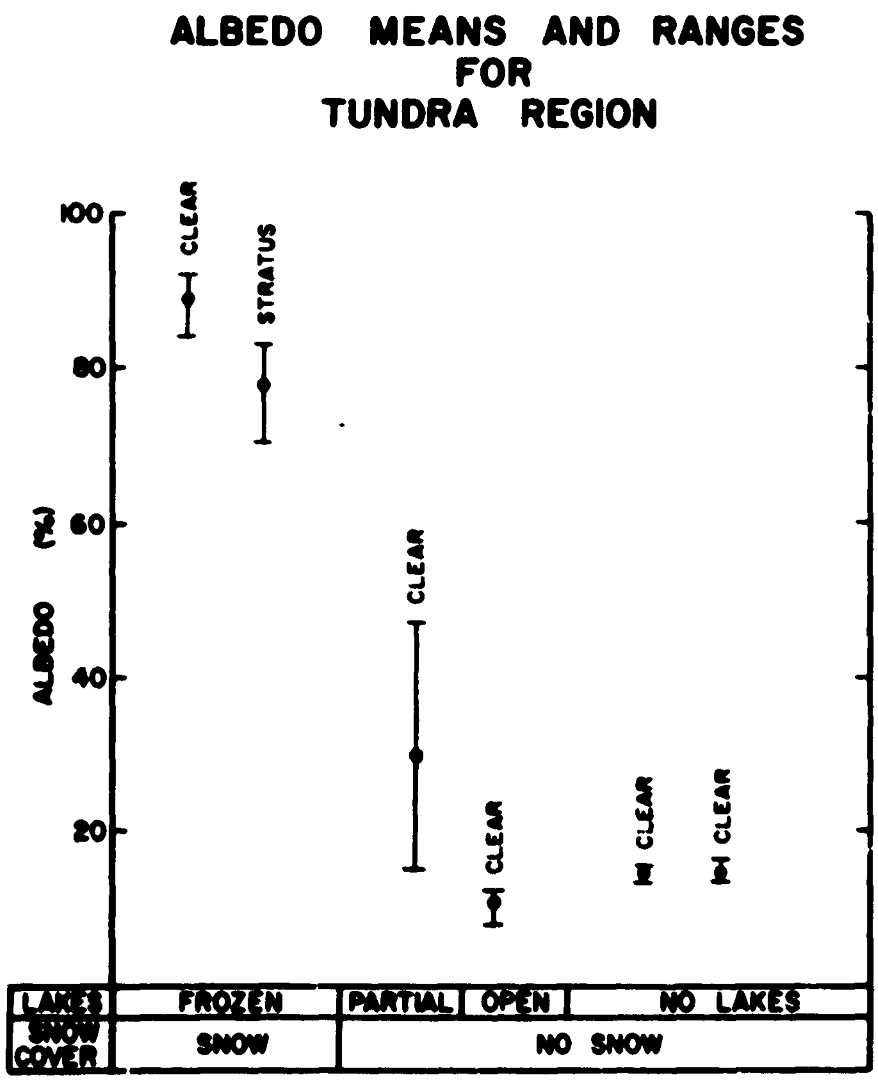


Figure 37. Albedo means and ranges for tundra region. Sky condition for each set of measurements is also shown.

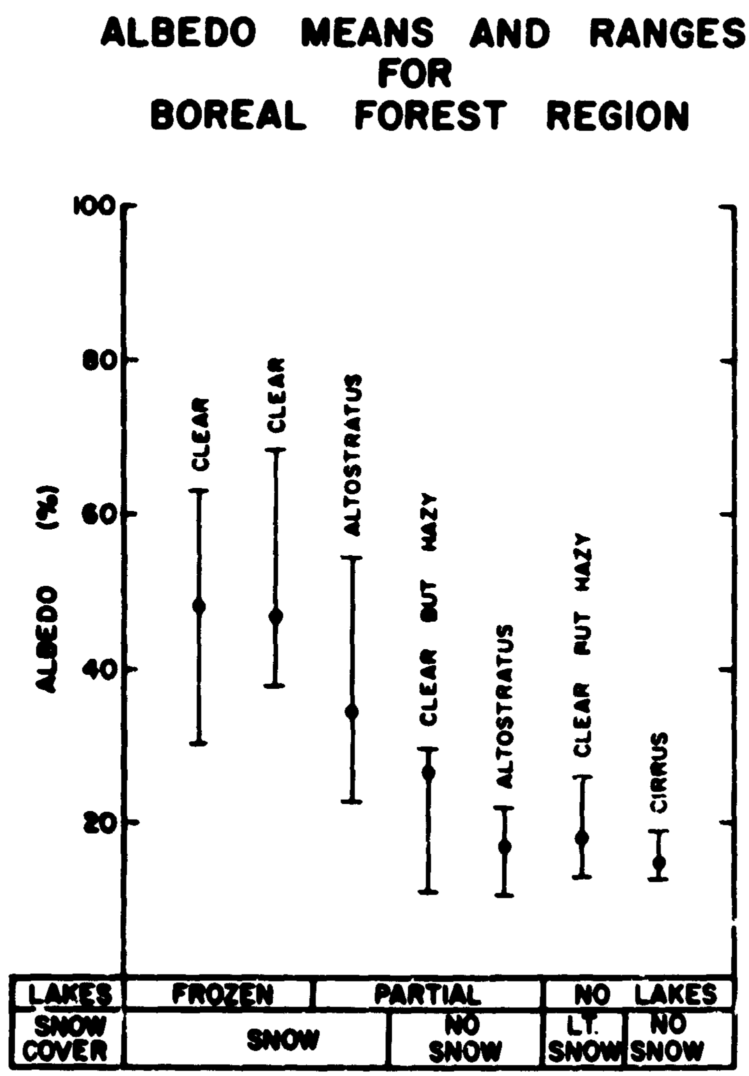


Figure 38. Albedo means and ranges for boreal forest region. Sky condition for each set of measurements is also shown.

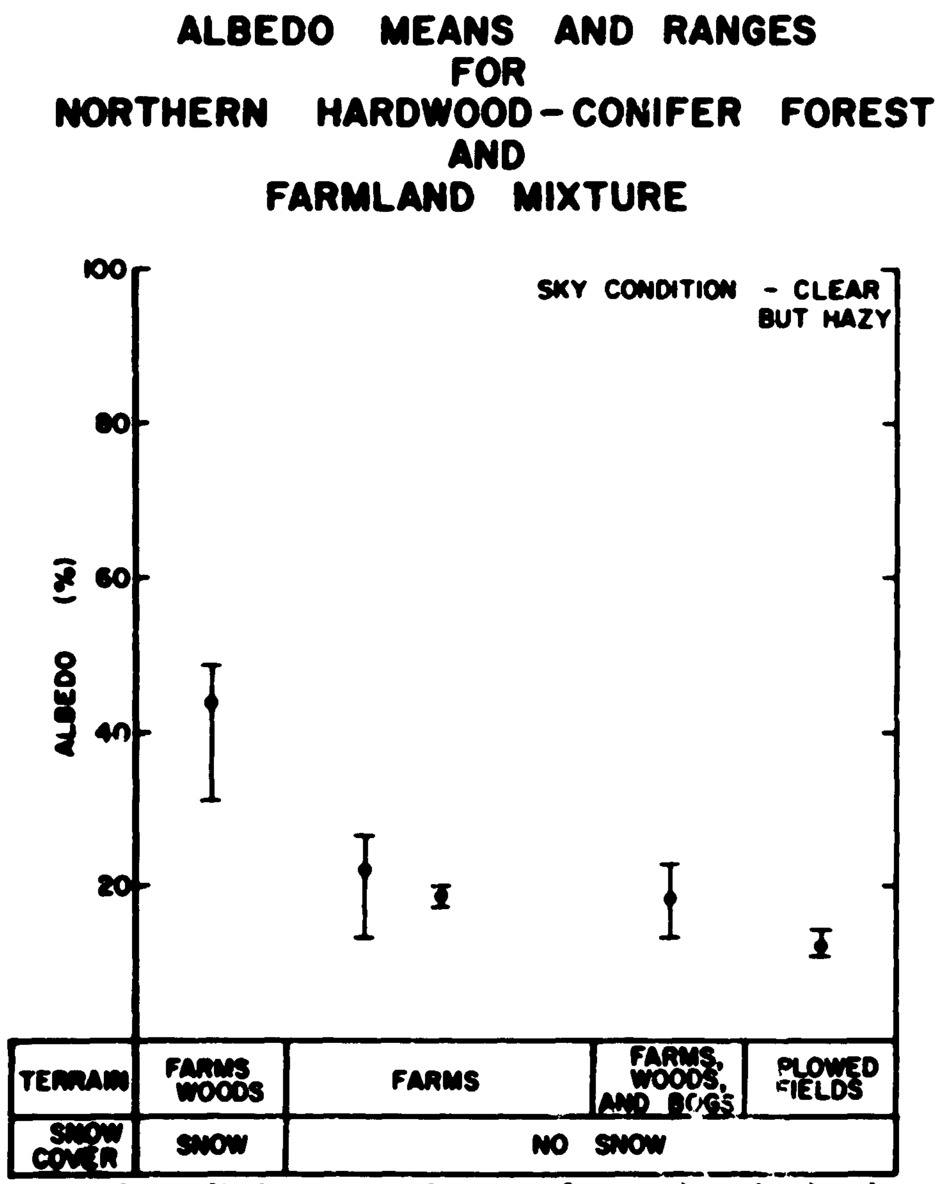


Figure 39. Albedo means and ranges for northern hardwood-conifer forest and farmland mixture.

albedo for various regions are presented in the appendix.

