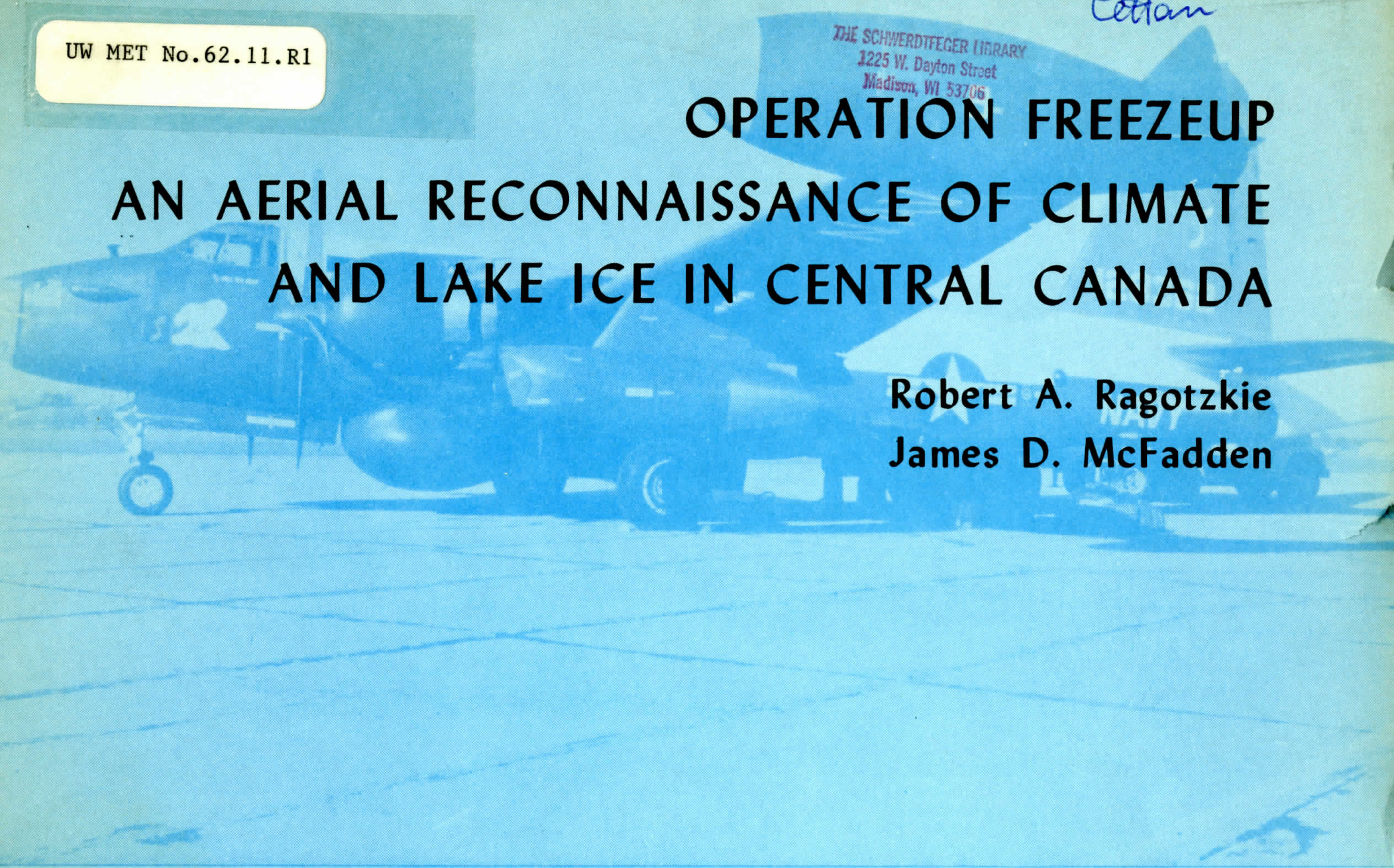
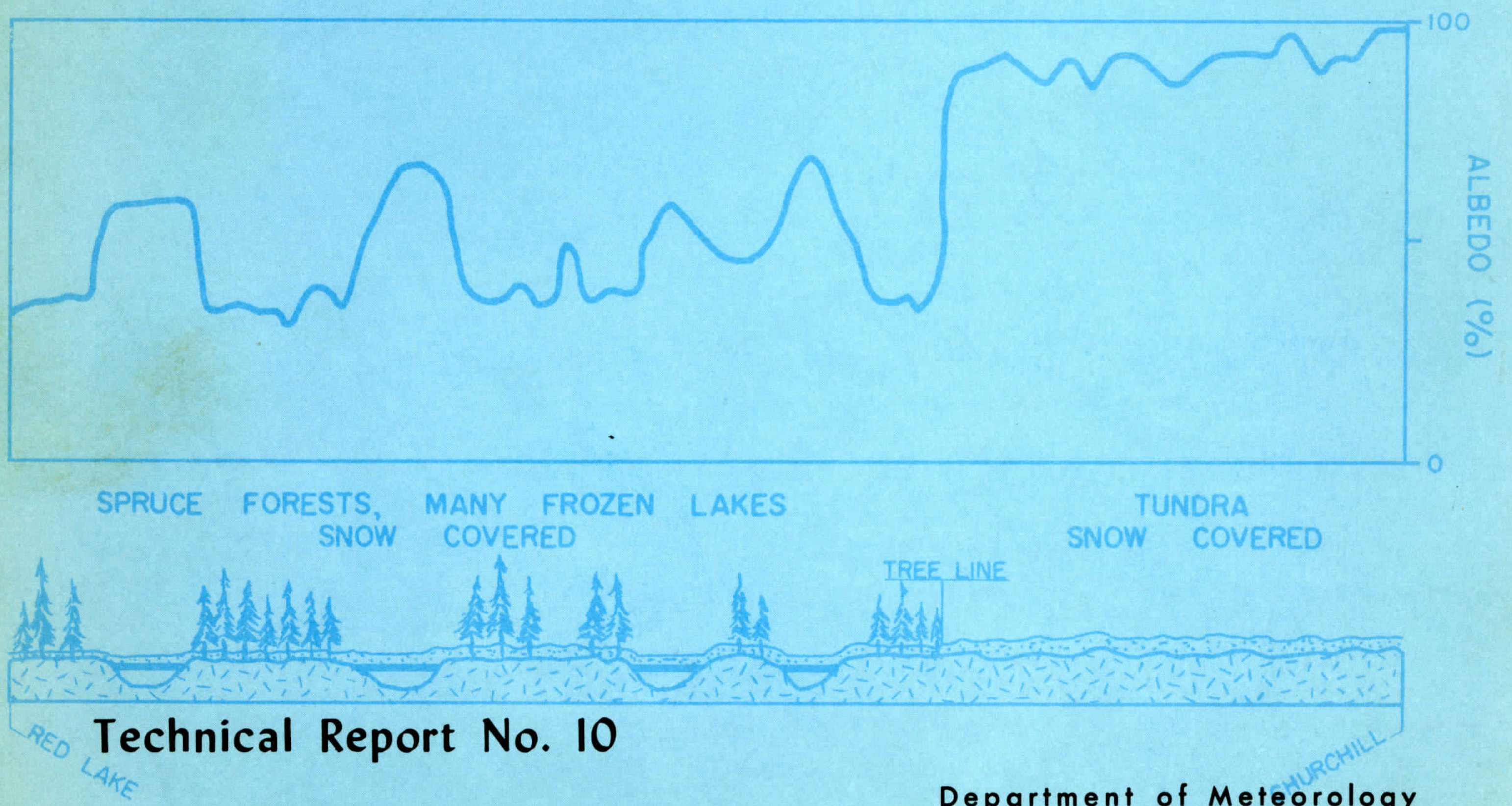
Cotton



OPERATION FREEZEUP
AN AERIAL RECONNAISSANCE OF CLIMATE AND LAKE ICE IN CENTRAL CANADA

Robert A. Ragotzkie
James D. McFadden



Technical Report No. 10

NR 387-022
NONR 1202(07)

Department of Meteorology
The University of Wisconsin
November 1962

Operation FREEZEUP

An aerial reconnaissance of climate and lake ice in central Canada

by

Robert A. Ragotzkie

James D. McFadden

Technical Report No. 10

Task No. NR 387-022 ONR Contract No.: Nonr 1202(07)

The research reported in this document has been sponsored by the Geography Branch of the United States Office of Naval Research.

The University of Wisconsin

Department of Meteorology

Madison

November 1962

ABSTRACT

An aerial reconnaissance of lake ice conditions in Manitoba, western Ontario, Minnesota, and Wisconsin was conducted during the period 24 October to 10 November 1961. Albedo measurements and cloud observations were also made on the flights. As the lake freezing zone migrated southward it grew wider in north-south extent. This zone, where some lakes were frozen and some open, was characterized by extremely variable albedo and by persistent low cloud and convective activity. The climatological significance of these findings are examined.

TABLE OF CONTENTS

Operation FREEZEUP

I. Introduction

Operation FREEZEUP was conceived as an aerial reconnaissance to obtain information on the freezing of lakes in north central Canada. Since lakes interact with the atmosphere in very different ways depending on whether their surfaces are liquid water or frozen, the dates and sequence of their freezeup is of great interest. The major role of lakes in this respect is indicated by the fact that in many parts of northern Canada lakes comprise between 10 and 25 percent of the terrain surface.

To facilitate this reconnaissance a long range aircraft with multi-engine reliability was indicated. In response to a request from the United States Office of Naval Research the Navy Air Test Center at Patuxent River, Maryland assigned a P2V Neptune aircraft and crew to support the operation.

