GROWTH OF WHITE ICE AT KNOB LAKE, QUEBEC - J.A.A. JONES

THE GROWTH AND SIGNIFICANCE OF WHITE ICE AT KNOB LAKE, QUEBEC

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science.

John Anthony Arthur Jones
Department of Geography, McGill University, Montreal.
July 1967

M.Sc. J.A.A. Jones Geography

The Growth and Significance of White Ice at Knob Lake, Quebec

ABSTRACT

The growth of frozen slush or white ice is studied on the surface of the winter ice cover of inland lakes in Central Labrador-Ungava in the East Canadian subarctic, based upon one year's fieldwork and records collected since 1954. Regression and correlation are used to study climatic controls and mapping for areal variation. Heavy snow fall, low minima and calm winds favour growth. Unidirectional winds initiate persistent growth locales aided by the lesser strength of the crystallographically distinct white ice. The early season is most critical. No evidence is found of marked ice expansion or buckling, but cracking is widespread and most common under high diurnal temperature ranges. Excessive growth causes black ice melting, but normally black ice and its controls are dominant. White ice is greatest in downwind snowdrifts, where it creates a peak ice thickness, just as black ice upwind. It is important in snow balance. Central sites and remote measurement improve quality of records.

CONTENTS

FIGURES

PLATES

TABLES

NOTE ON DIMENSIONAL UNITS

Normally measurements have been made in feet and Fahrenheit, except in the laboratory study of crystallography. In each case in the text the unit of measurement is placed first and followed in brackets by the appropriate conversion to metres and Centigrade or vice versa, except where obvious and repetitive. Mass and weight are normally quoted in grams, the distinction between grams mass and grams weight being commonly understood from context. The term density, ρ, is only used in some theoretical formulae. Elsewhere, as in snow survey data, the term unit weight, γ, is the correct measure for what is often loosely called "density", being ρg, the value measured in the field.

"Degree days" and "accumulated degree days" are in terms of the Fahrenheit scale, this being the form in which they are recorded in the weather station archives. One day of mean 30°F comprises two freezing degree days and two such days, four freezing degree days. Throughout, a base of 32°F is taken to distinguish between freezing degree days below and warming or heating degree days above. This thesis is primarily concerned with accumulated freezing degree days, which are also referred to as accumulated degree days where the meaning is clear.

ACKNOWLEDGEMENTS

The writer is especially indebted to: Dr. F. Müller of McGill University for sound advice and encouragement in supervision; Dr. W.P. Adams, formerly of McGill Sub-Arctic Research Laboratory, Schefferville, for suggesting the project, help in the field and permission to use the results of joint crystallographic work; Dr. E. Palosuo of the Institute of Marine Research, Helsinki, for introducing the writer to Finnish literature, and to Dr. E. Kataja of the Sodankyla Observatory, Lapland, for recommending him to Dr. Palosuo; Dr. J.T. Andrews of the Geographical Branch, Ottawa, for advise and for arranging for the data to be transferred to punchcards; Professor B. Greer-Wootten of McGill for formal instruction, stimulating discussion, and together with Don Proczesky for help with the program SYMAP; Professor G. Ratzer, Mrs. Toft and the staff of McGill Computing Centre generally for help in programming; to his colleagues at Knob Lake, Doug Barr, Bob Rogerson, Prince Dyke and Noel Pelletier for help in the field; to the Meteorological Branch, Mr. Dohler of the Marine Sciences Branch, Ottawa, and the Iron Ore Company of Canada for the loan of instruments; Pilot John Prast for aerial photos; to his friends Bruce Findlay, Jim Gray, Simon Ommaney and Dave Nunn for encouragement and discussion; and last and most important of all, to the numerous workers before him who made the whole project possible.

Warm thanks are offered. typists Mrs Klara Soos, Miss Janet Goodacre, Miss Lisa Baile and Miss Jenny Mann.

1. INTRODUCTION

Statement of the problem

Many formulae of both an empirical and a theoretical nature have been developed to explain the growth of a winter ice sheet on inland lakes. Dorsey (1940, p. 409), for example, quotes the empirical formula for x as ice thickness:

$$x + \frac{x^2}{2} = \frac{\tau K t}{L \rho}$$

where τ is the time of exposure in seconds, t the average temperature of the air in °C below freezing, K the thermal conductivity of ice = 0.0057 cal cm^{-1} sec^{-1} deg^{-1}, L the latent heat of fusion = 80 cal g^{-1}, and ρ is the density of ice $\simeq$ 0.9 g cm^{-3}.

A similar equation derived for sea ice was applied with "moderate agreement" to Knob Lake records by Andrews and McCloughan (1961), where:

$$TC = 0.69E + 0.85E^2$$

in which TC is accumulated degree days below freezing and E is ice thickness.

In 1938 Zubov produced the same form of equation (Zubov, 1963, pp. 204-214), which has been widely applied by the Canadian Sea Ice Forecasting Central in Halifax, Nova Scotia (Leahey, 1966):

$$I^2 + 50I = 8\Sigma\theta$$

where I is ice thickness and $\Sigma\theta$ is accumulated negative degree days (°C).

These equations ignore the effect of snow cover. More rigorous, theoretical equations which include snow cover were developed by Assur (1956, p.18) and by Leahey (op.cit.) modifying Stefan's Law. The theoretical formula developed by Kolesnikov is also well known, but Kolesnikov employs so many variables in his equation it is unwieldy to use and it is often impractical to extract or obtain the required data, especially on daily cloud height and cover.

None of these equations take into account the growth of new ice on the upper surface of the ice sheet due to flooding and freezing, that is, the white ice process, either theoretically or empirically. Williams (1967, in press) remarked on this limitation with special reference to Assur's formulae.

As stated by Adams and Findlay (1966, p. 108), the white ice component has varied between 13% and 57% of the total ice thickness at peak ice in 11 years of measurement on Knob Lake, Quebec. It is thus an important component here and surveys on lakes in the vicinity confirm its importance in the area. Yet the factors which control its growth have nowhere been rigorously measured. Outside Knob Lake, the only published work of any detail concerned with the problem is from the Institute of Marine Research in Finland (Palosuo, 1965). Palosuo does not attempt detailed climatological correlation or a study of areal differences.

Nature of the study.

This study concentrates on the white ice of the Knob Lake area. The area lies in the Labrador Trough, a zone of more or less metamorphosed geosynclinal sediments which occupies the central portion of the Labrador-Ungava Peninsula of Eastern Canada. Knob Lake itself is characteristic of the larger lakes of the Trough (approximately 2 km northwest-southeast and 1.5 km east-west, with the long axis oriented parallel to the trend of the Trough). The iron mining town of Schefferville occupies its northern shore. It forms the northern outlet of a small basin (21.6 km^2) in the headwaters of the Kaniapiskau-Koksoak system, which drains to Ungava Bay. The eastern divide of this basin forms the Labrador-Quebec provincial boundary.

The dissertation attempts to evaluate the role of "slush ice" or "white ice" in the development of the winter cover on Knob Lake and a number of nearby lakes. The McGill Sub-Arctic Research Laboratory at Schefferville has carried out a program of ice cover measurement over the past twelve years that has focussed progressively more closely upon the growth of white ice. This is reflected in papers published by members of the laboratory staff, beginning with the work of J.T. Andrews (1962; 1963) on the variability in growth, strength and "quality" of ice cover, and followed by J.B. Shaw's (1965) paper on growth and decay, and by Adams and Shaw's (1966) description of a device to measure thickness without drilling and artificial slushing. Details of the work at Knob Lake are also presented in the Annual Reports published by the laboratory and the Department of Geography, McGill University. These include:

K.J. Jones (1958); J.T. Andrews and C.H. McCloughan (1961); D.J. Fletcher (1962); B. Westlake (1964); W.G. Mattox (1964); J.B. Shaw (1963; 1964); M.L. Bryan (1964); W. Barr (1964); W.P. Adams and J.B. Shaw (1964); D.R. Archer (1966); D.R. Archer and B.F. Findlay (1966); M.A. Bilello, et.al., (1966); and J.T. Gray (1966). Generally, these articles refer to one year only, although Andrews and McCloughan (1961) made a graphic analysis of data accumulated between 1954 and 1960.

The available data includes both measurements of lake cover and climatological data collected by the laboratory in this capacity as a Class "A" Weather Station (v.i.). The investigation was organised in two phases. First, during the eight month ice season of 1965-6 the writer carried out an intensified study of ice cover development on Knob Lake and adjoining lakes. Secondly, this and previous data was standardised, coded and transferred to punchcards for storage and computer analysis (Appendix A).

Current research on ice in Canada is organised under the Canadian National Committee of the International Hydrological Decade (Young, 1967, in press). Under this the Knob Lake basin is registered as a special study watershed.

Development of the program at Knob Lake.

The ice observation program at Knob Lake began on a weekly basis in mid-winter 1954-5 under the leadership of Professor R.N. Drummond, field director of the laboratory, following an agreement with the Department of Transport. The first observation in December 1954 recorded ice thickness and snow cover at a hole opened by axe. In the early years, axes and chisels were the normal instruments for opening up the measurement holes, and often one hole was re-used through successive weeks. At this time similar measurements were made at more irregular intervals on various lakes used as airstrips along the developing Mid-Canada Defence Line. Unfortunately, these records are of little value, since even less is known of the circumstances and location of measurement than for Knob Lake.

The program did not really get under way until the winter of 1955-6, when a more rigid weekly system of measurement was followed and measurements were made for the first complete season. Much subsequent development reflects increasing sophistication in the requirements of the Department of Transport program. From the outset, information had been transmitted by teletype to Montreal after observations. Slowly the format has become more specific and succinct, and in 1965 a number code was established. Concurrently, instrumentation was improved and standardised. In 1958-9 the Meteorological Branch of the Department finally adopted a continuous weekly observation system for the whole of the country and introduced a tool kit of ice auger, ice chisel and a specially designed measuring tape (Department of Transport, MANICE, 1964, pp. 35-9).

However, from the beginning the Knob Lake program has included an ever increasing amount of measurements over and above that required by the Department of Transport. The first addition was the recording of ice "quality", the distinction between the "clear" or "black" ice sheet and the growth of "slush" or "white" ice over it. This required a larger hole for inspection than provided by the standard auger, and although this was used for a while when first introduced, it was soon dropped in favour of a Sandvik 3 inch (7.6 cm) hand operated spoon drill. A mechanical drill was found to be too heavy and suffered from icing.

Table 1.1 lists the available data. From this it can be seen that the first main expansion occurred in 1957-8, when three sites were established for measurement on Knob Lake and designated east, centre and west. For this and the two succeeding years snow and water temperatures were also taken at the three sites. In 1959 measurement were again extended to three sites on Maryjo Lake, a smaller lake conveniently located near the road leading east from Schefferville to Dolly Ridge about 2 km from the township. In 1961 drifted and clear sites were artificially maintained on Knob Lake in an attempt to isolate some of the characteristics of white ice growth (Shaw, 1965). Unfortunately, this was limited by the methods of measurement (Chapter 10). In 1962 lake-side screen temperatures, water temperature profiles and water level measurements were begun.

In 1964 Dr. W.P. Adams initiated a lakewide end-of-season ice survey on Knob Lake and in succeeding years this has been extended to all the major lakes upstream.

Field methods in 1965-6.

During the field season measurements were made of ice thickness and type, snow cover, water level, crystallography, "folding" of the ice sheet, ice and water temperatures, winds and air temperatures.

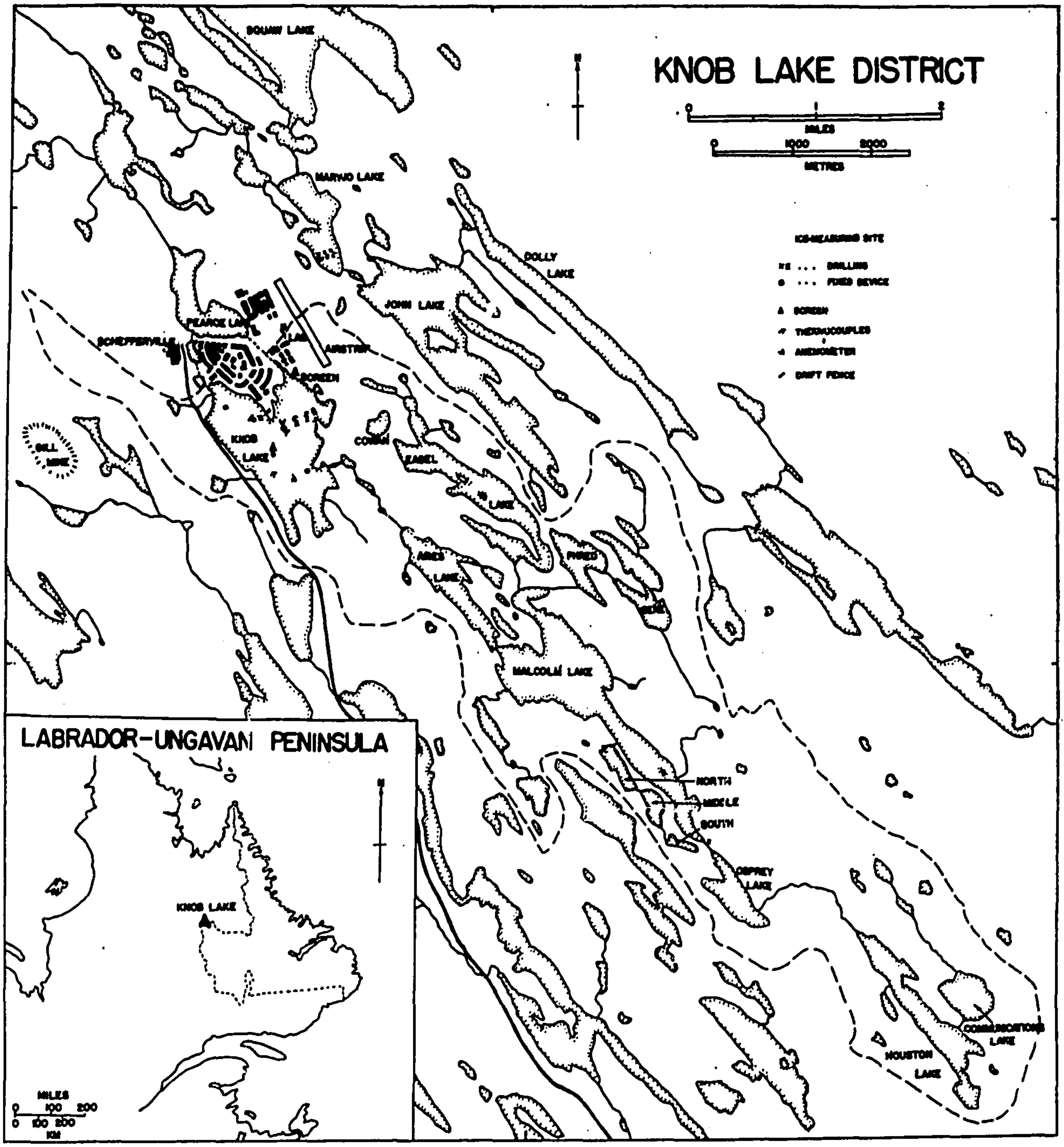

KNOB LAKE DISTRICT
LABRADOR-UNGAVAN PENINSULA
KNOB LAKE
JOHN LAKE
DOLLY LAKE
MALCOLM LAKE
NORTH
SOUTH
HOUSTON LAKE
SCREEN
AIRSTRIP
PEARCE LAKE
0 100 200

Figure 1.1.

Ice and snow covers were measured in the following ways: (1) the three sites on Knob Lake and the three sites on Maryjo Lake (Fig.1.1) were measured weekly, as in previous years, using 3 inch Sandvik spoon drills except at Knob Lake West (see 3); (2) a 400 x 400 ft (120 x 120 m) grid of wooden stakes was established across Knob Lake and measurements of snow cover and white ice increment were taken every two weeks at these stakes through the season; (3) five specially constructed Adams and Shaw (1966) "non-slushing" devices were installed in the ice sheet early in the season on Knob Lake, one being at the west site as in 1964-5; (4) a survey of the lakes of the Knob Lake basin (upstream from Schefferville) was carried out in March, drilling at 200 ft (60 m) intervals on chosen traverses for white ice and at 400 ft (120 m) intervals for total ice; (5) an artificial drift site was created around a paling fence as done by Shaw (1965), but now using a non-slushing device. The clear site was not established because of the difficulty of maintaining it reported by Shaw (1963).

Crystallography was studied from a block of ice removed from Knob Lake in March 1966. Attempts were made to measure vertical movement in the ice sheet by levelling, by standard tide gauge and by the polyethylene tube method outlined by Adams and Shaw (op.cit.). The ice and lake water temperature program was continued as routine from the previous year at two week intervals.

Some definitions.

There is at present no standard terminology used in lake

Table 1.1 AVAILABLE DATA ON ICE AT KNOB LAKE

Year	Snow depth, white ice, black ice, total ice.		Other data for sites West, Centre and East (Knob Lake only to 1959-60)									Weekly diary of lake conditions	Miscellanea
	Knob Lake site	Maryjo Lake site	Hydrostatic water level	Slush	White ice growth up a stake	Snow depth at a stake	Snow density	Water temperature	Snow surface temperature	Snow base temperature	Lake body temperature		
1954-5	"KLC"	-											
1955-6	"KLC"	-										X	Mid-Canada Line sites
1956-7	"KLC"	-										X	Mid-Canada Line sites
1957-8	KLW, KLC, KLE	-						X	X	X		X	
1958-9	KLW, KLC, KLE	-					X	X	X	X		X	
1959-60	KLW, KLC, KLE	MJW, MJC, MJE						X	X	X		X	
1960-1	KLW, KLC, KLE	MJW, MJC, MJE										X	
1961-2	KLW, KLC, KLE	MJW, MJC, MJE			X		X						Knob Lake: clear and drifted sites. Sona Lake data.
1962-3	KLW, KLC, KLE	MJW, MJC, MJE	X		X						(X)	X	Temperatures at John Lake outlet. Sporadic drillings on Squaw Lake and Sona Lake. *
1963-4	KLW, KLC, KLE KLT, KLM.	MJW, MJC, MJE									X	X	End-of-season survey of Knob Lake.
1964-5	KLW, KLC, KLE	MJW, MJC, MJE	X	X	X						X	X	Mid-season and end-of-season survey of Knob Lake. End-of-season survey of Knob Lake basin. Drift site.
1965-6	KLW, KLC, KLE, KLS, KLF, KLD, KLN.	MJW, MJC, MJE	X	X+	X	X					X	X	Fortnightly white ice surveys of Knob Lake. End-of-season surveys of Knob Lake and drainage basin. Drift site. Lake surface meteorological screen. Six non-slushing divices used on Knob Lake.

"KL" indicates Knob Lake. "MJ" indicates Maryjo Lake. W, C and E indicate West, Centre and East sites (see Fig.1.1). KLW, KLF, KLD and KLN are the "device sites" on Fig.1.1. KLT and KLM are located at "thermocouple profile" and "weekly check site, 1963-4" respectively on Adams and Shaw (1964, fig. 1)

\+ Only continuous record in 1965-6.

* Mattox (1964) mentions sporadic measurements for this year on Squaw Lake, John Lake, Attikamagen, Whitegull, Advance, Rauda and Malcolm which are not on file. Nor are the original lake water temperatures on file.

ice literature. It is not the multiplicity of terms used to describe the same phenomenon that is the real problem; time and fortune will, no doubt, whittle these down. But the problem is the use of the same term to describe different phenomena.

The following are the definitions attached to the important terms used in this dissertation with reference to their use by other writers, although these writers may not have originated the terms.

Ice year: used here for the period from first freezing degree day to break-up.

Frozen period: used for the period from freeze-up to break-up. Since break-up is usually quick the fact that a considerable portion of the lake may be open at the time of ice-breaking (v.i.) is of little importance.

First ice: the first appearance of ice at the margins of a lake or pond, commonly ephemeral; equivalent to "border ice" on rivers, used by Michel and Triquet (1966).

Freeze-over: establishment of the first complete or near complete cover of ice on a lake or pond. This may be completely melted or broken up into floes before the final winter cover is established. Occasionally freeze-over may coincide with freeze-up (v.i.), in which case no subsequent opening occurs. In previous publications of McGill Sub-Arctic Research Laboratory it has been defined as "first complete cover" (e.g. Bilello, Adams and Shaw, 1966), but because of the probability of a small, open water polynya (v.i.) remaining for some time after a definite cover is established, as noticed in 1964 and 1965 on Knob Lake, this should be modified to "first generally complete cover". Bilello (1964) used this term to embrace "freeze-up" and defined it as ice from shore to shore, or, on larger lakes, ice visible to the horizon. He noted that it is sometimes confusingly used to describe the growth of ice thick enough to support a man. This is equivalent to the "temporary freeze-up" of some authors. Many writers have not differentiated this event at all, with consequent confusion.

Freeze-up: the final establishment of a permanent winter ice cover. Also termed "permanent freeze-up". Some have used this term to denote the whole period from cooling of the water surface to the establishment of winter ice. "Cooling period" might be a better term for the whole period of ice establishment. Bilello (1964) avoided the term because it is often incorrectly applied to the first time the air temperature falls below 0^{o} C and he criticises Burbidge and Lauder (1957) on this score. Labedeva (1961) refers to "simultaneous" and "discontinuous" freeze-up, which are equivalent to coincident freeze-over and freeze-up and non-coincident freeze-over and freeze-up respectively as used here. It is clearer to retain two discrete concepts defined as simple events.

Initiation period: the pre-freeze-up period, in which the water is cooled and ice forms. It has an indeterminated beginning, which may be taken roughly as the first freezing degree day, i.e. it commences at "freeze-up" according to the erroneous definition mentioned by Bilello (1964). Scott and Ragotzkie (1961) and Archer (1966) have used cooling period in a similar sense. Williams (op.cit.) has termed the same period "fall cooling period or freeze-up period". The writer considers that freeze-up should be restricted to describe the terminal event only and that the period is thus essentially pre-freeze-up, comprising subperiods of "cooling" and "ice-formation".

Growth period: the period of increasing ice thickness. Williams (op.cit.) has used "ice-growth period or mid-winter period". Shaw (1964) and Archer (1966) have used a less specific term "post-freeze-up" for Knob Lake. Scott and Ragotzkie (1961) have used "ice-build-up". Bryson and Bunge (1956) have used "growth period" for the early part of the winter after freeze-up when ice growth is a function of cold air temperatures and low insolation, and have used "equilibrium period" for the following period when slow warming and increased insolation are increasing in importance. On Knob Lake growth, especially in white ice, is frequent during this "equilibrium" and since it also seems rather doubtful that this transitional period represents an equilibrium, the growth period is here divided simply into early and late, as defined in Table 1.2 below.

Wastage period: the final period when higher air temperatures and much increased insolation result in net loss of ice cover and snow cover (Bryson and Bunge, 1956). Williams (op.cit.) has used "ice-melting or spring break-up period" for this. Scott and Ragotzkie (op.cit.), Shaw (op.cit.) and Archer (op.cit.) have termed it simply "break-up period". Archer commences the period at the first decline in snow cover, because he considers this important to the final date of the disappearance of the ice, but it is a poor use of the term and a rather tenuous link. "Wastage period" does not require the logical link. It may be divided into "melting" and "breaking" subperiods, the former characterised by patchy snow and white ice, some bare black ice and the formation of shore cracks as the ice rises owing to the removal of the snow overburden. This

Table 1.2

DIVISIONS OF THE ICE YEAR

Major period	Subperiod	Boundary events
		first degree day
Initiation	cooling	
		first ice
	ice-formation	
		freeze-up
Growth	early	
		virtual limit of ice growth
	late	
		snow melt begins
Wastage	melting	
		continuous shore leads
	breaking	
		break-up

results in shore leads (v.i.) which become continuous during breaking, when candling is widespread and ice floes are shifted by the wind. Melting continues during the breaking subperiod, but is no longer the dominant process.

Break-up: final disappearance of ice (MANICE, 1964); a simple event.

White ice: "uppermost layer of lake ice or sea ice formed during the winter out of thawed or moist snow or slush on the surface of the ice" (Palosuo, 1965). It is generally translucent and bubbly but weakly transparent. An early use of the term was made by Gardiner (1861⁺). Other authors term it "snow-ice" (e.g. Swinzow, 1966), "slush-ice" and "frozen slush". Molchanov (1925⁺) proposed a classification of ice types into (a) transparent crystalline ice, (b) opaque glimmer ice and (c) iced snow, of which the second is equivalent to white ice. Bryson and Bunge (op.cit.) followed Marshall in calling white ice "granular ice formed from snow". Ager (1962) attempted to classify "snow ice" first by colour. He found that darkness or brightness had no clear relation to density and finally adopted a classification based on bubble frequency: abundant, frequent, local, occasional and rare, as in plant communities, and estimating the size of bubble by eye. He found the frequency of bubbles greater than 1 mm diameter significant to density and that most "snow ice" showed densities around 0.890 g cm^{-3}, whether formed by the flooding of bare ice or of snow-covered ice. Strictly, the problem of white ice involves this case of surface flooding when no snow is present. In this case none of the proposed terms is suitable. However, on Knob Lake this type remains undocumented because of the usual snow cover. Also, such a formation would require some force to substitute for snow overburden in depressing the ice sheet below water level.

Black ice: the part of the lake ice cover which forms from the direct freezing of the lake body as the freezing front migrates vertically downwards. It is dark when viewed in situ on the lake, but when removed from the water it is transparent and colourless. At the end of the frozen period it becomes bluish-white and loses much of its transparency because of selective melting along crystal boundaries and elevation of the sheet during breaking. Palosuo (op.cit.) calls this "normal lake ice". It is also called the "original ice sheet" or "blue ice". Unfortunately, Swinzow (op.cit.) uses "blue ice" to refer to ice during wastage when worm bubbles are well-developed under solar radiation. This is a special case of his "ordinary lake ice". Bryson and Bunge (op.cit.), following Marshall, use the terms "flagstone" for black ice formed in quiet water and "columnar" for ice formed in agitated water, but they have no general term. Ager (op.cit.) attributes a density of 0.918 g cm^{-3} to "blue ice". Shumskii (1964) ascribes a maximum density of 0.9168 g cm^{-3} to pure ice, which is rarely achieved in fresh-water ice because of impurities.

Hydrostatic water level: taken here as water level in relation to the upper surface of the ice sheet. It is a measure of slushing potential and has been used by Shaw (1962) and Williams (1963) as a measure of balance, although strictly buoyancy need not be the sole control (Chapter 4). Early records at Knob Lake were made with reference to the black-ice/white-ice interface, i.e. the original lake surface, but for white ice potential it needs to be measured from the ice surface. Unfortunately, data for the spring survey of the Knob Lake basin could not be normalised in this form and it is likely that the measurement would have to be taken from the base of the ice sheet for serious analysis by parametric statistics.

Candling: formed during wastage in black ice, involving radiation melting at the vertical crystal interfaces creating candle-like forms. Knight (1962) said that it occurs in fine-grained c-axis horizontal ice. However, it seems probable that orientation to the bare surface is more important than whether the ice sheet is c-axis vertical or horizontal. The writer has seen secondary development of vertical candles over spring cracks or holes in the ice with perfectly developed hexagonal symmetry about the vertical, long axis. Flagstone ice may not show the truly columnar candling commonly described.

Crystal mosaic pavement: a term proposed here to describe a phenomenon and a stage in which extensive areas of black ice are bare of snow and white ice and show mosaic patterns of flagstone or columnar candled ice at the surface (Chapter 7).

Lead: a strip of open water across or at the edge of an ice sheet. According to MANICE (1964, p.35), it is "a navigable passage through pack-ice", but this definition is not sufficiently embracing.

Polynya: a more or less rounded area of open water remaining in a lake ice cover after freeze-over or freeze-up. Dorsey (1940) has suggested that polynye are a normal occurrence and are the end-phase of the lakeward growth of ice from the shores. He suggests that they may remain open for some time, owing to mechanical turbulence in the water caused by surface winds which maintains an inflow of warmer water up to a critical point when air cooling overtakes heat advection in the water.

CHAPTER 2

GENERAL CHARACTERISTICS OF THE ICE YEARS

The available data on lake cover and climate during the ice years from 1955 to 1966 is summarized in Tables 2.1 and 2.2. The accuracy of the records used in Table 2.1 is questionable in more cases than are actually marked by a query. Those marked by a query are dates which appear rather unlikely from the evidence of freezing degree days. Bilello, Adams and Shaw (1966) considered the 1955 record one whole month out. It is just conceivable, but unlikely, that it is near correct. First ice, for example, occurs after three consecutive nights with air minima below freezing point, although no "degree days" are recorded. The 1958 records show a similar case. Since Table 2.2 is to the nearest week only, according to the form in which the data was extracted for transfer to punchcards, it can only give a crude indication of relationships. More detailed analysis of this aspect could be made, but this is thought sufficient for present purposes.

These tables were used as a partial basis for the tables derived for rank correlation analyses. However, in themselves they show a few interesting features. The highly variable nature of first ice is clear. Excluding the two doubtful years (1955 and 1958), freeze-over normally occurs two weeks after the real onset of cold air temperatures, i.e. when daily means are consistently below freezing, and deviation is slight. Conversely, break-up shows little variation from a mean of four

Table 2.1 DATES OF SIGNIFICANT EVENTS IN FREEZE-UP AND BREAK-UP ON KNOB LAKE

YEAR	Freeze-up: First ice	Freeze-up: Freeze-over	Freeze-up: Freeze-up	YEAR	Break-up: "Unsafe"	Break-up: First movement	Break-up: Clear
1965	6-10	7-10	29-10	1966	27-5	21-5	16-6
1964	5-10	20-10	31-10	1965	7-5	28-5	17-6
1963	8-10	-	2-11	1964	1st wk. Apr.	mid-May	13-6
1962	27-10	27-10	31-10	1963	-	-	18-6
1961	21-10	23-10	7-11	1962	early May	1-6	13-6
1960	15-10	26-10	3-11	1961	1-6	26-5	11-6
1959	24-10	-	29-10	1960	15-5	20-5	4-6
1958	4-10(?)	7-10	(?)	1959	-	14-5	28-5
1957	23-10	25-10	3-11	1958	20-5	24-5	12-6
1956	25-10	29-10	11-11	1957	20-5	11-6	20-6
1955	20-9(?)	-	3-10(?)	1956	20-5	5-6	15-6
1954	-	-	-	1955	7-5	20-5	1-6

Table 2.2 SUMMARY OF CLIMATOLOGICAL BOUNDARY FACT

Year	Flattening inslope of heating degree day curve	I	First acc. freezing degree day	I	First significant increase in acc. freezing dd.	I	Last acc. heating degree day	I	Firs heat degr day
1965/6	24-9	1	1-10	1	8-10	2	22-10	21	2
1964/5	2-10	0	2-10	2	16-10	1	23-10	19	
1963/4	13-9	1	20-9	2	4-10	5	8-11	24	2
1962/3	28-9	1	5-10	4	2-11	4	30-11	21	2
1961/2	6-10	1	13-10	1	20-10	3	10-11	25	
1960/1	7-10	1	14-10	1	21-10	2	4-11	20	3
1959/60	9-10	-1	2-10	2	16-10	2	30-11	16	1
1958/9	3-10	1	10-10	1	17-10	3	7-11	25	
1957/8	27-9	0	27-9	4	25-10	1	1-11	19	1
1956/7	14-9	0	14-9	4	12-10	4	9-11	19	2
1955/6	16-9	1	23-9	5	28-10	2	11-11	23	2
Range of dates (wks)	3		4		4		3		

Dates mark the end of the week in which the event occurred, in accorda been stored. This makes it easier to assign a date to the more subje

I = interval in weeks.

* 8 weeks excluding 1959/60

Table 2.2 SUMMARY OF CLIMATOLOGICAL BOUNDARY FACTORS IN THE ICE YEARS

Year	Flattening inslope of heating degree day curve	I	First acc. freezing degree day	I	First significant increase in acc. freezing dd.	I	Last acc. heating degree day	I	First acc. heating degree day	I	First significant increase in acc. heating dd.	I	Last acc. freezing degree day	Max. accumulated freezing deg. day	Total weeks involved
1965/6	24-9	1	1-10	1	8-10	2	22-10	21	25-3	8	20-5	0	20-5	4635	33
1964/5	2-10	0	2-10	2	16-10	1	23-10	19	5-3	10	14-5	2	28-5	5958	34
1963/4	13-9	1	20-9	2	4-10	5	8-11	24	24-4	1	1-5	3	22-5	5541	36
1962/3	28-9	1	5-10	4	2-11	4	30-11	21	26-4	3	17-5	2	31-5	5438	35
1961/2	6-10	1	13-10	1	20-10	3	10-11	25	4-5	2	18-5	2	1-6	5210	34
1960/1	7-10	1	14-10	1	21-10	2	4-11	20	31-3	6	5-5	4	2-6	5311	34
1959/60	9-10	-1	2-10	2	16-10	2	30-11	16	19-2	13	20-5	-1	13-5	5057	33
1958/9	3-10	1	10-10	1	17-10	3	7-11	25	1-5	1	8-5	4	5-6	5714	35
1957/8	27-9	0	27-9	4	25-10	1	1-11	19	14-3	9	16-5	3	6-6	3949	36
1956/7	14-9	0	14-9	4	12-10	4	9-11	19	22-3	10	31-5	1	7-6	5861	38
1955/6	16-9	1	23-9	5	28-10	2	11-11	23	20-4	6	1-6	2	15-6	4688	39
Range of dates (wks)	3		4		4		3		12*		4		4		$\bar{x}$ = 35

Dates mark the end of the week in which the event occurred, in accordance with the form in which the data has been stored. This makes it easier to assign a date to the more subjective boundaries.

I = interval in weeks.

* 8 weeks excluding 1959/60

to five weeks following the real onset of warm air temperatures and three weeks after the last degree day. More detailed records indicate that freeze-over normally occurs after c.50 freezing degree days have accumulated, whilst freeze-up occurs after c.150. This compares with figures quoted by Williams (op.cit.) for a small lake at Ottawa of 70-100 accumulated degree days for a substantial ice cover.

To obtain a preliminary measure of the factors affecting the gross development of the winter ice sheet, selected characteristics were viewed on a yearly basis for the ten years of tolerably good ice records, 1956 to 1966. This was approached by means of rank correlation, using the bracketing technique, from Tables 2.1 and 2.3. Run of wind, snowfall and sunshine hours, were summed and divided by the length of the frozen period to obtain a measure of average conditions for the winter. Length of the frozen period, i.e. first freeze-over to break-up, was taken rather than "ice year" since the first freezing air temperatures and first ice are very variable events not necessarily important to the general nature of frozen season.

Rank correlation tests were performed on successive rows of the matrix, using the test statistic rank difference χ^2, or χ_r^2. This indicated no relationship between length of frozen period and maximum accumulation of total ice, giving probability $P = 0.80$ that similarities are due to chance. Conversely, length of frozen period against sunshine hours and accumulated freezing degree days showed probable significance levels of approaching 10% and approaching 30%, respectively. No correlation of significance was found with snowfall, snow cover or wind.

<u>Table 2.3</u> GENERAL CHARACTERISTICS OF ANNUAL FROZEN PERIODS

Parameter		1956/7	1957/8	1958/9	1959/60	1960/1	1961/2	1962/3	1963/4	1964/5	1965/6
* Run of wind (miles)	early	10230	20383	24501	15663	17316	20254	17998	20828	17362	18934
	late	37690	41058	45034	36023	41542	45485	53555	43765	38890	35024
	total	47910	61441	69535	51686	58858	65739	71553	64593	56251	53958
	mean	204	268	313	231	258	283	306	261	235	214
Snow fall (w.e.) ins	early	2.78	4.82	3.41	5.60	3.31	5.57	2.76	2.65	5.35	5.85
	(X	0.044	0.072	0.040	0.089	0.050	0.081	0.043	0.045	0.075	0.069)
	late	6.03	6.31	9.08	6.97	3.95	4.68	6.20	6.59	5.74	6.01
	total	8.81	11.13	12.49	12.57	7.26	10.25	8.96	9.24	11.09	11.86
	mean	0.038	0.048	0.056	0.056	0.032	0.044	0.038	0.037	0.046	0.047
Sun-shine hours	early	163.5	93.8	156.0	135.6	112.7	92.3	125.7	63.2	121.0	174.3
	late	805.2	678.1	654.6	838.6	796.7	915.2	758.9	821.6	876.3	686.7
	total	968.7	771.9	810.6	974.2	909.4	1007.5	884.6	884.8	997.3	851.0
	mean	4.1	3.4	3.6	4.3	4.0	4.6	3.8	3.6	4.1	3.4
* Freezing degree days	early	1977	1587	2074	1886	1526	948	1477	1728	1856	1922
	late	3884	2362	3640	3171	3785	4262	3961	3813	4102	2713
	total	5861	3949	5714	5057	5311	5210	5438	5541	5958	4635
Length of season	early	63	67	85	63	66	69	65	59	71	85
	late	171	163	138	161	162	164	169	189	169	167
	total	234	230	223	224	228	233	234	248	240	252

Early and late signify before and after January 1st, respectively.

* To nearest Friday only.

This suggests, as a preliminary hypothesis, that calmer, clearer and colder seasons favour longer frozen periods. Comparison to early freeze-over and to late break-up indicated greater significance for late break-up (not significant and significant at the 10% level, respectively) in the length of the frozen period.

When ranks of length of frozen period were compared with ranks of white ice and black ice, neither showed any significant influence. White ice showed a level of c.40% which may be spurious, but equally, might be improved by longer records. Break-up date is the more important limit for length of period and neither black ice nor white ice show any marked relationship to break-up date. On non-statistical grounds, it seems probable that white ice might tend to delay break-up (Chapter 8), although Table 2.4 shows a number of glaring contradictions that suggest that its influence if it exists is relatively weak. Conversely, degree days show a relationship with late break-up at near 30% significance. Since this cannot be acting through the mechanism of increased snow cover or ice thickness, it must reflect spring temperatures. Table 2.2 shows that May is the critical month for the ending of winter temperatures and the beginning of heating degree days. Closer inspection of this table and the raw data confirms a close relationship between cold springs, especially Mays, and late break-up. This was clearly seen in spring 1966. Adding white ice into the degree day/break-up correlation makes no improvement.

Table 2.3 also crudely breaks the frozen periods down into two halves. The hypothesis to be tested was that events during the fall

Table 2.4 YEARLY RANK MATRIX FOR THE CHARACTERISTICS OF THE FROZEN PERIOD

	1956/7	1957/8	1958/9	1959/60	1960/1	1961/2	1962/3	1963/4	1964/5	1965/6
Run of wind (miles per day)	10	4	1	8	6	3	2	5	7	9
Snowfall (inches per day)	7	3	2	1	10	6	7	9	5	4
Sunshine hours per day	3	8	9	2	5	1	6	10	3	7
Accumulated freezing degree days	2	10	3	8	6	7	5	4	1	9
Early freeze-over	8	5	2	8	6	4	7	9	3	1
Late break-up	1	7	10	9	8	5	2	5	2	4
Max. snow KLC	2	8	1	7	8	8	5	3	5	3
Max. white ice KLC	10	6	9	2	8	4	6	3	1	5
Max. black ice KLC	1	5	2	9	3	8	4	6	6	10
Max. total ice KLC	5	8	3	6	1	10	4	6	1	9
Length of frozen period	4	7	10	9	8	6	4	2	3	1

and early winter are more critical for ice growth, especially white ice growth, than events later. This hypothesis is suggested by the experience of former workers; for example, Archer (1966) found the main white ice phases occurred in November and early January 1964/5. Only the relations that seemed likely to be more significant were studied out of the very large number of combinations possible. First, maximum white ice was set against absolute pre-January snowfall for the frozen period. A level better than 30% was indicated. Secondly, maximum white ice was set against relative pre-January snowfall, that is, the amount divided by the number of days in the period to give a measure of the rate of snowfall. This produced a value for χ_r^2 near the 10% level with nine degrees of freedom. This is a surprisingly high level of significance from the crudity of the classification. No correlation was found between later snowfall & maximum white ice. It suggests that rate of loading in early season may significantly affect the amount of white ice developed during that winter, more than the absolute amount of fall. To elucidate the problem further, relative and absolute pre-January snowfalls were compared to white ice thickness around January 1st. For this absolute snowfall approached the 10% level and "rate of fall" the 5% level. This is a considerable improvement, which would be natural to expect. It is interesting that no correlation whatsoever was found between accumulated degree days and white ice ranking.

Taken together the correlations indicate that snowfall and in particular the "rate of snowfall" are important in establishing the January thickness of white ice. Subsequent growth does not obliterate this. It may be surmised that this also means that the pattern of white ice growth is essentially established each year in the early part of the season and that later development tends to the same areas. The data used here show this to hold for Knob Lake Centre site. The analysis of lakewide patterns (Chapter 5) studies this more closely.

Conclusions.

The lengths of the frozen periods are primarily controlled, topographic environment constant, by spring weather and date of break-up. White ice growth is strongly influenced by events in the early part of the season, which control the potential though not necessarily the actual initiation, i.e. cracking. The implication is that distribution and growth of white ice may be described by one of the group of statistical distributions known as "more clustered than random", quasi-random or contagious. This is studied more closely in the biweekly records of white ice development on Knob Lake made in 1965-6.

CHAPTER 3

FACTORS IN THE DEVELOPMENT OF THE ICE SHEET THROUGH WINTER

It has been suggested (Shaw, 1963) that there is sufficient persistence in the seasonal curve of ice growth from year to year for ice thickness to be predicted from previous records solely in terms of date. Table 3.1 was drawn up as a preliminary test for this suggestion. In order to standardise the time interval, the table consists of total ice values measured or, in a few cases, interpolated at the end of four week periods counted forwards and backwards from the first measurement in January of each year. Hence, however, the month names are only approximate. Since the sample is small, the range is used as a measure of variance. The figures do, indeed, show a general persistence, but this is superficial. The range of error fluctuates between 29% of the mean in April and 89% in November (excluding October), and although the range of error decreases as a percentage through the growth period, the absolute range tends to increase, with the smallest in December-January and the greatest in March. October-November and May show high variability since they are boundary months.

In effect, date alone is a rather poor criterion in cumulative terms, and this is born out in this chapter, where step-wise multiple regression selected accumulated degree days as the overwhelming explanation for total ice growth. Indeed, Shaw's own graphs (Appendix E, Fig. E.1), contrary to his contention, show a generally lesser scatter for

Table 3.1 TOTAL ICE THICKNESSES IN INCHES AT THE END OF FOUR WEEK PERIODS CENTRED ON THE FIRST MEASUREMENT IN JANUARY

YEAR	JAN	FEB	MAR	APR	MAY	OCT	NOV	DEC
1957	30.0	39.5	40.0	42.5	45.0	0.0	12.5	21.5
1958	32.0	36.0	40.0	41.0	27.0	7.0	18.0	29.0
1959	32.0	41.0	44.5	49.0	33.0	0.0	10.0	22.5
1960	32.0	38.0	43.0	45.0	38.0	0.0	15.0	26.0
1961	34.0	42.0	48.0	50.0	34.0	0.0	8.5	20.0
1962	26.5	33.0	34.5	39.0	34.0	0.0	15.0	24.5
1963	30.5	40.0	44.5	47.0	35.0	0.0	9.5	21.5
1964	32.5	31.5	42.5	45.0	34.0	0.0	14.0	22.5
1965	38.0	44.0	49.0	52.0	52.5	12.0	21.0	23.0
1966	29.0	33.5	35.0	41.0	30.0			
Maximum	38.0	44.0	49.0	52.0	52.5	12.0	21.0	29.0
Mean	31.5	38.0	42.0	45.0	36.5	2.0	14.0	23.0
Minimum	26.5	31.5	31.0	39.0	27.0	0.0	8.5	20.0
Range	11.5	12.5	14.5	13.0	25.5	12.0	12.5	9.0

degree days than for date, without allowing for his curious approximation to a standard error for his confidence limits.

Time is however, important to rate of growth.

When these growth figures are treated as percentage of the preceding month (Table 3.2), a similarity can be seen with a normal growth curve up to April. It is clear that a set of arithmetically curvilinear relationships exists during the growth period between the cumulative elements in nature, in which each successive growth is conditioned by preceding growth. During wastage of the ice a new set of relationships is established. This chapter deals only with the set of relationships in the growth period, using multiple linear regression and introducing time as an independent variable into the equations to give some indication of time dependence. This method of introducing time is not rigorously accurate. Indeed, classical statistical theory requires that the data consist of independent, random samples. The values used here are neither randomly selected nor independent by virtue of autocorrelation through time. Strictly, the data require a full time-series analysis.

The data were "normalised" to satisfy, at least in symmetry, the characteristic properties of a normal, Gaussian distribution in order to apply covariance and regression analysis. In no case did regression residuals show any patterning indicative of an unexplained curvilinear relationship.

The climatological data was summed from Friday to Friday, so that it referred to the same time periods as the lake cover records, before it was transferred to punchcards. The two sets of data, the lake

Table 3.2 RATIOS OF ICE THICKNESSES TO PRECEDING 'MONTH'

YEAR	JAN	FEB	MAR	APR	MAY	OCT	NOV	DEC
1957	-	130.0	101.2	105.0	106.0	0.0	-	172.0
1958	149.0	112.5	111.1	102.5	65.8	-	258.8	161.1
1959	110.2	128.2	108.6	110.1	67.3	0.0	-	225.0
1960	142.2	108.9	113.2	104.8	84.4	0.0	-	173.2
1961	130.9	123.6	114.3	104.2	68.0	0.0	-	235.5
1962	132.5	124.6	104.5	113.0	87.0	0.0	-	160.1
1963	124.6	131.2	111.2	105.8	74.3	0.0	-	226.0
1964	151.4	96.8	135.0	106.0	75.6	0.0	-	160.9
1965	169.0	115.9	111.2	106.1	101.0	-	175.0	109.7
1966	126.1	115.5	92.5	132.3	73.2			
Mean	137.2	118.7	110.3	109.0	80.3	-	-	180.5

cover and the climate, were studied from two aspects: accumulated values over a defined period of time and rates of change. In the first approach, the climatological data was summed, where applicable, to give cumulative weekly records for the frozen periods of each year. Accumulated freezing degree days were used in the original punchcard values, although normally c.150 degree days have occurred before freeze-up (cf. Chapter 2, p.20). In the second, weekly rates of change were obtained for lake cover and accumulated degree days.

Normalisation was performed for the whole of the frozen period (for transformation details see Appendix C), but regression analysis was limited to the growth period for the ice cover, since the controlling factors change at the end of the growth period. The end of the growth period was defined not by maximum ice, but by the last measurement before the first notable decline in the ice sheet. These dates show much less scatter than the dates of maximum ice, which are very susceptible to slight differences in the measuring point around the marker stake. In all years the chosen date fell in May, usually some time before the last freezing degree day.

In the following equations the symbols used are:

T_{ice} = total ice thickness (inches)

W_{ice} = white ice thickness (inches)

B_{ice} = black ice thickness (inches)

K = accumulated freezing degree days

S_{fall} = snowfall in water equivalent (inches)

W = run of wind (miles)

S_h = sunshine hours

S_c = depth of snow cover (inches)

S_l = depth of slush (inches)

T = time period in weeks from Friday to Friday from July 1st

$\sum_{t_o}^{t_m}$ = sum from first appearance t_o to the time considered t_m, applied to accumulated freezing degree days, so that values are in the form commonly recorded

$\sum_{t_1}^{t_m}$ = sum from the beginning of the frozen period t_1 to a time t_m

$\frac{dx}{dT}$ = general form for total accumulation per week, which is the rate of accumulation, where x is any variable

<u>Analysis by multiple linear regression.</u>

In order to make a comparison between the development of the lake cover and the meteorological environment, the records on file at the laboratory and the data collected during the study year were standardised and transferred to IBM punchcards. The data was tested for normality and transformed where necessary to obtain a best approximation to the normal distribution using the computer program described in Appendix B as NORMSTAND. Standard scores were punched out from this correlation and regression performed on the standard scores matrix using the program described in Appendix B as REVATR. The standard scores regression provides "beta" coefficients that can be directly compared for importance, independent of the original units of measurement. These coefficients are available in Appendix C for all equations given below. The regression algorithm followed in REVATR gives a step-wise multiple regression, in which variables are held statistically constant while the variable that offers the greatest improvement in the statistical explanation of the dependent variable, i.e. greatest reduction in the variance of $Y_{computed}$, is introduced into the equation at each successive step.

The data used was limited to one site on Knob Lake that was considered to be a good approximation to the mean lake situation. The site chosen was "Knob Lake Centre" (see map, Fig.1.1). The time span of study was limited to winters 1957-8 to 1965-6, since earlier lake cover measurements were sporadic, and were not taken specifically at Knob Lake Centre site. Gaps in the data used were filled by interpolation. Some periods have extensive runs of gaps in the data, mainly in the black ice and white ice records, the worst being in the study year during April and May, when the unusually prevalent slushing made it impossible to distinguish the ice quality. However, it is felt that intelligent interpolation had sufficient control points to be reasonably representative. The validity of using the Knob Lake Centre record is discussed in Chapter 10.

Cumulative growth.

The accumulated approach was taken first. Variables were selected for the final equations only if the value of Snedecor's F statistic for the variable exceeded the tabled value for the 1% fiducial level, i.e. if there is less than 1% chance that the relationship found is not significant. In the first regression the variables included were total ice thickness as the dependent variable and accumulated freezing degree days, total run of wind, total sunshine hours, total snowfall water equivalent, depth of snow, depth of slush and time period (in weeks from July 1st) as the independent variables. From this it was found that accumulated degree days gave an almost complete "explanation" of ice growth. The simple regression equation was:

$$T^2_{ice} = - 55.12 + 0.39 \sum_{t_o}^{t_m} K \qquad \text{(eq. 3.1)}$$

with a standard error of the estimate of 0.330 and $r^2 = 0.897$, i.e. 89.7% explanation of the variance. Since regression was performed using standard scores, the standard error both here and in all following equations is in standard deviations of the normalised data. Where the dependent variable is not transformed a value in inches is included in brackets following, but for total ice such a conversion is meaningless.

This is a useful predictive equation. Mellor (1964, p.9) describes a similar relationship found by Assur, who pointed out that the coefficient varies according to local environmental factors. It is similar to the sea ice formula applied to Knob Lake with "moderate agreement" by Andrews and McCloughan (1961) quoted in equation 1.2. The equation appears to be a good fit even at the beginning of the season. Thus, the intercept and coefficient in equation 3.1 suggest that approximately 200 degree days are necessary before ice forms. As mentioned in Chapter 2, the mean for freeze-up appears to be 150 degree days.

The multiple equation gives a little more information. The beta coefficients indicate relative importance, larger values indicating greater importance. In this the subscript z indicates values measured

·on the standardised normal curve:

$$T^2_{ice(z)} = 1.28 \sum_{t_o}^{t_m} K_{(z)} - 0.37 \sum_{t_1}^{t_m} W_{(z)} \; 0.13 \sum_{t_1}^{t_m} S_{h(z)} - 0.10T_{(z)} \quad . \\ - 0.09S_{1(z)} + 0.09 \sum_{t_1}^{t_m} S_{fall(z)} \qquad \text{(eq. 3.2)}$$

Snow cover was rejected as of no real significance. This fuller equation has a standard error of Y = 0.303 and $r^2 = 0.914$. In effect, little is added numerically by the other variables. The negative sign for wind and positive sign for snow fall indicate that the significance of these two variables for encouraging white ice growth outweighs their respective thermal effects on normal ice growth, which are reverse: wind aids cooling and snow hampers cooling. Low winds and high snowfall favour total ice growth by increasing slushing potential. Sunshine hours, as an indicator of the general amount of cloud, also favour ice growth. Sunshine hours hold a more significant place in the black ice equation and this is probably partly due to loss of heat by long wave radiation from the lake cover to the atmosphere under less cloudy skies. But it may also be caused by the common link between a dense cover of low stratus and a warm easterly flow off the Atlantic from a quasi-stationary rotating low pressure area to the southeast. For slush, whilst the sign is intuitively correct, indicating that it is a pre-growth feature for white ice, the value must be viewed with caution since (1) it was very poorly observed until 1964 and depths were not carefully recorded until 1965-6, (2) the data was not satisfactorily normalised. As for all succeeding equations, the absolute residuals from this line showed no clear patterns and appeared random, a good indication of satisfactory explanation.

In terms of the original data, the equation for total ice is:

$$T^2_{ice} = 70.23 + 0.47 \sum_{t_o}^{t_m} K - 0.09 \sum_{t_1}^{t_m} W + 11.31 \sum_{t_1}^{t_m} S_h + 8.06T - 6.35S_1 + 19.53 \sum_{t_1}^{t_m} S_{fall} \qquad \text{(eq. 3.3)}$$

A similar analysis was made for black ice growth using the same variables with white ice added. White ice was not added in the total ice regression to avoid degeneracy, white ice being a component of total ice. Again, an equation could be obtained with high predictive power using only a few of the variables:

$$B_{ice} = 9.64 + 0.51 \sum_{t_o}^{t_m} K \times 10^{-2} - 0.60W_{ice} + 0.65 \sum_{t_1}^{t_m} W \times 10^{-3} \qquad \text{(eq. 3.4)}$$

Snowfall and snow cover were rejected. The equation has the properties $S.E._y = 0.405$ (3.7 in) and $r^2 = 0.837$. In this case, the important negative effect of white ice growth upon black ice growth is clear, although the beta coefficients (given in Appendix C) show that accumulated degree days are nearly three times as important as white ice.

The full black ice equation is:

$$B_{ice} = 2.92 + 0.54 \sum_{t_o}^{t_m} K \times 10^{-2} - 0.59W_{ice} + 0.12 \sum_{t_1}^{t_m} W \times 10^{-2} - 0.04 \sum_{t_1}^{t_m} S_h - 0.01S_1 + 0.09T \qquad \text{(eq. 3.5)}$$

with $S.E._y = 0.385$ (3.6 in) and $r^2 = 0.856$. Nothing of note is added. The signs for sunshine hours and time are curious, but each is near the lower fiducial limit (Appendix C).

The same form of analysis for white ice, using the variables selected for the total ice regression, showed snowfall rivalling accumulated freezing degree days as the major control as indicated by the beta coefficients, 1.18 and 1.29 respectively. In fact, the regression program introduced snowfall into the equation first as the most significant variable in terms of covariance, having an F level of 206.27 compared to 126.17 for degree days. Wind is the third major factor and acts against snowfall; clearly, this is a question of deposition versus deflation, although instantaneous net balance, i.e. snow cover, is of little significance in the overall pattern.

The full equation is:

$$W_{ice} = -6.24 + 0.70\sum_{t_0}^{t_m} K \times 10^{-2} + 3.66\sum_{t_1}^{t_m} S_{fall} - 0.67\sum_{t_1}^{t_m} W \times 10^{-2} \quad \text{(eq. 3.6)}$$

with $S.E._y = 0.496$ (3.1 in) and $r^2 = 0.746$. Slush was not found to be important to cumulative values, although it assumes a major role in rates of change. From the later analyses, especially in Chapters 4 and 5, it would seem likely that the significance of degree days is partially due to linking with high diurnal temperature ranges which may initiate cracking, as well as to freezing surface slush.

Rates of change.

Weekly rates of change in the lake cover parameters showed badly skewed distributions. These could not be normalised, partly because of the presence of negative values which made it impossible to use root transformations. A value of 30 was arbitrarily added to all readings, which then permitted normalisation (details of resulting distributions in

Appendix C). Although this analysis is only concerned with the growth period, negative values may occur for various reasons. They may be due to observer error or to error in measurement caused by choosing a slightly different site in the arbitrary six foot drilling area taken around the marker stake, i.e. by the irregularities in the ice sheet. However, such errors are just as likely to affect increases as decreases (and it should be noted that the device used at Knob Lake Centre site, described on page 140, (in Chapter 10), is just as susceptible to these errors unless rigorously oriented). Similarly, it is conceivable that natural circumstances maycause a decrease. This is particularly so in snow cover. It is also true of black ice that is forced to penetrate warmer water by the overburden weight of snow and white ice. It is less likely of white ice, although the writer and a number of observers at Knob Lake (e.g. Archer and Shaw, pers.comm.) have noted what seems to be slight surface melting of the white ice during the first stages of a flooding phase, when water at slightly above freezing point is spread on the surface.

All regressions performed in terms of rates of growth proved of very low "explanatory" power. The initial regression was made between snowfall water equivalent per week, accumulated freezing degree days per week, mast-level run of the wind in miles per week, and time in the same form as used in the cumulative approach. Time was included since it is clear that there is a continual change in relationships through time. Again, a full time-series analysis was not attempted and time was included as an independent variable as an approximation only to the more complex relationship in actuality.

The overriding importance of time to rates of increase is shown by the set of empirical equations obtained, which generally give greatest significance to date. The exact relative importance may be seen from the beta coefficients given in Appendix C.

White ice was taken as the first dependent variable. None of the variables introduced proved very significant and wind and degree days were discarded as insignificant. The resulting equation was, in order of importance:

$$\left(\frac{d\,W_{ice}}{dT} + 30\right)^3 = 27,910.79 - 13.48\left(\frac{d\,S_1}{dT} + 30\right)^2 + 4978.00\sqrt[3]{\frac{dS_{fall}}{dT}} - 118.17\,T - 3.60\left(\frac{d\,S_c}{dT} + 30\right)^2 \quad \text{(eq. 3.7)}$$

This has a standard error of Y = 0.881 and an r^2 of only 0.124. The simple correlation coefficients (Appendix C) confirm the poor correlations. The magnitudes of the intercept and coefficients could have been reduced by a more appropriate addition of 10 rather than 30 to the lake cover parameters during normalisation, but this would not materially alter the correlation, since it is based on covariance.

Statistically, this is a very weak relationship, and the deficiency must be accounted for. It may be due to a single factor or a group of factors not considered, a lag effect in the parameters considered, or to poor records. The first possibility suggests a spatially acting process such as localised cracking and folding. This was studied more closely on the basis of a series of maps of distributions in the winter of 1965-6 (Chapter 5), and of water level records (Chapter 4). The second possibility was explored by "advancing" the climatological records, so that, for example, white ice growth was correlated with the snowfall and snow cover of two weeks before, i.e. the week before that to which they refer (v.i.). It is unfortunate that, in fact, the third possibility may be important. The quality of measurements is most sensitive here: summing over slightly longer periods might improve this deficiency.

Qualitatively, however, the equation is interesting. Time and rate of snowfall are of roughly equal significance and account for 80% of the explanation achieved. The relationship to slush and snow cover appears to be essentially a secondary one in which an increase in white ice involves the creation of slush and a reduction in snow, i.e. these appear to be only semi-independent variables for most of the time. But, as shown in Chapter 4, rate of snowfall is not the basic cause. The basic cause must be cracking. Again, it is interesting that the number of degree days each week is rejected as a cause. It is not severity of temperatures so much as high diurnal ranges that initiate cracks. A useful addition to the analysis may thus be the range of daily temperatures.

A similar procedure was applied to total ice and black ice for comparison. Both showed poor explanatory power in terms of the independent variables considered. Thus, regression was run considering time period and rates of change or accumulation in snowfall, run of wind, degree days and snow cover. White ice was added as a variable in the black ice regression, but was excluded from the total ice regression as before.

Black ice showed the following relationship:

$$\log_{10} \left(\frac{d\,B_{ice}}{dT} + 30 \right) = 1.59 - 0.16T \times 10^{-2} - 0.19 \left(\frac{dW_{ice}}{dT} + 30 \right)^3 \times 10^{-5} \qquad \text{(eq. 3.8)}$$

Degree days, run of wind, snowfall and snow cover were found to be insignificant. These parameters are either attenuated by or act through the medium of white ice growth. The equation showed a standard error of Y = 0.88 and an $r^2 = 0.19$. Although this is a poor correlation, the equation again demonstrates the important negative effect which white ice growth has on the development of normal black ice.

The time factor again proved strongest for total ice:

$$\left(\frac{dT_{ice}}{dT} + 30 \right)^2 = 1381 - 9.62T - 0.08 \left(\frac{dS_c}{dT} + 30 \right)^2 + 0.03 \frac{dW}{dT} \qquad \text{(eq. 3.9)}$$

Here only snowfall and degree days were rejected. This offers $r^2 = 0.18$ and S.E. of Y = 0.78. The beta coefficient for time was 0.39 compared with 0.08 for the next most significant variable, namely snow cover. The correlation with wind is interesting. It probably arises more from the deflating effect than from windchill, although the F level is only 2.17. As a combination of white ice and black ice growth, the rate of total ice growth should be predictable in terms of the factors which favour the growth of these two components. These do not need to be weighted according to the proportions of each type of ice in the ice sheet, because of the reciprocal relationship in equation 3.8, although the theoretical equation would be very much more cumbersome than the empirical.

Lag relationships.

The process of white ice growth requires time to act and its

.course is determined by a group of factors acting over a certain period of time. The analyses described above have considered factors acting in the week prior to each measurement of white ice. This was extended to see whether correlation could be improved by considering the history of the preceding week. The technique is a very crude attempt to grapple with the complex problem of autocorrelation, which has been done more elegantly in time-series and in space-series analysis. The two approaches, rate of accumulation per week and total accumulation from the beginning of the season, were again used. In both cases the level of explanation for white ice growth was reduced, indicating clearly that, whilst history is important, lag relationships are limited amongst the parameters used.

This was begun by comparing white ice to period and to the values for accumulated snowfall, wind, degree days, snow cover and slush. For cumulative growth the multiple correlation coefficient, r, was reduced from 0.864 to 0.808. Snowfall, wind and degree days were again selected as the major significant variables, with previous snow cover added as of marginal importance. Slush and date were of minimal significance. As in the previous cases, time is partially implicit in the cumulative values themselves. The subscript p indicates values of the previous week. The equation is very similar to equation 3.6, except that degree days are displaced, which suggests that probably the influence of snowfall is larger than that of degree days, which is more important to final freezing, i.e. in the week before measurement. But this is only a change in relative importance superimposed on generally poorer correlations. Snowfall the week before is not any more important than snowfall in the week in hand.

$$W_{ice} = 0.78 + 4.49\sum_{t_1}^{t_m} S_{fall,p} - 0.61\sum_{t_1}^{t_m} W_p \times 10^{-2} + 0.48\sum_{t_1}^{t_m} K_p \times 10^{-2} + 5.47S_{c,p} \qquad \text{(eq. 3.10)}$$

Equation 3.10 has a standard error of $W_{ice} = 0.59$ and $r^2 = 0.65$. Significantly, all correlation coefficients against white ice were reduced including that for snow cover. At the time of the white ice measurement snow has $r = 0.49$, compared with $r = 0.41$ for one week previous. This implies that there is no commonly determinable lag from one week to the next between snow accumulation and white ice growth such as was suggested as an hypothesis by Andrews and McCloughan (1961). Although in Chapter 4 the two major slushing phases on Knob Lake in 1965-6 are correlated with the culmination of periods of above average snow accumulation, this affects only two or three weeks of white ice growth each year and the relationship is not a smooth curve but stepped. Thus in the general case through time snow cover is of minor statistical significance.

The rates of growth analysis provides additional information. The empirical equation is:

$$(dW_{ice} + 30)^3 = 29{,}127 - 130.61T + 3625.60\sqrt[3]{\frac{dS_{fall,p}}{dT}} + 6.48\left(\frac{dS_{1,p}}{dT} + 30\right)^2 - 4.68\left(\frac{dS_{c,p}}{dT} + 30\right)^2 \qquad \text{(eq. 3.11)}$$

with $S.E._y = 0.91$ and $r^2 = 0.08$.

The most interesting part of this equation is the change in sign for slush. An increase in slush in the previous week generally causes increased white ice, but an increase in snow remains in general statistically unfavourable. Again, only a very small part of the phenomenon is explained.

The analysis was extended to two weeks before the event, in search of an optimum period. This gave the following progression of results for simple correlation coefficient, r, beta regression coefficient, , and F level:

Slush against white ice at-a-time:

$r = -0.228$ $\beta = -0.218$ F level = 10.768

Slush one week before white ice:

$r = 0.126$ $\beta = 0.108$ F level = 3.136

Slush two weeks before white ice:

$r = 0.051$ $\beta = 0.070$ F level = 0.896

The results suggest an optimum lag around one week.

Conclusions.

The analyses show the distinctive controlling parameter for white ice growth is snowfall. In black ice, accumulated white ice and in the ice sheet as a whole accumulated freezing degree days dominate. The rates of growth analyses may be strongly affected by the quality of the data, but it also seems that some important variables should be added to the regression. White ice showed the poorest explanation in the three equations in all analyses. One variable that should be introduced here is the cause of cracking and flooding, which is studied further in Chapter 4, although only qualitatively since measurements are not available. Slushing phases usually last about one week or less. No extended runs of residuals of a given sign were found, which would indicate poorer explanation by the empirical equations for certain years or months.

CHAPTER 4

MOVEMENT IN THE ICE SHEET

The cause of cracking.

It has been suggested that snow loading may cause cracking. However, it can be shown that the pressure exerted is far too small: a cover of density 0.4 g cm^{-3} and depth 30 in (75 cm) will exert an overburden pressure, ρgd, where ρ is density, g gravity acceleration and d depth, on the ice of just 29,460 dynes cm^{-2} or 0.029 bars ([illegible] kg cm^{-2}) that is well below its flexural strength.

Dunham (1924[+]) ascribed cracks in the middle of a lake to the tensile strength being insufficient to draw the ice from the shore during contraction with falling temperatures. With temperature rise and expansion, cracking is less likely to occur since the compressive strength of ice is 5-6 times greater than the tensile strength. As stress builds up during expansion it is relieved first by creep deformation and then by shore push or buckling in suitable circumstances before failure occurs.

No measurements have been made of ice stresses at Knob Lake, although a relatively simple strain gauge of the type described by Olkkonen and Palosuo (1958) might be used. In the absence of field data, the magnitude of the pressures developed may be estimated from the formula used by Royen (1955) for the case of rising temperature, given that the ice is contained so that no change in length can occur:

$$p = Eat \qquad \text{(eq. 4.1)}$$

where p is the pressure developed by ice expansion, E is Young's modulus of elasticity ~ 500 kg mm^{-2}, a is the thermal coefficient of linear expansion in bulk $\sim 51 \times 10^{-6}$, and t is the rise in temperature in degrees C. Royen noted that this simplification ignores viscosity and plasticity, which would reduce the pressure, and variations of E with temperature, direction of compression and stress changes. If t is taken as $5^{o}C$, then the pressure developed is estimated as 12.75 kg cm^{-2}. Comparison with compressive strength values quoted by Royen in his paper, 12-70 kg cm^{-2}, suggests that the pressures developed by a $5^{o}C$ rise may be sufficient to cause failure during expansion. But insulation by snow limits the frequency of such fluctuations. From the simple harmonic formula for dampening of the heat wave

$$A_x = A_o . e^{-x\sqrt{\frac{\pi n}{a}}} \qquad \text{(eq. 4.2)}$$

where A is the amplitude of the wave, x the depth considered, o the surface, a the thermal diffusivity and n the wave frequency, it can be shown that a range of approximately $15^{o}C$ ($27^{o}F$) in the diurnal wave at the surface of snow 15 cm (6 in) deep would be required to cause a fluctuation of this magnitude at the ice surface in snow of unit weight γ = 0.4 g cm^{-3}, taking $k = 0.0085 \gamma^2$. This is not an unusual daily range for winter at Knob Lake, at least, at screen level. However, the mean snow depth across Knob Lake through winter 1965-6 was 25.6 cm (10.07 in) according to the fortnightly area survey data. The mean required fluctuation would then be $31^{o}C$ ($55^{o}F$), which is a very exceptional range. This suggests that generally the situation at Knob Lake is unfavourable to expansion cracking.

Royen does not discuss the case of a fall in temperature. However, it is probable that within the limitations of his formula, of which a major limitation is that no account is taken of work hardening due to the variety of crystal orientations, it might also be considered for this case. In this instance, a fall of 1-2°C would be sufficient to exceed the tensile strength quoted by Royen of 2 kg cm^{-2} for granular ice. An amplitude of 10°C in air temperature above the surface of snow 15 cm deep would cause an amplitude of 3.3°C at the ice surface. A 10°C (18°F) range is quite common at Knob Lake. A 25 cm cover would require a 12.5°C fluctuation at the surface, which is not unusual. It is therefore more likely that failure is induced by a fall in temperature than by a rise in temperature.

Many observers have noted extensive cracking occurring across the lake on a clear, sunny morning following a cold night and have tended, erroneously, to ascribe the cause to expansion on heating. A notable case occurred on the morning of January 7th, 1966, when cracking was heard all over Knob Lake and one crack occurred directly through the drill hole during drilling at Knob Lake East site. The following day cracks extending right through the snow cover were estimated to cover the lake at a density of 0.5 per 400 ft. grid square (c.120 m). This was following a night with a low of -46°F rising to -14°F during the day. However, the cause was more likely to be the arrival of the early morning low in the upper ice, which in the circumstances would have a lag of 4-5 hours, than heating from the rather weak winter sun. Somewhat fancifully, Bryson and Bunge (1956) quote Barnes as stating that cracking is first heard at one half the crushing strength and apply this to the "roaring" during early morning warming. This they contrast with evening "twanging" on contraction. But in the case of Knob Lake with its extensive snow cover the morning cracking could probably best be described as "twanging", a more musical sound than "roaring".

Because of the relatively low thermal conductivity of fresh-water ice of $k = 5.35 \times 10^{-3}$ cal $^{o}C^{-1}$ cm^{-1} sec^{-1} at $0^{o}C$, fluctuations in air temperature are transmitted slowly from the surface of the ice sheet downwards. Moreover, the base of the ice sheet must always remain near to $0^{o}C$, the ice/water boundary condition. Differential warming and cooling causes a more complex system of stresses to develop than was considered using Royen's equation. The resulting stresses may be analogous to folding. Frankenstein (1959) has studied the flexural properties of a lake ice sheet from in-place cantilever beam and small beam tests with centre loading. His measurements are important for a consideration of the importance of white ice and will be quoted.

He found that clear(black) ice showed higher flexural strength when the bottom was in tension. In contrast, white ice showed higher strength when the surface was in tension and layered specimens showed a tendency to higher strength in bottom tension, although there was little difference in mean values. The small beam tests showed generally slightly higher values, but the same characteristics. Generalised values from Frankenstein's work are:

	Clear ice	White ice	Combination
surface tension	4.0	5.5 - 7.5	2.0 - 6.5 kg cm^{-2}
bottom tension	5.0 - 6.0	5.0	2.0 - 7.0 kg cm^{-2}

Hence, white ice may have a significant effect upon the flexural strength of the ice sheet. With little or no white ice flexural strength is greater in cases of down-buckling, depression under a snow cover or when falling temperature causes contraction at the upper ice surface. Overall flexural strength is reduced later in the season by the growth of white ice, thus tending to offset the reduced probability of failure with increasing ice thickness. It may also be an important factor supplementing snow drift patterns in causing the persistence of certain white ice locales following initial growth.