Relative variance, or coefficient of variability (see Steel and Torrie, 1960, and Kung, Bryson, and Lenschow, 1964), which is the ratio of standard deviation to mean in percent, expresses generally the variation of the reflectivity caused by the heterogeneity of the surface.

The tundra region of Canada, because of the general absence of trees, exhibits the highest seasonal range of albedo of the three major areas studied (see Fig. 37). The numerous lakes in this region do not, however, have a large effect on the horizontal variation of albedo in the winter or the summer seasons. During the winter when all lakes are frozen, the surface can be considered continental, and with a snow cover it has a high albedo with a low coefficient of variability. During the summer the albedo of the tundra is low enough so that the addition of lakes causes only a slight decrease in the mean reflectivity of the surface. However, in spring and autumn, when the lakes are partially frozen with no snow cover on the ground, there is a pronounced lake effect on the albedo. During these seasons the albedo is extremely variable, and the standard deviation and relative variance are very high.

In the boreal forest region the seasonal changes of albedo are not as great as in the tundra, but the lake effect is larger as indicated by wider ranges of values and generally higher coefficients of variability. Considering the nature of the terrain this is understandable.

FIGURE 40. View of snow covered terrain in boreal forest region.

The crowns of the trees do not support the generally dry and powdery snow, and the forest appears dark during both winter and summer, particularly when viewed from the direction parallel with the incident solar radiation. Interspersed throughout the forest are numerous lakes and bogs. In the winter when these are frozen and snow covered, they appear as light areas, raising the average albedo of the region by a factor of two compared to forest areas without lakes and bogs (Fig. 40).

When analyzing the albedo data for this type of terrain, it is important to consider whether the values of reflected radiation were obtained through the use of a beam or hemispheric solarimeter. (All values herein were obtained by the hemispheric method.) The reflectivity of a snow covered forest of the type observed in central Canada is much higher when viewed from above than from an angle because more of the lighter snow covered ground is visible. A beam solarimeter, then, would probably give higher reflected values over this region than a hemispheric device because the latter instrument "sees" the darker ground at an angle also. Actually, the surface might absorb more energy than either albedo method would indicate because the hemispheric solarimeter does receive most of its energy from the vertical also. When considering the amount of energy absorbed by the boreal forest and by the tundra in the autumn and spring, the albedo measurements obtained by either method, and in particular the beam method, might tend to indicate smaller absorbed energy differences between the two regions than actually exist. An estimate of the mean albedo of this region, considering the difference in reflectivity of direct solar and diffuse sky radiation by this anisotropic surface, indicates that the measured values were 40 to 60 percent too high. Mean albedo values for the snow covered forest of 29 to 35 percent were provided by the estimate.

Albedo values obtained from the northern hardwood-conifer forest and farmland mixture region (Fig. 39) are included primarily for comparison with values obtained over similar areas by Bauer and Dutton (1960) and Kung, Bryson, and Lenschow (1964).

Of significance to the meteorologist are the effects that seasonal changes of albedo have on regional climate and general circulation patterns. For example, Bryson and Lahey (1958) have suggested that a rapid and drastic change of the albedo of the tundra in June might trigger the change from one natural season to another natural season. By using albedo values given above, snow observations from Operation Breakup 1963, and solar radiation values estimated from the results of Bernhardt and Phillips (1958), it is possible to estimate the change in absorbed solar radiation between snow and no snow conditions. The results shown in Table 13 were computed for the tundra area of northern Canada lying south of the 68th parallel and west of Hudson Bay.

On the flight of 22 May 1963, the snow line was observed some 250 miles south of the forest-tundra border, and on the flight of 14 June, no snow was observed as far north as 64°N., or 450 miles north of the 22 May snow line position. No snow was observed on the 1 July flight to the Arctic Ocean. It is reasonable to assume from these three observations that the tundra was still completely snow covered as late as 1 June and probably snow free no later than 21 June. During this three week period the albedo of the tundra dropped from an average of approximately 83 percent to about 20 percent (15 percent for the land surface and about 40 percent for the partly open lakes which constitute up to 15 percent of the tundra surface). This decrease in the reflectivity of the surface plus the increase in incident radiation at the surface between 1 and 21 June resulted in a 600 percent increase in the absorbed radiation of from 60 to 363 ly/day during this period.

TABLE 13

EFFECT OF OBSERVED ALBEDO ON EFFECTIVE SOLAR RADIATION FOR TUNDRA REGION

		June 1	June 21
Albedo of land		83 percent	15 percent
Albedo of lakes (15 percent of surface)		83 "	40 "
Solar radiation at surface under average cloud conditions (estimated from Bernhardt and Philipps, 1958) (ly/day)		352.8	446.4
Radiation absorbed per unit area (ly/day)	land	60.0	379.4
	lakes	60.0	267.8
	Total	60.0	362.6

TABLE 14

HEAT BALANCE ESTIMATE FOR TUNDRA REGION 1963 (ly/day)

	June 1	June 21
Incoming solar radiation	352.8	446.4
Reflected solar radiation	-292.8	- 66.9
Effective long wave radiation	-131.0	-132.5
Net radiation	- 71.0	247.0
Heat storage (land)		2.5
Heat required to melt permafrost (0.5 cm/day)		36.0
Heat for evaporation (latent)*		-160.4
Sensible heat*		- 48.1

*Using Bryson and Kuhn's Bowen ratio value (0.30)

Whether this sudden and drastic change of albedo actually served as a triggering mechanism for the atmosphere will have to await further study, but it seems plausible that this tremendous increase of energy occurring suddenly and at about the same time in all the tundra regions of the northern hemisphere should produce a noticeable effect.

To obtain some idea of the partitioning of this energy absorbed by the tundra and the amount available as sensible and latent heat, the heat balance for the area was estimated (Table 14).

The equation for estimating the net radiation at the tundra surface is given by

$$R_N = R_I + R_R + R_{Leff.} \qquad (2)$$

where

R_N = net radiation

R_I = incoming short wave radiation

R_R = reflected short wave radiation

$R_{Leff.}$ = effective long wave radiation.

The values of incoming solar radiation and albedo are the same as given in Table 13, and the formula for computing effective long wave radiation is that of Budyko (1958).

The heat balance equation for estimating sensible and latent heat transfer over the land surface is given by

$$S + M = R_N + Q + E \qquad (3)$$

where

S = heat stored in the soil

M = permafrost melt (estimated at 0.5 cm/day from *in situ* measurements)

Q = sensible heat

E = heat for evaporation (latent heat).

For estimating the storage and melting terms of the heat budget equation, Larsen's (1965) values for permafrost depths and soil temperatures in tussock muskeg material for the period 1 - 21 June 1963 near Ennadai, N.W.T. were used. The July Bowen ratio estimate of Bryson and Kuhn (1962) for the region from Norman Wells, N.W.T. to Fort Smith, Alta., was used for determining the sensible and latent heat terms because a ratio estimate for June was not available.

Applying the estimated value for sensible heat transfer to the atmosphere, 48.1 ly/day, to a column of air 1000 meters in height and with a mean temperature of 0°C. gives a heating rate of approximately 1.6°C. per day. This heating rate does not appear to be unrealistic. From radiosonde data obtained at Baker Lake on 20 June 1963, the average temperature increase between 0600 and 1800 hours CST in the lower 1000 meters was computed to be 1.3°C. An average temperature increase of 1.85°C. per day for this layer was also computed for the period between 1800 hours on 17 June and 1800 hours on 21 June. This agrees quite well with the results in Table 14. Winds at this station during this period were very light to calm and more northerly in frequency.

VII. THE RELATIONSHIP OF LAKE ICE TO AIR MASSES

It was suggested in the introduction of this paper that the areal pattern of freeze-up might give information about the movement and modification of air masses. This chapter presents the results of an examination of the relationship between lake ice and air masses, in particular with regard to the deep lake freeze line.

Ragotzkie and McFadden (1962) suggested that the freezing of shallow lakes was due to outbreaks of cold continental Polar (cP) air, one or two of which were sufficient to freeze the shallowest lakes, and that the deep lake line marked the dominant position of the polar front behind which continental Polar air was the dominant air mass.

Before relating freeze-up to continental Polar air it is best to have a working definition for that air mass. The original classification of air masses was made some 30 years ago by such investigators as Willett (1933), Wexler (1936), and Showalter (1939) for the winter and summer months only. They agreed generally that the cP air mass is the coldest and driest of all North American air masses at low levels during most of the year, and that its characteristic properties are acquired within its source region.

