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SPECIAL PUBLICATION

MANUAL OF SHORT-TERM SEA ICE FORECASTING

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May 1964

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PREFACE

The authors wish to acknowledge assistance of the many individuals and organizations whose contributions made possible this initial formulation of short-term ice forecasting procedures. The NAVOCEANO aerial ice reconnaissance program, pioneered by the late Henry S. Kaminski from 1951 through 1954, provided the foundation for this manual. Many of Mr. Kaminski's forecasting concepts were substantiated with aerial ice reconnaissance data. U.S. Navy and Canadian patrol squadrons obtained much of the basic data under difficult flying conditions in arctic regions.

Mr. Rudolph J. Perchal of the Oceanographic Office performed the necessary work required to include ice conditions in the Bering Sea area in supplementing H.O. Pub 705. This work is presented as appendix C. Lt. W. A. Dotson, who was head of the Oceanographic Office ice observer team between 1960 and 1963 and intimately associated with the program since 1954, contributed valuable advice and suggestions. A. G. Voorheis, AGC, also of this Office, deserves special recognition for the skill and speed with which he completed the graphics presented in this manual.

General credit is due all ice forecasters of the Oceanographic Prediction Division and to all aerial oceanographic observers of the U.S. Naval Weather Service who were assigned to ice reconnaissance missions.

W.I.W.
G.P.M.

FOREWORD

Ice forecasting services in support of surface shipping operations in the Arctic have proved to be of value since 1952. This manual represents an initial attempt to systematically present recommended methods of ice prediction. All methods are based completely on regularly collected and continually disseminated environmental data readily available at field stations such as Kodiak, Alaska, and Argentia, Newfoundland.

Rapid advances in knowledge of ice distribution are expected during the next decade owing to development of remote sensing equipment. Sonic equipment aboard nuclear submarines, vidicon imagery from the TIROS weather satellites, and airborne infrared and radar sensors are providing unparalleled data on ice coverage. Commensurate developments may be expected in knowledge of processes controlling pack ice behavior and in the capability for its prediction. Timely supplements to and revisions of this manual will therefore be necessary. Comments and constructive criticism that may improve the manual are welcome and should be forwarded to the Commander, U.S. Naval Oceanographic Office.

Denys W. Knoll

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Rear Admiral, U.S. Navy
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MANUAL OF SHORT-TERM SEA ICE FORECASTING

1. INTRODUCTION

1.1 PURPOSE AND OBJECTIVES

Knowledge of arctic ice distribution and of environmental influences that control the distribution is still expanding and is far from complete. Nevertheless, since 1952 the U.S. Naval Oceanographic Office (NAVOCEANO) has been engaged in supporting fleet operations within the marginal arctic seas of North America with ice predictions of varying durations. These prediction services have proved to be of considerable value to surface ship operations into regions such as the Labrador Sea-Baffin Bay and the Bering Sea-Chukchi Sea areas. Thule Air Base (1951) and the DEWLINE radar network (1955) are important examples of military activities supported by ice forecasting services.

The intent of this manual is to describe in as great a detail as possible the procedures and techniques hitherto developed in provision of short-term ice forecasts. The procedures are formulated for application; all ice features to be predicted are correlated with known or readily predictable environmental variables.

Three basic types of knowledge are prerequisite to development of the ice prediction capability. Not necessarily in order of importance, these are: a thorough understanding of ship capabilities and operational problems unique to polar regions (see par. 1.3), basic knowledge of pack ice distribution and variation in time and space (see par. 1.4), and knowledge of the physical processes which govern sea ice formation, movements, and behavior (see par. 1.5, 1.6, and 1.7). The techniques described are tailored for adaptation to machine computation.

1.2 TRADITIONAL SEA ICE PREDICTION SERVICES

1.21 ICE OUTLOOKS

Normally, support of arctic surface logistical operations begins in fall, at which time U.S. Navy or Coast Guard icebreakers obtain oceanographic stations over the general area of future operations. Data from these stations are used for determining thermal characteristics of the hydrosphere. It is then possible to theoretically predict potential ice formation and growth. Considerably in advance of forthcoming operations, a comprehensive aerial survey is conducted to determine ice coverage and characteristics for comparison with normal ice conditions. Weather conditions during the important period of formation, growth, and early development of the ice cover are also investigated. Analysis of the data collected during the above surveys permits ice forecasters to estimate ice conditions for the coming shipping season. The results of such analysis and study are issued as an ICE OUTLOOK for the particular area under consideration.

NAVOCEANO issues long-range ice outlooks for the eastern Arctic, covering Baffin Bay and the Labrador Sea. A similar outlook covering the Bering, Chukchi, and Beaufort Seas off the Alaskan mainland is issued as required for the western Arctic. The basic concept of the long-range outlook in the Alaskan area is presented in figure 1. The Canadian Ice Central, established in 1958 by the Meteorological Division, Department of Transport, Canada, has assumed NAVOCEANO's responsibility for publishing ice outlooks and short-range predictions for the Canadian Archipelago and predicts for the St. Lawrence Seawa

Ice outlooks are prepared essentially for naval and military planning purposes. These outlooks include expected mean positions of ice boundaries for periods up to approximately 120 days and expected mean categorical concentrations of ice accompanied by descriptions of some anticipated ice dynamics. The outlook also contains tables of expected opening dates of harbors and landing sites.