Air temperature fluctuations during three winters.

A measure of the causes and likelihood of cracking is needed. In the absence of field measurements, an attempt was made to test the rule-of-thumb determination from the above formulae of a lower critical limit for daily ranges that would be likely to cause cracking over much of the lake. All days showing a range equal to or greater than 12.5°C ($\simeq$ 22°F) at below freezing point were noted. These were found to occur on the following percentage of days per month in 1965-6:

October 0%, November 7%, December 42%, January 19%, February 43%, March 58%, April 20%, May 3%, June 0%.

This indicates December and March as the preferred months for cracking. February follows, but in this case the percentage is slightly exaggerated by a month of only 28 days. December and March were, indeed, the months in which the two major slushing phases occurred on Knob Lake, as shown in the maps of Chapter 5.

A scan was also made of the records for winters 1963-4 and 1964-5 for comparison and in Chapter 5 the information is used in comparing end-of-season white ice maps. The same limit of 12.5°C was taken although no overall mean snow depth is available for these years. It is also easier to compare years. It is likely that mean snow depth was approximately the same for 1964-5 and less for 1963-4. The percentages of occurrances were:

1963-4: October 0, November 7%, December 13%, January 48%, February 21%, March 68%, April 33%, May 0, June 0.

1964-5: October 0, November 33%, December 23%, January 36%, February 61%, March 42%, April 50%, May 0, June 0.

The months of highest percentages clearly change from year to year. Whether a corresponding shift is found in white ice phases will depend partly upon snowfall. Snowfall may, for example, have been most critical in the phase described by Archer (1966) in early January, 1965. The implications and limitations of this information are more fully discussed in Chapter 5.

The possibility of buckling.

Buckling is a well-known feature on some lakes. Bryson and Bunge discuss major "pressure ridges" or "reefs" on Lake Mendota, Wisconsin, and described by other authors from elsewhere in the Mid-West and New England. These may consist of rucks of ice three feet high and five feet across, representing an expansion in the ice sheet of 3 ft 6 in (107 cm). The authors cite observations by H.J. Richgels on Mendota in 1953-4 which show relief of compressive strain by rafting onshore, by buckling downwards causing eventual cracking, flooding and new ice formation above, by shearing and overlapping, and by buckling upwards with or without failure. Each case resulted in increased ice thickness near the apex of the fold, either by surface flooding or by black ice growth within the apical angle. Conversely, the outer edges of the ridges showed ice thinning, which may be due to penetration into warmer water and/or erosion by current action. The records of development at the drift site on Knob Lake (Fig. 106) offer an interesting parallel.

No such spectacular features have been reported for the Knob Lake area. However, it is possible that similar processes operate but are dampened by the subarctic climate, that is, by thicker ice, by colder and more brittle ice that cracks before noticeable ridges are formed, by deeper snow cover and perhaps by the nature of the shorelines. Yet they may be important in white ice formation in the area.

The problem was tackled by direct field observation and by indirect analysis of data.

Field measurements.

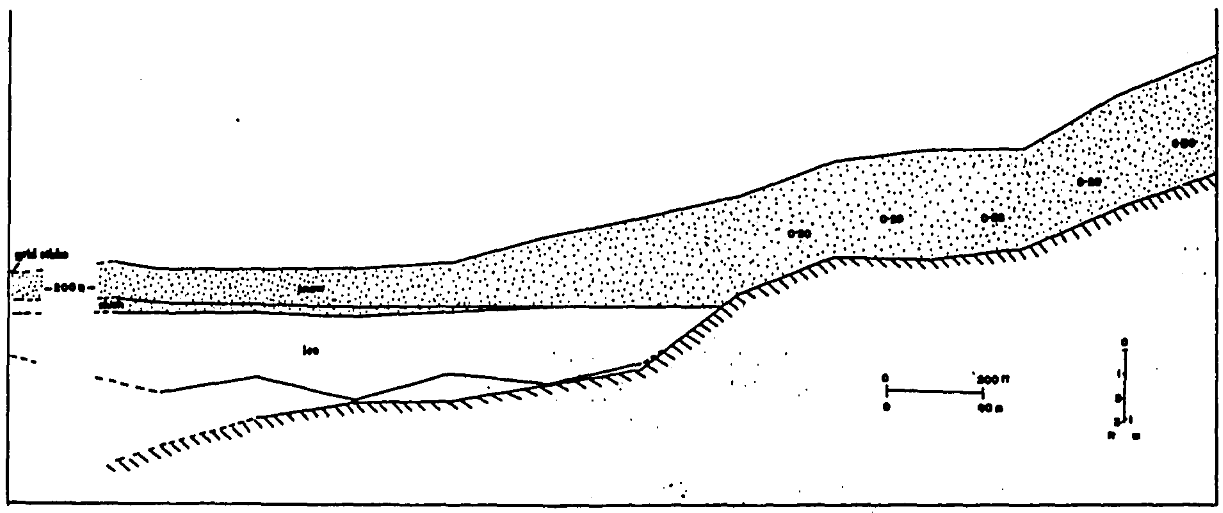
Attempts were made to record movements of the ice sheet by regular observation. Three polyethylene tubes were installed in holes drilled in the ice sheet, following the suggestion of Adams and Shaw (1965). One was installed midway across the mouth of Post Office Bay. A second was installed near the meteorological screen and non-slushing ice measuring device in the centre of the lake. The third was installed at the southern end of the lake, near the entrance to Knob Bay. The approximate water depths at the sites were 25 ft. (7.3 m), 20 ft. (5.8 m) and 35 ft. (10.6 m) respectively. To calibrate, the hydrostatic water level was recorded in relation to the ice surface. The tube was held upright, the lower end sealed and a quart of light machine oil poured into the top end. The equilibrium level reached by the oil was then scored onto the polyethylene tubing and recorded in the field notes. In subsequent readings this was taken as the original water level and variations recorded with respect to it. Variations in oil level were assumed to be directly proportional to hydrostatic pressure. Enough oil was used so that the tube would remain unfrozen and in free communication with the lake body throughout the winter. The upper part of the tubing was curved downwards to reduce the possibility of catching snow.

These tubes were read weekly. The Post Office Bay tube was unaccountably lost before any significant measurements were made. The other two tubes produced rather inconclusive results. Measurement of fluctuations preceding a slushing phase is complicated by a general sinking of the original ice surface due to the accumulation of ice and snow. This trend reduces the amplitude of variations progressively through the season. Rigorous, quantitative measurements of this process require a continuous water level recorder of the type used in stream-gauging and compensation for the upward trend line and dampening effects.

On the suggestion of the Marine Sciences Branch, Ottawa, a Foxboro tide gauge was used in an attempt to measure continuously. The instrument was kindly loaned by the Branch and used in conjunction with the polyethylene tube at the southern site. Charts were changed daily at first, but later only once a week as it became apparent that no measurable variation was occurring. The instrument chart is graduated to measure fluctuations of down to 2 inches (5 cm) in tide height. Assuming the instrument was functioning correctly as it was both before and after installation, it would seem that fluctuations in hydrostatic pressure registering on the diaphragm of the gauge on the bed of the lake were minimal at the site. At least one marked white ice phase was recorded by the tube, four feet away. It seems probable that constant pressure was maintained over the diaphragm during this phase and that the premises on which the instrument was used are invalid; that depression of the ice sheet results in depleting the water column, but that this is offset by the added weight of the overlying mass. Even in the case of externally induced buckling, it is probable that this is also true, the pressure maintaining buckling being analogous to much increased atmospheric pressure in the open water situation.

A more successful device for measuring the vertical movement of an ice sheet has been described and used recently by Arnborg, Peippo and Larsson (1965) in Sweden. It is based on the principle of the Stevens water level gauge. Irecli (1960) obtained measurements of ice movement

Figure 4.1: Shoreline section at southern tip of Knob Bay, Knob Lake, March, 1966. (Unit weight of snow shown)



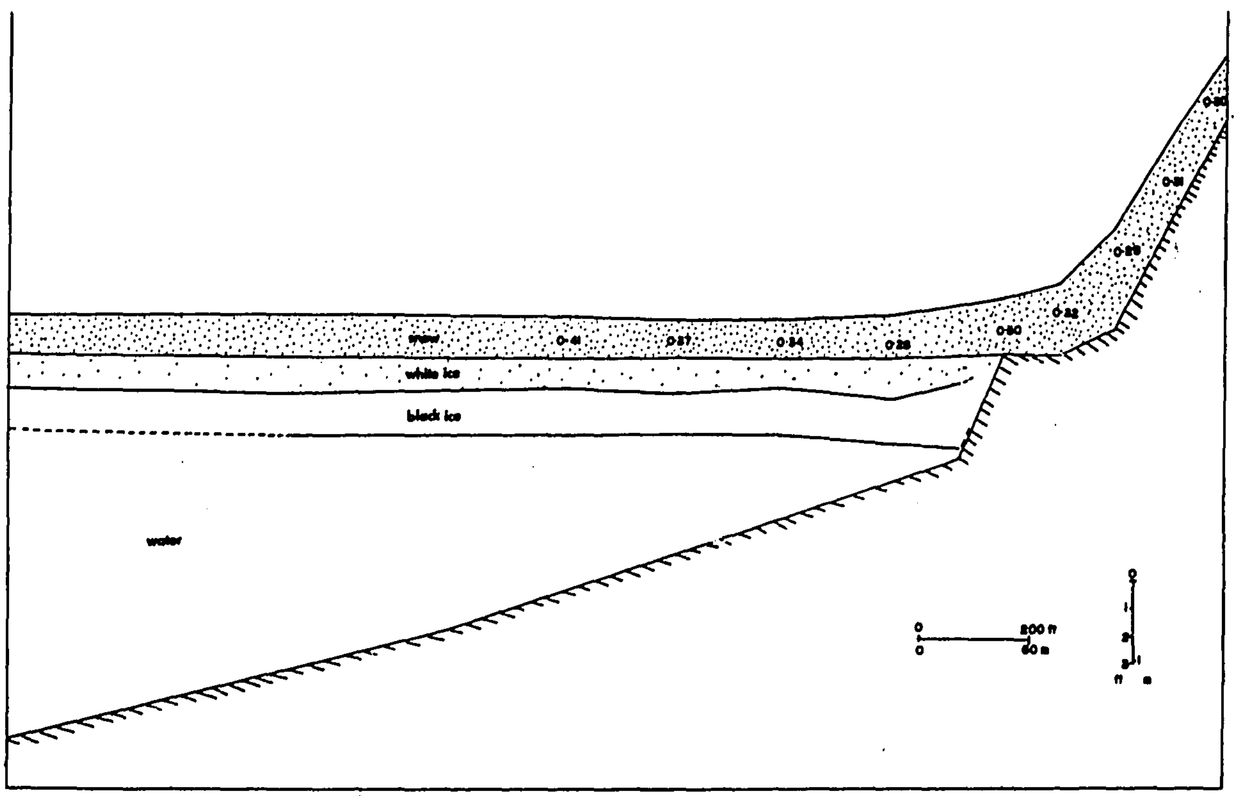


Figure 4.2: Shoreline section at midpoint on western shore of Knob Lake by railway embankment, March, 1966. (Unit weight of snow shown)

with a tide gauge, but in tidal waters.

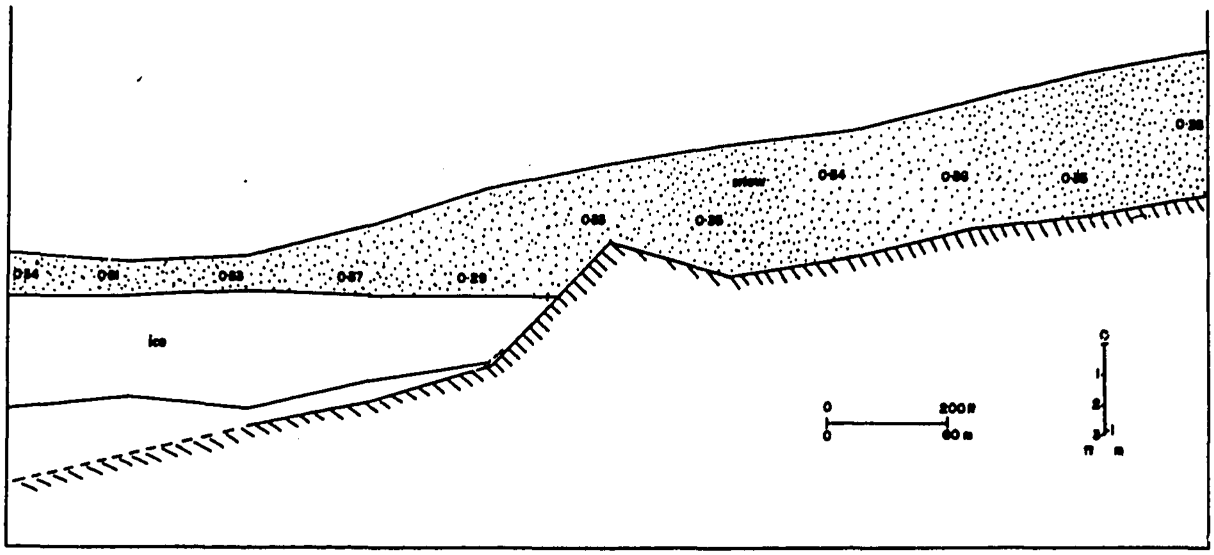
A third field investigation consisted of levelling by theodolite across the lake in early March. Two lines were chosen along the length and breadth, from Guest House Point to Knob Bay and along a line perpendicular to this at the southern tube site (see Fig. 1.1). At the ends of these traverses four shoreline sections were surveyed following a similar method to that used at a point on the eastern shore by Archer and Findlay (1966) in spring, 1965 (Appendix E, Fig. E.2). These are plotted in Figs. 4.1 to 4.4, but the cross traverses are excluded. Plotting failed to give any conclusive evidence of buckling. A suggestion of an up-buckling of c.6 inches (15 cm) towards the shorelines was considered spurious from water level evidence taken a few days later. No significant bending of the ice sheet can be seen in the shoreline traverses. However, they do give an indication of the different shore conditions. None of the traverses shows the gently shelving conditions favourable to ice push, i.e. these shores should favour buckling in preference if expansion is sufficiently great.

The final section of the field investigation involved inspection of shoreline features after break-up.

Evidence from shoreline features.

It has been common to make deductions about the amount of expansion in a lake ice sheet from morphological features on the shoreline, in particular from "ice push ramparts", mounds of material built up in

Figure 4.3: Shoreline section north-south from tip of Guest House Point, Knob Lake, in March, 1966.
(Unit weight of snow shown)



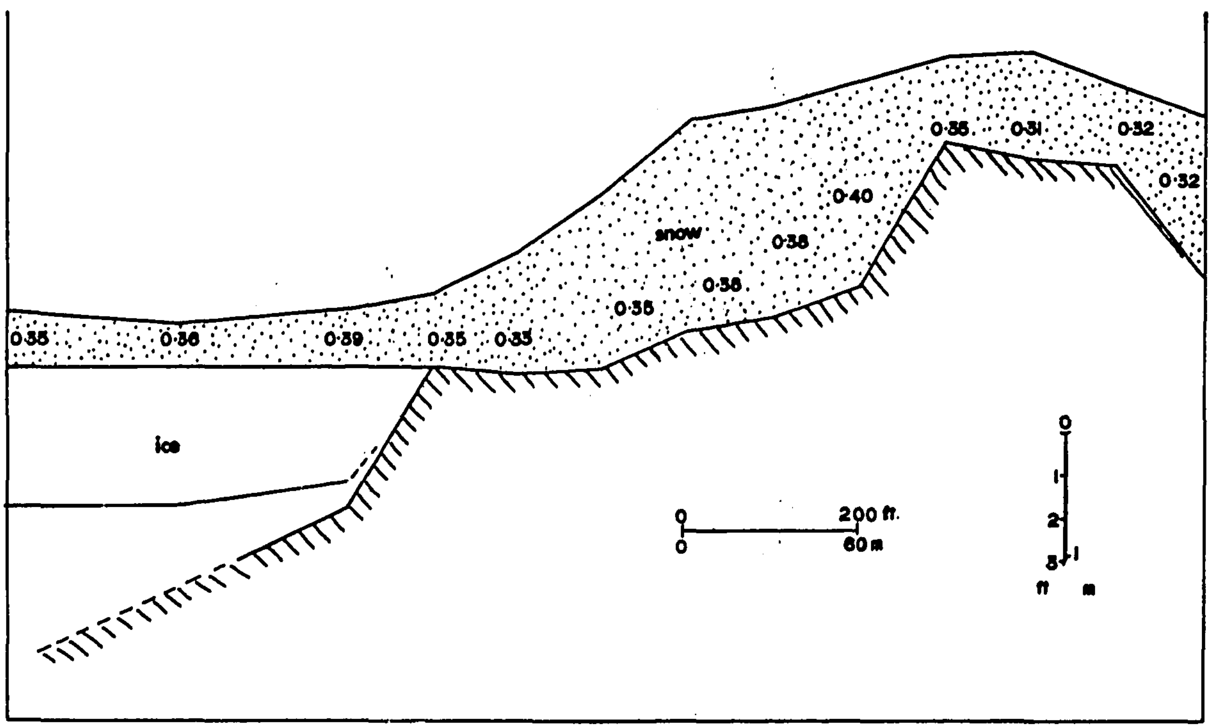


Figure 4.4: Shoreline section at midpoint on eastern shore of Knob Lake, in March, 1966.
(Unit weight of snow shown)

lines roughly parallel to the shoreline attributed to onshore ice-shove. Early observers like Buckley (1900^{+}) in his work on Lake Mendota, tended to favour the expansion of the ice sheet as the explanation of these features. Generally these writers linked ice-shove with fluctuations in air temperature and alternating centrifugal expansion and contraction. Dumble (1858^{+}) recorded a maximum observed expansion of six feet (2 m) during a rise in air temperature of 20°F (rate and ice cover character unspecified), and a maximum contraction of 3 in (8 cm) during a fall in air temperature from 30°F to -20°F (-1 to -32°C). He concluded that temperature decreases are responsible for fracturing the ice and that increases are the cause of shoving. Unequal pressures may be caused by variations in ice thickness, density, albedo and reaction to heat. Goebeler (1891^{+}) propounded the theory that expansion causing "ice ramparts" and buckles was the result of the freezing of secondary ice in fissures and impedement by the shoreline. Elaborating on Goebeler's theory, Krauss (1891^{+}) suggested that the mechanism resulted from cracking caused by night cooling and contraction, freezing of water in the cracks and expansion during the day. This, according to Krauss, explains why buckling normally develops during the day, not at night.

More exacting work has been done on the problem by Zumberge and Wilson (1953), in which they measured ice movement with respect to air temperature on Wampler's Lake, S.E. Michigan. They found that a rise of 1°F per hour for 12 hours on an 8 in (20 cm) ice sheet caused a thrust onshore in unconsolidated glacial outwash containing a few boulders.

Rapid cooling, on the other hand, caused sets of concentric and radiating cracks in the sheet. Note that this was on a lake with virtually no snow cover.

Dumble (op.cit.) noted that a snow cover of over 6 in (15 cm) effectively prevented ice expansion or contraction by providing insulation on Canadian lakes. In Lapland, Hamberg (1917[+]) attributed the lack of ice ridges or ice-shove to the depth of snow. Also working in Canada, Tyrrell (1910) contended that expansion on these lakes was small under a snow cover and that the shore features often interpreted as showing expansion can, in fact, be explained by wind-driven ice floes at break-up. However, Tyrrell considered that when expansion does occur it is greater in the vertical than in the horizontal. His contention should be viewed in the light of recent knowledge of the anisotropic expansion properties of ice crystals that suggest marginally greater horizontal expansion for ice sheets of dominantly c-axis horizontal ice. (Dorsey (1940, p.474), quotes coefficients of linear thermal expansion (α_m) for the unit cell of ice between 0° and $-66^\circ C$ of $\alpha_m = 17 \times 10^{-6}$ for the basal plane and $\alpha_m = 29 \times 10^{-6}$ for the prismatic.) In 20 years of sporadic observations in Canada, Tyrrell claims never to have seen shore push, although ice ridges in the centre of lakes he found common. It is also probable that large amounts of bubbly, white ice such as experienced at Knob Lake may reduce the pushing power of the ice sheet by providing internal release in crushing the bubbles.

Various degrees of wind interference have been recorded. Dybovskii and Godlevskii (1870[+]) reported wind cracking and hummocking on the large inland Lake Baikal. Oak (1955+) for the Great Lakes reports that, when the cover is reduced to 60-90% of the lakes, wind causes pressure ridges of up to 10-20 ft (3-7 m) above lake level or 30-35 ft (c.100 m) below in the ice. Norrman (1964+) also noted ice pans piled onshore causing damage on Lake Vattern, Sweden, which is rarely completely covered with ice.

In Eastern Canada, most workers have favoured wind action as a cause. Ward (1959) describes observations of grounded ice floes on Generator Lake, Baffin Island, in the summer of 1950, although winter activity was not observed. Assuming ice push features are a result of wind action, Matthew (1961) postulated a short partial open water season to explain the absence of ice push features on the Naskaupi and modern shorelines. Peterson (1964a) suggests that the shoreline boulder ridges of the Whitegull Lake area may be due to either the washing out of fines from glacial moraines or lake ice action during the partial open water season, and concludes that ice pans are the most likely cause. Peterson points out that, according to Jones (1958), the partial open water season in the Knob Lake area is only 13 days long. Longer records support the mean of about two weeks.

It is generally agreed that both mechanisms occur, but that they vary in intensity between different areas. This is illustrated in the dialogue by Jennings and Ward following Goldthwait's (1957) assertion that in New England expansion and push could be linked with warm-cold-warm cycles on all but the smaller lakes, less than c.1.2 x 0.4 km across.

Plate 4.1: Site 1, grounded ice on northeast shore of Astray Lake. The lake, still abnormally high, can be seen at left centre. Alder and spruce have been stripped of bark and uprooted. June 25th, 1966.

Plate 4.2: Site 1, young spruce tree c,6 in (15 cm) girth with broken trunk. June 25th, 1966.

Working in the Central Plateau of Tasmania, Jennings (1958) considered both mechanisms and favoured ice expansion, whereas Ward (op.cit.) on Baffin Is. favoured wind-driving.

No features were observed in the Knob Lake area that could categorically be assigned to ice expansion. By contrast, there was abundant evidence at break-up of ice pan damage on the shorelines. Plates 4.1 to 4.4 show grounded piles of rafted ice at two locations on the northeastern shore of Astray Lake, 20 miles south of Knob Lake, observed on the 25th June, 1966, eight days after official break-up on Knob Lake. Three main areas of ice damage were noticed during a canoe trip along this shore. Each one was located at a point where the shore turned southwestward across the long fetch of the dominant northwest winds. Site 1 (Fig. 4.5, Plates 4.1 and 4.2) showed a pile of grounded ice c.250-300 ft (c.90 m) long and 30-50 ft (c.12 m) wide of rafted, candled black ice and disintegrating, round-grained white ice. The shore was heavily covered with vegetation at this point and most of the damage was sustained by trees and shrubs. At site 2 (Fig. 4.5, Plate 4.3) there was less vegetation and a 3 ft square boulder of iron ore had been shifted about 20 ft (7 m) from its original hole in the Sphagnum carpet. No ice remained at this point. But the damage was ascribed to wind action, since (a) the orientation of vegetation damage was similar to site 1 and (b) the grooves cut in the gravel beach by small, shifted stones showed a northwest-southeast orientation and were not directed toward the centre of the lake. The fact that no ice remained may indicate that less ice was piled up here than at site 1. Ice remained in situ at site 3 (Fig. 4.5, Plate 4.4),

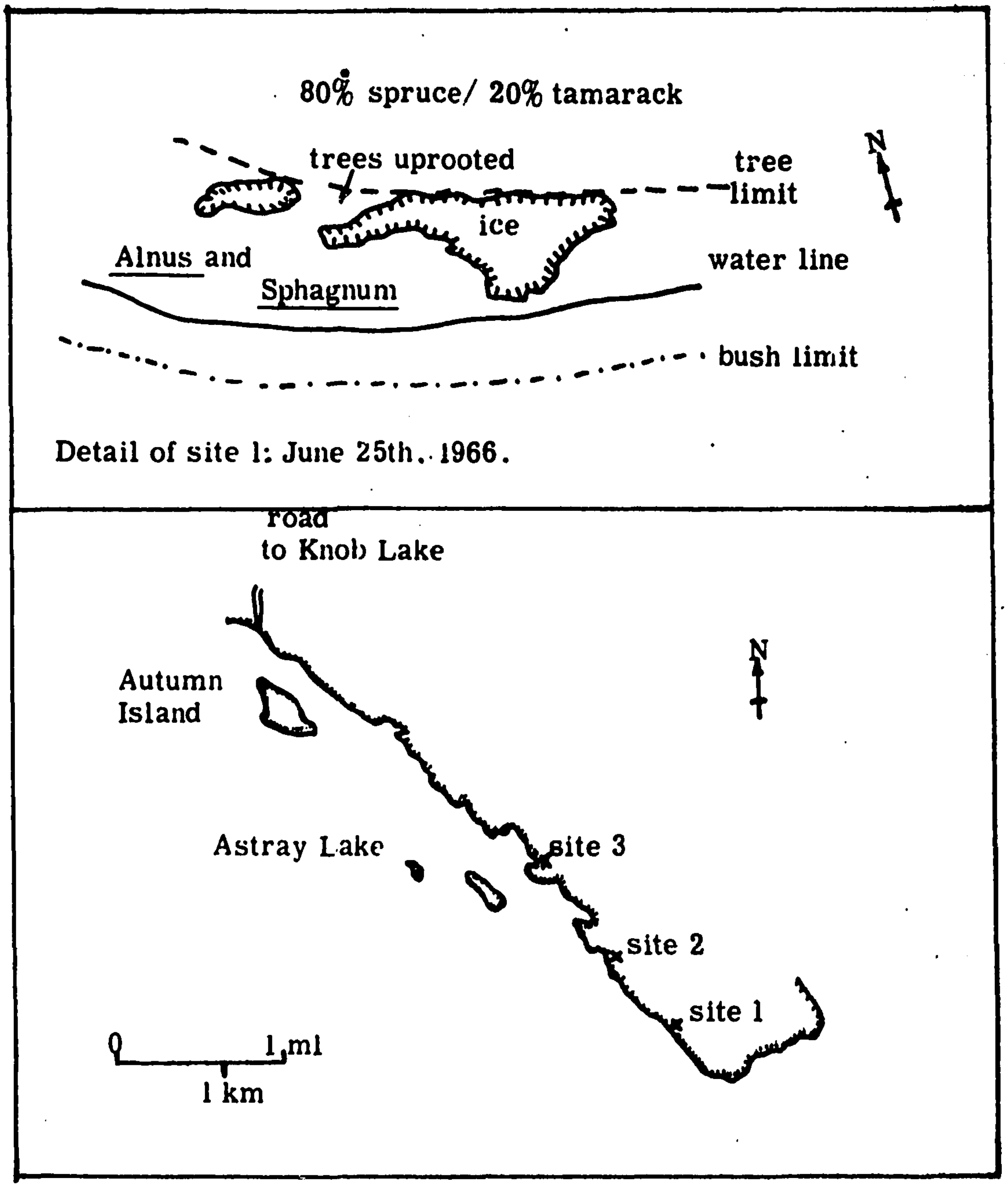


FIG.4.5. Sites of grounded ice.

where it had been pushed 12 ft (4 m) above the current lake level, which from the debris line was seen to be still at maximum. Photographs of similar damage have been published, for example, by Laskar and Strenzke (1941) in Germany.

Plate 4.5 of a point on the downwind shore of Knob Lake was the only damage of any sort noticed there. The vegetation had clearly been dead for some time and the damage had not occurred during the 1966 break-up. The site is in a partially enclosed bay of the eastern shore and does not seem a likely site for expansion damage. From the rather poor evidence, wind action of some form is suggested, either as wind-driven ice pans or as wind toppling the high spruce. Bryan (1965, p.159) concluded that similar vegetation damage at the southern end of Knob Lake had occurred due to ice pans in spring, 1964. He also records minor, gravel features from Dolly Lake and Attikamagen Lake. Similar features to those described by Bryan, less than 6 in (15 cm) high, were observed in 1966 on Squaw Lake and Attikamagen Lake on gently sloping gravel shores. They were oriented normal to the northwest wind, but they may be due solely to wave action at spring high water. According to local inhabitants, this level was at least a foot above normal spring floods in 1966.

Plate 4.6 shows a minor feature observed on the northernmost of the two shallow (less than 10 ft or 3 m deep) lakes immediately west of Knob Lake. It resembles an offshore bar built in silt. However, it was clearly unstable in the open wave environment. It was first observed soon after break-up and disappeared within two weeks. This may be a small replica of the turf pressure ridges described by Hansen (1948-9)

Plate 4.5: Shore damage in cove on east shore of Knob Lake, photographed in July of 1966, but clearly old. It is doubtful whether this damage is due to ice.

Plate 4.6: A small, ephemeral "offshore bar" in sill-developed in the northernmost of the shallow pools west of Knob Lake. It lasted no more than two or three weeks after break-up in June 1966.

in Denmark, caused by minor ice push. Ives (1960) has used the argument that a long open season may destroy ice push ridges. This is probably true in some cases, but it does not appear to explain the lack of large scale features in the Knob Lake area.

Explanation must be sought in other directions. It is clear that size of lake and nature of shoreline are important besides orientation of main fetch with respect to the wind. In the Knob Lake area vegetation generally protects the shores and gently shelving offshore areas dissipate the energy of the waves carrying the ice pans. On other lakes the common shore type is boulder strewn, which resists the momentum developed over the relatively small fetches compared with those available for Peterson's (1964b) ridges on Michikamau and Whitegull. The same gentle shelving might aid expansion shove, if it occurred to any marked degree. It is difficult to make precise, quantitative judgements, since there are so many variables and such little systematic work has been done in this particular field. Each shore must have its own optimum angle for shove to occur. Since no evidence exists of the phenomenon in the Knob Lake area, it may be concluded that expansion is relatively small in magnitude.

Evidence from water level data.

Three surveys were made on a grid pattern over Knob Lake in the springs of 1964, 1965 and 1966. These offer over 250 cases for 1964 and about 120 cases for the subsequent years of measurements of snow depth, ice thickness and hydrostatic water level. In the absence of other

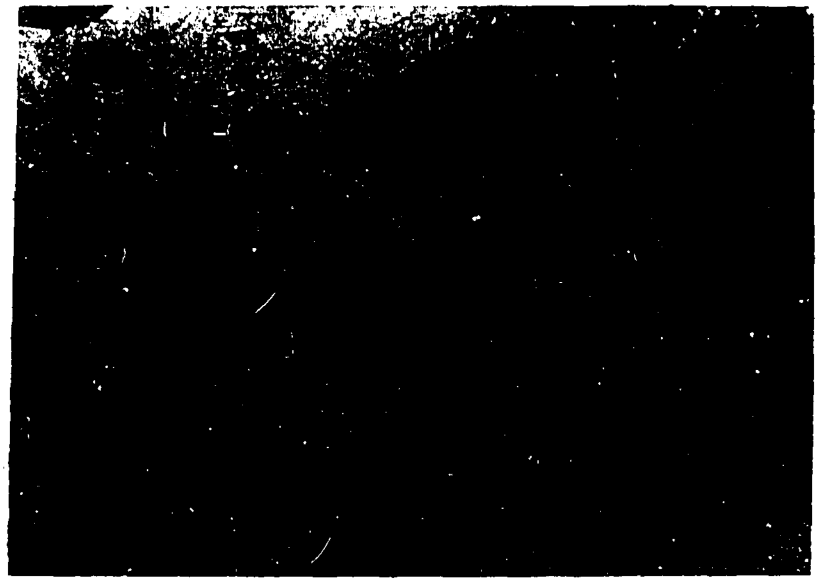


Plate 4.7: Loose black ice candles c. 12 in (30 cm) long at site 1 on Astray Lake.

evidence, it was decided to apply a theoretical buoyancy equation to these data. The simple equation used was:

$$h_w \gamma_w = h_s \gamma_s + h_i \gamma_i \qquad \text{(eq. 4.3)}$$

where h is depth or height, γ is unit weight and the subscripts w, s and i describe water, snow and ice respectively. The height of water is measured from the base of the ice sheet.

Shaw (1964) used a similar equation as a technique for calculating snow density on a lake in conditions unfavourable to direct density measurement. Even assuming perfect buoyancy, this is theoretically valid only if (1) no slush or water layers are present in the ice sheet, (2) the point of measurement is buoyant and free from shoreline effects, (3) the effect of the observer's weight is minimal and constant, (4) the measurements are representative for a few hundreds of feet around, (5) the unit weight of ice may be accurately assessed, (6) the ice thickness, assuming the site is representative, may then be accurately measured. Shaw himself noted the problem of measurement for this hypothesis: an error of $\pm$ 0.5 inches (1.3 cm) in ice thickness may cause a range of computed values from 0.06 g cm^{-3} to 0.25 g cm^{-3}. In using this equation to look for evidence of buckling interfering with natural buoyancy these other limitations must also be born in mind.

It was hoped that mapping the deviations from this equation would indicate areas or points where normal buoyancy was interfered with by expansive and compressive stresses. Given adequate knowledge of unit weight this approach should give a good indication. However, since these data were not collected, assumed values were taken, 0.4 g cm^{-3} for snow and 0.85 g cm^{-3} for ice as a whole. The sophistication of distinguishing between unit weight and proportions of black and white ice was ignored as not merited by the probable errors in other parameters. If a maximum range of average snow profile unit weight is taken as $\sim$0.3 to 0.5 g cm^{-3} and a mean snow depth of c. 18 inches (46 cm), it is reasonable to assume a probable error of estimation of 3 inches, i.e. $\pm$ 1.5 in (3.8 cm). Taking into account the presence of greater snow depths and errors in the assumed unit weight of ice (which are likely to be small), it is likely that a deviation greater than $\pm$ 3 in is significant.

The results obtained from the 1964 data were not mapped because of the irregular grid system used, but inspection of the traverses showed a few marked deviations. 27 cases (9.4%) were found of deviations greater than 4 in (10.1 cm) of which three were at the ends of traverses near the shore and the remainder well out on the lake. Many of these were isolated instances which may be observational errors, but three cases were found of runs of similar values that may indicate a systematic variation.

More detail was obtained from maps of differences between actual and calculated values for 1965 and 1966. The maps were produced by computer using the program "SYMAP" devised by H.T. Fisher, formerly of Northwestern University (description in Appendix B). Negative values indicate an overestimate of water level by the equation and positive values indicate an underestimate of water level, i.e. in areas of positive deviations the ice sheet is depressed more than explained by the equation.

DATA MAPPED IN 7 LEVELS BETWEEN EXTREME VALUES OF -6.40 AND 5.70
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

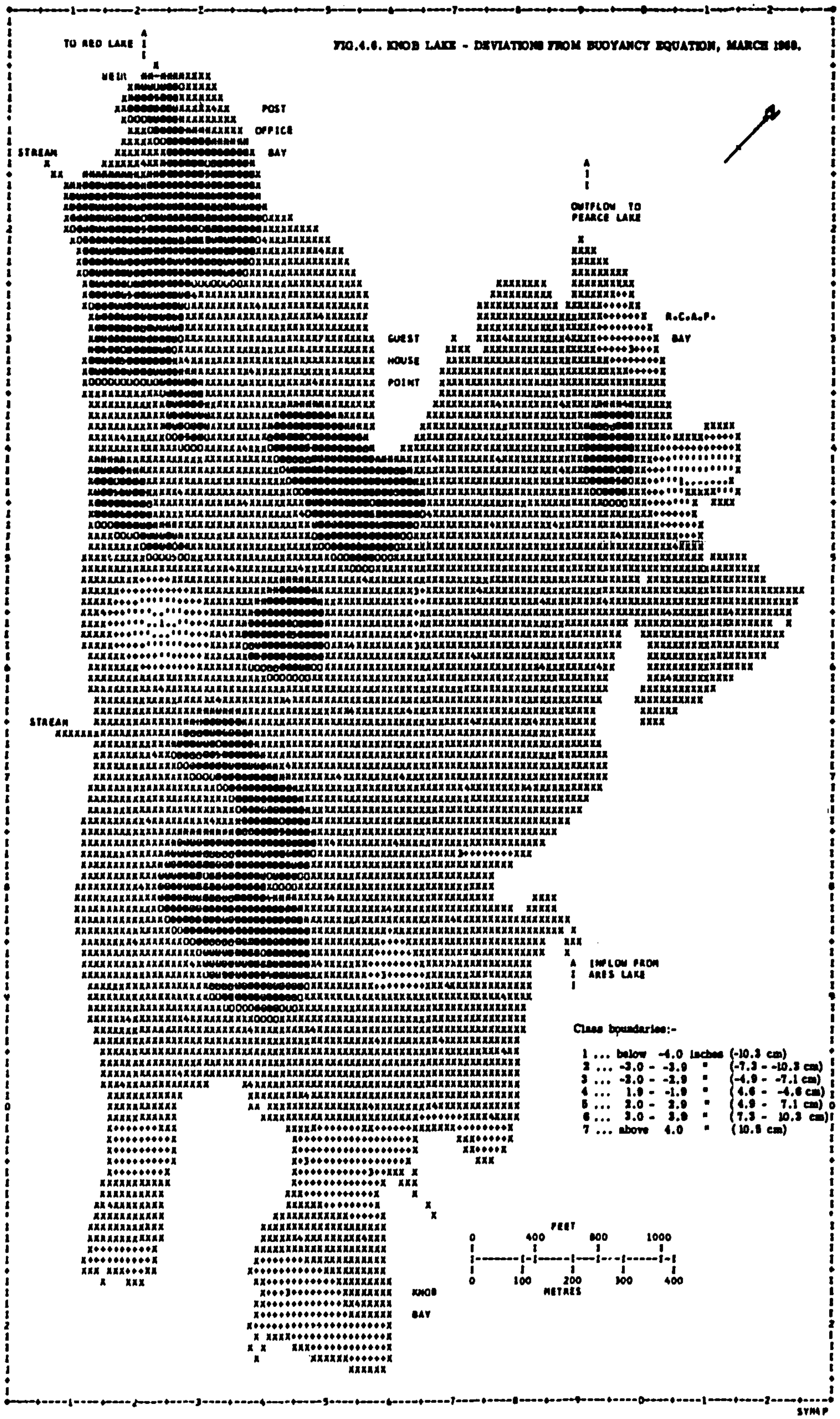


FIG.4.6. KNOB LAKE - DEVIATIONS FROM BUOYANCY EQUATION, MARCH 1968.

Slight evidence for buckling was found. On the first map produced a pattern of deviations was found very similar to that of snow depth (map by Archer, 1966, Appendix E, Fig. E.3). This indicated that the assumption of a uniform unit weight for snow of 0.40 g cm^{-3} was not fulfilled. It appeared that snow was of generally lower unit weight in drifted sectors. Compare to the shore profile at the southern end of Knob Bay (Fig. 4.1) on March 19th, 1966, with six unit weight measurements ranging from 0.28 to 0.30 g cm^{-3} in depths of 39.5 to 58.0 in (100 to 147 cm). However, a set of new class intervals were specified which disregarded minor variations. The maps in Figs. 4.6 and 4.7 are of the March situations in 1965 and 1966 respectively.

The histograms in Appendix C (Figs. C.18 and C.19) show that most of the computed values fall within 2.0 in of the actual. Thus, the variations mapped are likely to be significant, except in the case of measurement error. Because of this possibility of error, attention should be directed to areas substantiated by more than one data point. (Data points are indicated on the map by the class number from the histogram.)

In 1965 negative areas around the south and east edges suggest shore support (Cf. profile by Archer and Findlay, 1966, Appendix E, Fig. E.1). The positive areas in the north and centre indicate excessive depression of the ice sheet and suggest the possibility of down-arching along the central north-south axis. A more definite indication of a fold is given in the 1966 map, in which the main feature is a negative area (-2.0 to -2.9 in or -5.1 to -7.4 cm) extending east-west off Guest House Point. This may well have been an upfold, associated with the crack that

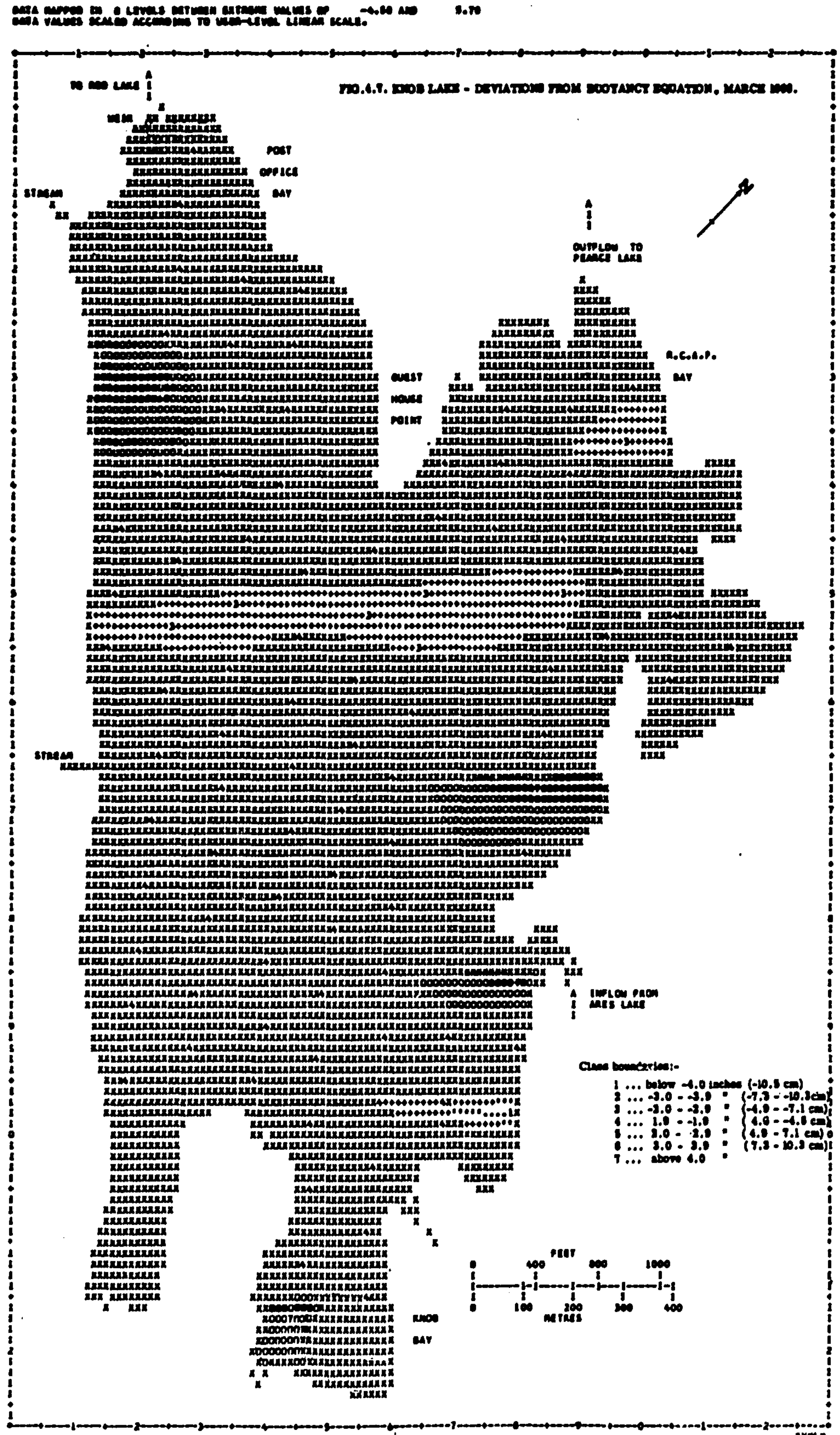


FIG.4.7. KNOB LAKE - DEVIATIONS FROM BUOYANCY EQUATION, MARCH 1969.

opened immediately north (Chapter 5, p. 76).

Conclusions.

None of the methods of measurement used showed any marked evidence of folding in the ice sheet other than bending caused by snow loading. But most of the data taken referred to the latter part of the season. It may prove more fruitful to conduct detailed surveying in the early season, i.e. in November, to establish angular measurements on stakes frozen into the ice sheet similar to the technique used by Bryson and Bunge (1956) to study ice divergence during expansion or contraction. However, qualitative field observation suggests that folding and horizontal ice divergence under the stake network on Knob Lake are very slight if they exist at all. No noticeable movement occurred.

The main cause of cracking appears to be contraction due to the penetration of cold diurnal waves of high amplitudes which are most common in early and late winter.

CHAPTER 5

VARIATIONS IN WHITE ICE GROWTH ACROSS KNOB LAKE DURING WINTER 1965-66.

Sequent white ice surveys: Method.

To study the variability of white ice growth across Knob Lake, a rectangular grid of 117 8 ft wooden 2 in x 2 in stakes was frozen into drill holes in the ice cover in mid-November 1965. The grid origin was the same as used for the January survey in 1965 (as marked by sites on Figs. 5.1 to 5.14) that is, a base line was established between the southern tip of Guest House Point and a marker boulder roughly directly west, on the banks of the Quebec North Shore and Labrador Railway line. The tip of the point was designated NOOS and EOOW, i.e. 0000 in the manuscript records now on file at the laboratory. The first few grid squares were set off 400 ft x 400 ft (c.120 m square) from this base line using a Wild T2 theodolite. Later squares were set off by eye, lining up the diagonals. Four quadrants of the grid were distinguished in the field records by prefixes NW, NE, SE, and SW, in relation to the axial lines EOOW and NOOS. This grid was convenient to establish in the field, but for transfer to punchcards a non-repeating system was used with the origin moved to the extreme northwest corner (Appendix A).

Each stake was placed in a 3 in (7.6 cm) hole drilled through the ice sheet to allow water to rise up, packed with snow and allowed to freeze in place. A mark was etched on the stakes 1 yard (1 m) above the black-ice/white-ice interface, which was to serve as reference. The first measurements were made on November 24th. Observations were made in inches with a standard Canadian Department of Transport Meteorological Branch yard snow ruler at a point 2 inches (5 cm) to the east of every stake to minimise the disturbing effect of small variations around the stake. Dry snow depth, slush depth and white ice thickness were recorded. In effect, slush records are very sparse and have been ignored, since it is difficult to distinguish slush depth when a hole is not dug into the snow.

It is probable that the first survey had been strongly affected by the method of installation, but it served as a fixed reference for succeeding surveys. The nine mile survey was made variously on snowshoes, skis and skidoo, at intervals of approximately two weeks up to the fuller ice survey in March, 1966.

Area surveys involving complete drillings had been made previously in March 1964 and March 1965 (maps in Appendix E, Figs. E.4 to E.7, from Archer, 1966 and from Shaw, 1965, and others in the original publications), with which the complete survey made in March, 1966, is compared later in this chapter. But, unfortunately, the only similar white ice survey that exists for comparison is that of January, 1965 (Appendix E, Figs. E.4 and E.5).

The data on snow and white ice was normalised for the season, using the computer program described in Appendix B as NORMSTAND. Normalisation required a cube-root transformation for snow cover and a square-root transformation for white ice (see Appendix C). From this standard scores in relation to the season mean were punched out for use in the computer mapping program described in Appendix B as SYMAP. The plotting of standard scores gives a probability significance to the data. Class intervals were set to correspond to standard deviations (Fig. 5.1, or Appendix C, histogram 1, Fig. C.4). The mean falls at the class boundary between levels 5 and 6 on the maps, and these two levels combined have a 68.26% probability of occurrence. Similarly, levels 4 and 7 each have a 13.6% probability, levels 3 and 8 a 2% probability and the remainder are very exceptional. In the white ice, since it is cumulative, the mean standard score progressively ascends the classes through the season. Sudden increases are shown by increased area devoted to the higher levels. It is possible to compare increases and decreases in snow cover with increases in white ice in terms of "average conditions".

The maps in Figs. 5.1 through 5.14 show snow cover and white ice distribution on seven days during the winter. The histograms referring to these maps have been included in Appendix C.

Results.

These maps show two centres of dispension for white ice growth. The main centre is the southern and eastern edges of the lake, which are generally areas of above average snow cover for most of the winter. This tendency has been noted implicitly and explicitly by a number of authors (e.g. Andrews, 1962). However, a secondary centre also appears to exist in the centre of the lake, associated with more transient peaks of snow cover. The two centres were already present at the November 24th survey: note the area south of the Ares Lake inflow, in the west-centre of Knob Lake and across the narrow entrances to the southern bays, where areas already show a thickness greater than the season mean. The general pattern of white ice has been established, with the minimum in the northwest corner. The mode is in class 4 (mean to -1s). However, snow distribution is not markedly localised. The mode for snow distribution extends across levels 5 and 6 (near the season mean). Hence loading is not excessive on any particular part of the lake, but at this period the ice is thin (c. 12 in or 30 cm).

These centres alternate in growth through the winter and likewise snow distribution is not always markedly concentrated at the southern and eastern shores. The map of snow cover for January 22nd thus shows deeper snow patches in the northern half of the lake and lee dunes can be seen before and after slushing around Guest House Point on the maps of December 10 and December 23rd.

It is clear that snow distribution is related to prevailing winds, and can be compared to the prevailing wind (classified as in Appendix A) as follows:

Nov.24th:	prevailing	wind in	preceding	2 weeks	SE/NW	- even snow distribution
Dec.10th:	"	"	"	"	NW/NW	- lee dune off G.H.Pt., southern concentration
Dec.23rd:	"	"	"	"	NW/NW	- similar
Jan. 8th:	"	"	"	"	NW/NW	- similar

Jan. 22nd:	prevailing wind in preceding 2 weeks	NW/NW - similar
Feb. 5th:	" " " "	SE/varied - even distribution
March 3rd:	" " " 4 "	NW/NW/NW/varied - southern concentration

There is a similar liaison between drifting and the degree of subsequent white ice growth because of the hydrostatic head thus developed by snow loading and depression of the sheet. A good example is the realisation of the potential offered by the lee dune off Guest House Point between December 10th and 23rd. Hence it is inferred that marked local increases in white ice often result after an extended run of wind from one direction. However, as shown in Chapter 4, the prime cause of cracking is diurnal range. In drifts a higher surface amplitude is needed than was considered for mean depth in the previous chapter. Thus, cracking is likely to be less frequent the deeper the drift. The longer the wind persists, the longer the drift is likely to remain free from slushing. Hence the liaison between drifting and slushing involves large, sudden increases separated by longer periods of quiescence. This is born out by comparing the graph of development at the more normal northern "non-slushing device" site with that of the drift site (Figs. 10.5 and 10.6) in Chapter 10. Therefore, in lake-wide terms as opposed to the local drift, the fact that the two major slushing phases on the lake were preceded by a number of weeks of northwest winds is probably incidental to favourable temperature ranges.

The events leading up to these lake-wide slushing phases may best be represented in terms of the lake cover in the following list

November 24th, 1965: snow and white ice distribution maps.

Slushing has already occurred, reducing snow cover in the north-central part of the lake and along parts of the eastern shore and forming isolated growths of white ice already greater than the season mean (11 in - 27.5 cm). Minimum white ice is in the northwest and is to be persistently so through the season, commonly associated with a snow deflation area, although at this point snow distribution is relatively even following two weeks of contrasting wind directions.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -3.85 AND 2.70
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

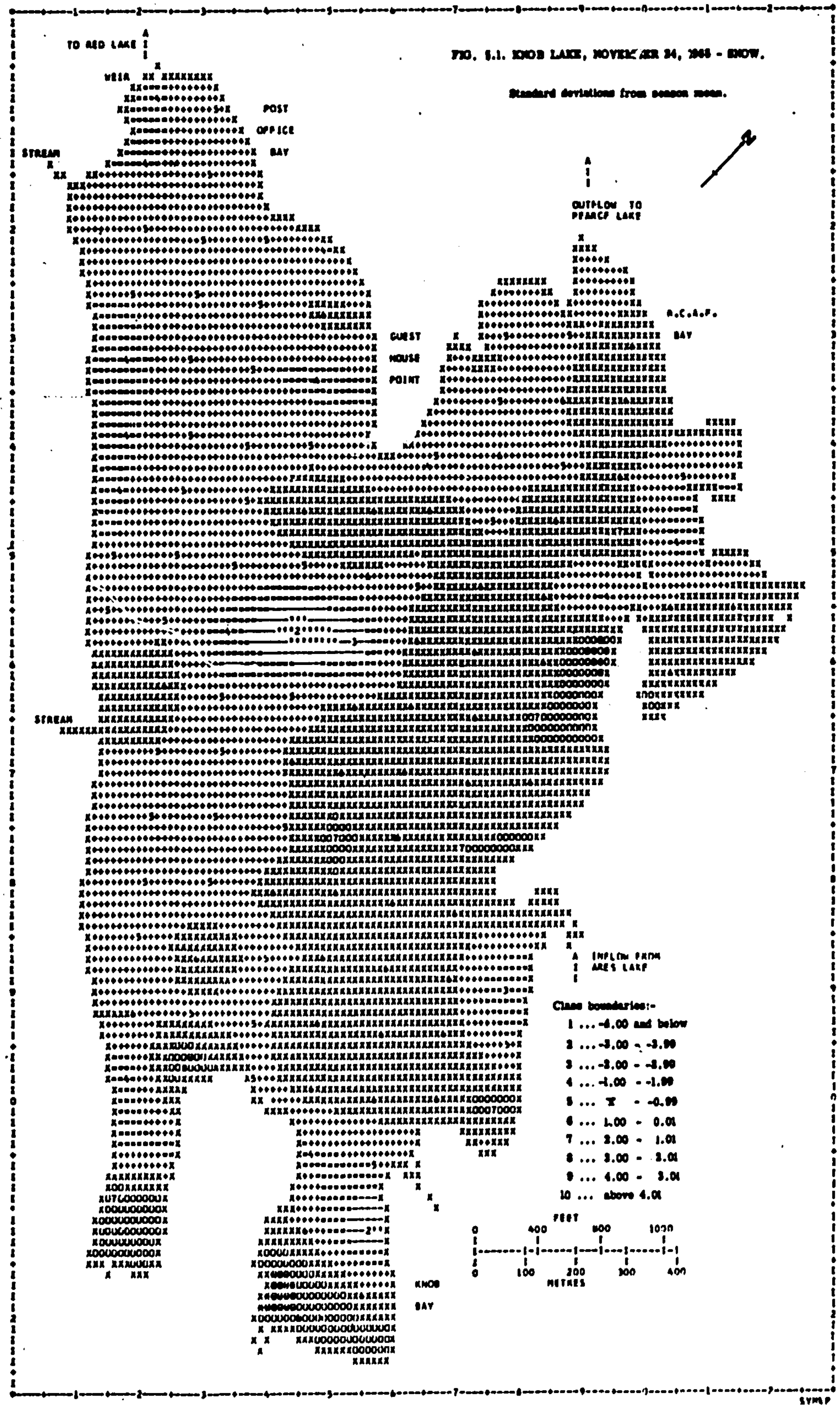


FIG. 5.1. KNOB LAKE, NOVEMBER 24, 1968 - SNOW.

Standard deviations from season mean.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -2.08 AND 0.94
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

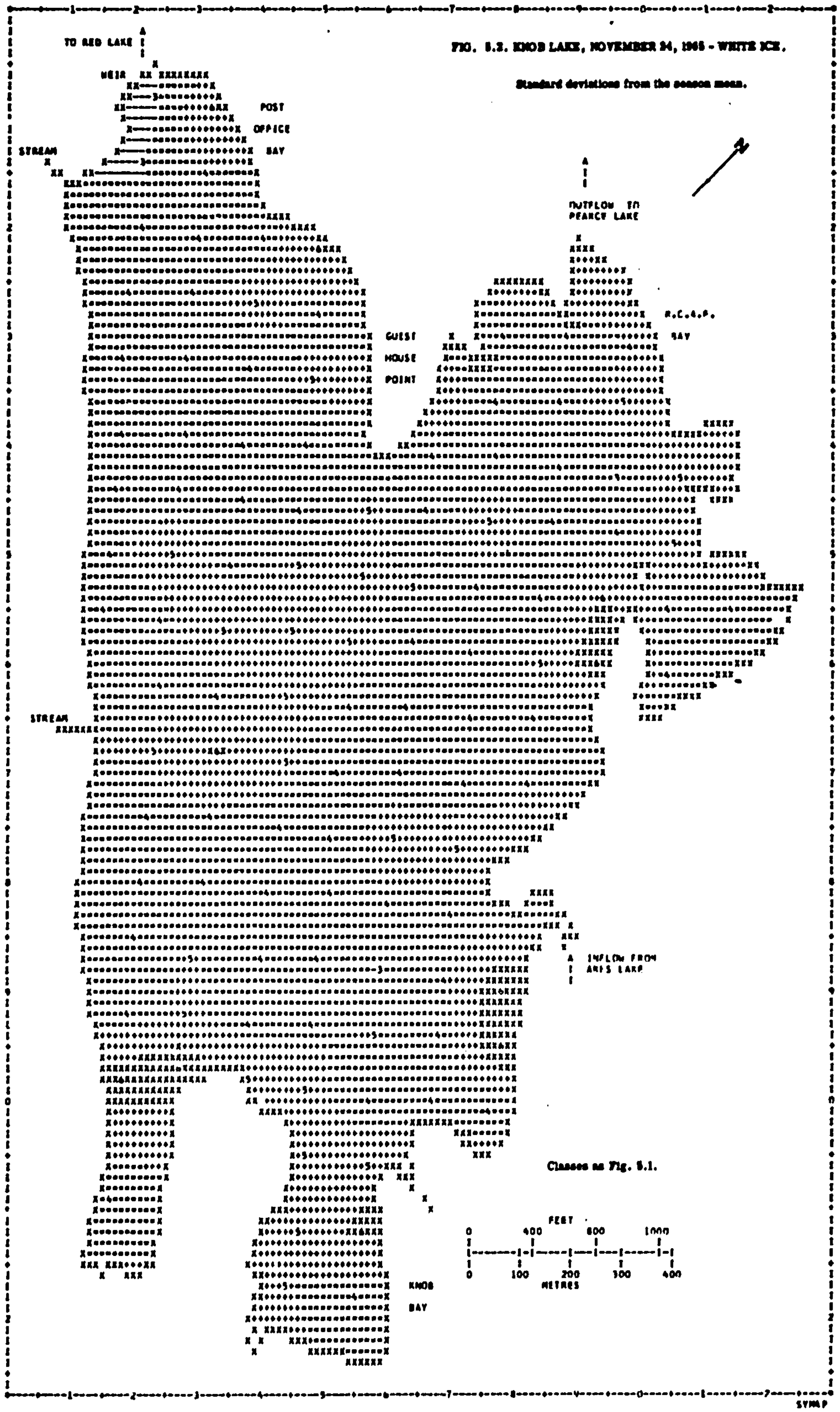


FIG. 5.2. KNOB LAKE, NOVEMBER 24, 1965 - WHITE ICE.

Standard deviations from the season mean.

Classes as Fig. 5.1.

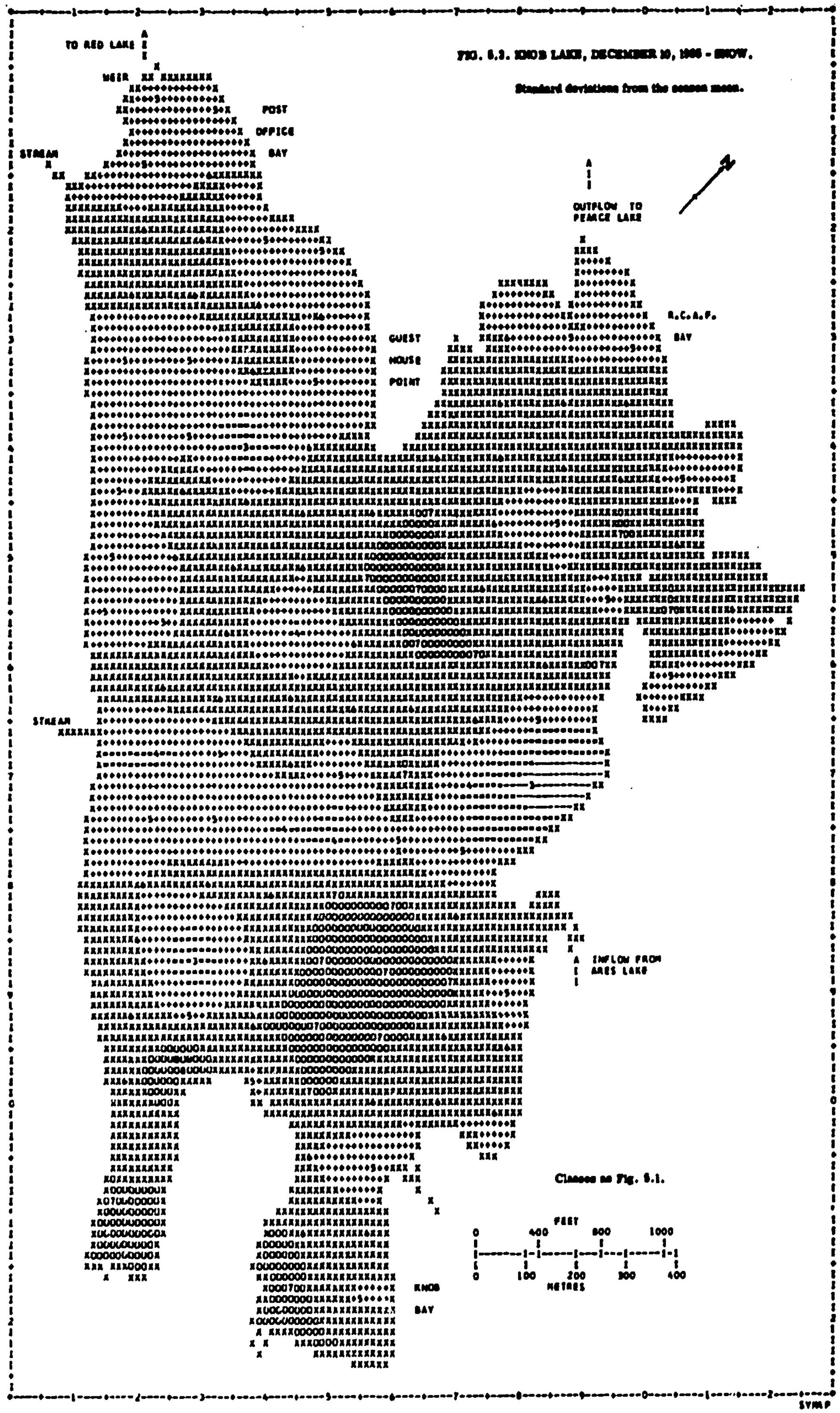
December 10th, 1965: snow and white ice distribution maps.

White ice has increased in the east. The centre growth is again increasing, surrounded and divided from the eastern peak by areas of below mean growth. A slushing has occurred at south-west-centre and a potential appears to exist at south-east-centre. A potential seems to have developed off Guest House Point with a lee dune, which is to be realised in the following weeks.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -2.53 AND 2.40
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

FIG. 5.3. KNOB LAKE, DECEMBER 10, 1966 - SNOW.

Standard deviations from the season mean.



Classes as Fig. 5.1.

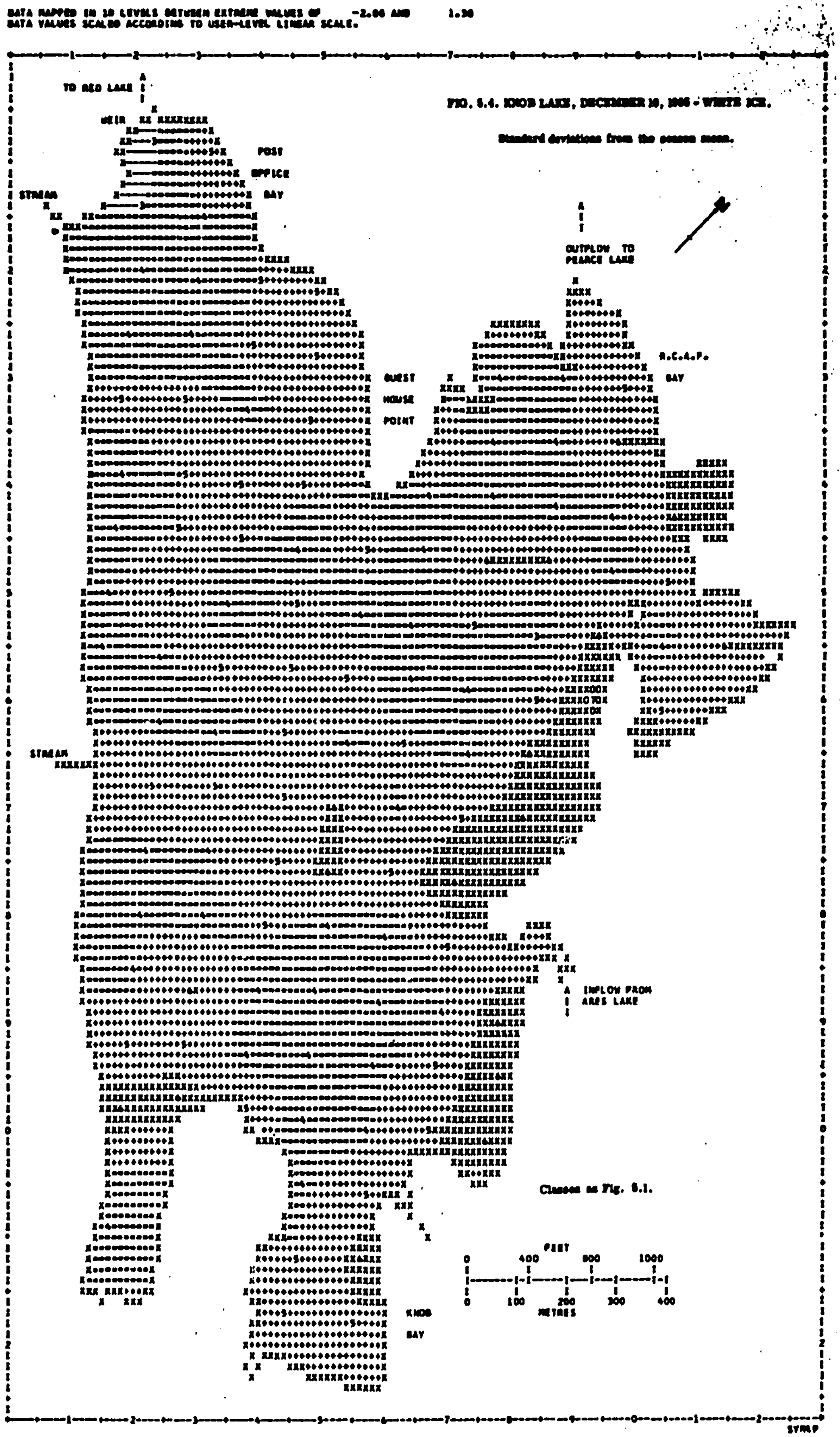


FIG. 5.4. KNOB LAKE, DECEMBER 10, 1966 - WHITE ICE.

Standard deviations from the season mean.

Classes as Fig. 5.1.

<u>December 23rd, 1965: snow and white ice distribution maps.</u>

A major slushing phase has occurred. The mode (level 6) is established to remain for the rest of the season. (Compare to rank correlations with snowfall.) The main change in distribution of white ice has occurred in the middle of the lake. Increases have not crossed the class boundaries in the extreme northwest, the moderate white ice area in the west and in the high white ice area in the southeast. Snow is generally reduced, especially in south and centre. The Guest House Point drift has gone. However, the apparent potential at south-east-centre has only partially been realised.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -2.86 AND 3.90
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

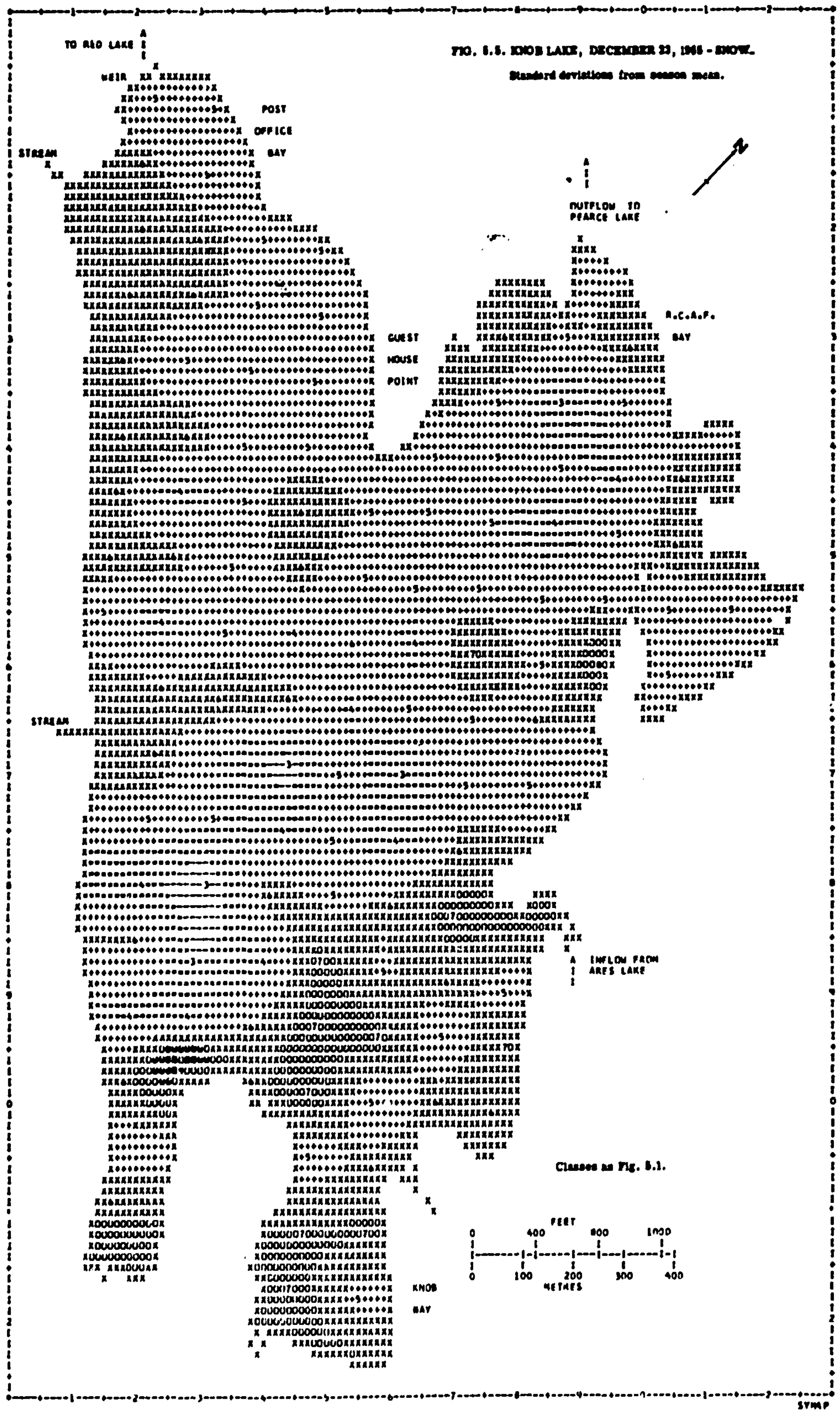


FIG. 8.5. KNOB LAKE, DECEMBER 23, 1965 - SNOW.