The Government of Canada graciously granted permission for the aerial observations over Canada and to operate this aircraft from Churchill and Winnipeg, Manitoba during the period of the observations.

II. Operational Plan

During the period when the lakes in Canada are freezing 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 lies a zone of transition which we shall call the <u>lake freezing zone</u>. The location of the lake freezing zone and its boundaries were determined by flying from the region of 100 percent frozen lakes to the region of 100 percent open lakes and vice versa. Migration of the lake freezing zone was followed by repeated flights over the same tracks and extending these tracks southward as the season progressed.

The area of interest was the District of Keewatin, Manitoba, and western Ontario. Fort Churchill, Manitoba was chosen as the base of operations because of its geographical location and because it is a military base and as such has the facilities required by a military aircraft. From the scanty information on the freezing of lakes in this region, the period 15 October - 15 November seemed to be most desirable. The results indicated that this was a week or two too late to observe the movement of the freezing zone from Keewatin southward, and since the first flight was not actually accomplished until 24 October, the observations were limited in the north to Manitoba and western Ontario and extended southward to Minnesota and Wisconsin. Figure 1 is a base map of the area of observation.

A total of eight observational flights were accomplished from 24 October through 10 November 1961 during which a total of 7000 miles were flown of which 6300 miles were in weather good enough for visual and photographic observation.

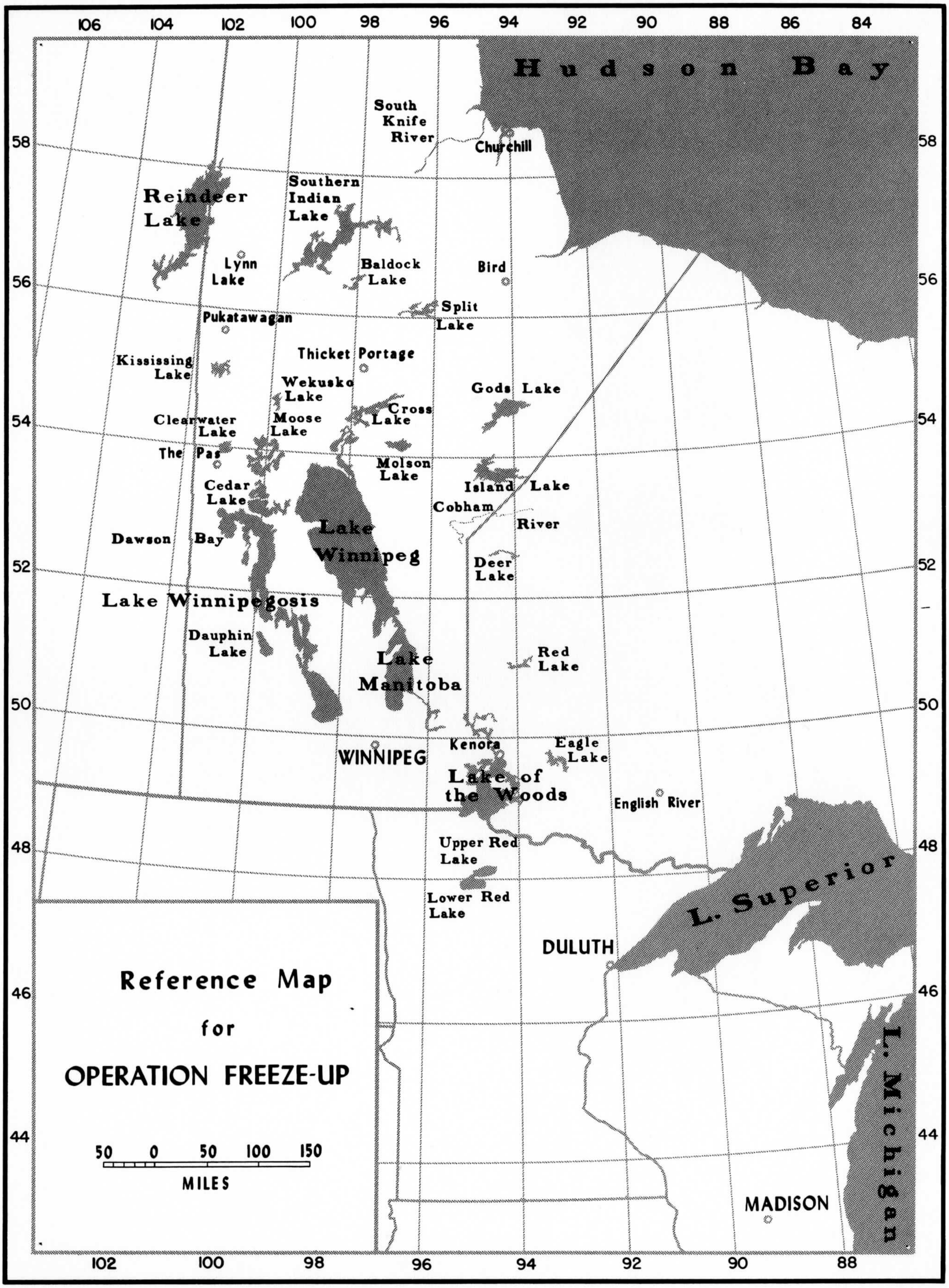


Figure 1 -- Base map of the area of the reconnaissance.

It had been planned to stage all flights from Churchill, Manitoba. However, the lake freeze zone was well south of Churchill by 26 October and it was clear that Winnipeg would be a more central base of operations. Therefore, on 1 November the aircraft was moved to Winnipeg and flights staged from there until 9 November when the aircraft and crew returned to Madison. On 10 November a flight from Madison to Lake Superior and return was made to establish the southern boundary of the lake freeze zone which then lay across the middle of Wisconsin.

III. Lake Ice

A. Data collection

The primary purpose of the flights was to obtain information on the freezing of lakes over a broad latitudinal range. In addition albedo measurements of the surface and cloud observations were made over much of the area under observation.

Ice information was obtained in two ways: (1) by visual observations, and (2) by photographic techniques. Both methods were used whenever possible, but when poor weather prevented reliable photographic coverage, visual observation was continued as long as visual contact with the ground could be maintained. A continuous photographic record was made of the significant portions of each flight by means of a 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 and loaned to us specifically for this project. 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 8 times the real speed of the aircraft or about 1600 miles per hour. Despite this apparent speed, the picture is not especially jerky, nor is it too fast to identify lakes and determine whether or not they are frozen. By using a projector with an adequate heat filter the film can also be slowed down or stopped for detailed study of a particular frame.

Visual observations were also made from the plexiglass nose of the aircraft. Ice conditions were entered directly on maps, and snow cover, general weather conditions, and particularly cloud cover were also recorded. The observer also served as photographer and kept an accurate log of location of the aircraft at the start and end of each roll of movie film. For maps the National Topographic Series of Canada and the Sectional Aeronautical Charts for the United States were used. Both of these series have a scale of 8 miles to the inch and show good detail of lakes.

Ideally, observational flights were conducted at 2500 to 4000 feet (all altitudes stated in height above the terrain), however low stratus clouds or snow frequently forced the aircraft below 1000 feet in order to maintain visual contact. Under these conditions, the quality of the photographic coverage was doubtful, and visual observation became the primary means of obtaining data. These conditions also made the task of the observer much more difficult because of the problem of maintaining continuous navigational orientation, taking notes, and advising the pilot about future changes if weather conditions deteriorated as they frequently did. If the observer became "lost" under these conditions it was most improbable that he would find himself again in time to maintain observational continuity, if at all. This difficulty was eliminated by laying out a ground track in advance, and having it marked on World Aeronautical Charts (WAC) for use by the pilots. One of the pilots maintained a continuous position check on this chart and supplied this position to the observer on request. The navigator, who could not see outside the plane, carried on dead reckoning or radio navigation with occasional position reports from the pilot. This system worked quite well and by permitting visual observations to be continued from altitudes as low as 500 feet, it often facilitated the extension of observations through critical parts of the lake freezing zone.

After each flight the observer translated his crude notes to a log of the flight which was then placed with the set of annotated maps. The observations were also transcribed to Jet Navigation Charts (scale: 25 miles per inch) in order to view the overall location of the lake freezing zone and to plan the next flight.

B. Ice distribution

Observations of lake ice conditions as recorded on the working maps were verified or corrected by reviewing the film record of the flights. The north and south boundaries of the lake freezing zone were determined by locating two or more points where each of these boundaries intersected the flight tracks and interpolating between them using all available historical and geographical information on lake freezing dates (Ragotzkie, 1960). Flights closely spaced in time but in different sectors were combined in order to extend as much as possible the length of the freezing zone boundaries.

Figures 2, 3, and 4 show the results of this grouping of observations. The results of flights 1 and 2 are combined in Figure 2, flights 3 and 4 in Figure 3, and flights 5, 6, 7, and 8 in Figure 4. In addition observations made from a commercial flight on 31 October, 1961 of the southern boundary of the freezing zone are included in both Figures 2 and 3 to demonstrate the movement of this line.

C. Lake freezing zone

From the flights of 24 and 26 October, 1961 (Figure 2) it was clear that the lake freezing zone was already well south of Churchill. All lakes north of a line from Lynn Lake, Manitoba to Gods Lake, Ontario were closed with the exception of Stupart Lake, a long thin lake about 40 miles (all distances in nautical miles) north of Gods Lake. Stupart Lake is on the headwaters of the Hayes River and is apparently quite deep. The southern boundary of the freezing zone extended from The Pas, Manitoba to Island Lake, Ontario. The northern boundary trended from northwest to southeast while the southern boundary was approximately east-west. Thus the freezing zone narrowed toward the east, being only 60 miles wide along the Island Lake - Churchill transect, longitude 94° W.