In addition to ice conditions affecting shipping, the outlook provides information concerning environmental influences of importance. Special sections of the outlook may be devoted to iceberg distribution and frequency. Dates of normal freezeup are also included.

Detailed recommendations for utilization of long-range outlooks are contained in section 2 below.

1.22 THIRTY-DAY ICE FORECASTS

Concentration and thickness of pack ice are considerably influenced by growth, movement, volume, environmental history during development, and environmental conditions both at the time of the forecast and during the recent past.

A 30-day ice forecast serves as a medium for implementing, extending, and correcting the character and behavior of pack ice predicted in the long-range outlook. The 30-day forecast thus permits the forecaster to pass along the latest environmental indications and predictions. Referring again to figure 1 as an example, very strong north to south drift and/or colder than predicted air temperatures over the pack off Wainwright in July may result in persistence of more heavily ridged and concentrated pack ice and narrower shore leads in August than had been predicted in the outlook.

The 30-day forecast also furnishes outlook information for stations where operations occur considerably before publication of the outlook. St. Paul Island (figure 1) would exemplify this condition, because ice has usually disappeared at this location before the ice outlook is published. Furthermore, new operational requirements may develop after publication of the outlook; the 30-day forecast may supplement the outlook for locations that have been omitted from the outlook because of lack of operational requirements.

The 30-day forecast contains general information concerning the operation to be supported. Mean and extreme ice boundaries may be included; mean pack concentrations are described for specific regions where operations are in progress; predominant and secondary stages of ice may be anticipated; predominant floe sizes and the expected size and shape of shore and larger offshore leads, which may be utilized by shipping, are described when important; special ice phenomena, such as iceberg concentrations and ice islands or fragments, are also included.

The 30-day forecasts are disseminated primarily by radio dispatch, thus permitting rapid availability of the data for operational planning.

1.23 FIVE-DAY ICE FORECASTS

For the purpose of this manual all ice predictions for a duration of five or less days are considered short-term forecasts. Short-term ice forecasts are formulated primarily for active fleet users, such as task groups, task units, individual ships, and shore-based field activities engaged in arctic operations. Planning commands, however, generally receive short-term forecasts to maintain cognizance of ice conditions. Five-day forecasts are more specific in geographic scope and contain more detail of ice features than do outlooks and 30-day forecasts. These forecasts place greater emphasis on expected dynamics of the pack.

Examples of ice dynamics in the sense employed here are:

(1) widening, narrowing, or closing of navigable leads

(2) changes in preference of alternative routes

(3) changes in expected ice pressure and ridging

(4) changes in concentration, age, and thickness

(5) changes in predominant and secondary forms of ice

(6) changes in amount of shore ice and drift ice in offloading and lighterage areas.

Ice forecasts are disseminated from field forecasting activities to tactical and planning fleet units by radio dispatch. For brevity in communications during the last several ice seasons, the 5-day forecasts have been appended to 48-hour forecasts discussed in section 1.24 below. Five-day forecasts are based in considerable part on meteorological information provided by the Extended Forecast Section, U.S. Weather Bureau, two or three times per week depending upon operational requirements. Where facilities are available, 5-day forecasts may also be disseminated by radio facsimile.

1.24 FORTY-EIGHT-HOUR ICE FORECASTS

Several days prior to reaching pack ice by means of an open water access route, tactical groups or individual ships usually begin to receive daily forecasts of the ice boundary lying in their track. These forecasts indicate whether a change from ice free to close or very close pack is sharp or whether the expected boundary is diffuse and ill-defined, marking a gradual change from ice free to open ice conditions. Also described between the boundary and the terminals along the track are expected concentrations, stage of development, ice thickness, predominant floe sizes, ridging, topography, open water features, and stage of melting. Drift and dynamics of the pack ice expected over the 2-day period, as well as ice conditions in the offloading and lighterage areas, are also considered. Detail accorded to nearshore conditions depends on the magnitude and duration of the task, on quantity of drift and grounded ice present, and on force and variability of expected winds and tidal currents.

Forty-eight-hour forecasts may be based on meteorological predictions and services of the U.S. Naval Weather Service; the USAF Air Weather Service; the Weather Analysis Center, USWB; and the Meteorological Division, Department of Transport, Canada. Provision of meteorological services depends on the location of field ice forecasting activities. NAS Argentia, NAS Kodiak, Thule AFB, Eielson AFB, Frobisher Bay, and Goose Bay have all served as field stations; the appropriate meteorological services available at these stations have been utilized by the short-term ice forecasting activity.

1.25 SHIPBOARD FORECASTS

Another ice prediction service provided traditionally by NAVOCEANO has been the shipboard ice forecasting service. This service, providing larger tactical commands and operations with trained ice forecasters, furnished the command with an individual consultatory and interpretive service pertaining to ice predictions, conditions, and related oceanographic and meteorological phenomena. Shipboard ice forecasters utilize considerable knowledge of past operations and experience in study of ice distribution in the area of the particular operation to interpret and implement traditional ice predictions.