Standard deviations from season mean.

Classes as Fig. 8.1.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -2.08 AND 3.60
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

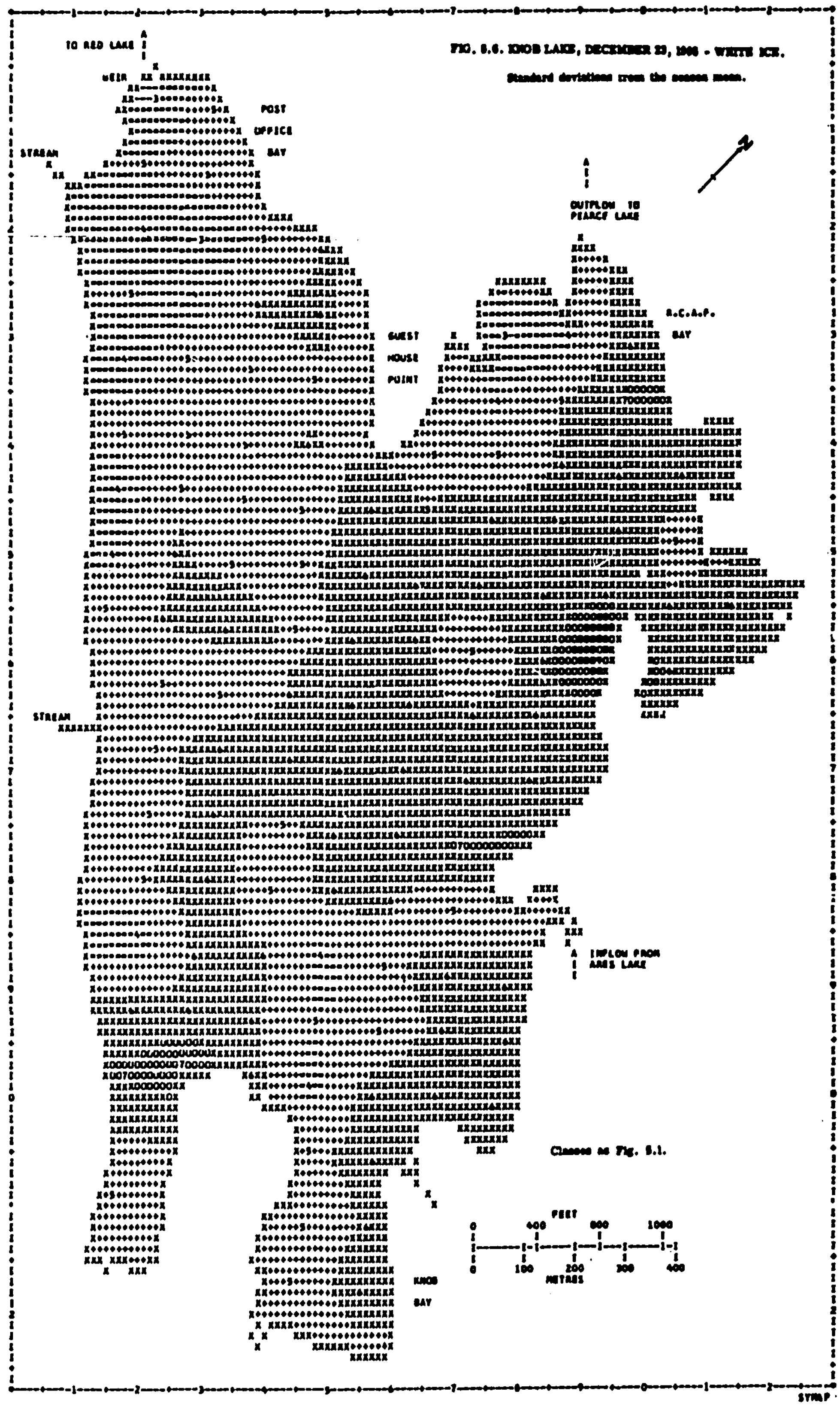


FIG. 5.6. KNOB LAKE, DECEMBER 23, 1966 - WHITE ICE.

Standard deviations from the season mean.

Classes as Fig. 5.1.

January 9th, 1966: snow and white ice distribution maps.

Filling in has now occurred in the white ice pattern in southeast and south-centre, and snow is likewise reduced here. The severe cracking that occurred on January 7th following a night of $-46^{o}F$ or $-41.5^{o}C$ (amplitude of cold wave $32^{o}F$ or $15^{o}C$) does not appear to have initiated much flooding, perhaps because of intense freezing and a snow cover which is the shallowest of the winter.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -3.27 AND 2.70
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

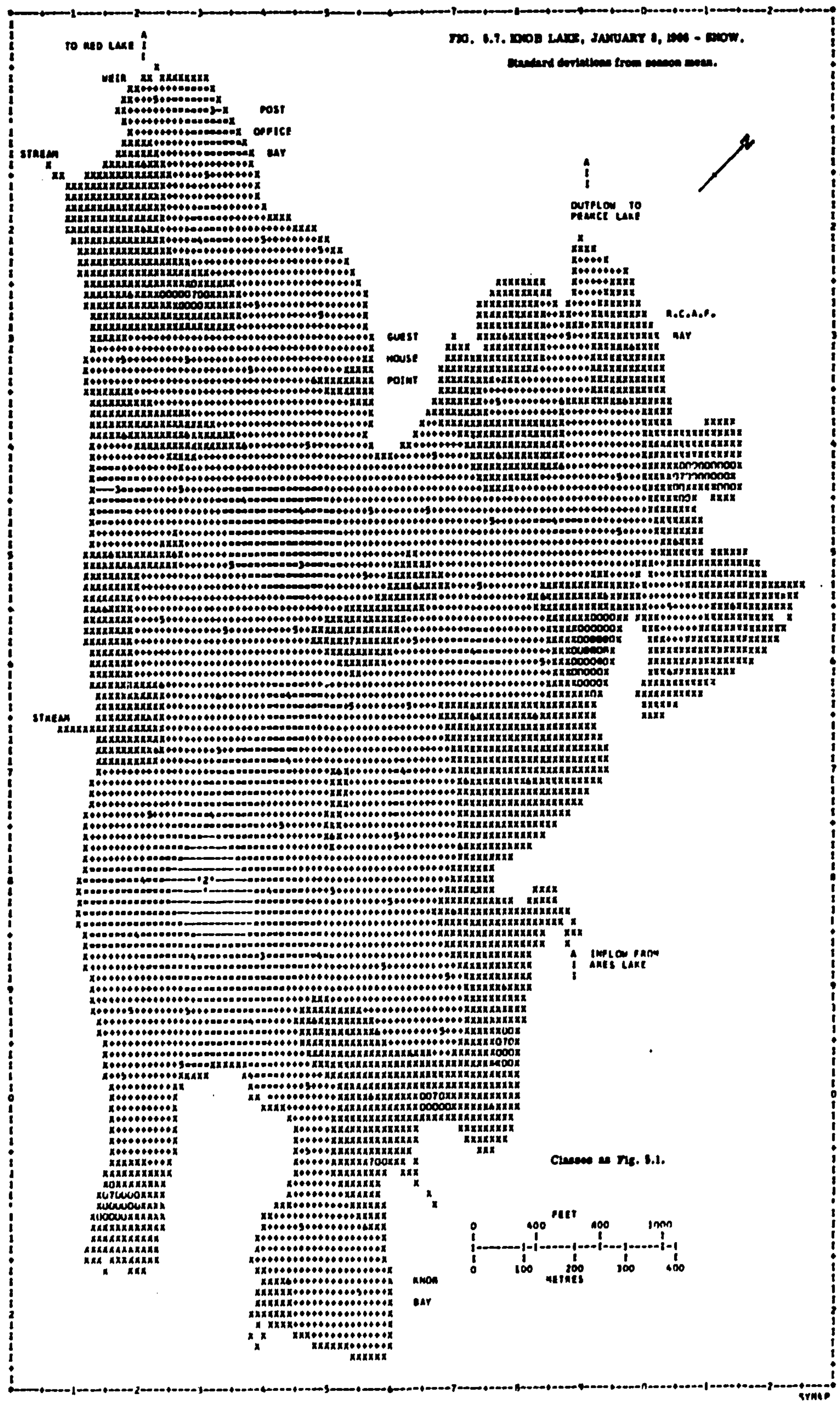


FIG. 5.7. KNOB LAKE, JANUARY 8, 1966 - SNOW.

Standard deviations from season mean.

Classes as Fig. 5.1.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -2.08 AND 2.64
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

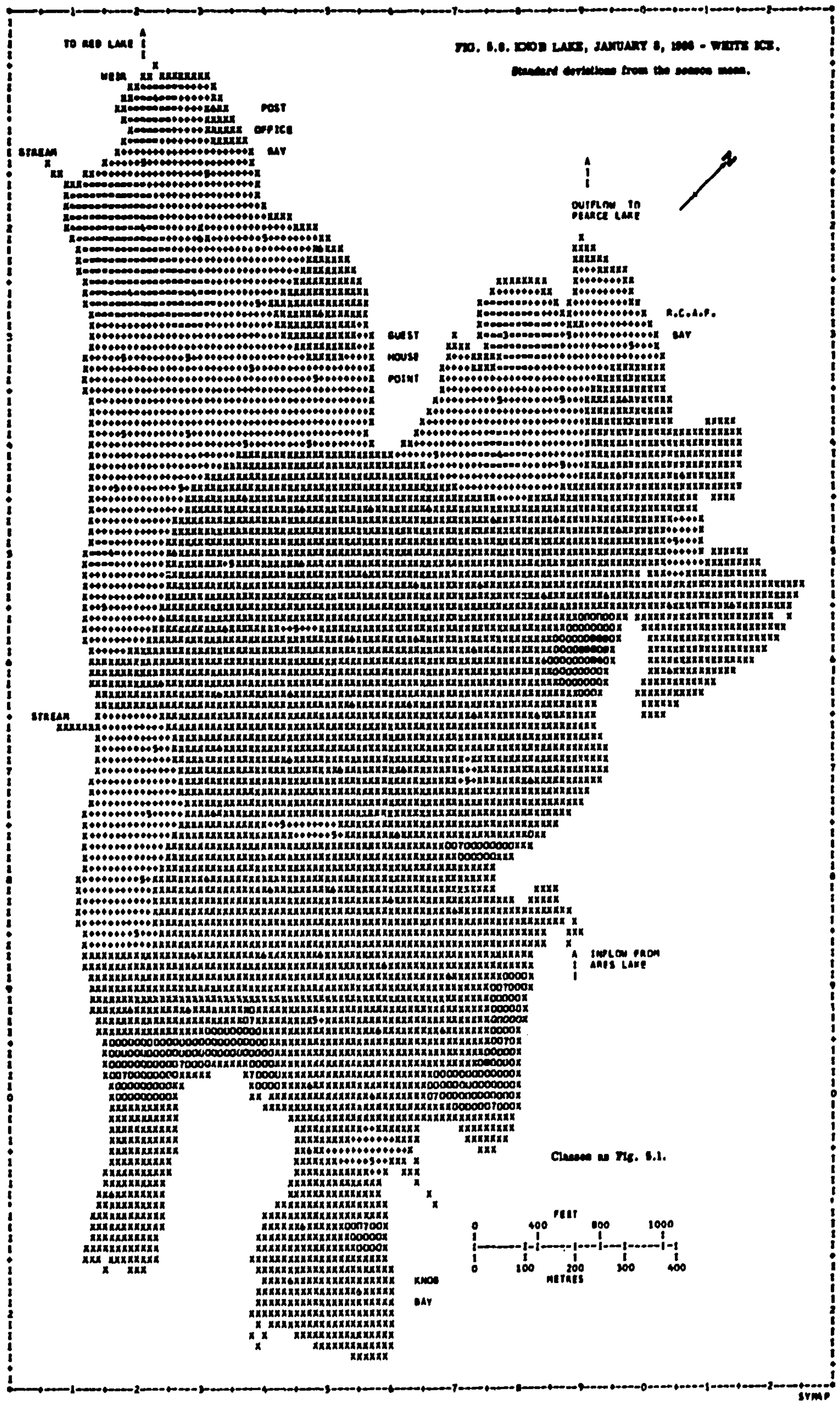


FIG. 5.6. KNOB LAKE, JANUARY 8, 1966 - WHITE ICE.

Standard deviations from the season mean.

Classes as Fig. 5.1.

January 22nd, 1966: snow and white ice distribution maps.

Another increase in white ice has occurred at the constricted entrances to the southern bays, where snow appears to be more commonly deposited than deflated (although the sample sites are somewhat eccentric). The northern half of the lake is essentially unchanged in white ice distribution, but patches of deep snow drifts are found. Wind direction is still prevailingly northwest.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -1.27 AND 3.34
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

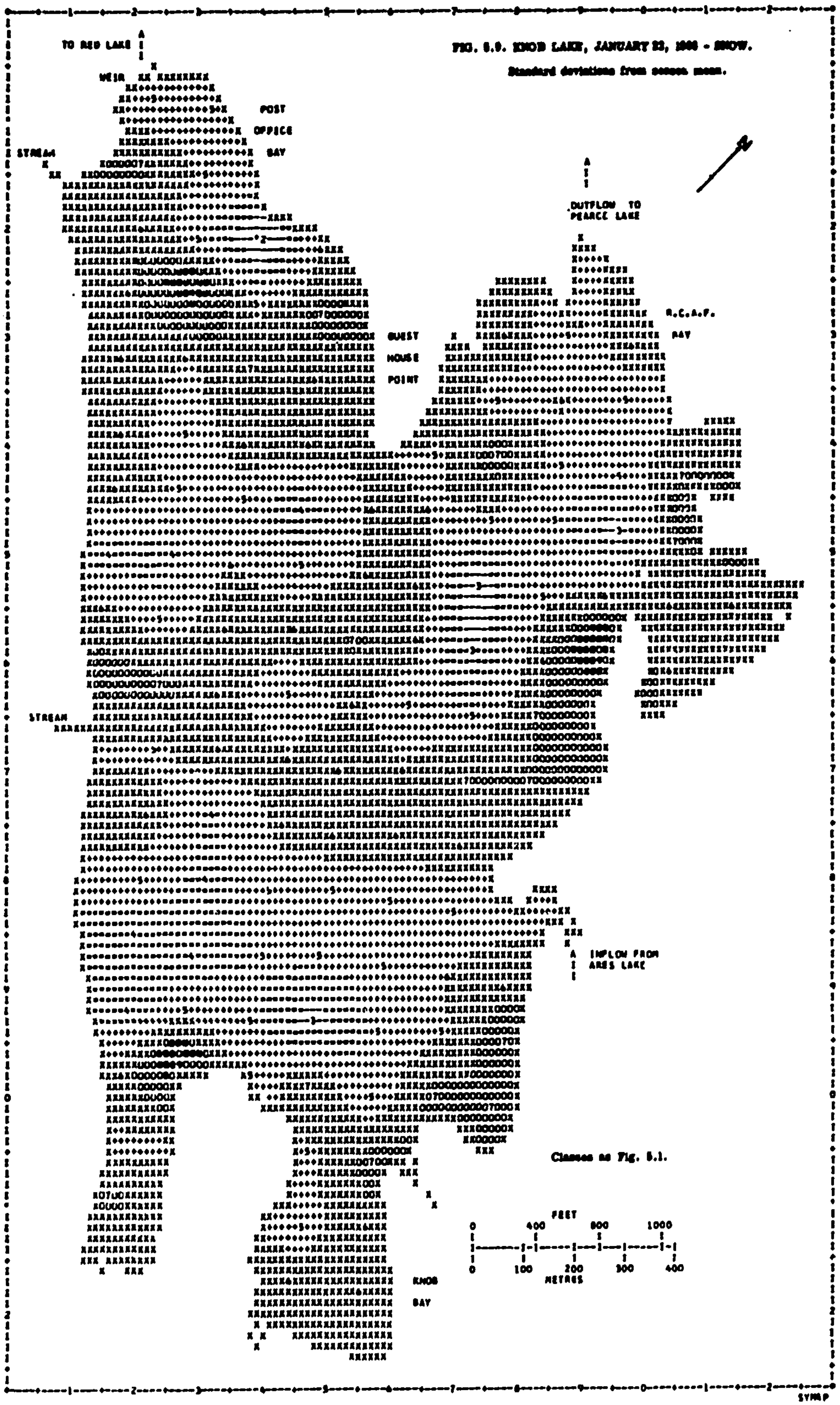


FIG. 5.9. KNOB LAKE, JANUARY 22, 1968 - SNOW.

Standard deviations from season mean.

Classes as Fig. 5.1.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -1.87 AND 2.72
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

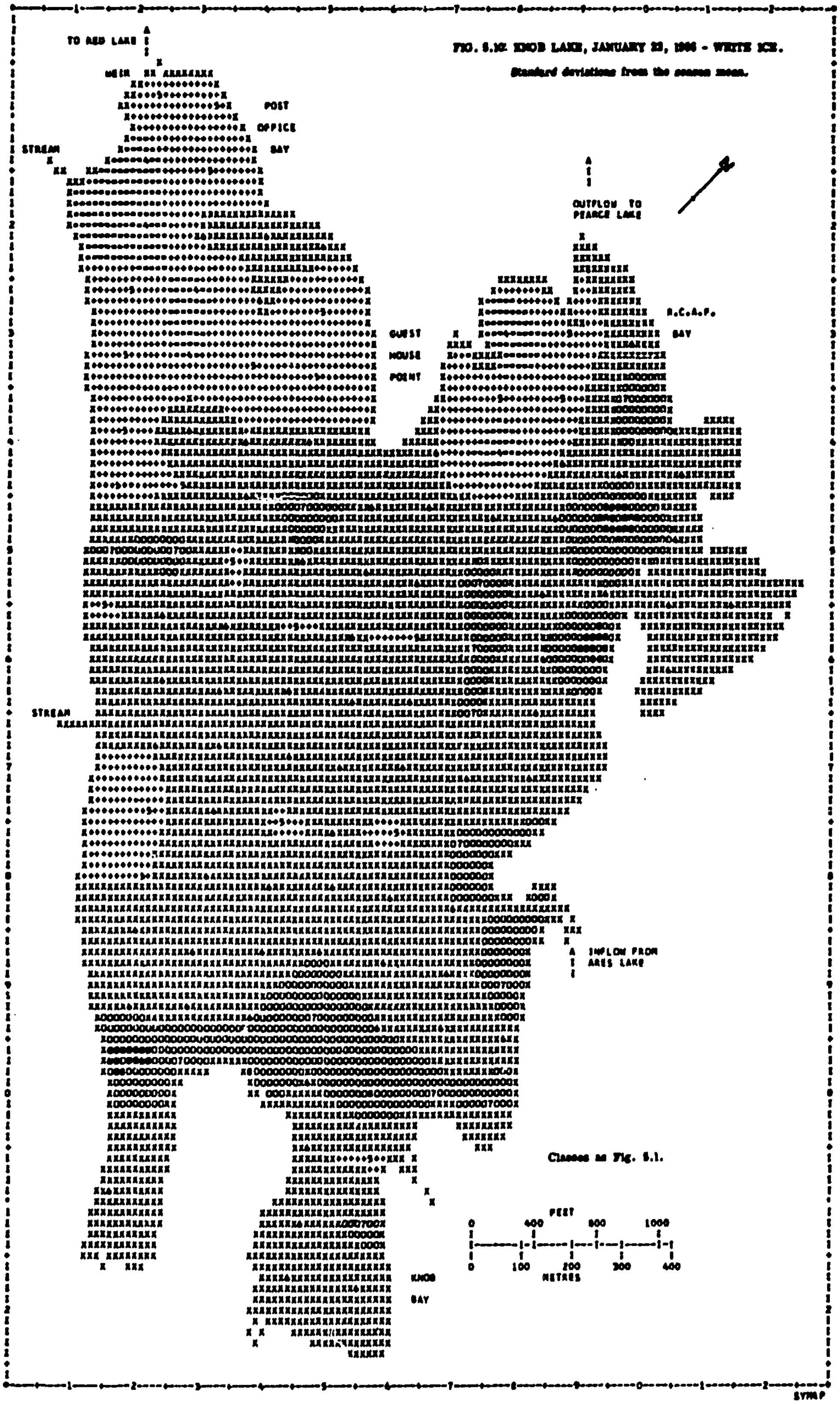


FIG. 5.10: KNOB LAKE, JANUARY 23, 1966 - WHITE ICE.

Standard deviations from the season mean.

Classes as Fig. 5.1.

February 5th, 1966: snow and white ice distribution maps.

A general increase in white ice has occurred, but of smaller magnitude than in December or March. It is mostly in the former northern drift areas and especially in the central area. Snow has been evenly distributed apparently by variable winds.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -2.53 AND 3.34
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

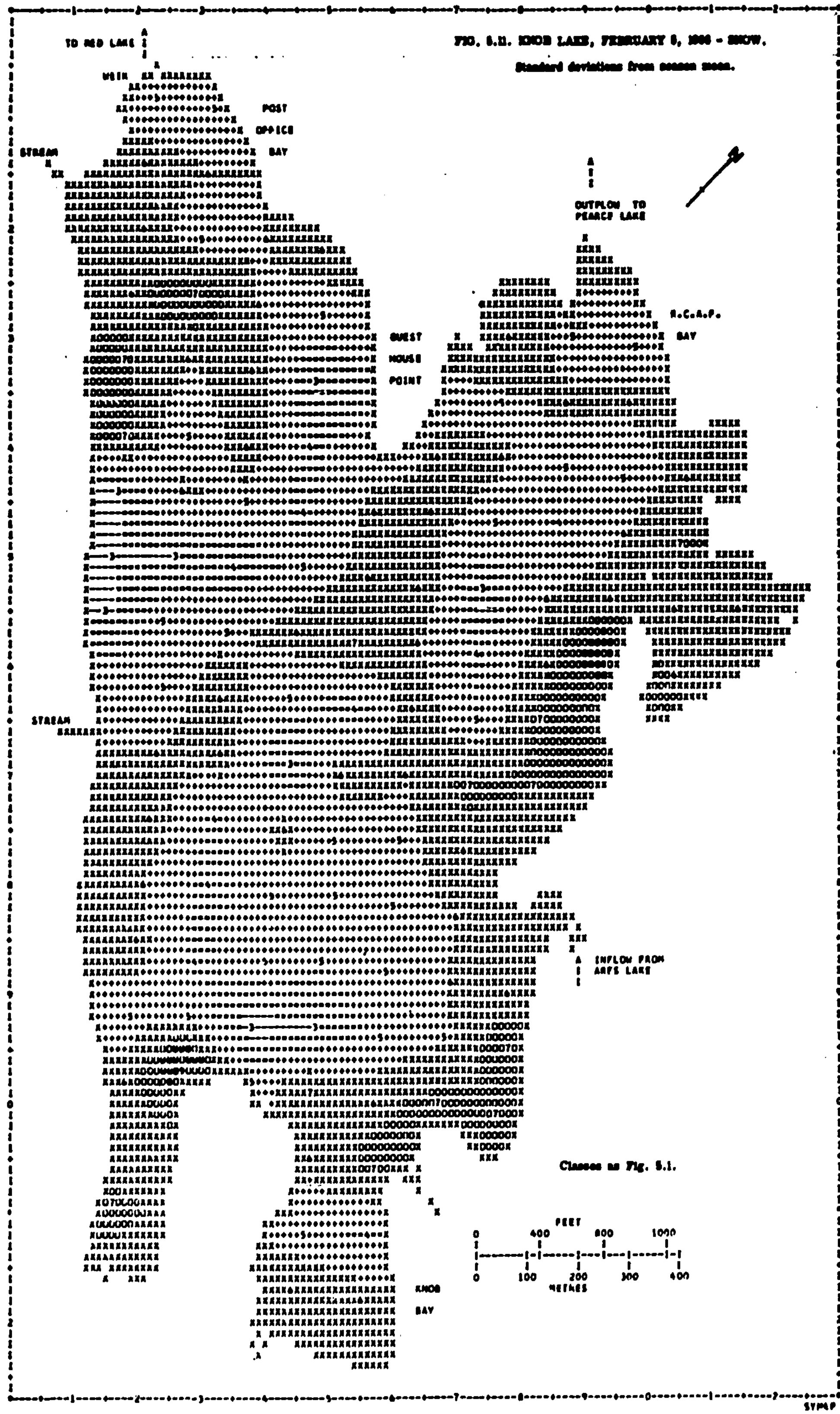


FIG. 5.11. KNOB LAKE, FEBRUARY 8, 1966 - SNOW.
Standard deviations from season mean.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -2.08 AND 2.68
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

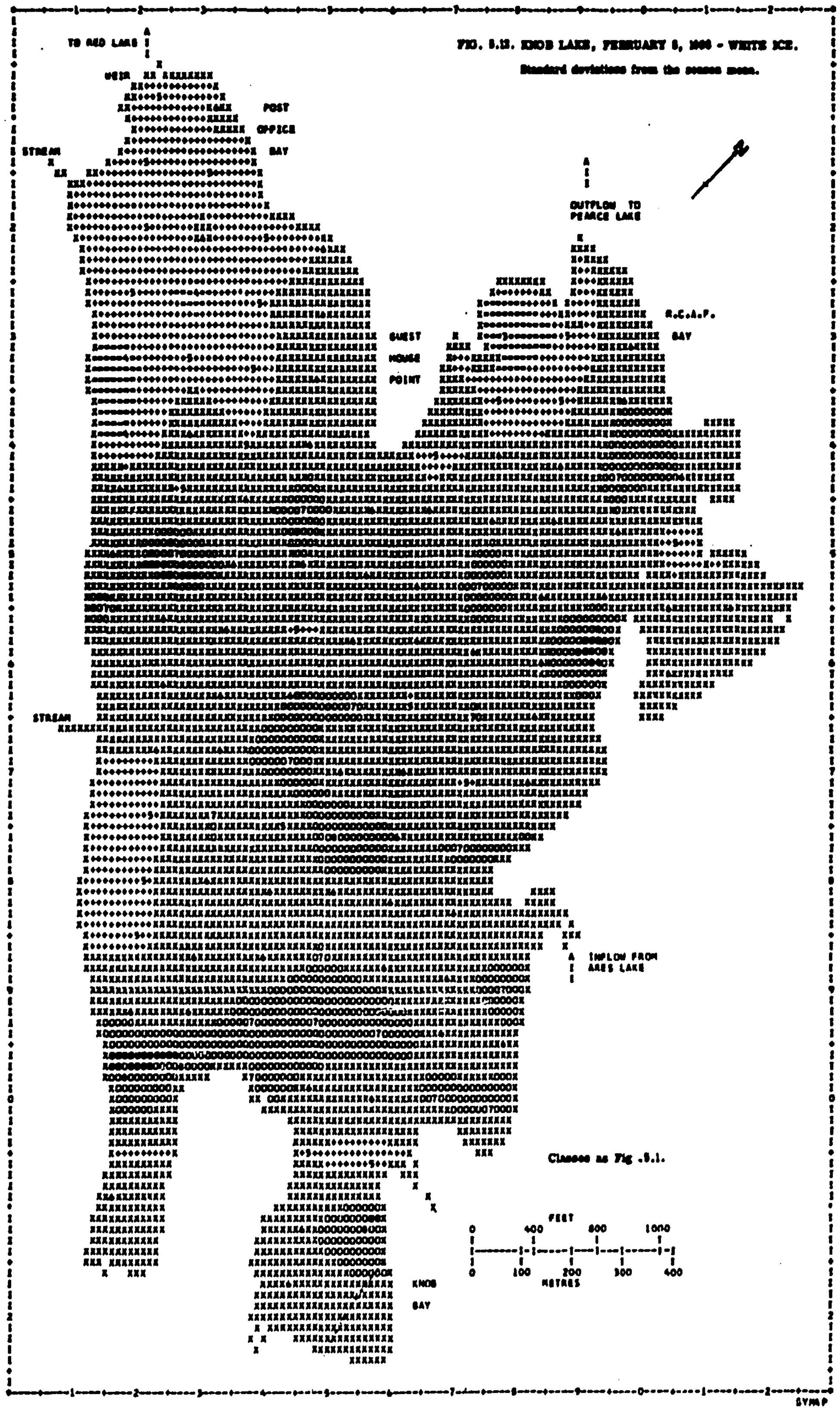


FIG. 5.12. KNOB LAKE, FEBRUARY 8, 1966 - WHITE ICE.

Standard deviations from the season mean.

March 3rd, 1966: snow and white ice distribution maps.

Marked growth of white ice has occurred in the east and centre areas. The south and east are re-established as the major areas. This appears coincident with a marked snow accumulation, although the gap of one month from the last survey may hide a lag. This is the beginning of a slushing phase that was concluded after the larger survey in late March.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -1.26 AND 3.98
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

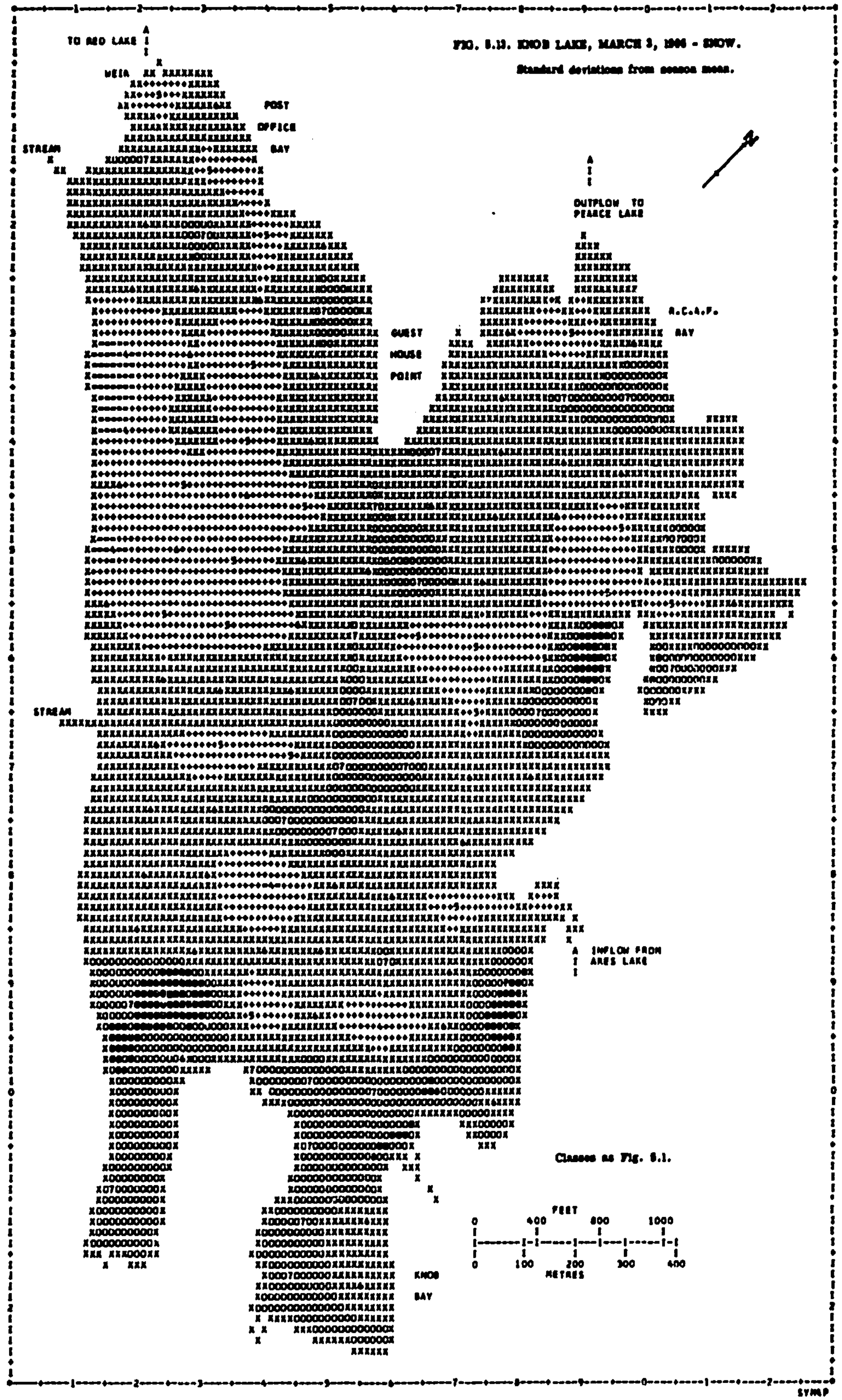


FIG. 8.13. KNOB LAKE, MARCH 3, 1966 - SNOW.

Standard deviations from season mean.

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -1.16 AND 2.64
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

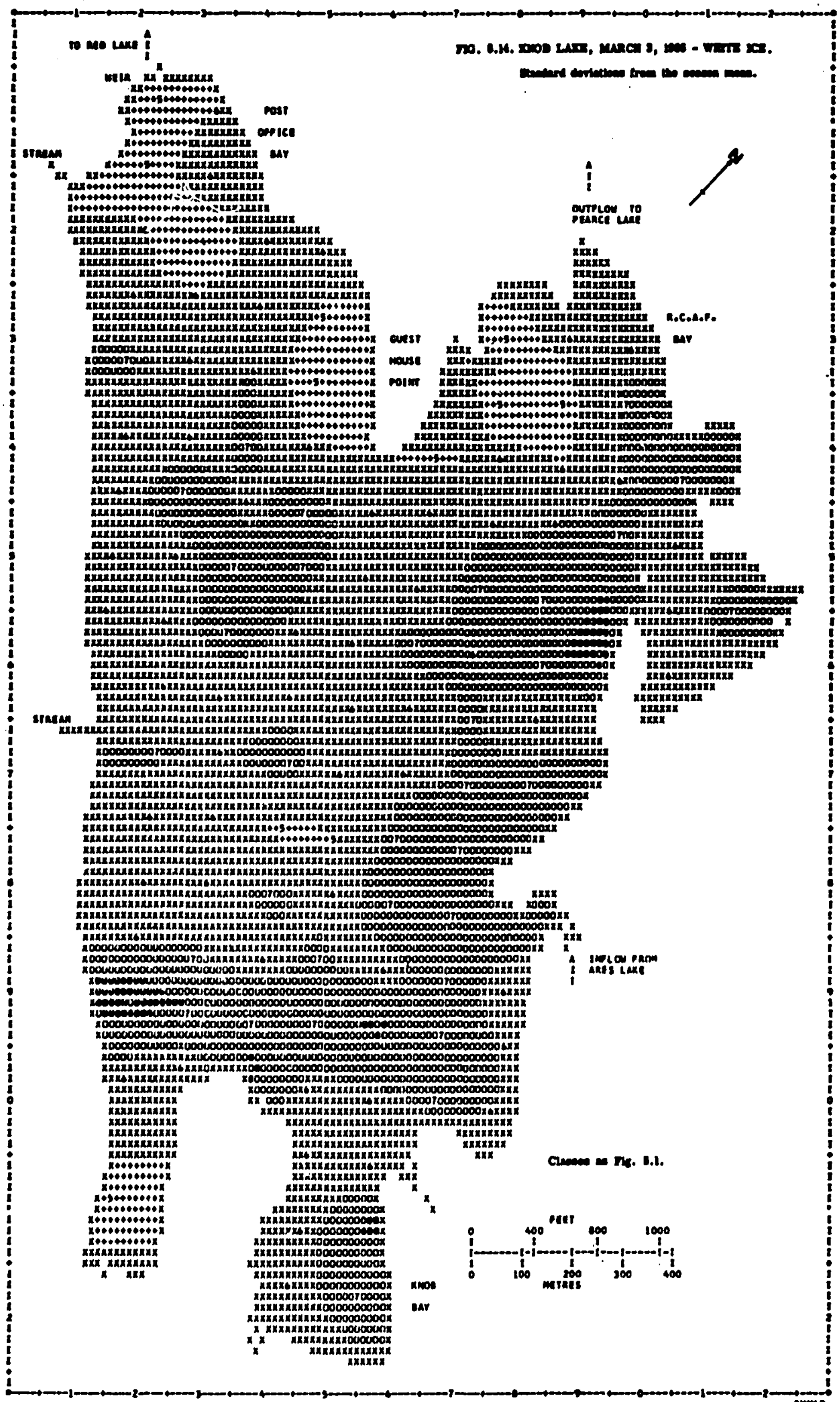


FIG. 8.14. KNOB LAKE, MARCH 3, 1966 - WHITE ICE.

Standard deviations from the season mean.

compiled from the histograms in Appendix C.

date of survey	snow distribution			white ice distribution		
	mean	> + 1s	modal level	mean	> + 1s	modal level
Nov. 24th	47.0%	7.7%	5-6	8.6%	0.0%	4
Dec. 10th	65.8%	17.1%	6	16.2%	0.9%	4-5
Dec. 23rd	41.8%	11.1%	5	54.7%	3.4%	6
Jan. 8th	41.9%	6.8%	5	65.8%	9.4%	6
Jan. 22nd	55.5%	18.0%	6	75.2%	16.2%	6
Feb. 5th	55.5%	13.7%	6	75.2%	19.7%	6
March 3rd	77.0%	28.2%	6	90.0%	34.2%	6

The list shows that the modal level for white ice was established by the end of December. This appears to confirm the general validity of the rank correlation obtained in Chapter 2 for Knob Lake Centre site. The first major slushing phase and part of the second are recorded here. The phases seem to have been initiated as nearly three-quarters of the lake became covered by above average snow depths, i.e. greater than 10.07 inches (25.6 cm). The later phase would *a priori* require greater snow depths to cause the same degree of slushing because of the lower buoyancy level of the ice.

These phases are reflected in graph form for sites east, centre and west and various additional sites in Figs. 10.2 to 10.6 in Chapter 10.

The discussion on the cause of cracking in Chapter 4 showed that December and March had the most frequent fluctuations in air temperature of a magnitude that might be sufficient to exceed the limit tentatively assumed for tensile strength in the ice sheet. These months mark the beginning and end of "deep winter" in 1965-6. Although deeper snow at these periods would reduce the effectiveness of these fluctuations, many of the fluctuations recorded for winter 1965-6 are likely to have penetrated. It is not simply in frequency that December and March excell, but also often in amplitude.

Probability of white ice growth.

The patterns presented above show concentrations of white ice in parts of the lake commonly bearing deeper snow cover. An attempt was made to see whether snow depth also affected the initiation of cracks. This was achieved in terms of "probability of growth" using a simple yes/no approach and the elementary relationship

$$P = \frac{n}{N} \times 100 \qquad \text{(eq. 5.1)}$$

where P is the percentage probability, n the number of times an increase is recorded and N the total number of times the site was measured. This was applied in a small computer program to the data of the white ice surveys rearranged into 117 sets of 7 observations. The information was then fed into SYMAP. Fig. 5.15 is the result. There was a scatter from 43% to 86%. Since no site lacked white ice on November 24th, each site was allocated a 14% probability from the start.

In this map the former strong patterning has been destroyed and is not replaced. The northwest is no longer a "low" area. There is just the tendency for the centre of the lake to have lower values;

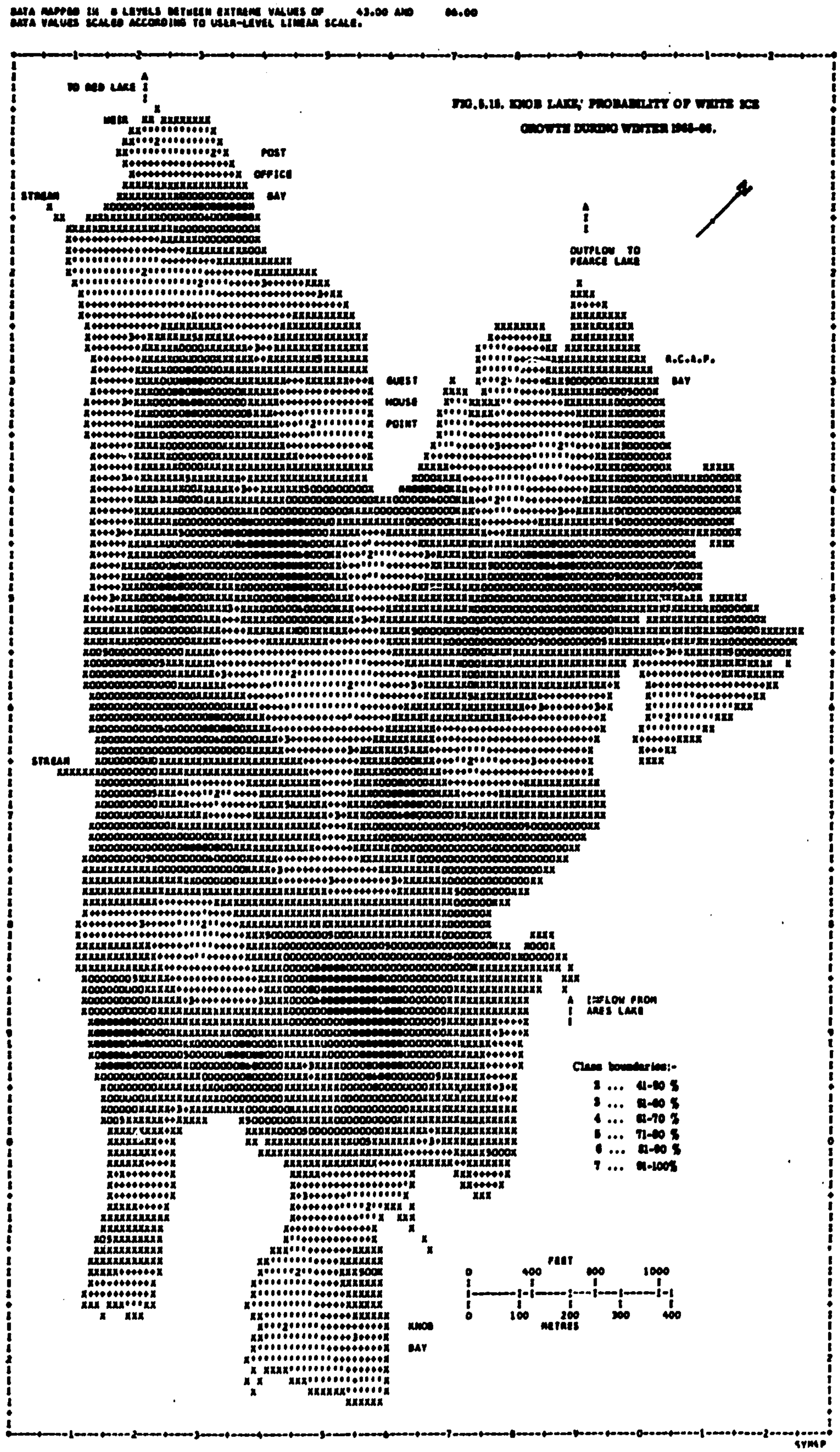


FIG. 5.15. KNOB LAKE; PROBABILITY OF WHITE ICE GROWTH DURING WINTER 1965-66.

a difference of 3 or 4 cases. This contrasts with the centre of growth commonly found in the distribution maps and suggests that floodings are fewer but larger in the centre of the lake. If this is anything more than a freak occurrence, it suggests that the critical stresses are more often achieved nearer the shores.

The general lack of pattern suggests that the basic cause of flooding, i.e. cracking, is fairly randomly distributed across the lake, as would be expected when air temperature is the dominant control. It would be interesting to establish a series of threshold limits, i.e. map probability of growth greater than chosen values.

Approach to areal explanation.

It is clear that there is considerable variation across the lake in addition to differences through the season, which cannot be explained by the temporal correlations established in Chapter 3. An attempt was made to define the areal component more rigorously by regression. Ideally, explanation should be sought in time and space simultaneously. The problem of achieving this was given some thought, but was not solved. Qualitatively, it may be supposed that as accumulated snowfall is the best criterion for predicting white ice at-a-site through the season so snow depth is the best criterion for predicting white ice at each stage over the lake. No significant relationship was found for over 1100 cases of snow depth and white ice at-a-time through 1965-6 and clearly a causal relationship involves a time lag.

An approach was made to the second half of the problem, using the computer to obtain mean snow depths at each of the 117 sites throughout the season, normalise mean snow depth and white ice thickness on March 3rd, the final white ice survey (Appendix B, NORMSTAND), and obtain punchcards of absolute residuals from regression (REVATR modified), which were then plotted by SYMAP. The result is reproduced in Fig. 5.16.

The "explanation" offered by the regression is very poor, with $r^2 = 0.017$. The estimating equation,

$$W_{ice} = 3.983 + 0.1468\log_{10}\bar{S} \qquad \text{(eq. 5.2)}$$

where $\bar{S}$ is mean snow cover at-a-site, has a standard error of Y = 1.0 standard deviations (since regression was on the standard scores matrix). The map of residuals shows marked patterning, which indicates that the regression hypothesis is consistently deficient over certain areas of the lake. In fact, the pattern bears strong resemblance to the maps of white ice growth, most especially that of March 3rd. The plane of regression intersects the map along the boundary between levels 5 and 6. Levels 6 and above are positive, i.e. the equation under-estimates white ice growth in these areas, and these show groupings in the centre of the lake and in the south and east. These are the two centres of growth found in the March 3rd white ice map (Fig. 5.14). Negative residuals are most prevalent in the northwest. The map levels are in standard deviations of the normalised white ice cover (Appendix C), and also, by coincidence, since $S.E._y \doteq 1.0$, in standard errors of the

DATA MAPPED IN 10 LEVELS BETWEEN EXTREME VALUES OF -2.02 AND 2.92
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

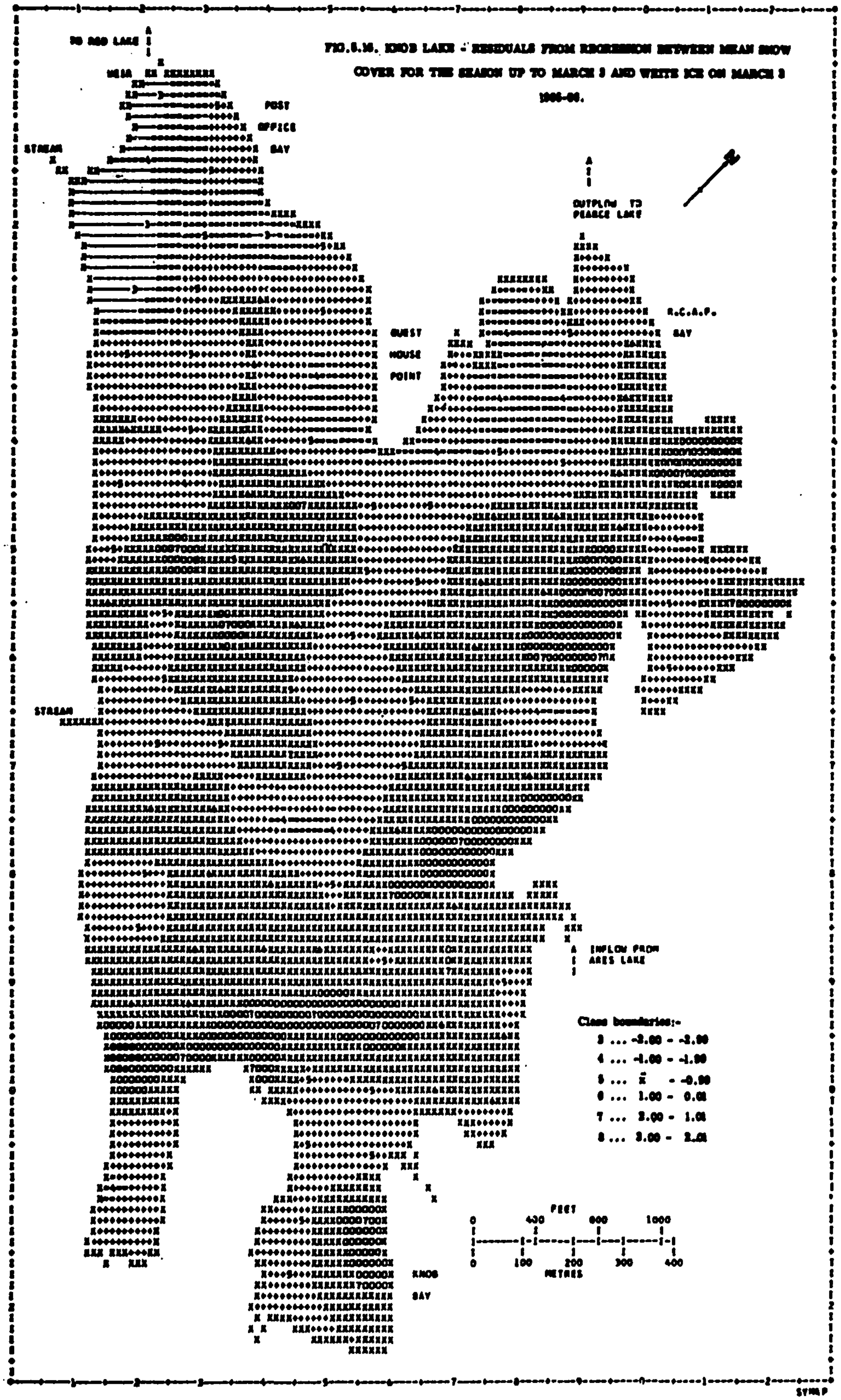


FIG.5.16. KNOB LAKE - RESIDUALS FROM REGRESSION BETWEEN MEAN SNOW COVER FOR THE SEASON UP TO MARCH 3 AND WHITE ICE ON MARCH 3

estimate.

It therefore appears that mean snow depth gives a very low level of explanation and does not describe peaks or lows in white ice growth. The explanation may be complex and involve parameters which have not been measured and may be difficult to measure. The following deducations can be made: (1) an important part of the problem may be in comparing a single, static pattern with an average of a changing pattern; (2) density of snow and ice thickness are factors affecting the hydrostatic head potential which may be important; (3) since white ice has generally lower strength than black ice, perhaps a clustered distribution is created by white ice growth making the area more susceptible to cracking in spite of the increased ice thickness, i.e. white ice encourages more white ice; (4) buckling may favour certain areas, adding to or reducing the hydrostatic head created by snow cover.

In the case of deduction (1), maps of snow cover (Figs. 5.1, 5.3, 5.5, 5.7, 5.9, 5.11, 5.13) have shown that there is a moderate continuity of depth in the areas of extreme residuals. The pattern is more changeable across the middle of the lake. However, it has also been shown that the white ice process is discontinuous. Growth is stepped up when favourable air temperatures and an above average snow cover coincide. This will give extra emphasis to ephemeral patterns of snow. To study this would require integration over time and space and probably more detailed records of snow cover. For (2), it was found in the study of buckling that there were important deviations in density from an assumed mean. However, it was also found that mean density seemed lower in drifted areas and higher in low, windpacked snow. It can be seen that this acts in a reverse direction to that needed to increase the explanation of residuals, i.e. the equation overestimates growth where the snow is likely to be more dense and the overburden proportionally greater. But increasing ice thickness through the season suggests that early season snow depths should be weighted as more important. The third possibility is a problem which cannot be tackled here for lack of data. The final consideration is still not proven.

Hence, there seem to be other important factors that remain undefined.

Comparison of end-of-season ice cover: 1964, 1965 and 1966.

White ice and total ice were selected from the records of the March survey, 1966, and mapped using SYMAP for comparison with the two former years (Figs. 5.17 and 5.18). The maps of lake cover for previous years, which were published by Adams and Shaw (1966) and Archer (1966), are included for reference in Appendix E, Figs. E.4 to E.6. In all maps of white ice and total ice the isopleth interval is set arbitrarily at 5 in (12.7 cm) of ice thickness.

The three years show marked differences in the amount of white ice present. Visually, the modal level is less than 5 inches in 1964, between 5-10 and 10-15 inches in 1965 and (from histogram, Appendix C, Fig. C.17) 10-15 inches in 1966. From equation 3.4 accumulated snowfall

DATA MAPPED IN 6 LEVELS BETWEEN EXTREME VALUES OF 4.50 AND 24.00
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

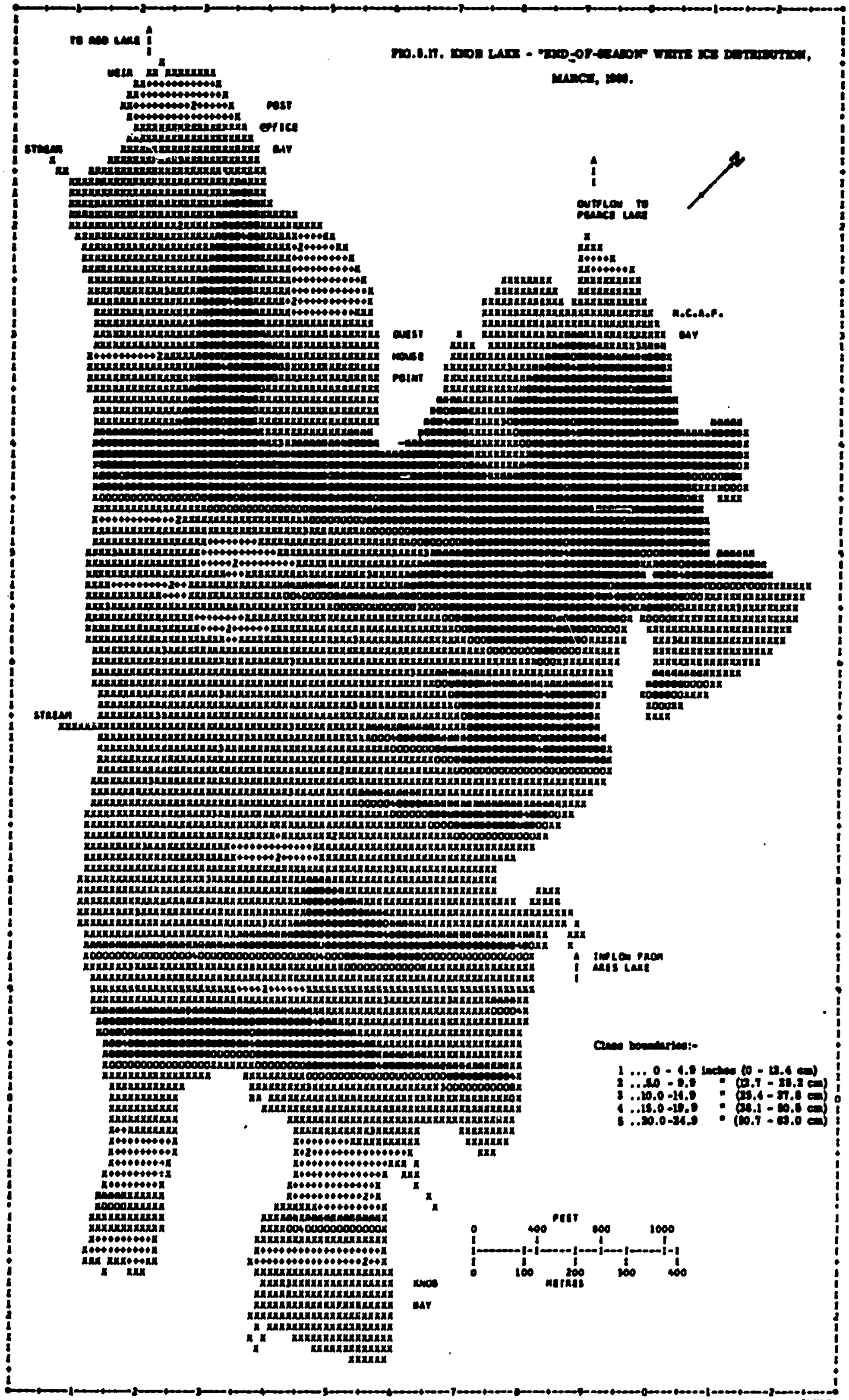


FIG.8.17. KNOB LAKE - "END-OF-SEASON" WHITE ICE DISTRIBUTION,
MARCH, 1966.

Class boundaries:-

1 ... 0 - 4.9 inches (0 - 12.4 cm)
2 ..5.0 - 9.9 " (12.7 - 25.2 cm)
3 ..10.0 -14.9 " (25.4 - 37.8 cm)
4 ..15.0 -19.9 " (38.1 - 50.5 cm)
5 ..20.0 -24.9 " (50.7 - 63.0 cm)

is expected to be a major determinant. This is largely born out by the records: total snowfall up to March 27th, 1964 was 6.79 inches (17.24 cm) water equivalent, up to March 26th 1965, 9.52 in (24.19 cm) w.e., and to March 25th 1966, 9.16 in (23.26 cm) w.e. The second factor in the equation, accumulated run of wind, is certainly outweighed, since this offers no explanation of the differences: 40,487 miles (64,779 km) in 1964, 37,552 miles (60,083 km) in 1965 and 35,078 miles (56,125 km) in 1966. Nor, indeed, does accumulated degree days explain the contrast: 4,976 in 1964, 5,291 in 1965 and 4,215 in 1966. But the mildness of 1965-6 was accompanied by many large diurnal ranges. Notably, December, 1965, showed 42% of the days with ranges greater than 22°F or 12.5°C, and this coincided with a favourable snow cover. Both 1965-6 and 1964-5 experienced a greater frequency of high diurnal ranges than 1963-4 (Chapter 4).

The distribution of white ice shows poor concordance from year to year. Only the south and east shores, where the prevailing northwest wind deposits a windward dune, show any trend towards persistance. However, 1964 and 1965 both show a slight trend towards a central peak of growth, which has also been found for 1966 up to early March (v.s.). The peak of white ice across the mouth of Post Office Bay in 1966 is interesting. The crack responsible for this upwelling can be seen in Plate 5.1. It was first noticed in November, but it seems to have re-opened in March, when a deep snow cover gave it greater significance. In fact, this late growth is reflected in the total ice map.

Total ice was greatest in 1965 with a modal level apparently

Plate 5.1: Decaying ice surface on Knob Lake from the air, early June 1966. Note cracking, especially the old crack extending west (left) from the Guest House Point.

Plate 5.2: Aerial view of Knob Lake and its basin in early June 1966.

DATA MAPPED IN 7 LEVELS BETWEEN EXTREME VALUES OF 21.90 AND 42.00
DATA VALUES SCALED ACCORDING TO USER-LEVEL LINEAR SCALE.

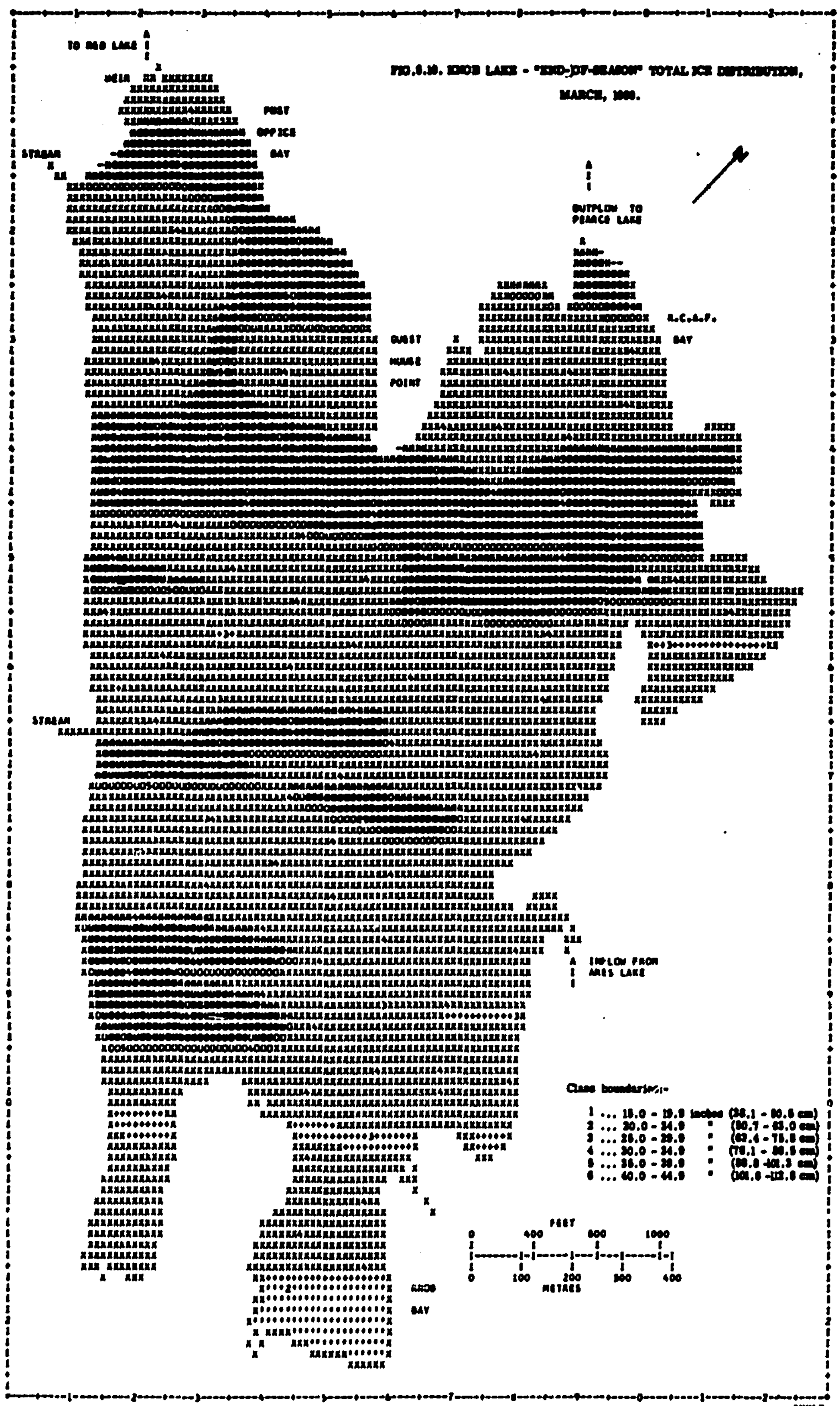


FIG.5.10. KNOB LAKE - "END-OF-SEASON" TOTAL ICE DISTRIBUTION, MARCH, 1960.

between 40 and 50 inches (c.100 to 127 cm). 1964 and 1966 are more comparable, with clear modes at 30-35 in (76 to 89 cm). From equation 3.2 accumulated degree days would be expected to explain this variation and this is born out by the figures quoted above. However, in detail the controls are more complex, involving also the controls affecting white ice, and this is indicated in the maps of 1964 and 1966. The milder winter of 1965-6 is compensated for by greater snowfall and frequency of "critical" diurnal ranges and consequently more white ice.

Distribution suggests peaks of total ice generally north-of-centre largely of black ice and at the southeastern shore largely of white ice. In general, this is comparable to the distributions found through the Knob Lake basin (Chapter 6), with the exception of the apparently anomalous feature off Guest House Point in March 1966.

Conclusions.

Cracking is not markedly localised through the season, but appears to have a more or less random distribution across the lake. The amount of white ice formed is basically controlled by the buoyancy level of the ice sheet, which depends on ice thickness, snow depth, snow density and any stresses affecting buoyancy such as shore support or folding. Mean snow depth alone is found to be a poor indicator, and slushing may "fossilise" ephemeral snow patterns. The most powerful criteria for lakewide growth appear to be (1) generally above average snow depths and (2) a high frequency of "critical" daily ranges of air temperature.

Plate 5.3: The first white ice phase off the west side of Guest House Point, November 1965. The entire foreground is composed of new ice.

The two phases of white ice growth in the winter of 1965-6 occurred in December and March, and were lake-wide. These coincided with months of exceptional sub-freezing diurnal temperature ranges, which are likely to have caused widespread tension cracks. Snow cover slowly increased during the preceding weeks, forming a hydrostatic head.

CHAPTER 6

VARIATIONS IN ICE COVER IN THE KNOB LAKE BASIN

In March and April 1965 and 1966 surveys were made of the ice and snow cover of the basin upstream from Knob Lake. The basin covers an area of c. 13.5 ml^2 (21.6 km^2) to the south of Knob Lake itself. The outflow is mainly through the weir in Post Office Bay (Knob Lake), where the McGill Laboratory maintains a gauging station, although a small amount drains through the old exit in RCAF Bay (Knob Lake), mainly in summer (Findlay, 1966, p.43). 23.9% of the watershed is lake or swampland that receives a winter cover of ice. According to Findlay (ibid., p.18), the basin retains over 29,000 ac ft (13,900 m^3) of permanent surface water in these water bodies.

Tables 6.1 and 6.2 summarise the main characteristics of the lake covers during the two "spring surveys". Standard deviations for each characteristic and each lake, are intended to give an indication of variability within each lake, although the data were not normalised at this level. Figs. E.7 to E.12 in Appendix E are the maps of raw data for spring 1965 produced by Archer (1966). Maps 6.1 through to 6.6 here plot variations in the different characteristics across the major lakes of the basin for spring 1966 in terms of standard deviations from the basin mean, excluding Knob Lake. The data were tested for normality by Snedecor's tests of skewness and kurtosis and transformed where necessary to obtain a normal distribution using NORMSTAND (Appendix B).

Table 6.1 CHARACTERISTICS OF LAKES IN THE KNOB

Lake	Area 10^6 sq. ft	Volume ac. ft	Total ice Thickness n	Total ice Thickness $\bar{x}$	Total ice Thickness s	Total ice Vol 10^6 cf	White ice Thickness n	White ice Thickness $\bar{x}$	White ice Thickness s	White ice Vol 10^6 cf	Black ice Thickness n	Black ice Thickness $\bar{x}$	Black ice Thickness s	Black ice V[illegible] $10^{[illegible]}$
Knob	20.68	8780	80	35.0		60.50	276	14.0	4.4	24.50	80	20.0		34.
Malcolm	18.88	8420		31.0	5.6	49.00	37	12.0	3.5	18.88		17.5	3.0	27.
Easel	9.68	4670		32.0	4.2	25.80		(14.5)		16.39		(15.0)		12.
Houston	6.40	1750		32.0	2.9	17.15	48	14.5	3.2	7.73		15.5	4.3	8.
Ares	5.76	1110		29.0	5.3	13.92	9	18.5	5.9	8.88		13.0	6.0	6.
Gene	4.25	617		30.5	5.2	10.81		(14.5)		5.17		(15.0)		5.
Osprey	3.23	875		30.5	3.7	8.20	11	13.5	3.4	3.64		16.0	3.4	4.
Phred	2.62	664		30.0	1.1	6.54		15.5	1.8	3.38		12.5	-	2.
Communi-cations	2.27	514		34.0	3.6	6.43	3	14.0	-	2.65		14.5	-	2.
South	1.20	315		30.0	4.7	3.00	6	14.0	2.1	1.40		15.5	1.4	1
North	1.08	242		29.5	1.6	2.66	5	14.5	3.0	1.31		14.0	4.2	1
Middle	0.57	54		30.0	2.5	1.43		14.0	1.4	0.67	6	15.5		0
Cowan	0.51	64		24.0	-	1.02		(14.5)		0.62		(15.0)		0
Barr	0.48	51		30.0	3.4	1.20	11	15.5	5.4	0.62		14.5	1.8	0
(Others	7.88	903		(30.5)		19.20		(14.5)		9.43		(15.0)		9
TOTALS	85.49	29029				226.86				104.97				117

* a% = Percentage occurrence at the surface. b% = Percentage occ

Table 6.1 CHARACTERISTICS OF LAKES IN THE KNOB LAKE BASIN, SPRING 1966

Lake	Area 10^6 sq. ft	Volume ac. ft	Total ice				White ice				Black ice				Snow				Slush					Water level	
			Thickness			Vol 10^6 cf	Thickness			Vol 10^6 cf	Thickness			Vol 10^6 cf	Thickness			Vol 10^6 cf	Depth		$\bar{x}$ when present	a%*	b%*	$\bar{x}$	s
			n	$\bar{x}$	s		n	$\bar{x}$	s		n	$\bar{x}$	s		n	$\bar{x}$	s		$\bar{x}$	s					
Knob	20.68	8780	80	35.0		60.50	276	14.0	4.4	24.50	80	20.0	-	34.40	276	17.0		29.30			7.0	11%	25%	+2.5	
Malcolm	18.88	8420		31.0	5.6	49.00	37	12.0	3.5	18.88		17.5	3.0	27.12		18.0	4.7	28.40	2.5	4.1	5.0	27%	63%	+1.0	1.2
Easel	9.68	4670		32.0	4.2	25.80		(14.5)		16.39		(15.0)		12.10		14.5	3.0	16.80	4.0	4.1	7.0	66%	100%	+1.5	3.5
Houston	6.40	1750		32.0	2.9	17.15	48	14.5	3.2	7.73		15.5	4.3	8.26		19.0	4.3	10.20	0.0	-	2.0	9%	14%	+1.5	0.9
Ares	5.76	1110		29.0	5.3	13.92	9	18.5	5.9	8.88		13.0	6.0	6.25		18.5	4.7	8.86	3.5	4.7	8.5	45%	69%	+4.0	4.2
Gene	4.25	617		30.5	5.2	10.81		(14.5)		5.17		(15.0)		5.31		14.0	4.6	4.95	7.0	2.3	8.0	88%	85%	+7.5	5.0
Osprey	3.23	875		30.5	3.7	8.20	11	13.5	3.4	3.64		16.0	3.4	4.30		18.5	4.7	4.97	3.0	2.9	5.0	60%	78%	+3.5	2.6
Phred	2.62	664		30.0	1.1	6.54		15.5	1.8	3.38		12.5	-	2.73		15.0	-	3.28	7.0	4.7	8.5	33%	33%	+0.5	2.1
Communi-cations	2.27	514		34.0	3.6	6.43	3	14.0	-	2.65		14.5	-	2.74		17.5	3.1	3.34	1.0	1.9	2.5	50%	78%	+2.0	1.5
South	1.20	315		30.0	4.7	3.00	6	14.0	2.1	1.40		15.5	1.4	1.55		16.0	3.9	1.60	1.0	-	7.0	25%	44%	+3.0	3.1
North	1.08	242		29.5	1.6	2.66	5	14.5	3.0	1.31		14.0	4.2	1.26		18.0	3.9	1.62	1.0	-	4.0	33%	43%	+1.5	1.9
Middle	0.57	54		30.0	2.5	1.43		14.0	1.4	0.67	6	15.5		0.74		15.0	2.6	0.71	2.0	-	2.0	37%	25%	+3.0	1.1
Cowan	0.51	64		24.0	-	1.02		(14.5)		0.62		(15.0)		0.64		12.5	-	0.53	10.0	-	13.0	100%	100%	+10.0	-
Barr	0.48	51		30.0	3.4	1.20	11	15.5	5.4	0.62		14.5	1.8	0.58		19.0	5.0	0.76	3.5	4.7	8.5	41%	42%	+3.5	3.3
(Others	7.88	903		(30.5)		19.20		(14.5)		9.43		(15.0)		9.45		(16.5)		10.40			(5.5)				)
TOTALS	85.49	29029				226.86				104.97				117.93				127.06							

* a% = Percentage occurrence at the surface. b% = Percentage occurrence above and within.