The source region for the continental Polar air mass on the North American continent in winter is northwestern Canada, parts of Alaska, and the neighboring arctic. This region is protected from low level, warm, maritime air invasions from the North Pacific by such lofty mountains as the Alaska and the St. Elias Ranges and the Cassiar and Mackenzie Mountains. East of the Mackenzie Mountains the source region is characterized almost entirely by plains, high in the west and sloping down very gently east and northeast to the ice-bound sounds of the Archipelago on the north and to Hudson Bay on the east. Furthermore, this entire region from central Canada northward over Hudson Bay and the Arctic Ocean has a general snow cover throughout the winter season. Thus the high latitude, snow cover, and protection at least in the low levels against invasion of warm maritime air from the North Pacific, make this region ideally suited for the formation of a cold, dry air mass of great extent.

The mechanism that produces the continental Polar air mass was first pointed out by Willett (1933) to be extreme radiational cooling of the lower layer of the atmosphere. Wexler (1936) developed the theory for this radiational transfer process. The process involves a consideration of the radiative equilibrium between the atmosphere and the snow surface and takes into account the radiation absorptive properties of the carbon dioxide and water vapor in the air.

Finally, these investigators described the thermodynamic nature of the cP air mass in a winter situation by using two of the more conservative properties of air, potential temperature and mixing ratio, and plotting characteristic soundings of this air mass on Rossby diagrams. These plots all showed,for a sounding through the first 3 km. of the air mass, potential temperatures less than 290°K. and mixing ratios generally less than 1.0 gm./kgm. Willett (1935) concluded that a marked thermal stratification and a moderate moisture stratification is typical of a cP air mass during the cold season in any continental or effectively continental (frozen maritime) source region.

Although November is not considered a winter month, soundings made at 60°N during this month in an air mass originating in northwestern Canada should have properties approaching those described by earlier investigators, but not necessarily identical. For this investigation, an air mass moving from northern or northwestern Canada southward across the tundra will be called continental Polar.

In this study the plan was to analyze radiosonde data from stations on both sides of the deep freeze lines on days when the source of the air arriving at each station was the cP source region in northwestern Canada. If the assumption is true that north of the deep lake freeze line a typical winter cP air mass is dominant, then soundings of stations north of this line plotted on a Rossby diagram should resemble the cP air masses described by the early investigators. The sounding from a station south of the deep lake freezo line should show the modification of the cP air produced by the addition of sensible heat and moisture from the as yet unfrozen lakes.

The sparseness of radiosonde stations in Canada and in particular within the study area made detailed analysis difficult. In central Canada only the stations at Baker Lake, N.W.T., Churchill, Manitoba, and The Pas, Manitoba obtain upper air data.

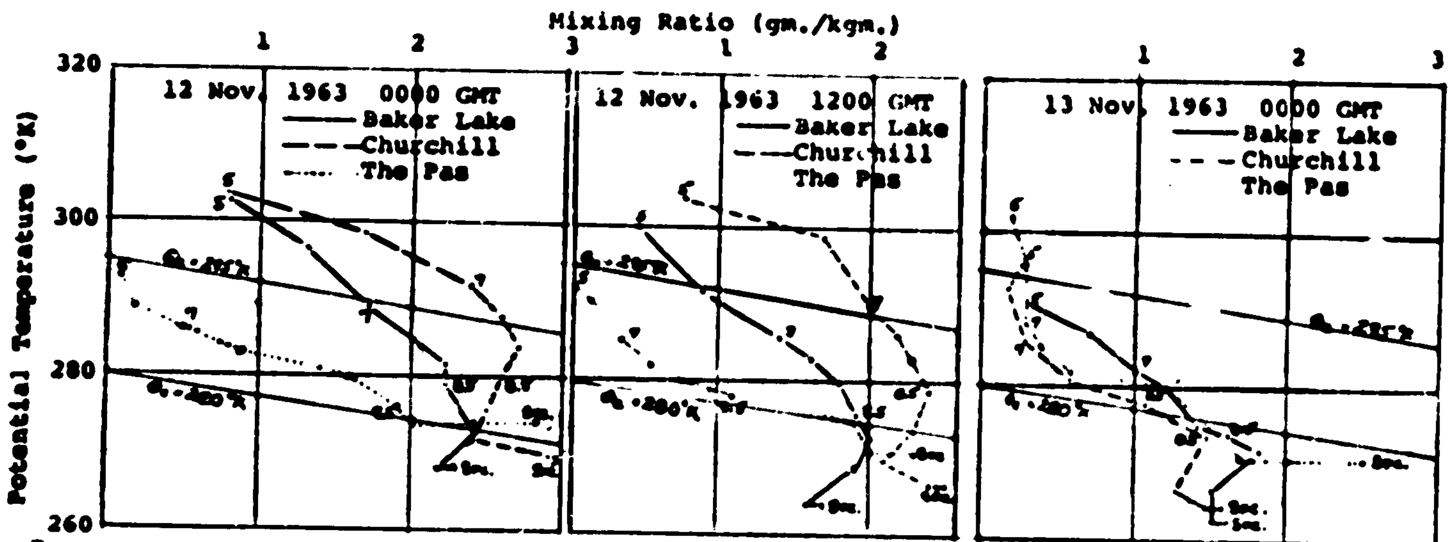
After completing the analysis of the data from many of the radiosonde stations in central Canada for several different dates from September through November, 1963, it was apparent that the soundings obtained north of the deep lake freeze line were not the typical winter cP air mass soundings reported by the early investigators.

Figure 41 shows the Rossby diagram plots and winds from upper air soundings obtained at these three stations for the 24-hour period beginning at 0000 G. M. T. on 12 November. This time interval was picked for two reasons. A large high pressure region was situated over central Canada, and the air arriving at the three stations was from the north-northwest. Secondly, the location of the deep lake freeze line was known to be about 4000 miles south of Baker Lake, about 125 miles south of Churchill, and about 300 miles north of The Pas.

While these plots are not typical of winter cP air masses, the modification influences of frozen versus unfrozen lakes is apparent. The soundings made at Baker Lake and Churchill at 0000 G. M. T. on 12 November reveal a great deal of moisture throughout the column. The moisture is a result of the air arriving at these two stations having passed over Hudson Bay the day before. (The wind direction on the surface at Baker Lake at 0000 G. M. T., 11 November was 020° and at 900 mb, 050°.) The sounding at The Pas for the same time shows

FIGURE 41.

ROSSBY DIAGRAMS AND WIND DATA FOR INDICATED STATIONS AND DATES



Press (mb)	WIND DIRECTION/SPEED (mps) Baker L.	Churchill	The Pas	WIND DIRECTION/SPEED (mps) Baker L.	Churchill	The Pas	WIND DIRECTION/SPEED(mps) Baker L.	Churchill	The Pas
Sfc.	360/10	340/13	320/08	340/10	340/18	340/12	340/12	340/17	340/05
950	001/11	331/15	326/11	358/14	336/14	335/12	346/14	321/15	344/05
850	009/07	353/10	330/16	359/08	340/10	355/13	335/08	328/10	350/06
750	004/08	353/08	332/13	344/06	334/05	340/13	326/08	321/11	351/07

a much drier column of air, which is a result of its winds being northwesterly the previous day. Note, however, that in the lower layers (surface to 850 mb.) the air is generally stable at Baker Lake and Churchill but convectively unstable at The Pas.

During the next 24 hour period, the air arriving at Baker Lake and Churchill, having traveled over a frozen and snow covered tundra, became increasingly drier while remaining stable throughout. The air reaching The Pas, after traveling over a region of partially open lakes, remained convectively unstable from the surface to the 900 mb level. It is suggested that this instability was a result of heat and moisture being added to the cold air as it moved across the unfrozen lakes. Data on cloud distribution and precipitation from the many flights through the transition zone during periods of freeze-up lend support to this idea. Ragotzkie and McFadden (1962) reported a great deal of convective activity, clouds not apparently associated with cyclonic storms and fronts, and precipitation mostly in the form of snow showers within the transition zone. Very little activity of this nature was observed either side of this zone.

While the above gives some information about the effects of unfrozen lakes on the modification of cold, dry air, it does not show whether cP air is the dominant air mass behind the deep lake freeze line. If such a situation actually exists, then there might be a correlation between deep lake freeze lines and mean polar front positions as delineated by the mean monthly wind patterns. While these patterns would not show the thermodynamic character of the air, they would show, on the average, from what source region the air at the different stations originated. If the deep lake freeze line marks an air mass boundary, then such a correlation should show agreement between the location of the mid-month deep lake freeze line and the mean monthly position of a confluent zone between air of cP origin and that of another origin.

Data for computing mean monthly wind patterns were taken from hourly wind tables in the Monthly Records of Meteorological Observations in Canada (1961 and 1963). These tables list winds for various stations in frequency in hours at 8 or 16 points of the compass. The directional frequencies for each station for October and November, 1961 and 1963, were punched on cards and the mean wind direction for each month for each station was computed on the CDC 1604 computer. These data were then plotted on maps. The term resultant wind is not used because wind speeds were not available and therefore not used in the computation.