When the DEWLINE radar network was established, large operations were planned and effected in both the western and eastern areas of the North American Arctic. Task group commanders were faced with decisions involving extremely variable ice conditions along the northwest and northern coasts of Alaska and eastward through the enclosed straits, gulfs, and bays of the southwestern Canadian Archipelago. During some operations, more than 40 ships were engaged simultaneously in various convoy, independent transiting, and offloading operations between the Alaskan coast and eastern Shepherd Bay. With such diverse operational areas and ice conditions, it was not considered adequate to have the central forecasting agency in Washington, D.C., and field activities, such as those located at Kodiak and Fairbanks, Alaska, render complete services in support of such a large-scale operation. The solution to such a problem is provision of an individual who can interpret and make special predictions for specific unforeseeable problems that might arise.

Once established, the short-term forecasting activity should be geared to provide shipboard ice forecasting personnel in future logistical, arctic, surface marine operations.

Detailed description of shipboard ice prediction services rendered to operational commands is not possible. Thorough knowledge and cognizance of the procedures described below will prepare short-term ice forecasting facilities with the capability of meeting the unique individual needs of future large-scale logistical operations. Optimum shipboard capability depends on considerable advance planning and liaison between the short-term ice forecasting activity and the operational task group commands.

1.26 ICE ROUTINGS

The most recent development in ice intelligence methods is the ice routing service which provides the shipmaster with an analysis and interpretation of ice conditions in terms of an optimum track with minimum ice conditions. Therefore, it is important that the forecaster have a general knowledge of the capability of different type vessels in various ice concentrations and thicknesses for use when icebreaker assistance is not available. When icebreaker escort is provided in harbor approaches, ships are escorted from a rendezvous point to which they have been routed. Similar ice routing services are also provided when ships are ready for departure.

Ice routing of ships was initiated in August 1960 after the USNS YUKON (T-5 tanker) sustained heavy ice damage near Cape Dyer while enroute to Thule, although a wide ice-free lane was (and historically is) located further eastward. An oblique leg through moderate pack ice, a course which would not appear superior to the shipboard observer, can obviate a longer, more hazardous track through heavier ice concentrations. Thus, ice routings may or may not be easily determined, particularly when ice conditions are viewed from shipboard. Shipboard radar can give a fairly good indication of ice concentrations; however, an ice-free lead which ends in a cul-de-sac beyond the effective radar range may not coincide with the optimum route.

Ice routings are requested by shipmasters and appropriate MSTS commands or by port representatives of the latter. The majority of eastern Arctic ice routings in 1960, 1961, and 1962 (25, 116, and 102, respectively) were prepared at NAVOCEANO. Ideally, routings should be provided by the field ice forecasting facility, so that the latest synoptic ice data are available for use in initial forecasts.

In addition to ice concentrations, age, and floe size, a forecast indicates areas of significant iceberg concentration. As the ship proceeds along the route, daily situation reports (SITREPS) received at the field forecasting facility inform the forecaster of observed ice conditions. If ice conditions are not as expected after initial routing, the ship is advised if the change (ice increase) is minor. If conditions change significantly, a route change is recommended. If ice conditions warrant, the rendezvous point may be changed by the icebreaker command. Therefore, close coordination should be maintained between the ice forecaster and the icebreaker command.

At present, ice routes are furnished to individual ships steaming to or from arctic ports. It is quite possible that once very open pack or open water conditions prevail in the approaches to certain ports regular optimum lanes along which all ships could steam could be established. Routes could be revised at 2-week intervals or sooner if needed. A typical location is Baffin Bay where lanes probably could be established to and from Thule between the latter part of July and the latter part of October. Increased knowledge of the pattern of breakup will determine if such a program is feasible.

1.3 OPERATIONAL BACKGROUND KNOWLEDGE

Icebreaker convoys enroute in pack ice to remote arctic sites and landing beaches make the greatest use of short-term ice predictions. Knowledge of shipping schedules, tracks to be followed, and ship capabilities is mandatory to the short-term ice forecaster. With information such as speed of advance, optional routes, ice-breaking capabilities, and maneuverability, the ice forecaster can give maximum attention during analysis and final formulation of a forecast to ice and water features which are of greatest importance on the scheduled track.

Even icebreakers operating alone can receive extremely helpful information from short-range ice predictions. Icebreakers usually investigate ice conditions from the surface point of view. In such cases, knowledge of conditions beyond helicopter range is extremely useful for locating areas of relatively light ice and navigable leads. If the icebreaker is occupying oceanographic stations, the forecast should include information concerning relatively stable ice conditions and areas subject to lead closing, pressure ice, or other conditions which may affect operations.

Ships without icebreaker support may be more interested in exact locations of individual ice floes and pack ice of low concentration. Assurance that ice-free conditions or very light ice concentrations will persist is important to the unescorted ship.

The short-range ice forecaster also may be required to formulate emergency advisories and predictions in support of special air force requirements and should be ready to provide information for search and rescue activities and to intelligence agencies which may have special requirements.