Ten days later (Figure 3) the northern boundary had moved 90 miles southward along longitude 101° W. but only 50 miles south along longitude 94° W. However the southern boundary had moved southward 225 miles along 101° W. and 240 miles along 94° W. The freezing zone was expanding in the north-south direction.

The last set of observations on 7, 8, 9, and 10 November, 1961 (Figure 4) showed a continuation of this north-south expansion of the lake freezing zone. It is of interest that the expansion of the freezing zone was due primarily to

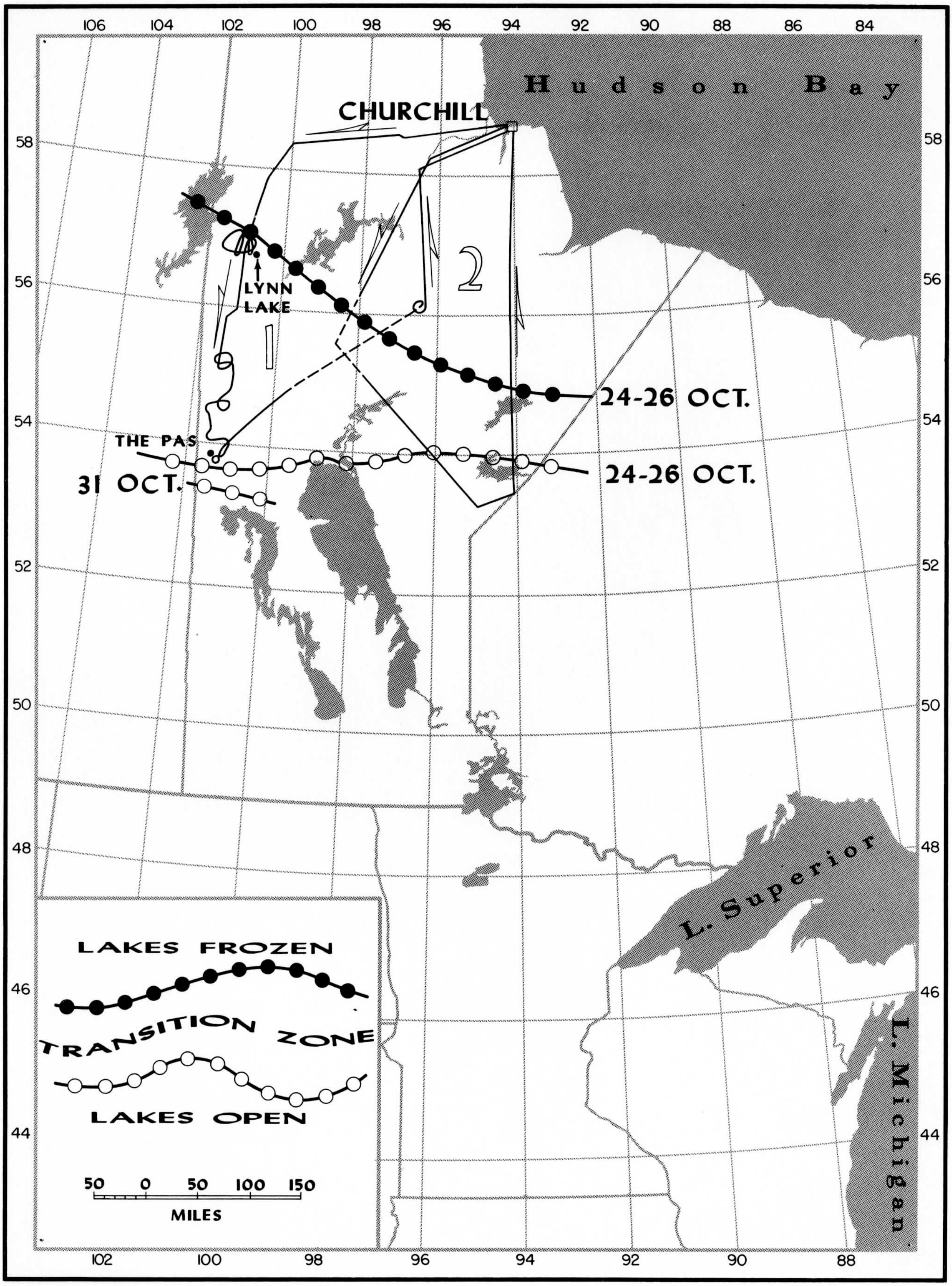


Figure 2 -- Lake freezing zone and flight lines during the period 24-26 October 1962, data from flights 1 and 2 combined. Observation from commercial flight of 31 October also shown.

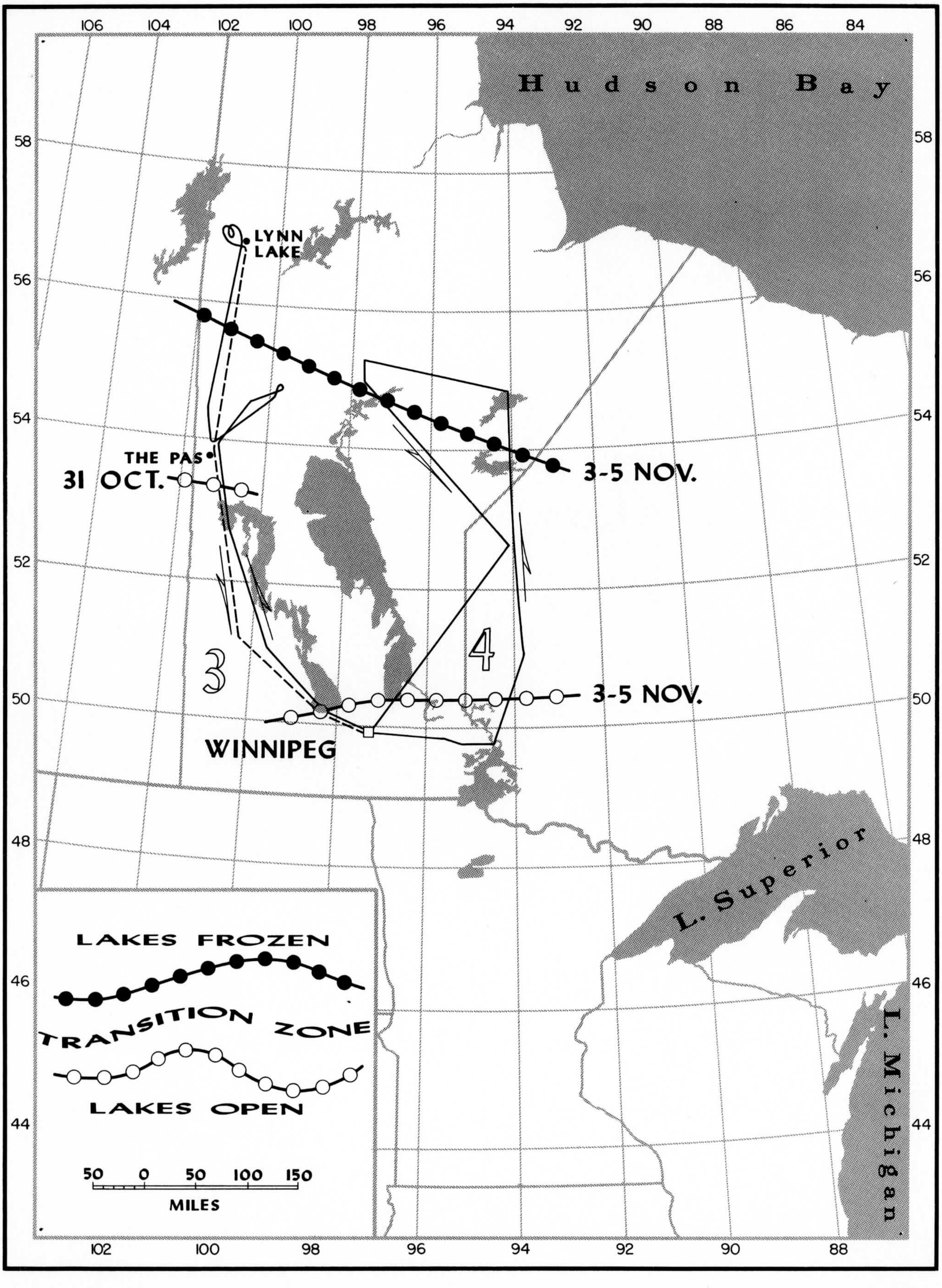


Figure 3 -- Lake freezing zone and flight lines during the period 3-5 November 1962, data from flights 3 and 4 combined. Observation from commercial flight of 31 October also shown.