Figures 42-45 show the mean wind directions for the selected stations, the line of confluence between northern Canada or cP air and air from a southerly direction, and the actual or estimated mid-month position of the deep lake freeze line for October and November, 1961 and 1963. Figures 42 and 43 show that for October, 1961 and 1963, there is fairly good agreement between the position of the confluence of the air masses and the mid-month position of the deep lake freeze line. Figures 44 and 45 show that for November 1961 and 1963, the agreement between these variables is poor, particularly for November, 1961. A suitable explanation for this lack of agreement may be found if the factors involved in the freezing of a lake are considered more closely.

As has already been mentioned, a lake cools primarily by losing heat to the atmosphere through the transfer of sensible and latent heat. This occurs when the air temperature is less than the water temperature. As long as this is the case, the lake will continue to lose heat until it eventually freezes. Wind direction is of no direct consequence. Air temperature is the important factor. Figures 44 and 45 show that cP air, as defined for this study, played a more prominent role in freezing lakes in November 1963 than in November 1961. The deep lake freeze line, however, is further south along 100°W. longitude in 1961, implying that temperatures were lower in this region in 1961. Figure 46 shows the mean November soundings for 1961 and 1963 obtained at The Pas, Manitoba, plotted on a Stüve diagram and then computed potential temperatures and mixing ratios plotted on a Rossby diagram. This information shows quite clearly that the temperature

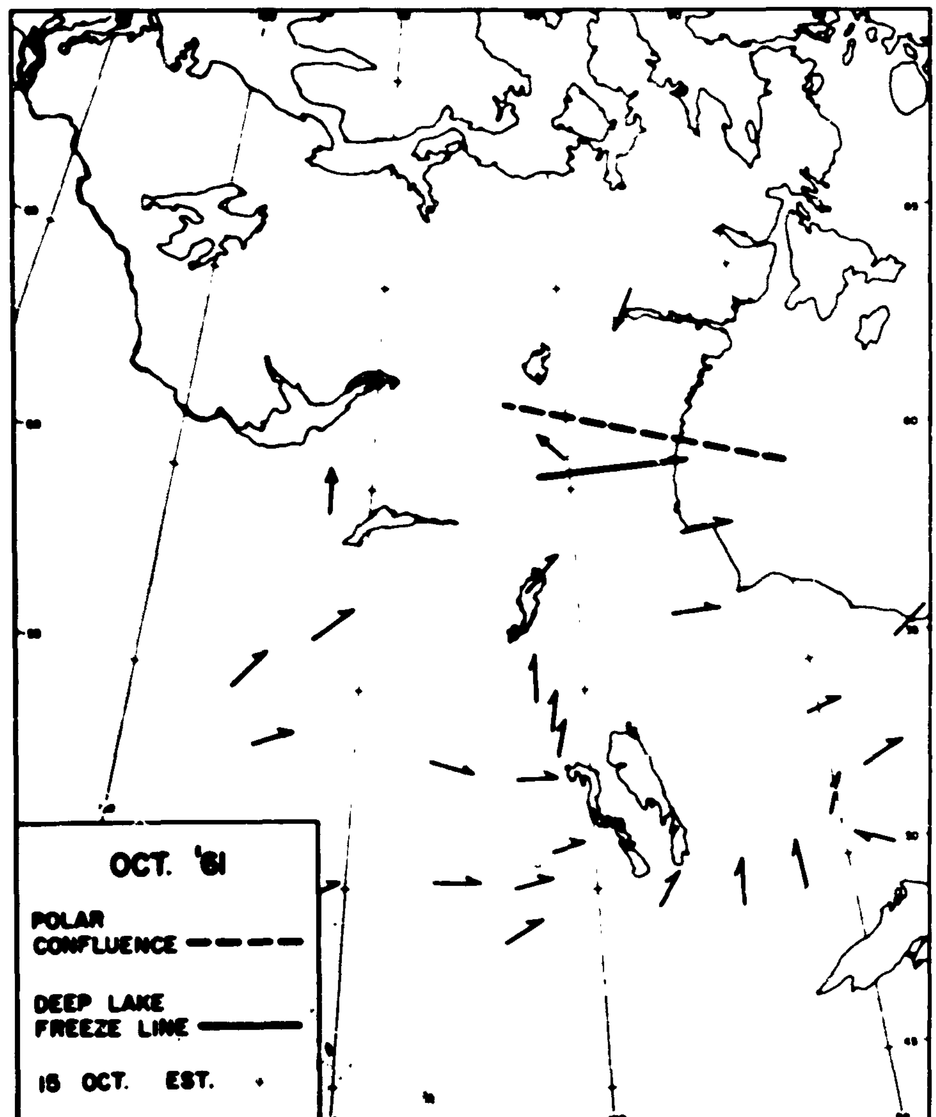


Figure 42. Mean wind directions for selected stations, the polar confluence and mid-month position of the deep lake freeze line for October 1961.

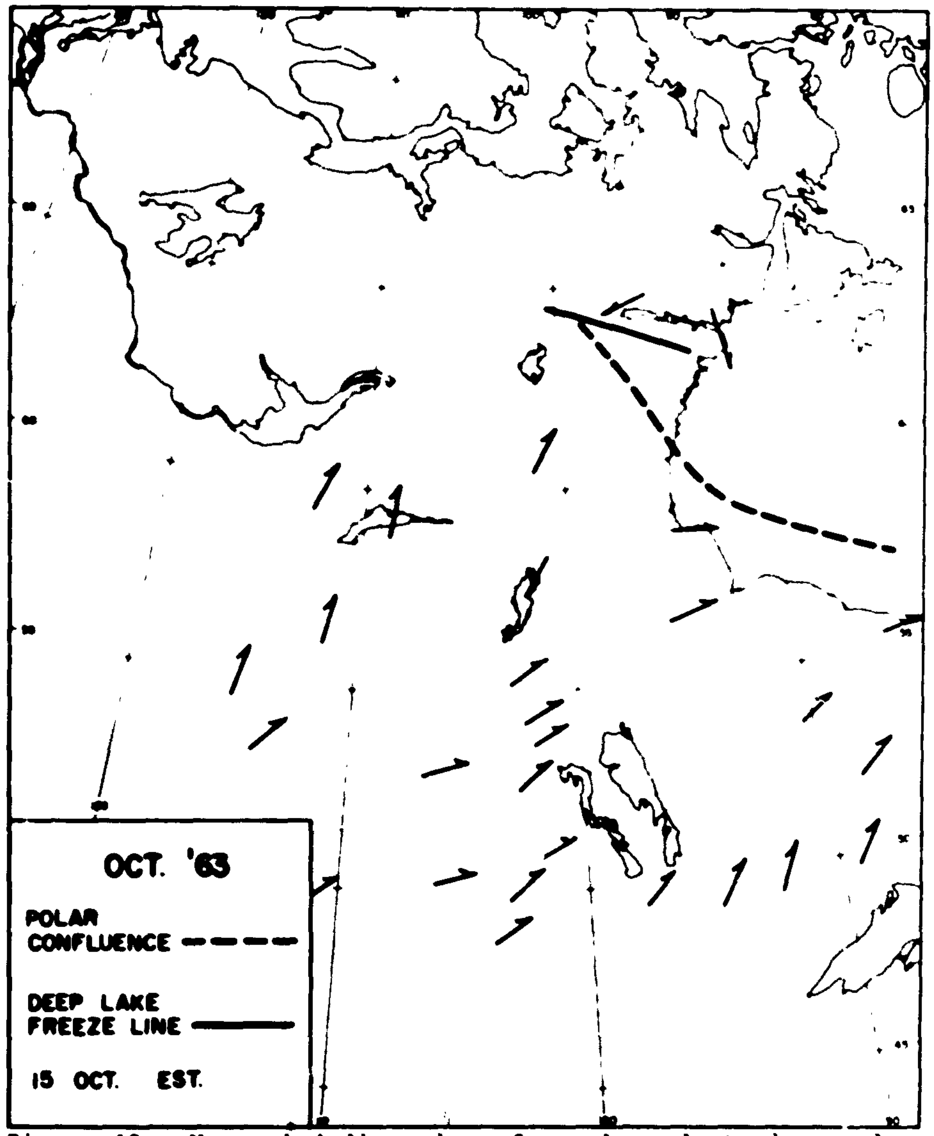


Figure 43. Mean wind directions for selected stations, the polar confluence and mid-month position of the deep lake freeze line for October 1963.