The U.S. Army or engineering activities may occasionally request short-term ice predictions for scheduling loading or offloading operations. The forecaster should include important information, such as expected influx of ice into areas of interest, rapid increase or decrease in shore ice, and increased movements of ice which may make small boat operations dangerous or impossible.

Certain types of operations are not considered in this manual. Submarine operations have been supported on an experimental basis; however, prediction techniques have not been developed to the stage where procedures are standardized. In most cases, the very nature of underice operations makes short-term predictions on a daily basis impractical from communications and other operational viewpoints.

Prediction of the movement of individual arctic drift stations on day-to-day or week-to-week bases is not included in this manual. Such stations are usually situated well within the arctic pack ice, and methods of obtaining short-term ice information by aerial reconnaissance and other methods are not sufficiently advanced to warrant consideration of short-term predictions of ice station drift. In addition, navigational plotting by the drift stations has not been sufficiently accurate to verify and evaluate short-term movements of individual floes within the thicker and more heavily concentrated arctic pack ice.

Only a general introductory treatment of operational needs is given above and throughout the manual. The short-term ice forecaster is assumed to possess this background knowledge. Attendance at MSTS presailing briefings and active participation in MSTS arctic operations are to be encouraged to provide optimum background knowledge which will supplement suggested reading material.

A selected bibliography concerning background information on arctic operations is included in appendix A.

1.4 BACKGROUND KNOWLEDGE OF SEA ICE DISTRIBUTION

1.41 IMPORTANCE OF AERIAL RECONNAISSANCE

Prior to supporting an operation, the short-term ice forecaster must study intensively the sequential history of ice reconnaissance data in the area of interest. The best data for such study are contained in NAVOCEANO's annual ice observing and forecasting reports (SP-70). Pertinent data may also be found in H.O. Pub 705, "Oceanographic Atlas of the Polar Seas, Part 2, Arctic." Additional key references, including past annual reports, are given in appendix B.

1.42 SPECIAL SUPPLEMENT TO H.O. PUB 705

Unlike older atlases prepared by NAVOCEANO and foreign government activities, H.O. Pub 705 was prepared with aerial ice reconnaissance data collected between early 1952 and late 1956 and other data. However, this publication does not cover extremely important portions of the Bering Sea. Therefore, a special supplement for the Bering Sea is included in this manual as appendix C. Considerable amounts of aerial ice reconnaissance are frequently precluded from observation missions by adverse weather. In such cases, the short-term forecasting activity should use historical data on mean ice conditions. The Bering Sea supplement corrects the deficiencies of H.O. Pub 705 and improves short-term Alaskan forecasts when aerial reconnaissance is precluded.

1.43 ORGANIZATION OF AERIAL RECONNAISSANCE IN SUPPORT OF SHORT-TERM ICE FORECASTS

Availability of aerial ice reconnaissance data to ice forecasters and operational commands engaged in arctic activities has always been limited. Independent requirements for aerial ice reconnaissance are usually imposed on patrol squadrons and ice observation personnel by (1) long-term ice prediction activities, (2) fleet operational task groups and elements, and (3) the short-range ice prediction activity.

Certain basic requirements are mandatory for optimum operation of a short-term ice prediction activity. Comprehensive coverage, including at least three flights per week, should be available for areas for which ice predictions are to be formulated. Requirements of the short-term ice prediction activity should be flexible enough to include daily coverage when forecasting commitments are unusually heavy, when ice conditions are severe, or where sudden operational commitments require attention to new areas.

The short-term ice prediction activity should also be flexible enough to permit rescheduling flights over areas that have been precluded from observation by adverse weather. Finally, the short-term ice forecasting activity should insist upon coverage of not only the operating area but also of source areas of ice within approximately 60 miles of the operation area.

Experience indicates that close cooperation with aerial ice observers is of utmost importance to a field ice forecasting activity. It is suggested, therefore, that the prediction activity take full advantage of debriefing aerial ice observers. Preflight instruction of observational personnel by the ice forecaster is strongly advised. In this way, emphasis may be placed on special ice features.

The ice prediction activity should also maintain close relationship with the ice reconnaissance squadron. Experience indicates that flight personnel are extremely interested in conducting operations in accordance with prediction requirements. Periodic briefings and close contacts between operational commanders and key flight personnel are most helpful in furthering understanding and cooperation.

The field ice forecaster also benefits from occasional familiarization flights.