Table 6.2 SUMMARY OF ICE COVER CHARACTERISTICS IN THE KNOB LAKE BASIN, SPRING 1965

Lake	Total ice			White ice			Black ice			Snow			Water level	
	n	$\bar{x}$	Vol	n	$\bar{x}$	Vol 10^6cf	n	$\bar{x}$	Vol	n	$\bar{x}$	Vol	n	$\bar{x}$
Knob	188	46.0	81.80	310	12.0	20.68	166	35.0	60.35	351	18.0	31.12	186	+0.5
Malcolm	88	40.0	62.60	130	14.0	21.24	84	25.0	39.25	143	18.0	28.30	86	+1.5
Easel	39	35.0	28.20	49	14.5	10.74	36	20.0	16.15	97	18.5	14.95	40	+1.0
Houston	39	40.0	21.32	64	17.0	9.15	38	20.0	10.65	67	16.0	8.54	36	+2.0
Ares	40	37.0	17.80	45	17.0	8.06	37	20.0	9.60	50	19.5	9.35	40	+1.0
Gene	29	36.5	12.92	30	16.5	5.87	27	19.0	6.73	34	18.0	6.37	26	+1.4
Osprey	17	37.5	10.09	19	17.0	4.53	12	20.5	5.52	27	16.0	4.31	15	+1.5
Phred	19	36.0	7.85	19	13.0	2.86	19	28.0	6.11	19	18.0	3.93	19	+1.5
Communi-cations	5	43.0	8.13	20	13.5	2.57	5	28.6	5.39	21	14.5	2.74	5	-0.5
South	2	26.0	3.60	7	15.5	1.57	2	22.0	2.20	7	16.5	1.65	2	+1.0
North	7	41.0	3.69	8	13.5	1.43	6	28.0	2.52	9	14.5	1.31	7	0.0
Middle	3	42.0	2.00	12	13.0	0.62	3	29.5	1.40	12	13.0	0.62	3	0.0
Cowan	3	25.0	1.06	3	14.0	0.60	3	10.5	0.45	3	28.5	1.21	3	+2.5
Barr	(	38.0)	1.52	4	12.5	0.50	(	23.0)	0.92	4	13.0	0.52	1	(+1.0)
Trigger	5	30.0	0.80	5	15.5	0.42	5	14.0	0.37	11	19.0	0.51	5	+1.5
Others	(	38.0)	23.95		(15.0)	9.45		(23.0)	25.19		(17.5)	11.10		(+1.0)
TOTALS/ MEANS		38.0	287.33		15.0	101.49		23.0	192.80		17.5	126.53		+1.0

The standard scores were then plotted for each variable with the exception of hydrostatic water level, which could not be normalised in the existing form of the records. (For transformation details see Appendix C.) Because of incomplete data, it was necessary to repeat the normalisation process for each variable independently.

The maps are shaded to distinguish areas of exceptional variations in the data, that is, variations greater than one standard deviation from the mean value. This gives a visual and quantitative indication of the significant variations both within and between lakes. No attempt was made to make a more rigorous analysis of covariance between lake cover and local environment, because of the enormity of the problem and the fact that the analysis that was made suggested that the data did not merit it.

Analysis began with Table 6.1 on which various tests were made with rank correlation between the lake covers and environmental parameters. From the table there appears to be some correlation between size of lake and the mean total ice thickness. Volume is included in the table, but was not used in analysis since in the few cases where it does not rank equal with surface area lake cover data were poor and mean basin values had been interpolated. No interpolated values were used. The χ_r^2 statistic indicated a correlation approaching the 30% significance level between lake area and mean total ice. Excluding the rather anomalous mean for Communications Lake, this correlation becomes significant approaching the 5% level. It is reasonable to regard Communications Lake as a special case, since (1) when it is removed from the analysis the significance level based on the other 13 lakes improves considerably and, (2) only two of the seven measurements made on the lake were free from water layers in the ice, which were counted in the total, among the seven two readings of 40 in (nearly 1 m) with multiple layering.

Given this, the question then arose as to whether this is more a function of black ice growth or of white ice growth. Chi square values indicated that black ice showed a correlation approaching 30% significance with area of lake, but that a slight negative correlation existed for white ice, which, however, was not significant. The data show a clearer negative correlation (approaching the 30% level) for white ice versus black ice within the basin that is more clearly and accurately shown by tests elsewhere (Chapter 3, eq. 3.3), which is the basis for this slight negative correlation. Thus, larger lakes have thicker ice owing more to increased black ice than to white ice. Snow, slush, water level and snow-with-slush showed no relationship to size of lake. Hence it appears that the increased black ice on larger lakes is not directly due to greater snow deflation resulting from exposure. It seems rather to be related through white ice development.

It is unlikely that the thicker black ice of the larger lakes is due to larger surface area exposed to the atmosphere, since volumes and hence heat storage within the lake body vary approximately in proportion to surface area. It is more likely that the difference is created by the more important role played by the area of downwind deposition of snow on smaller lakes. Boundary effects are less on the larger lakes and hence slushing potential is less.

Size is the crudest environmental parameter. Orientation of long axes, shape, shore vegetation and shore slope were added. It is difficult to appraise these factors, since classification is poorly developed in some and measurement units are often by attributes. The classification used here for vegetation is that devised by Hare (1959) from air photo study over Labrador-Ungava. It is based more on physical aspects of the vegetation cover than on botanical considerations and, whilst it may be criticised on botanical grounds, it nevertheless has proven useful in studying snow distribution; this is the main importance of vegetation for lake ice. Cowan (1966) and Adams et.al. (1966) have found significant differences in water content between cover types in Hare's classification. These authors have also pointed out that differences would be greater if transition zones could be differentiated. It is the extent of these frontier zones upwind and downwind of vegetation blocks that is important to snow cover on lakes. According to these authors, lake snow cover has the lowest mean depth and water content of the four categories used.

Mean shore slope was classified into categories of less than 5%, 5-10% and over. This was done by taking lines on the map perpendicular to the shore at intervals of 200 ft (c.60 m) along the shore beginning at an arbitrarily chosen point. The lines were extended 1000 ft from shore and estimates made from a contour interval of 50 ft.

Orientation of long axes and classification of shape were investigated with limited application. Bryan (1964; 1966) used Welch's (1948) "maximum effective length", the longest straight line that can be fitted into a lake to measure orientation, and then arbitrarily distinguished groups for every 10 degrees of displacement from True North. Table 6.3 shows the major lakes of the basin classified according to orientation. The number of classes was determined by the empirical formula:

$$k = 1 + 3.33 \log_{10} n \qquad \text{(eq. 6.1)}$$

in which k is the number of classes and n the number of values. This indicated four classes. Strong parallelism, however, virtually nullifies the validity of such a classification for the purposes of this study. Similarly, shape indices such as Welch's shore development index (op.cit.) gave poor differentiation and were not used.

A systematic inventory was made of the relationships indicated by Figs. 6.1 to 6.6 and anomalous areas investigated more closely using the original data.

Gene Lake (Fig. 6.1) offers an interesting case of local slushing. The western arm shows a marked wave effect in snow, slush and water level maps, not reflected in total ice. White and black ice distribution could not be mapped here because of the abnormally deep slush. Snow and slush together are abnormally high for the basin and show the influence of the steep side-slopes and heavily wooded southern and eastern shores. The banding suggests a possibility of folding in the ice sheet. But when the buoyancy formula (eq. 4.3) was applied to points on the profile along this arm, almost perfect agreement was found between predicted and actual water levels, if a

KEY TO LAKE COVER MAPS OF KNOB LAKE BASIN

1. Maps of topographic environment:

A	close lichen woodland
B	open lichen woodland
C	open lichen scrub
D	swamp or muskeg
||//||	slopes greater than 5% (average over 200 ft)
--30--	isobaths in feet

2. Maps of lake cover:

~-1~	isolines at intervals of one standard deviation from the mean ($\bar{x}$) for the basin in each variable.
|||||	areas greater than one standard deviation above average.
⁚⁚⁚	areas greater than one standard deviation below average .

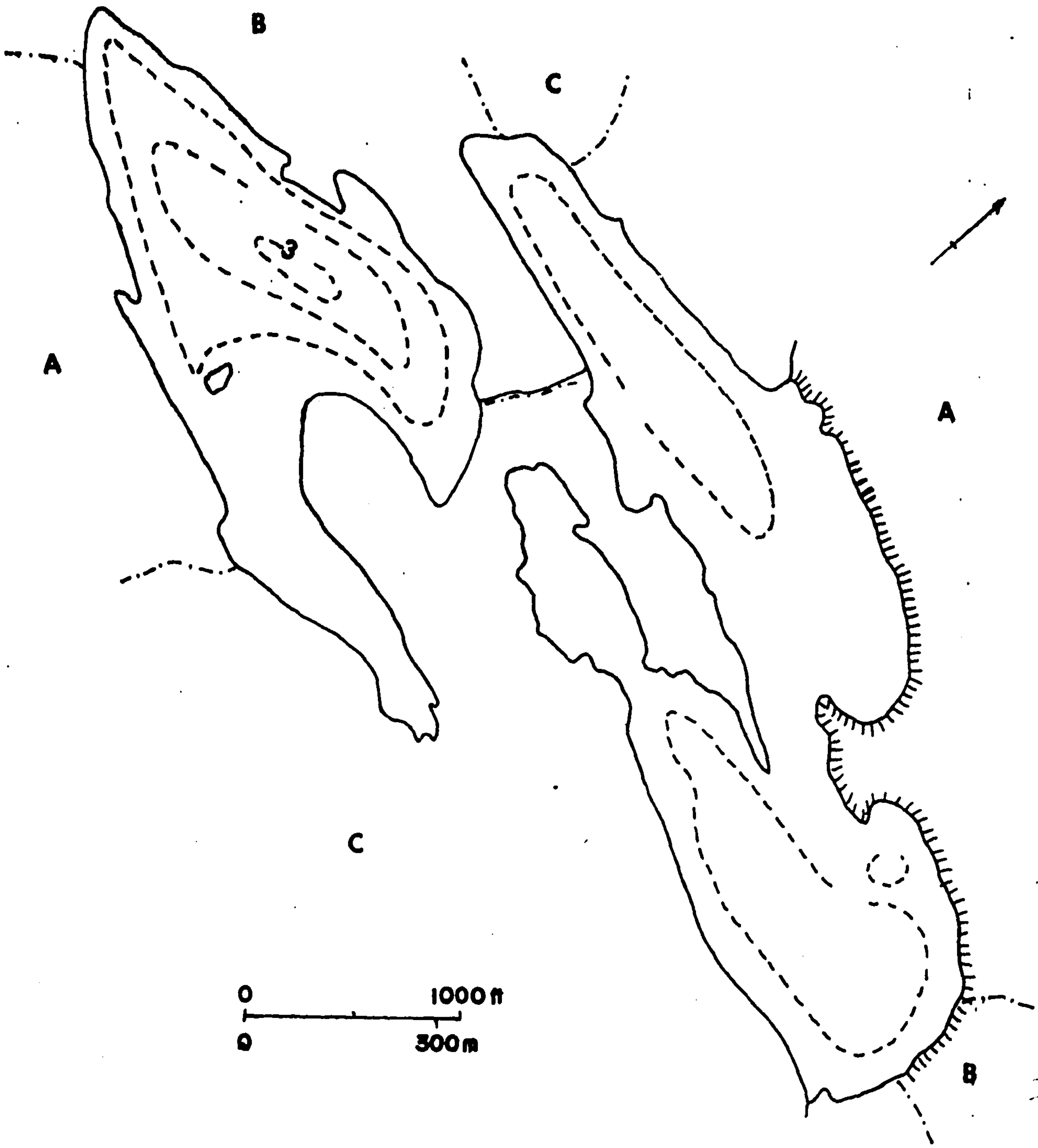


Figure 6.1a: Gene and Phred Lakes topographic environment.
(key following page 92)

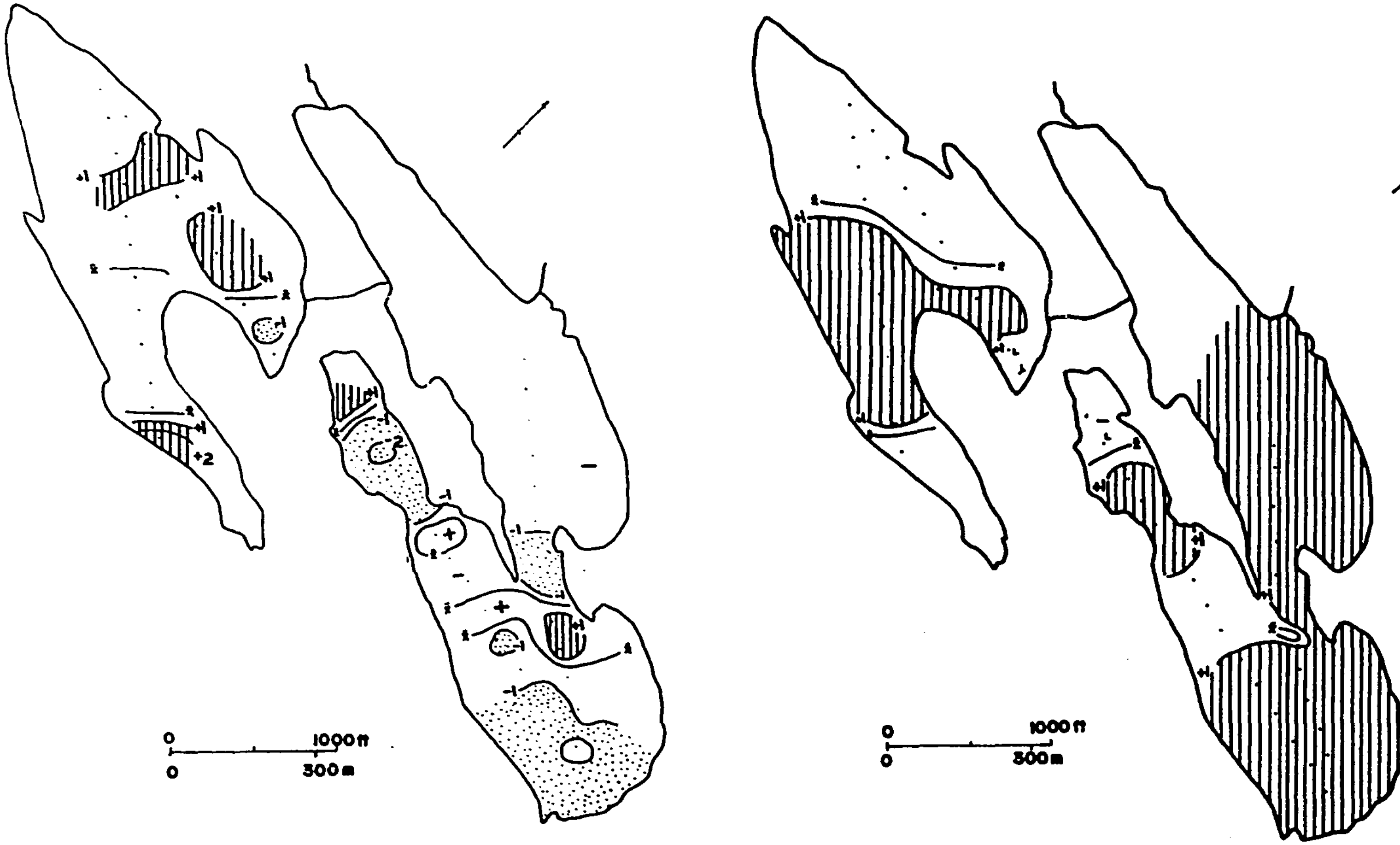


Figure 6.1b: Gene and Phred Lakes snow(left and slush distribution(right), March, 1966. (key following page 92)

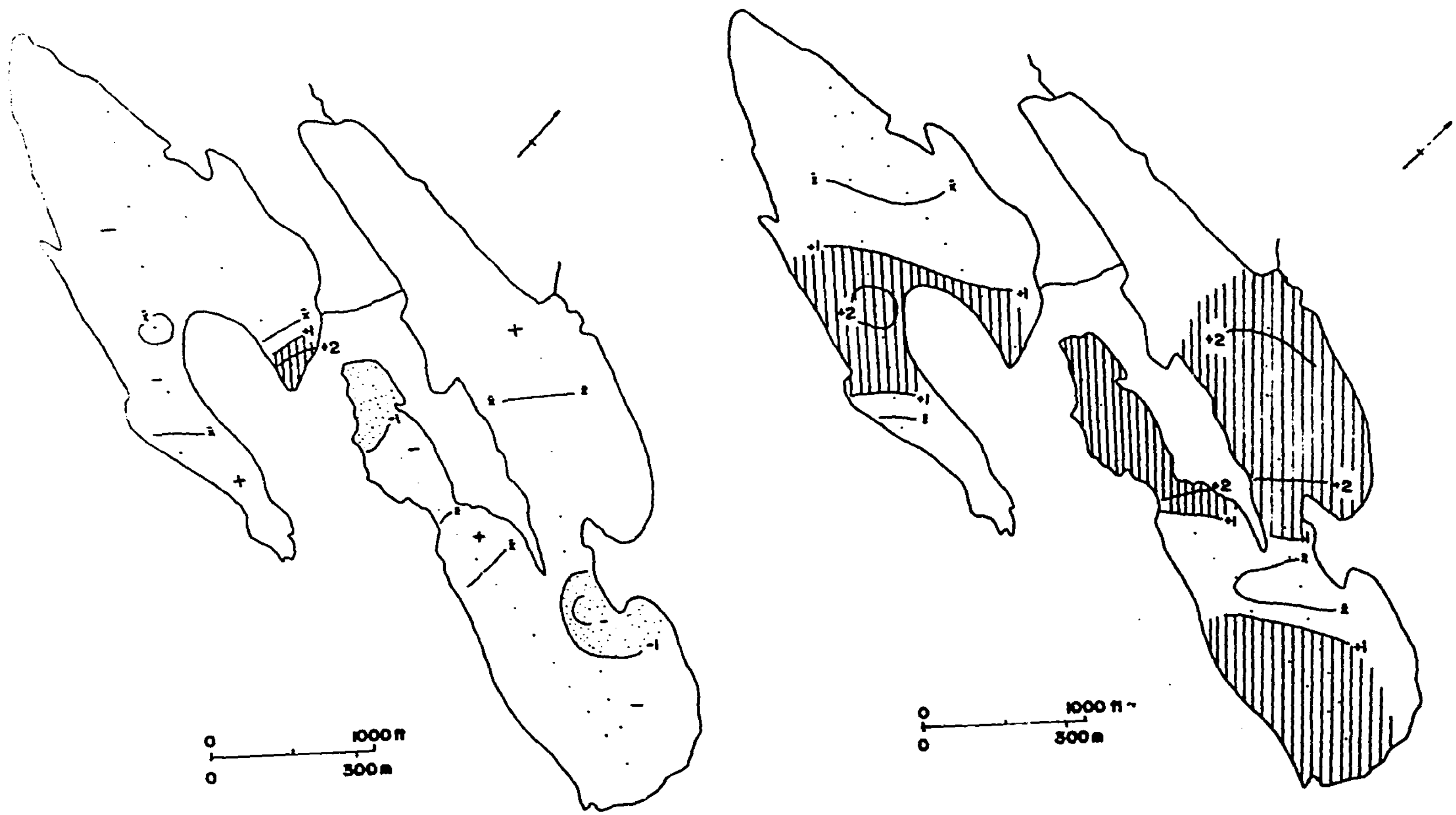


Figure 6.1c: Gene and Phred Lakes total ice(left) and water level distribution (right), March, 1966. (key following page 92)

Table 6.3

LAKE ORIENTATIONS

Class boundaries (T.N.)	Lakes	Frequency
31°45' - 40°45'	Malcolm, Osprey, Houston, Phred, Middle	5
40°45' - 49°45'	Knob, Ares, Gene, North	4
49°45' - 58°45'	Easel	1
58°45' and greater	Communications, South	2

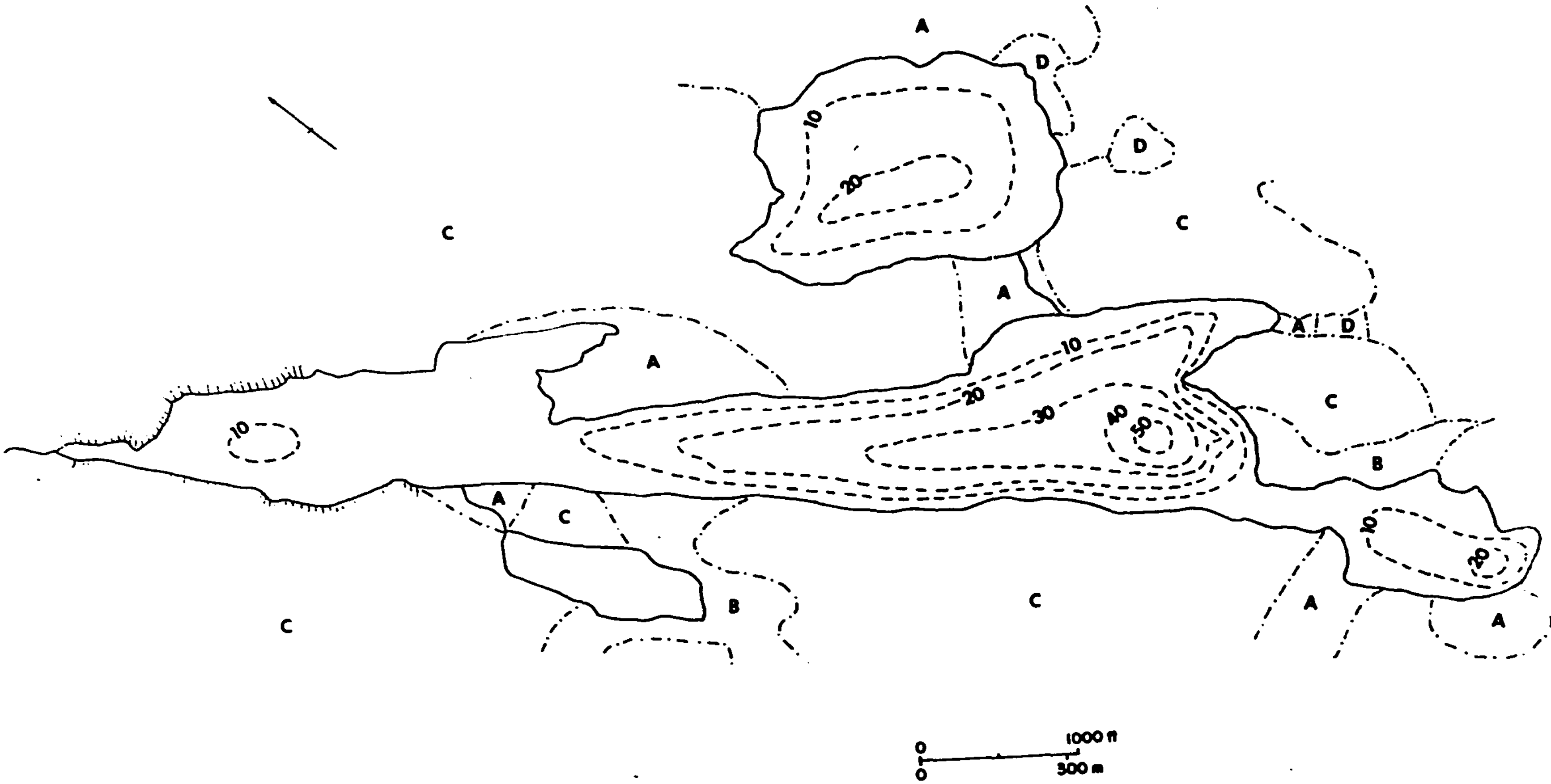


Figure 6.2a: Houston and Communications Lakes, topographic environment
(key following page 92)

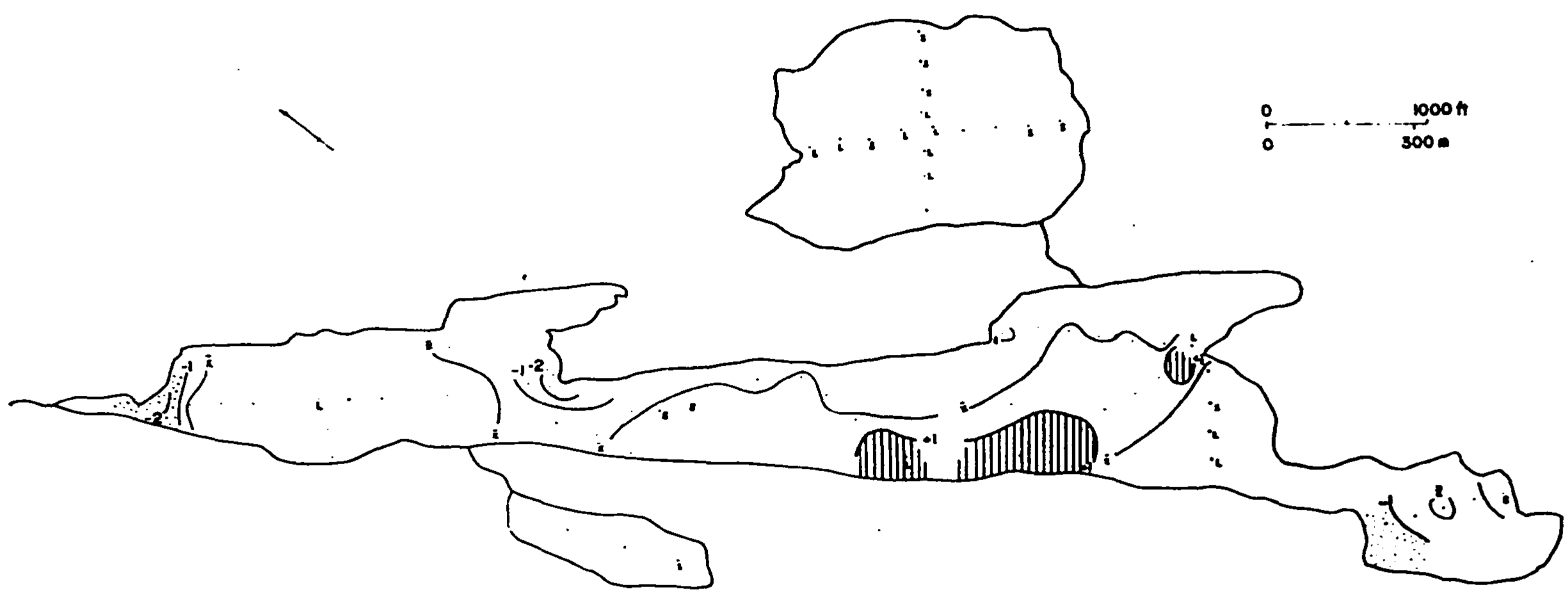


Figure 6.2b: Houston and Communications Lakes White ice distribution, March, 1966. (key following page 92)

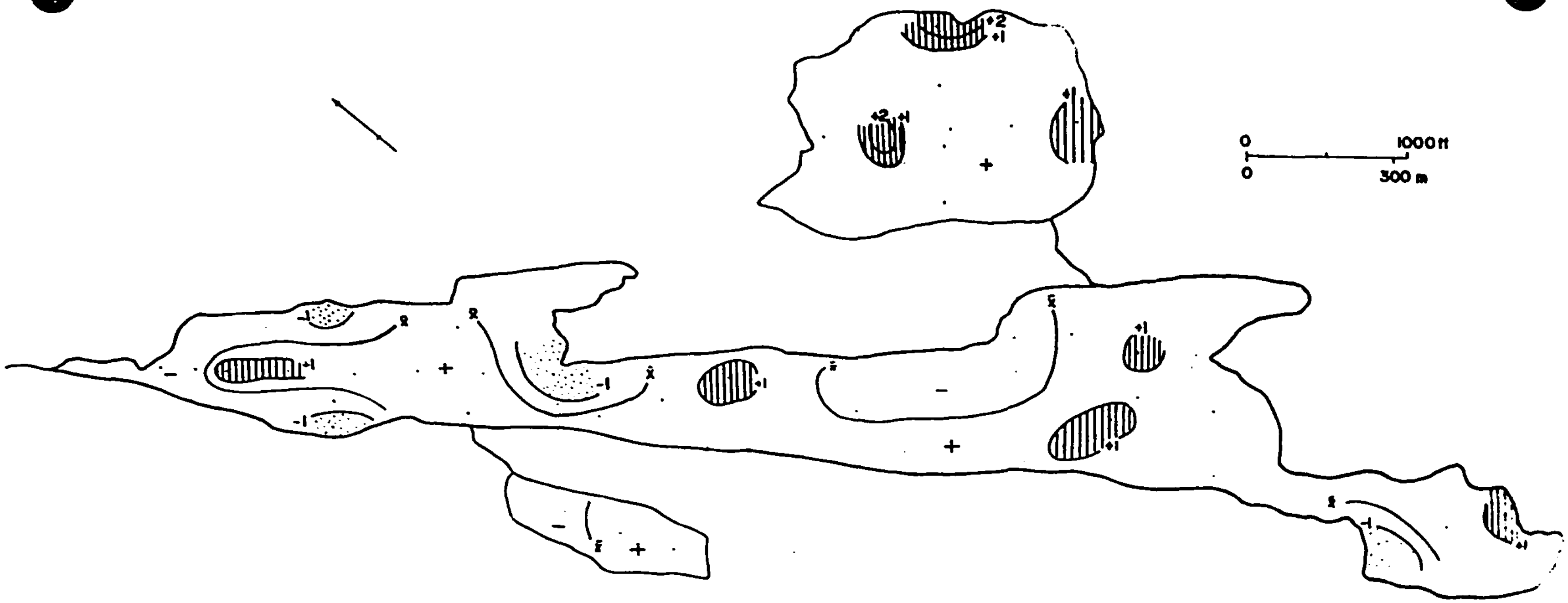
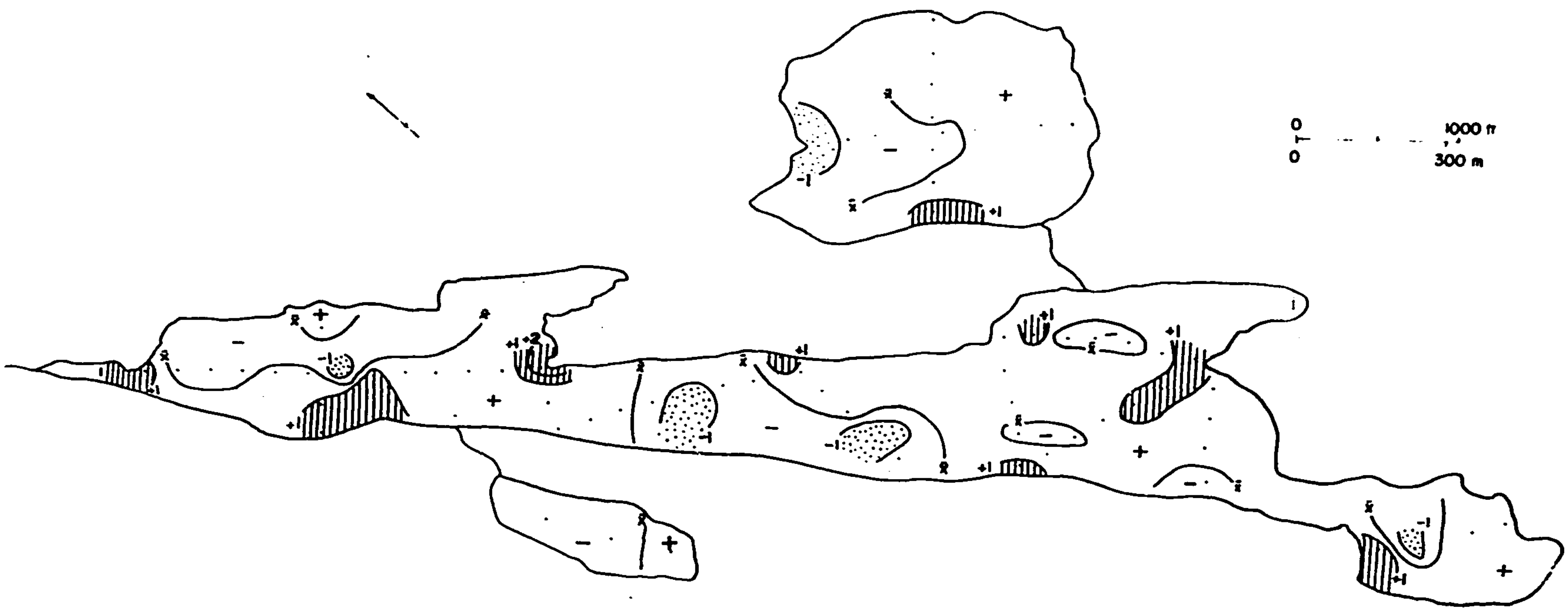


Figure 6.2c: Houston and Communications Lakes total ice (above) and snow(below), March, 1966 (key following page 92)



mean unit weight of $\gamma = 0.7 \text{ g cm}^{-3}$ was assumed for the slush. Excluding the slush from the equation would result in an apparent upfold midway along the arm. The problem thus arises of whether slushing caused depression or simply followed the slope of a folded surface. It seems likely that slushing could be a self-perpetuating process for a brief period until the rate of flooding is sufficiently reduced and hydrostatic equilibrium is attained, extra loading creating added flood potential. Initial localisation may result from a slightly tilted surface or from a slightly irregular surface formed by the quick freezing of minor up-wellings.

Phred Lake (Fig. 6.1) also shows higher than average amounts of snow and slush. Here total ice increases southwards as black ice decreases and white ice increases, suggesting, as on Knob Lake, a strong persistence through the winter of this snow pattern and hence continuity in the area of white ice potential. In the case of Phred Lake it is notable that this southern accumulation occurs in spite of the open lichen scrub borders and a low shore slope.

The general tendency for accumulation at the downwind end is common to all the lakes of the basin irrespective of shore characteristics and is only enhanced by containing shore features. Likewise, there is a general tendency for white ice to increase downwind and black ice to decrease. Houston Lake shows this clearly. Here, in a large lake, slushing was very slight and did not affect the overall distribution of dry snow. Being among the most northerly oriented group of lakes in the basin, Houston (Fig. 6.2) shows lee dunes of snow on its western side,

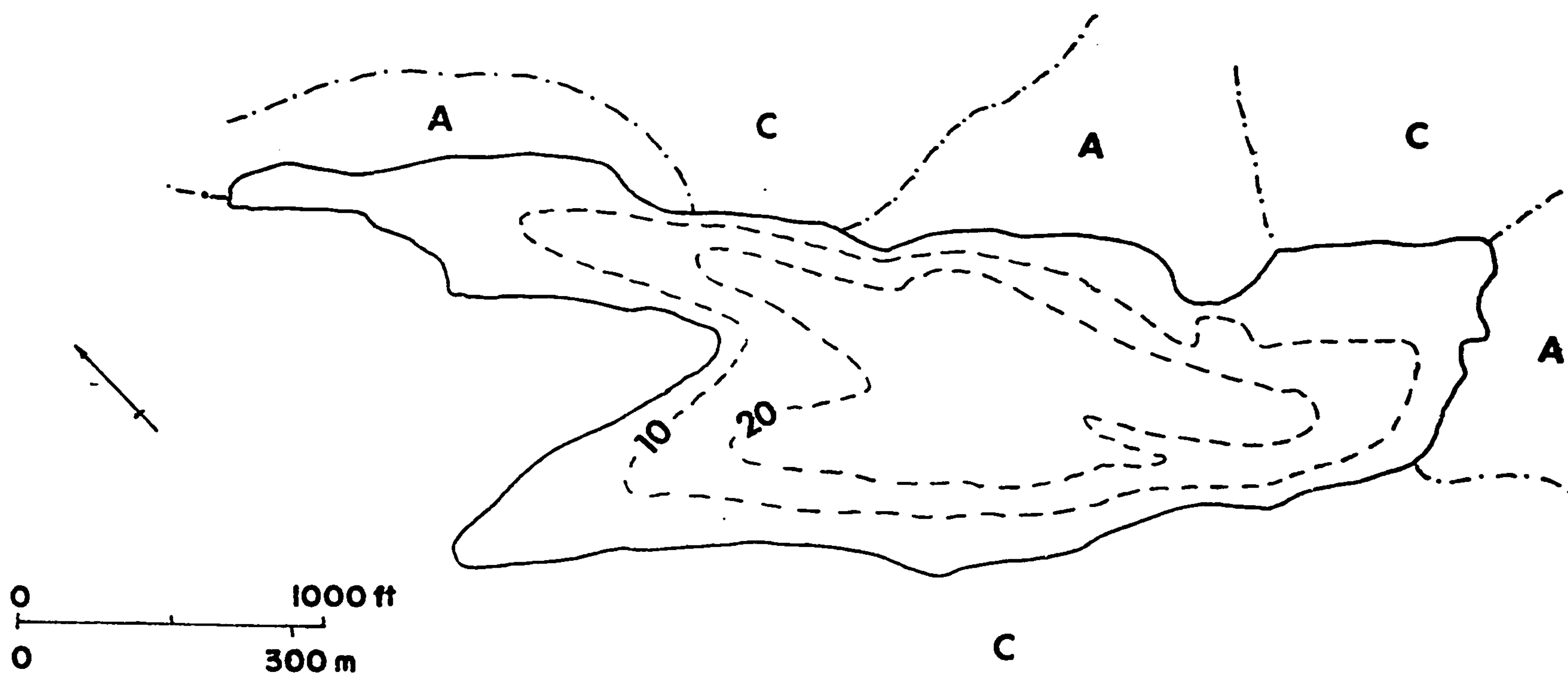


Figure 6.3a: Osprey Lake topographic environment (key following page 92)

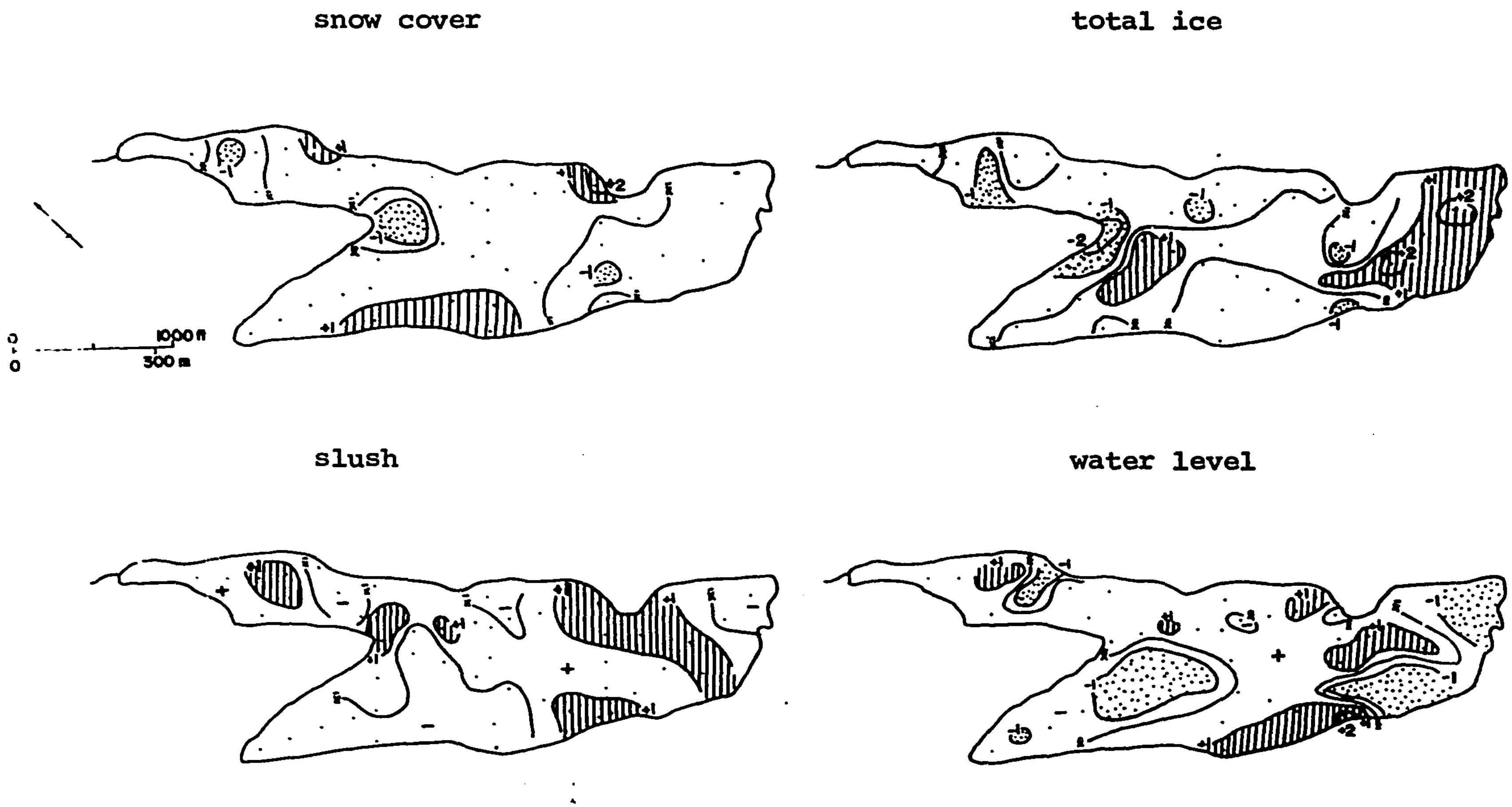


Figure 6.3b: Osprey Lake distribution, March, 1966. (key following page 92)

but the steep-sided exit funnels the wind down the centre of the lake at the northern end resulting in deflation. Here a small area of thicker total ice is the result of increased black ice. Total ice also increases towards the centres of the two southern bathymetric basins, where snow has accumulated. Here white ice is the cause. Thus, as on Knob Lake, the dominant element in total ice thickness changes from upwind to downwind edges. Water level measurements show that loading was still creating a slushing potential at the time of survey.

Osprey Lake (Fig. 6.3) shows the common, dual ice thickness peaks, but is unusual in terms of snow cover. Size, orientation and surrounding vegetation favour the normal southern concentration of snow. However, snow is below average here. Presumably the lake has just completed an extensive white ice phase at the southern end. Slush is still present away from peak ice thickness. Ares (Fig. 6.4) is exceptional among the lakes in having maximum ice in the deep northern basin and no peak in the south, where water level indicates a still unrealised flooding potential of c. 3 in (8 cm) that could raise thickness to, at least, just above the basin mean.

Easel Lake (Fig. 6.5) again shows the twin ice peaks, the southern of which is formed largely of newly frozen white ice full of water lenses. An additional peak occurs around the northern island. It has been suggested that cracking (and flooding) tend to occur in constrictions (Persson, 1954). However, this peak is due to snow defation and black ice growth in the constriction. Malcolm (Fig. 6.6) shows the

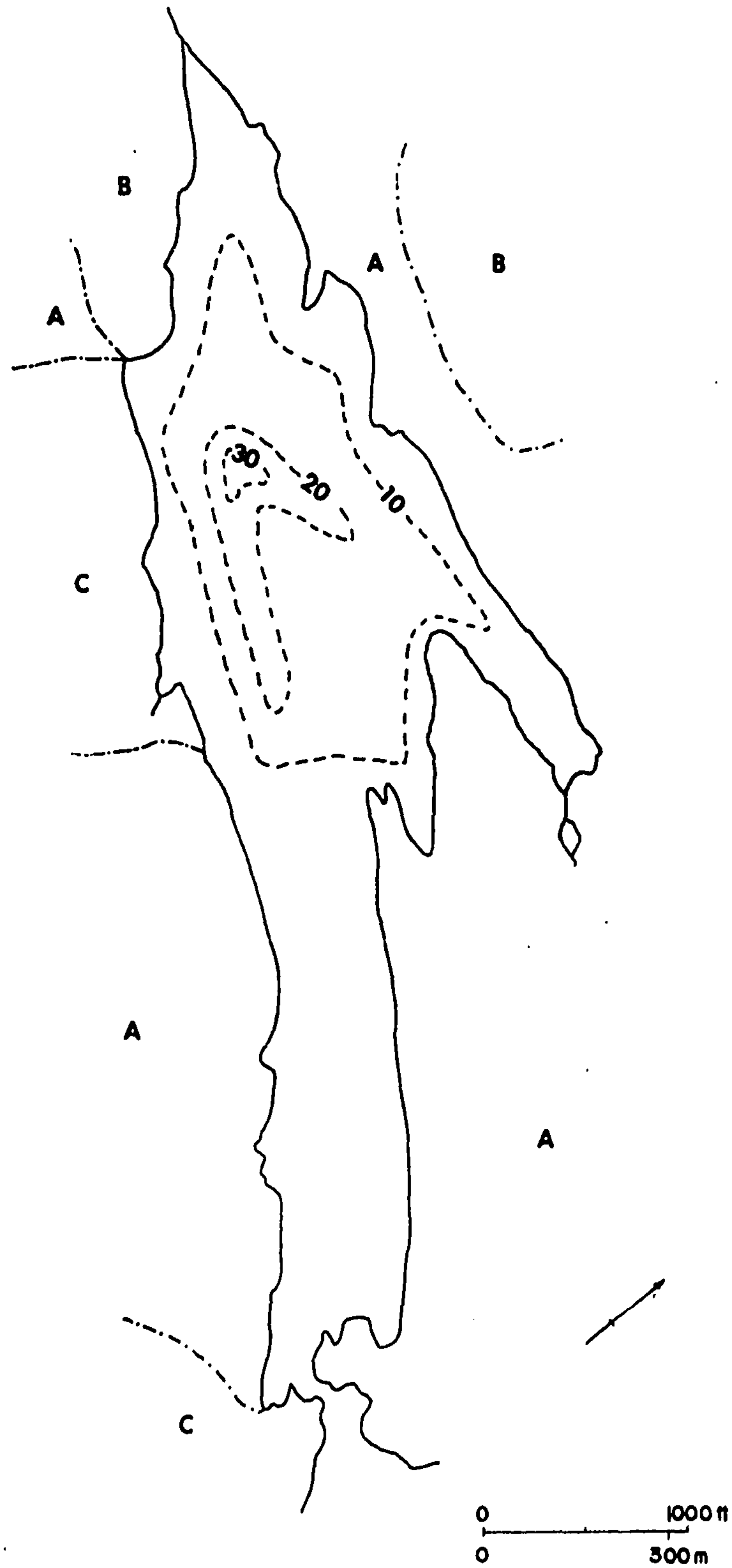
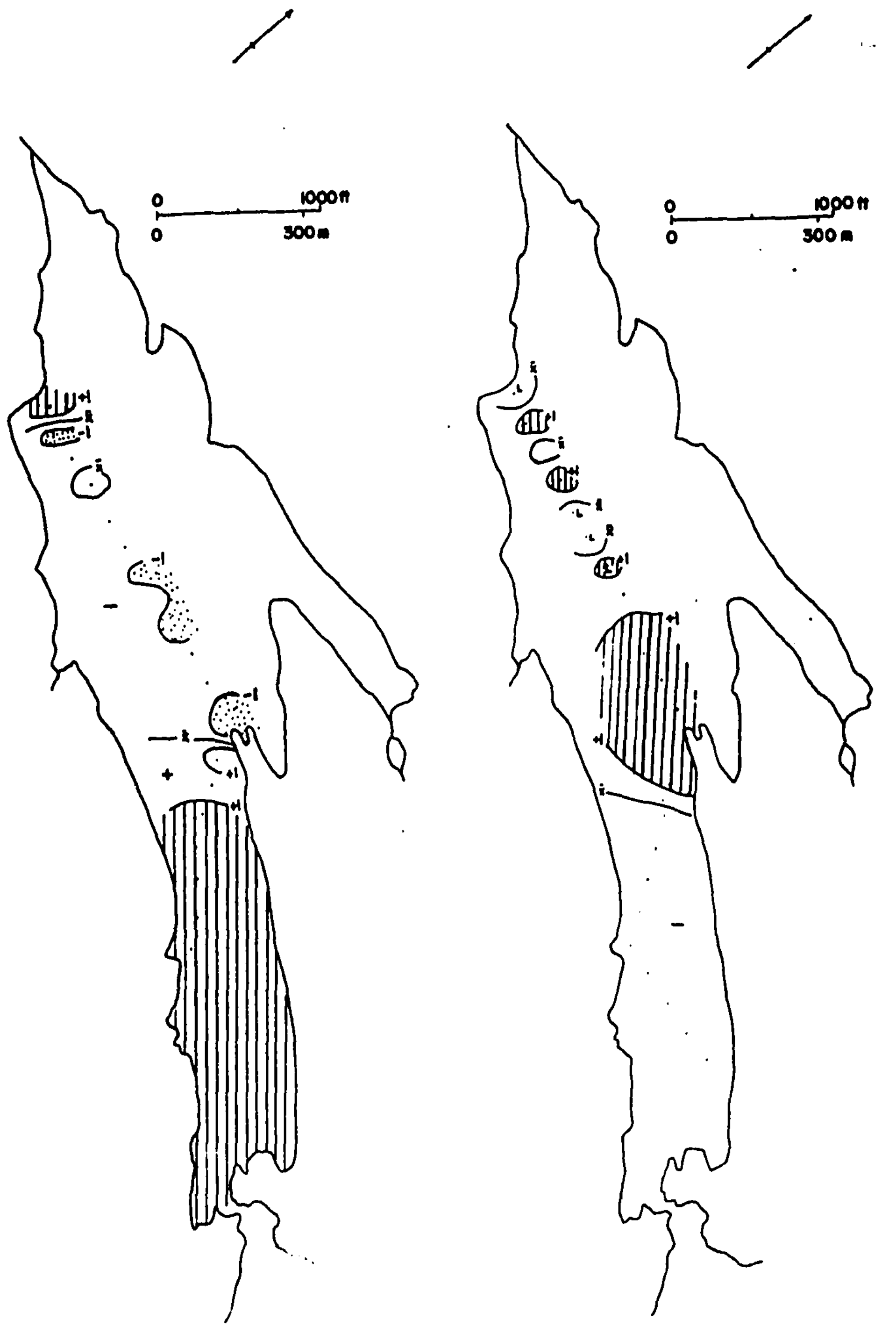


Figure 6.4a: Ares Lake topographic environment
(key following page 92)

Figure 6.4b: Ares Lake snow(left) and white ice distribution (right), March, 1966. (key following page 92)



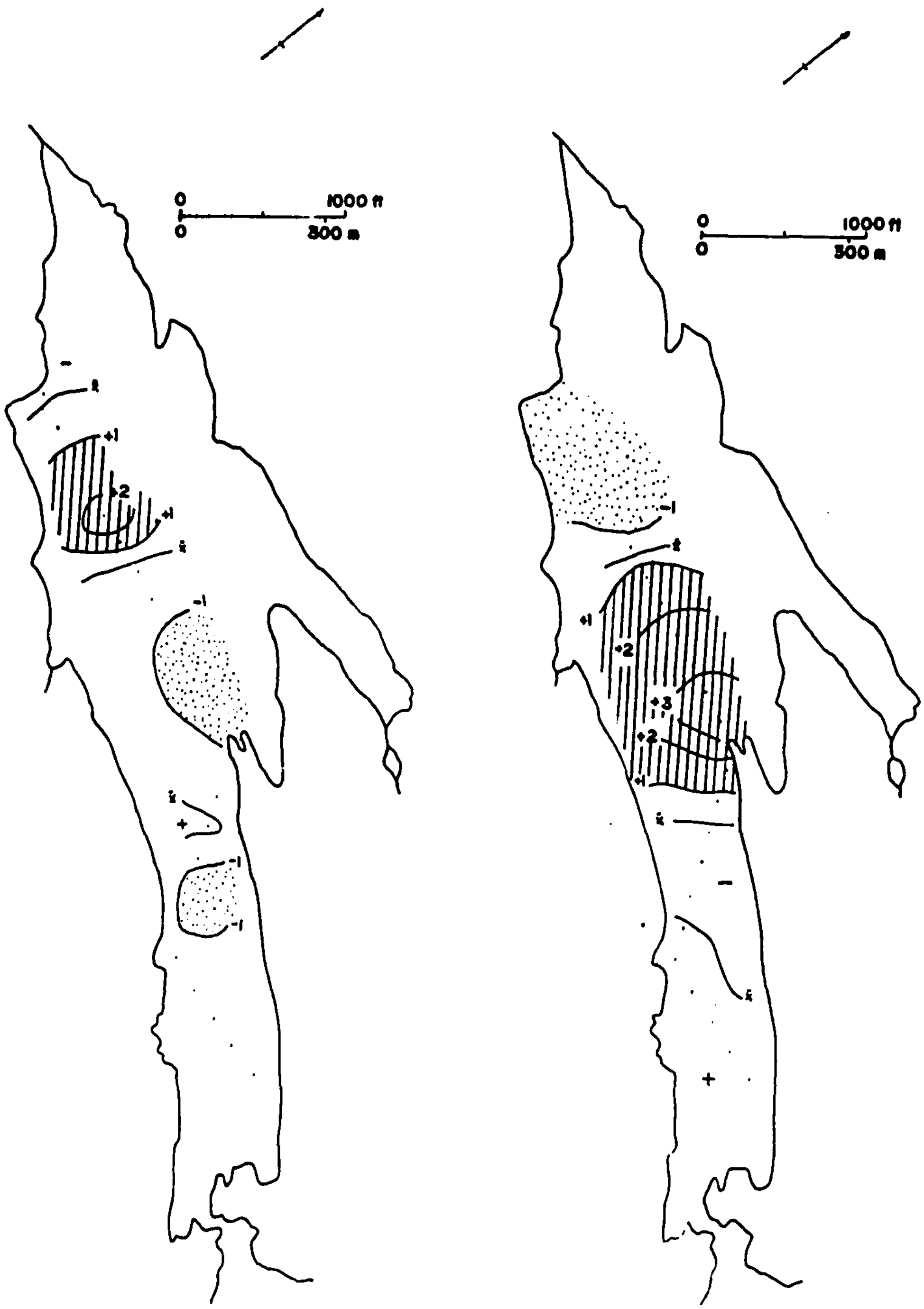


Figure 6.4c: Ares Lake total ice (left) and water level(right), March, 1966.(Key following page 92)

.same feature in the constriction at the northern end of the longer southern arm. Malcolm also shows extensive slushing in the area of thinner ice on the northern arm. This is a sheltered area with deep snow, contrasting with the western arm.

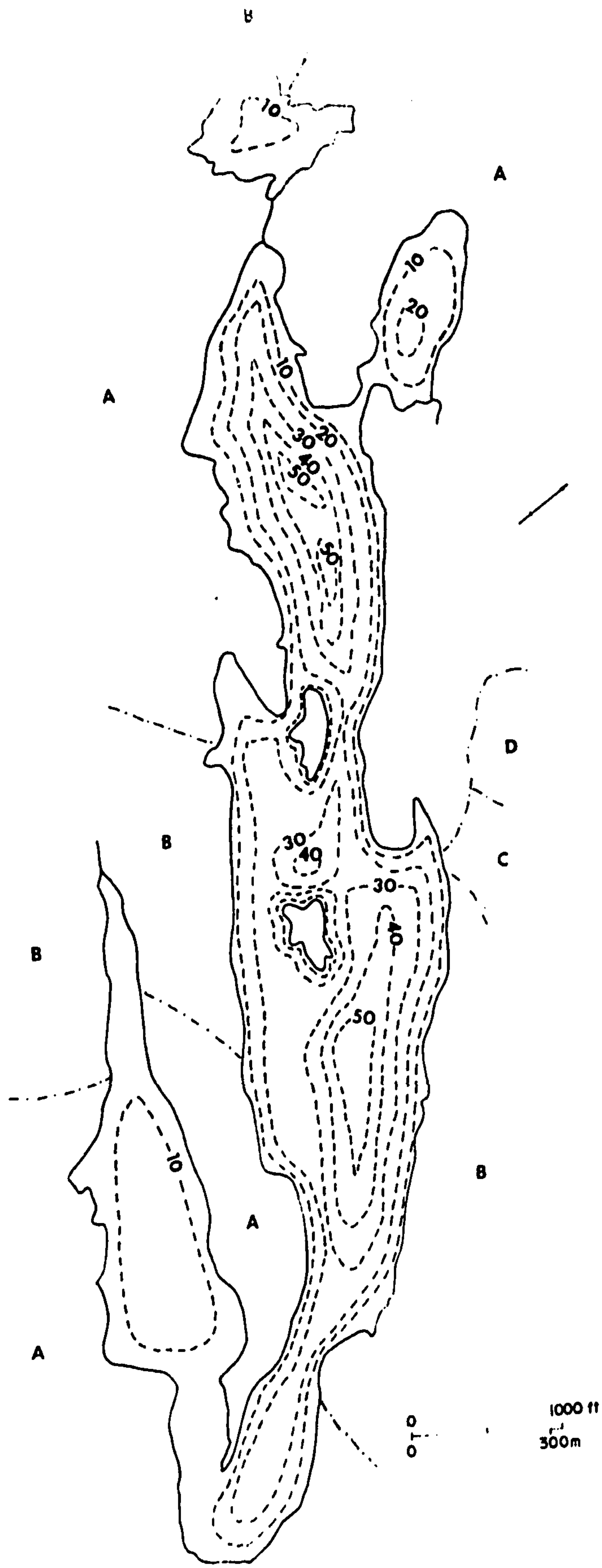
Comparison with 1965.

The maps of the March survey for 1965 reproduced from the work of Archer (1966) in Appendix E are not directly comparable to the maps of 1966, since they indicate raw data values not a normalised statistical surface. However, some similarities and discrepancies may be remarked upon.

The maps show a year in which accumulation of snow at the southern ends of the lakes was less marked. This is a clear reflection of the greater variety of wind direction for the winter of 1964-5. In 1965-6 northwest winds prevailed during 77% of the weeks between freeze-over and the survey and in 1964-5 only 45% with a long stretch in February in which northwest winds did not prevail. Nevertheless, Ares, Gene and Phred lakes still showed the tendency.

This had an important effect upon the white ice. Ares, Gene and Phred lakes showed similar patterns to 1966. Elsewhere white ice showed clustering in areas of deeper snow, with the exception of Easel Lake where it may show evidence of the changing distribution of snow with prevailing wind during the winter. Easel shows a rare case of increased white ice in an ice thickness peak at the northern end of a lake.

Figure 6.5a: Easel Lake topographic environment (key following page 92)



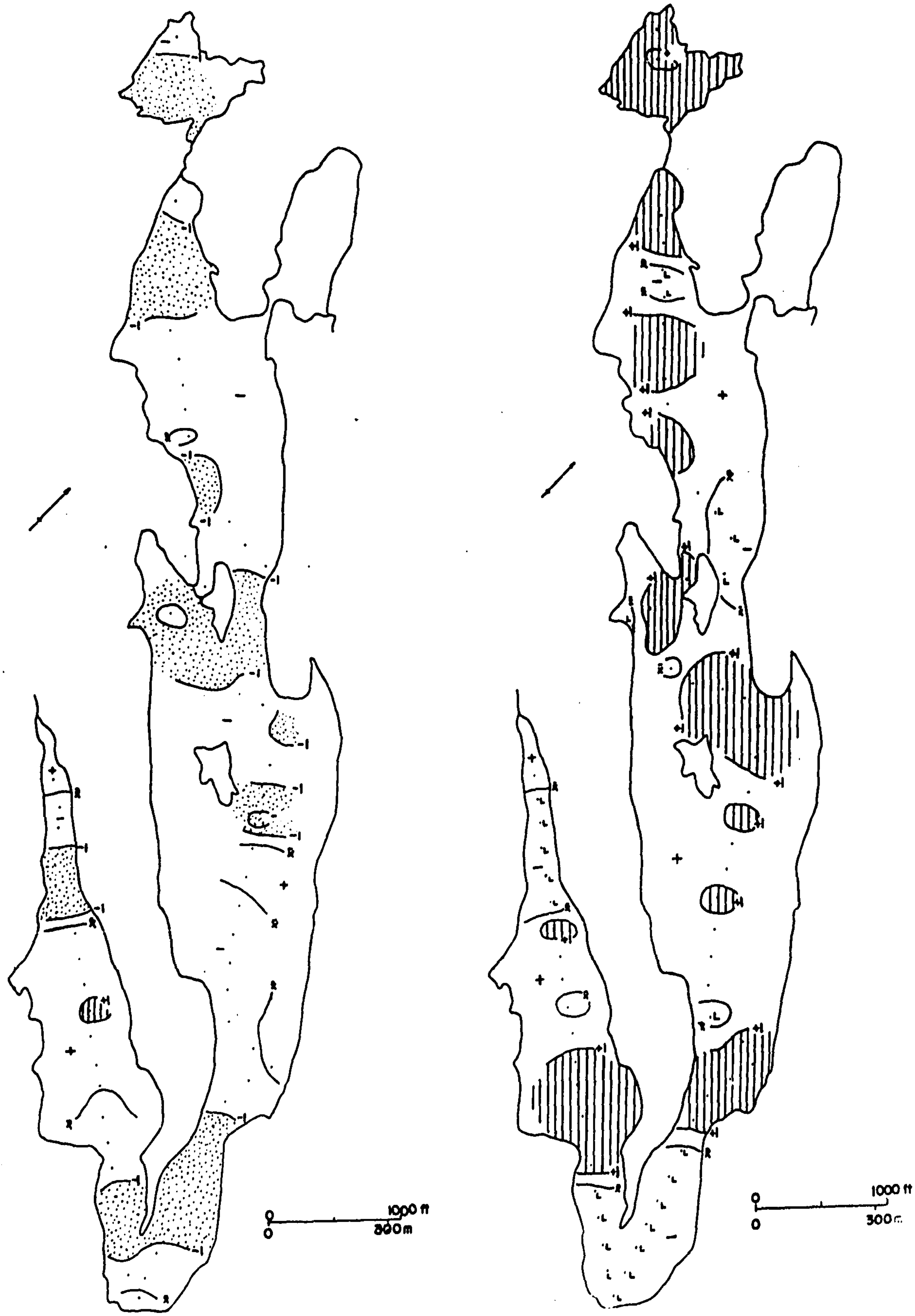


Figure 6.5b: Easel Lake snow (left) and white ice distribution (right), March, 1966. (key following page 92)

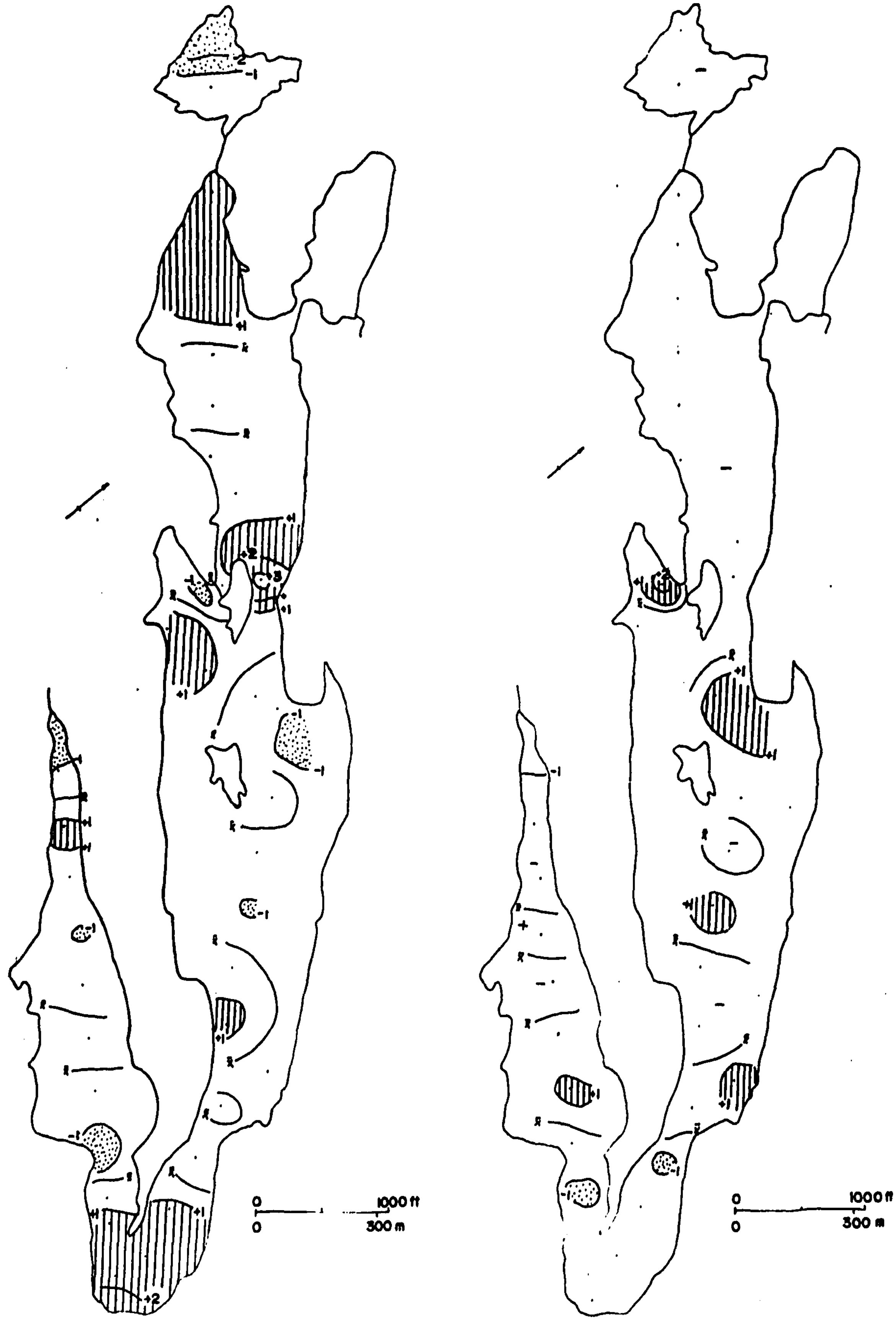


Figure 6.5c: Easel Lake total ice(left) and water level distribution(right), March, 1966. (key following page 92)

From the comparison, it appears that snow and white ice distribution varies from year to year with the prevailing wind. Inspection of wind direction records (criteria in Appendix A) for former years indicates the following range of variability in the prevailing wind by weeks between freeze-over and the first full week in March: 1963/4 NW 72%, 1962/3 NW 54%, 1961/2 NW 50%, 1960/1 NW 35%, 1959/60 NW 5%, 1958/9 NW 77%, 1957/8 NW 32%, 1956/7 NW 58%. This shows that 1965/6 was unusually dominated by northwest winds. It may, therefore, be inferred that the tendency for snow and white ice to accumulate at the southern end of the lakes is shown near its acme in these maps.

Conclusions.

The method of obtaining information on the variations of lake cover within the basin leaves much to be desired. The maps can be only partially constructed, since in most cases the sampling traverses do not give adequate coverage, and the interpolated isolines give an exaggerated value to variations in the statistical surface normal to the line of traverse and underemphasise parallel variations. Hence exaggerated banding is found on a number of the maps. Similarly, the data are not truly randomly selected. It is known that the most efficient technique for obtaining good coverage of an area by random samples is the "systematic unaligned", based on random choice of column-wise and of row-wise coordinates within a randomly oriented quadrat system. A quadrat system per lake would produce better coverage and data, and reduce the labour expended on obtaining the information.

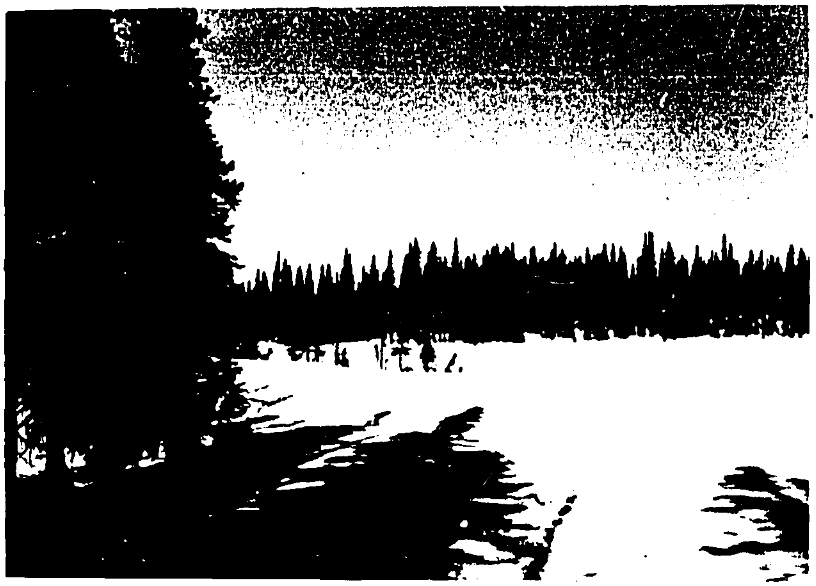


Plate 6.1: Cowan Lake, an example of strong influence from boundary conditions. Slush, snowdrifts and white ice prevail.

Plate 6.2: Easel Lake, an example of lesser boundary interference. The lake is oriented towards the dominant wind and, although the lake is not very broad, the wind gives emphasis to the long axis and maintains marked deflation at this northern end. Black ice is the main ice component here.