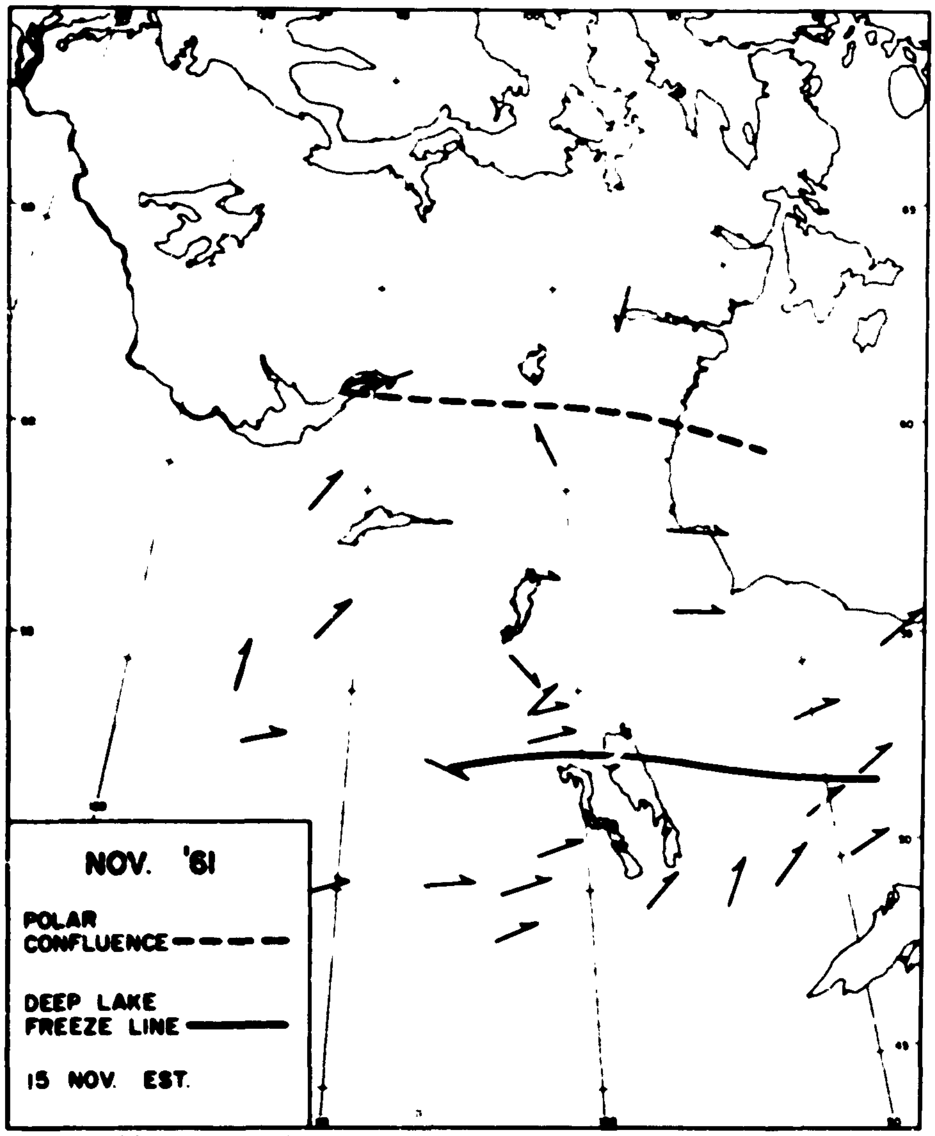


Figure 44. Mean wind directions for selected stations, the polar confluence and mid-month position of the deep lake freeze line for November 1961.

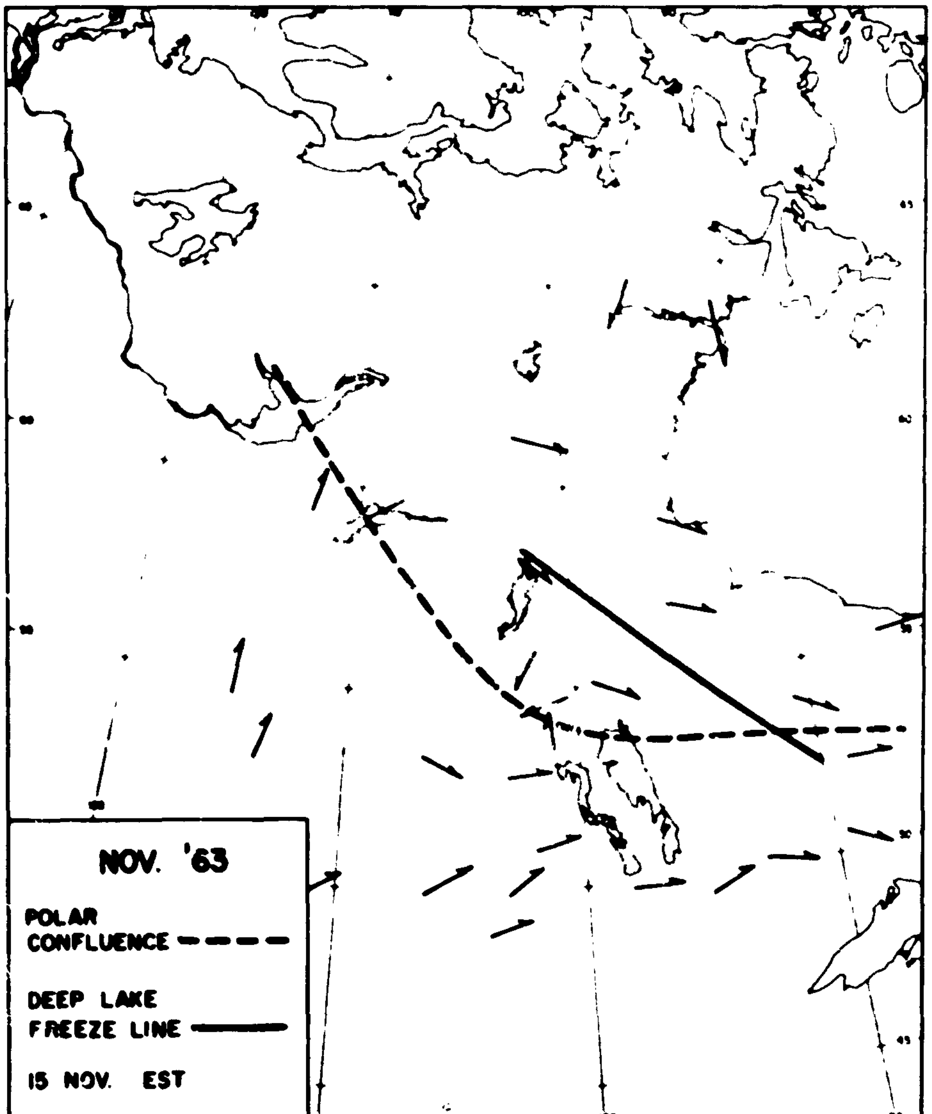
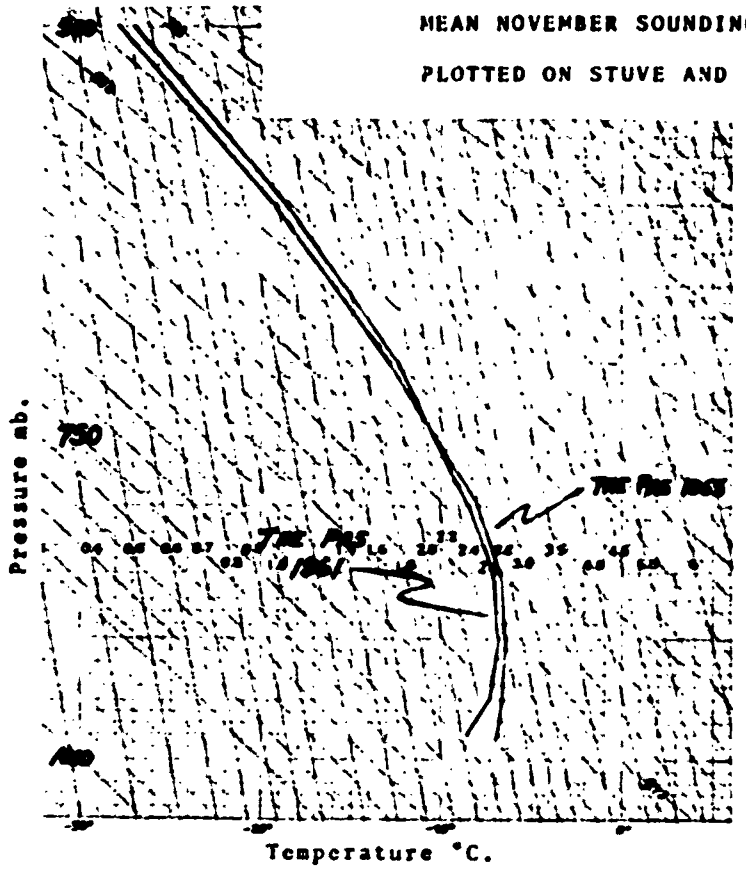


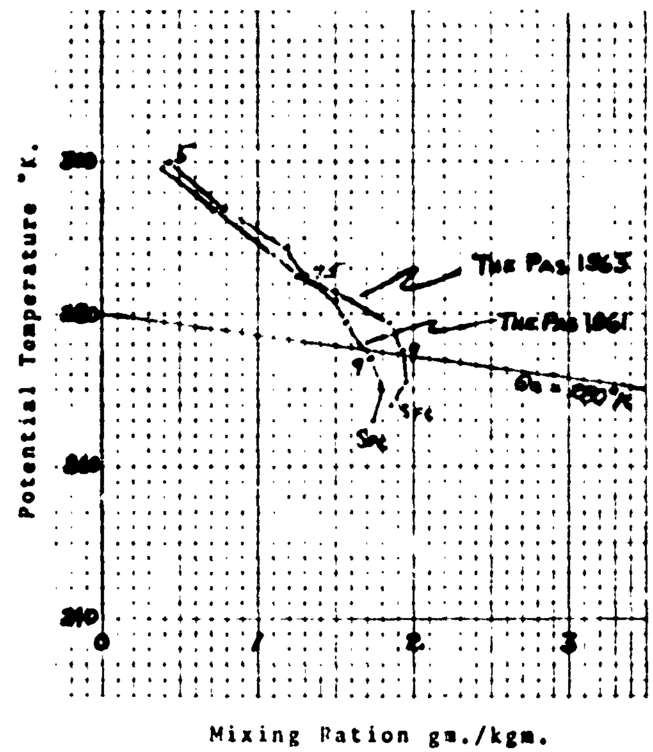
Figure 45. Mean wind directions for selected stations, the polar confluence and mid-month position of the deep lake freeze line for November 1963.