1.44 TYPES OF SEA ICE AND DEFINITIONS

Before considering procedures to be followed in formulating short-term ice predictions, we must briefly discuss certain large-scale characteristics of polar pack ice which require special procedures or methods of prediction. Decision of which technique should be stressed or used exclusively should be based on consideration of the North American Arctic where local sea ice predictions in support of surface shipping may be applied. Figure 2, showing the seasonal extent of sea ice, has been compiled mainly from aerial ice reconnaissance data acquired since 1952. In general, this manual applies to regions which became partially or entirely ice free at some time during the ice season (figure 2). Such areas are predominantly characterized by winter ice (ice less than one year in age) during the prenavigation or early navigational season. Owing to dynamic factors, this may not be true in every season. North and northwest of Alaska, in the upper regions of Baffin Bay, Foxe Basin, and in the Canadian Archipelago, some pack ice may persist through summer. Figure 2 identifies certain ice packs and ice streams with which the short-term ice forecaster must become familiar and to which he must sometimes apply special techniques and procedures. H.O. Pub 609 defines "ice pack" as "any large area of floating ice driven closely together". The term, "ice stream", not defined in the WMO and HO ice glossaries will also be employed in this manual. An "ice stream" is an ice pack area that is superimposed on any established permanent or gradient current. Figure 3 shows major ice packs and ice streams within the North American Arctic. These will be frequently referenced below.

A "winter pack" (figure 3) is defined as conglomerated pack ice located in regions where ice usually consists exclusively of winter ice. Winter packs exist in the Bering Sea, Baffin Bay, Foxe Basin, Hudson Bay, and the Gulf of St. Lawrence. Without exception, weak and variable cyclonic (counter-clockwise) circulation patterns are characteristic of these areas.

Although generally excluded from consideration in this manual, a portion of "polar pack" (figure 3) composed of ice streams north of the western Queen Elizabeth Islands and the Alaskan-Canadian mainland is important to short-range prediction in this area and will be treated accordingly. Owing to constant divergent and shearing motions, polar pack contains ice of all ages and consists predominantly of young polar pack (>1- to 2-year-old ice) and arctic pack (>2 years old). However, if the polar pack has been subjected to persistent offshore or divergent stresses, great quantities of winter ice or even younger ice types may predominate in a particular locale.

A "winter ice stream" is defined as a moving conglomerate of winter ice in a region dominated by permanent or gradient currents or by persistent winds. The best example of a winter ice stream is the

Baffin Island-Labrador ice stream (figure 3). Even in the absence of wind, pack ice designated as a winter ice stream moves with considerable speed (0.5-2.0 nautical miles/day). The effect of wind on winter ice streams will be discussed below. No consequential quantities of polar pack ice are advected into a winter ice stream.

A "polar ice stream" is predominantly arctic pack ice in a region containing a significant gradient current of at least 1 to 2 nautical miles per day. A polar ice stream is further identified by the predominant age or stage of development of the ice which characterizes it (>1 year's growth). A good example of a polar ice stream is the East Greenland drift stream. One of the primary sources of this ice stream is the area north of and between the New Siberian Islands and Wrangel Island. Ice also enters the East Greenland drift stream from an area near the geographic pole and continues through the Greenland Sea between Spitzbergen and Northeast Greenland. These merging trajectories continue without interruption during the season of maximum ice coverage to Kap Farvel where the stream turns, flows around the tip of Greenland, and continues northward to the vicinity of 62N. During the season of minimum ice coverage, the East Greenland drift stream may only extend to 65° or 70°N on the east coast of Greenland, depending upon the severity of the past ice season and on the circulation pattern of the preceding months.

An "archipelagic winter pack" exhibits qualities of quasi-stationary pack and fast ice. From time of formation to time of solid freezing, there is virtually no difference between a winter pack in waters such as Baffin Bay and the Bering Sea and that contained in shallow archipelagic waters. Upon attaining complete coverage, however, the archipelagic winter ice pack "sets", i.e., the ice becomes shorefast from coast to coast. Good examples of archipelagic winter ice pack are found in Dolphin and Union Strait, Coronation Gulf, Dease Strait, Queen Maud Gulf, and Shepherd Bay where ice formation begins in late September or early October, depending upon the severity of the past ice season. After mid-December or somewhat later when the ice sets, deformational features and water openings rarely occur.

An "archipelagic polar pack" occurs within archipelagic waters where, at some time during the year, considerable quantities of arctic pack ice are advected into the region, and in which complete melting or disappearance of most of the ice does not occur. The most interesting archipelagic polar packs are those in M'Clure Strait, Viscount Melville Sound, M'Clintock Channel, and Peary Channel. During summer, considerable quantities of polar pack are advected into this region. By late September or early October this ice generally becomes consolidated, and complete freezeup occurs in the open water areas between floes. Very few openings develop thereafter, because wind stress is not great enough to create open water features. The opposite is true for the vast majority of other ice types discussed above.

"Trapped ice" is defined as local ice conglomerate, usually between 100 and 10,000 square miles in area and characterized by a semi-enclosed coastal configuration. Furthermore, the ice tends to be contained in such areas. Examples of such trapped ice (figure 3) are found in the eastern half of the North American Arctic. The predominant wind in Ungava Bay has a northerly component; ice tends to drift eastward along the southern shore of Hudson Strait and into the Bay where the northerly winds retain it. Similar phenomena sometimes occur in St. James Bay, southeastern Hudson Bay, Committee Bay, and in the Hopedale area off the Labrador coast. Trapped ice occurs to a lesser extent in Kotzebue and Norton Sounds on the Alaskan coast. Areas of trapped ice require special consideration in predictin ice disintegration on a short-term basis.