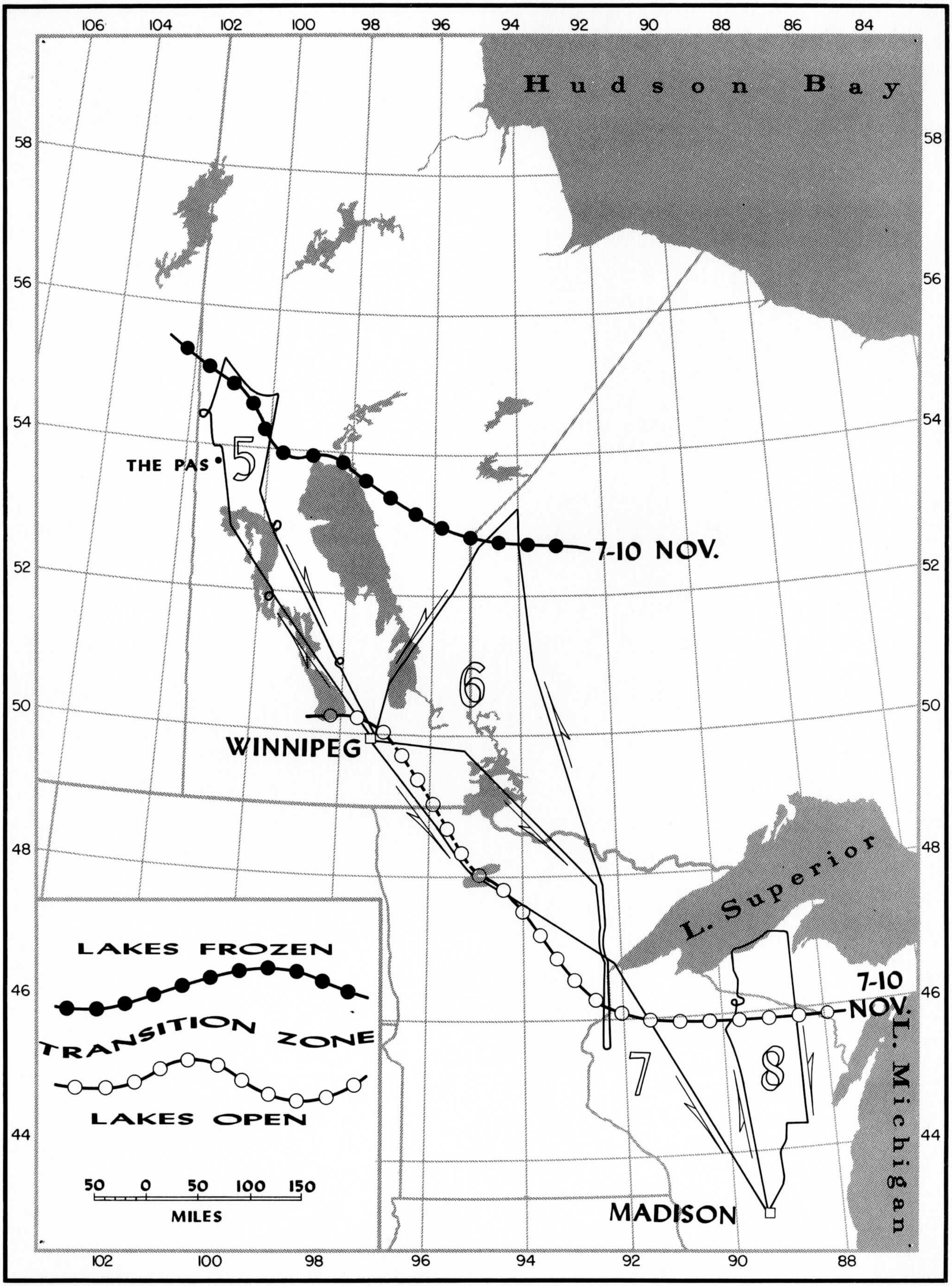


Figure 4 -- Lake freezing zone and flight lines during the period 7-10 November 1962, data from flights 5, 6, 7, and 8 combined.

the very rapid migration of its southern boundary especially on the eastern side of the area of study where the southern boundary moved 240 miles south in the 10 days between 26 October and 5 November, 1961 and 270 miles south the next 5 days or over 500 miles in 15 days, an average of 33 miles per day. During the same 15-day period the northern boundary moved southward only 120 miles along both meridians or only 8 miles per day.

Although no systematic observations were made after 8 November, a later position of the northern boundary of the freezing zone can be obtained by taking the freezing of Lake Mendota at Madison, Wisconsin as an indicator of the northern boundary's arrival. In 1961 this occured on 18 December. Thus during the 40 days between 8 November and 18 December, 1961 the northern boundary moved 600 miles or 15 miles per day. Although this is nearly double the rate of migration observed during the period of the observation flights, it is still much slower than that of the southern boundary which moved 33 miles per day during the period 24 October to 10 November, 1961.

As explained in more detail in the next section, the freezing of lakes is dependent to some degree on their depth, the shallow lakes freezing before the deep ones. The southern boundary of the lake freezing zone is established by the freezing of very shallow lakes while the northern boundary represents the limit of the freezing of the deepest lakes. Since the two boundaries are established by differences in the thermal response time of shallow and deep lakes, the movements of the boundaries indicate different stages of the change of season. It is suggested that the migration of the southern boundary represents an increase in outbreaks of cold continental polar (cP) airmasses, one or two of which may be sufficient to freeze a very shallow body of water. This idea is supported by the extremely rapid southward movement of the shallow lake boundary especially on the eastern side of the region under observation. The bulging of the southern boundary in the south-southeast direction corresponds to the trajectory of the continental Polar outbreaks which usually begin about 1 November (Bryson & Lahey, 1958). Deep lakes, however, containing a much larger heat reserve, do not freeze until they have been exposed to cold air for fairly long periods, that is only after cP air becomes the dominant airmass. The rate of movement of the northern boundary, then may be a measure of the rate of movement of the dominant position of the polar front.

D. Lake depth effects

The freezing of a lake is a thermal event in response to climatic conditions preceding it. Freezing occurs only after the entire water column has cooled to well below 4°C. Since heat flux through the surface of a lake is an areal process while total heat content depends on depth, the rate of change of temperature is partly dependent on depth. Thus the deeper the lake, the greater its heat content and the slower it will respond to climatic changes. It follows then that shallow lakes cool faster and freeze sooner than deep lakes. Similarly the trapping of radiant energy by the "greenhouse effect" of the winter ice cover is the same per unit area of deep and shallow lakes so that the temperature rise of the water under the ice is greater in shallow lakes than in deep lakes. The net result is that shallow lakes break up earlier in the spring than do deep lakes. These relations are borne out by freezing and thawing data for several lakes in the Madison, Wisconsin area for which extensive records are available (Table 1) and by data for 2 years for lakes in Vilas County in northern Wisconsin (Table 2).

TABLE 1

Lake	mean depth (m)	mean freeze date	mean break-up date
Wingra	2.3	25 Nov (32)*	29 March (34)
Kegonsa	4.6	11 Dec (18)	29 March (23)
Monona	8.4	14 Dec (106)	3 April (104)
Mendota	12	17 Dec (107)	6 April (107)

*(no.) = number of years record

TABLE 2

Lake	Mean depth (m)	Freeze date 1959	Freeze date 1961	Break-up date 1960	Break-up date 1961
Mystery	1.0		before 19 Nov	19 Apr	19 Apr
Spruce	1.8		before 19 Nov	20 Apr	20 Apr
Escanaba	3.4	11 Nov		22 Apr	23 Apr
Nebish	5.0	11 Nov	before 19 Nov		22 Apr
Pallette	8.5	15 Nov	after 19 Nov	22 Apr	28 Apr
Trout	12.5		after 19 Nov		5 May

If the relationship of freezing date and depth has indicator value, a series of freezing date observations on many different lakes in a remote area exposed to a similar climatic regime should yield some information on the depth of these lakes, the order of freezing representing the order of increasing depth. If the depths of a few of these lakes are known, actual depth ranges can be estimated for the unknown lakes.

The only transect of the present study where we have some information on actual lake depths is in Manitoba from Lynn Lake to The Pas. Therefore we will examine this transect to see what lake depth data can be extracted from the aerial observations of ice conditions. For this analysis detailed data from within the lake freezing zone (Figure 2) were taken from the annotated maps used by the observer on the flight of 24 October 1961 and from the time lapse movies of the same flight. Along this transect depth data are available for 8 lakes (Table 3).

TABLE 3

Known depths of lakes between Lynn Lake and The Pas, Manitoba

name	latitude	mean depth (m)	max. depth (m)
Zed (near Lynn Lake)	56°55'	6.5	25
Athapapuskow	54°33'	---	50
Goose	54°23'	shallow < 4	--
Egg	54°17'	6*	13
Rocky	54° 9'	5	7
Root	54° 2'	2*	--
Clearwater	54° 2'	15	40
Grace (The Pas)	53°50'	1*	2

* estimated from mean of several soundings

A summary of the following analysis is given in Table 4. North of the town of Lynn Lake all lakes were frozen and snow covered, hençe no depth estimations were possible. Zed Lake which lies 10 miles west of Lynn Lake is a deep lake and was the only lake open within a circle of 10 mile radius centering on Lynn Lake. Therefore we can conclude that all lakes within this circle are shallower than Zed or have a mean

TABLE 4

Lake depths estimated from ice observations.