FIGURE 46.

MEAN NOVEMBER SOUNDINGS FOR 1961 AND 1963 AT THE PAS

PLOTTED ON STUVE AND ROSSBY DIAGRAMS





and moisture content of the air at The Pas were lower in 1961, even though the mean position of the polar front was much further north.

Figure 47 depicts the 15 November snow line for 1961 and 1963 and the estimated position of the deep lake freeze line for these two dates. Note that the air moving into the study area from the southwest passed over snow covered terrain in 1961 and snowless terrain in 1963. It is apparent that the air moving into the study area in 1961 from the snow covered plains of Alberta and Saskatchewan acquired characteristics very similar to cP air even though it was of Pacific origin. This air was sufficiently cold to freeze all of the lakes well in advance of the passage of the Polar front.

It was pointed out earlier in this chapter that the original classification of cP air was thermodynamic in nature, and that the character of the air in this type of air mass had been described for winter and summer months. As this investigation considered the transitional months just prior to winter, the true winter type properties of continental Polar air were not observed. In order to relate the distribution of lake ice to a known air mass, however, it was necessary to redefine cP air based on trajectory instead of the thermodynamic properties used by the early investigators.

It was also demonstrated in an earlier chapter that the freezing of a lake depends on air temperature. The cold temperature required to freeze all of the lakes in a given region at this time of year can always

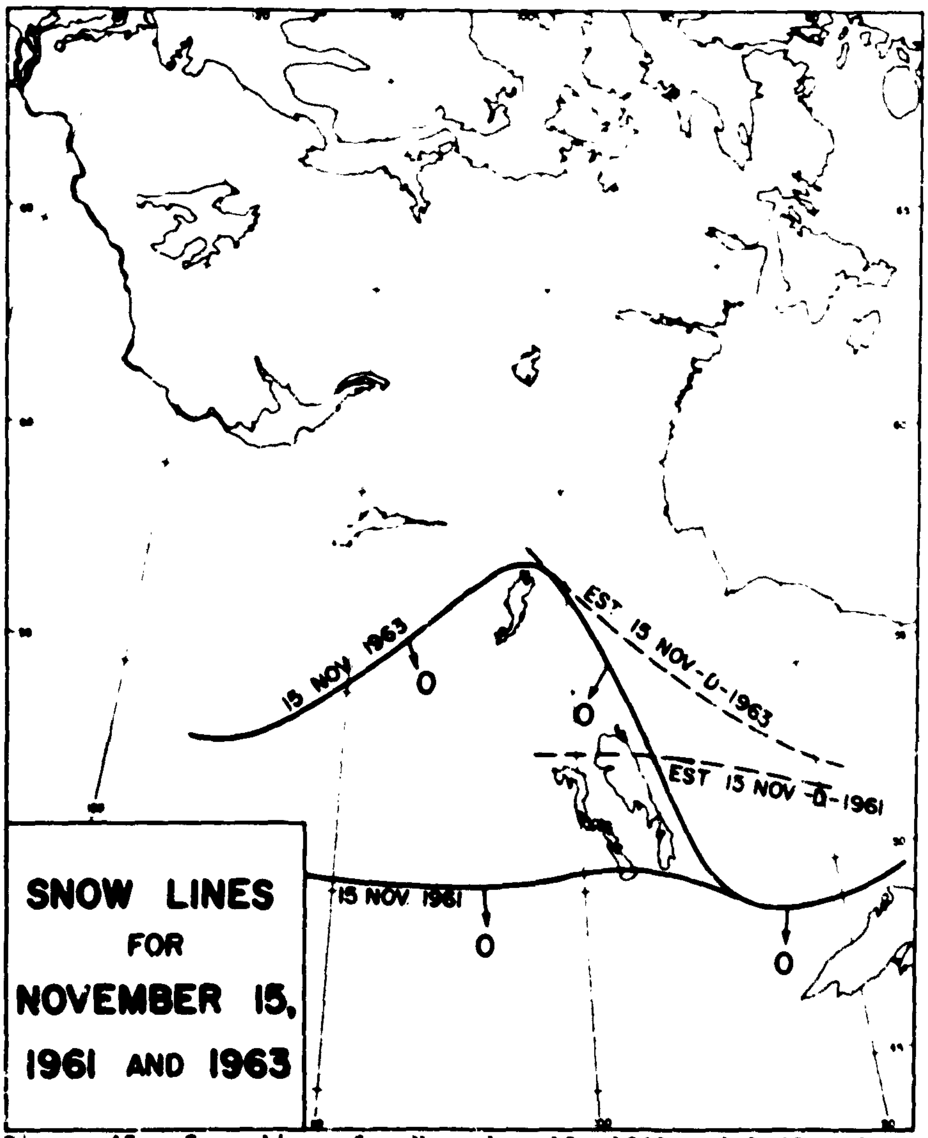


Figure 47. Snow lines for November 15, 1961 and 1963 and the estimated mid-month positions of the deep lake freeze lines.

be provided by a polar air mass, but it was also observed that air of another type (Pacific) may have essentially the same properties and thereby affect freezing of the lakes provided it is modified by a snow cover and has cP-like properties when it reaches the region of the lakes.

It is suggested, therefore, that for this time of year, if there is no snow in advance of the southward moving polar front, the mean monthly position of this front will agree reasonably well with the mid-month position of the deep lake freeze line. If good snow cover does exist south of the advancing front, then there need not be any association between the front and the deep lake line.

VIII. ESTIMATION OF MEAN LAKE DEPTHS FROM FREEZE DATES

After concluding that the morphology of lakes does affect their response to climate in that deeper lakes react more slowly to changes in climate than shallower ones, it is then feasible to examine the possibility of estimating mean depths of lakes remotely by observing their freeze dates. From lake ice data obtained during Freezeup 1961, estimates were made of the mean depths of several lakes between The Pas and Lynn Lake, Manitoba based on their freezing dates as compared with the freezing date of a lake with a known mean depth located nearby. The results of these estimates were reported by Ragotzkie and McFadden (1962), but it was not until the summer of 1963 that data were obtained to verify these estimates.

The method used for verifying the 1961 estimate was that described by Stewart (1964) which utilizes Merian's formula to determine the mean depth of a lake, given the primary seiche period of that lake. The primary seiche period of the lake is determined by applying a spectral analysis to the seiche record obtained from the lake (Fig. 48). Stewart concluded from his study that for lakes that are free of channels and obstructions, such as bars or large islands, Merian's formula provides an estimate of mean depth with an error of less than 1 meter for lakes that vary between 2 and 30 meters in mean depth. A portion of the actual seiche record obtained from Clearwater Lake, near The Pas, along with its spectrum is shown in Fig. 48.