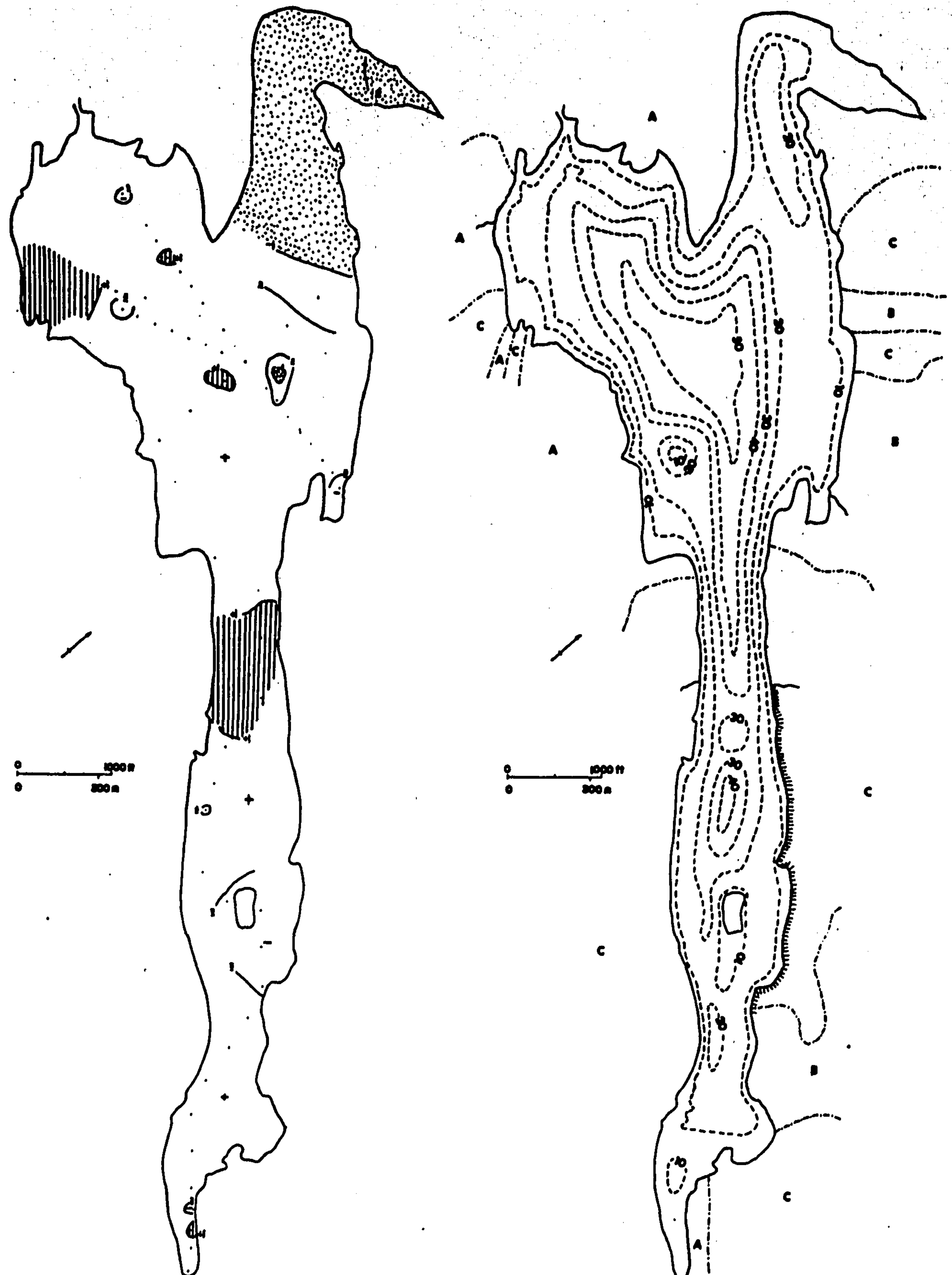
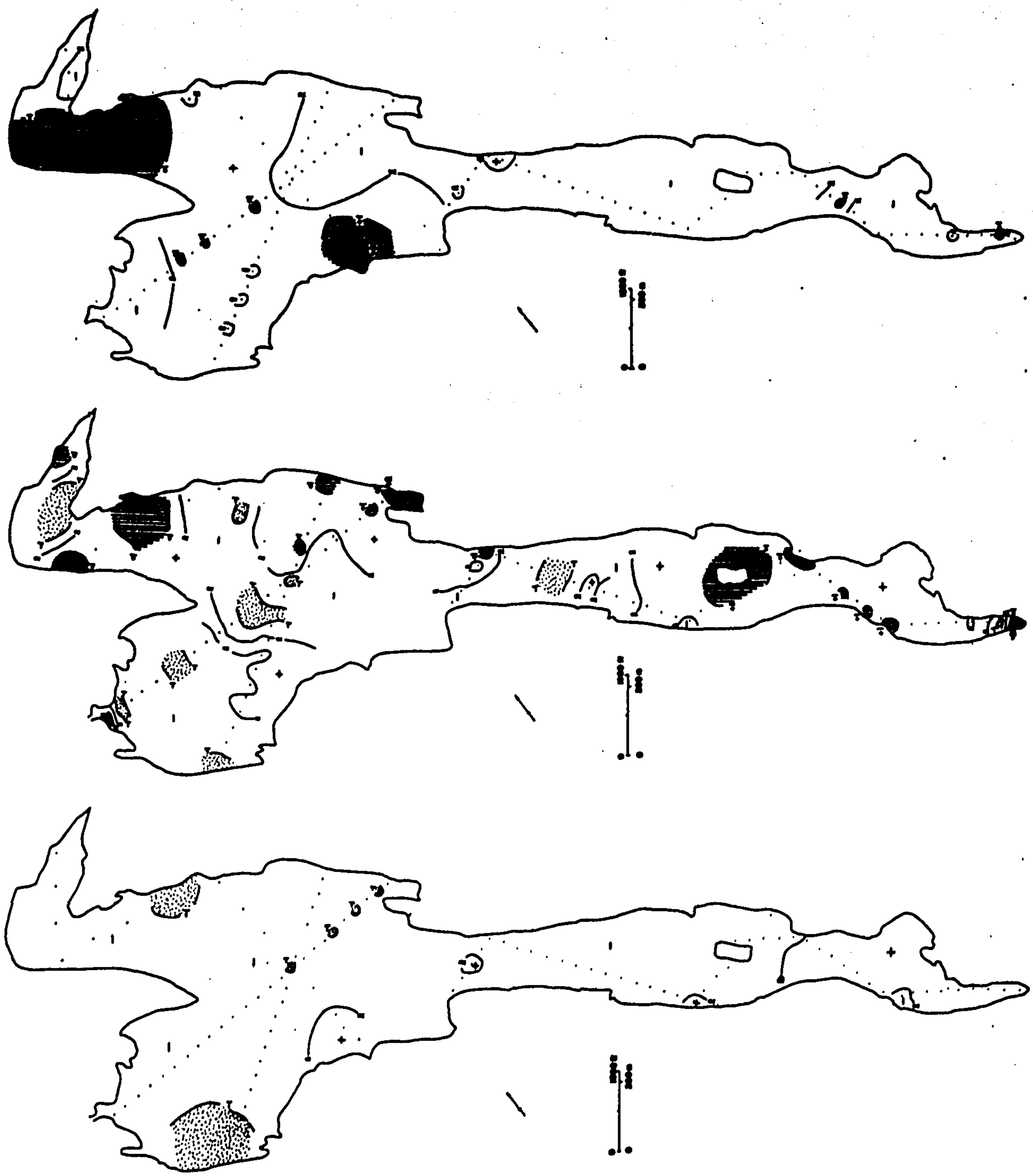


Figure 6.6a: Malcolm Lake topographic environment(right) and total ice(left), March, 1966. (key following page 92)

Figure 6.6b: Malcolm Lake white ice(bottom), snow(middle) and slush distribution(top), March, 1966. (key following page 92)



The methods of establishing the topographic features of the basin that are used here are not sufficiently sophisticated to adequately differentiate the small variations involved. Furthermore, the analysis suffers from being based on a brief, at-a-time cross-section. It is clear that the timing was important in the 1966 survey from the different stages in a current basin-wide slushing phase that are apparent from one lake to another. The 1966 survey probably presents a less accurate picture of the end-of-winter cover than did the 1965 survey. It does suggest, nevertheless, some tendency for the smaller lakes to be more advanced in the slushing process, which may be an indication of a general rule.

The distribution of lake cover in the basin confirms the relationships found for Knob Lake and show the twin ice peaks to be normal on all the large and medium sized lakes ($\sim 2.5 \times 10^6$ sq ft or 9.1×10^5 sq m). Total ice appears to be slightly greater on larger lakes owing to weaker boundary effects. Locations of white ice growth vary from year to year in relation to snow re-distribution by prevailing winds.

CHAPTER 7

THE CRYSTALLOGRAPHIC DISTINCTION BETWEEN WHITE AND BLACK ICE

As the total thickness of white ice increases, it becomes more difficult to observe the black-ice/white-ice interface through a 3 inch (8 cm) diameter drill hole, especially on a dull winter's day. This is aggravated by variations in the tone of the white ice itself caused by differences between flooding phases.

The same observation led Andrews and McCloughan (1961) to conclude that white ice is gradually absorbed into the black ice during the "pre-thaw period", approximately from mid-October to mid-April. On this basis, they suggested a corrected white ice term, "equivalent black ice". This ageing of white ice during the winter until it resembles black ice was assumed to follow a normal growth curve of the type:

$$B_e = We^{-y} \qquad \text{(eq. 7.1)}$$

where B_e is the equivalent black ice thickness, W the original white ice and $y = (1 - t/T)^{-1}$, in which t is the time in days since freeze-up and T is the total length of freeze-up. Andrews and McCloughan took a mean length for T of 180 days for Knob Lake and plotted data for the east site for 1959-60, against degree days, and compared this to a curve based on the squares formula for sea ice growth quoted in eq. 1.2. (Graph reproduced in Appendix E, Fig. E.17.) They found

Plate 7.1: The polariscope.

.that this "correction" gave a better y-intercept value with degree days.

However, their premises seem somewhat dubious.

Contrary to the suggestions of Andrews and McCloughan (op.cit.), the results of a small-scale study of the crystallography of ice from Knob Lake suggest that in spite of appearances the distinction between white ice and black ice is rigid and remains so throughout the winter. It is especially clear towards break-up.

Methods of study.

The first attempt to study the crystal structure and texture of ice on Knob Lake was made in 1963, when a block of ice was harvested and shipped to the CRREL establishment at Hanover, New Hampshire, for analysis (Mattox, 1964). Unfortunately, this sample was destroyed in a fire en route. A second attempt was made on April 4th 1966, using slightly less elaborate methods than those described by Mattox (ibid). The block of ice was cut from a site 8 metres (24 ft) northwest of the weekly drilling site at "Knob Lake Centre". It measured 50x50x90 cm. A 5 inch Snabb spoon drill, a cross-cut saw and a pair of ice tongues were used for this operation. Despite 20 cm (8 in) of slush overlying the ice, no undue difficulty was experienced, except that the topmost 23 cm of the block (composed of white ice) sheared off from the rest of the block at the first attempt to lift the ice with the tongues.

The block was examined for macrostructural features and

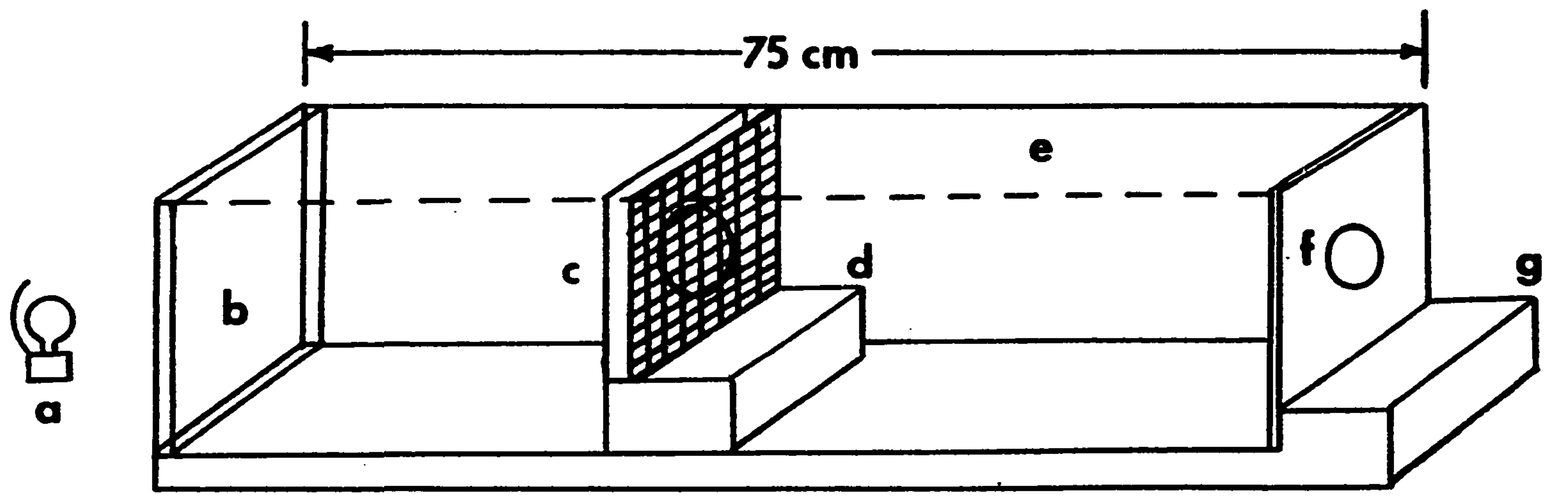


Fig. 7.1. A simple polariscope.

photographed in daylight (Plate 7.2). Because of its somewhat irregular shape, orientation presented no difficulty and the problem of sublimation of markings experienced by Mattox (op.cit.) was not encountered. The ice was stored in a deepfreeze for a week at c.-15°C (5°F) before detailed study.

A simple polariscope, illustrated in Fig. 7.1 and Plate 7.1, was improvised for studying and photographing thin sections of the block under polarised light. The set-up could be improved by incorporating a device for easily rotating the thin section and taking angular measurements of extinction. The analysis made was basically qualitative. More detailed work would require an instrument such as the Rigsby stage described by Langway (1958).

To prepare slides for study, slices approximately 2 cm thick were cut vertically and horizontally out of the ice block at intervals selected to cover the whole length with special attention to features of the macrostructure. The sawn-off slices were then reduced in thickness to c. 0.25 cm or less by melting on a flat-bottomed tinplate placed upside-down in an electric frying pan containing some water to act as a coolant. Although the resulting thickness was large compared to the normal geological thin section, it was sufficient to obtain slides of less than one crystal in depth in the black ice, and often also in the white ice. These thin sections were then viewed and photographed through the polariscope in a cool room under plane polarised light and crossed polaroids. Both black-and-white and colour photographs were taken using a Honeywell Pentax and an Ashahi Pentax single lens reflex cameras. Only the monochrome photographs were used in the analysis.

Results

The results show the strong contrast between the ice of two different origins. The interface is shown in Plate 7.3 in a vertical section under crossed polaroids. The distinction is both structural and textural. In ordinary light (Plate 7.2) the unconformity is marked by a transition from a layer of concentrated and unoriented air bubbles, which give the characteristic colour to the white ice, to a layer with relatively few and generally organised air bubbles, which is transparent as well as translucent. In the white ice in the upper part of Plate 7.3 melted-out air bubbles can be seen as extinguished areas, and at the edges smaller, less disturbed bubbles can be seen reflecting stray light. The textural contrast is best seen under crossed polaroids, an abrupt change from small, sub-rounded crystals with no preferred orientation in the upper ice to the larger, elongated crystals with marked orientations of the lower ice. Plates 7.4 and 7.5 show horizontal sections of the white ice and black ice respectively under polarised light.

The interface is so marked that any "ageing" of white ice to black ice seems highly unlikely. The interface was at approximately the level suggested by the stake frozen into the ice at Knob Lake Centre at the beginning of the season.

The interface appeared at the surface of the ice sheet during break-up, when the white ice had been reduced to scattered patches of firn-like material by radiation melting. At this time an interesting parallel was observed between the crystal orientation in the thin sections and the patterns found on the lake. Plate 7.3 appears to illustrate the Perey-Pounder effect. Perey and Pounder (1958) and Pounder (1965, p.22) showed the tendency for a-axis sub-vertical crystals to grow at the expense of a-axis sub-horizontal crystals as a result of the general property of faster growth in the basal plane of the crystal lattice. The latter crystals are wedged out downwards by the sub-vertical crystals. (See illustration in Perey and Pounder, op.cit; Pounder, op.cit.; Lyons and Stoiber, 1963) This normally leads to an increase in crystal size with depth in the black ice, and smaller, wedged out crystals at the upper interface. In Plate 7.3 at least two small, bright, wedge-shaped crystals can be seen either side of the large, extinguished crystal at lower centre. The main axis of the extinguished crystal was found by rotation to be nearly normal to the plane of the section. Thus the basal plane is perpendicular to the upper interface. This crystal grows in cross-sectional area downwards at the expense of the bright crystals. The bright crystals had near vertical c-axes.

During ice decay the intercrystalline bonds are weakened principally by increased solar radiation. The snow cover is removed first and this is followed by the patchy disintegration of the white ice into wet, round ice pellets (Plate 7.7). By May 25th 1966, patches of bare black ice were visible on Knob Lake in Post Office Bay, which showed an effect which it is proposed to call here a "crystal mosaic pavement". Plate 7.6 is a photograph of part of this pavement characteristically composed of a mosaic of black and white crystals 3-6 cm across in plan view. There is a marked tendency towards a triangular outline amongst the lighter crystals, which suggests that their axes of symmetry are vertical and that they are approaching trigonal symmetry as a result of inhibited hexagonal growth. Inhibition may result from a surfeit of crystallisation nuclei. Ragle (1963) has noted a tendency for crystal size to increase with distance from the lake margins and has suggested that it may be due to a larger number of nuclei inshore. However, it seems likely that rate of cooling is also an important factor as the ice grows from the shoreline.

The lighter crystals in Plates 7.6 and 7.7 are transmitting light reflected upwards from air bubbles and the faces of underlying crystals in the approximate direction of the optic axis (c-axis). When rubbed gently with the hand these lighter crystals were found to be loose, and, although the crystal boundaries were closely interlocked, some could be prised out for inspection. When removed, they showed the vertical wedging characteristic of the crystals described by Perey and Pounder (op.cit.).

Plate 7.8 was taken in the same area as Plate 7.6 after a night of extended rain. The loose crystals had been removed by the rain leaving a local relief on the surface of up to 6 cm flooded with water. The lens hood shows that the hollows left are smaller than would be expected from the crystals in Plate 7.6. This illustrates the tendency mentioned by Ragle (op.cit.). The former was located about 2 metres offshore, whereas Plate 7.6 was located 3 metres further out, although surface lowering probably occurred reducing the size of the hollows.

Rate of cooling is probably also significant in the general vertical increase in crystal size in the black ice section of an ice sheet noted by many authors (e.g. Knight, 1962). In as far as generalisation may be made from the 30 sections taken from this one block, this phenomenon was found on Knob Lake. Vertical profiles of crystals near the upper interface tended to have horizontal cross-sectional areas of 2-3 sq.cm . (Plate 7.5) compared to areas in excess of 15 sq cm at a depth of 35-40 cm below the upper interface, ie. 62-70 cm from the top of the block and 14 cm from the bottom (Plate 7.9). It is important to note, however, that very few writers apart from Palosuo (1965) have carefully restricted the generalisation to the black ice only.

In the white ice the reverse tendency was found, an increase in crystal size upwards (Plate 7.3). This is probably, however, not as general a statement as for the black ice, since in closer proximity to the atmosphere the white ice is subject to a greater variety of rates of freezing which together with the discontinuous nature of growth result in layering more marked than in the black ice. This constraint is also affected by the grain size of the snow that is flooded.

Study of the variation in crystallography across the lake was only partially successful. A set of aerial photographs of the lake taken when the black ice crystal pavement was at its greatest extent by Pilot John Prast of Norfolk Aerial Surveys failed to give any indication because of scale and patches of white ice. Full study would require an ice corer and sampling from various sectors of the lake (Knight, op.cit.). Three of the four textures listed by Ragle (op.cit., p.7), after Wilson, Zumberge and Marshall, were observed in the black ice. Truly tabular crystals with greatest development in the horizontal plane were not encountered. Granular and columnar textures were most common in the area examined, which was the area of Post Office Bay and a little further out into the main body of the lake that became clear of white ice whilst still reachable across shore cracks and leads. However, most crystals also showed a tendency to be more or less crenulate at the surface. Ragle suggests that granular ice is a product of slow freezing in quiet waters just below $0^{o}C$, and that ruly crenulate crystals are formed in agitated water. The crystal pavements observed seem to fall within Ragle's definition of granular ice although on the night of freeze-up winds were running 20 mph and the bay in which most of the investigation took place is not particularly sheltered. Indeed, records of windspeed at the 1 m level over this portion of the lake through the winter of 1965-6 indicate slightly higher winds than at the southern anemometer site. (Note: Bryson and Bunge, 1956, after Marshall, applied the term "granular" to white ice, in a different sense.)

Columns were found off Guest House Point. According to Ragle, columns "grow in quiet, deep water in the centre of the lake or more

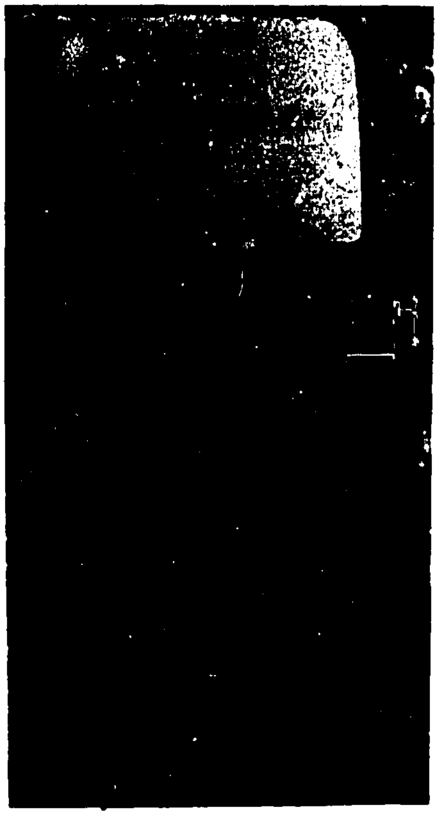
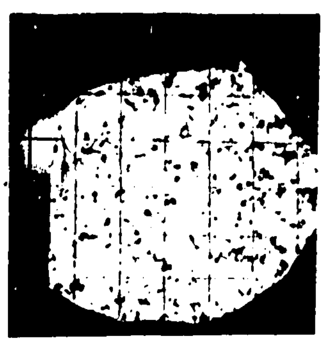


Plate 7.2

The ice block; note white ice and bubble horizons.

Plate 7.3

Vertical thin section of black-ice/white-ice interface under crossed polaroids, 24 cm from top of block; note wedging and crystal sizes on centimetre grid.



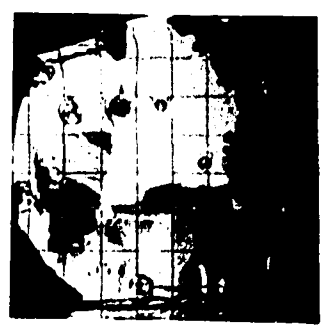


Plate 7.4

Horizontal thin section of white ice under crossed polaroids, 20 cm from top. Centimetre grid.

Plate 7.5

Horizontal thin section of black ice in a bubble layer. 50 cm from top.

usually in a zone just beneath the other three textures". Conversely, Bryson and Bunge (op.cit.) followed Marshall in attributing columnar ice to agitated water. On Knob Lake only the shoreward areas were sufficiently clear of white ice to allow inspection. Here on June 3rd and following days columns c.8 cm in length were seen. Fig. 7.2 is a schematic cross-section of the ice surface at this period, showing how black ice candling occurred mainly in areas free of white ice and appeared to be absent under more than 8-10 cm (c. 3 in) of white ice. The largest candles found this season were about 25 cm (10 in) long amongst grounded ice on Astray Lake, 20 miles south of Knob Lake (Plate 4.2 , in Chapter 4.).

Bubble layers were found in both black and white ice. In the white ice they occurred between different freezing horizons that could be distinguished by different grain sizes. They seem to represent exsolution gases trapped by a freezing front progressing mainly from above downwards. In the black ice the bubbles have not been trapped in the same way, but banding is even clearer. Ragle (op.cit.) has compared the bubble layers to those formed during rapid solidification in metal ingots and concluded that the cause of inclusion is rapid freezing. He and others have traced single layers across an entire lake and attributed them to periods of rapid growth. Swinzow (1966) used the formula developed by Elbaum, a metallurgist, in 1959 to describe this process, but concluded for the special case of a proglacial lake that extra gases were being added from melting glacier ice. Hourglass expansions at uniform levels through the ice block (Plate 7.10) suggest periods of exceptionally rapid increase.

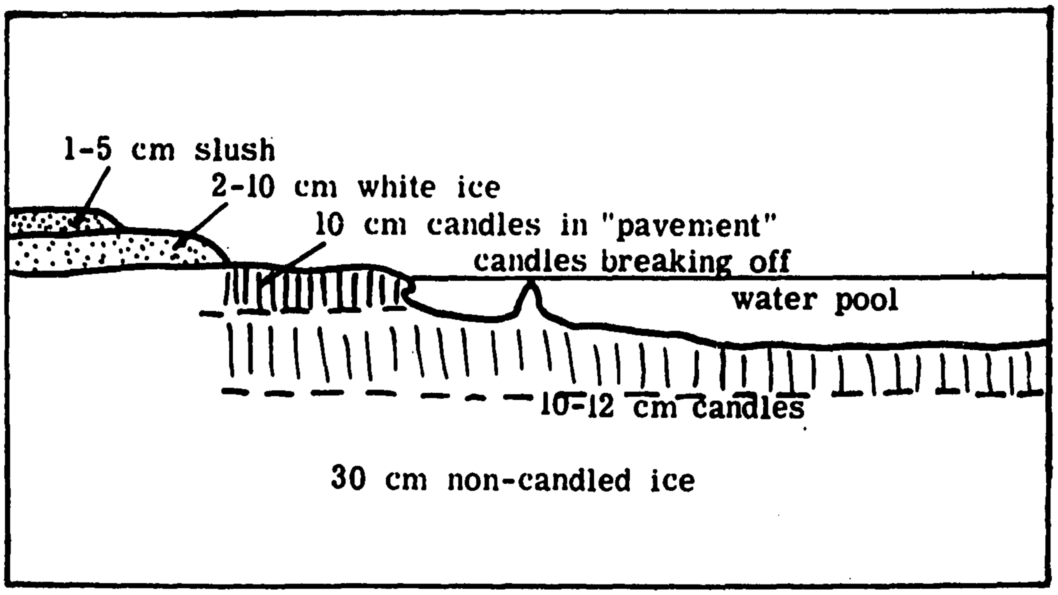


FIG.7.2. Sketch section of wasting ice surface.

Plate 7.6
Crystal mosaic pavement in Post Office Bay, May 25th, 1966; note white, c-axis vertical crystals, open tubules and some crenulate boundaries.

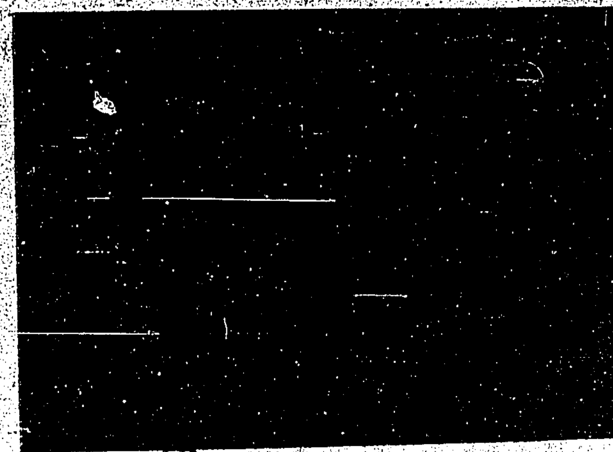


Plate 7.7
Oblique black-ice/white-ice interface in grounded ice on the north shore Astray Lake, June 25th, 1966.

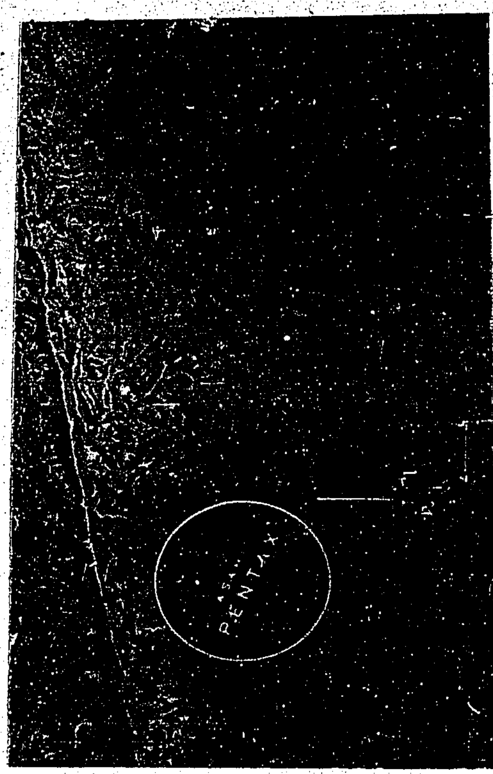


Plate 7.8
Shoreward of Plate 7.6 after rain; white crystals removed, crystals generally smaller than in 7.6.

Plate 7.9
Vertical thin section of black ice, 62-70 cm from top, 14 cm from base, under crossed polaroids.

Plate 7.6
Crystal mosaic pavement in Post Office Bay, May 25th, 1966; note white, c-axis vertical crystals, open tubules and some crenulate boundaries.

Plate 7.7
Oblique black-ice/white-ice interface in grounded ice on the north shore Astray Lake, June 25th, 1966.

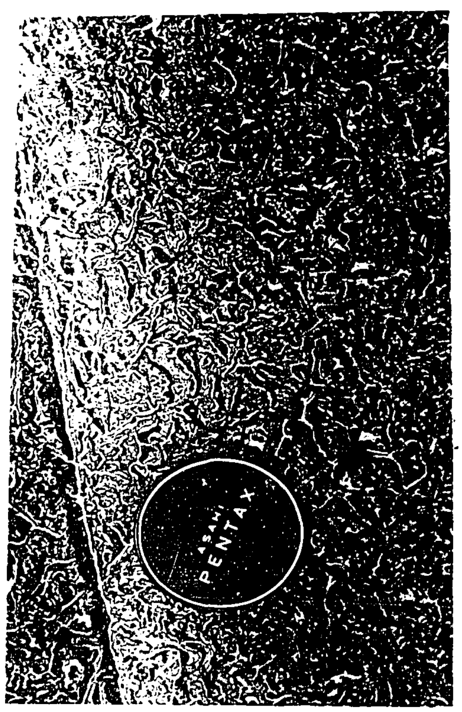


Plate 7.8
Shoreward of Plate 7.6 after rain; white crystals removed, crystals generally smaller than in 7.6.

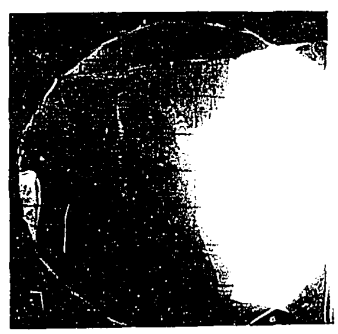
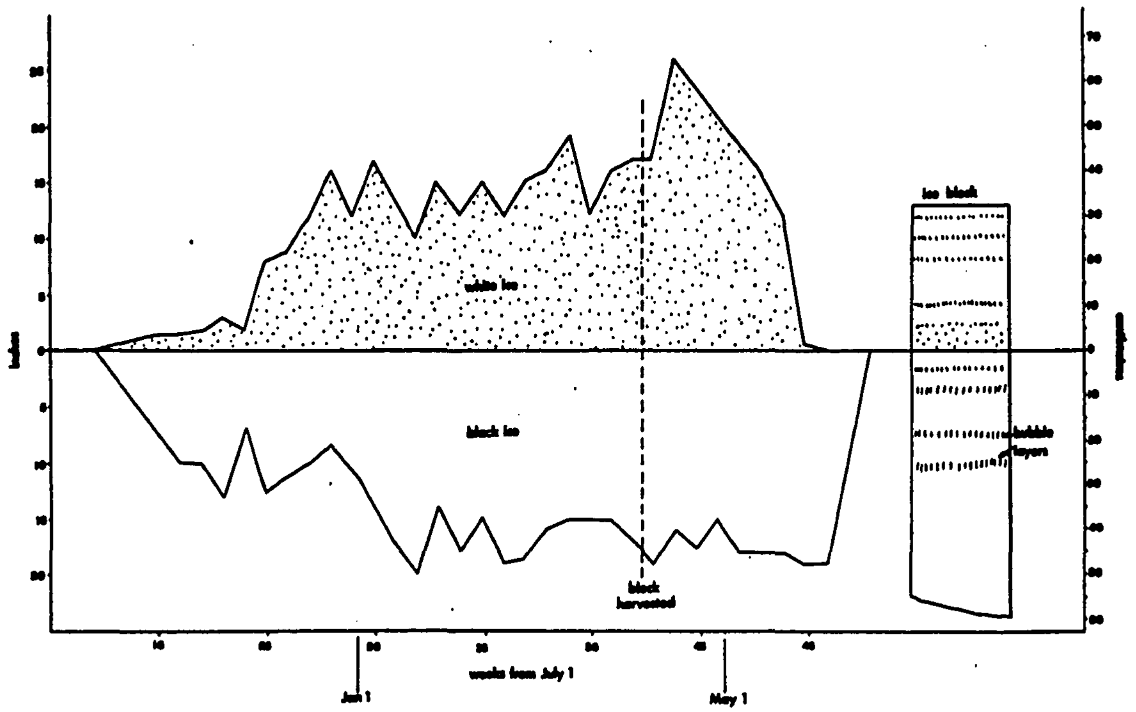


Plate 7.9
Vertical thin section of black ice, 62-70 cm from top, 14 cm from base, under crossed polaroids.

Figure 7.3 represents an attempt to correlate the bubble layers of the block to weekly increments recorded at site Knob Lake Centre. Quite a close correlation was found in essentials. Such correlation should be made with caution in the light of evidence of bubble migration from Lyons and Stoiber, (op.cit.). However, it seems that the prime cause of migration is radiation melting at the top end of the bubble and freezing at the bottom. If this is so then it seems unlikely to have played any important role in the block which was removed from beneath 30 cm (12 in) of snow on April 4th 1966. Concentration of bubble layers in the upper 60% of the black ice probably represents faster growth in early season. Six distinct bubble horizons were found in this zone, which could be correlated with increases at the drill site up to mid-November, when the first major growth period ended. The second period of black ice growth, in January, appears to have left no mark. Growth was slower, and the ice covered by over 30 cm (12 in) of white ice and almost an equal amount of snow. Swinzow (op.cit.) noted a bubble rich zone just below the black-ice/white-ice interface as shown here, which was visible at the surface just before break-up. At this time migration is active. Open "worm holes" were a noticeable feature of the crystal pavements at break-up (Plate 7.6). Both the sides and the bodies of the crystals removed were pockmarked and pierced by air holes. Neither in the field nor in the thin sections was any fixed crystallographic location seen amongst the bubbles, although many showed near perfect hexagonal symmetry about their long axes, showing that they had developed in association with c-axis vertical crystals.

Fig.7.3. Ice block related to growth at centre site.



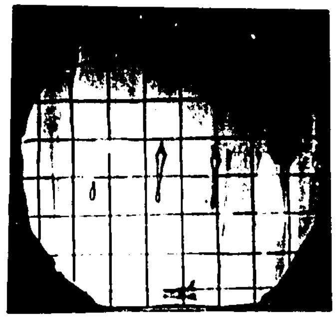


Plate 7.10
Vertical section of ice at 40 cm depth showing bolt-shaped air bubbles (section 0.5 cm thick).

Plate 7.11
Highly irregular "candles" floating on Lejeune Lake at break-up.

Conclusions.

The structural and textural differences between the two types of ice are quite distinct. The interface has the structure that is characteristic of the first growth stage and metamorphosis of white ice through ageing is unlikely. The differences are most manifest in the field towards break-up, when the white ice disintegrates and as the black ice is exposed it begins to "candle" and form mosaic pavements. Growth layers are most marked in the white ice, but bubble layers seem to be an analogous form in the black ice.

CHAPTER 8

WHITE ICE DURING FORMATION AND WASTAGE

White ice during the freeze-up process.

From the very beginning of the frozen period, a small amount of "white ice" is sometimes present, which has not been created in the strictly genetic sense of true white ice. This is the product of slush frozen into the original ice sheet when freeze-up is accompanied by a snowstorm.

The probability of this situation occurring is likely to be high, for late fall and early winter is commonly a period of heavy snowfall in the area (Tout, 1964, p.124). According to Tout (ibid., p.124), November and December normally account for 30% of the annual snowfall total of 12.75 inches (32.4 cm) water equivalent, and from his table of monthly snowfall (ibid., p.125, Table 25) it can be seen that in bad years September and October may receive as much snow as January and February. This concentration of snowfall has been related by a number of authors to conditions in Hudson Bay. Burbidge (1949) noted the importance of advection to the climate of interior Labrador-Ungava and the instability and cumulus created in the cPK modified air by its trajectory over the Bay. The Bay provides 300,000 square miles of water to the windward of Labrador-Ungava, which is shallow, generally less than 200 fathoms deep, and almost landlocked. Its circulation consists solely of arctic waters, and it is thus not only of greater importance to the peninsula than the leeward ocean, but it is also more susceptible to freezing. Hare (1950) accords ice formation in Hudson Bay an important role amongst the climatic factors affecting the peninsula.

The reduction in snowfall at inland stations caused by the mid-winter freezing of much of the Bay has been noted by Burbidge (1949), Lotz and Nebiker (1957) and Tout (1964). Lotz and Nebiker (1957) correlate the later reduction in snowfall with the dominance of unmodified cP air coming from the Bay area, which marks the virtual ceasing of evaporation over the sea.

Consequently, the snowfall maximum at Knob Lake comes in November, just before the main ice formation in the Bay: this month has an average of 22.5 inches (57 cm) of snow, whereas no other month exceeds an average of 20.0 in or 50.7 cm (based on Shaw and Tout, 1962, Appendix, p.7, table 2). November also has the maximum mean number of snow days, 17.6 compared with 15.9 in December and 13.0 in October (Tout, op.cit., p.139, Table 31). Table 8.1 shows that freeze-up on Knob Lake commonly falls in the last week of October or the first week in November, at the very beginning of the snowfall maximum. From annual diaries and drilling records it can be estimated that approximately one third of freeze-ups have contained noticeable "original white ice" at the measurement sites, and many more show the accumulation of normal, superimposed white ice to form more or less general covers in the first two weeks following freeze-up. Table 8.2 shows the situation broken down into the six measurement sites for the period 1957-58 to 1965-66.

Table 8.1 WEATHER AT FIRST ICE, FREEZE-OVER AND FREEZE-UP AND AMOUNT OF "ORIGINAL WHITE ICE"

Year	FIRST ICE								FREEZE-OVER								FREEZE-UP								Estimated+ "Original white ice" on Knob Lake
	Date	Snowfall w.e. (in)		Wind (miles)		Temperature (°F)		Sunshine hours on day	Date	Snowfall w.e. (in)		Wind (miles)		Temperature (°F)		Sunshine hours on day	Date	Snowfall w.e. (in)		Wind (miles)		Temperature (°F)		Sunshine hours on day	
		Prec. week	Day	Prec. week	Day	Max.	Min.			Prec. week	Day	Prec. week	Day	Max.	Min.			Prec. week	Day	Prec. week	Day	Max.	Min.		
1955	20-9	.23	.16		E9	37	27	4.8	3-10	.24	TR		W13g	33	26	2.7	15-11	.64	.02		NW13g	20	14	0	?
1956	24-10	.51	.01		NW26g	16	10	0	25-10	.36	TR		SE1	29	22	1.5	11-11	.29	.13		S14g	22	1	6.0	?
1957	23-10	.34	TR		W14g	24	13	3.4	25-10	.36	.03		NW13g	19	14	0	3-11	.01	0		S7	25	19	6,2	0
1958	4-10	.23	.38 (rain)		S18g	26	46	1.2				N O N E					7-10	.30	0		NW10	33	24	2.9	0
1959	24-10	.27	1.35 (rain)		S16g	36	49*	0*				N O N E					29-10	.44	.01		NW18g	19	6	3.2	0
1960	15-10	.13	TR		NW8	29	21	0	26-10	.83	.04		N10	30	26	0	3-11	.23	.01		NW6	36	32	0	0
1961	21-10	.82	.01		NW12g	29	10	4.8	23-10	.45	0		S10g	35	11	6.2	7-11	.33	.01		SWg	25	19	0	0.5
1962	27-10	.36	.15		NE14g	25	17	0				N O N E					31-10	.32	.02		S9	21	6	7.6	1.5
1963	8-10	.18	.06		NW17g	29	18	0.5				N O N E					2-11	1.04	.11 (.02		NE6g NW16g	21 25	12 13	0** 4.4)	0
1964	5-10	.05	TR		NW11g	31	27	1.2	20-10	.51	.02		SW10g	31	26	2.4	31-10	.21	TR		NW16g	17	8	0.3	2.0
1965	6-10	.80	.03		NW20	28	22	0	7-10	.80	.03‡		11	23	18	0.4	29-10	.15	TR		12	24	4	0	1.5

+ Estimation is generally a mean of records at the first week of measurement.

* Probably, in fact, first ice formed at night. Day before with mean of 24° and minimum of 31°F.

‡ Since freeze-over is known to have occurred at night, the figure here is for the 6th October up to 2.0 a.m. on the 7th. Other correlations might be improved if data were available.

** Previous day gusting 45 mph. Freeze-up likely to have occurred at night.

g indicates gusting.

Table 8.2: Periods without "original white ice"

Weeks without measured white ice at the beginning of the season at three sites on Knob Lake (west, centre, east) and at three sites on Maryjo Lake (west, centre, east)

year site	1957-8	1958-9	1959-60	1960-1	1961-2	1962-3	1963-4	1964-5	1965-6
KLW	2	2	3	6‡	2	0	1	0	0
KLC	4	4	2	6‡	2	5	2	0	0
KLE	3	2	2	6‡	1	1	1	0	0
MJW	0	0	2	7‡	0	0	1	1	1
MJC	0	0	2	7‡	0	3	1	0	0
MJE	0	0	1	7‡	0	4	1	0	0

‡ Suspect records; appear to be records for one site recorded as three each.

The early winter snowfall is probably an important cooling factor in the inland lakes, accelerating freeze-up and the advance of winter. Forel (1888[+]) noticed this process at work on Lake Geneva, where he claims it lowered the surface temperature from 5°C to 4°C. The snowflakes also provide the much needed crystallisation nuclei to initiate ice growth. To be most effective a snowfall must be accompanied and preceded by light winds or calm. This creates minimum convective and mechanical overturning in the water body and permits cooling of the surfical layers below the isothermal temperature (maximum density at c.39°F or 4°C) to create slight supercooling, which Devik (1944) suggests must be c. -1.5°C, to initiate crystallisation. Overturning is also reduced by the shielding effect of clouds during the day, although clear skies at night encourage long wave radiation cooling. Whilst frontal storms are common at all seasons, snowfalls from convective, cumuliform clouds that are often accompanied by the above conditions are more common in early winter than later.

Unfortunately, the data do not exist for a detailed and accurate analysis of this problem.

A critical scan of Table 8.1 suggests that, whilst light winds are not necessary for freezing, low wind speeds are closely associated with the occurrence of "original white ice". It is evident that freezing during high winds tends to be linked with lower air temperatures than are necessary to trigger the process with light winds. Snowstorms occurred at freeze-over on October 6-7th 1965, October 19-20th 1964, October 26-7th 1962, October 22-3rd 1961, and on October

25-6th 1960, but notably not at the succeeding freeze-up on November 3rd 1960.

Inaccuracies in correlation are unavoidable since the exact time periods referred to in the records do not coincide, and only in 1965 was white ice amount measured immediately after freeze-up. Similarly, other factors enter the correlation which are not taken into account here. Records for 1957 and 1958 (Table 8.2, first and second columns) suggest likely chance differences between lakes.

In the first weeks following freeze-over or freeze-up white ice is frequently added by surface flooding. The thin ice is highly susceptible to cracking under thermal stresses. The snowcover is generally too slight to provide much insulation against the fluctuations about the freezing point which are common at this period, yet may depress the thin sheet sufficiently to cause a flood potential. These conditions may, in fact, cause temporary melting of the original white ice surface, as observed on Knob Lake between October 7th and October 13th 1965, when the ice was 3 in thick. It seems unlikely that much of the surface flooding at this period is caused by radiation melting, except in so far as surface pools may absorb heat during the day and general albedo is reduced in the slushings. This process is more important in break-up, when the elevation of the sun is higher, reflectance lower and incoming solar radiation greater. Records of incoming short wave radiation from 1963 to 1965 measured at the Laboratory with an Eppley pyrheliometer show weekly accumulations of c.1000 langleys for October as compared with a characteristic c.2000 ly for March.

Freeze-over in 1965 was an exceptionally fine example of the development of original white ice. Freeze-over occurred on the night of October 6-7th during a snowstorm with moderate winds. Over an inch of snow fell and a white ice surface was found over Knob Lake next morning. This October was the coldest on record with a mean of 24.6°F (-3.5°C) whereas the average mean from 1955 to 1964 was 30.4°F or -0.8°C (Barr, mimeo, 1965), and almost twice the average snowfall of 11.3 in (28.7 cm), 21.0 in (53.3 cm). The number of snow days was normal and the extra snowfall was due to a number of heavier than normal falls, such as that on the night of freeze-over. The mean wind speed of 11 mph (17.6 km hr^{-1}) was below average. Mean daily temperature remained below freezing point from 3rd to 17th October and the period 6th to 9th October was relatively calm.

Freeze-over and virtual freeze-up thus occurred abnormally early, for the cover that formed on the night of October 6-7th remained through the winter. It is a small technicality that a stretch of open water, estimated at 130 x 80 ft (43 x 27 m), stayed ice free until the end of the month, by which time the ice sheet was generally 7 in thick. This polynya was used by Bilello, Adams and Shaw (1966) in arguing for the value of their "permanent freeze-over" (i.e., freeze-up) prediction curve.

Similar situations have been described in some former years. Archer (1966, p.170) noted relative calm and snowfall before freeze-up in 1964 and Bryan (1964, p.18) gives a more detailed account of the situation in 1963. He notes that, following a warm period with a maximum of 45°F (6.1°C) lasting from October 15th to October 18th, a cold front passed through at 0900 LST on October 20th, which brought temperatures of 20°F (-5.7°C). However, snowfall and cold were insufficient to promote freezing in winds gusting to 70 mph (112 km hr^{-1}). The ice that had formed and been partially melted on some lakes in the vicinity was broken and not finally re-established until the night of November 1-2. Unfortunately, the author does not refer to Knob Lake specifically in this discussion. Westlake's diary for 1962 (Westlake, 1964, p.40) suggests how freezing was associated with a sudden cooling to a mean of 19°F (-6.1°C) in the last week of October, although climatological records suggest that this was also accompanied by snows. In fact, 4.3 in (10.9 cm) or 83% of the total monthly snowfall fell in the last ten days of October 1962. In 1961 Shaw observed that freezing on the night of October 22-23rd was under light winds, clear skies and air temperatures of 8°F (-11.3°C), suitable conditions for intense cooling by black body radiation (Shaw, 1963, p.38). Shaw mentions subsequent melting of 50% of the ice cover on Knob Lake and Maryjo, but does not refer to freeze-up conditions. Records show that freeze-up on November 7th 1961, was linked with light winds and 0.1 in of snowfall, which appears to have initiated a probably discontinuous white ice surface.

<u>Conclusion.</u>

Unfortunately, the data which exist are too scanty to develop a study of the importance of snowfall and white ice at freeze-over to any advanced level. It is probable that Knob Lake has been one of

.the most carefully watched lakes in Canada and therefore it is unlikely that such a study would be any more practicable in other parts of the country. This is of no great consequence to general freeze-over predictions such as those based on probability of occurrence by Williams (1963) from the data of Ryder (1953) and the Canadian Meteorological Branch. The difference in time of freeze-over involved is likely to be small and use of this information is limited by the accuracy of weather prediction. However, it would be a helpful addition to theory if measurements and detailed observations of this phenomenon could be made.

The processes of wastage and break-up.

Archer (1966, p.175) took break-up as beginning with the first decline in snow cover, because, he claimed, this is significant in determining the final date of break-up. More usually break-up is limited to a short period of time immediately prior to the complete disappearance of ice from the lakes. In this section the "wastage" period is taken as extending from first snow melt to final break-up, i.e. when the lakes are completely free of ice (as MANICE, 1964 and Allen, 1964; published by Department of Transport).

In 1966 this period was longer than normal. Early melt began in the snow pack caused by the warm weather, rains and high insolation of March and April: March was 7.5°F (3.5°C) above average and April 4.6°F (2.1°C) (Barr, mimeo., Dec. 1966). This melt resulted in a lagged peak in the hydrograph in the first week in June (Findlay, in press). A reversal in early April resulted in peak ice. The snow cover on Knob Lake was finally removed by slushing in the week prior to April 20th, and was never really re-established, although a new, thin cover appeared briefly at the end of May, freezing in the surface pools, and lasted for just two days until dissipated by heavy drizzle. The cold May was important. The mean monthly temperature was nearly $2^{o}F$ below the eleven year mean, the first since December 1965 to be below average (Barr, mimeo., May 1966). Until the May cold snap there seemed strong indication of an early decay from the amount of "rotten" ice commonly encountered towards the shorelines in the spring survey, but ice remained until mid-June.

The characteristic pools, leads and surface rivulets were present during this period (Plate 8.1). Fig. 7.2 is a cross-section of part of this surface sketched on June 3rd 1966.

The subperiod of "ice-breaking" was only slightly longer than average for Knob Lake, although, as for freeze-over, records are highly subjective on this point. For the basin as a whole it appears to have been longer (from the opinions of J.B. Shaw, D.R. Archer and W.P. Adams, personal communication), although no records have been kept for previous years. This gave an interesting opportunity for a daily vigil on the state of decay on the various lakes. The vigil was kept from The Knob, south of Knob Bay, or from Dolly Ridge, three miles east, between June 6th and June 22nd, with supplements from other sources. Table 8.3 summarises the records.

On June 6th no major lake in the watershed was open. Knob

Table 8.3 SUMMARY DATA FOR ICE-BREAKING, 1966

LAKE	SNOW CLEAR	SHORE LEADS	PARTIAL LOSS OF WHITE ICE	PARTIAL CLEARANCE	JUNE BREAK-UP DATE
Ponds*					6
Pearce	1-6	26-5	26-5	27-6	7
Small lakes+					before 7
Oboe					before 12
Barr		before 12-6			before 16
Knob	1-6	25-5	25-5	11-6	16
Bean			13-6		16
Mines lakes‡					before 17
Peter					17
Hanas					17
Maryjo		19-5		13-6	17
Lejeune		before 13-6	13-6	13-6	17 (estim)
Astray					before 21
Squaw		7-6	7-6	c19-6	21
Houston				c19-6	21-22
Osprey		13-6	13-6	c19-6	21-22
Easel		13-6	13-6	c19-6	21-22
Ares		13-6	13-6	c19-6	21-22
Malcolm		13-6	13-6	c19-6	23
John		13-6	13-6	c19-6	23
Dolly		9-6	13-6		23
Wishart					25
Abel			13-6		

* Small pools along road immediately west of Knob Lake (c.200sq.yds. in area).

\+ Small lakes on road between Squaw Lake and Maryjo Lake.

‡ Small lakes between Squaw and the Iron Ore Company of Canada mines.

.Lake had the only extensive area of bare black ice, mainly in Post Office Bay. On Lejeune Lake (outside the watershed) waves developed in the small, surface pools were seen eroding the loose, surrounding white ice by undercutting. White ice was still commonly continuous on all lakes in the basin on June 11th and the shore leads only partial. By the 13th the white ice surface was discontinuous and shore leads generally complete. As expected, white ice remained longer at the southern ends of the lakes, except on Maryjo Lake (outside the basin) where the active inflow stream and low vegetation and snow drifting favoured clearing from this end.

Break-up thus generally proceeded from north to south across the lakes, governed by white ice distribution. Candling and break-up of the black ice began with the removal of the white ice and snow cover. The nature of decay in the black ice suggests that this process is faster than in white ice. However, quantitative judgement demands careful measurement at-a-site, which does not involve the use of any marking device that is permanently installed and will conduct heat to the ice. In the data of Table 8.3 the time periods are confused by the different stages of decay from north to south across the lakes. Measurement is complicated by increases in air temperature and receipts of solar radiation during the period.

Although Knob Lake was representative for the basin at the time of the March survey and was probably so for the mid-winter period as a whole, it was patently uncharacteristic during wastage. It was amongst the earliest of the lakes to clear. Pearce Lake is exceptional, since it is filled with town and company effluents. During early wastage, Squaw Lake was the only lake approaching the stage of Knob Lake. The cause may be that Knob Lake receives more dust from the mines. Although the orange iron dust was not as conspicuous on the surface near break-up as at some periods in the fall, local cryoconite hollows were very common and pockets of ore dust developed within the black ice after exposure to the sun's radiation. A critical event was the opening of Post Office Bay, which may have been due to a combination of (1) downwind transfer of heat from the town, (2) markedly thinner white ice in a very windswept area, (3) although black ice was consequently thicker, this may be destroyed faster than white ice, (4) adiabatic heating of air descending from the 150 ft ridge to the west-northwest and turbulence favouring evaporation. No other lakes in the basin possess any of these locational characteristics and there was little difference in the decay rates.

Conclusions

White ice delays break-up by creating the ice peak in March-April. After the snow is removed, the white ice presents a surface of higher albedo than black ice and further slows the process. Davies (1962, pp. 57-8) described a mean albedo of 20.9% for ice of "grey and mottled appearance", which probably represents the partial white ice stage and c. 30% "over lakes with whiter ice". The winter distribution of white ice is more critical to break-up date than total ice variations or minor differences in topographic location among the lakes of the basin.

CHAPTER 9

THE HYDROLOGICAL IMPORTANCE OF WHITE ICE

This aspect of white ice has perhaps received most attention of all at Knob Lake. McGill Sub-Arctic Research Paper No. 22 (1966) contains studies by Findlay, Adams and Findlay, and Adams et.al., which embrace this topic. The present chapter updates this work, which is based largely upon the surveys of spring 1965, in terms of the spring survey in 1966 and re-assesses some of the deductive premises that have been used to determine the importance of white ice.

Former work has concentrated upon the problem of determining the true snowfall in the area. One of the basic theses of these workers is that the white ice process depletes the amount of snow lying by an amount that can be approximated by assuming that the water equivalent of the original snow cover is equal to about one third that of the resulting white ice. If, therefore, this amount is added to the mean snow water equivalent obtained from a basin survey, this will give a best estimate of accumulated winter snowfall. The spring surveys of 1965 and 1966 were thus timed to fall at the peak winter accumulation, before the beginning of the spring thaw. In 1966 the thaw began within a week following the survey. The corrected mean may then be compared with the accumulated Nipher gauge records (Table 9.1 and sources).

From such comparisons various estimates have been given of the amount of undermeasurement by the standard Nipher gauge, which need

Table 9.1 SUMMARY OF SPRING SNOW COVER IN THE KNOB LAKE BASIN SHOWING HYDROLOGICAL IMPORTANCE OF WHITE ICE FOR 1965 AND 1966

YEAR		Snow course	1300 x 1300ft sample grid	Mid-March basin survey	White ice correction	Corrected mean water content	Nipher receipts (period snow-lying to survey)
1965	arithmetic mean	11.4			3.7		9.36
	geometric mean		12.3	11.0		11.9	
	Nipher as 100%	122%	132%	118%	40% (33%)*	127%	100%
	Number of sample cases	12	88	114			
1966	arithmetic mean	12.1			4.3		9.42
	geometric mean		13.3	12.1		13.1	
	Nipher as 100%	129%	141%	129%	45% (33%)*	139%	100%
	Number of sample cases	12	84	137			

* Percentage in final corrected mean.

Based on Adams and Findlay (1966, text, plus table 1, p.100, and table 4, p.109); Adams et al. (1966, table 3, p.125; table 4, p.126, and table 5, p.130), with additions and changes.

to be considered in assessing the importance of white ice and in correcting the precipitation values used in the ice growth correlations. Tout (1964) calculated a ten year mean of 12.75 in (32.4 cm) snow water equivalent. The twelve year mean to 1966 of 12.8 in was found by Adams et.al. (op.cit., p.118) to have a non-normalised standard deviation of 1.51 in. Comparison with data gathered from the basin suggest undermeasurement of this snowfall by 37% (Findlay, 1966, p.81), 23% (Adams and Findlay, 1966, p.110), 23-28% (Adams et.al., 1966, p.130) and 49% (Findlay, 1967, in press). According to Adams et.al. (op.cit., p.121), the true fall is probably over 15 in (38 cm) of water equivalent. Bruce and Clark (1966, p.70) summarise various estimates of undermeasurement after Wilson of "true catch" and indicate a reduction to 60% in winds of 10 mph (16 km hr^{-1}) and 45% of true fall in 20 mph winds. According to Findlay (in press, Table 1), the total snowfall for the water year is estimated to be 21.44 in (54.3 cm) using his 1.487 correction factor for the gauge. With simultaneous corrections for rain gauge receipts, Findlay finally obtained a surplus of corrected precipitation amounting to 2.24 in (6.8 cm) for 1965/6, which he suggests may be due to divide leakages. Figures for 1964/5 (Findlay, 1966b, p.83) show a similar calculated surplus: 36 in (91.3 cm) total adjusted precipitation, 23 in (58.4 cm) runoff, 11 in (27.9 cm) evapotranspiration and 2 in (5.1 cm) for watershed leakage. In all these estimates the basis for adjustment has been the March survey data, although the need for some adjustment is apparent from the discharge figures competently analysed by Findlay.

There are a few considerations that suggest the possibility that the figures obtained by previous workers have been an exaggeration of the undermeasurement involved. The approach implicitly assumes a true or approximate steady state, in which as much snow is blown into the basin as is deflated from it. Shaw and Tout (1962, Part III, Appendix, p.4, table 1) indicate that blowing snow occurs on c.25% of the days from November through to March. Similarly, various workers (e.g. Cowan, 1965; Gardner, 1964) have shown differences in snow depth and water equivalent between vegetation cover types that indicate considerable lateral re-distribution of snow. It would therefore seem that an equilibrium state is not implicit. The basin presents a rough, wooded surface sloping counter to the prevailing and dominant northwest wind towards the northern edge of the taiga belt and it is possible that, in fact, it provides a small snow trap.

A second difficulty appears to be in assessing how much undermeasurement in the station gauge is due to error by the gauge and how much due to the natural distribution of precipitation through the basin. It was noted by Adams et.al. (loc.cit.) that the exposed, windswept site of the laboratory, near the airstrip, was unusual in the basin and would tend to reduce catch. It was noted also that this is the usual type of site for meteorological stations in Labrador-Ungava (cf. Hare, 1966, for a general discussion of the problem of budget for the peninsula). Findlay (1966b) found that rain gauges distributed through the basin during the summer of 1965 showed receipts up to 10% greater at the higher sites. Weighting on the Thiesson polygon system (ibid., pp. 36-7) reduced this to 5.54%, using the laboratory gauge as the reference point for one of the five polygons. Clearly, receipts were higher in the upper part of the basin than at the laboratory for the summer of 1965. Applying a t-test to Findlay's data for station and Gene Lake gauges, with a Bessel correction for the small sample, gives a value for t well beyond the 1% level, i.e. the difference in receipts is significant and likely to be systematic. Findlay (ibid., p.37) offers two explanations for the difference: (1) the absence of turbulent air currents caused by buildings near the laboratory and (2) the higher elevations in the upper basin causing a slight orographic effect (although the difference is only of the order of 150-200 ft). If the measurements were representative, if the summer of 1965 was representative and if winter snowfall follows similar patterns, then ore might expect more snow to fall in the upper basin. In fact, summer 1965 was abnormally wet: July was 1.65 in (4.2 cm) above average and August the second highest monthly total since records began, so that June, July and August had a total precipitation of 14.83 in (46.4 cm) compared to the second highest of 13.96 in (or 35.4 cm) in 1958 (Barr, mimeos., 1965). It may be that the differences were exaggerated this summer.

The problem remains that there are no data on winter snowfall distribution in the basin. It is likely that the tendency suggested by Tables 6.1 and 6.2 for Knob Lake to have less white ice than the basin average may be due to its size and topographic surroundings than to lower snowfall in this part of the basin. As elsewhere, re-distribution appears to dominate and is reflected in persistent white ice locales.

Lake snow cover tended to be slightly greater in the upper basin in 1966, but this was due to widespread slushing on the medium-sized lakes in the lower part of the basin and is not born out by 1965 data.

Errors of field measurement and weighting must also be considered. Of these, the latter proves negligible: a 5% error in the assessment of the area under any given cover type makes no more than 0.1 in water equivalent difference in the 1965 and 1966 figures. Errors of measurement technique, for example, those caused by slush, wet samples or rough under-surface have received attention elsewhere (e.g. Adams et.al., 1966). To this should be added Findlay's latest work (in press) that indicates overestimation by the Mount Rose sampler on one day in February, 1967, of only 1%, compared with an estimate of 10% by Work et.al. in 1965. At the present level of sophistication it is not possible to fully appraise the error involved here.

The final possible error lies in the sampling method, which applies equally to snow survey data and to the ice data, namely, that the samples were not made by independent random selection. It is not possible to account for the bias this may introduce, although from the large number of sample cases it may intuitively be considered small. Reference to a log-log probability chart entered for sample size and probable error in the estimate of the mean shows that for both Knob Lake and the basin the error at 99% certainty is c.0.45 inches, which is less than the limit of measurement set for ice and snow in the field at 0.5 inches. But this estimate is based upon classical statistical principles involving normal distribution.

Table 9.1 is a summary of basin snow cover statistics obtained by three methods in the springs of 1965 and 1966, compared with accumulated Nipher receipts from the first date of permanent winter snow cover on land. It gives an estimate of the importance of white ice in the snow budget, based on the assumption that the incorporated snow had a mean unit weight $\gamma = 0.3$ g cm^{-3} and that the white ice had a mean unit weight of $\gamma = 0.8$ g cm^{-3}. The sums of the elements in Table 6.1 give estimates of the total quantities of ice and snow present on the lakes of the basin during the spring of 1966, from mean values derived for each lake. Thus, white ice accounted for 47.0% of the total ice volume of 226.86 x 10^6 ft^3 (7.09 x 10^6 m^3) present in the basin and 4.3 in (10.9 cm) former snow water equivalent.

It should be noted that the percentage of slush or water lenses within the ice sheets in March 1966 was very high, higher than in the same month in 1965, and that this is included in total ice thickness. Only on rare occasions was the exact or estimated thickness of these talik-like pockets recorded during field observations, because of the difficulty of obtaining a measurement with the drilling technique used. On occasions lenses were found in the black ice body, but generally they were characteristic of the white ice and especially of the upper part, indicating partial completion of a growth phase. Hence the value for white ice volume is an overestimate at the time of survey.

Since the surveys were oriented mainly towards snow cover, the timing was dictated by the beginning of the ablation season rather than by peak ice. Thus, in 1966 it is likely that much of the surface slush and internal water encountered in the basin froze into white ice after the survey was completed. On Knob Lake peak ice at the regular sites (42 in or 106.5 cm) was recorded during April, two to three weeks after the survey, during the cold snap of 20th - 22nd. It was clear on Knob Lake that the new increase was due to the freezing of the former slush and not to an increase in black ice (indeed, Knob Lake West site showed a decrease in black ice at this time). The values for 1965 more accurately portray the end of winter peak.

In March 1965 the total amount of white ice in the basin was 101.49×10^6 ft^3 (3.15×10^6 m^3), which compares well with 104.97×10^6 ft^3 (3.25×10^6 m^3) for 1966. This is reflected in the greater amount of white ice recorded on Knob Lake in 1966. In 1965 white ice represented, at peak, 36% of the total ice and 3.7 in (9.4 cm) former snow water equivalent.

Thus, in the two years of surveys, white ice has accounted for almost half the total ice in the watershed, which would be 22% of the lake volume, assuming that the ice surface were approximately at the height of the former average lake level. This approximation is acceptible in terms of the accuracy of Welch's stratum method of estimating volumes and of the weight of the snow cover, which counteracts the ice buoyancy; for example, for 104 sites on Knob Lake in spring 1965 the overall discrepancy between water level and ice surface was only +12.4 in (31.5 cm). However, this does not mean that 22% of the surface water is frozen. Only 60% of this can be said to be black ice. The remainder is white ice, of which c.30% of the water content is gained from snow as opposed to lake water. From these assumed approximations it appears that in 1965/6 19%

of the permanent surface water was frozen in situ within the basin.

Ice formation also affects the hydrograph by displacing water out of the basin. Taking a unit weight $\gamma \simeq 0.9$ g cm^{-3} for black ice and assuming that on average snow weight perfectly counteracts buoyancy then

$$\text{Vol. of water displaced} = \text{Vol.}_{ice} - (\text{Vol.}_{bice}.0.9 + \frac{2}{3}\,\text{Vol.}_{wice}.0.8) \qquad \text{(eq.9.1)}$$

where Vol. is volume and the subscripts are total ice, black ice and white ice respectively. In 1965-6 the estimate from the March data is then 65 x 10^6 ft^3 (2.09 x 10^6 m^3) of water displaced. Summing the data calculated by Findlay (in press, table 2) from freeze-over 1965 to March 1966 produces a total winter runoff of 27.31 csm (cubic feet per second per square mile of drainage), or c.480 x 10^6 ft^3. This suggests that 1/7th of the winter runoff has been caused by ice growth. This is assuming a perfectly communicating drainage system. Some minor streams may be cut off, but it is generally thought that the major arteries remain open. In 1965 Findlay (1966a) found in a cross-section of the inflow stream for Knob Lake that the stream remained open in two tubes under the ice either side the central portion which was frozen completely to the bed.

The greatest displacement and most sensitive response occurs early in the season. Findlay (1966a; 1966b, pp. 60-62) gives a neat description of one of the details from November, 1964:

> "While almost 6 inches of ice had formed in the centre of Knob Lake by November 5th, the water near the stop log dam and

culvert area remained open for a few tens of square feet well into December. This was a result of body currents near the discharge point, but the flow was accentuated by water surging out from beneath the ice. On November 20th 3.8 inches of snowfall were measured in the Nipher gauge. The wind was from the southwest blowing at 5 mph, but increased on the 21st to 25 mph and considerable quantities of snow were blown off the ridges and down the lake to the vicinity of the gauge. Here, some of the snow was melted in the open water, but most served to weigh down the ice sheet while the pulsating wind flexed the whole sheet up and down promoting wave action under the ice and produced strong surging at the sheet edges. Moderate southwesterly winds continued until the 24th. The discharge had risen to 20 cfs from 15 cfs on the 20th. A snowfall on the 26th deposited 6.7 inches (Nipher measurement), and the discharge response was notable. By the 28th the flow had reached 44 cfs and the ice had grown in thickness to more than 15 inches, from less than 10 on the 20th. White ice had grown by three inches due to the flooding which accompanied the snow and strong winds. More snow on December 1st and 2nd, followed by strong southwest winds and snow on the 3rd and 4th, induced a flow of 71 cfs. Lighter winds from the northwest on the 5th and the absence of snowfall permitted the discharge to return to a state of normal depletion of ground water supplies".

In November 1966 the same "early December stream rise" was found (Findlay, in press, fig.2).

Break-up waters also contributed to the hydrograph rise in mid-June, 1966. By the second week in June there was probably 12-16 inches (30.5 to 40.7 cm) of (mainly) black ice remaining on the lakes, which rapidly disappeared in mid-month. Findlay (in press, fig.1) found a main runoff peak of over 160 cfs at the end of May with continued high level runoff through June. A second peak passed through the basin outlet at the end of July reaching a rate of 90 cfs briefly. He attributes the first peak to snowmelt and the second to higher precipitation and probably the re-surfacing of infiltrated melt water. It seems likely that break-up added a significant amount to the "tail" of the first peak. Break-up could account for 107 x 10^6 ft^3 (3.32 x 10^6 m^3) of rise by addition of water from the now freely buoyant ice to the lakes bodies that had been replenished previously with meltwater. Displacement is therefore again involved in break-up.

Conclusions.

White ice has been shown to be important in considering any assessment of true snowfall in the area, although methods of doing this have not been fully perfected. It is also important in its effects upon stream discharge.

CHAPTER 10

MEASUREMENT ERRORS AND IMPLICATIONS FOR DATA COLLECTION

Some local climatic differences between lake and laboratory.

The first attempt to measure some of the local climatic differences between Knob Lake and the laboratory site, half a mile to the north and 25 ft (7.6 m) higher, was made in the winter of 1965-66. The techniques used were rudimentary. The prime concern that led to the establishment of a Stevenson screen in the centre of Knob Lake on December 1st 1965, was to determine differences in overnight minima and accumulated degree days. It had been suggested by Archer (1966) on the basis of lake-side measurements that the lake experiences marked temperature inversions generally at least once a week.

The screen was mounted on a wooden stand frozen into drill holes in the ice. Much of the winter it stood at approximately the 1.5 m level, except in the earlier and later parts of the season when snow depth was less. It was equipped with maximum and minimum thermometers and maintained on a weekly basis until May 27th 1966. From mid-January to the end of April a check was kept by a Negretti and Zamba thermograph.