Name	No. latitude	Reference lake (Table 3)	Estimated Mean depth (m)
All lakes within 10 miles of Lynn Lake except Zed	56°50'	Zed	< 6.5
Vandekerckhove	57° 0'	"	6.5
McMillan	56°58'	"	6.5
Tenklei	56°52'	"	6.5
Finch	56°35'	"	> 6.5
McGavock	56°33'	"	6.5
Russell	56°20'	"	> 6.5
Granville (west arm)	56°18'	"	> 6.5
Trophy	56°14'	"	probably < 6.5
2 un-named	56°22', 56°28'	"	> 6.5
All other lakes within 5 miles of 101 W. long. between 56°10' and 56°40'		"	< 6.5
McKnight	56°0'	"	6.5
Pukatawagan	55°45'	"	6.5
Pukatawagan (north arm)		"	< 6.5
All other lakes within 5 miles of 101°30' W. long. between 55°45' and 56°10'		"	< 6.5
Kississing			
east arm	55°10'	Egg	6.0
northwest arm		Egg	< 6.0
remainder of lake		Egg	<< 6.0
Heming	54°52'	"	> 6.0
Simonhouse	54°30'	"	> 6.0
Cranberry	54°30'	"	> 6.0
elongated lake 5 mi. south of Egg	54°17'	Rocky	5.0
Atik	54°14'	Rocky	5.0
lake 10 mi. south of Clearwater airport	53°50'	Grace	1.0

depth of less than 6.5 meters. Vandekerckhove Lake had a few openings in the ice and is therefore probably the second deepest of this group of lakes. McMillan and Tenklei Lakes which are about 25 miles west of Lynn Lake were both open but had ice in the bays as did Zed. Thus these two lakes are probably about the same depth as Zed.

About 12 miles south of Lynn Lake, Counsell and Story Lakes were open; also open were Finch, McGavock (partly), Russell, the west arm of Granville, Trophy and two elongated un-named lakes. All of these lakes were within 30 miles of Zed and are probably as deep as Zed. There may be some question about Trophy Lake because it is fed by the Laurie River and hence reacts less sharply to climate than a more hydrologically isolated lake. All other lakes in this vicinity were closed and are therefore shallower. South of this group (56°10'N.) more open water was observed. Although we do not have any actual depth informations from here to Athapapuskow (54°33' N.), it is probable that more open lakes are an indication of less severe weather rather than greater depths. McKnight Lake (56° N) was open but had patches of skim ice floating on it. Pukatawagan Lake (55°45' N.) was open except for the north arm. All small lakes between those two lakes were frozen and snow covered indicating they are certainly shallower than Zed.

Kississing Lake (55°10' N.) is a large lake with high shoreline development and high insulosity. The northwest arm of this lake was skimmed over but not snow-covered, indicating very recent freezing, the east arm was completely open indicating deeper water, and the rest of the lake was frozen and the ice mostly snow-covered indicating earlier freezing. From this we can deduce that the east arm is the deepest, the northwest arm is less deep, and the remainder of the lake is shallower with a mean depth of less than 6 meters.

Heming Lake ($54^{\circ}52'$ N.) which is 20 miles south of Kississing and 35 miles north of Egg Lake was open except for snow-covered ice in the bays. Based on Egg, a conservative estimate for the mean depth of Heming is 6 meters. Near latitude $54^{\circ}30'$ are located several known deep lakes-- Cranberry Lakes, Simonhouse, Athapapuskow-- all of which were entirely ice-free. At the same latitude Goose Lake, which is a large, shallow lake was skimmed with freshly formed ice. Egg Lake, however, was open as would be expected from its depth. Atik and Rocky Lakes which are adjacent to each other were both open, indicating a mean depth of at least 5 meters for Atik. The southwest arm of Rocky which is shallow and weedy was closed and snow-covered indicating a much earlier freeze-up than even Goose. Root, a shallow lake, was closed but not snow-covered as expected and Clearwater (Atikameg) Lake being deep was open. An un-named lake 10 miles south of

Clearwater was freshly frozen and is assumed to be as shallow as Grace, namely about one meter. Grace Lake at The Pas is very shallow and was covered with fresh skim ice. This was taken as the southern extent of frozen lakes although very shallow ponds south of here may have been skimmed. Very shallow ponds exhibit almost no thermal lag behind the prevailing weather (Dutton and Bryson, 1962), and freezing and thawing of their surface may occur several times in the autumn before final freezeup occurs. Hence the formation of skim ice on these water bodies is not a definite thermal event in the same sense that it is for lakes.

IV. Albedo

A. Data collection and reduction

Albedo was computed as the ratio of reflected to incident shortwave radiation as 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 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 because the aircraft was always oriented so that the vertical stabilizer never came between the uplooking sensor and the sun when measurements were being made.

Terrain, height, time, and cloud observations were made by the observer in the nose of the plane and by an additional observer near the recorder in the aft section for documentation of the albedo records. The data from each flight were stratified according to terrain type and snow cover. The values for incident and reflected radiation along with the calibration constant for each solarimeter were punched on IBM cards, and the mean albedo and standard deviation for each stratified section computed.

B. Results

While snow is the dominant factor affecting albedo, (Budyko, 1954), (Miller, 1955), and (Bauer and Dutton, 1962), terrain features such as vegetation, lakes, and bogs, are important in modifying the albedo of snow covered terrain. For example, where there are a large number of lakes present, as in north central Canada, the effect of lakes is very pronounced. When these lakes are unfrozen, the very low albedo of the water surface, five percent or less, results in the average albedo of the entire region being much lower than a region where very few lakes are present. Later on when all the lakes are frozen and snow covered, a region with many lakes exhibits a much higher average albedo than a region with few lakes.

Trees, particularly spruce, are also very important in that their foliage will mask snow covered ground. After a snow fall both the ground and the trees will be covered with snow, but because of wind action and the structure of the spruce the snow is quickly shed and the foliage becomes an effective absorbing surface for the incoming radiation. This results in a lower albedo and therefore increased surface heating. This effect has been discussed in more detail by Miller (1955) in his studies of the albedo and climate in the Sierra Nevada.

The effect of snow cover and terrain type on albedo along a north-south transect made in late October and early November, 1961 from Churchill, Manitoba to Madison, Wisconsin is illustrated by the data in Table 5 and Figure 5. Figure 6 is a pictorial representation of this transect. It illustrates the surface features that existed at that time and the albedo of these features. The albedo values shown are samples of the actual record obtained over the terrain type indicated.

The highest albedo values recorded were from the tundra or false barrens of the Hudson Bay lowland. In this region there was continuous snow cover and no vegetation protruding above the snow. All lakes were frozen and covered with snow.

South of the tree line to approximately latitude 53° N, all lakes were frozen, and the entire area, which is made up of spruce forests, bogs, and lakes, was snow covered. The average albedo value of this region was about 47 percent, or one-half the values of the tundra. This difference was due

TABLE 5

Variation of Albedo with Terrain Type, Snow Cover, and Lake Ice Condition

Predominant Terrain Type	Snow Cover	Lakes			Mean Albedo
		open	frozen	partial	± σ
Tundra (barrens)	X	-	X	-	90.7 ± 4.5
Spruce forests and lakes	X	-	X	-	48.0 ±11.4
Spruce forests and lakes	X	-	X	-	46.9 ± 9.7
Bogs	Tr.	-	-	X	35.4 ± 2.8
Bogs and Lakes	Tr.	-	-	X	25.6 ± 3.5
Bogs and Lakes	Tr.	-	X	-	40.4 ±10.6
Lakes	X	-	X	-	77.3 ± 0.3
Spruce forests and lakes	X	-	-	X	34.5 ± 8.0
Spruce forests and lakes	-	-	-	X	16.9 ± 2.0
Spruce forests	-	No lakes			14.9 ± 2.0
Plowed fields	-	No lakes			12.3 ± 1.6
Fields and wooded areas	X	No lakes			43.8 ± 4.0
Farms, woods, and bogs	-	No lakes			18.6 ± 2.5