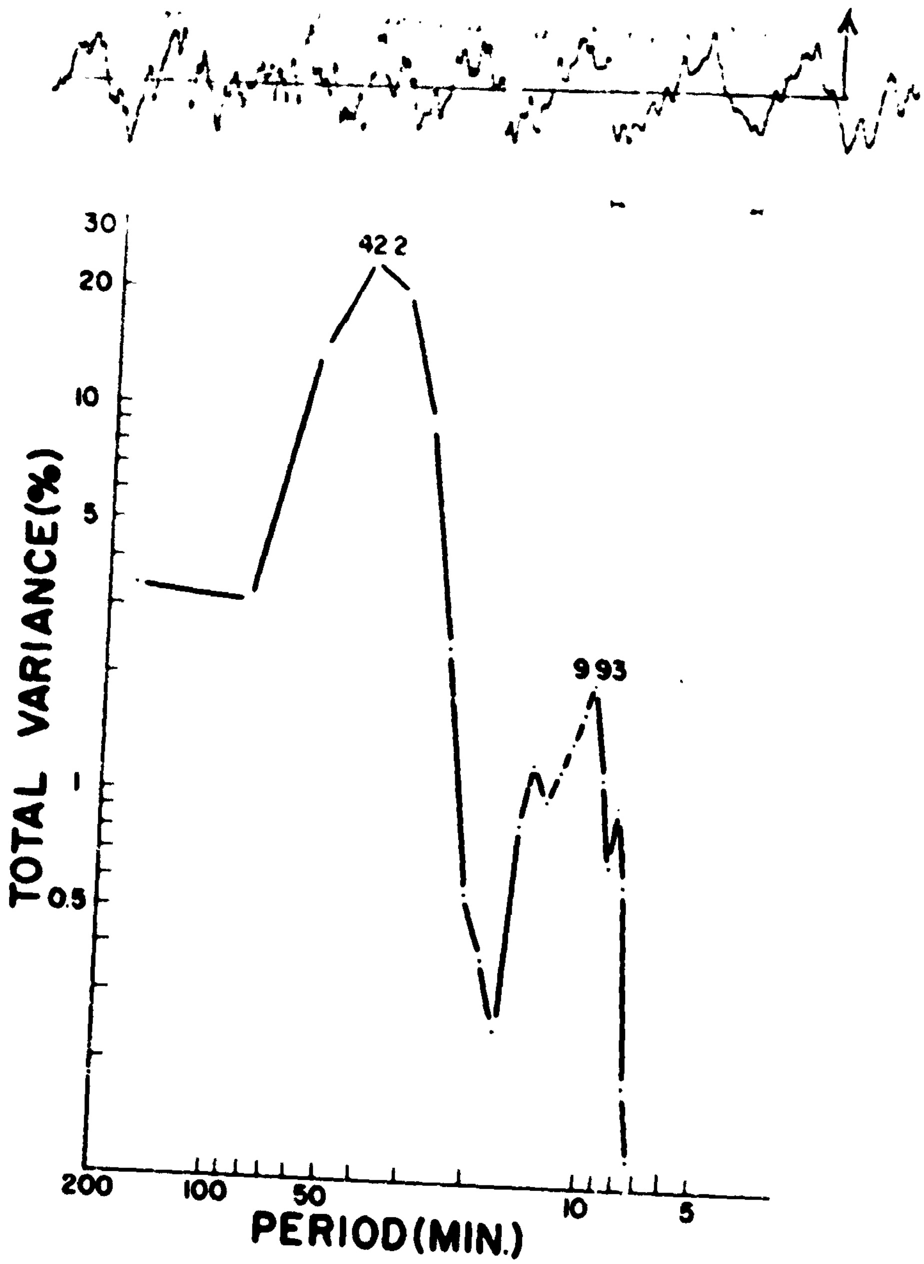


Figure 48. A portion of the actual seiche record from Clearwater Lake, Manitoba and the computed variance spectrum for the entire record.

As a further check on Stewart's work, records of the seiches on lakes with both known and unknown mean depths were obtained.

TABLE 15

MEAN DEPTH COMPARISONS

Lake	MEAN DEPTH (m.) Seiche Est.	Ice Est.	By sounding
Clearwater Lake	19.1	-	15.0 $\pm$
Clearwater Bay	1.6	-	-
Grace Lake	1.0	(1.0)	1.0
Egg Lake	5.8	(6.0)	6.0
Rocky Lake	5.1	(5.0)	5.0
Athapapuskow Lake	11.9	> 6.0	-
" (East Arm)	10.0	> 6.0	-
Heming Lake	2.9 (S. Basin)	> 6.0	3.0*
Storey Lake	7.7	> 6.5	-
Counsell Lake	6.7	> 6.5	-
Reeder Lake	-	< 1.0	< 1.0

*mean depth according to Lawler and Watson (1958)
(depth) = reference lake depth used for ice estimate

With the exception of Clearwater Lake the agreement between the estimates from the seiche periods and the measured values is reasonably good (Table 15). The high value for Clearwater Lake is possibly explained by the fact that the peak in the spectral analysis at 42.2 minutes is actually representative of the range 37.5 – 48.2 minutes. Using these limits in computing the mean depth yields a range of 14.6 - 24.2 meters. The known depth falls within this range. The lack of precision for this lake is a result of the shortness of the record. For a lake this size a very long record is desirable.

Lake freezing dates can be used to indicate relative depths. In addition, if the mean depths of one or several lakes in an area where climatic conditions are the same throughout are known, then it is possible to estimate the mean depths of the remaining lakes relative to the known mean depths from freezing date information. This method worked in all of the above cases with the exception of Heming Lake. Seiche estimated and known depths agree, but the ice estimate does not. This discrepancy is most probably a result of an identification error made during the reconnaissance flight.

IX. SUMMARY

The interrelationship of lake ice and climate on a regional basis has been demonstrated, and, as observed by Scott (1964), there are seasonal and lake-to-lake variations in the patterns of freezing and thawing of lakes within and between different regions. As this paper considered several relationships in some detail, this summary is presented to review the important findings and to suggest courses of action concerning further investigations of several of these relationships.

It seemed rather remarkable that the pattern of freezing of lakes in central Canada in 1963 was very similar to the 1961 pattern. Whether this similarity persists in all years is, of course, unknown. The freezing pattern was found to reflect and apparently be related to the climatic singularity "Indian Summer" described by Bryson and Lahey (1958).

No comparison could be made between the patterns of break-up in 1963 and 1964 because two different areas were investigated. The transition zone during break-up was observed to become narrower and its boundaries more sharply defined northwest of the 1963 study area. Current botanical studies indicate more sharply defined vegetative boundaries to the northwest also.

The processes involved in the freezing and thawing of lakes are different, with the transfer of sensible and latent heat to the atmosphere being almost entirely responsible for the cooling and eventual freezing of lakes, and radiation being also important in the wastage of the ice prior to break-up. These findings of Scott (1964) show the importance of air temperature as a factor in the freezing and thawing of lakes.

Comparisons of running mean air temperature with freeze dates show that there is very good agreement between the freezing date of deep lakes and the date the 40-day mean air temperature passes through 0°C. and almost as good agreement between the freezing of shallow lakes and the date the 3-day mean air temperature passes through 0°C. These findings are in contrast to those of Burbidge and Lauder (1957) who concluded that there was very poor agreement between these variables.

The agreement between break-up and mean air temperature was relatively poor. There was some agreement between the thawing dates of deep lakes and a 40-day mean air temperature of between 4.5 and 5°C., but the results were not consistent as in the case of freeze-up. For small lakes radiation affected the ice wastage and the air temperature hypothesis falls short of being a good indicator for break-up dates.

While the major change in the albedo of central Canada was a result of the presence or absence of snow, the effects of lakes were strikingly different in the tundra and boreal forest regions. Lakes caused very little horizontal variation in either the summer or winter in the tundra, but produced a large horizontal variation in the boreal forest when snow was present.

The rapid disappearance of snow from the tundra observed in June 1963 caused an estimated 600 percent increase in the absorbed radiation at the surface. Whether this rather sudden and drastic change in absorbed radiation occurring over the entire tundra region had any effect on the general circulation pattern must await further study. The estimated heating of 1000 meters of atmosphere by an average of 1.6°C. per day during this period does agree fairly well with radiosonde observations at Baker Lake, N. W. T.

The initial supposition (Ragotzkie and McFadden, 1962), that the position of the deep lake freeze line probably coincided with the dominant position of the polar front does not appear to be correct. Although the mid-month deep lake freeze line and the dominant position of the polar front for the months of October 1961 and 1963 did lie close together when their positions were in the tundra, the November data show very poor agreement, particularly for 1961. It is apparent that wind direction has no direct effect on the freezing of lakes, and that it is not necessary for a continental polar air mass to be the dominant air mass before all lakes are frozen. Analysis of snow cover and radiosonde date for November 1961 showed that air of apparently Pacific origin acquired cP-like characteristics flowing across the snow covered plains of Alberta and Saskatchewan, and that this air was sufficiently cold to freeze even the deepest lakes well south of the polar front.

The freezing date of a lake is dependent on its mean depth.

This fact permits an estimation of the relative depths of a group of lakes by a comparison of their dates of freeze-up, which in turn can be obtained by aerial observation. If the mean depth of one or two of the lakes in the group is known, then the mean depths of the other lakes can be estimated relative to the known depths. This procedure worked quite well for a group of lakes in Manitoba whose mean depths were estimated from freeze-up data and later verified by measurement.

Because of the scope of this investigation it was not possible to examine in great detail all of the relationships mentioned in this dissertation. It is suggested that additional work be done with regard to the relationship of lake ice and air masses and in studying the effects of the rapid disappearance of snow from the tundra in early June.

It would also be interesting to study the feasibility of using a Nimbus type satellite for observing the pattern of freezing and thawing of lakes. If it is possible to observe the ice patterns from satellite altitudes, then information on the climate of some remote regions of the world could be obtained through the interrelationship of lake ice and climate.