"Occasional ice" occurs in all arctic regions and in subarctic areas as far south as Cheaspeake Bay where the water is shallow and brackish. Notable examples of areas where shipping is affected are southern Newfoundland, northern Nova Scotia, and Cook Inlet in Alaska. Freezeup in such regions is largely attributable to sudden periods of continuing, very low temperatures, and light wind conditions.

Prediction of the formation, growth, and disintegration of "fjord ice" (figure 3) is a localized problem confined to the Greenland coasts and to the northeastern arctic archipelagic regions.

"River ice" (figure 3) does not seriously affect logistical shipping operations in the eastern Arctic. River ice usually melts rather suddenly during the early spring thaw or freshet. Prediction services for river ice are provided in the Alaskan Arctic by the U. S. Weather Bureau. Experience indicates that rivers generally break up and discharge their ice considerably prior to the onset of shipping operations and prior to the disappearance of offshore and coastal fast ice. As a result, river ice is largely omitted from consideration in this manual.

1.5 BASIC OCEANOGRAPHIC KNOWLEDGE

1.51 GENERAL

An understanding of basic physical oceanography is required for making short-term ice predictions. A suggested bibliography for gaining the necessary oceanographic background is presented in appendix D. Only relationships between sea ice physics and physical oceanography which have direct application are described in detail in this report. Many theoretical or empirical relationships between oceanographic variables and processes and sea ice features to be predicted have been omitted owing to lack of continuing synoptic data concerning such relationships. For example, the growth rate of ice is dependent upon thermal structure of the water, rate of melt is closely related to salt content of the ice, and ice movement is related to the coefficient of friction between water and the underside of the ice. Daily synoptic data concerning these variables are not available to the short-term ice forecaster.

1.52 THEORIES OF ICE ACCRETION AND DISINTEGRATION

Certain empirical relationships developed at NAVOCEANO and suggested below for use by the short-term ice forecaster are based on theory. Figure 4 shows the relative tensile strength of sea ice as a function of its temperature in relationship to tensile strength of fresh-water ice. Sea ice physicists have noted that strength of sea ice is not a linear function. Tensile strength of sea ice relative to that of fresh-water ice increases abruptly at temperatures below approximately 23°F for salinities between 5 and 10 parts per thousand. In this range of salinities which is very characteristic of winter packs and winter ice streams, precipitation of sodium sulfate results in abrupt strength changes.

At temperatures above 23°F ice tends to weaken and, therefore, to melt rapidly. At temperatures below 23°F ice tends to harden and to grow rapidly without interruption. Furthermore, considerably before mean air temperature exceeds 32°F, melting begins in most arctic locales as a result of solar energy striking the steep slopes of pressure ridges. During fall, after the mean air temperature is less than 23°F, freezing is retarded by considerable agitation of open pack ice by wind waves and swell. For such reasons, empirical relationships concerning ice melt, formation, and growth processes were formulated on the basis of air temperature relationships using threshold values of 23° and 32°F. Although its usual salinity permits subarctic ice to melt at 28° or 29°F, the actual melting point of the pack ice snow cover is approximately 32°F.

The physics of sea ice, although not required in mechanical application of the empirical procedures described below, is a prerequisite to short-term ice forecasting. Therefore a basic bibliography on sea ice physics is included as appendix E.

1.53 ICE DRIFT THEORY

Considerable theoretical work concerning sea ice drift in arctic areas has been performed. In the United States this work has been highlighted by Sverdrup (1928), Rossby and Montgomery (1935), and by Reed and Campbell (1962) at the University of Washington. The best theoretical explanation for sea ice drift appears to be that of Shuleikin (1953) (figure 5).

In figure 5, "V" represents velocity of the wind. Ice has a tendency to move to the right of surface wind in the Northern Hemisphere with a speed varying from approximately 0.01 to 0.03 that of the wind. The force diagram for wind drift, when equilibrium conditions are reached, is represented on the lower left side of figure 5, where T_W represents the

The short-term ice forecaster is frequently able to determine why techniques applied, omitting oceanographic influences that are known to be important, do not fully verify. Close subjective study of sequential ice reconnaissance data enables the forecaster to take those oceanographic factors into account through continual modification and correction of the objective prediction techniques based solely on air temperatures and surface pressure patterns.

To summarize, short-term ice forecasts must make use of meteorological background in subjective extrapolation of certain meteorological influences which are known to affect predictions, but for which synoptic data are not available. Examples of such important influences on formation and growth of ice are: actual air temperature over the water and pack ice versus extrapolated temperatures from land station data, snow cover over the ice, cloud type and amounts, and varying heat flux over the ice. Wind waves and swells generated into the pack fracture the ice floes, contributing to their disintegration. Winds, meteorological tides, and storm surges affect ice movements. Since most of these processes must be extrapolated from coastal data, the background of the ice forecaster should include experience in weather forecasting and a thorough understanding of arctic climatology.