The temperature records from this screen show that the lake commonly experiences minima averaging about $4^{o}F$ ($1.9^{o}C$) below those of the laboratory. Fig. 10.1 shows differences between lake centre and lake-side screen records and laboratory records. Unfortunately, direct comparison between lake centre and lake-side measurements is belied by

Fig.10.2. KNOB LAKE SCREEN DEVICE SITE

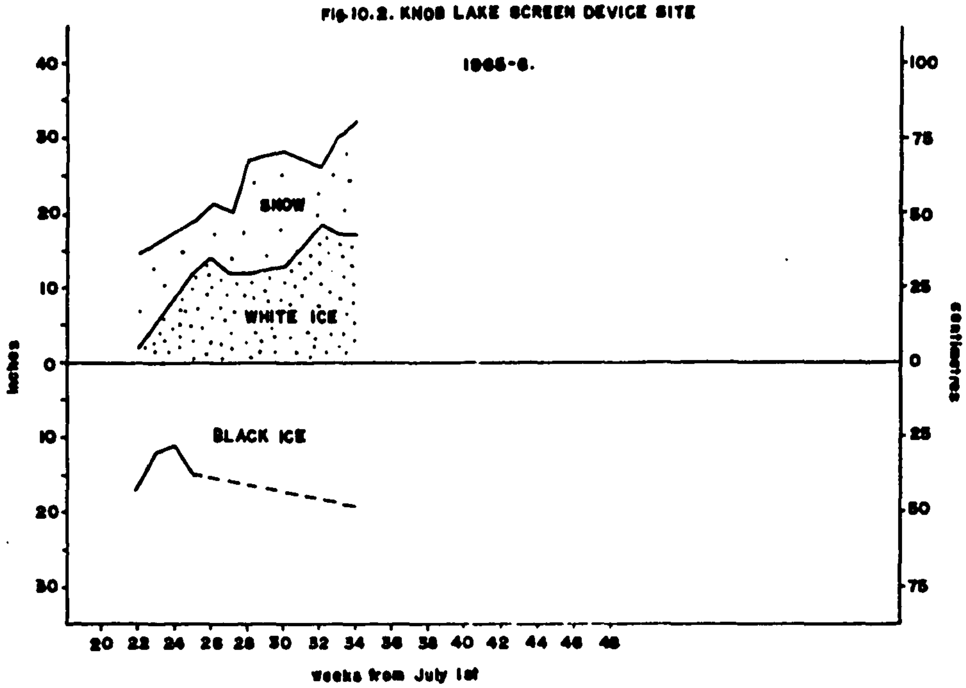


Fig.10.1a. Lake centre weekly temperatures related to lab.

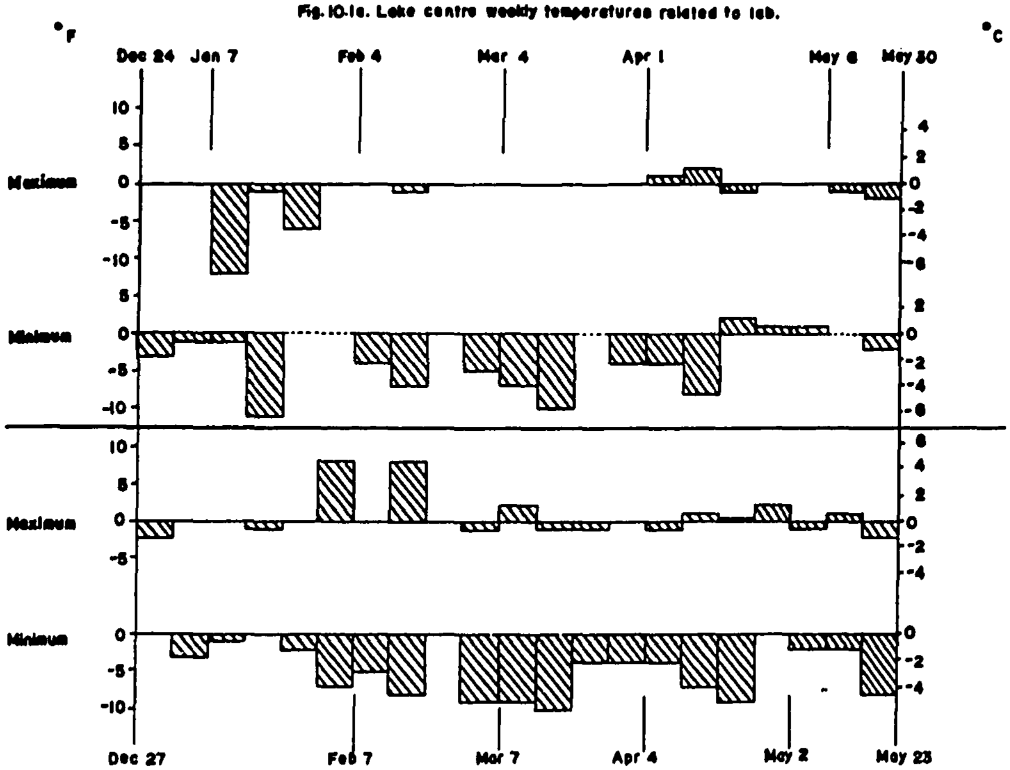


Fig. 10.1b. Lake-side weekly temperatures related to lab.

·the fact that the latter were collected according to a Monday to Monday schedule followed for the laboratory substations and not in line with the Friday to Friday lake measurements. However, the lake-side records showed very similar characteristics to the lake centre records as compared through the main station records. In mean maxima the lake shows highs of 1°F below the laboratory, whilst the lake-side records show a tendency to equal or slightly exceed those at the laboratory. The difference is small and probably spurious.

In general, it seems that the lake-side screen is reasonably representative of the lake conditions and that the mean conditions on the lake can be expected to be 2-3°F (c. 1.2°C) colder than at the laboratory. Summing this difference over the growth period on the lake suggests that possibly the lake experienced up to 500 more freezing degree days than the laboratory, i.e. 10% more in 1965-66.

The lake cover.

At selected meteorological stations throughout Canada break-up/ freeze-up and weekly measurements of ice and snow cover are recorded on Meteorological Branch files (form 2317). The weekly thickness records normally refer to "a site adjacent to a jetty or an airstrip.... in a depth of water greater than the maximum ice thickness for one year ... as near as practicable to the same spot... (and) a new hole drilled for each observation" (MANICE, 1964, p. 35).

It has been suggested for Knob Lake how significant this choice of site may be in determining the measurements obtained. The mean situ-

Plate 10.1: One of the "non-slushing" ice measuring devices in position on Knob Lake.

Plate 10.2: The Snabb hand-drill.

Plate 10.1: One of the "non-slushing" ice measuring devices in position on Knob Lake.

Plate 10.2: The Snabb hand-drill.

'ation is best represented by a mid-lake location. This may be an important consideration, since measuring stations are so few in Labrador-Ungava and in the Canadian North generally and inferences are made from these measurements for wide regions.

The normal method of measuring ice thickness at these stations is by drilling. The standard Canadian kit consists mainly of a hand-operated helical auger and a chisel. Using this kit it is virtually impossible to distinguish changes in the quality of the ice in the drill hole.

At Knob Lake it was found that the 3 in Snabb spoon drill provided the size of drill hole necessary to permit measurement of white ice thickness. Sandvik of Canada Ltd. kindly constructed extension joints to special order that made it possible to measure thicknesses of ice greater than 3 feet with relative ease. For the ultimate strength and bearing capacity of the ice sheet measurement of white ice may not be of general practical importance, although its effect has been noted (e.g. Frankenstein, 1959). But to the understanding of the hydrological budget of the Canadian subarctic it is of vital importance.

Secondly, all forms of drilling produce a potentially high level of observer interference. If there is a slushing potential developed during or immediately after observation, then flooding may be caused which would not otherwise occur. Adams and Shaw (1965) note this and developed their so-called "ice-measuring device", of which the prototype was used at the Knob Lake West site by Archer (1966) in 1965. Five similar devices were used in the winter of 1965-66. Fig. E.14 shows the salient points in the construction of the device. Black ice growth is measured on the central aluminum rod after this has been calibrated to the original black-ice/white-ice interface. White ice and snow are measured up the outer steel tube held by the tripod. As suggested by Adams and Shaw, the final parameter, hydrostatic water level, was also measured "remotely" by polyethylene tubes (Chapter 3). Three main difficulties were encountered in the use of the devices. First, installation and removal the elbow of the device required a slit at least 2 feet long in the ice and the whole structure was somewhat unwieldy. Secondly, trouble was encountered at the Knob Lake West device because low-therm grease had not been used. Thirdly, one or two sites were temporarily lost under the unusually deep snow cover at certain points in the winter. Of these only the first seems inherent. By rotating the elbow a number of thickness measurement could be made on a circle of 4 foot radius around the central tripod. This gave an indication of the variability of the underice surface. Variations of up to 4 in (c. 10 cm) were found on occasions within this short distance. These measurements, however, refer only to the black ice body and the variation in total ice may not be as great. Nevertheless, it is pertinent to note that the base of the ice block removed on April 4th 1966, for crystallographic sampling showed a 6" variation in total ice thickness that was entirely due to black ice variation at the base. The block was just 20 in (50 cm) square. In 1964 this short distance variation was studied by drilling

Fig.10.3. KNOB LAKE WEST DEVICE SITE

1965-6.

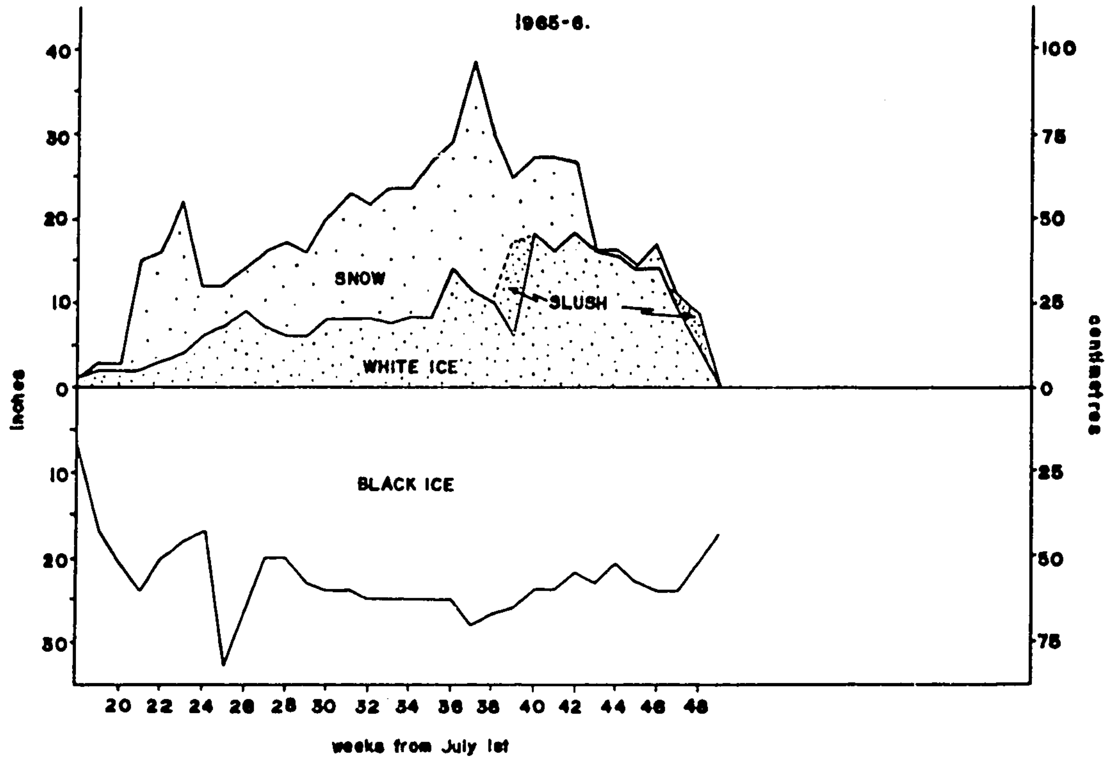
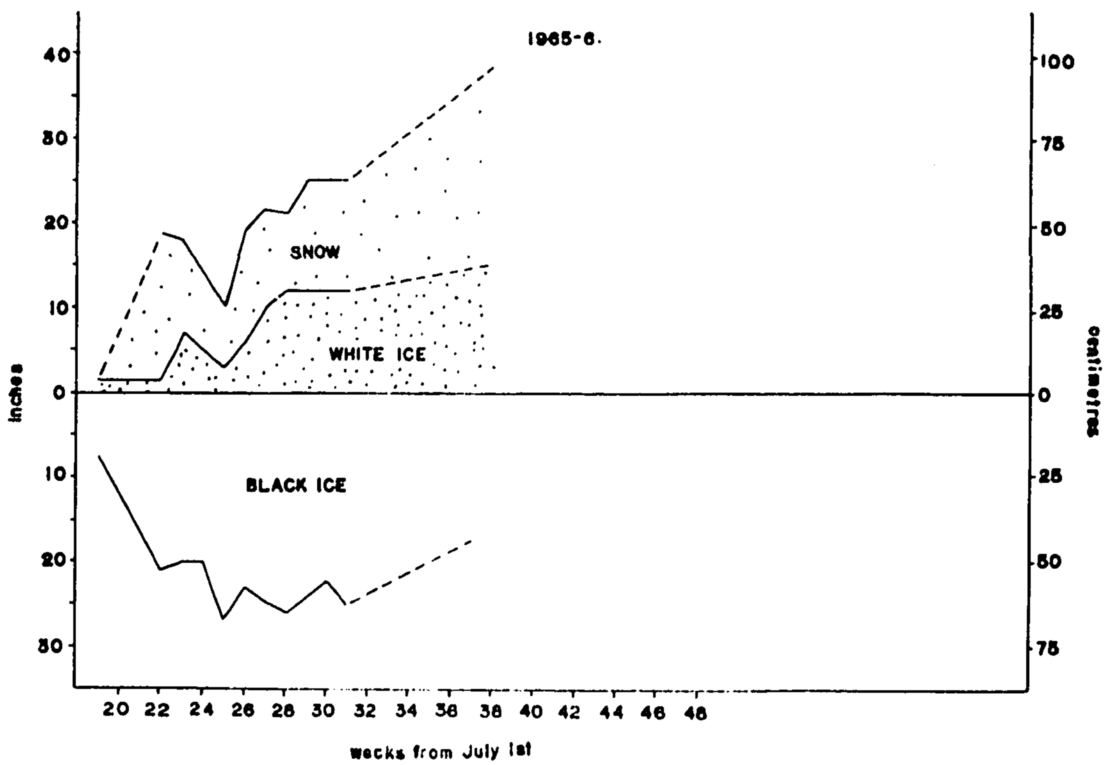


Fig.10.4. KNOB LAKE SOUTH DEVICE SITE

1965-6.



on two small ice plots on Knob Lake (Appendix E, Fig. E. 15 from Adams and Shaw, 1965, pp. 44-45). The measurement of variability on the devices could be improved by carefully noting the orientation of the elbow during installation and following the development at a rigidly determined point.

In general the devices worked well. A device located in the drift site gave the first opportunity to make continuous records of snow loading and ice growth without interference by drilling. The devices were distributed across the lake in a rough cruciform, cutting across the pattern of snow and white ice distribution found in former years (Fig. 1.1).

Development of ice cover at the non-slushing device sites.

Figs. 10.2 to 10.6 plot the development of the lake cover at these sites for the periods of records during the winter 1965-66. Unfortunately, the screen site device broke in late December and the southern site device was destroyed by vandals in January. The contrast is clear between the drift site and the northern site, also in Post Office Bay. The northern site represents the deflated, upwind area of the lake with thick black ice and low white ice and snow. At the artificial drift site the graph is rotated 180 degrees so that the sharp initial increase in the black ice at the northern site now occurs in the white ice and black ice is thin and shows hardly any increase throughout the season. Since there was no interference from drilling in the vicinity, the drift site graph shows a situation in which snow loading has

Fig.10.5. KNOB LAKE NORTH DEVICE SITE

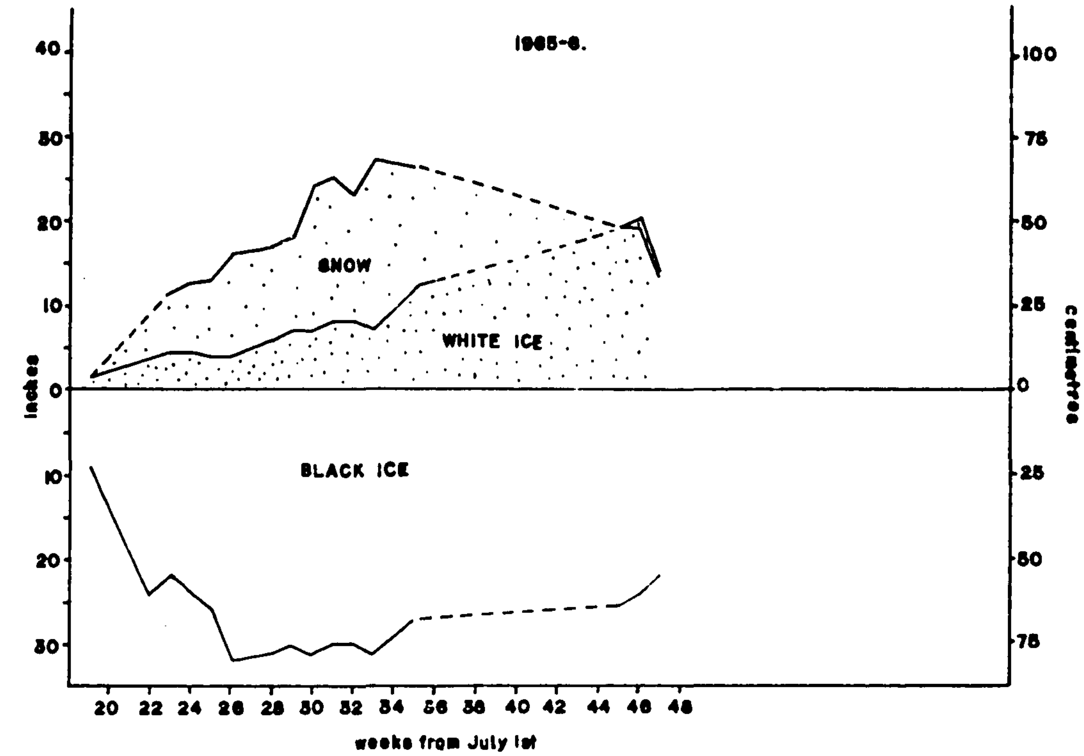
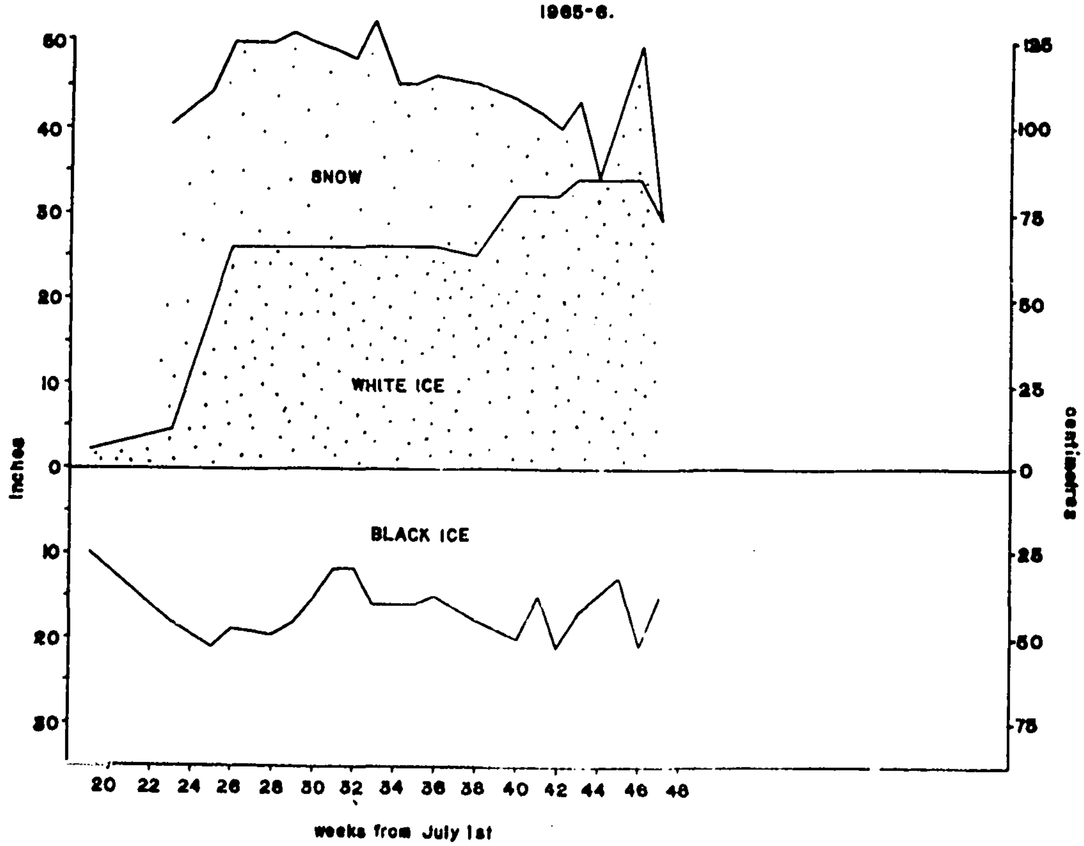


Fig.10.6. KNOB LAKE DRIFT DEVICE SITE

1965-6.



contributed naturally to a thicker ice sheet. Each site shows the tendency for black ice to decrease immediately after a new growth of white ice, which is probably due to penetration into warmer water. Hence, the regression coefficients obtained for black ice and total ice are very specifically only valid for this situation in which white ice plays such a major role. The north and south sites, from the deflation and deposition zones respectively, show a qualitatively similar contrast to that between the drift site and the north site, notably in white ice growth, in spite of the truncated record at the southern site.

Simple regression was performed between white ice and black ice data to define the contrasts more specifically. In the absence of better records for the development of ice in the deposition zone, the drift site was taken as representative, although it is clearly an exaggerated case, and compared to the northern site. The data were not transformed on the assumption that they possessed the same distribution as found for the ten years of black ice and white ice records used in the general multiple regressions. The results show a high scatter indicative of the poor correlation between the two quasi-independent elements and of limited records, but the contrast is clear. Thus, at the northern site

$$B_{ice} \simeq 20.468 + 0.538\, W_{ice} \qquad \text{(eq. 10.1)}$$

with a standard error of $B_{ice} = 8.47$ inches.

At the drift site

$$B_{ice} \simeq 16.822 - 0.008\, W_{ice} \qquad \text{(eq. 10.2)}$$

with a standard error of B_{ice} = 2.93 inches.

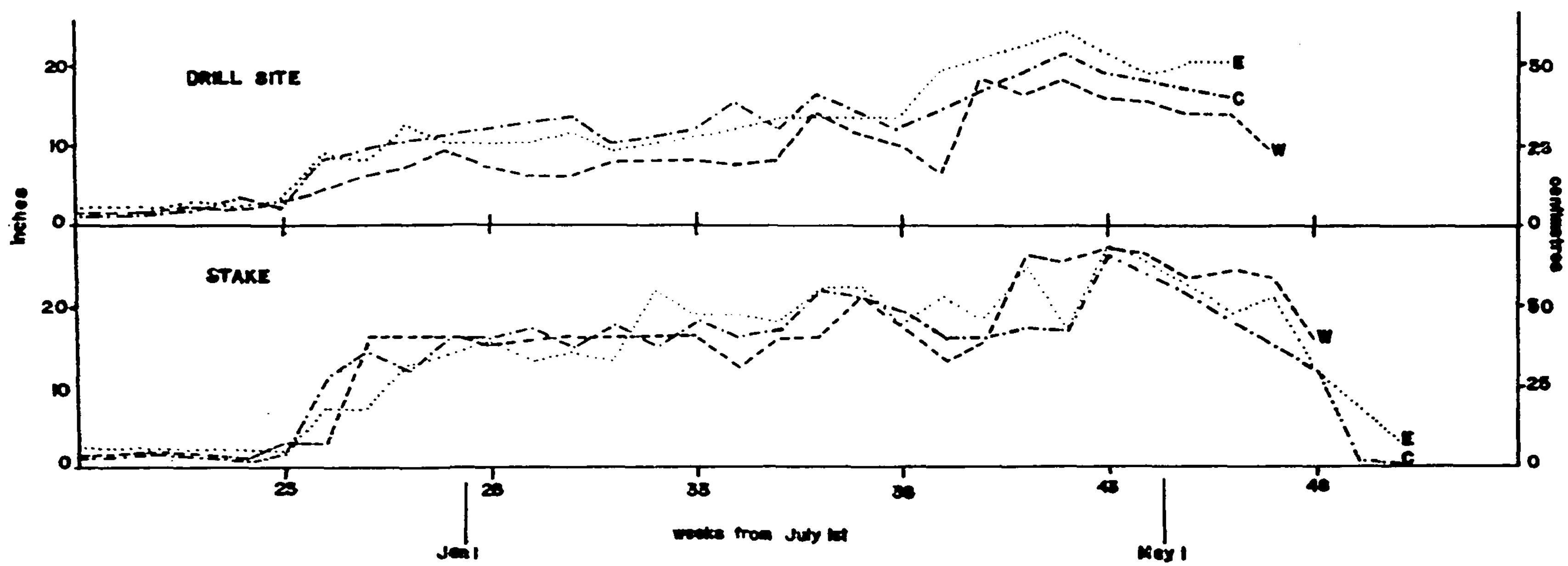
At the northern site the simple correlation coefficient is 0.3395, whilst at the drift site the relationship is slightly negative, r = -0.0180. The relationship is also more clearly defined at the drift site, i.e. less scatter, which suggests that there is sufficient white ice present to noticeably control the black ice growth. Unfortunately, parametric tests (t-test) indicate that the correlation for this small sample (18 and 16 cases) is not statistically significant. More data are needed, but on non-statistical grounds it seems likely that a relationship does exist.

Further correlations showed that white ice "explained" 49.2% of total ice growth at the northern device site, 71.8% at the west device site and 85.0% at the drift site. The southern site showed only a 56.8% explanation: theoretically, and according to the distribution maps the explanation should lie between western and drift sites. This is presumably because the site was destroyed by vandals before the major spring slushing phase.

In order to obtain results in which observer interference was reduced to a minimum, the devices were necessary. However, since they require extra effort to install and cost in construction, it is pertinent to ask how much observer interference is reduced or how much of a problem observer interference presents.

The west, north and drift sites alike show two major slushing phases during the season, in December and at the end of March. The same

Fig. 10.7. Ice growth at regular sites, 1965-6.



pattern is shown in Fig. 10.7 which plots the development of white ice at the regular survey sites. These include the device site at Knob Lake West, which shows somewhat slighter slushing than the east and centre sites. However, the lower part of the graph plots the records from the marker stake just six feet away, and here there is no discernible difference.

<u>The validity of using only Knob Lake Centre site.</u>

Fig. 10.7 indicates that throughout the winter of 1965-6 Knob Lake Centre showed white ice values generally very close to those recorded for sites Knob Lake East and Knob Lake West. Indeed, in both stake and drill hole graphs it generally occupies a position between the two "side" sites. However, this is not so for all years. Inspection of the records shows that the centre site often underemphasises the role of white ice indicated at the other sites, although in 1965 it actually showed more white ice. Underemphasis is illustrated, for example, in the graphs produced by Andrews and McCloughan (1961, figs. 2 and 8), which show that agreement between lakes (Knob and Maryjo) and between regular sites on Knob Lake was fairly good for black ice in 1959-60 but not so good for white ice. This seems to occur in a number of winters because of the sporadic and localised nature of white ice growth and consequently larger contrast are usual in years of marked white ice growth. It appears that greatest variability is caused by white ice. The relationships do not remain as constant from year to year as suggested by Andrews (1962) and Andrews and McCloughan (1961). This makes it

difficult to assess the probable representiveness of a site for a given year before the event. It is easier to predict for an area as opposed to a site knowing the probable distribution of white ice on the lake studied. In the Knob Lake area it seems that a number of sites near the centre of the lake is the best solution, to which the three regular sites on Knob Lake are probably a fair approximation. This is most true for at-a-time estimates. However, in the longer record the variations tend to cancel out.

Conclusions.

The non-slushing ice measuring devices reduce the work necessary during routine data collection at a number of sites throughout a season. It is possible to read the device in 5 minutes and obtain a number of measurements of variability about the site as "confidence" limits, whereas drilling may take 20 minutes and longer if hampered by slush or water layers for one measurement. Installation of the device may take an hour or two. They do not appear to improve the quality of the records. Slushing phases are essentially similar at both device and drill sites.

Nevertheless, in principle they provide a superior technique of measurement. Two or three such sites at mid-lake or mean white ice locations should provide a better estimate of all lake cover parameters than is at present generally obtained.

CHAPTER 11

GENERAL CONCLUSIONS

White ice is an important component of the ice sheet in the Knob Lake area of central Labrador-Ungava. It is likely to be a common element of all lake ice covers in similar subarctic regions. Scope thus exists for a wider, regional study to define the boundaries of its distribution. The study has shown that in areas of white ice snow cover no longer acts solely as an insulator, which reduces the loss of heat from the water body to the atmosphere. It directly encourages ice growth by (1) cooling the water and possibly providing freezing nuclei during freeze-up, and (2) by increasing flooding potential during the growth period. White ice may thus be predicted in terms of snowfall, and it permits ice growth in spite of snow accumulation.

Unfortunately, the data do not exist for a proper study of the causes of cracking prior to flooding. There remains wide scope for study in this field. However, this thesis has been forced to consider the gross causes and effects of cracking in seeking to explain white ice growth and distribution. It was found that there was a close link between high diurnal temperature ranges and high rates of white ice growth.

Thus the main controls of white ice growth appear to be snowfall and high diurnal temperature ranges. In Canada such conditions are best fulfilled within the taiga section of the subarctic, Koppen's Dfd zone with a continental mesothermal climate of well-distributed precipitation and at least three months with mean temperatures below the freezing point. To the north, precipitation decreases in the tundra or ET climatic zone, and white ice is likely to be more restricted to areas where conditions favour local drifting. To the south, the Dfc zone has milder winters, and high diurnal ranges below the freezing point are likely to be less frequent.

White ice partially insulates the original ice sheet from the cold air above by its thickness as well as its slightly lower coefficient of thermal diffusivity which follows from its slightly lower density. Because it insulates and at the same time depresses the black ice into warmer water, white ice does not appear to cause a general increase in ice thickness. Indeed, the parameters which best explain overall ice growth (notably accumulated freezing degree days) are those which are most important to normal ice growth. In general, therefore, existing predictive equations may work tolerably well in "white ice areas", although based on wrong premises. This does not mean that white ice is not locally responsible for peaks in ice thickness.

There is no evidence that white ice materially affects the length of frozen period. However, it is important in break-up and in the annual water balance as a temporary repository for atmospheric moisture. Whilst black ice is essentially a magmatic rock, white ice is metamorphic, consisting of one third snow. It is necessary that surveys made to estimate solid precipitation storage consider white ice.

Future data collection and analysis could usefully be directed to the heat balance of its growth and its role in the heat balance of the lake body.

APPENDIX A

DATA STORAGE

The data available for studies of lake ice at Knob Lake are summarised in Table A.1. Most of this information was coded and transferred to punchcards in 1966. These cards are deposited with the Department of Geography, McGill University. The following table is a list of the coding and punch formats used. All measurements of lake cover are recorded in inches and tenths to the nearest half inch.

1) Weekly ice thickness data cards:

FORMAT (I3, 1X, I2, 1X, I2, 1X, I2, 1X, F4.1, 7F6.1, 2X, I3)

Variables, left to right:

1. site code: 051 for Knob Lake West.
   041 for Knob Lake Centre.
   031 for Knob Lake East.
   052 for Maryjo Lake West.
   042 for Maryjo Lake Centre.
   032 for Maryjo Lake East.
2. day, e.g. 04.
3. month, e.g. 04.
4. year, e.g. 58.
5. period numbered in weeks from the first Friday in July.
6. SNOW - snow depth in vicinity of drilling.
7. SLUJ - slush depth at drill hole. A negative sign in column 22 indicates that the measurement refers to water lenses in the ice profile.

8. WICE - white ice thickness.

9. BICE - black ice thickness.

10. TICE - total ice thickness.

11. WELV - hydrostatic water level in hole.

12. POSO - depth of snow on site stake.

13. POWI - depth of white ice on site stake.

14. SURF - general character of lake surface according to following code:

Column 66	Column 67	Column 68
1 = no snow	1 = soft	1 = a few closed cracks
2 = discontinuous snow	2 = hard (snowshoe)	2 = many closed cracks
3 = smooth	3 = hard (foot)	3 = open leads and cracks
4 = light hummocks	4 = soft on hard	
5 = moderate to strong hummocks	5 = crusted	
6 = light ridging	6 = very slushy	
7 = moderate to strong ridging.		

Blanks are missing data. These have been interpolated for analysis at site Knob Lake Centre.

2) Climatological data cards:

FORMAT (I3,2X,I2,1X,I2,1X,I2,3X,I2,4X,I4,6X,I4,7X,I1,4X,I4, F4.2,3X,F4.1)

Variables, left to right:

1. identification of climatological card (001).

2. day, e.g. 04.

3. month, e.g. 04.

4. year, e.g. 58.

5. period numbered in weeks from the first Friday in July.

6. KDAY - accumulated freezing degree days based on July 1st.

7. IDAY - accumulated heating degree days based on January 1st.

8. DOWI - dominant wind by miles of run accumulated. Coded: 1-NE, 2-E, 3-SE, 4-S, 5-SW, 6-W, 7-NW, 8-N, and 9-varied, with dominant and "varied" defined by whether or not one direction prevails over all others by more than 100 miles.

9. RUWI - run of the wind in miles per week.

10. SNOF - snowfall water equivalent from standard gauge measurements (Nipher).

11. SNUR - sunshine hours recorded on a Campbell-Stokes pyrheliometer. Official climatological records used to December 31st, 1964. Laboratory records used from January 1st, 1965, to June 30th, 1966.

Wind, sun, snowfall and temperature data are accumulated for weekly periods Friday to Friday.

3) End-of-season surveys of Knob Lake:

a) for 1965 and 1966.

FORMAT (I1,I4,1X,F4.1,5F6.1,6X, I4)

Variables, left to right:

1. 1 or 2 for first and second year using the grid network shown in Fig. 5.1.

2. site coordinates; origin at northwest corner and moving in steps of 1 = 200 ft.

3. SNOW
4. SLUJ
5. WICE
6. BICE
7. TICE
8. WELV

(3–8) coded as in (1).

9. LAZW - 1 if water lenses found within ice sheet.
10. STAW - white ice at wooden, grid stake.
11. STAS - snow depth at wooden, grid stake.
12. OSNO - depth of "old snow".
13. YSNO - depth of "new snow".
14. 1965 or 1966.

b) The end-of-season survey for Knob Lake for 1964 was conducted on a very irregular "grid". Data is coded according to order of listing in the manuscript field records held at the McGill Sub-Arctic Research Laboratory, Schefferville.

FORMAT (I1,I3,6F6.1,5X,I1,5F6.1)

Variables, left to right:

1. 4 for 1964.
2. site numbered 1 through 254 in order of recording in the manuscript field notes.

3-13 as for 1965 and 1966.

14. DEPV - depth of water at drill hole to nearest 6 inches (in feet and tenths).

.4) Mid-season and white ice surveys for Knob Lake, 1965 and 1965-66.

FORMAT (I1,I4,1X,F4.1,2F6.1)

Variables, left to right:

1. identification of survey.

   1 = January, 1965.

   2 = November 24th, 1965.

   3 = December 10th, 1965.

   4 = December 23rd, 1965.

   5 = January 8th, 1966.

   6 = January 22nd, 1966.

   7 = February 5th, 1966.

   8 = March 3rd, 1966.

2. coordinates as in (3).

3. SNOW
4. SLUJ
5. WICE

} coded as in (1).

5) Knob Lake basin surveys, 1965 and 1966:

FORMAT (I1,I2,I2,1X,F4.1,5F6.1,5X,I1)

Variables, left to right:

1. 5 if 1965, 6 if 1966.

2. code for each lake.

   01 = Osprey Lake
   02 = Communications Lake
   03 = Houston Lake
   04 = Barr Lake

05 = North Lake
06 = Middle Lake
07 = South Lake
08 = Malcolm Lake
09 = Phred Lake
10 = Gene Lake
11 = Cowan Lake
12 = Easel Lake
13 = Ares Lake
14 = Trigger Lake
15 = extension of Malcolm Lake (over 100 drillings).

3. code for site on lake in order of recording in the two sets of manuscript field notes deposited at the McGill Sub-Arctic Research Laboratory, Schefferville.

4-10 as 3-13 in (3).

6) Supplementary meteorological data, 1962-66.

FORMAT (A2,2X,I2,1X,I2,1X,I2,1X,I2,3X,I4,I5,5X,2F5.2,4F5.1,2I5)

Variables, left to right:

1. KL for Knob Lake
2. day
3. month
4. year
5. period numbered in weeks from the first Friday in July.
6. incoming short-wave radiation measured by an Eppley radiometer, in langleys summed Friday to Friday.
7. net radiation indicated from a Kipp and Zonen solarimeter, in langleys summed Friday to Friday
8. weighted mean temperature of lake body beneath original black-ice/white-ice interface at site KLW, a twenty foot thermocouple string

9. as 8 for the 40 ft. site in the middle of Knob Lake

10. maximum temperature for week (Friday-Friday) recorded at screen on Knob Lake

11. minimum temperature for screen on Knob Lake

12. maximum temperature for week (Monday-Monday) recorded at screen on lake-side (in RCAF Bay). (The Monday is that next following the Friday for 10.)

13. minimum as 12

14 and

15 run of wind at 3 ft level recorded at southern site (Fig. 1.1) on Knob Lake (14) and at the drift site (15).

Information from weekly measurements is retained on file at the laboratory in the format laid down by the Meteorological Branch (form 2317). Additional coding forms were drawn up, duplimated and used for supplementary data in 1965-66 and will be used in future years.

APPENDIX B

COMPUTER PROGRAMS

A number of ready-made and library programs used in analysing the data are described below. In addition to these, a number of smaller programs were written to prepare the data for mapping or regression analysis, for example, to calculate probability of growth, to cumulate or to obtain rates of change in various meteorological and lake cover parameters and to calculate buoyancy, etc.

NORMSTAND

This program was originated by Professor B. Greer-Wootten of the Department of Geography, McGill University. It is based upon the techniques devised by Snedecor for determining degree of normality (Snedecor, 1956: Statistical Methods, pp. 199-205, tests for skewness and kurtosis) and selects, when necessary, the transformation best suited to approximate a normal distribution of the data to enable the use of parametric statistics. The available transformations are: $\log_{10}$, square-root, cube-root, square and cube. The program provides t-test values for skewness and kurtosis both before and after transformation. The original data matrix, the transformed matrix, standard scores and simple correlation coefficients on transformed or standard scores matrices may be obtained as desired. Transformed scores or standard scores may be punched out for use in other programs, as was done in this study for use in REVATR.

REVATR

This is a step-wise multiple regression program devised by Clive Minto for IBM and distributed in the IBM Share Library. A copy of the source is held at the Computing Centre, McGill University, and the program is available on tape library. For most of the analyses the tape was used, but for mapping the source cards were modified to obtain punched output. The program provides for certain specified and specifiable transformations of the raw data, although it is not suitable for producing standard scores. Sums of transformed variables, raw sums of squares and cross-products, means, residual (or deviation) sums of squares, and simple correlation coefficients are available from the regression algorithm. Intermediate equations may be obtained as the program introduces successive variables, holding the other variables statistically constant. An F-level may be set for rejection of insignificant variables. At each step a standard error of Y, the dependent variable is given together with a multiple correlation coefficient, r. Simple residuals from the final best-fit equation are provided.

SYMAP

The program was developed by Professor H.T. Fisher, formerly of Northwestern University and now of Harvard University, and termed by its originator a "Synagraphic Computer Mapping Program". The source obtained by Professor B. Greer-Wootten of the Department of Geography, McGill University, is Version 03.

In this form the program requires:

. (1) a base grid is drawn and laid over a base map. The grid is 129 columns of 1/10th inch broad and n rows of 1/6th inch long. On this grid the map boundaries and side legends are marked. The co-ordinates of each point are then counted and transferred to punchcards (termed "row legends"). Blank cells are included on the punchcards where it is intended to omit any interpolated choropleths on the final print out.

(2) the location of each data point is then transferred to the appropriate grid cell and coordinates recorded on punchcards in suitable format. In order to obtain interpolations to the very edge of the mapped area, "non-differentiated" data points must be similarly specified with dummy values which are transferred by the program from some specified differentiated data point nearby. Unwanted interpolation is erased by row legends.

(3) symbols and class intervals may be specified or left as determined by the program. The program provides ten symbols for choropleth levels, which include overprinting to obtain darker shades.

(4) the program also provides a histogram of classified data and the option of obtaining data punched out in classes.

(5) more than one map may be drawn at one compilation and, with suitable control cards, the base map may also be changed.

(6) provision is made for a user-written subroutine to read in data in any format.

In order to program the Knob Lake data it was necessary to specify two data point networks. One was used for 1964-65 and white ice survey data. The other was used for March, 1966, data, where a staggered grid had been used in the field, to facilitate interpolation (following the suggestions of Robinson, A.H., 1962: Mapping the correspondence of isarithmic maps, Annals of the Association of American Geographers, December, pp. 414-425).

The source program originally provided for storage of up to 1,000 data points. For use on the McGill IBM 7044 computer this was reduced to 400 (near maximum storage). As taken in the field, the white ice data points of the March 1966 survey were too close and numerous. Initially, an attempt was made to program this grid, but it was abandoned owing to storage and related problems. A 117 point graticule was used as for the other surveys.

CORRIN

This program was written by Mrs. Manley of the Computer Centre at McGill University. It provides simple correlation coefficients and a t-test for significance of correlation for sets of complete or incomplete data. Sums, sums of squares and cross-products and number of cases are provided.

APPENDIX C

STATISTICAL CHARACTERISTICS OF THE DATA

This appendix comprises information upon the statistical distributional characteristics of the data used in this thesis, and histograms relating to the distributions of mapped data.

Abbreviations: "A" signifies accepted at coefficient of risk, $\alpha = 0.05$, that a given value falls outside a normal curve, and likewise "R" is rejected.

Parameter	t values before transformation		Transformation selected	t values after transformation		Degrees of freedom	Acceptance at $\alpha = .05$	
	skewness	kurtosis		skewness	kurtosis		skewness	kurtosis
1.) Characteristics of cumulative data								
Date (week from July 1st)	0.29	3.76	none			262	A	R
Snow cover	0.88	3.66	none			262	A	R
Slush	21.19	72.30	not improved by any transformation available			262	R	R
White ice	1.75	2.64	none			262	A	R
Black ice	0.11	2.49	none			262	A	R
Total ice	2.87	2.42	x^2	1.42	2.98	262	A	R
Accumulated degree days	0.94	5.07	none			309	A	R
Run of wind	1.10	3.36	none			291	A	R
Snowfall water equivalent	0.34	3.61	none			291	A	R
Sunshine hours	4.14	3.09	$\sqrt{x}$	0.37	4.16	291	A	R

Parameter	t values before transformation		Transformation selected	t values after transformation		Degrees of freedom	Acceptance at $\alpha = .05$	
	skewness	kurtosis		skewness	kurtosis		skewness	kurtosis

2.) <u>Characteristics of rates of change data.</u>

For lake cover data the figures used were weekly change in inches plus 30. The text should be referred to for a detailed discussion of the problems (Chapter 3).

Parameter	skewness	kurtosis	Transformation selected	skewness	kurtosis	Degrees of freedom	skewness	kurtosis
Date (weeks from July 1st)	0.29	3.76	none			262	A	R
Snow cover	3.30	14.57	x^2	3.21	15.42	257	R	R
Slush	9.97	70.79	x^2	4.06	59.85	257	R	R
White ice	6.50	14.68	x^3	1.75	7.70	257	A	R
Black ice	3.33	3.07	$\log_{10}$	1.23	1.86	257	A	A
Total ice	4.69	10.16	x^2	0.33	6.97	257	A	R
Accumulated degree days	0.57	52.19	none			246	A	R
Run of wind	1.63	1.04	none			278	A	A
Snowfall water equivalent	12.90	14.61	$\sqrt[3]{x}$	1.12	1.54	278	A	A

3.) <u>Characteristics of white ice survey data.</u>

Parameter	skewness	kurtosis	Transformation selected	skewness	kurtosis	Degrees of freedom	skewness	kurtosis
Snow cover	21.29	42.47	$\sqrt[3]{x}$	0.57	8.24	818	A	R
White ice	13.65	26.67	$\sqrt{x}$	0.22	0.54	818	A	A

4.) <u>Characteristics of basin survey data, 1966.</u>

It was necessary to re-sort and run each variable independently, because incomplete data is not provided for in NORMSTAND.

Parameter	t values before transformation		Transformation selected	t values after transformation		Degrees of freedom	Acceptance at $\alpha = .05$	
	skewness	kurtosis		skewness	kurtosis		skewness	kurtosis
Snow cover	5.53	0.65	$\log_{10}$	1.02	2.90	392	A	R
Slush	11.47	4.01	$\sqrt[3]{x}$	4.89	5.67	392	R	R
White ice	5.06	8.18	$\log_{10}$	1.36	13.33	134	A	R
Black ice	3.92	5.72	x^2	0.78	0.35	81	A	A
Total ice	1.39	5.10	none			238	A	R
Hydrostatic water level	8.10	2.82	not improved by any transformation available			225	R	R

Hydrostatic water level could not be normalised in the present form of the data. This was probably due to the fact that measured in terms of the upper ice surface the data contain many negative values, which preclude the use of square-root and cube-root transformations. It is likely, though not certain, that normality might be approximated by transformation if the levels were measured from the bottom surface of the ice (as, indeed, was the practice in early observations). It was not considered of sufficient importance to merit adding total ice thickness to water level in the case for which this information was used.

5) Characteristics of variables in regression equations.

	Significant independent variable (as pp.30-31)	Correlation coefficient with dependent variable	F level	Beta coefficient in final equation
Equations 3.1 to 3.3: total ice accumulation dependent T_{ice}^2	K	0.95	1835.7	1.28
	W	0.86	15.9	0.37
	Sh	0.89	1.7	0.13
	T	0.80	2.7	0.10
	S_1	-0.02	20.0	0.09
	S_{fall}	0.82	2.4	0.09
Equations 3.4 & 3.5: black ice accumulation dependent B_{ice}	K	0.85	80.3	1.10
	W_{ice}	0.26	19.0	0.39
	W	0.87	660.8	0.37
	Sh	0.81	5.4	0.33
	S_1	-0.02	17.2	0.11
	T	0.76	1.6	0.08
Equation 3.6: white ice accumulation dependent W_{ice}	K	0.62	126.2	1.29
	S_{fall}	0.70	205.3	1.18
	W	0.45	53.9	-1.86

	Significant independent variable (as pp. 30-31)	Correlation coefficient with dependent variable	F level	Beta coefficient in final equation
Equation 3.7: white ice rates of growth dependent $\left(\frac{dW_{ice}}{dT} + 30\right)^3$	$\left(\frac{dS_1}{dT} + 30\right)^2$	-0.23	10.8	-0.22
	$\sqrt[3]{\frac{dS_{fall}}{dT}}$	0.22	9.3	0.20
	T	-0.18	0.9	-0.15
	$\left(\frac{dS_c}{dT} + 30\right)^2$	-0.02	0.9	-0.12
Equation 3.8: black ice rates of growth dependent $\log_{10}\left(\frac{dB_{ice}}{dT} + 30\right)$	T	-0.31	25.7	-0.38
	$\left(\frac{dW_{ice}}{dT} + 30\right)^3$	-0.27	27.5	-0.34

	Significant independent variable (as pp. 30-31)	Correlation coefficient with dependent variable	F level	Beta coefficient in final equation
Equation 3.7: white ice rates of growth dependent $\left(\frac{dW_{ice}}{dT} + 30 \right)^3$	$\left(\frac{dS_1}{dT} + 30 \right)^2$	-0.23	10.8	-0.22
	$\sqrt[3]{\frac{dS_{fall}}{dT}}$	0.22	9.3	0.20
	T	-0.18	0.9	-0.15
	$\left(\frac{dS_c}{dT} + 30 \right)^2$	-0.02	0.9	-0.12
Equation 3.8: black ice rates of growth dependent $\log_{10} \left(\frac{dB_{ice}}{dT} + 30 \right)$	T	-0. [illegible]1	25.7	-0.38
	$\left(\frac{dW_{ice}}{dT} + 30 \right)^3$	-0.27	27.5	-0.34

	Significant independent variable (as pp.30-31)	Correlation coefficient with dependent variable	F level	Beta coefficient in final equation
Equation 3.9: total ice rates of growth dependent $\left(\frac{dT_{ice}}{dT} + 30\right)^2$	T	-0.41	46.1	-0.39
	$\left(\frac{dSc}{dT} + 30\right)^2$	-0.01	2.7	-0.08
	$\frac{dW}{dT}$	0.13	2.2	0.07
Equation 3.10: white ice accumulation dependent W_{ice}	$S_{fall,\ p}$	0.66	174.2	1.45
	W_p	0.40	67.2	-1.69
	K_p	0.53	52.4	0.89
	$S_{c,\ p}$	0.41	2.1	-0.08
Equation 3.11: white ice rates of growth dependent $(dW_{ice} + 30)^3$	T	-0.16	5.3	-0.16
	$dS_{fall,\ p}$	0.14	3.9	0.15
	$(dS_{l,\ p} + 30)^2$	0.13	3.1	0.11
	$(dS_{c,\ p} + 30)^2$	-0.09	2.1	-0.13

6.) Histograms from the sequent white ice surveys.

Histograms of deviations from the buoyancy equation refer to figs. 4.6 and 4.7 in the text.

Snow cover and white ice distribution histograms are grouped for each of the seven surveys mapped in Chapter 5. Reference should be made to Chapter 5 and to the captions on the respective maps in conjunction with these histograms.

Class intervals are one standard deviation. Ten classes run from -5 to +5 standard deviations.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE - WEEK 1 . . NOVEMBER 24, 1965

FIG. C.1.

Refer to Fig. 5.1.

. . . . SNOW DISTRIBUTION . . . .
PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

1	I''2''I	I--3--I	I==4==I	I++5++I	IXX6XXI	IOO7OOI	I@@8@@I
2	I''2''I	I--3--I	I==4==I	I++5++I	IXX6XXI	IOO7OOI	I@@8@@I
3			I==4==I	I++5++I	IXX6XXI	IOO7OOI	IOO8OOI
4			I==4==I	I++5++I	IXX6XXI	IOO7OOI	
5			I==4==I	I++5++I	IXX6XXI	IOO7OOI	
6			I==4==I	I++5++I	IXX6XXI	IOO7OOI	
7			I==4==I	I++5++I	IXX6XXI		
8			I==4==I	I++5++I	IXX6XXI		
9			I==4==I	I++5++I	IXX6XXI		
10			I==4==I	I++5++I	IXX6XXI		
11			I==4==I	I++5++I	IXX6XXI		
12			I==4==I	I++5++I	IXX6XXI		
13				I++5++I	IXX6XXI		
14				I++5++I	IXX6XXI		
15				I++5++I	IXX6XXI		
16				I++5++I	IXX6XXI		
17				I++5++I	IXX6XXI		
18				I++5++I	IXX6XXI		
19				I++5++I	IXX6XXI		
20				I++5++I	IXX6XXI		
21				I++5++I	IXX6XXI		
22				I++5++I	IXX6XXI		
23				I++5++I	IXX6XXI		
24				I++5++I	IXX6XXI		
25				I++5++I	IXX6XXI		
26				I++5++I	IXX6XXI		
27				I++5++I	IXX6XXI		
28				I++5++I	IXX6XXI		
29				I++5++I	IXX6XXI		
30				I++5++I	IXX6XXI		
31				I++5++I	IXX6XXI		
32				I++5++I	IXX6XXI		
33				I++5++I	IXX6XXI		
34				I++5++I	IXX6XXI		
35				I++5++I	IXX6XXI		
36				I++5++I	IXX6XXI		
37				I++5++I	IXX6XXI		
38				I++5++I	IXX6XXI		
39				I++5++I	IXX6XXI		
40				I++5++I	IXX6XXI		
41				I++5++I	IXX6XXI		
42				I++5++I	IXX6XXI		
43				I++5++I	IXX6XXI		
44				I++5++I	IXX6XXI		
45				I++5++I	IXX6XXI		
46				I++5++I	IXX6XXI		

Class boundaries:-

1 ... -4.00 and below
2 ... -3.00. - -3.99
3 ... -2.00 - -2.99
4 ... -1.00 - -1.99
5 ... $\bar{x}$ - -0.99
6 ... 1.00 - 0.01
7 ... 2.00 - 1.01
8 ... 3.00 - 2.01
9 ... 4.00 - 3.01
10 ... above 4.00

FIG. C.2.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE - WEEK 1 . . . NOVEMBER 24, 1965

Refer to Fig. 5.1.

. . . WHITE ICE DISTRIBUTION . . .
PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

Classes as Fig. C.1.

```
 1   I--3--I  I==4==I  I++5++I  IXX6XXI
 2   I--3--I  I==4==I  I++5++I  IXX6XXI
 3   I--3--I  I==4==I  I++5++I  IXX6XXI
 4   I--3--I  I==4==I  I++5++I  IXX6XXI
 5            I==4==I  I++5++I  IXX6XXI
 6            I==4==I  I++5++I  IXX6XXI
 7            I==4==I  I++5++I  IXX6XXI
 8            I==4==I  I++5++I  IXX6XXI
 9            I==4==I  I++5++I  IXX6XXI
10            I==4==I  I++5++I  IXX6XXI
11            I==4==I  I++5++I
12            I==4==I  I++5++I
13            I==4==I  I++5++I
14            I==4==I  I++5++I
15            I==4==I  I++5++I
16            I==4==I  I++5++I
17            I==4==I  I++5++I
18            I==4==I  I++5++I
19            I==4==I  I++5++I
20            I==4==I  I++5++I
21            I==4==I  I++5++I
22            I==4==I  I++5++I
23            I==4==I  I++5++I
24            I==4==I  I++5++I
25            I==4==I  I++5++I
26            I==4==I  I++5++I
27            I==4==I  I++5++I
28            I==4==I  I++5++I
29            I==4==I  I++5++I
30            I==4==I  I++5++I
31            I==4==I
32            I==4==I
33            I==4==I
34            I==4==I
35            I==4==I
36            I==4==I
37            I==4==I
38            I==4==I
39            I==4==I
40            I==4==I
41            I==4==I
42            I==4==I
43            I==4==I
44            I==4==I
45            I==4==I
46            I==4==I
47            I==4==I
48            I==4==I
49            I==4==I
50            I==4==I
51            I==4==I
52            I==4==I
53            I==4==I
54            I==4==I
55            I==4==I
56            I==4==I
57            I==4==I
58            I==4==I
59            I==4==I
60            I==4==I
61            I==4==I
62            I==4==I
63            I==4==I
64            I==4==I
65            I==4==I
66            I==4==I
67            I==4==I
68            I==4==I
69            I==4==I
70            I==4==I
71            I==4==I
72            I==4==I
73            I==4==I
```

FIG. C.3.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE - WEEK 2. . . DECEMBER 10, 1965

Refer to Fig. 5.3.

. . . . SNOW DISTRIBUTION . . . .
PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

1	I--3--I	I==4==I	I++5++I	IXX6XXI	IOO7OOI	IOO8OOI
2	I--3--I	I==4==I	I++5++I	IXX6XXI	IOO7OOI	
3	I--3--I	I==4==I	I++5++I	IXX6XXI	IOO7OOI	
4		I==4==I	I++5++I	IXX6XXI	IOO7OOI	
5		I==4==I	I++5++I	IXX6XXI	IOO7OOI	
6			I++5++I	IXX6XXI	IOO7OOI	
7			I++5++I	IXX6XXI	IOO7OOI	
8			I++5++I	IXX6XXI	IOO7OOI	
9			I++5++I	IXX6XXI	IOO7OOI	
10			I++5++I	IXX6XXI	IOO7OOI	
11			I++5++I	IXX6XXI	IOO7OOI	
12			I++5++I	IXX6XXI	IOO7OOI	
13			I++5++I	IXX6XXI	IOO7OOI	
14			I++5++I	IXX6XXI	IOO7OOI	
15			I++5++I	IXX6XXI	IOO7OOI	
16			I++5++I	IXX6XXI	IOO7OOI	
17			I++5++I	IXX6XXI	IOO7OOI	
18			I++5++I	IXX6XXI	IOO7OOI	
19			I++5++I	IXX6XXI	IOO7OOI	
20			I++5++I	IXX6XXI		
21			I++5++I	IXX6XXI		
22			I++5++I	IXX6XXI		
23			I++5++I	IXX6XXI		
24			I++5++I	IXX6XXI		
25			I++5++I	IXX6XXI		
26			I++5++I	IXX6XXI		
27			I++5++I	IXX6XXI		
28			I++5++I	IXX6XXI		
29			I++5++I	IXX6XXI		
30			I++5++I	IXX6XXI		
31			I++5++I	IXX6XXI		
32			I++5++I	IXX6XXI		
33				IXX6XXI		
34				IXX6XXI		
35				IXX6XXI		
36				IXX6XXI		
37				IXX6XXI		
38				IXX6XXI		
39				IXX6XXI		
40				IXX6XXI		
41				IXX6XXI		
42				IXX6XXI		
43				IXX6XXI		
44				IXX6XXI		
45				IXX6XXI		
46				IXX6XXI		
47				IXX6XXI		
48				IXX6XXI		
49				IXX6XXI		
50				IXX6XXI		
51				IXX6XXI		
52				IXX6XXI		
53				IXX6XXI		
54				IXX6XXI		
55				IXX6XXI		
56				IXX6XXI		
57				IXX6XXI		

Classes as Fig. C.1.

FIG. C.4.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE - WEEK 2. . . DECEMBER 10, 1965

Refer to Fig. 5.4.

```
                                        . . .  WHITE ICE DISTRIBUTION  . . .
                                      PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

  1        I--3--I   I==4==I   I++5++I   IXX6XXI   IOO7OOI
  2        I--3--I   I==4==I   I++5++I   IXX6XXI
  3        I--3--I   I==4==I   I++5++I   IXX6XXI
  4                  I==4==I   I++5++I   IXX6XXI
  5                  I==4==I   I++5++I   IXX6XXI
  6                  I==4==I   I++5++I   IXX6XXI
  7                  I==4==I   I++5++I   IXX6XXI
  8                  I==4==I   I++5++I   IXX6XXI
  9                  I==4==I   I++5++I   IXX6XXI
 10                  I==4==I   I++5++I   IXX6XXI
 11                  I==4==I   I++5++I   IXX6XXI
 12                  I==4==I   I++5++I   IXX6XXI
 13                  I==4==I   I++5++I   IXX6XXI
 14                  I==4==I   I++5++I   IXX6XXI
 15                  I==4==I   I++5++I   IXX6XXI
 16                  I==4==I   I++5++I   IXX6XXI
 17                  I==4==I   I++5++I   IXX6XXI
 18                  I==4==I   I++5++I   IXX6XXI
 19                  I==4==I   I++5++I
 20                  I==4==I   I++5++I
 21                  I==4==I   I++5++I
 22                  I==4==I   I++5++I
 23                  I==4==I   I++5++I
 24                  I==4==I   I++5++I
 25                  I==4==I   I++5++I
 26                  I==4==I   I++5++I
 27                  I==4==I   I++5++I
 28                  I==4==I   I++5++I
 29                  I==4==I   I++5++I
 30                  I==4==I   I++5++I
 31                  I==4==I   I++5++I
 32                  I==4==I   I++5++I
 33                  I==4==I   I++5++I
 34                  I==4==I   I++5++I
 35                  I==4==I   I++5++I
 36                  I==4==I   I++5++I
 37                  I==4==I   I++5++I
 38                  I==4==I   I++5++I
 39                  I==4==I   I++5++I
 40                  I==4==I   I++5++I
 41                  I==4==I   I++5++I
 42                  I==4==I   I++5++I
 43                  I==4==I   I++5++I
 44                  I==4==I   I++5++I
 45                  I==4==I
 46                  I==4==I
 47                  I==4==I
 48                  I==4==I
 49                  I==4==I
 50                  I==4==I
 51                  I==4==I
```

Classes as Fig. C.1.

END-OF-DATA ENCOUNTERED ON SYSTEM INPUT FILE.

FIG. C.5.

Refer to Fig. 5.5.

```
BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE  -  WEEK 3. . . DECEMBER 23, 1965

                                         . . . . SNOW DISTRIBUTION . . . .
                                  PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

                                                                 -- --    XX XX
  1   I--3--I  I**4**I  I++5++I  IXX6XXI  I007001  I008001  I009001
  2   I--3--I  I**4**I  I++5++I  IXX6XXI  I007001
  3   I--3--I  I**4**I  I++5++I  IXX6XXI  I007001
  4   I--3--I  I**4**I  I++5++I  IXX6XXI  I007001
  5   I--3--I  I**4**I  I++5++I  IXX6XXI  I007001
  6            I**4**I  I++5++I  IXX6XXI  I007001
  7            I**4**I  I++5++I  IXX6XXI  I007001
  8            I**4**I  I++5++I  IXX6XXI  I007001
  9            I**4**I  I++5++I  IXX6XXI  I007001
 10            I**4**I  I++5++I  IXX6XXI  I007001
 11            I**4**I  I++5++I  IXX6XXI
 12            I**4**I  I++5++I  IXX6XXI
 13            I**4**I  I++5++I  IXX6XXI
 14            I**4**I  I++5++I  IXX6XXI
 15                     I++5++I  IXX6XXI
 16                     I++5++I  IXX6XXI
 17                     I++5++I  IXX6XXI
 18                     I++5++I  IXX6XXI
 19                     I++5++I  IXX6XXI
 20                     I++5++I  IXX6XXI
 21                     I++5++I  IXX6XXI
 22                     I++5++I  IXX6XXI
 23                     I++5++I  IXX6XXI
 24                     I++5++I  IXX6XXI
 25                     I++5++I  IXX6XXI
 26                     I++5++I  IXX6XXI
 27                     I++5++I  IXX6XXI
 28                     I++5++I  IXX6XXI
 29                     I++5++I  IXX6XXI
 30                     I++5++I  IXX6XXI
 31                     I++5++I  IXX6XXI
 32                     I++5++I  IXX6XXI
 33                     I++5++I  IXX6XXI
 34                     I++5++I  IXX6XXI
 35                     I++5++I  IXX6XXI
 36                     I++5++I  IXX6XXI
 37                     I++5++I
 38                     I++5++I
 39                     I++5++I
 40                     I++5++I
 41                     I++5++I
 42                     I++5++I
 43                     I++5++I
 44                     I++5++I
 45                     I++5++I
 46                     I++5++I
 47                     I++5++I
 48                     I++5++I
 49                     I++5++I
 50                     I++5++I
```

Classes as Fig. C.1.

FIG. C.6.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE - WEEK 3. . . DECEMBER 23, 1965

Refer to Fig. 5.6.

```
                                          . . . WHITE ICE DISTRIBUTION . . .
                                     PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

                                                                               XX XX
  1    I--3--I  I==4==I  I++5++I  IXX6XXI  IOO7OOI                            IOO9OOI
  2    I--3--I  I==4==I  I++5++I  IXX6XXI  IOO7OOI
  3    I--3--I  I==4==I  I++5++I  IXX6XXI  IOO7OOI
  4             I==4==I  I++5++I  IXX6XXI  IOO7OOI
  5             I==4==I  I++5++I  IXX6XXI
  6             I==4==I  I++5++I  IXX6XXI
  7             I==4==I  I++5++I  IXX6XXI
  8             I==4==I  I++5++I  IXX6XXI
  9             I==4==I  I++5++I  IXX6XXI
 10             I==4==I  I++5++I  IXX6XXI
 11                      I++5++I  IXX6XXI
 12                      I++5++I  IXX6XXI
 13                      I++5++I  IXX6XXI
 14                      I++5++I  IXX6XXI
 15                      I++5++I  IXX6XXI
 16                      I++5++I  IXX6XXI
 17                      I++5++I  IXX6XXI
 18                      I++5++I  IXX6XXI
 19                      I++5++I  IXX6XXI
 20                      I++5++I  IXX6XXI
 21                      I++5++I  IXX6XXI
 22                      I++5++I  IXX6XXI
 23                      I++5++I  IXX6XXI
 24                      I++5++I  IXX6XXI
 25                      I++5++I  IXX6XXI
 26                      I++5++I  IXX6XXI
 27                      I++5++I  IXX6XXI
 28                      I++5++I  IXX6XXI
 29                      I++5++I  IXX6XXI
 30                      I++5++I  IXX6XXI
 31                      I++5++I  IXX6XXI
 32                      I++5++I  IXX6XXI
 33                      I++5++I  IXX6XXI
 34                      I++5++I  IXX6XXI
 35                      I++5++I  IXX6XXI
 36                      I++5++I  IXX6XXI
 37                      I++5++I  IXX6XXI
 38                      I++5++I  IXX6XXI
 39                      I++5++I  IXX6XXI
 40                               IXX6XXI
 41                               IXX6XXI
 42                               IXX6XXI
 43                               IXX6XXI
 44                               IXX6XXI
 45                               IXX6XXI
 46                               IXX6XXI
 47                               IXX6XXI
 48                               IXX6XXI
 49                               IXX6XXI
 50                               IXX6XXI
 51                               IXX6XXI
 52                               IXX6XXI
 53                               IXX6XXI
 54                               IXX6XXI
 55                               IXX6XXI
 56                               IXX6XXI
 57                               IXX6XXI
 58                               IXX6XXI
 59                               IXX6XXI
 60                               IXX6XXI
```

Classes as Fig. C.1.

FIG. C.7.

Refer to Fig. 5.7.

```
BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE  -  WEEK 4. . . JANUARY 8, 1966

                                        . . . . SNOW DISTRIBUTION . . . .
                                 PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

                                                                            -- --
  1     I**2**I  I--3--I  I**4**I  I++5++I  IXX6XXI  IOO7OOI  IOO8OOI
  2              I--3--I  I**4**I  I++5++I  IXX6XXI  IOO7OOI
  3              I--3--I  I**4**I  I++5++I  IXX6XXI  IOO7OOI
  4              I--3--I  I**4**I  I++5++I  IXX6XXI  IOO7OOI
  5                       I**4**I  I++5++I  IXX6XXI  IOO7OOI
  6                       I**4**I  I++5++I  IXX6XXI  IOO7OOI
  7                       I**4**I  I++5++I  IXX6XXI  IOO7OOI
  8                       I**4**I  I++5++I  IXX6XXI
  9                       I**4**I  I++5++I  IXX6XXI
 10                       I**4**I  I++5++I  IXX6XXI
 11                       I**4**I  I++5++I  IXX6XXI
 12                       I**4**I  I++5++I  IXX6XXI
 13                       I**4**I  I++5++I  IXX6XXI
 14                       I**4**I  I++5++I  IXX6XXI
 15                       I**4**I  I++5++I  IXX6XXI
 16                       I**4**I  I++5++I  IXX6XXI
 17                                I++5++I  IXX6XXI
 18                                I++5++I  IXX6XXI
 19                                I++5++I  IXX6XXI
 20                                I++5++I  IXX6XXI
 21                                I++5++I  IXX6XXI
 22                                I++5++I  IXX6XXI
 23                                I++5++I  IXX6XXI
 24                                I++5++I  IXX6XXI
 25                                I++5++I  IXX6XXI
 26                                I++5++I  IXX6XXI
 27                                I++5++I  IXX6XXI
 28                                I++5++I  IXX6XXI
 29                                I++5++I  IXX6XXI
 30                                I++5++I  IXX6XXI
 31                                I++5++I  IXX6XXI
 32                                I++5++I  IXX6XXI
 33                                I++5++I  IXX6XXI
 34                                I++5++I  IXX6XXI
 35                                I++5++I  IXX6XXI
 36                                I++5++I  IXX6XXI
 37                                I++5++I  IXX6XXI
 38                                I++5++I  IXX6XXI
 39                                I++5++I  IXX6XXI
 40                                I++5++I  IXX6XXI
 41                                I++5++I  IXX6XXI
 42                                I++5++I
 43                                I++5++I
 44                                I++5++I
 45                                I++5++I
 46                                I++5++I
 47                                I++5++I
```

Classes as Fig. C.1.

FIG. C.8.

Refer to Fig. 5.8.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE - WEEK 4. . . JANUARY 8, 1966

. . . WHITE ICE DISTRIBUTION . . .
PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

						-- --
1	I--3--I	I==4==I	I++5++I	IXX6XXI	IOO7OOI	IOO8OOI
2		I==4==I	I++5++I	IXX6XXI	IOO7OOI	
3		I==4==I	I++5++I	IXX6XXI	IOO7OOI	
4		I==4==I	I++5++I	IXX6XXI	IOO7OOI	
5		I==4==I	I++5++I	IXX6XXI	IOO7OOI	
6		I==4==I	I++5++I	IXX6XXI	IOO7OOI	
7			I++5++I	IXX6XXI	IOO7OOI	
8			I++5++I	IXX6XXI	IOO7OOI	
9			I++5++I	IXX6XXI	IOO7OOI	
10			I++5++I	IXX6XXI	IOO7OOI	
11			I++5++I	IXX6XXI		
12			I++5++I	IXX6XXI		
13			I++5++I	IXX6XXI		
14			I++5++I	IXX6XXI		
15			I++5++I	IXX6XXI		
16			I++5++I	IXX6XXI		
17			I++5++I	IXX6XXI		
18			I++5++I	IXX6XXI		
19			I++5++I	IXX6XXI		
20			I++5++I	IXX6XXI		
21			I++5++I	IXX6XXI		
22			I++5++I	IXX6XXI		
23			I++5++I	IXX6XXI		
24			I++5++I	IXX6XXI		
25			I++5++I	IXX6XXI		
26			I++5++I	IXX6XXI		
27			I++5++I	IXX6XXI		
28			I++5++I	IXX6XXI		
29			I++5++I	IXX6XXI		
30			I++5++I	IXX6XXI		
31			I++5++I	IXX6XXI		
32			I++5++I	IXX6XXI		
33			I++5++I	IXX6XXI		
34				IXX6XXI		
35				IXX6XXI		
36				IXX6XXI		
37				IXX6XXI		
38				IXX6XXI		
39				IXX6XXI		
40				IXX6XXI		
41				IXX6XXI		
42				IXX6XXI		
43				IXX6XXI		
44				IXX6XXI		
45				IXX6XXI		
46				IXX6XXI		
47				IXX6XXI		
48				IXX6XXI		
49				IXX6XXI		
50				IXX6XXI		
51				IXX6XXI		
52				IXX6XXI		
53				IXX6XXI		
54				IXX6XXI		
55				IXX6XXI		
56				IXX6XXI		
57				IXX6XXI		
58				IXX6XXI		
59				IXX6XXI		
60				IXX6XXI		
61				IXX6XXI		
62				IXX6XXI		
63				IXX6XXI		
64				IXX6XXI		
65				IXX6XXI		
66				IXX6XXI		

Classes as Fig. C.1.