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APPENDIX

ALBEDO MEANS, STANDARD DEVIATIONS, AND RANGES IN PERCENT FOR VARIOUS SURFACES

Date	Time (CST)*	Area Description	Mean	Std. Dev.	Range
7/13/62	1714	Kazan River, tundra, clear sky, alt. 2200'	17.1	1.82	[illegible].8-21.3
"	1800	Tundra and lakes, clear sky	19.9	1.24	18.0-21.8
"	1830	Tundra and lakes, clear sky 2000'	19.1	1.00	18.3-19.6
"	1845	Tundra and lakes, 2000'	20.4	1.26	17.4-23.7
7/15/62	1103	Hudson Bay Water (no ice)	4.9	.616	4.6-5.1
"	1120	Fog banks over Hudson Bay	9.0	.436	7.7-10.1
"	1130	Fog banks over Hudson Bay	10.2	.995	8.5-11.4
"	1130	Ice flow on Hudson Bay	2[illegible].7	3.94	24.5-33.1
"	1130-1200	Marshy tundra and lakes, coastal lowlands, high percentage of lakes	10.8	1.14	7.9-12.4
"	1200	Tundra and small lakes, stratus	16.1	2.28	12.3-19.3
"	1210	Tundra and lakes, 70 percent lakes, mostly ice covered, thin stratus	16.7	2.42	13.5-21.4
"	1220	Tundra and lakes, some ice on lakes, 40-50 percent lakes, 63°30'N, thin stratus	15.4	2.24	11.5-20.0
"	1330	White Hills Lake, ice covered 10/10 cirrus	27.5	.773	26.8-28.8

APPENDIX TABLE — continued

Date	Time(CST)*	Area Description	Mean	Std. Dev.	Range
7/15/62	1330	Tundra and few lakes, North of Rossby Lake	14.9	1.14	13.8-16.5
"	1445	Chantrey inlet, floating ice	21.7	1.60	18.3-23.8
"	1450	Chantrey inlet, light colored water	13.4	.894	11.3-15.3
"	1530	Sherman inlet, ice; Alto-stratus clouds 3500'	25.8	2.10	23.4-29.0
"	1530	Sherman inlet, ice, 3500' Alto-stratus	25.1	2.09	20.6-27.7
"	1730	Tundra and lakes, 3500'	16.0	.949	12.6-19.1
"	1830	Dabawnt Lake, ice; stratus	31.7	.671	29.7-33.4
"	1920	Tundra and Lakes, near Ennadai	20.0	2.561	16.4-25.6
"	1950	Tundra east of Ennadai	18.5	1.76	13.6-22.7
5/22/63	1100-1200	Spruce trees, no snow, frozen lakes—darkish ice, bogs, clear sky	12.3	1.31	10.2-18.9
"	1300-1345	Spruce forest, lakes—no ice, bogs, altitude 8000'	10.4	1.23	7.2-12.2
"	1030	Lake Athapapuskow, ice, no snow one reading	41.1	0	0
6/9/63	1215	Kasba Lake, ice covered, stratus, thinning, heavy snow cover	60.1	3.16	57.5-63.0
"	1230	Ennadai Lake, ice cover, stratus Thinning, heavy snow cover	63.7	3.85	58.6-70.8

APPENDIX TABLE — continued

Date	Time(CST)*	Area Description	Mean	Std. Dev.	Range
6/9/63	1325	Large lake surrounded by rocky tundra, ice, no snow, clear	29.4	7.5	17.7-38.7
"	1420	Spruce forest, heavy snow cover, lakes open, stratus thinning	23.0	3.38	16.7-28.4
6/12/63	0835-0922	N. of Winnipeg, farms and marshes, no snow, stratus, var. thickness	17.8	1.55	16.2-20.3
"	0922-0941	Lake Winnipeg, stratus-var. thickness	11.1	1.18	9.7-12.4
"	1015-1030	55°40'N, 98°W, spruce forest, no snow	10.5	1.45	7.6-11.8
"	1225-1245	Mostly trees, some bogs (may be tundra), lakes open, stratus	14.2	1.38	11.3-17.0
"	1250-1308	(Mostly trees) mixed forest-tundra, lakes partly frozen, stratus	13.3	2.09	8.6-16.1
"	1308-1508	(Mostly trees) mixed forest-tundra, lakes partly frozen, thinning stratus	18.2	2.72	14.5-29.4
"	1508-1528	Marsh and bogs, east of Lake Winnipeg stratus	17.2	2.72	12.5-27.2
6/14/63	0835-0853	Bog and marshy area NNW of Winnipeg, some scattered lakes, clear	15.2	1.23	11.0-16.9
"	0855-0915	Bog and marshy area NNW of Winnipeg, some scattered lakes, clear	14.2	1.38	12.6-15.7
"	0933-0937	Lake Winnipegosis, clear	8.0	.77	7.8-8.5
"	0941-0945	Cedar lake 53°15'N, 100°W., clear	7.3	.84	6.8-8.1

APPENDIX TABLE — continued

Date	Time(CST)*	Area Description	Mean	Std. Dev.	Range
6/14/63	1023-1029	Forests, lakes, and some open areas near Cranberry Portage	15.2	1.95	12.7-18.0
"	1334-1344	Dubawnt L., ice, light colored, heavy stratus	53.1	5.93	41.8-64.2
6/15/63	0905-0945	Cultivated fields S. of Winnipeg, prairies, no lakes, clear sky	17.7	1.32	15.2-21.1
6/29/63	0900-0920	Tundra, open lakes, clear sky	12.7	1.34	9.4-14.8
"	940	Tundra, open lakes, clear sky	12.7	1.70	8.2-15.2
"	950	Tundra, open lakes, clear sky	13.1	1.72	10.1-15.3
"	1035	Lakes and Tundra	11.6	1.79	8.0-14.8
"	1145-1200	McLeod bay, open but with some small ice floes, clear	6.6	.028	6.1-8.7
"	1200-1245	Rocky tundra and lakes north of G. Slave lake, most lakes open, some partly frozen	14.6	2.57	8.9-28.7
"	1245-1255	Rocky tundra north of G. Slave lake, some lakes open, more frozen, clear	24.9	8.82	15.2-47.1
"	1325-1410	Mostly tundra, some small lakes and some ice, clear	16.2	1.10	14.1-20.4
"	1420	Lakes with fairly dark ice, tundra small lakes open, stratus	32.7	9.54	20.1-48.7
7/1/63	1108-1112	Mostly lt. brown and green tundra, very little water, just S. of Aberdeen Lake, clear	14.8	.95	13.5-15.6

APPENDIX TABLE — continued

Date	Time(CST)*	Area Description	Mean	Std. Dev.	Range
7/1/63	1115–1121	Mostly lt. brown and green tundra, but more lakes and ice. Just N. of Aberdeen Lake, clear	14.9	2.38	13.0–20.2
"	1150–1210	Greenish tundra with some sandy areas, lakes 5/10 ice N. of Gary L., clear (some Cu.)	16.4	4.29	12.0–31.6
"	1225–1238	67°25'N, 97°–98°W. Dark brown tundra, lakes partly open, some light ice, some snow banks	16.8	2.72	13.2–25.7
"	1245	Sea ice in Chantrey Inlet, clear	47.5	1.84	45.5–49.8
"	1630	Hudson Bay, open waters, under thin stratus near Churchill	10.9	.539	9.7–11.6
10/15/63	1407–1447	63°30' to 64°30'N, Tundra, frozen lakes, snow cover, under stratus	77.7	3.45	70.5–83.2

*Where time intervals are given distance of transect in nautical miles may be estimated by: (3 x time interval in minutes).

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13 ABSTRACT

An aerial reconnaissance of lake ice conditions in the Shield region of Central Canada west of Hudson Bay, and northeastern Minnesota and Wisconsin was conducted during the periods of lake freeze-up 1961 and 1963 and lake break-up 1963 and 1964 using a P2V patrol aircraft provided by the United States Navy. Albedo measurements of the surface were also made during these flights. The data from these surveys were compared with climatic data of the region, and the following interrelationships were found. (U)

Observations of the freezing of lakes showed that between the area of all frozen lakes and the area of all open lakes there is a transition zone. The southern boundary of this zone is determined by the freezing of the shallowest lakes and the northern boundary by the freezing of the deepest lakes. The width of this zone and the directional trend and movement of its boundaries showed a recognizable pattern from year to year for the same region. These patterns reflect and are apparently related to the climatic singularity "Indian Summer". (U)

(continued)

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13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.

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Unclassified
Security Classification

The patterns of ice break-up for 1963 and 1964 could not be directly compared because different areas were investigated, but the transition zone was observed to be narrower and better defined in the northwest section of the study area, indicating that the climatic boundaries are also more distinct toward the northwest. This agrees with the more sharply defined vegetative boundaries found in this region. (U)

Comparison of lake freezing dates with running mean air temperatures shows that there is good agreement between the freezing date of deep lakes and a 40-day running mean air temperature of 0°C., and a fair agreement between freezing dates of shallow lakes and a 3-day mean air temperature of 0°C. The agreement between thawing dates and mean air temperature is relatively poor. (U)

Aerial measurements show that there is very little horizontal variation in the albedo of the tundra in the summer when lakes are free of ice and in the winter when they are frozen and the region is snow covered. Large horizontal variations of albedo occur in the tundra when lakes are frozen but there is no snow, and in the boreal forest region when the lakes are frozen and snow covered. (U)

The rapid disappearance of the snow from the tundra observed in 1963 produced a sudden increase of 600 percent in the amount of absorbed radiation at the surface. A heat budget estimate for the tundra land surface after the snow had disappeared indicates that the sensible heat transfer to the atmosphere was sufficient to heat the lower 1000 meters of air at a rate of 1.6°C. per day, a figure that agrees quite well with actual observations. (U)

The freezing of lakes does not appear to be dependent on the presence of a particular type of air mass. Sufficiently cold air temperatures to freeze all lakes can be present in an air mass of polar origin, or in an air mass of Pacific origin that has been modified over an extensive snow surface. (U)

Because the freezing date of a lake is dependent on its mean depth, the relative depths of a group of lakes can be estimated from the sequence of their freezing dates. (U)