1.62 PREREQUISITE KNOWLEDGE OF EXTENDED WEATHER FORECASTING TECHNIQUES

Because of complete absence or paucity of arctic weather reporting stations and because 5-day weather predictions are utilized in preparing 5-day ice predictions, it is essential that the ice forecaster have a thorough knowledge of the techniques and services rendered by the Extended resistance force caused by water acting on the underside of the ice, and C represents Coriolis force which acts at right angles to the direction of ice drift. Coriolis and water resistance forces are balanced by wind stress, F_A, acting in the direction of the wind. Wind stress is assumed to be proportional to the square of the wind velocity. Furthermore, lack of data and basic theoretical knowledge requires assumed values for many physical constants employed in theoretical ice drift formulations. Owing to the unreality of the assumptions underlying theoretical formulations, empirical relationships are usually recommended for predicting sea ice drift.

1.6 BASIC METEOROLOGICAL KNOWLEDGE

1.61 IMPORTANCE AND LIMITATIONS OF METEOROLOGICAL DATA

Interaction of the atmosphere, the ice, and the hydrosphere are important after ice formation. From the background point of view, the basic physical principles of meteorology cannot be overemphasized in ice formation, growth, drift, deformation, and disintegration stages. It is unfortunate that weather station coverage is considerably more sparse in the Arctic than it is in temperate latitudes.

An attempt to correct this situation is progressing through development and use of automatic, drifting meteorological stations. Arctic meteorological facilities, considerably expanded since 1948, have provided the ice forecaster with limited synoptic meteorological information. If ice reconnaissance information is the foundation for short-term ice forecasting procedures, synoptic meteorological data rank close second in importance insofar as the promulgation of procedures is concerned. Therefore, the empirical techniques described below are based largely upon meteorological data.

Forecast Section of the U.S. Weather Bureau. In many cases, the output of the Extended Section is a basic input of short-term ice prediction procedures. Appendix F is a bibliography of essential references, including short-term, extended, and numerical weather prediction techniques which should improve the meteorological background of the short-term ice forecaster.

1.7 ADDITIONAL ENVIRONMENTAL KNOWLEDGE

In addition to physical oceanography, meteorology, and basic sea ice physics, a thorough understanding of bathymetric features in the forecast area is extremely important. Bathymetric features affect ice distribution and behavior directly and indirectly. By limiting mixing depths in shallow water regions, these features influence rates of ice formation, growth, and melt. Deep-drafted ice grounds and piles up in shallow areas.

Confluences and venturi effects influence currents and, therefore, control the amount of ice advected into a given area. Thus, a thorough understanding of geography is also invaluable. Orographic features can and do affect ice primarily through their influence on local meteorological conditions; at times these effects are direct. Foehn winds may cause local shore leads. Constrictions between northern Greenland and Ellesmere Island encourage formation of an ice bridge or an ice dam as ice drifts southward through the straits and channels. An area of relatively thin ice or a completely ice-free area occurs south of the ice bridge thus formed.

2. USE OF LONG-TERM ICE PREDICTIONS IN FORMULATING SHORT-TERM FORECASTS

2.1 USE OF LONG-RANGE ICE OUTLOOK

The short-term ice forecasting activity should maintain a continuing plot of all ice reconnaissance data pertaining to the area of interest. The initial chart in this sequence is generally obtained from any early ice survey conducted for the primary purpose of furnishing a comparative analytical tool for formulation of the ice outlook (see figure 1). The series of ice survey charts will serve as a basis for later short-term prediction of pack ice conditions. Operational areas where ice is heavy should be given special attention. When short-term ice reconnaissance requirements are formulated, sequential ice reconnaissance charts provide continuity for following the ice distribution pattern. As the situation develops, continuing coverage is provided by reconnaissance flights in areas that are extremely important as source regions for ice advection.

Ice drift computations, theoretical ice growth data, and other environmental aids contained in the outlook also facilitate the short-term ice forecaster's work.

The ice edge should be delineated during construction of prognostic ice charts, working tools for the formulation of short-term predictions. The ice edge for the particular ice season and area of interest is initially based on ice potential computations made from the early oceanographic survey and is usually contained in the ice outlook. The ice edge can sometimes be checked with bathythermograph casts made by icebreakers or other survey ships. The ice edge is generally marked by a transition zone between warm water and cold water areas; ice drifting across the line melts rapidly.

Objective data are not available for determining melt rates; however, table 1, compiled from data collected by the International Ice Patrol, gives an indication of how rapidly glacial ice melts when advected into waters with varying mean temperatures in the upper layers. Sea ice consisting of much less mass per unit of exposed surface can be expected to deteriorate more rapidly than glacial ice. The short-term ice forecaster should maintain a continuing plot of sea surface temperatures from all icebreakers and survey ships for use as a working tool in determining melt rates along the outer ice boundary.

Table 1

Melting Rate of Icebergs (from USCG - International Ice Patrol)

Water Temperature (°F)	Iceberg Melting Rate
28.5 - 32.0	Nearly zero
32.0 - 40.0	Immeasurable
40.0 - 45.0	Measurable but slight
45.0 - 50.0	Disintegration in 2-3 weeks
50.0 - 60.0	Disintegration in 1 1/2 - 2 weeks
> 60.0	Disintegration in 1 week or less

2.2 THIRTY-DAY ICE FORECASTS

Short-term ice forecasts should also utilize 30-day ice forecasts as shown on page 130, appendix G. Close study of these forecasts should include the following objectives:

(1) Search for modification and implementation of predictions contained in the long-range outlook.