FIG. C.9.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE – WEEK 5. . . JANUARY 22, 1966

Refer to Fig.5.9.

. . . . SNOW DISTRIBUTION . . . .
PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

							-- --	XX XX
1	I**2**I	I--3--I	I==4==I	I++5++I	IXX6XXI	IOO7OOI	IOO8OOI	I##9##I
2		I--3--I	I==4==I	I++5++I	IXX6XXI	IOO7OOI		IOO9OOI
3		I--3--I	I==4==I	I++5++I	IXX6XXI	IOO7OOI		
4		I--3--I	I==4==I	I++5++I	IXX6XXI	IOO7OOI		
5			I==4==I	I++5++I	IXX6XXI	IOO7OOI		
6			I==4==I	I++5++I	IXX6XXI	IOO7OOI		
7			I==4==I	I++5++I	IXX6XXI	IOO7OOI		
8			I==4==I	I++5++I	IXX6XXI	IOO7OOI		
9				I++5++I	IXX6XXI	IOO7OOI		
10				I++5++I	IXX6XXI	IOO7OOI		
11				I++5++I	IXX6XXI	IOO7OOI		
12				I++5++I	IXX6XXI	IOO7OOI		
13				I++5++I	IXX6XXI	IOO7OOI		
14				I++5++I	IXX6XXI	IOO7OOI		
15				I++5++I	IXX6XXI	IOO7OOI		
16				I++5++I	IXX6XXI	IOO7OOI		
17				I++5++I	IXX6XXI	IOO7OOI		
18				I++5++I	IXX6XXI	IOO7OOI		
19				I++5++I	IXX6XXI			
20				I++5++I	IXX6XXI			
21				I++5++I	IXX6XXI			
22				I++5++I	IXX6XXI			
23				I++5++I	IXX6XXI			
24				I++5++I	IXX6XXI			
25				I++5++I	IXX6XXI			
26				I++5++I	IXX6XXI			
27				I++5++I	IXX6XXI			
28				I++5++I	IXX6XXI			
29				I++5++I	IXX6XXI			
30				I++5++I	IXX6XXI			
31				I++5++I	IXX6XXI			
32				I++5++I	IXX6XXI			
33				I++5++I	IXX6XXI			
34				I++5++I	IXX6XXI			
35				I++5++I	IXX6XXI			
36				I++5++I	IXX6XXI			
37				I++5++I	IXX6XXI			
38				I++5++I	IXX6XXI			
39				I++5++I	IXX6XXI			
40					IXX6XXI			
41					IXX6XXI			
42					IXX6XXI			
43					IXX6XXI			
44					IXX6XXI			

Classes as Fig. C.1

FIG. C.10.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE - WEEK 5. . . JANUARY 22, 1966

Refer to Fig. 5.10.

. . . WHITE ICE DISTRIBUTION . . .
PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

1	I==4==I	I++5++I	IXX6XXI	IOO7OOI	I88888I
2	I==4==I	I++5++I	IXX6XXI	IOO7OOI	I88888I
3	I==4==I	I++5++I	IXX6XXI	IOO7OOI	I88888I
4	I==4==I	I++5++I	IXX6XXI	IOO7OOI	I88888I
5	I==4==I	I++5++I	IXX6XXI	IOO7OOI	I008001
6	I==4==I	I++5++I	IXX6XXI	IOO7OOI	
7		I++5++I	IXX6XXI	IOO7OOI	
8		I++5++I	IXX6XXI	IOO7OOI	
9		I++5++I	IXX6XXI	IOO7OOI	
10		I++5++I	IXX6XXI	IOO7OOI	
11		I++5++I	IXX6XXI	IOO7OOI	
12		I++5++I	IXX6XXI	IOO7OOI	
13		I++5++I	IXX6XXI	IOO7OOI	
14		I++5++I	IXX6XXI	IOO7OOI	
15		I++5++I	IXX6XXI		
16		I++5++I	IXX6XXI		
17		I++5++I	IXX6XXI		
18		I++5++I	IXX6XXI		
19		I++5++I	IXX6XXI		
20		I++5++I	IXX6XXI		
21		I++5++I	IXX6XXI		
22		I++5++I	IXX6XXI		
23		I++5++I	IXX6XXI		
24			IXX6XXI		
25			IXX6XXI		
26			IXX6XXI		
27			IXX6XXI		
28			IXX6XXI		
29			IXX6XXI		
30			IXX6XXI		
31			IXX6XXI		
32			IXX6XXI		
33			IXX6XXI		
34			IXX6XXI		
35			IXX6XXI		
36			IXX6XXI		
37			IXX6XXI		
38			IXX6XXI		
39			IXX6XXI		
40			IXX6XXI		
41			IXX6XXI		
42			IXX6XXI		
43			IXX6XXI		
44			IXX6XXI		
45			IXX6XXI		
46			IXX6XXI		
47			IXX6XXI		
48			IXX6XXI		
49			IXX6XXI		
50			IXX6XXI		
51			IXX6XXI		
52			IXX6XXI		
53			IXX6XXI		
54			IXX6XXI		
55			IXX6XXI		
56			IXX6XXI		
57			IXX6XXI		
58			IXX6XXI		
59			IXX6XXI		
60			IXX6XXI		
61			IXX6XXI		
62			IXX6XXI		
63			IXX6XXI		
64			IXX6XXI		
65			IXX6XXI		
66			IXX6XXI		
67			IXX6XXI		
68			IXX6XXI		
69			IXX6XXI		

Classes as Fig. C.1.

FIG. C.11.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE - WEEK 6. . . FEBRUARY 5, 1966

Refer to Fig. 6.11.

. . . . SNOW DISTRIBUTION . . . .
PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

						-- --	XX XX
1	I--3--I	I**4**I	I++5++I	IXX6XXI	IOO7OOI	IOO8OOI	IOO9OOI
2	I--3--I	I**4**I	I++5++I	IXX6XXI	IOO7OOI		
3	I--3--I	I**4**I	I++5++I	IXX6XXI	IOO7OOI		
4	I--3--I	I**4**I	I++5++I	IXX6XXI	IOO7OOI		
5	I--3--I	I**4**I	I++5++I	IXX6XXI	IOO7OOI		
6	I--3--I	I**4**I	I++5++I	IXX6XXI	IOO7OOI		
7	I--3--I	I**4**I	I++5++I	IXX6XXI	IOO7OOI		
8	I--3--I	I**4**I	I++5++I	IXX6XXI	IOO7OOI		
9	I--3--I	I**4**I	I++5++I	IXX6XXI	IOO7OOI		
10		I**4**I	I++5++I	IXX6XXI	IOO7OOI		
11			I++5++I	IXX6XXI	IOO7OOI		
12			I++5++I	IXX6XXI	IOO7OOI		
13			I++5++I	IXX6XXI	IOO7OOI		
14			I++5++I	IXX6XXI	IOO7OOI		
15			I++5++I	IXX6XXI			
16			I++5++I	IXX6XXI			
17			I++5++I	IXX6XXI			
18			I++5++I	IXX6XXI			
19			I++5++I	IXX6XXI			
20			I++5++I	IXX6XXI			
21			I++5++I	IXX6XXI			
22			I++5++I	IXX6XXI			
23			I++5++I	IXX6XXI			
24			I++5++I	IXX6XXI			
25			I++5++I	IXX6XXI			
26			I++5++I	IXX6XXI			
27			I++5++I	IXX6XXI			
28			I++5++I	IXX6XXI			
29			I++5++I	IXX6XXI			
30			I++5++I	IXX6XXI			
31			I++5++I	IXX6XXI			
32			I++5++I	IXX6XXI			
33			I++5++I	IXX6XXI			
34				IXX6XXI			
35				IXX6XXI			
36				IXX6XXI			
37				IXX6XXI			
38				IXX6XXI			
39				IXX6XXI			
40				IXX6XXI			
41				IXX6XXI			
42				IXX6XXI			
43				IXX6XXI			
44				IXX6XXI			
45				IXX6XXI			
46				IXX6XXI			
47				IXX6XXI			
48				IXX6XXI			
49				IXX6XXI			

Classes as Fig. C.

FIG. C.12.

Refer to Fig. 5.12.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE - WEEK 6 . . . FEBRUARY 5, 1966

. . . WHITE ICE DISTRIBUTION . . .
PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

1	I--3--I	I**4**I	I++5++I	IXX6XXI	I00700I	I##8##I
2		I**4**I	I++5++I	IXX6XXI	I00700I	I##8##I
3		I**4**I	I++5++I	IXX6XXI	I00700I	I##8##I
4			I++5++I	IXX6XXI	I00700I	I##8##I
5			I++5++I	IXX6XXI	I00700I	I##8##I
6			I++5++I	IXX6XXI	I00700I	
7			I++5++I	IXX6XXI	I00700I	
8			I++5++I	IXX6XXI	I00700I	
9			I++5++I	IXX6XXI	I00700I	
10			I++5++I	IXX6XXI	I00700I	
11			I++5++I	IXX6XXI	I00700I	
12			I++5++I	IXX6XXI	I00700I	
13			I++5++I	IXX6XXI	I00700I	
14			I++5++I	IXX6XXI	I00700I	
15			I++5++I	IXX6XXI	I00700I	
16			I++5++I	IXX6XXI	I00700I	
17			I++5++I	IXX6XXI	I00700I	
18			I++5++I	IXX6XXI	I00700I	
19			I++5++I	IXX6XXI		
20			I++5++I	IXX6XXI		
21			I++5++I	IXX6XXI		
22			I++5++I	IXX6XXI		
23			I++5++I	IXX6XXI		
24			I++5++I	IXX6XXI		
25			I++5++I	IXX6XXI		
26				IXX6XXI		
27				IXX6XXI		
28				IXX6XXI		
29				IXX6XXI		
30				IXX6XXI		
31				IXX6XXI		
32				IXX6XXI		
33				IXX6XXI		
34				IXX6XXI		
35				IXX6XXI		
36				IXX6XXI		
37				IXX6XXI		
38				IXX6XXI		
39				IXX6XXI		
40				IXX6XXI		
41				IXX6XXI		
42				IXX6XXI		
43				IXX6XXI		
44				IXX6XXI		
45				IXX6XXI		
46				IXX6XXI		
47				IXX6XXI		
48				IXX6XXI		
49				IXX6XXI		
50				IXX6XXI		
51				IXX6XXI		
52				IXX6XXI		
53				IXX6XXI		
54				IXX6XXI		
55				IXX6XXI		
56				IXX6XXI		
57				IXX6XXI		
58				IXX6XXI		
59				IXX6XXI		
60				IXX6XXI		
61				IXX6XXI		
62				IXX6XXI		
63				IXX6XXI		
64				IXX6XXI		
65				IXX6XXI		

Classes as Fig. C.1.

FIG. C.13.

Refer to Fig. 5.13.

```
BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE  -  WEEK 7. . .  MARCH 3, 1966

                                              . . . . SNOW DISTRIBUTION . . . .
                                       PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

                                                                       -- --     XX XX
  1         I==4==I   I++5++I   IXX6XXI   I00700I   I88888I   I99999I
  2         I==4==I   I++5++I   IXX6XXI   I00700I   I88888I   I00900I
  3         I==4==I   I++5++I   IXX6XXI   I00700I   I88888I
  4         I==4==I   I++5++I   IXX6XXI   I00700I   I00800I
  5         I==4==I   I++5++I   IXX6XXI   I00700I
  6                   I++5++I   IXX6XXI   I00700I
  7                   I++5++I   IXX6XXI   I00700I
  8                   I++5++I   IXX6XXI   I00700I
  9                   I++5++I   IXX6XXI   I00700I
 10                   I++5++I   IXX6XXI   I00700I
 11                   I++5++I   IXX6XXI   I00700I
 12                   I++5++I   IXX6XXI   I00700I
 13                   I++5++I   IXX6XXI   I00700I
 14                   I++5++I   IXX6XXI   I00700I
 15                   I++5++I   IXX6XXI   I00700I
 16                   I++5++I   IXX6XXI   I00700I
 17                   I++5++I   IXX6XXI   I00700I
 18                   I++5++I   IXX6XXI   I00700I
 19                   I++5++I   IXX6XXI   I00700I
 20                   I++5++I   IXX6XXI   I00700I
 21                   I++5++I   IXX6XXI   I00700I
 22                   I++5++I   IXX6XXI   I00700I
 23                             IXX6XXI   I00700I
 24                             IXX6XXI   I00700I
 25                             IXX6XXI   I00700I
 26                             IXX6XXI   I00700I
 27                             IXX6XXI   I00700I
 28                             IXX6XXI
 29                             IXX6XXI
 30                             IXX6XXI
 31                             IXX6XXI
 32                             IXX6XXI
 33                             IXX6XXI
 34                             IXX6XXI
 35                             IXX6XXI
 36                             IXX6XXI
 37                             IXX6XXI
 38                             IXX6XXI
 39                             IXX6XXI
 40                             IXX6XXI
 41                             IXX6XXI
 42                             IXX6XXI
 43                             IXX6XXI
 44                             IXX6XXI
 45                             IXX6XXI
 46                             IXX6XXI
 47                             IXX6XXI
 48                             IXX6XXI
 49                             IXX6XXI
 50                             IXX6XXI
 51                             IXX6XXI
 52                             IXX6XXI
 53                             IXX6XXI
 54                             IXX6XXI
 55                             IXX6XXI
 56                             IXX6XXI
 57                             IXX6XXI

END-OF-DATA ENCOUNTERED ON SYSTEM INPUT FILE.
```

Classes as Fig. C.1.

FIG. C.14.

Refer to Fig .5.14.

BIWEEKLY WHITE ICE SURVEY OF KNOB LAKE - WEEK 7. . . MARCH 3, 1966

. . . WHITE ICE DISTRIBUTION . . .
PLOTTED IN STANDARD SCORES FROM THE SEASON MEAN.

Classes as Fig. C.1.

1	I**4**I	I++5++I	IXX6XXI	IOO7OOI	I88888I
2		I++5++I	IXX6XXI	IOO7OOI	I88888I
3		I++5++I	IXX6XXI	IOO7OOI	I88888I
4		I++5++I	IXX6XXI	IOO7OOI	I88888I
5		I++5++I	IXX6XXI	IOO7OOI	I88888I
6		I++5++I	IXX6XXI	IOO7OOI	I88888I
7		I++5++I	IXX6XXI	IOO7OOI	
8		I++5++I	IXX6XXI	IOO7OOI	
9		I++5++I	IXX6XXI	IOO7OOI	
10		I++5++I	IXX6XXI	IOO7OOI	
11		I++5++I	IXX6XXI	IOO7OOI	
12			IXX6XXI	IOO7OOI	
13			IXX6XXI	IOO7OOI	
14			IXX6XXI	IOO7OOI	
15			IXX6XXI	IOO7OOI	
16			IXX6XXI	IOO7OOI	
17			IXX6XXI	IOO7OOI	
18			IXX6XXI	IOO7OOI	
19			IXX6XXI	IOO7OOI	
20			IXX6XXI	IOO7OOI	
21			IXX6XXI	IOO7OOI	
22			IXX6XXI	IOO7OOI	
23			IXX6XXI	IOO7OOI	
24			IXX6XXI	IOO7OOI	
25			IXX6XXI	IOO7OOI	
26			IXX6XXI	IOO7OOI	
27			IXX6XXI	IOO7OOI	
28			IXX6XXI	IOO7OOI	
29			IXX6XXI	IOO7OOI	
30			IXX6XXI	IOO7OOI	
31			IXX6XXI	IOO7OOI	
32			IXX6XXI	IOO7OOI	
33			IXX6XXI	IOO7OOI	
34			IXX6XXI	IOO7OOI	
35			IXX6XXI		
36			IXX6XXI		
37			IXX6XXI		
38			IXX6XXI		
39			IXX6XXI		
40			IXX6XXI		
41			IXX6XXI		
42			IXX6XXI		
43			IXX6XXI		
44			IXX6XXI		
45			IXX6XXI		
46			IXX6XXI		
47			IXX6XXI		
48			IXX6XXI		
49			IXX6XXI		
50			IXX6XXI		
51			IXX6XXI		
52			IXX6XXI		
53			IXX6XXI		
54			IXX6XXI		
55			IXX6XXI		
56			IXX6XXI		
57			IXX6XXI		
58			IXX6XXI		
59			IXX6XXI		
60			IXX6XXI		
61			IXX6XXI		
62			IXX6XXI		
63			IXX6XXI		
64			IXX6XXI		
65			IXX6XXI		

END-OF-DATA ENCOUNTERED ON SYSTEM INPUT FILE.

FIG. C.15.

Refer to Fig. 5.15.

PERCENTAGE PROBABILITY OF WHITE ICE GROWTH ON KNOB LAKE 1965-66

				-- --
1	I**2**I	I++3++I	I005001	I886881
2	I**2**I	I++3++I	I005001	I886881
3	I**2**I	I++3++I	I005001	I886881
4	I**2**I	I++3++I	I005001	I886881
5	I**2**I	I++3++I	I005001	I886881
6	I**2**I	I++3++I	I005001	I886881
7	I**2**I	I++3++I	I005001	I886881
8	I**2**I	I++3++I	I005001	I886881
9	I**2**I	I++3++I	I005001	I886881
10	I**2**I	I++3++I	I005001	I886881
11	I**2**I	I++3++I	I005001	I886881
12	I**2**I	I++3++I	I005001	I886881
13	I**2**I	I++3++I	I005001	I886881
14	I**2**I	I++3++I	I005001	I886881
15	I**2**I	I++3++I	I005001	I886881
16	I**2**I	I++3++I	I005001	I006001
17	I**2**I	I++3++I	I005001	
18	I**2**I	I++3++I	I005001	
19	I**2**I	I++3++I	I005001	
20		I++3++I	I005001	
21		I++3++I	I005001	
22		I++3++I	I005001	
23		I++3++I	I005001	
24		I++3++I	I005001	
25		I++3++I	I005001	
26		I++3++I	I005001	
27		I++3++I	I005001	
28		I++3++I	I005001	
29		I++3++I	I005001	
30		I++3++I	I005001	
31		I++3++I	I005001	
32		I++3++I	I005001	
33		I++3++I	I005001	
34		I++3++I	I005001	
35		I++3++I	I005001	
36		I++3++I	I005001	
37			I005001	
38			I005001	
39			I005001	
40			I005001	
41			I005001	
42			I005001	
43			I005001	
44			I005001	
45			I005001	
46			I005001	

Class boundaries:-

2 ... 41-50 %
3 ... 51-60 %
4 ... 61-70 %
5 ... 71-80 %
6 ... 81-90 %
7 ... 91-100 %

END-OF-DATA ENCOUNTERED ON SYSTEM INPUT FILE.

FIG. C.16.

Refer to Fig. 5.16.

RESIDUALS FROM REGRESSION

RESIDUALS FROM REGRESSION BETWEEN MEAN SNOW DEPTH AT-A-SITE THROUGH THE SEASON 1965-66 FROM NOVEMBER TO MARCH AND WHITE ICE THICKNESS ON MARCH 3RD.

```
                                                                   -- --
 1    I--3--I   I==4==I   I++5++I   IXX6XXI   I007001   I008001
 2    I--3--I   I==4==I   I++5++I   IXX6XXI   I007001
 3    I--3--I   I==4==I   I++5++I   IXX6XXI   I007001
 4    I--3--I   I==4==I   I++5++I   IXX6XXI   I007001
 5              I==4==I   I++5++I   IXX6XXI   I007001
 6              I==4==I   I++5++I   IXX6XXI   I007001
 7              I==4==I   I++5++I   IXX6XXI   I007001
 8              I==4==I   I++5++I   IXX6XXI   I007001
 9              I==4==I   I++5++I   IXX6XXI   I007001
10              I==4==I   I++5++I   IXX6XXI   I007001
11              I==4==I   I++5++I   IXX6XXI   I007001
12              I==4==I   I++5++I   IXX6XXI   I007001
13                        I++5++I   IXX6XXI   I007001
14                        I++5++I   IXX6XXI   I007001
15                        I++5++I   IXX6XXI   I007001
16                        I++5++I   IXX6XXI   I007001
17                        I++5++I   IXX6XXI   I007001
18                        I++5++I   IXX6XXI   I007001
19                        I++5++I   IXX6XXI   I007001
20                        I++5++I   IXX6XXI
21                        I++5++I   IXX6XXI
22                        I++5++I   IXX6XXI
23                        I++5++I   IXX6XXI
24                        I++5++I   IXX6XXI
25                        I++5++I   IXX6XXI
26                        I++5++I   IXX6XXI
27                        I++5++I   IXX6XXI
28                        I++5++I   IXX6XXI
29                        I++5++I   IXX6XXI
30                        I++5++I   IXX6XXI
31                        I++5++I   IXX6XXI
32                        I++5++I   IXX6XXI
33                        I++5++I   IXX6XXI
34                        I++5++I   IXX6XXI
35                        I++5++I   IXX6XXI
36                        I++5++I   IXX6XXI
37                        I++5++I   IXX6XXI
38                        I++5++I   IXX6XXI
39                        I++5++I
40                        I++5++I
41                        I++5++I
42                        I++5++I
43                        I++5++I
```

Class boundaries:-

```
3 ... -2.00 - -2.99
4 ... -1.00 - -1.99
5 ...   0   - -0.99
6 ...  1.00 -  0.01
7 ...  2.00 -  1.01
8 ...  3.00 -  2.01
```

END-OF-DATA ENCOUNTERED ON SYSTEM INPUT FILE.

Fig.C.17

Refer to Fig. 5.17.

MARCH 18TH, 1966.

WHITE ICE DISTRIBUTION.

```
                                           -- --     XX XX
 1          I++2++I   IXX3XXI   I00400I   I00500I
 2          I++2++I   IXX3XXI   I00400I   I00500I
 3          I++2++I   IXX3XXI   I00400I   I00500I
 4          I++2++I   IXX3XXI   I00400I   I00500I
 5          I++2++I   IXX3XXI   I00400I   I00500I
 6          I++2++I   IXX3XXI   I00400I   I00500I
 7          I++2++I   IXX3XXI   I00400I
 8          I++2++I   IXX3XXI   I00400I
 9          I++2++I   IXX3XXI   I00400I
10          I++2++I   IXX3XXI   I00400I
11          I++2++I   IXX3XXI   I00400I
12          I++2++I   IXX3XXI   I00400I
13          I++2++I   IXX3XXI   I00400I
14          I++2++I   IXX3XXI   I00400I
15          I++2++I   IXX3XXI   I00400I
16          I++2++I   IXX3XXI   I00400I
17          I++2++I   IXX3XXI   I00400I
18                    IXX3XXI   I00400I
19                    IXX3XXI   I00400I
20                    IXX3XXI   I00400I
21                    IXX3XXI   I00400I
22                    IXX3XXI   I00400I
23                    IXX3XXI   I00400I
24                    IXX3XXI   I00400I
25                    IXX3XXI   I00400I
26                    IXX3XXI   I00400I
27                    IXX3XXI   I00400I
28                    IXX3XXI   I00400I
29                    IXX3XXI
30                    IXX3XXI
31                    IXX3XXI
32                    IXX3XXI
33                    IXX3XXI
34                    IXX3XXI
35                    IXX3XXI
36                    IXX3XXI
37                    IXX3XXI
38                    IXX3XXI
39                    IXX3XXI
40                    IXX3XXI
41                    IXX3XXI
42                    IXX3XXI
43                    IXX3XXI
44                    IXX3XXI
45                    IXX3XXI
46                    IXX3XXI
47                    IXX3XXI
48                    IXX3XXI
49                    IXX3XXI
50                    IXX3XXI
51                    IXX3XXI
52                    IXX3XXI
53                    IXX3XXI
```

END-OF-DATA ENCOUNTERED ON SYSTEM INPUT FILE.

Class boundaries:-

1 ...	0 - 4.9	inches	(0 - 12.4 cm)
2 ...	5.0 - 9.9	"	(12.7 - 25.2 cm)
3 ...	10.0 -14.9	"	(25.4 - 37.8 cm)
4 ...	15.0 -19.9	"	(38.1 - 50.5 cm)
5 ...	20.0 -24.9	"	(50.7 - 63.0 cm)

FIG. C.18.

MARCH 18TH, 1966.

Refer to Fig. 5.18.

TOTAL ICE DISTRIBUTION.

				-- --	XX XX
1	I..2..I	I++3++I	IXX4XXI	IBB5BBI	IBB6BBI
2		I++3++I	IXX4XXI	IBB5BBI	IBB6BBI
3		I++3++I	IXX4XXI	IBB5BBI	IBB6BBI
4		I++3++I	IXX4XXI	IBB5BBI	IBB6BBI
5		I++3++I	IXX4XXI	IBB5BBI	
6		I++3++I	IXX4XXI	IBB5BBI	
7			IXX4XXI	IBB5BBI	
8			IXX4XXI	IBB5BBI	
9			IXX4XXI	IBB5BBI	
10			IXX4XXI	IBB5BBI	
11			IXX4XXI	IBB5BBI	
12			IXX4XXI	IBB5BBI	
13			IXX4XXI	IBB5BBI	
14			IXX4XXI	IBB5BBI	
15			IXX4XXI	IBB5BBI	
16			IXX4XXI	IBB5BBI	
17			IXX4XXI	IBB5BBI	
18			IXX4XXI	IBB5BBI	
19			IXX4XXI	IBB5BBI	
20			IXX4XXI		
21			IXX4XXI		
22			IXX4XXI		
23			IXX4XXI		
24			IXX4XXI		
25			IXX4XXI		
26			IXX4XXI		
27			IXX4XXI		
28			IXX4XXI		
29			IXX4XXI		
30			IXX4XXI		
31			IXX4XXI		
32			IXX4XXI		
33			IXX4XXI		
34			IXX4XXI		
35			IXX4XXI		
36			IXX4XXI		
37			IXX4XXI		
38			IXX4XXI		
39			IXX4XXI		
40			IXX4XXI		
41			IXX4XXI		
42			IXX4XXI		
43			IXX4XXI		
44			IXX4XXI		
45			IXX4XXI		
46			IXX4XXI		
47			IXX4XXI		
48			IXX4XXI		
49			IXX4XXI		
50			IXX4XXI		
51			IXX4XXI		
52			IXX4XXI		
53			IXX4XXI		
54			IXX4XXI		
55			IXX4XXI		
56			IXX4XXI		
57			IXX4XXI		
58			IXX4XXI		
59			IXX4XXI		
60			IXX4XXI		
61			IXX4XXI		
62			IXX4XXI		
63			IXX4XXI		
64			IXX4XXI		
65			IXX4XXI		
66			IXX4XXI		
67			IXX4XXI		
68			IXX4XXI		
69			IXX4XXI		
70			IXX4XXI		
71			IXX4XXI		
72			IXX4XXI		
73			IXX4XXI		
74			IXX4XXI		

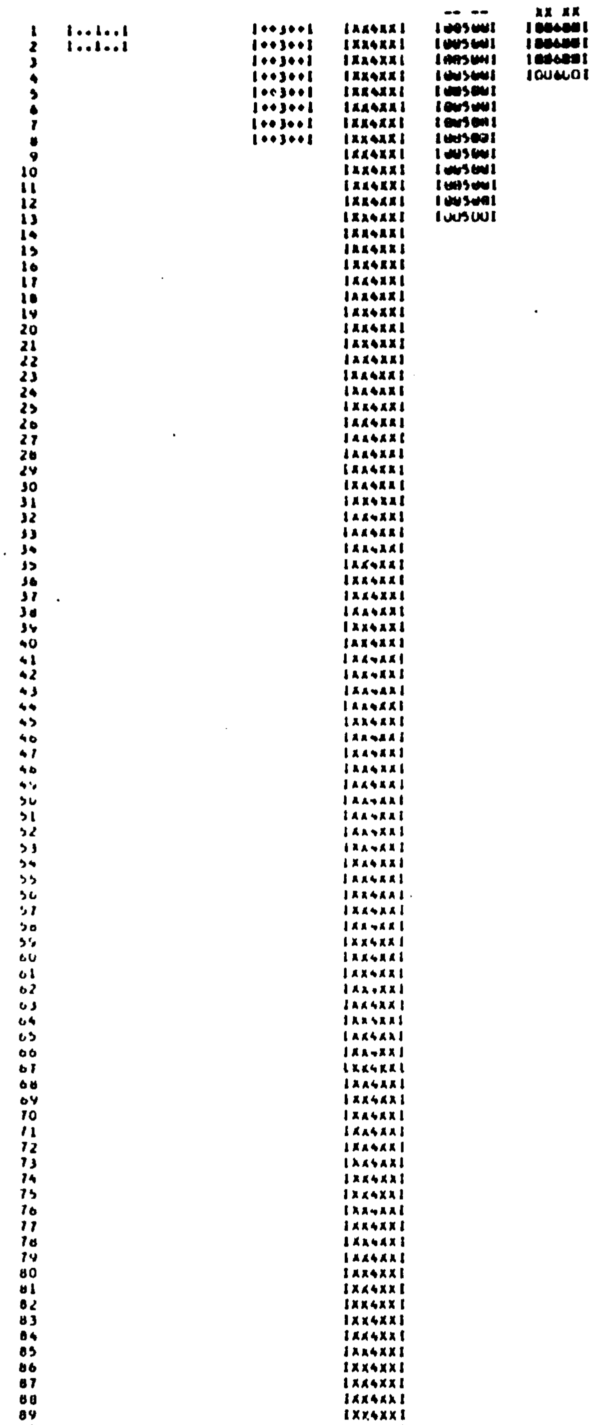
Class boundaries:-

1 ... 15.0 - 19.9 inches (38.1 - 50.5 cm)
2 ... 20.0 - 24.9 " (50.7 - 63.0 cm)
3 ... 25.0 - 29.9 " (63.4 - 75.8 cm)
4 ... 30.0 - 34.9 " (76.1 - 88.5 cm)
5 ... 35.0 - 39.9 " (88.8 - 101.3 cm)
6 ... 40.0 - 44.9 " (101.6 - 112.8 cm)

FIG. C.19.

Refer to Fig.4.6.

MAP OF DEVIATIONS FROM SIMPLE BUOYANCY EQUATION
WITH ASSUMED MEAN UNIT WEIGHT FOR SNOW OF 0.4 GM.WT./C.C.
AND FOR ICE OF 0.85 GM.WT./C.C.
SEE TEXT FOR DISCUSSION.



Class boundaries:-

1 ...	below -4.0	inches	(-10.5 cm)
2 ...	-3.0 - -3.9	"	(-7.3 - -10.3 cm)
3 ...	-2.0 - -2.9	"	(-4.9 - -7.1 cm)
4 ...	1.9 - -1.9	"	(4.6 - -4.6 cm)
5 ...	2.0 - 2.9	"	(4.9 - 7.1 cm)
6 ...	3.0 - 3.9	"	(7.3 - 10.3 cm)
7 ...	above 4.0	"	(10.5 cm)

END-OF-DATA ENCOUNTERED ON SYSTEM INPUT FILE.

FIG. C.20.

Refer to Fig. 4.7.

```
MARCH 18TH, 1966.

                                                   MAP OF DEVIATIONS FROM SIMPLE BUOYANCY EQUATION
                                                   WITH ASSUMED MEAN UNIT WEIGHT FOR SNOW OF 0.4 GM.WT./C.C.
                                                   AND FOR ICE OF 0.85 GM.WT./C.C.
                                                   SEE TEXT FOR DISCUSSION.

                                                                -- --    XX XX
  1  I..1..I          I..3..I  IXX4XXI              IOO6OOI  IOO7OOI
  2                   I..3..I  IXX4XXI                       IOO7OOI
  3                   I..3..I  IXX4XXI                       IOO7OOI
  4                   I..3..I  IXX4XXI
  5                   I..3..I  IXX4XXI
  6                   I..3..I  IXX4XXI
  7                   I..3..I  IXX4XXI
  8                            IXX4XXI
  9                            IXX4XXI
 10                            IXX4XXI
 11                            IXX4XXI
 12                            IXX4XXI
 13                            IXX4XXI
 14                            IXX4XXI
 15                            IXX4XXI
 16                            IXX4XXI
 17                            IXX4XXI
 18                            IXX4XXI
 19                            IXX4XXI
 20                            IXX4XXI
 21                            IXX4XXI
 22                            IXX4XXI
 23                            IXX4XXI
 24                            IXX4XXI
 25                            IXX4XXI
 26                            IXX4XXI
 27                            IXX4XXI
 28                            IXX4XXI
 29                            IXX4XXI
 30                            IXX4XXI
 31                            IXX4XXI
 32                            IXX4XXI
 33                            IXX4XXI
 34                            IXX4XXI
 35                            IXX4XXI
 36                            IXX4XXI
 37                            IXX4XXI
 38                            IXX4XXI
 39                            IXX4XXI
 40                            IXX4XXI
 41                            IXX4XXI
 42                            IXX4XXI
 43                            IXX4XXI
 44                            IXX4XXI
 45                            IXX4XXI
 46                            IXX4XXI
 47                            IXX4XXI
 48                            IXX4XXI
 49                            IXX4XXI
 50                            IXX4XXI
 51                            IXX4XXI
 52                            IXX4XXI
 53                            IXX4XXI
 54                            IXX4XXI
 55                            IXX4XXI
 56                            IXX4XXI
 57                            IXX4XXI
 58                            IXX4XXI
 59                            IXX4XXI
 60                            IXX4XXI
 61                            IXX4XXI
 62                            IXX4XXI
 63                            IXX4XXI
 64                            IXX4XXI
 65                            IXX4XXI
 66                            IXX4XXI
 67                            IXX4XXI
 68                            IXX4XXI
 69                            IXX4XXI
 70                            IXX4XXI
 71                            IXX4XXI
 72                            IXX4XXI
 73                            IXX4XXI
 74                            IXX4XXI
 75                            IXX4XXI
 76                            IXX4XXI
 77                            IXX4XXI
 78                            IXX4XXI
 79                            IXX4XXI
 80                            IXX4XXI
 81                            IXX4XXI
 82                            IXX4XXI
 83                            IXX4XXI
 84                            IXX4XXI
 85                            IXX4XXI
 86                            IXX4XXI
 87                            IXX4XXI
 88                            IXX4XXI
 89                            IXX4XXI
 90                            IXX4XXI
 91                            IXX4XXI
 92                            IXX4XXI

END-OF-DATA ENCOUNTERED ON SYSTEM INPUT FILE.
```

Class boundaries:-

1 ... below -4.0 inches (-10.5 cm)
2 ... -3.0 - -3.9 " (-7.3 - -10.3 cm)
3 ... -2.0 - -2.9 " (-4.9 - -7.1 cm)
4 ... 1.9 - -1.9 " (4.6 - -4.6 cm)
5 ... 2.0 - 2.9 " (4.9 - 7.1 cm)
6 ... 3.0 - 3.9 " (7.3 - 10.3 cm)
7 ... above 4.0 " (10.5 cm)

APPENDIX D

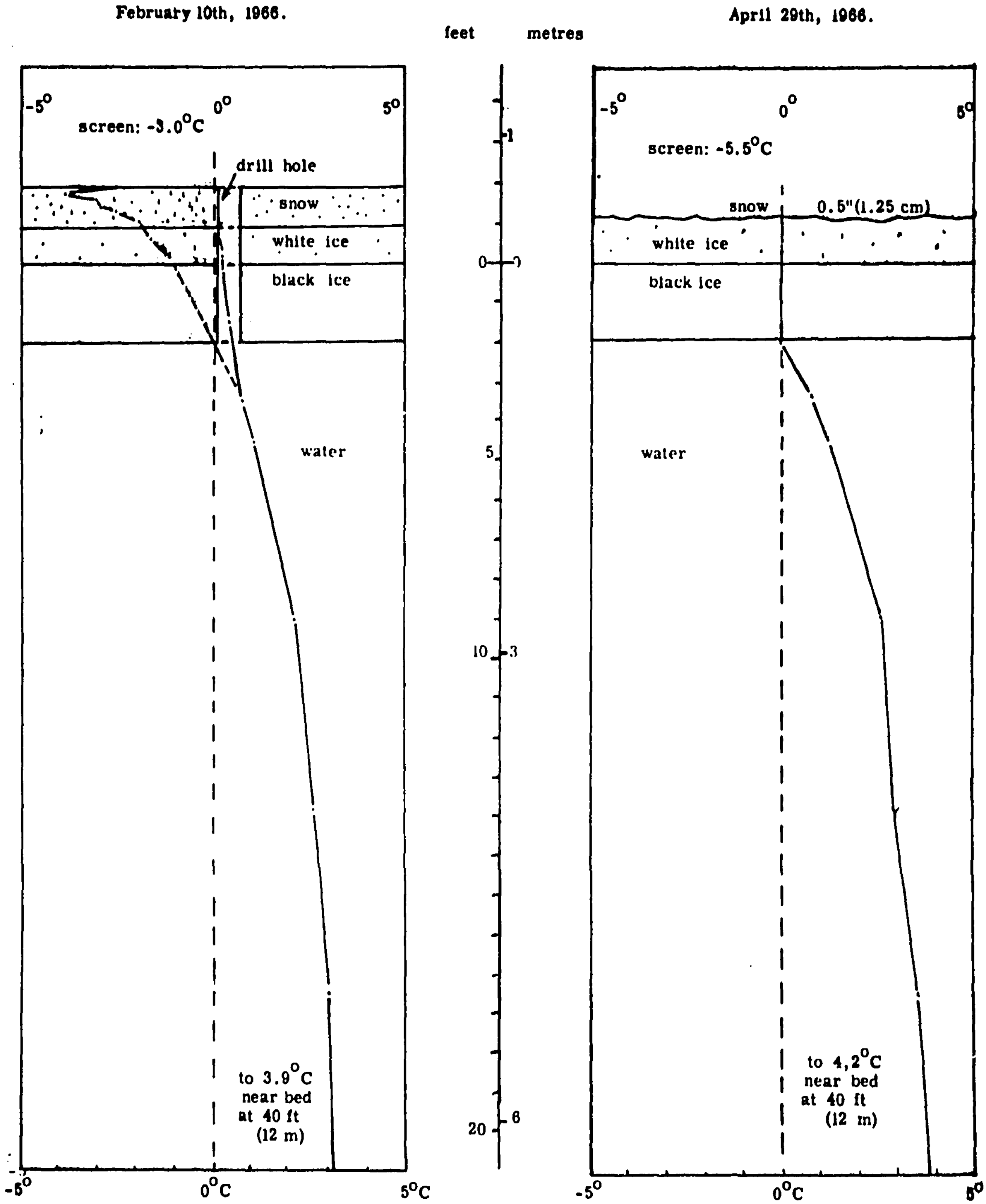
LAKE TEMPERATURES

Temperatures in Knob Lake have been measured by potentiometer from one or two thermocouple strings suspended from a post in the ice sheet since the winter of 1962-3. The records for 1962-3 have been lost, but the graph published by Mattox (1964, p.30, fig.2) is reproduced in Appendix E, Fig.E.20. In the four years of measurement, the general pattern of temperatures through the winter has remained very similar (Barr, 1964; Gray, 1966).

The main variations in the temperature profiles occur in the ice sheet. The most marked temperature gradients were recorded by Gray in the severe winter of 1964-5. For example, on January 6th 1965, the temperature 18 in (46 cm) above the black-ice/white-ice interface was -28.4^{o}C (-19.2^{o}F), at 12 in (30 cm) below the interface it was still -24.6^{o}C (12.2^{o}F), but at 3 ft (91 cm) a temperature of -0.1^{o}C indicates that the sensor was close to the freezing front. 1963-4 and 1965-6 were milder winters, although similar measurements might have been made on January 8th 1966, with an overnight low of -46^{o}F. (Cf. total accumulated degree day records in Table 2.3.) The black ice temperatures for 1965-6, in Table D.3, all tend to be slightly higher than for the two previous years.

Tables D.1 to D.3 summarise the data on lake temperatures in averages over four week periods based on the first week in January. They are comparable in periods to the ice thickness records in Table 3.1.

FIG. D.1. TEMPERATURE AND ICE COVER, KNOB LAKE - TWO DATES.



The figures suggest a level of 10 ft or 3 m below the ice surface for the average winter thermocline, below which an almost steady temperature is maintained at each successive level throughout the season, reaching near to the maximum density temperature of 4^{o}C (39^{o}F) at the bed. However, as noted by Gray (op.cit.) there is a slight tendency in each year for bottom temperatures to rise in spring for reasons which remain somewhat obscure. One suggestion is that the latent heat of fusion (80 cal gm^{-1}) is transferred towards the bed from the ice sheet by the sinking of the warmed water.

Unfortunately, static or average figures give little information of use in studying the probability or mechanism of cracking, since it is the amplitude of frequent heat waves that is important (Chapter 3). However, they do suggest (1) that temperatures below 0^{o}F are rare in the black ice sheet and strong gradients are maintained by the low coefficient of thermal diffusivity of the ice, κ = 40 cm^{2} hr^{-1}, and (2) that water temperatures just beneath the ice sheet may be sufficient to cause melt during local depression of the ice sheet.

Typical mid-winter and spring temperature profiles are illustrated in Figs. D.1 and D.2. In spring the ice tends to become isothermal near the melting point as air temperatures increase. In the winter profile, the ice and snow temperatures were measured by inserting metal probe thermometers.

Measurements of temperatures would be of more use to the study of lake ice, if a system of continuous measurement, based, for example, on a remote recording thermograph, could be installed.

Table D.1 LAKE TEMPERATURE RECORDS, KNOB LAKE, 1963-4

Mean monthly temperatures (°C) at each depth for 40ft (c.10.3m) profile (centre of lake).

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
+0.75'			-8.3	-9.4	-5.9	-5.4	-1.5	+1.5	+2.0
+0.5'			-4.2	-9.5	-4.9	-4.3	-1.3	+1.4	+1.7
b/w interface			-2.7	-6.9	-3.9	-3.5	-1.2	+0.1	+0.2
-0.5'			-0.9	-5.2	-2.8	-2.7	-1.0	0.0	+0.1
-1.0'			-0.2	-2.8	-1.5	-1.9	-0.7	0.0	+0.1
-1.5'			+0.2	-0.9	-0.7	-1.1	-0.5	0.0	0.0
-2.0'			+0.5	+0.9	+0.7	-0.4	-0.3	0.0	0.0
-3.0'			+0.8	+1.2	+1.2	0.0	0.0	+0.4	+2.3
-5.0'			+1.4	+1.6	+1.7	+0.3	+0.3	+1.2	+2.8
-20.0'			+1.7	+2.0	+2.8	+1.4	+1.5	+2.2	+3.1
-40.0'			+3.3	+3.5	+3.5	+2.4	+2.7	+3.0	+3.5

Table D.2a LAKE TEMPERATURE RECORDS, KNOB LAKE, 1964-5

Mean monthly temperatures (°C) at each depth for 40ft (c.13m) profile (centre of lake).

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
+1.5'				-25.3	-18.9	-4.9	-4.8	-3.8	+2.7
+1.0'				-25.1	-19.4	-6.3	-5.1	-2.8	+4.8
+0.5'				-25.0	-16.6	-7.1	-6.0	-2.8	+4.4
b/w interface									
-1.0'				-22.4	-8.2	-4.4	-3.5	-1.0	0.0
-3.0'				-6.6	-2.9	-1.8	-1.8	-0.5	0.0
-6.0'				+0.5	+1.3	+0.7	+0.8	+0.6	+1.8
-9.0'				+1.2	+1.6	+1.5	+1.6	+1.6	+2.2
-14.0'				+1.8	+1.8	+2.1	+2.3	+2.4	+2.5
-19.0'				+2.2	+2.4	+2.4	+2.6	+2.7	+2.7
-29.0'				+2.6	+2.6	+2.7	+2.9	+3.0	+3.0
-39.0'				+3.0	+3.3	+3.3	+3.5	+3.5	+3.6

Table D.2b LAKE TEMPERATURE RECORDS, KNOB LAKE, 1964-5

Mean monthly temperatures (°C) at each depth for 20ft (c.7m) profile (Knob Lake West site).

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
+0.5'				-26.8	-12.2	-4.3	-3.3	-0.7	+6.0
b/w interface				-20.5	-7.9	-3.4	-2.2	-0.6	+4.5
-0.5'				-16.1	-6.6	-2.8	-1.8	-0.5	+2.6
-1.0'				-11.8	-5.1	-2.3	-1.2	-0.5	+0.7
-2.0'				-5.6	-3.5	-1.7	-1.0	-0.2	+0.5
-4.0'				+0.4	-1.0	-0.7	-0.5	0.0	0.0
-7.0'				+1.0	+1.0	+0.8	+0.4	+0.8	+2.1
-10.0'				+1.3	+1.4	+1.4	+1.5	+1.4	+2.2
-12.5'				+1.4	+1.7	+1.8	+1.6	+1.8	+2.3
-15.0'				+1.5	+1.9	+1.9	+1.8	+2.0	+2.3
-18.0'				+1.9	+2.1	+2.2	+2.1	+2.4	+2.6

Table D.3a LAKE TEMPERATURE RECORDS, KNOB LAKE, 1965-6

Mean monthly temperatures (°C) at each depth for 40ft (c.13m) profile (centre of lake).

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
+0.75'						-1.4	-0.7	-0.1	
+0.25'						-1.2	-0.6	-0.4	
b/w interface									
-0.25'						-1.2	-0.7	-0.5	
-1.5'						-1.3	-0.6	-0.4	
-3.5'					+0.8	-0.1	+0.1	+0.6	
-4.5'					+1.1		+0.4	+0.9	
-8.5'					+2.2	+0.9	+1.8	+2.1	
-13.75'					+2.7	+1.5	+2.5	+2.8	
-18.5'					+3.1	+1.7	+2.7	+3.2	
-27.5'					+3.4	+2.0	+3.0	+3.5	
-36.75'					+3.9	+2.6	+3.6	+4.0	

Table D.3b LAKE TEMPERATURE RECORDS, KNOB LAKE, 1965-6

Mean monthly temperatures (°C) at each depth for 20ft (c.7m) profile (Knob Lake West site).

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
b/w interface									
-0.75'			-1.7	-2.1	-2.2			-0.3	
-1.25'			+0.8	-1.5	-1.7			-0.2	
-1.75'			+0.4	0.0	-1.0			-1.1	
-2.25'			+0.5	0.0	-0.5			0.0	
-2.5'			+0.5	0.0	-0.1			-0.4	
-3.5'			+1.0	+0.9	+0.4			+0.4	
-5.25'			+1.3	+1.5	+1.1			+0.4	
-7.5'			+1.8	+2.1	+1.5			+2.1	
-9.0'			+2.7	+2.7	+1.9			+2.5	
-10.75'			+2.6	+2.6	+2.1			+2.8	
-15.0'			+2.6	+3.4	+2.6			+3.0	

APPENDIX E

SELECTED ILLUSTRATIONS FROM McGILL SUB-ARCTIC RESEARCH PAPERS RELATED TO KNOB LAKE

This appendix draws together for early cross-reference sixteen illustrations from previous work on Knob Lake by Messrs. Adams, Andrews, Archer, Findlay, Mattox, McCloughan and Shaw. Most are referred to directly in the text for comparison with data presented for 1965-66.

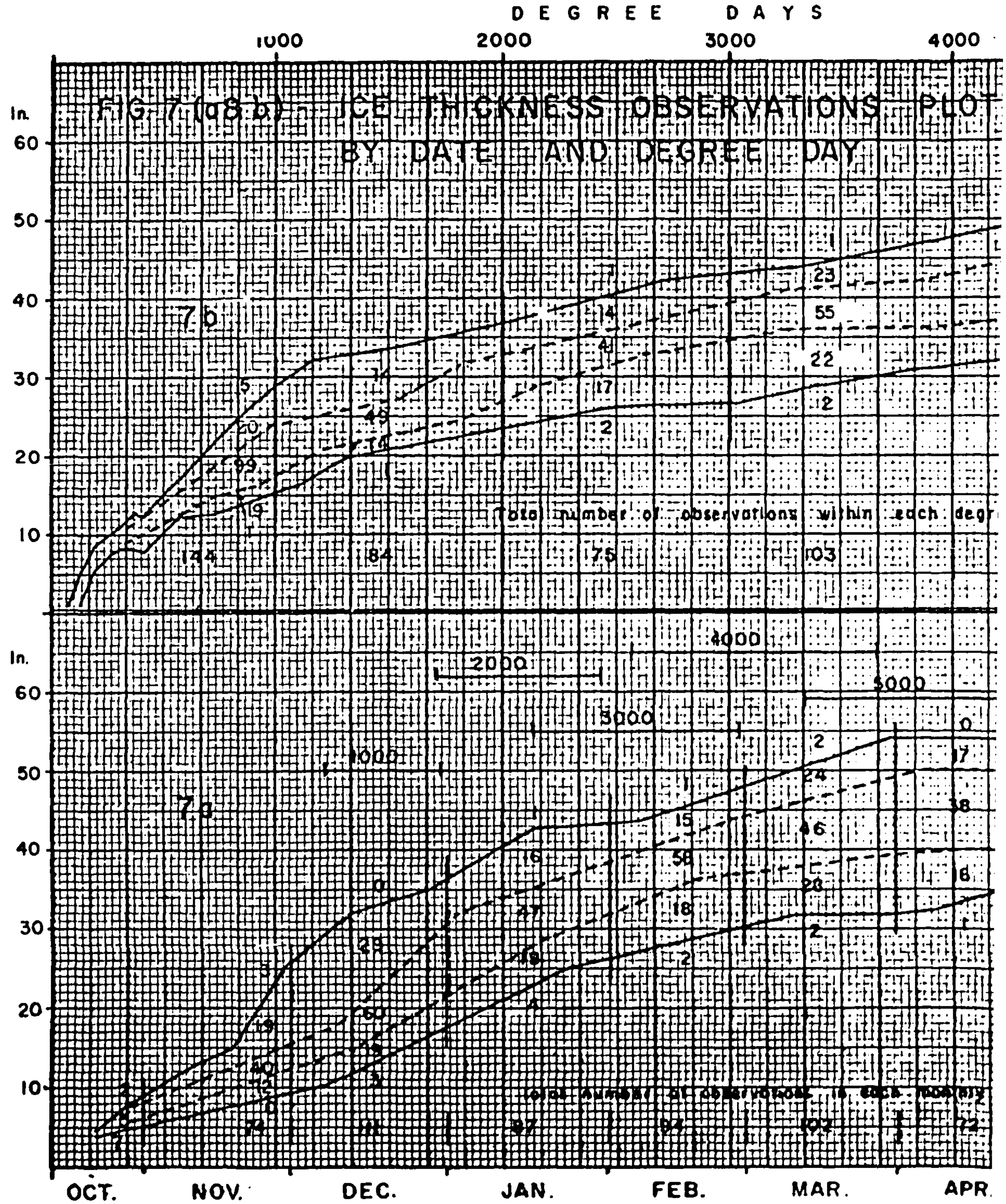
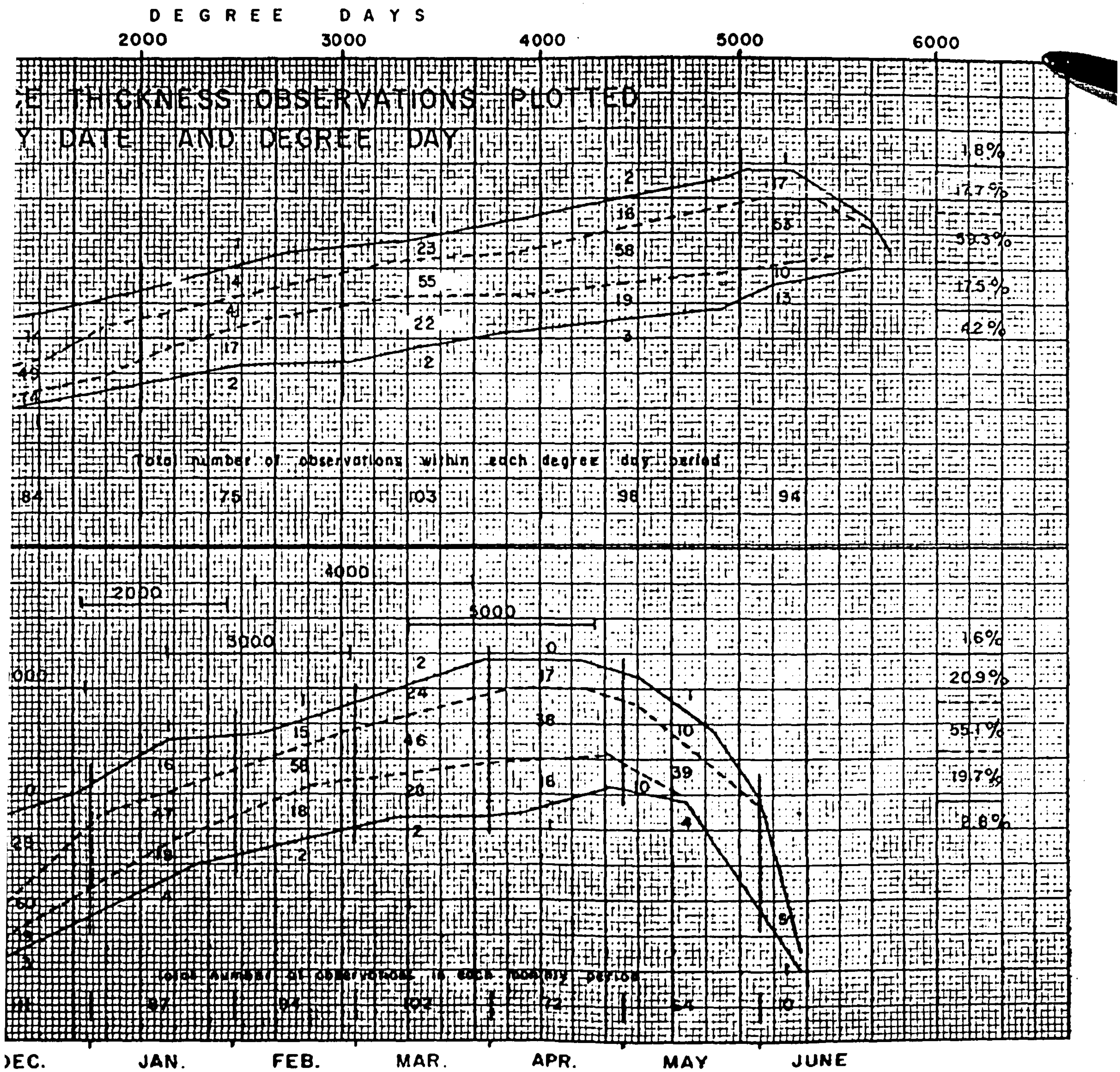


Figure E.1: from Shaw, 1963.



e E.1: from Shaw, 1963.

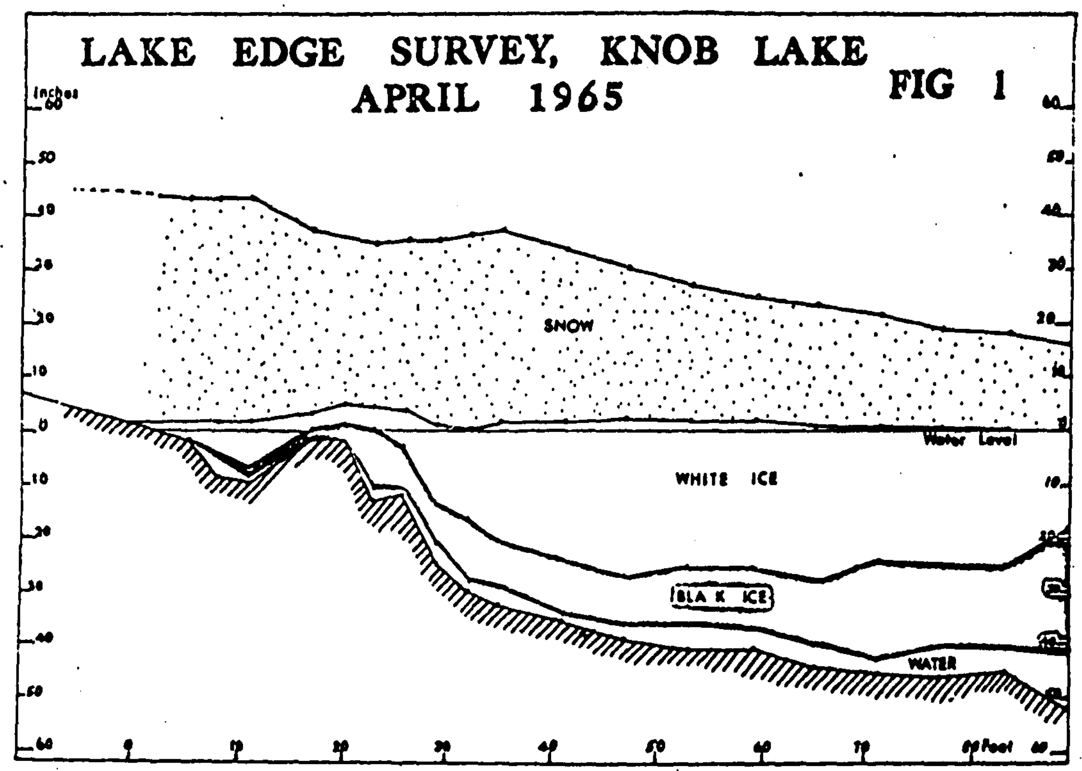
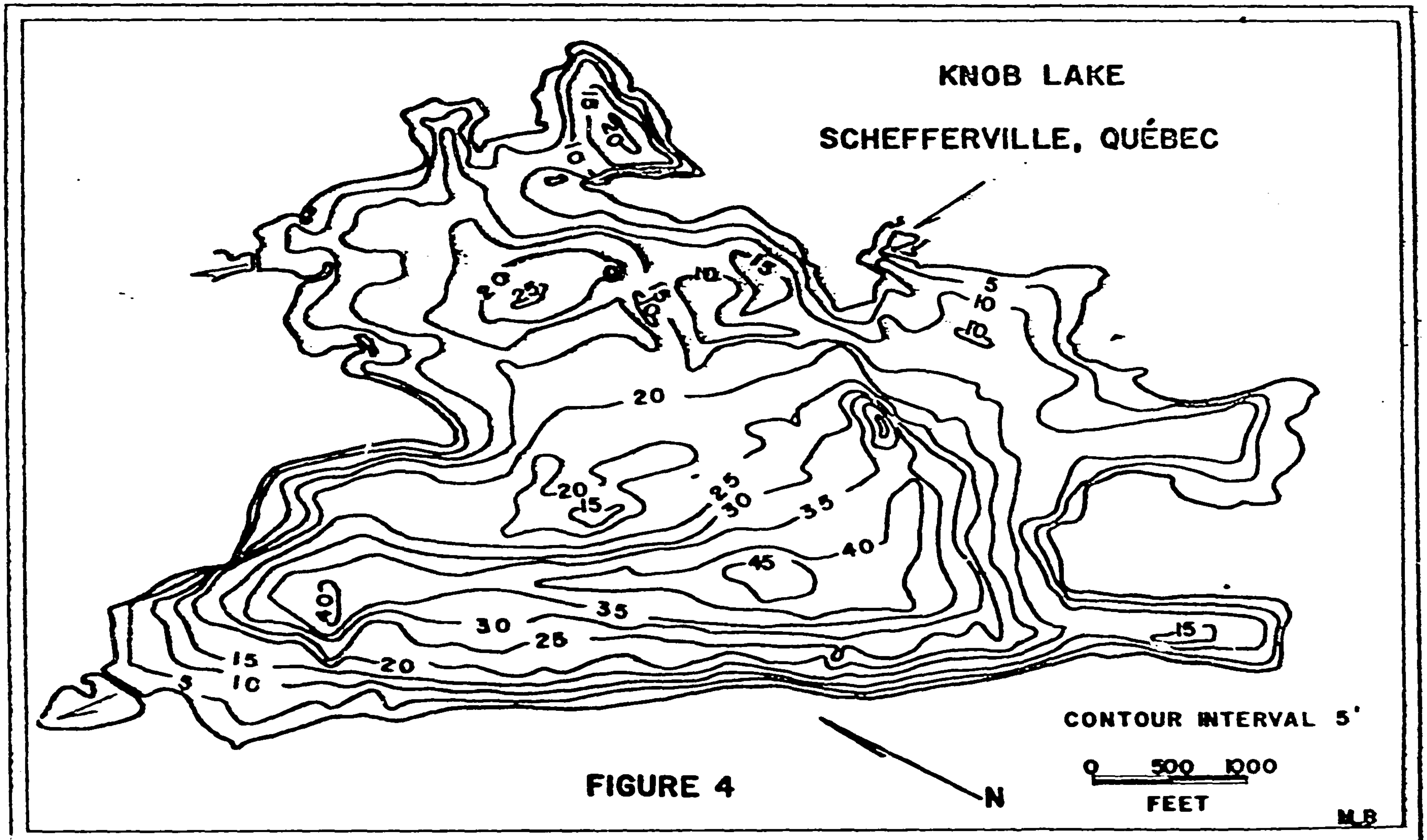


Figure E.2: From Archer and Findlay, 1966.

Figure E.3: from Bryan, 1964.



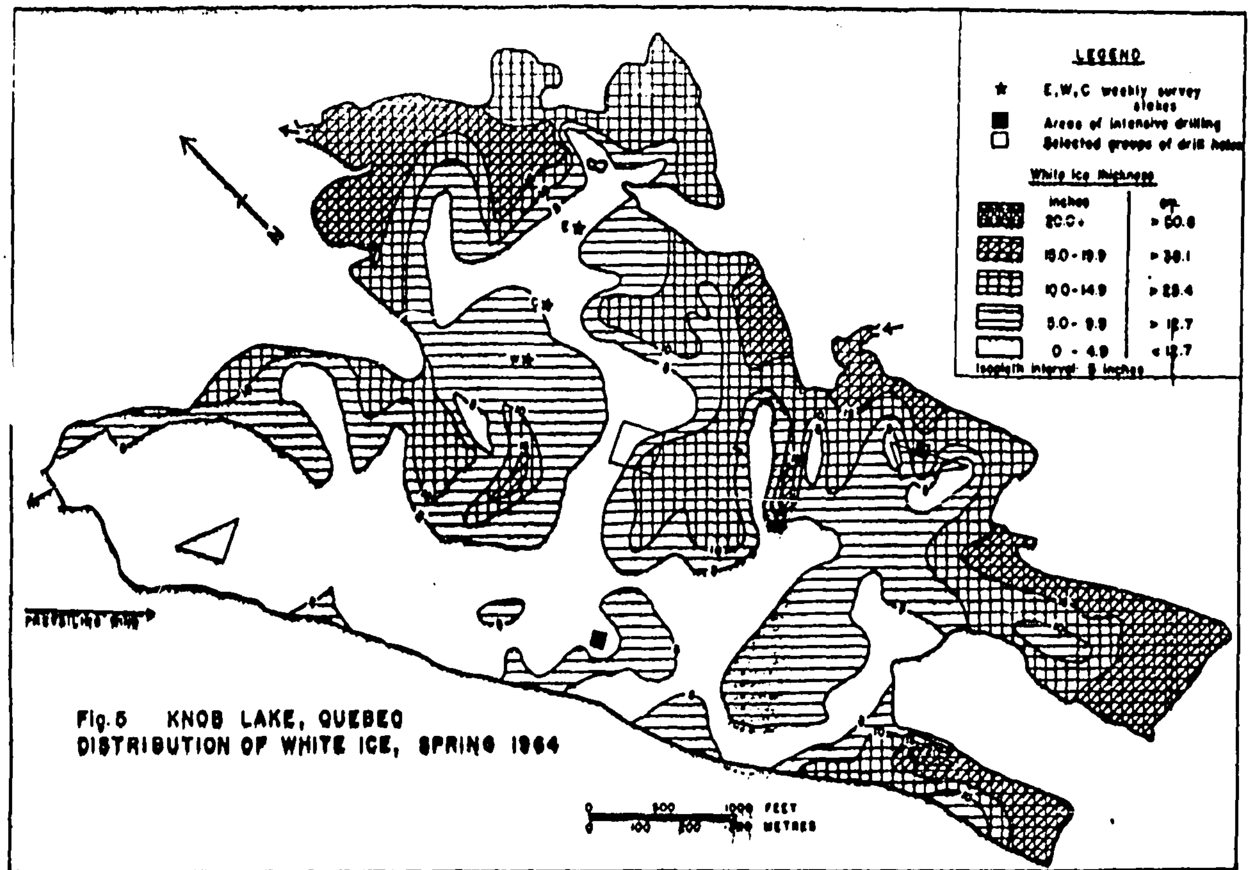
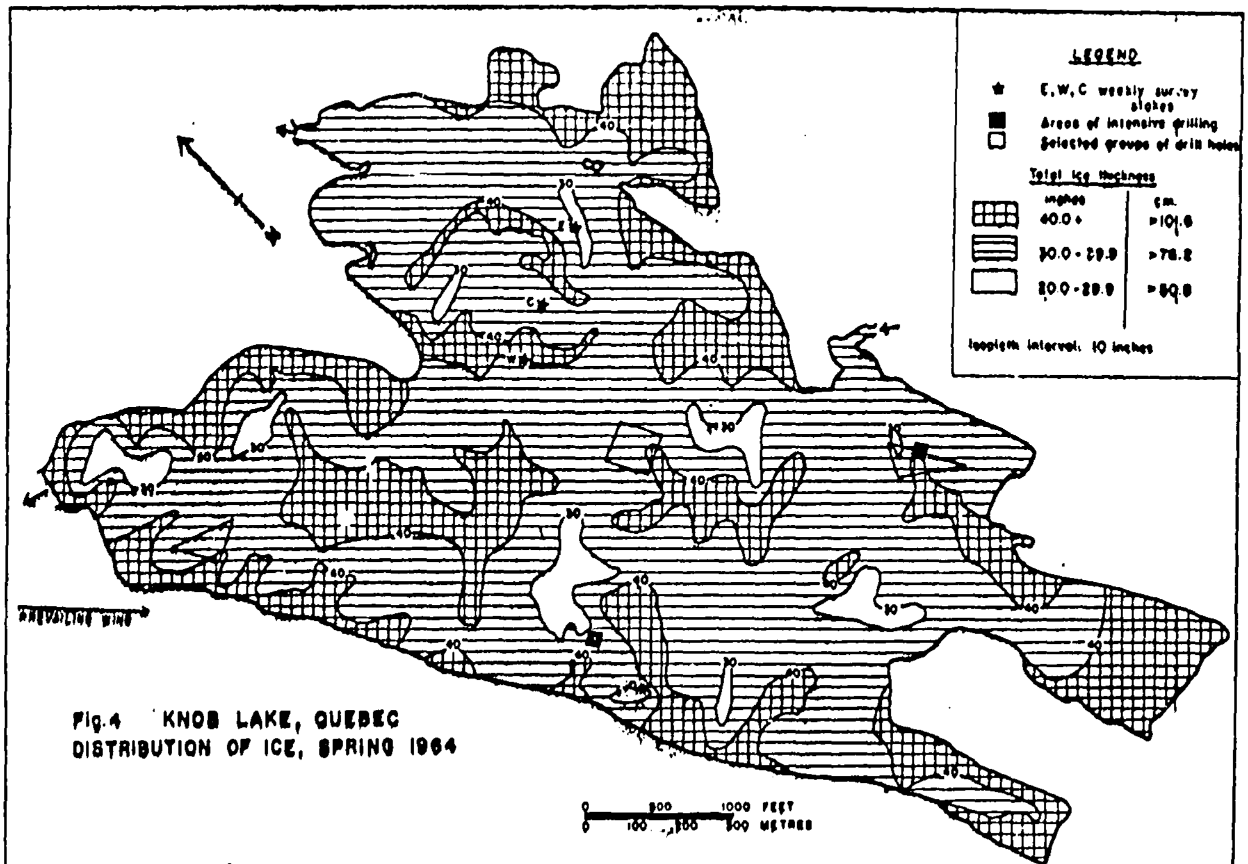


Figure E.4: from Adams and Shaw, 1966



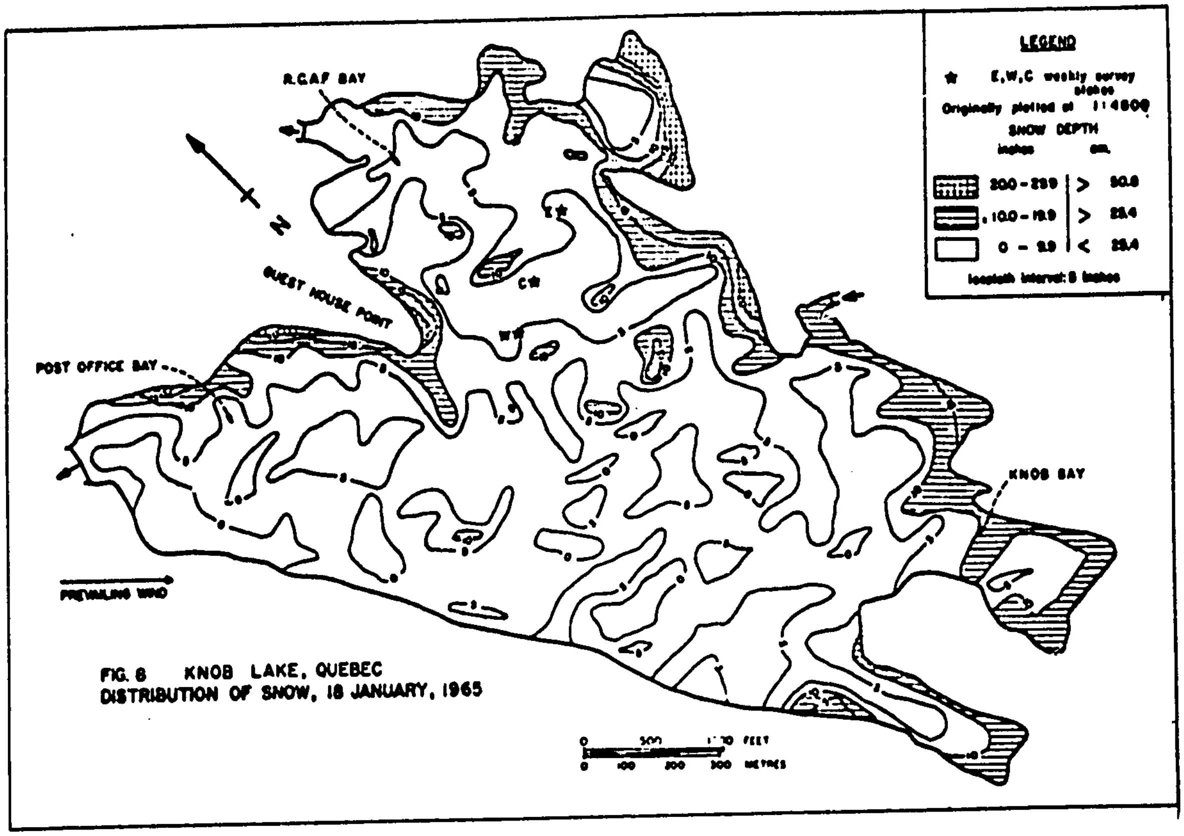


FIG. 8 KNOB LAKE, QUEBEC
DISTRIBUTION OF SNOW, 18 JANUARY, 1965

Figure E.5: from Archer, 1966

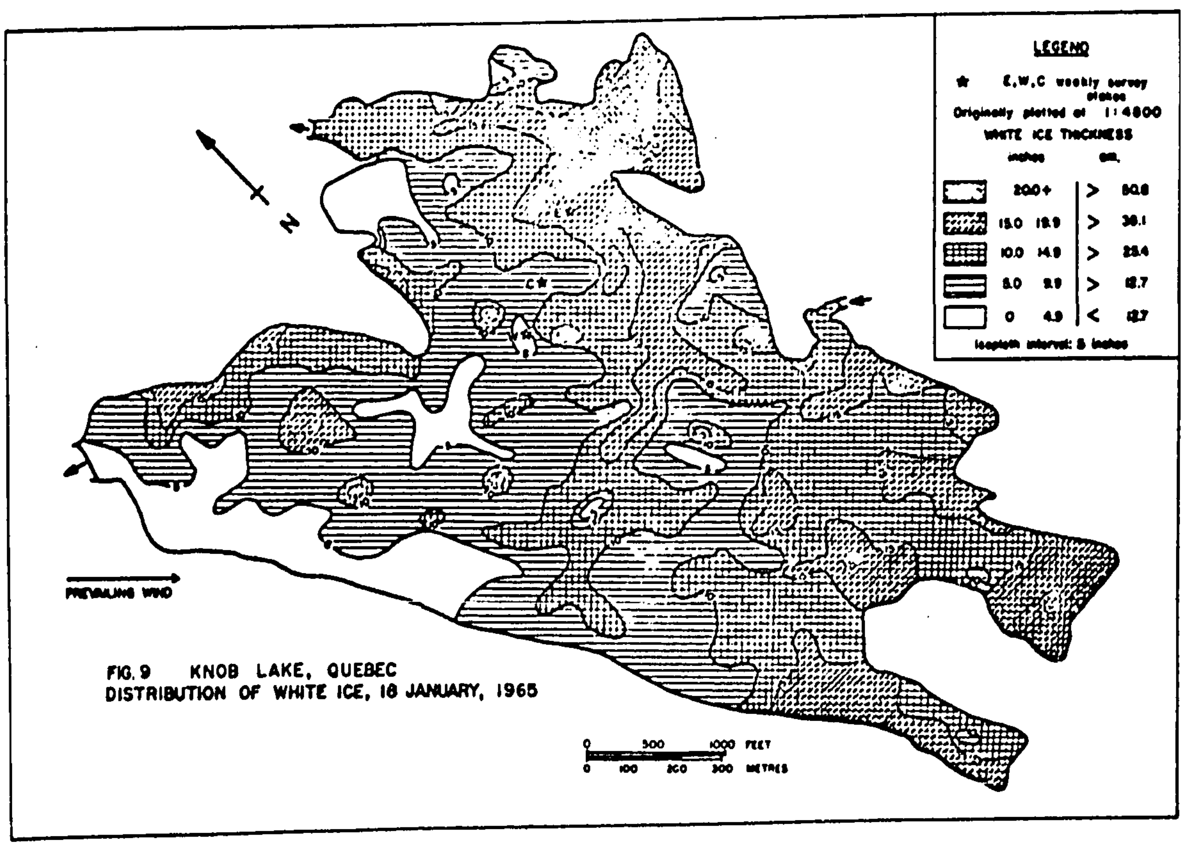


FIG. 9 KNOB LAKE, QUEBEC
DISTRIBUTION OF WHITE ICE, 18 JANUARY, 1965

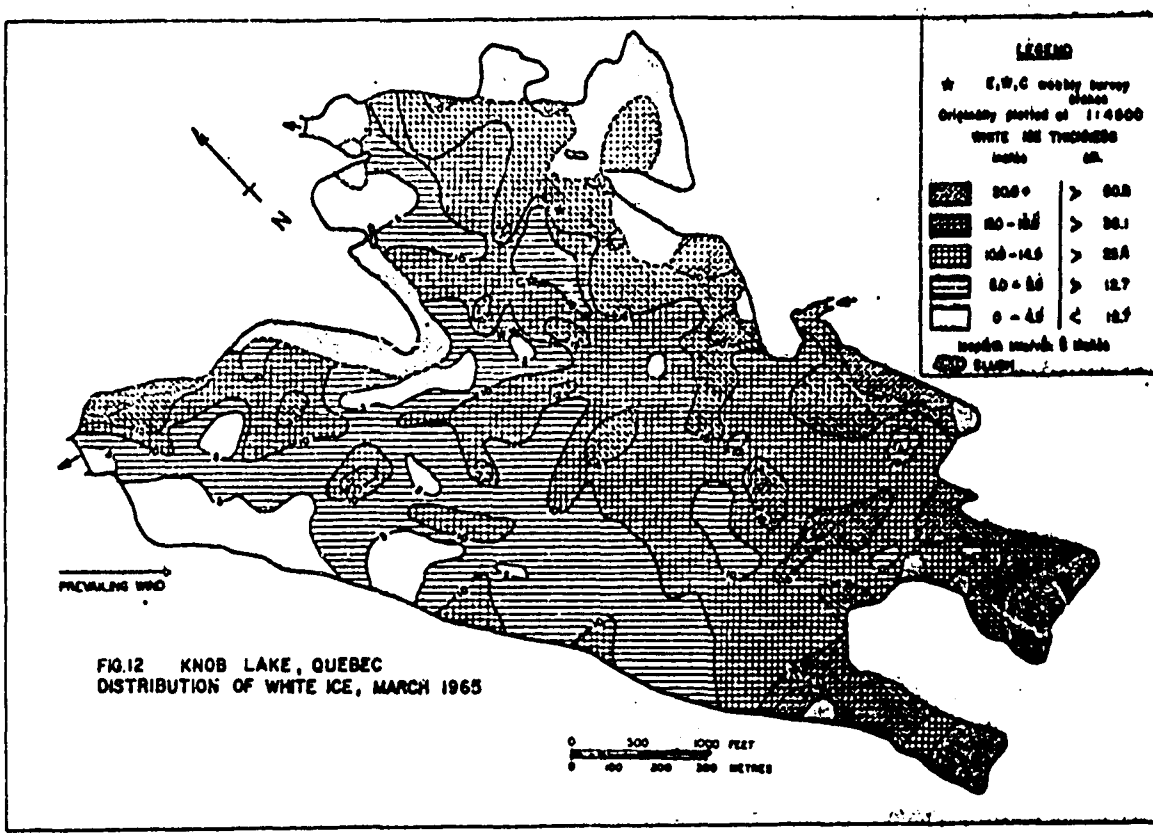


FIG.12 KNOB LAKE, QUEBEC
DISTRIBUTION OF WHITE ICE, MARCH 1965

Figure E.6: from Archer, 1966.