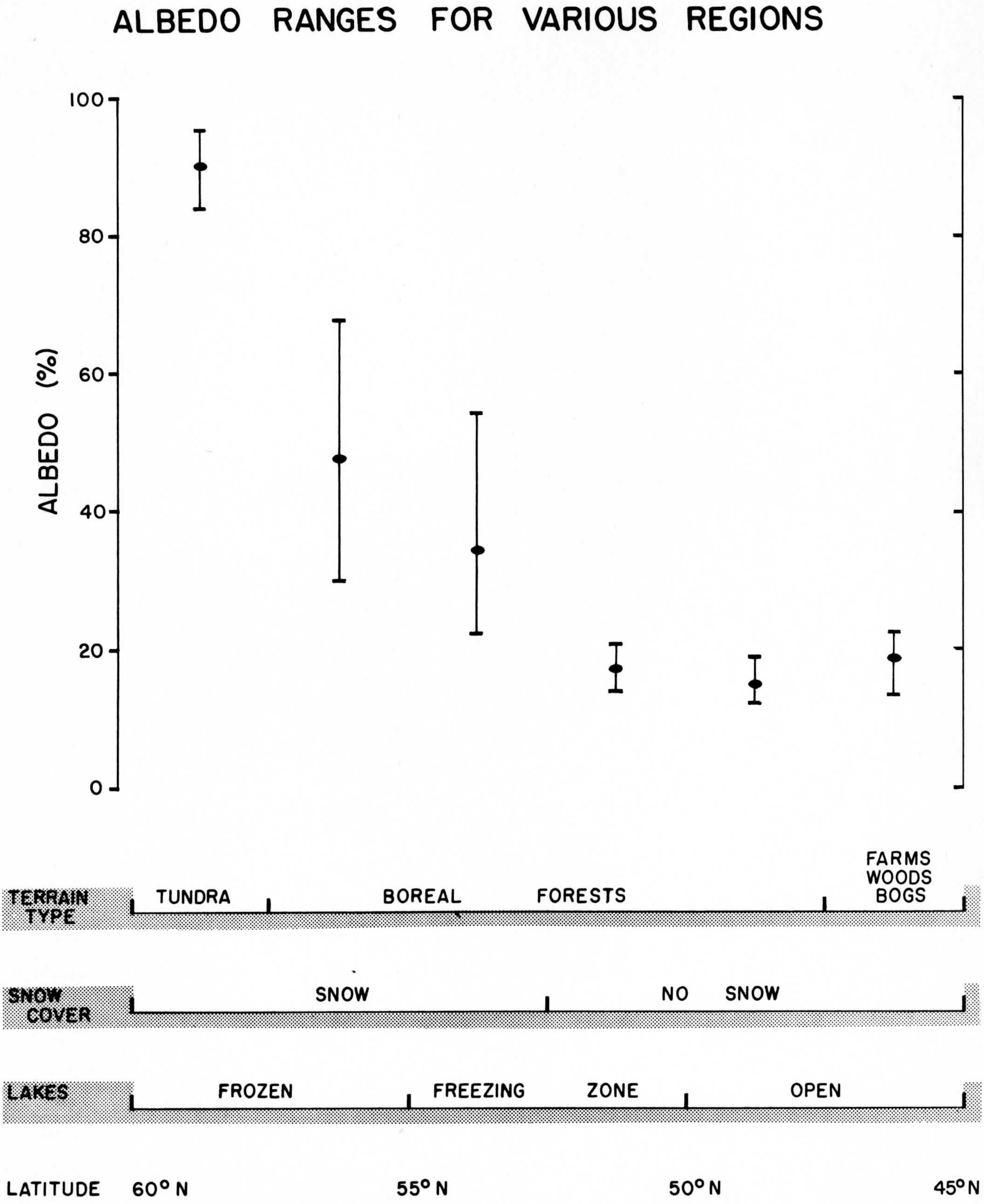


Figure 5 -- Mean and range of albedo values for various terrain types, snow cover, and ice conditions.

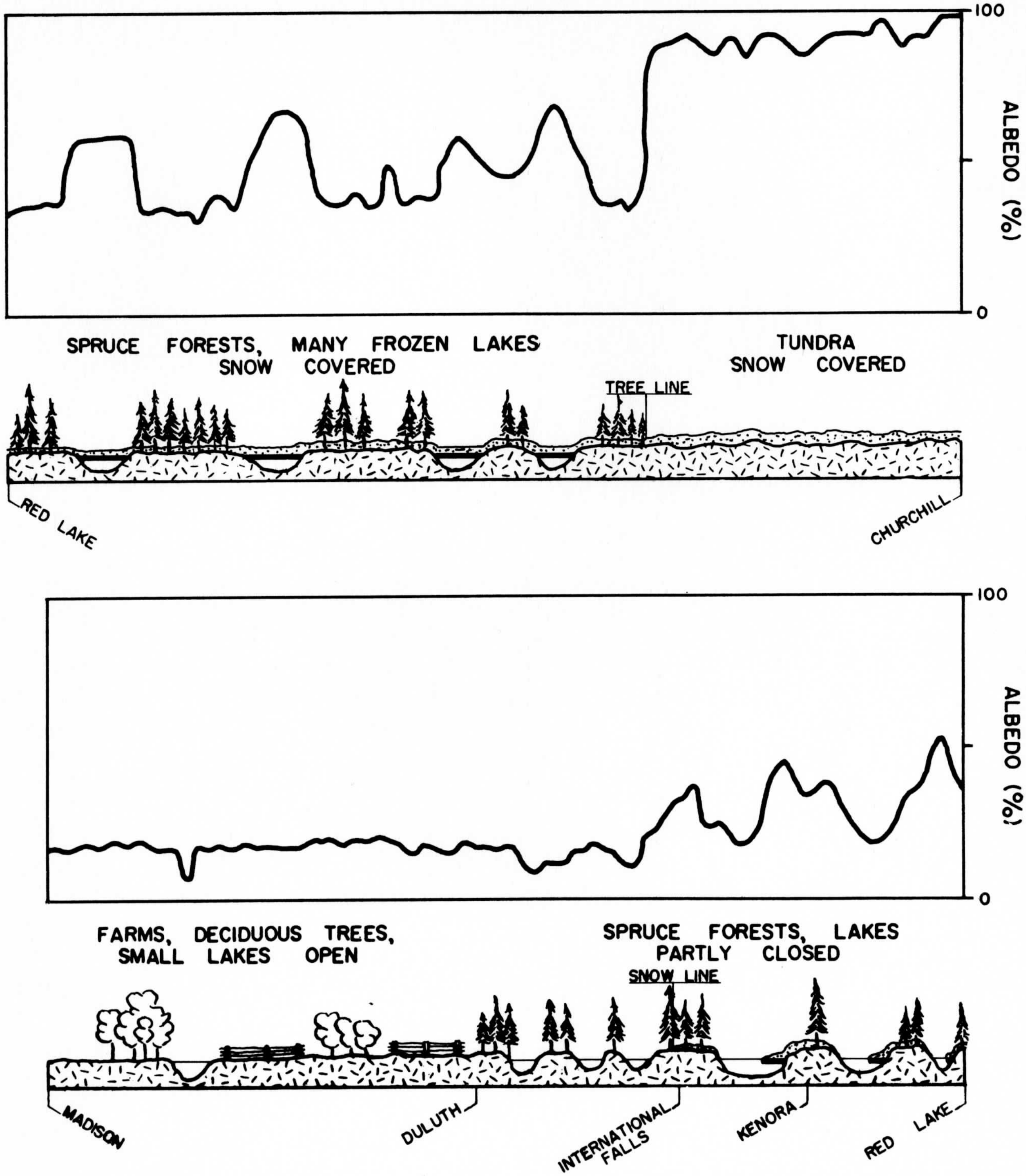


Figure 6 -- Pictorial representation of albedo over various terrain types on a transect from Fort Churchill, Manitoba to Madison, Wisconsin. Actual values taken from the records are shown.

to the masking effect of spruce or other conifers south of the tree line.

From latitude 53° N. south to Kenora, Ontario (50° N.) there was very light snow cover and from this point south to the U. S. border at International Falls, Minnesota only a trace of snow. Not all the lakes in this region were frozen and those that were had only a trace of snow covering. Because of this very light snow cover and the presence of more open water, the average albedo value in this forested region was 34 percent or slightly lower but more variable than the forested region north of latitude 53° N.

The region between International Falls and Duluth, Minnesota has essentially the same type of terrain and vegetation as the region to the north, but there was no snow cover. The albedo of this area was about 17 percent and less variable than north of International Falls. In this region also some lakes were frozen and some were open.

From Duluth to Madison the terrain is characterized by farms, small patches of deciduous trees, bogs, and only a very few small lakes, all of which were unfrozen. The average albedo of this region was about 19 percent and quite uniform, a value in agreement with Bauer & Dutton (1960). This value is slightly higher than that observed immediately to the north because of the preponderance of farmland, which is slightly more reflective than forests.

C. Climatological Significance--an hypothesis

Since the characteristics of an air mass are determined by radiation, heat, and water vapor fluxes across the air-earth interface (Byers, 1959), the rate of air mass formation and subsequent modification is a function of the nature of the surface and the time the air remains over that surface. In autumn the cold cP air mass of North America forms in a large high pressure area in northwestern Canada. The circulation in this region is such that the air remains there long enough to take on its identifying characteristics.

During the fall months, as the number of daylight hours decreases, the amount of solar energy available to heat the land surface also decreases, and the surface begins to cool. When the first snow of the season covers the land, the albedo changes abruptly. For a surface devoid of trees, such as the tundra, the albedo rises to over 90 percent. This means that there is very little surface heating, and the surface and the air above it will cool rapidly by radiation.

South of the tree line in the boreal forest, on the other hand, the effective radiation surface is no longer the ground itself but the foliage of the trees. The trees absorb a large part of the incoming short wave radiation and emit long wave radiation which heats the air above them. The denser the tree population, the lower the albedo, and the more heat available to heat the air. This results in reduced stability of the surface layer of cold air characteristic of the cP air mass and favors modification of this southward flowing air.

As long as the cP air mass is over snow-covered tundra, its motion is relatively unhindered by the terrain. High albedo precludes modification by surface heating, and in addition, the surface roughness is small, thus reducing surface drag.

In the boreal forest the lower albedo results in an increase in surface heating which, in effect, slows down the southward movement of the air by greatly modifying the leading edge of the cold air mass. Besides this "eroding effect" caused by the increase in available heat, a retardation in the southward movement of this air may result from the increase in the surface roughness of the forest. (Note: Roughness parameters for November computed by E. C. Kung of this department show values of about 1.2 cm. for the tundra region and 71 to 108 cm. for the boreal forest.)

V. Cloud observations

A. Cloud cross-sections

Although the Project FREEZEUP was planned and conducted primarily as an ice reconnaissance, the distribution of cloud types and heights in the vicinity of the lake freezing zone suggested a relation between clouds and lake ice conditions. Hence the film records of portions of the flights were reviewed and cloud types and amounts along the flight tracks extracted from the films. In addition cloud base heights were recorded in detail on some flights. By combining these sources of information it was possible to construct cross-sections of cloud conditions along some of the tracks across the lake freezing zone. These are shown pictorially in Figures 7, 8, and 9.