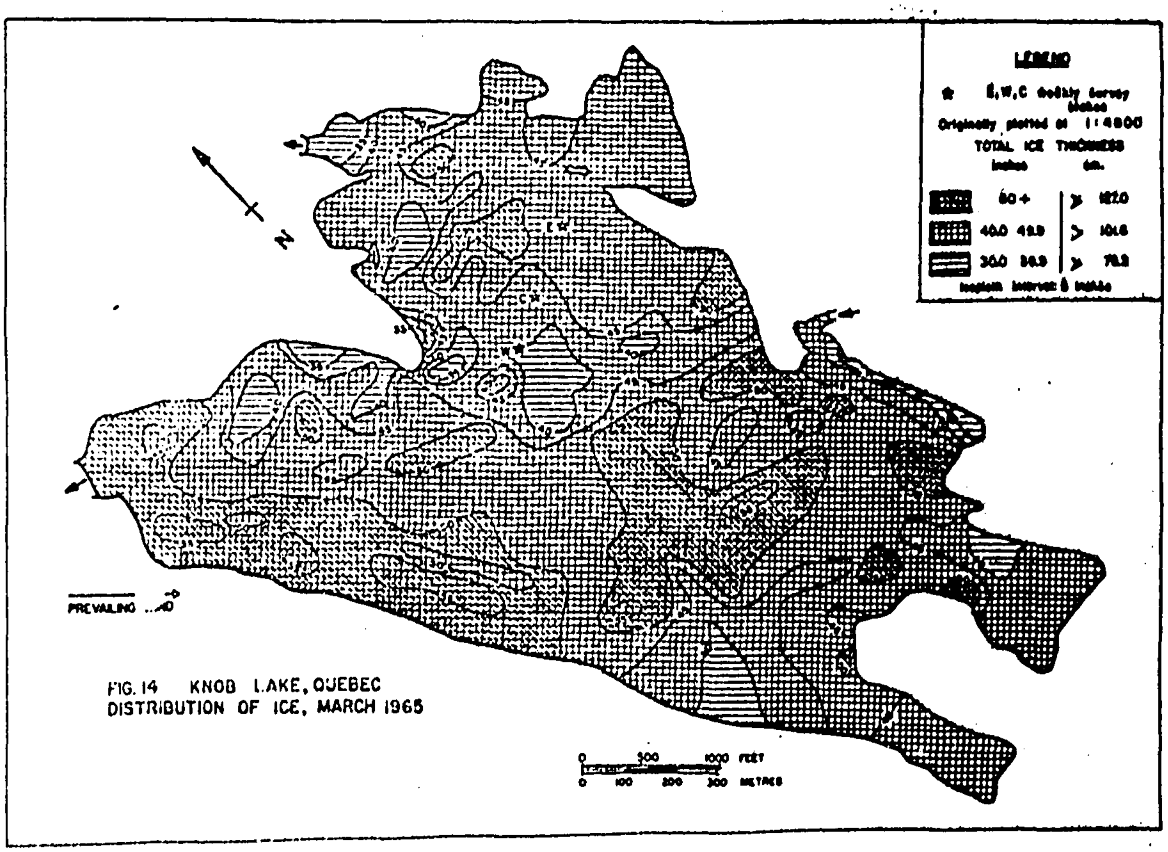


FIG. 14 KNOB LAKE, QUEBEC
DISTRIBUTION OF ICE, MARCH 1965

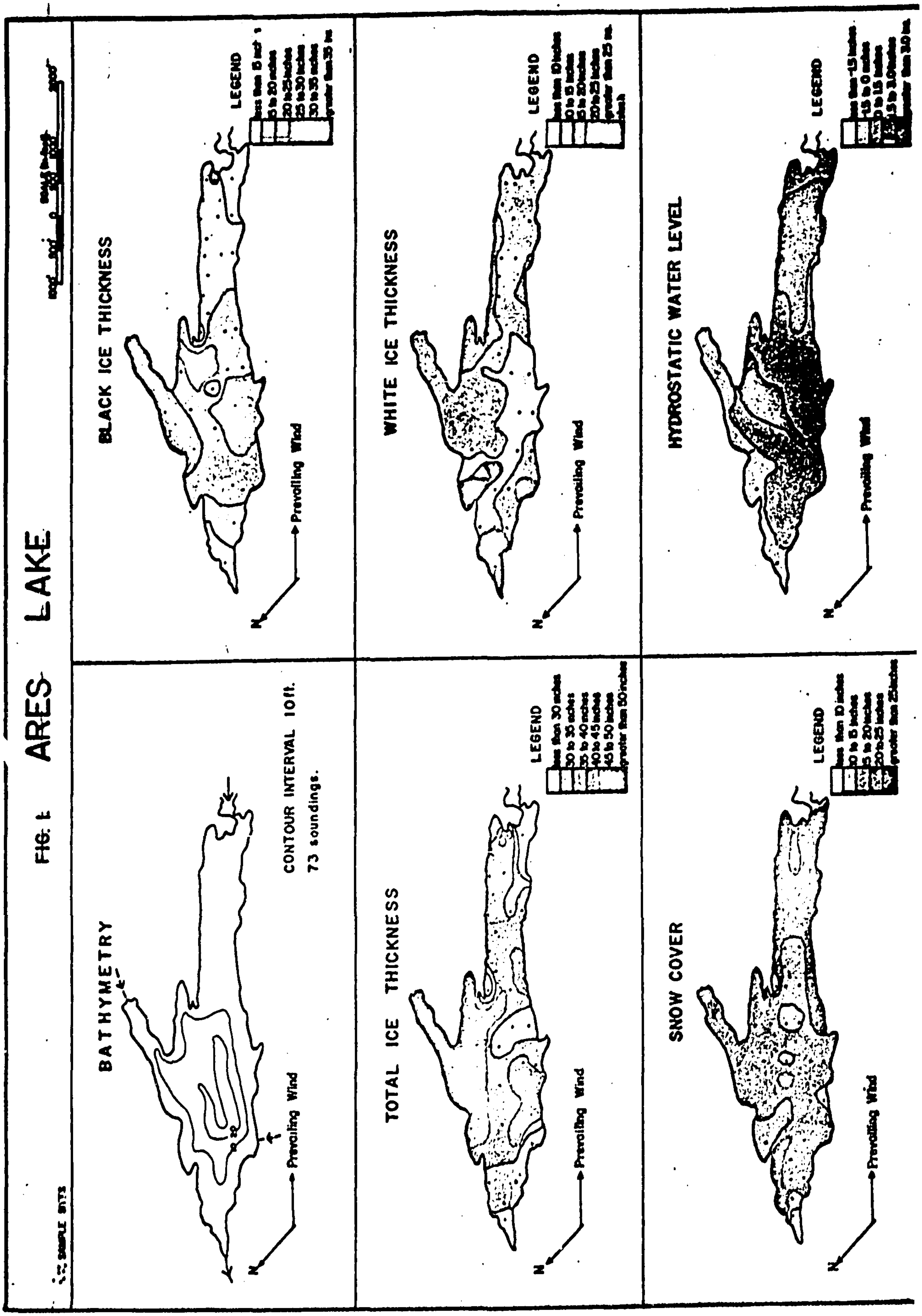


Figure E.7: from Archer, 1966.

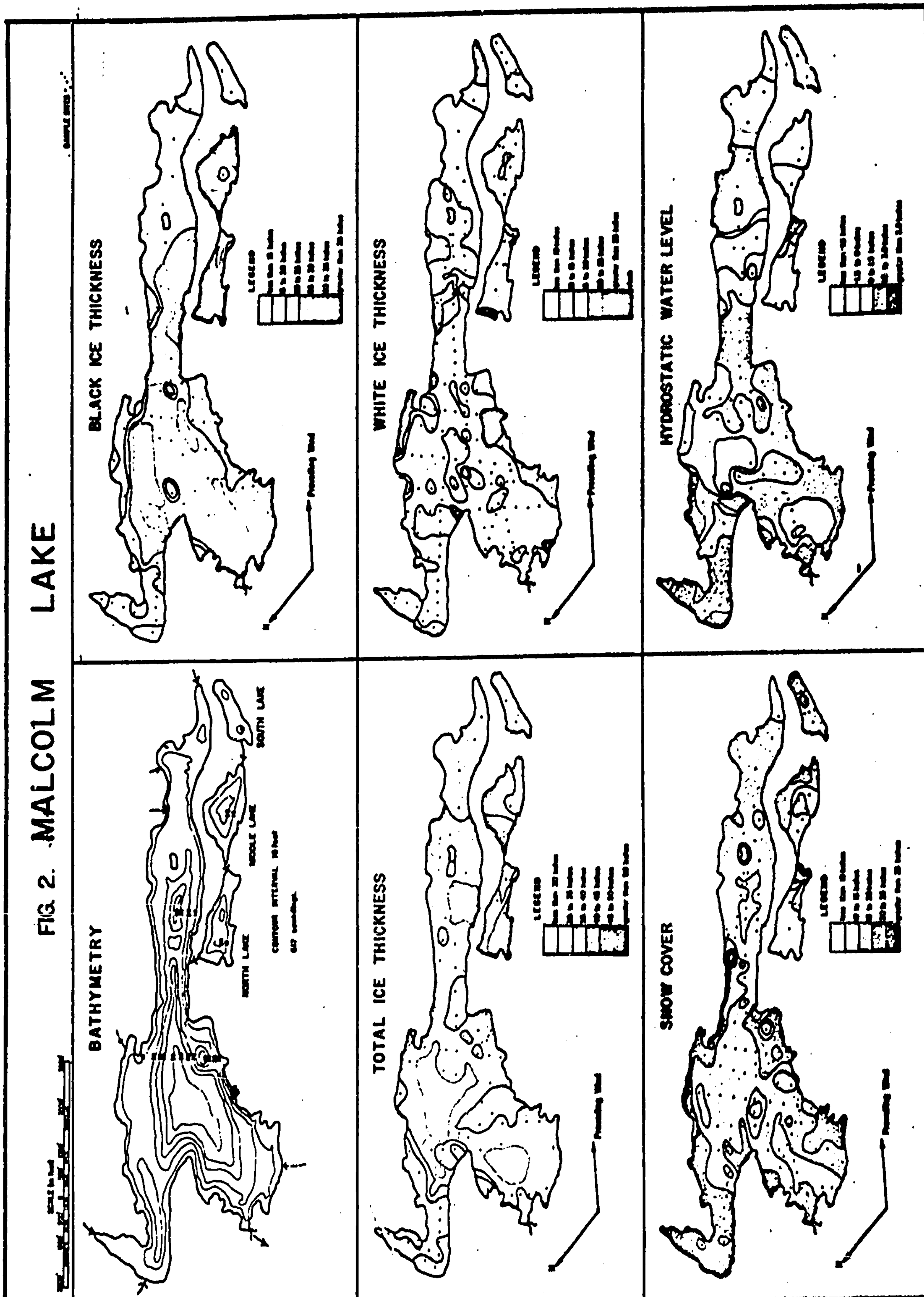


Figure E.8: from Archer, 1966.

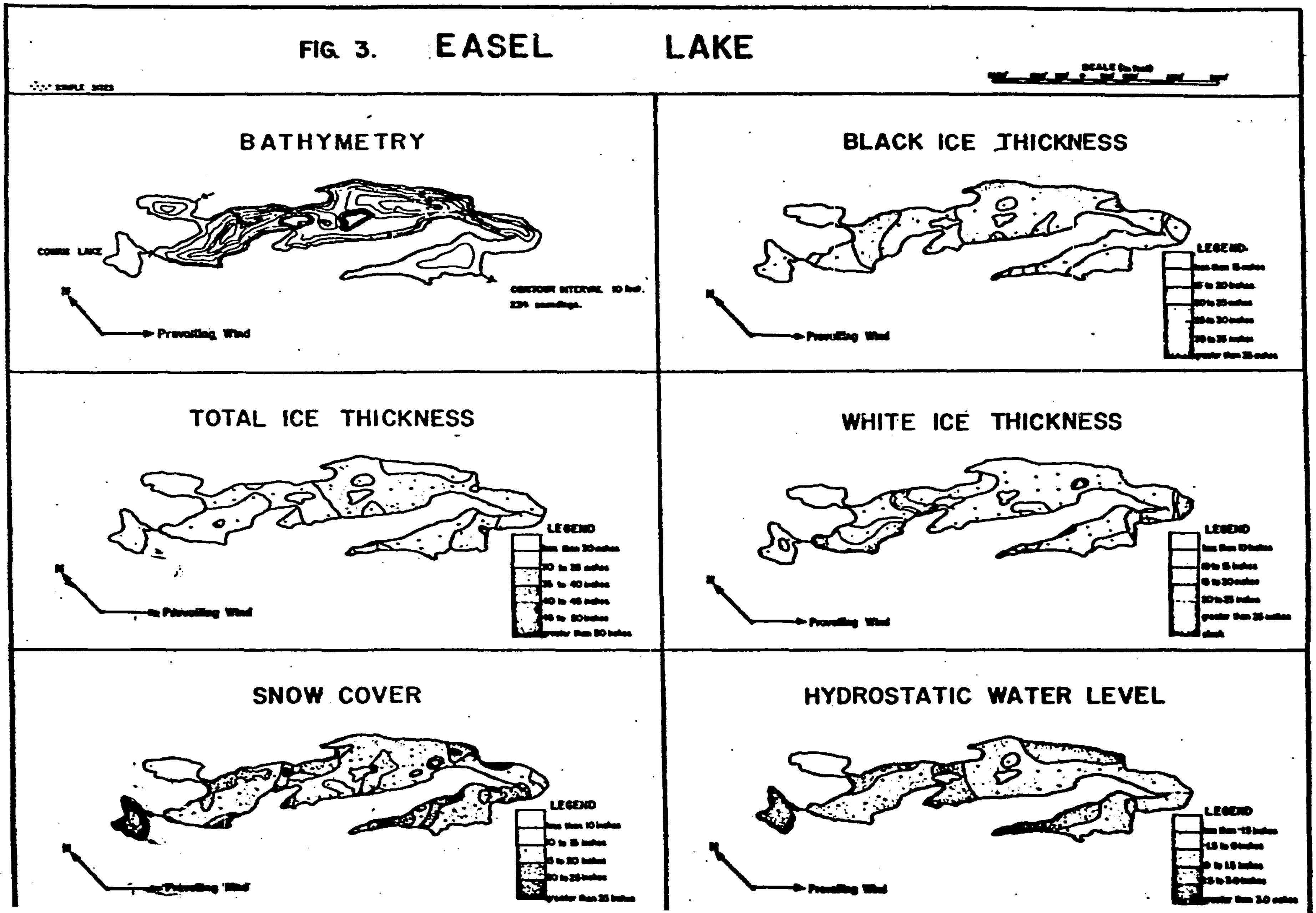
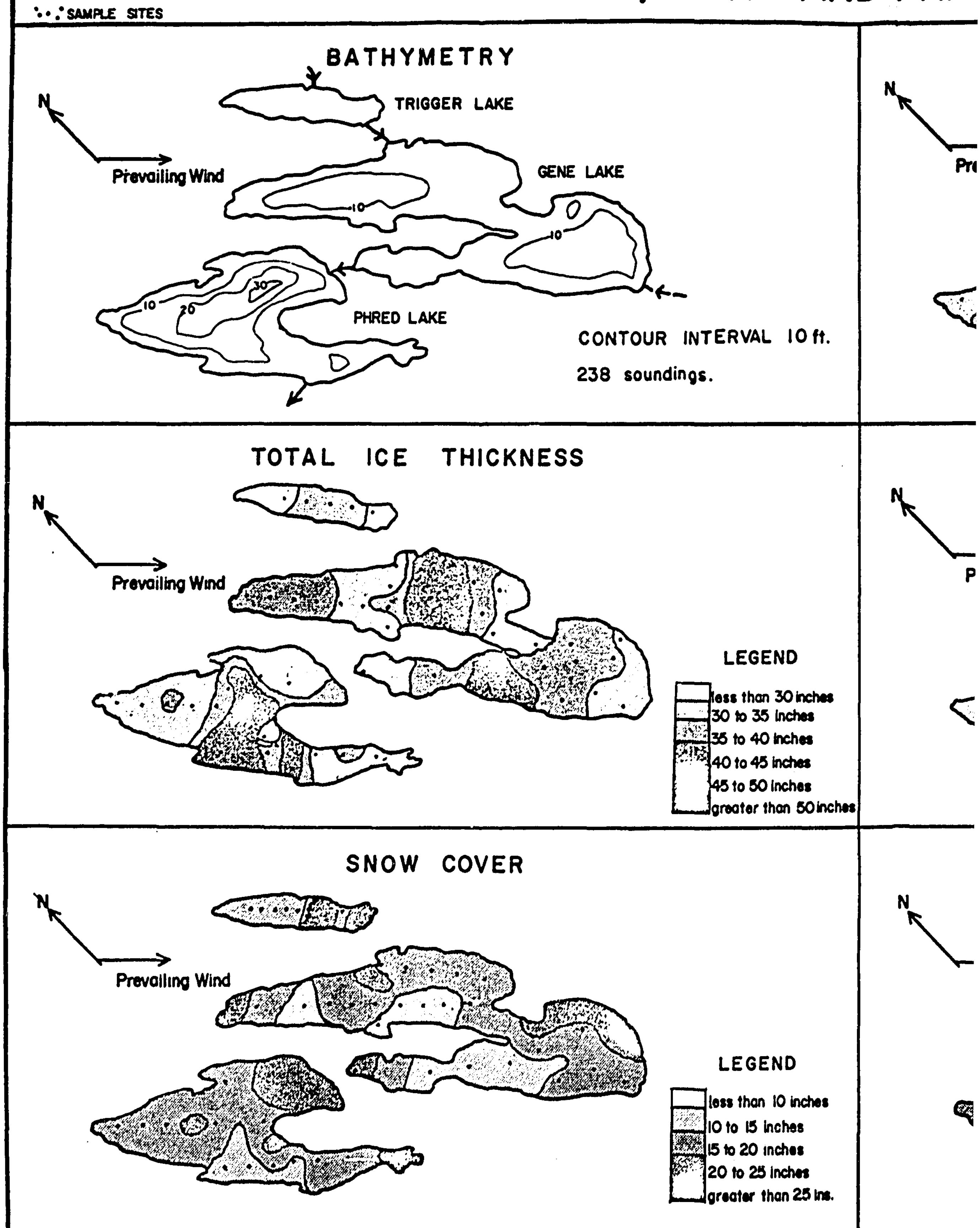


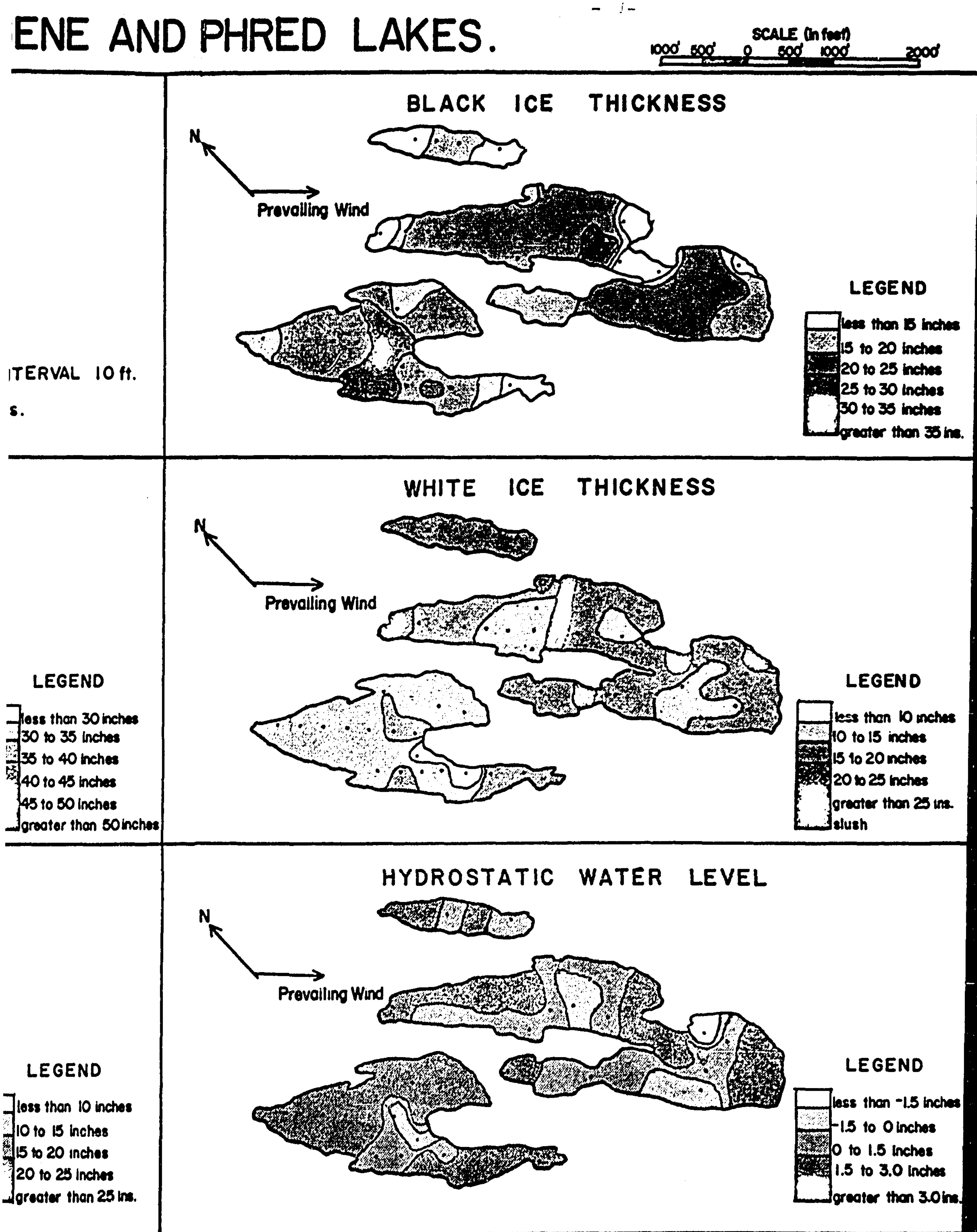
Figure E.9: from Archer, 1966.

Figure E.10: from Archer, 1966.

FIG. 4. TRIGGER, GENE AND PHR



ENE AND PHRED LAKES.



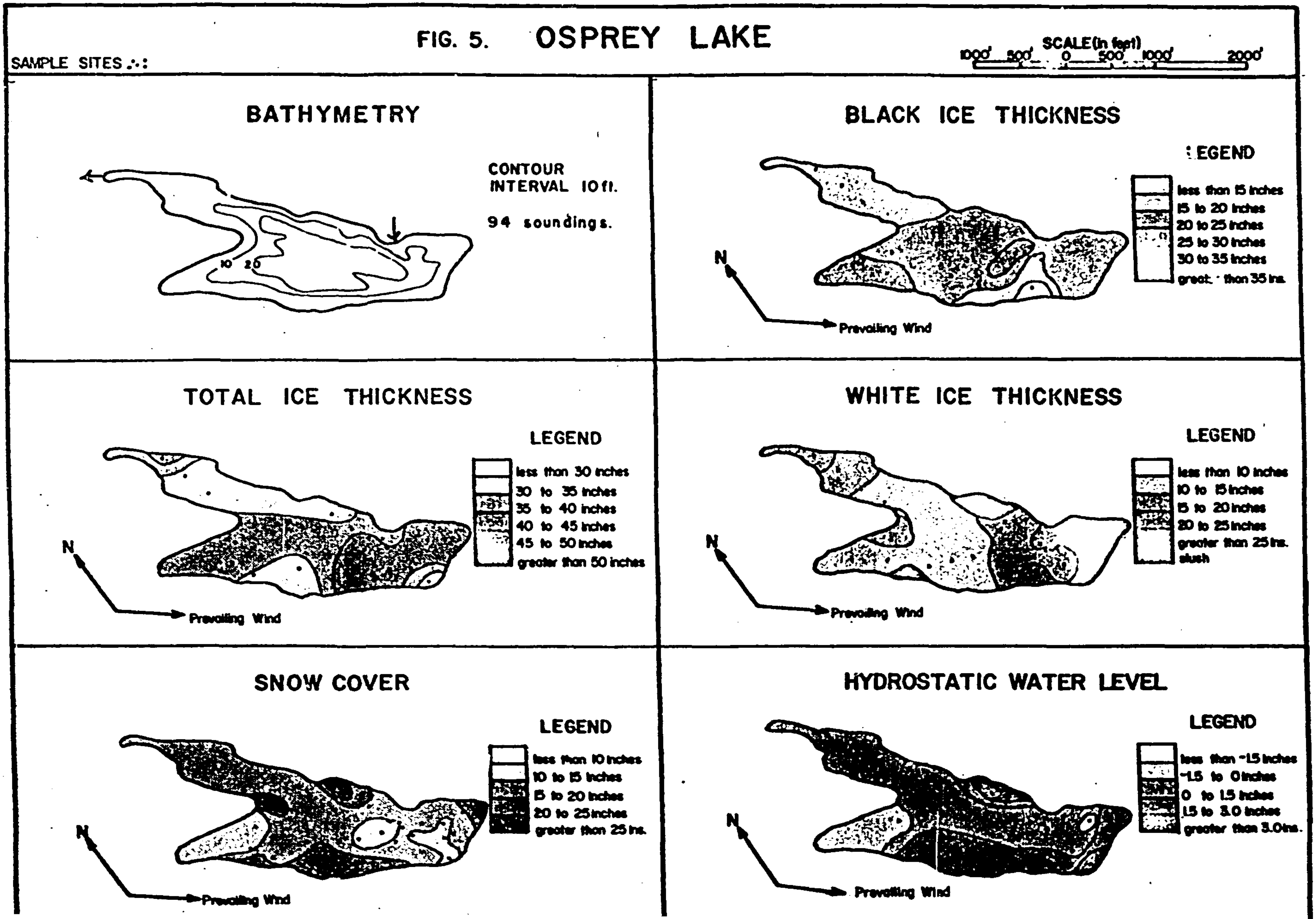


Figure E.11: from Archer, 1966.

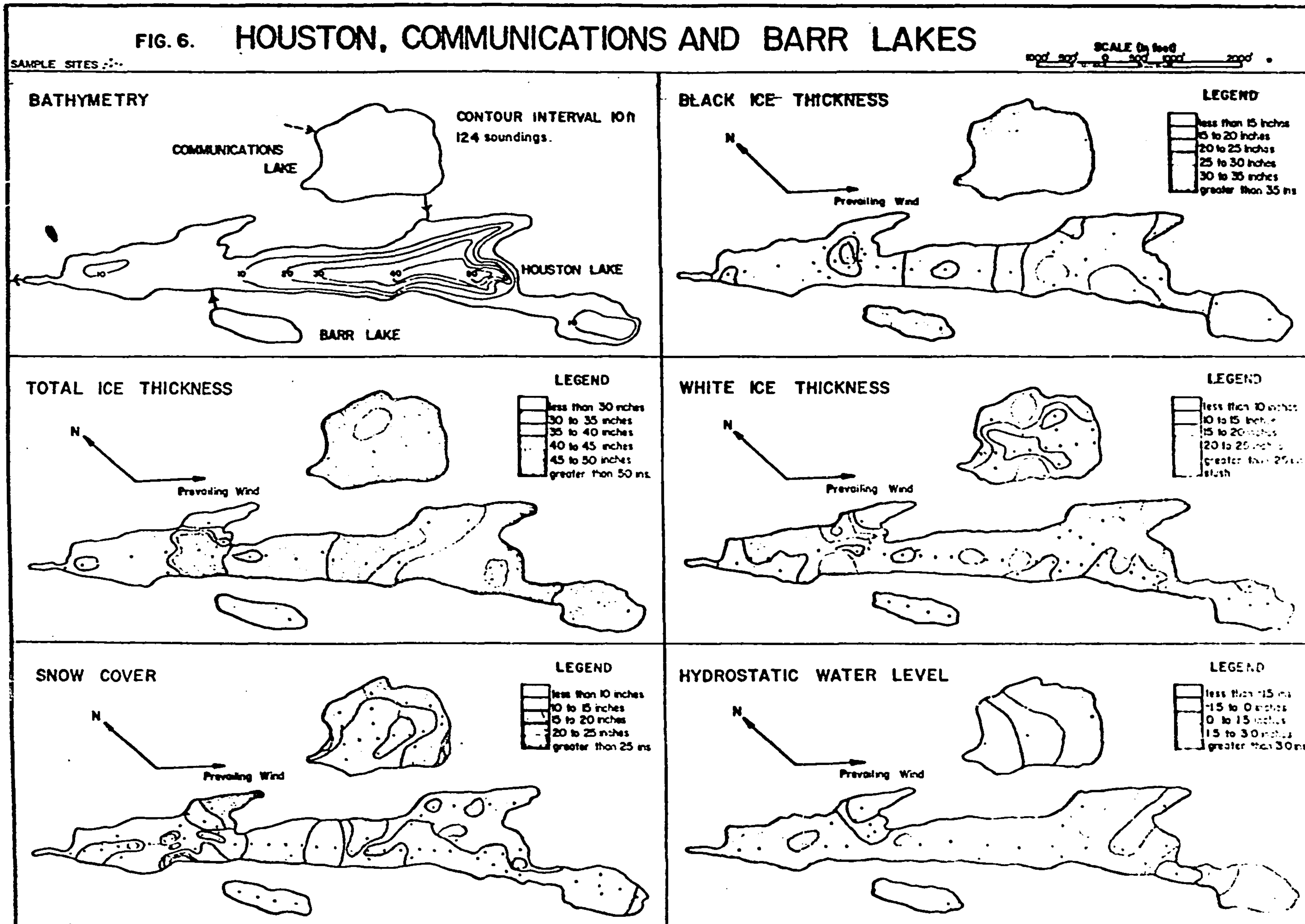


Figure E.12: from Archer, 1966.

Figure E.13: from Andrews and McCloughan, 1961.

Ice thickness against degree days for Knob Lake East, applying an "equivalent white ice" factor in the upper curve.

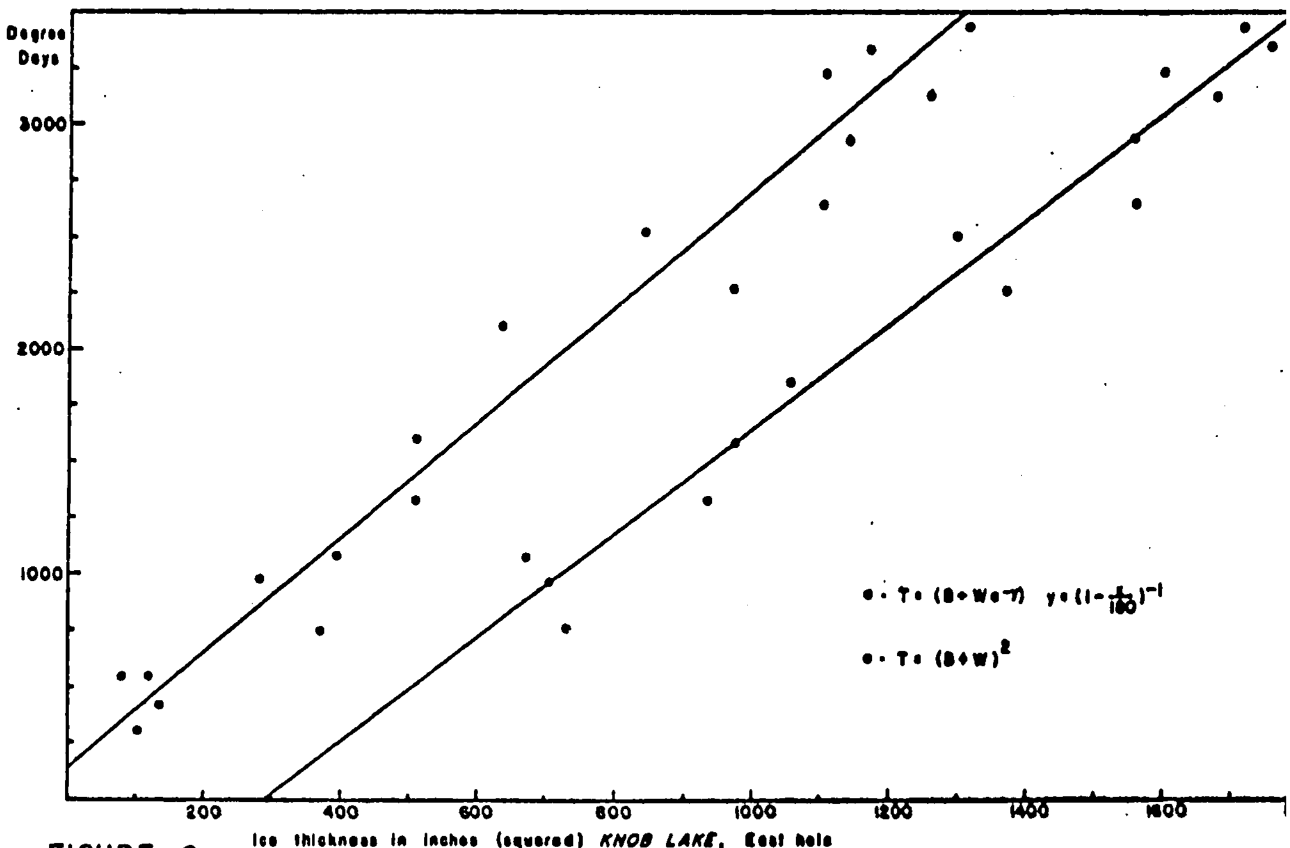


FIGURE 9

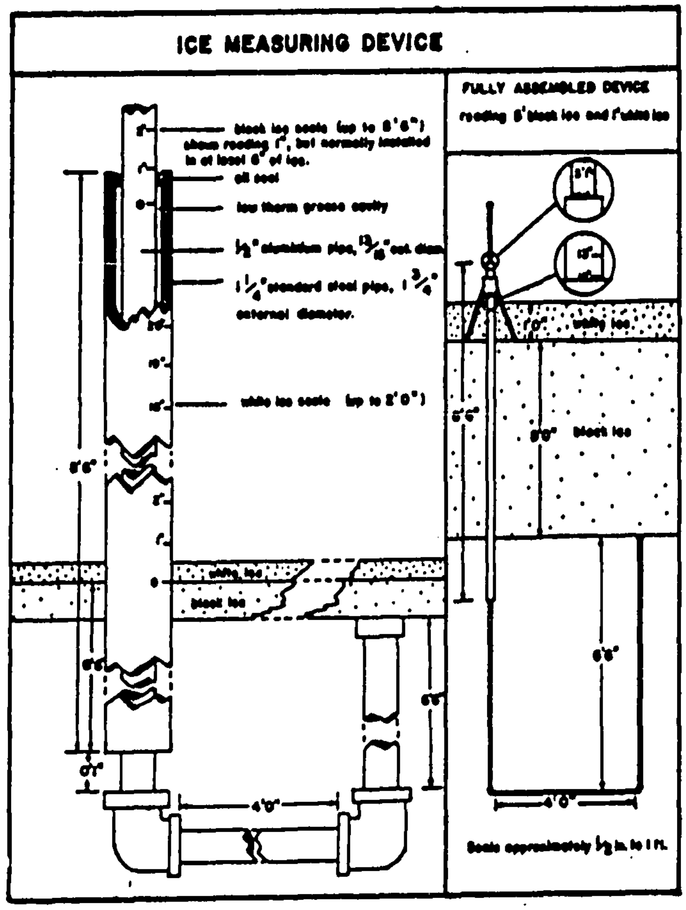


Figure E.14: From Adams and Shaw, 1966 (Drawn by the author)

Fig. 10 (a) SKETCH OF VARIATIONS IN ICE AND SNOW COVER OF SOUTHEAST SQUARE

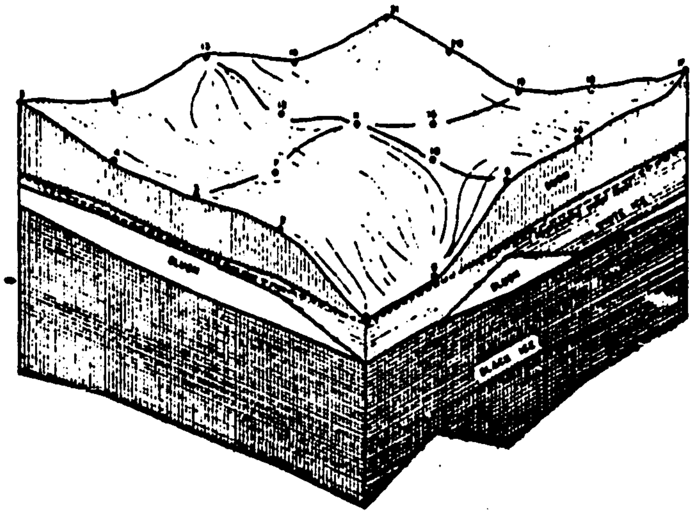


Figure E.15: from Adams and Shaw, 1966.

Fig. 10(b) DRILL HOLE PROFILES, SOUTHEAST SQUARE

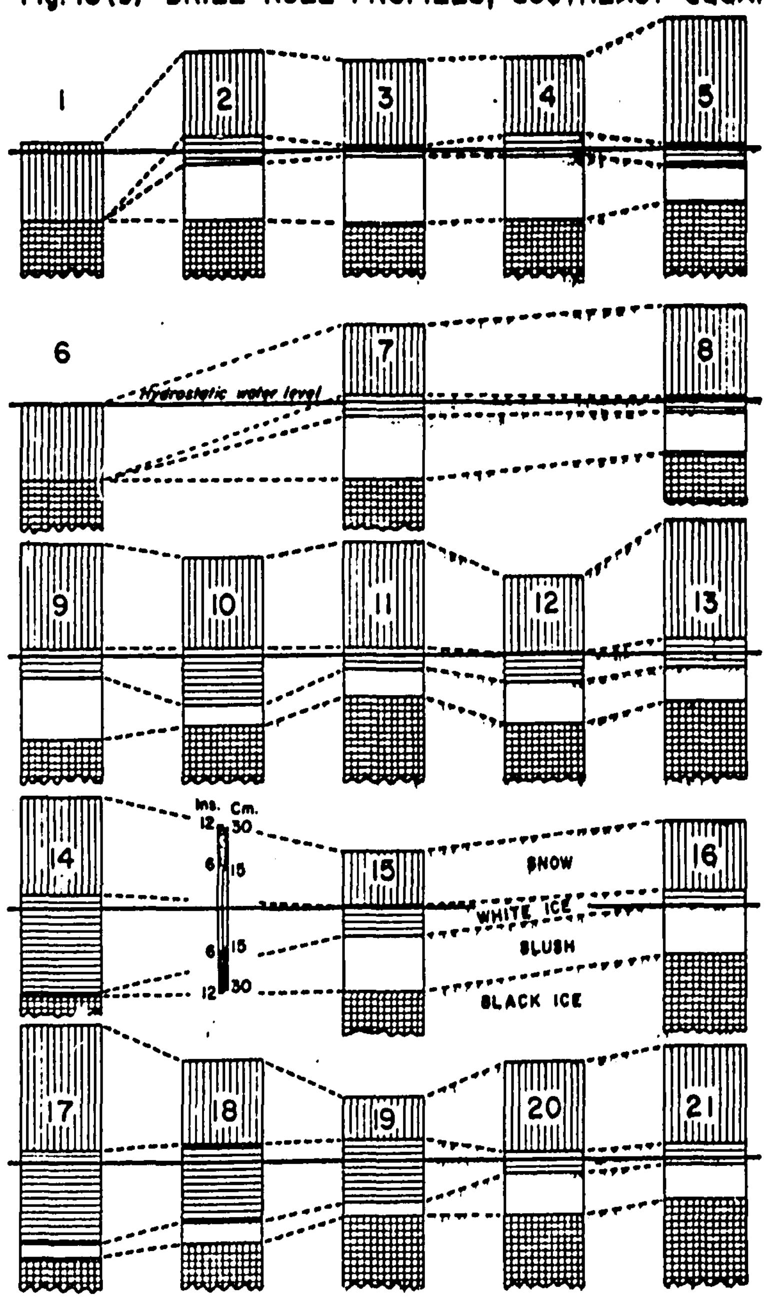
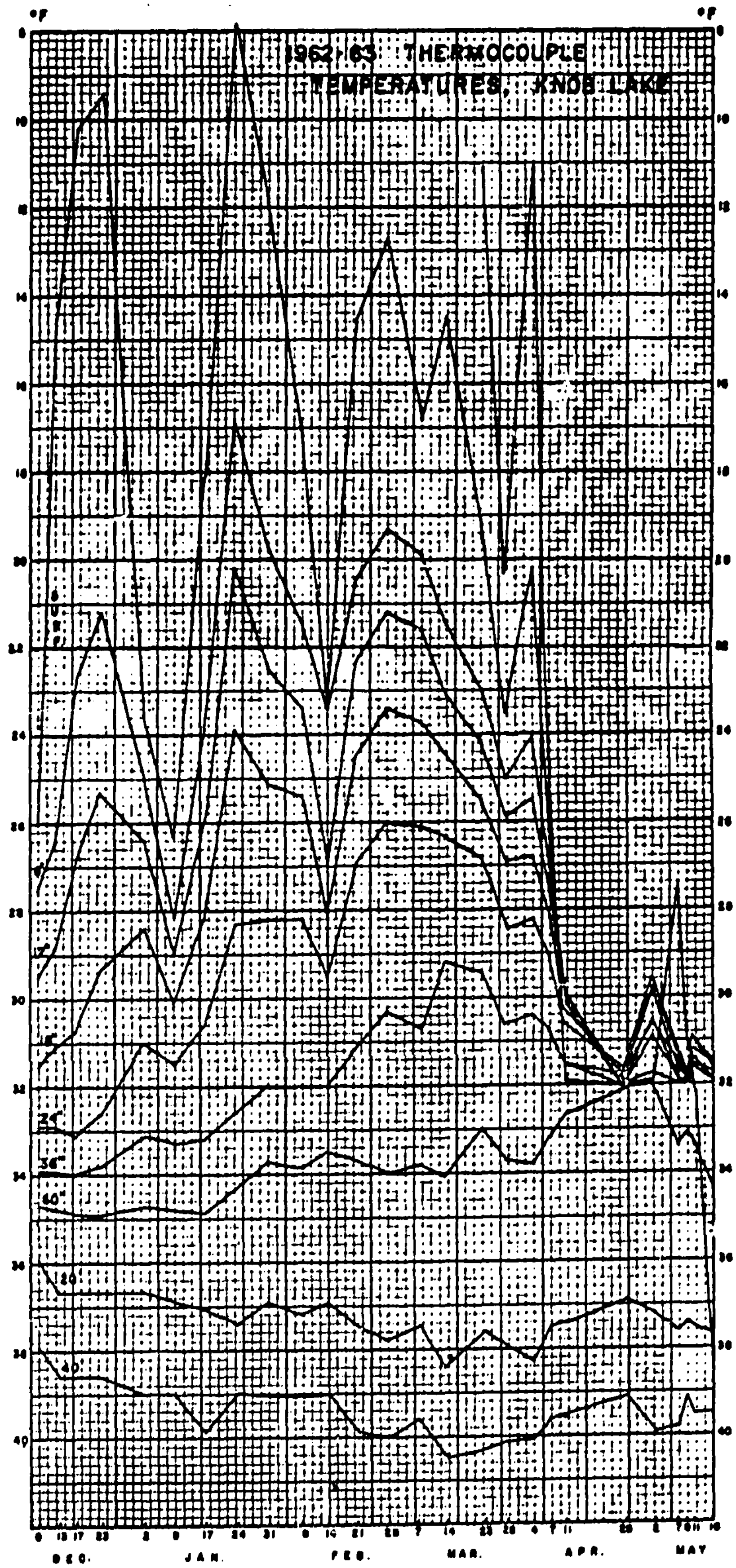


Figure E.16: from Mattox, 1964.



BIBLIOGRAPHY

In cases where only the SIPRE Bibliography abstract has been consulted the reference is preceded by the sign +, both here and in the text. "SIPRE" itself is the Snow, Ice and Permafrost Research Establishment, now CRREL, Cold Regions Research and Engineering Laboratory, of the US Army Corps of Engineers, Hanover, N.H., U.S.A. The abbreviation "MSARP" or "MSARL" refers to McGill Sub-Arctic Research Papers or to early, unnumbered publications of the McGill Sub-Arctic Research Laboratory, Schefferville, Quebec, Canada, in association with the Department of Geography, McGill University, Montreal.

Adams, W.P., and Shaw, J.B., 1966a: Spring ice survey. MSARP 19, pp. 35-49.

Adams, W.P., and Shaw, J.B., 1966b: Instruments and Methods: Improvements in the measurement of a lake ice cover. MSARP 21, Jan., pp. 191-195.

Adams, W.P., Shaw, J.B., and Archer, D.R., 1966: The bathymetry and ice cover of lakes in the Schefferville Area. MSARP 21, Jan., pp. 201-213.

Adams, W.P., and Findlay, B.F., 1966: Snow measurements in the vicinity of Knob Lake, Central Labrador-Ungava. MSARP 22, pp. 96-114, and presented to Eastern Snow Conference, January, Hanover, N.H., U.S.A.

Adams, W.P., Cowan, W.R., Findlay, B.F., Gardner, J.S., and Rogerson, R.J., 1966: Snowfall and snow cover at Knob Lake, Central Labrador-Ungava. MSARP 22, pp. 114-141.

Ager, B.H:son, 1962: Studies on the density of naturally and artificially formed fresh-water ice. J. of Glac., v.4, no. 32, pp. 207-214.

Andrews, J.T., 1962: Variability of lake ice growth and quality in the Schefferville region, Central Labrador-Ungava. J. of Glac., v. 4, pp. 337-347.

Andrews, J.T., 1963: Estimating the strength of lake ice. New Scientist, v. 17, pp. 702-705.

Andrews, J.T., and McCloughan, C.H., 1961: Patterns of lake ice on Knob Lake 1954-60. MSARP 11, pp. 64-90.

Arnborg, L., Peippo, J., and Larsson R., 1965: The ice gauge. Geografiska Annaler, v. 47A, no. 4, pp. 237-239.

Archer, D.R., 1966: The ice survey 1964-65. MSARP 21, pp. 170-189.

Archer, D.R., and Findlay, B.F., 1966: Comments on littoral ice conditions at one site on Knob Lake. MSARP 21, pp. 189-191.

Assur, A., 1956: Airfields on floating ice sheets for regular and emergency operations. SIPRE Tech. Rep. No. 36, 24 pp.

Barr, W., 1964: Temperature measurements in Knob Lake, 1963-4. MSARP 19, pp. 29-35.

Barry, R.G., 1959: A synoptic climatology for Labrador-Ungava. MSARP 8, and Arctic Met. Res. Gp. Pub. in Met. No. 17, August.

Bilello, M.A., 1964: Ice prediction curves for lake and river locations in Canada. CRREL Res. Paper 129, 12 pp. plus Appendices.

Bilello, M.A., Adams, W.P., and Shaw, J.B., 1966: Prediction of ice formation on Knob and Maryjo Lakes, Schefferville, Canada. MSARP 21, pp. 213-226.

Bruce, J.P., and Clark, R.H., 1966: Introduction to hydrometeorology. 1st edition, Pergamon Press, N.Y., 319 pp.

Bryan, M.L., 1964a: Ice survey report. MSARP 19, pp. 16-29.

·Bryan, M.L., 1964b: Preliminary report on investigations of the lakes of Schefferville (Knob Lake), Quebec, vicinity. MSARP 19, pp. 59-79.

Bryan, M.L., 1965: Lakes of the Knob Lake Area, Labrador-Ungava; a study in morphology and morphometry. M.Sc. thesis (unpub.), McGill University, Montreal, 183 pp.

Bryan, M.L., 1966: The morphology and morphometry of lakes in the Schefferville, Quebec, area. MSARP 22, pp. 154-183.

Bryson, R.A., and Bunge, W.W., 1956: Ice on Wisconsin lakes. Madison Department of Meteorology Report to University of Wisconsin Lakes and Streams Investigation Committee, nos. 13, 14, and 15 (three volumes).

+Buckley, E.R., 1900: Ice ramparts. Trans. of Wisconsin Academy of Science Arts and Letters XIII, Part 1, pp. 141-157.

Burbidge, F.E., and Lauder, J.R., 1957: A preliminary investigation into break-up and freeze-up conditions in Canada. Department of Transport, Meteorological Branch, Ottawa, CIR-2939, July.

Burbidge, F.E., 1949: The modification of Continental Polar Air over Hudson Bay and Eastern Canada. M.Sc. thesis (unpub.), McGill University, Montreal.

Callaway, E.B., 1954: An analysis of environmental factors affecting ice growth. U.S. Navy Hydrographic Office, Washington, D.C., TR-7, September, 31 pp.

Cowan, W.R., 1966: Snow survey at Schefferville, 1964-65: MSARP 21, pp. 135-143.

Davies, J.A., 1962: Albedo measurements over Sub-Arctic surfaces. MSARP 13, and Arctic Met. Res. Gp. Pub. in Met. No. 52, 86 pp.

Davies, J.A., 1963a: Albedo investigations in Labrador-Ungava. Archiv fur Meteorologie, Geophysik und Bioklimatologie, Serie B, Allgemeine und biologische Klimatologie, Band 13, 1 Heft, pp. 137-151.

·Davies, J.A., 1963b: Net radiation studies in the Schefferville area. Arctic, v. 16, no. 1, pp. 41-46.

Department of Transport, Meteorological Branch, Ottawa, 1959: Break-up and freeze-up dates of rivers and lakes in Canada. CIR-3156, Ice-2, 30 Jan.

Department of Transport, Meteorological Branch, Ottawa, 1964 (ed. W.T.R. Allen): Break-up and freeze-up dates of rivers and lakes in Canada. CIR-4116, Ice-17, 10 Oct.

Department of Transport, Meteorological Branch, Ottawa, 1964: Manice. CIR-4130 ice-18 23 Oct. 64, Third Provisional Edition, Manual of Standard Procedures and Practices for Ice Reconnaissance.

Department of Transport, Meteorological Branch, Ottawa: Monthly Radiation Summary.

Department of Transport, Meteorological Branch, Ottawa: Monthly Weather Record.

Devik, O., 1944: Ice formation in lakes and rivers. Geographical Journal, v. 103, no. 5, pp. 193-203.

Dorsey, N.E., 1940: Properties of ordinary water substance. Reinhold, N.Y., Monograph Series No. 81, 673 pp.

+Dumble, J.H., 1891: Some observations on the expansion and contraction of ice on Canadian waters. Trans. Can. Soc. Civil Engrs., v. 5, pp. 270-278 (SIP 11706).

+Dunham, H.F., 1924: Ice formation on lakes. Engineering News Record XCII, pp. 209-210.

+Dybovskii, V., and Godlevskii, V., 1870: Investigations in the south-western part of Lake Baikal. (Text in Russian.) Izvest. Vostochno-Sibirshogo Otdiela Russkogo Geograficheskogo Obshchestva v. 1, no. 2-3, pp. 35-48, November. (SIP 14737.)

Findlay, B.F., 1966a: A hydrologic study in the Knob Lake area, New Quebec, with general bibliography. MSARP 21, pp. 144-163.

.Findlay, B.F., 1966b: The water budget of the Knob Lake area: a hydrologic study in Central Labrador-Ungava. In "Hydrological Studies in Labrador-Ungava", MSARP 22, pp. 1-96.

Findlay, B.F., 1966c: The water budget of the Knob Lake area: A hydrological study in Central Labrador-Ungava. M.Sc. thesis (unpub.), McGill University, Montreal.

Findlay, B.F., 1967 in press: paper on the water balance of Knob Lake area for 1965-6. MSARP.

Fletcher, D.J., 1962: Ice thickness report for the winter of 1960-61. MSARP 12, pp. 53-64.

+Forel, F.A., 1888: Snow sludge on the Lake of Geneva. (Text in French.) Bull. soc. vandoise sci. nat. 3rd Series, v. 24, pp. 77-79, (SIP 11724.)

Frankenstein, G.E., 1959: Strength data on lake ice. SIPRE Tech. Rep. No. 59, December.

+Gardiner, R.H., 1861: On the disappearance of ice. Ann. Rep. Smithsonion Inst. 1860, pp. 401-403.

Gardner, J.S., 1964: Snow studies at Schefferville, Quebec: winter 1963-64. MSARP 19, pp. 1-15.

Goldthwait, L., 1957: Ice action on New England Lakes. J. of Glac., v. 3, no. 22, p. 99.

Gray, J.T., 1966: Winter temperatures in Knob Lake, Central Labrador-Ungava 1964-5. MSARP 21, pp. 195-201.

Hare, F.K., 1950a: The climate of the Eastern Canadian Arctic and Sub-Arctic and its influence on accessibility. Doctor es Arts thesis (unpub.), University of Montreal, two volumes.

Hare, F.K., 1950b: Climate and zonal divisions of the boreal forest formation in Eastern Canada. Geographical Review, v. 40, pp. 615-635. Also in Readings in the geography of North America, American Geographical Society, 1952, pp. 446-466.

Hare, F.K., 1951: The present day snowfall of Labrador-Quebec. A.J.S. 249, pp. 654-670.

Hare, F.K., 1959: A photo-reconnaissance survey of Labrador-Ungava. Geographical Branch Memo No. 6, Department of Mines and Technical Surveys, Ottawa, 83 pp.

Hare, F.K., 1966: Recent climatological research in Labrador-Ungava. Cahiers de Geographie de Quebec, v. 10, no. 1a, pp. 5-12.

+Hamberg, 1917: Observations on the movement of lake ice in Lake Sommen and remarks on the geographical distribution of similar phenomena. Bull. Geog. Inst., Uppsala, v. 16, pp. 181-194.

Hansen, K., 1949: Ice pressure in Tystrup Lake and Esrum Lake in the winter. Geografisk Tidschrift XLIX, 1948-9, pp. 67-72.

+Hellaakoski, A., 1932: Ice push on Leitvesi, Lake Saimaa, during the winter of 1932. Fennia v. 57, no. 3. (SIP U3975.)

Irecli, N.P., 1960: Tide-gauge installation on shore-ice employing auxiliary water level gauge. Canadian Defence Research Board translation from Russian, T336R.

Jennings, J.N., 1958: Ice action on lakes. J. of Glac., v. 3, no. 28, p. 228.

Jones, K.J., 1958: Fresh water ice in Quebec-Labrador and its utilization by aircraft. MSARP 4.

Lotz, J.R., and Nebiker, W., 1957: "Climate". In "The Knob Lake Area". Supplement No. 1 to Annual Report 1955-56 of MSARL.

Knight, C.A., 1962: Studies of Arctic lake ice. J. of Glac., v. 4, no. 33, October, pp. 319-335.

Kraus, E., 1941: Ice-thrust ridges and their geological significance. (Text in German.) Natur und Volk, v. 71, February, pp. 74-78.

+Läbedeva, V.V., 1961: Application of atmospheric pressure and circulation characteristics to forecasts of the simultaneous regional onset of ice phases. (Text in Russian.) Trudy Glavnoi Geofiz. Obs., Vyp. III, pp. 182-92.

Langleben, M.P., and Pounder, E.R., 1964: Arctic sea ice of various ages I: ultimate strength. J. of Glac., v.5, no. 37, pp. 93-98.

Langway, C.C., 1958: Ice fabrics and the Universal Stage. SIPRE Tech. Rep. No. 62, August.

Laskar, K., and Strenzke, K., 1941: Ice thrust on the shores of North German lakes and its effects. (Text in German.) Natur und Volk, v. 71, February, pp. 67-70.

Leahey, D.M., 1966: Heat exchange and sea ice growth in Arctic Canada. McGill University, Marine Sciences Centre, Montreal, Manuscript Report No. 1, September, 48 pp.

Lyons, J.B., and Stoiber, R.E., 1959: Crystallographic orientation in lake and artificial ice. Geophysics Research Directorate, Air Force, Cambridge Research Center, Air Research and Development Command USAF Bedford, Mass., October 31st, AFRCR-TN-59-655.

Lyons, J.B., and Stoiber, R.E., 1962: Orientation fabrics in lake ice. J. of Glac. v. 4, no. 33, October, pp. 367-370.

Luosto, U., and Saastamoinen, P., 1964: Observations about ice-shocks on Lake Saaksjarvi. Geophysica, v. 9, no. 1, pp. 87-91.

Mattox, W.G., 1964: The study of a small area ice plot on Knob Lake, 1962-63. MSARP 4, pp. 25-36.

Matthew, E.M., 1961: The glacial geomorphology and deglacierization of the George River Basin and adjacent areas in Northern Quebec. M.Sc. thesis (unpub.), McGill University, Montreal.

Mellor, M., 1964: Snow and ice on the Earth's surface. CRREL, II-Cl, July, US Army Material Command, Hanover, N.H., 163 pp.

+Meyer, R., 1922: Observations on the behaviour of a snow cover. (Text in German.) Wetter, v. 39, Sept.-Oct., pp. 138-141. (SIP 12805)

Michel, B., and Triquet, C., 1966: Ice cover progression in the Chaudiere River. Paper delivered to Eastern Snow Conference, January, Hanover, N.H., U.S.A.

+Molchanov, I.V., 1925: Structure of lake ice and meteorological conditions. (Text in Russian.) Izvest. Rossiiskogo Gidrologichoskogo Instituta, no. 14, pp. 31-51. (SIP 11687.)

+Norrman, J.O., 1963: Lake Vattern investigations on shore and bottom morphology. Hydrology. Geografiska Annaler, v. 46, nos. 1-2, pp. 53-69.

+Oak, W.W., 1955: Ice on Great Lakes. Weekly Weather and Crop Bulletin National Summary, v. 42, no. 8, pp. 7-8. (SIP 14989.)

Olkkonen, E., and Palosuo, E., 1958: A resistance gauge for measurement of ice pressure. Geophysica, v. 5, no. 4, pp. 221-226.

Orvig, S., 196 : Net radiation flux over sub-arctic surfaces. J. of Met. v. 18, pp. 199-203.

Palosuo, E., 1965: Frozen slush on lake ice. Geophysica, v. 9, no. 2, Helsinki, pp. 131-147.

Palosuo, E., 1964: The Gulf of Bothnia in Winter II: freezing and ice forms. Mereotutkimustailokses julkaiso No. 208, Helsinki.

Perey, F.G.J., and Pounder, E.R., 1958: Crystal orientation in ice sheets. Canad. J. Phys. v. 36, pp. 494-502.

Persson, B.O.E., 1954: Durability and bearing capacity of an ice layer. ACFEL, US Army Corps of Engineers Translation No. 22, 19 pp.

Peterson, J.A., 1964: The Whitegull Lake Area, Labrador-Ungava: studies of the late glacial geomorphology. M.Sc. thesis (unpub.), McGill University, Montreal.

Peterson, J.A., 1966: Ice-shove ridges and other ice-shove features, Whitegull Lake Area, Labrador-Ungava. MSARP 21, pp. 82-95.

Pounder, E.R., 1965: Physics of Ice. 1st edition, The Commonwealth and International Library, Pergamon Press, Oxford.

Ragle, R.H., 1963: Formation of lake ice in a temperate climate. CRREL Res. Rep. 107, 22 pp.

Ragotzkie, R.A., and Scott, J.T., 1961: Heat budget of an ice covered inland lake. Madison Department of Meteorology Tech. Paper No. 6; Report No. 22 of University of Wisconsin, Department of Meteorology to Lakes and Streams Investigation Committee.

Royen, N., 1955: Ice Pressure with increasing temperatures. SIPRE Translation 45, August.

Ryder, T., 1954: Compilation and study of ice thicknesses in the Northern Hemisphere. Publication of the American Geographical Society, June.

Seliakov, N.Ia., 1956: Some observations on processes connected with the formation of ice. Translated from Russian original (1951) by J.A. Gwyer, SIPRE Translation 13, October.

Shumskii, P.A., 1964: Principles of Structural Glaciology. Translated from Russian by D. Kraus, Dover Books, N.Y., 497 pp.

Shaw, J.B., 1963: Ice survey Knob Lake 1961-2: a critical re-evaluation of main environmental factors of lake ice growth. MSARP 15, pp. 34-46.

Shaw, J.B., 1964: Calculation of the density of a lake snow cover. MSARP 18, pp. 56-60.

Shaw, J.B., 1965: Growth and decay of lake ice in the vicinity of Schefferville (Knob Lake), Quebec. Arctic v. 18, no. 2, pp. 123-131.

Shaw, J.B., and Tout, D.G., 1962: Selected climatological data for McGill Sub-Arctic Research Laboratory, September 1954 - December 1962, with supplement to 1964 by D. Barr. Published by the Department of Geography, McGill University, Montreal.

+Simojoki, H., 1939: About the ice of the inland lakes of Finland. Union geodesique, geophys. intern., Assoc. hydrol. sci., Comm. de Limnol. 1 Quest 2 Rapport 4. (SIP U4060)

Simojoki, H., 1960: On seiches in some lakes in Finland. Geophysica, v. 7, no. 3, pp. 145-151.

Simojoki, H., 1966; On short period fluctuations of water level of an ice-covered lake. Geophysica, v. 9, no. 3, pp. 251-257.

Swinzow, G.K., 1966: Ice cover of an Arctic proglacial lake. CRREL Res. Rep. 155, 43 pp.

Tout, D.G., 1964: The climate of Knob Lake. MSARP 17, 236 pp.

Tyrrell, J.B., 1910: Ice on Canadian Lakes. Trans. Can. Inst., v.9, pp. 13-21.

Ward, W.H., 1959: Ice action on shores. J.of Glac., v. 3, no. 25, p. 437.

Westlake, B., 1964: Ice survey 1962-3. MSARP 18.

+Wedderburn, W.S., 1908: The freezing of fresh-water lakes. J.of Scottish Met.Soc., v. 14, pp. 219-224.

Welch, P.S., 1948: Limnological methods. Blakiston Co., Philadelphia, 381 pp.

Williams, G.P., 1963: Probability charts for predicting ice thickness. Res.Paper No. 190 DBR, July; and The Engineering Journal, June.

Williams, G.P., 1967 (in press): Freeze-up and break-up of fresh-water lakes. Paper delivered to "IHD Workshop Seminar on Ice Formation and Break-up in Lakes and Rivers", in Conference on Ice Pressure Against Structures at Laval University, Quebec City, November 9, 1966.

+Woodcock, A.H., and Riley, G.A., 1947: Patterns in pond ice. J. of Meteorology, v. 4, June, pp. 100-101.

Young, H.A., 1967 (in press): Address to the IHD Workshop Seminar on Ice Formation and Break-up in Lakes and Rivers, Laval University, Quebec City, November 9-10, 1966.

Zubov, N.N., 1963: Arctic Ice. Translation by U.S. Navy Oceanographic Office and American Meteorological Society. Published by U.S. Navy Electronics Laboratory, 491 pp.

Zumberge, J.H., and Wilson, J.T., 1953: Quantitative studies on thermal expansion and contraction of lake ice. J.of Geology, v. 61, pp. 374-383.

Data on File at McGill Sub-Arctic Research Laboratory:

Manuscript diaries of ice growth deposited at the McGill Sub-Arctic Research Laboratory, Schefferville, Quebec, by B. Westlake, D.R. Archer and J.B. Shaw.

Manuscript weather and ice records held at the McGill Sub-Arctic Research Laboratory, Schefferville, Quebec.

Mimeographed monthly climate summaries (Barr et al).