B. Relation to lake freezing zone

It is apparent from the cloud diagrams that in the lake freezing zone, delineated by arrows in Figures 7, 8, and 9, cloud bases were lower, and convective activity increased sharply. In some cases snow showers indicated vertical cloud development, and in almost all cases there was an increase in turbulence in the lower levels as indicated by the jerky character of the movie film or by observer notes. There remained the question of whether this correlation between cloud development and the lake freezing zone was fortuitous or whether there was a physical relation between the phenomena. To answer this question it was first of all necessary to examine the surface weather maps of the area on the days when observations were made in order to determine whether or not the observed cloud forms and precipitation were associated with the plotted circulation patterns

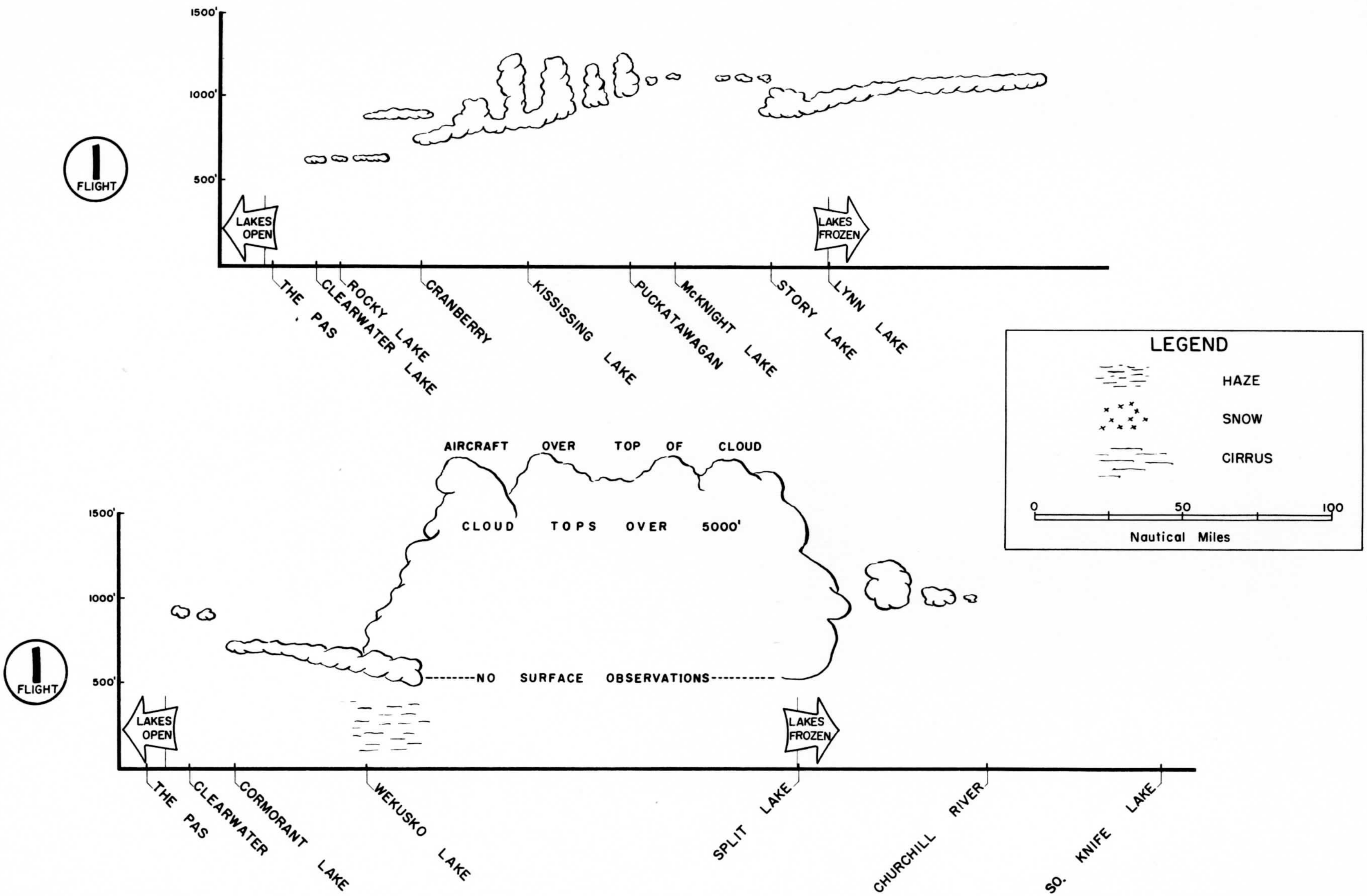


Figure 7 -- Distribution of clouds across the lake freezing zone on 24 October 1962.

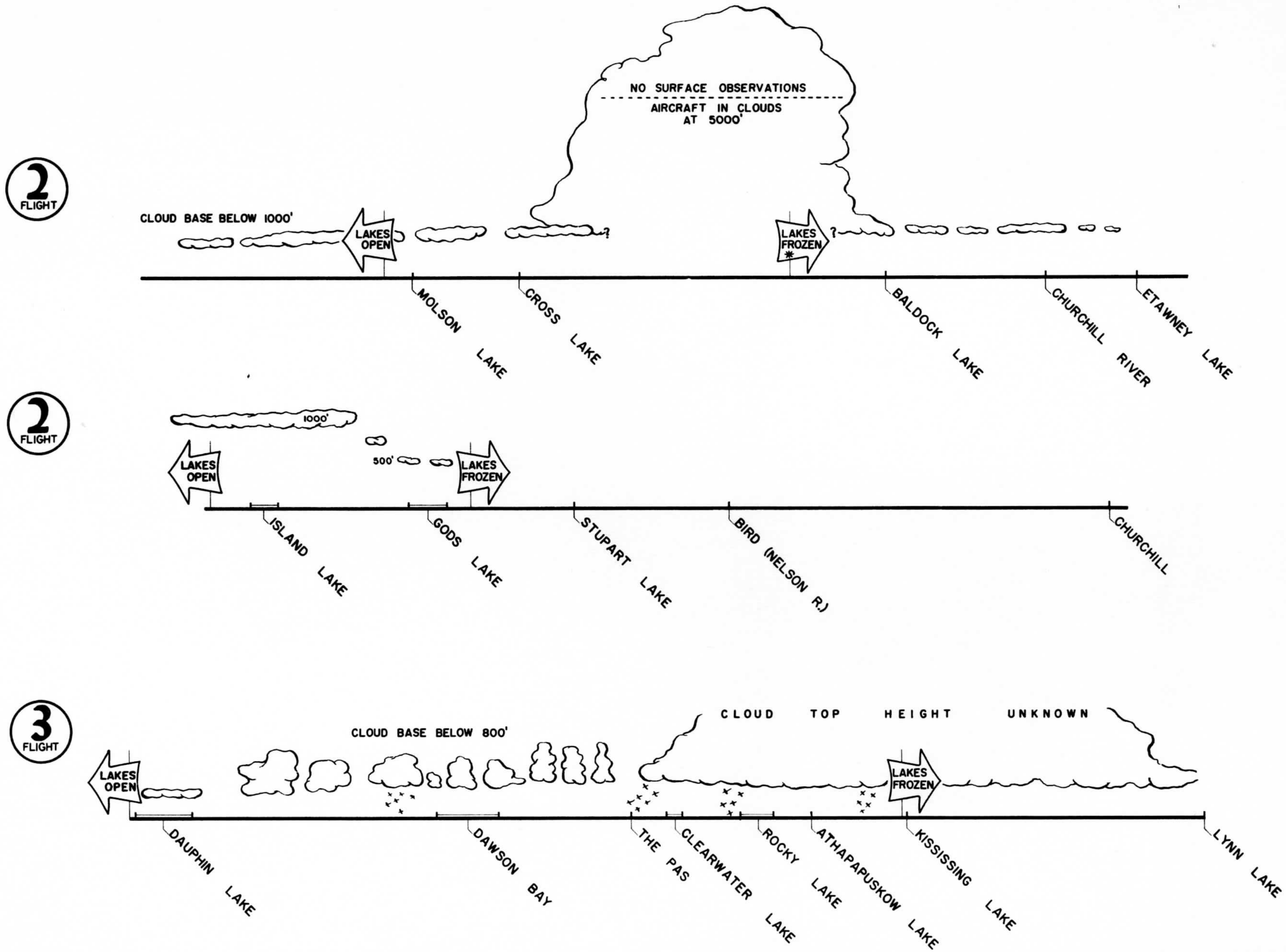


Figure 8 -- Distribution of clouds across the lake freezing zone on 26 October and 3 November 1962.

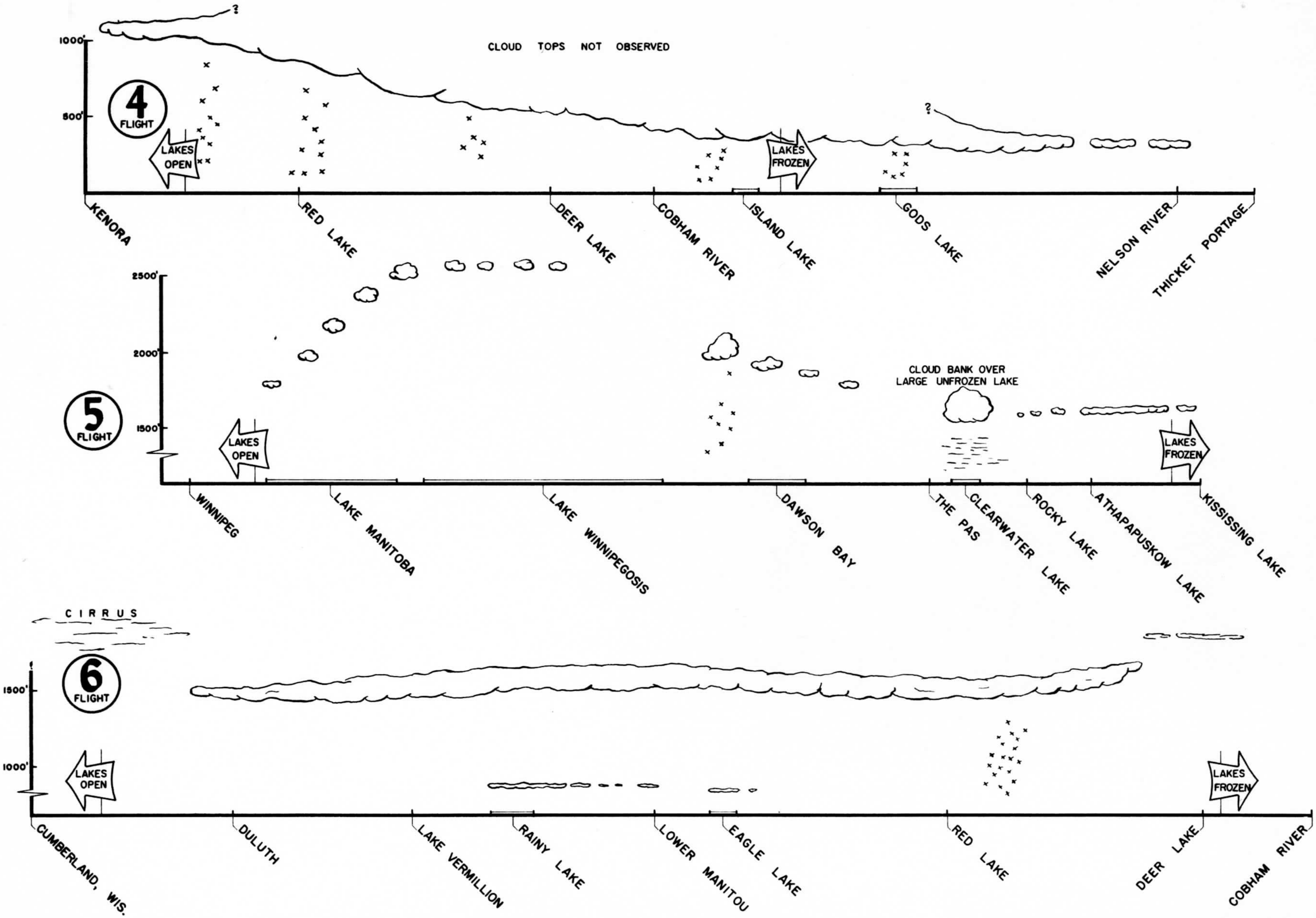


Figure 9 -- Distribution of clouds across the lake freezing zone on 5, 7, and 8 November 1962.

and frontal activity.

Flight no. 1, 24 October 1961

On this date there was an occluded front plotted from the southwest corner of Hudson Bay to northwest Alberta and coinciding with the lake freezing zone in Ontario and Manitoba. This front was drawn across the ridge and separated a high pressure area in south-central United States from a high in north-central Canada. This front could not be identified on the map for the preceding day but was carried on the map on the day following. It was not clearly related to any low pressure center. It appeared that the analyst had put in the front because of the presence of a band of clouds and light snow and not because of a relation to a circulation pattern.

Flight no. 2, 26 October 1961

The ridge mentioned above was displaced slightly to the east, but no front was drawn on the surface map. There was a warm front approaching the area under observation, but it was more than 500 miles to the southwest. Despite this absence of frontal activity, a similar band of cumulus clouds was observed over the lake freezing zone with clearing to the north and south of the zone (Figures 7 and 8). In neither this nor the previous case did the plotted synoptic situation adequately account for the observed weather.

Flight no. 3, 3 November 1961

During this flight the area observed was under the influence of a large, well developed cyclonic storm which was centered slightly northeast of Lake Winnipeg and east of the observation area. There was a large area of precipitation entirely surrounding this low pressure area, and although the clouds were best developed in the vicinity of the lake freezing zone, no great significance could be attached to this. The weather observed on this flight could be attributed almost entirely to this cyclonic storm.

Flight no. 4, 5 November 1961

At the time of this flight there was a high pressure area in west-central United States which dominated the entire mid section of the continent. There were fronts along the east and west coasts, but none in the central part of the continent. The clouds and snow showers associated with the lake freezing zone (Figure 9) were not clearly attributable to any major circulation feature on the surface map.

Flight no. 5, 7 November 1961

The observed area of scattered to broken clouds over the lake freezing zone was about 300 miles behind a cold front that passed through the area the previous day. There was an area of light precipitation trailing behind this cold front which approximately coincided with the lake freezing zone. Although it cannot be positively stated whether the cloud pattern was related to the recent cold front passage or to the lake freezing zone, the conclusion that both effects were operating seems justified.

Flight no. 6, 8 November 1961

By the next day another frontal system had developed to the west of the observed area. At the time of the flight the front was about 300 miles west of the observed track and no precipitation was shown on the map along this track. There was continuous low cloud cover (mostly stratus) across the lake freezing zone (Figure 9). A few snow showers were observed in the northern part of this zone. Skies were clear to the north and south of the zone. The clear area to the north was of particular interest because the occluded portion of the plotted front trended eastward along a trough at the northern end and about 100 miles north of the northern edge of the lake freezing zone. Horizontal visibility in this region was excellent, and any significant cloud masses would have been readily visible to the observers, yet they reported none. Furthermore the movie film record of the flight which included the horizon and some sky while the aircraft was on a north heading across this northern boundary revealed no clouds to the north. It is concluded that clouds and precipitation observed on this flight were not attributable to any circulation feature on the surface weather map.

C. Climatological significance

In four out of the six flights for which cloud cross-sections were constructed (Figures 7, 8, and 9) the observed cloudiness and occasional snow showers which were consistently associated with the lake feezing zone were not related to cyclonic storms or fronts. It is suggested that the cloud distribution and particularly the frequent convective nature of the clouds were caused by the horizontal temperature differences of the surface in the lake freezing zone. These differences were due to: (1) the existence of unfrozen lakes which are necessarily above 0°C interspersed in partly or completely snow-covered terrain the surface of which was well below 0°C, and (2) differential heating of the surface as demonstrated by the high variability of albedo in this zone (Figures 5 and 6). The unfrozen lakes were losing heat rapidly to the colder atmosphere and thus inducing convective activity. Moisture was also being added to the lower atmosphere from the free water surfaces. North of the lake freezing zone, the albedo was uniformly high and no open water existed. Hence the atmosphere tended to be stable and was not receiving water vapor from below. South of the lake freezing zone the albedo was more uniform but low; however this region was not yet dominated by cold air so that convective activity was less, and more moisture was required to form clouds.

It is suggested that the lake freezing zone is a region of rapid air mass modification. Extensive open water areas coupled with the convective activity produced by relatively warm surfaces under a cold air favors the rapid addition of both heat and moisture to the relatively thin cP air mass encroaching from the north. Thus the lake freezing zone may be considered as a major climatic control, and, in a sense, a barrier to the southward migration of the continental polar air mass.

ACKNOWLEDGEMENTS

The success of this aerial reconnaissance was due in no small part to the skillful operation of the P2V aircraft by Joe Jackson, Jr., Lt. USN. and his crew. The authors are also indebted to James A. Larsen, Bernhard Lettau, M. E. Sabbagh* of the University of Wisconsin and Victor W. Sim of the Canadian Department of Mines and Technical Surveys who with the authors served as aerial observers on the flights. The RCAF personnel at Fort Churchill and Winnipeg aided the project materially by making hanger space available for servicing the aircraft. The staff of the Defence Research Northern Laboratory at Fort Churchill provided transportation and other services for project personnel at Fort Churchill. To all of these people we express our gratitude.

Finally we wish to acknowledge the generous cooperation of the Canadian government in allowing us the use of the airfields and facilities at Fort Churchill and Winnipeg and in permitting the reconnaissance flights over Canadian territory.

---

*Now affiliated with the University of California.

References

1. Bauer, K. G. and J. A. Dutton, 1960. Flight investigations of surface albedo. University of Wisconsin, Dept. of Meteorology, Technical Report No. 2, Contract No. DA-36-039-SC-80282, Madison, Wisconsin.

2. ________1962. Albedo variations measured from an airplane over several types of surface. J. Geophy. Res., 67:2367-2376.

3. Bryson, R. A. and J. F. Lahey, 1958. The march of the seasons. University of Wisconsin, Dept. of Meteorology, Final Report Air Force, Contract No. 19-(604)-992, March 1958.

4. Budyko, M. I., 1958. The heat balance of the earth's surface. Off. of Tech. Services, U. S. Dept. of Commerce, Washington 25, D. C.

5. Byers, H. R., 1959. General Meteorology, 3rd Edition. Chap. 14, McGraw-Hill Book Company, Inc., 325-342.

6. Dutton, J. A. and R. A. Bryson, 1962. Heat flux in Lake Mendota. Limnol. and Oceanogr. 7 (1): 80-97.

7. Miller, D. H., 1955. Snow cover and climate in the Sierra Nevada, California. University of California publications in geography, Vol. 11. Univ. of Calif. Press, Berkeley and Los Angeles, 213 p.

8. Ragotzkie, R. A., 1960. Compilation of freezing and thawing dates for lakes in north central United States and Canada. University of Wisconsin, Dept. of Meteorology, Tech. Rep. No. 3, Contract No. Nonr 1202 (07), Sept. 1960.