(2) Examination for additional knowledge of ice features and movements in areas outside the immediate area of interest, especially for ice advection due to extraordinary short-range drift patterns.

(3) Utilization of forewarnings of heavy ice or important leads for planning future reconnaissance.

(4) Employment of information for scheduling reconnaissance of areas precluded from observation by adverse weather conditions.

(5) Additional data for maintenance of continuity and increased background knowledge of ice boundaries, ice distribution, and ice behavior in order to support possible operational requirements outside the immediate area of interest.

3. PREDICTING INITIAL FORMATION AND GROWTH OF SEA ICE

3.1 GENERAL PROCEDURE FOR COMPUTING ACCUMULATED FROST DEGREE DAYS

The physical processes of ice formation and growth are described in H.O. Pub 551, in H.O. technical reports 4 and 7, and in L'dy Arktiki (Zubov, 1945). These processes depend upon present and recent past stability and other characteristics of thermal structure, cloud cover, snowfall, wind and wave action, and air temperature. Accumulated frost degree days in a particular locale are especially useful in the autumn months in preparing short-term forecasts of ice formation, growth, and attainment of various concentrations.

A frost degree day is defined as a day with a mean temperature 1°F below an arbitrary base. For the purpose of this manual, two bases, 23°F and 32°F, have been chosen (see par. 1.52).

In order to facilitate computations, a further limitation is placed upon the definition of degree days. All accumulations and computations are based upon monthly temperature curves plotted on one-year-by-days graph paper (K & E 358-141L or suitable equivalent). Observed, predicted, or normal mean monthly temperatures, as available, are plotted on the ordinate against days on the abscissa for each coastal station and are extrapolated as required for offshore locations. Also plotted on a different scale on the ordinate are the accumulated monthly degree days, base 32°F, as approximated from table 2. For the purposes of this manual, monthly mean temperature

Table 2

CONVERSION TABLE: Monthly accumulated frost and warming degree days, base 32°F. from smoothed air temperature

MONTHLY MEAN SMOOTHED AIR TEMPERATURES(°F)		ACCUMULATION RATE DEGREE DAYS COL III	DEGREE DAYS IN MONTH			MONTHLY MEAN SMOOTHED AIR TEMPERATURES(°F)		ACCUMULATION RATE DEGREE DAYS COL III	DEGREE DAYS IN MONTH		
COL I*	COL II**		28	30	31	COL I.	COL II		28	30	31
31	33	1	28	30	31	-8	72	40	1120	1200	1240
30	34	2	56	60	62	-9	73	41	1148	1230	1271
29	35	3	84	90	93	-10	74	42	1176	1260	1302
28	36	4	112	120	124	-11	75	43	1204	1290	1333
27	37	5	140	150	155	-12	76	44	1232	1320	1364
26	38	6	168	180	186	-13	77	45	1260	1350	1395
25	39	7	196	210	217	-14	78	46	1288	1380	1426
24	40	8	224	240	248	-15	79	47	1316	1410	1457
23	41	9	252	270	279	-16	80	48	1344	1440	1488
22	42	10	280	300	310	-17	81	49	1372	1470	1519
21	43	11	308	330	341	-18	82	50	1400	1500	1550
20	44	12	336	360	372	-19	83	51	1428	1530	1581
19	45	13	364	390	403	-20	84	52	1456	1560	1612
18	46	14	392	420	434	-21	85	53	1484	1590	1643
17	47	15	420	450	465	-22	86	54	1512	1620	1674
16	48	16	448	480	496	-23	87	55	1540	1650	1705
15	49	17	476	510	527	-24	88	56	1568	1620	1736
14	50	18	504	540	558	-25	89	57	1596	1710	1767
13	51	19	532	570	589	-26	90	58	1624	1740	1798
12	52	20	560	600	620	-27	91	59	1652	1770	1829
11	53	21	588	630	651	-28	92	60	1680	1800	1860
10	54	22	616	660	682	-29	93	61	1708	1830	1891
9	55	23	644	690	713	-30	94	62	1736	1860	1982
8	56	24	672	720	744	-31	95	63	1764	1890	1953
7	57	25	700	750	775	-32	96	64	1792	1920	1984
6	58	26	728	780	806	-33	97	65	1820	1950	2015
5	59	27	756	810	837	-34		66	1848	1980	2046
4	60	28	784	840	868	-35		67	1876	2010	2077
3	61	29	812	870	899	-36		68	1904	2040	2108
2	62	30	840	900	930	-37		69	1932	2070	2139
1	63	31	868	930	961	-38		70	1960	2100	2170
0	64	32	896	960	992	-39		71	1988	2130	2201
-1	65	33	924	990	1023	-40		72	2016	2160	2232
-2	66	34	952	1020	1054	-41		73	2044	2190	2263
-3	67	35	980	1050	1085	-42		74	2072	2220	2294
-4	68	36	1008	1080	1116	-43		75	2100	2250	2325
-5	69	37	1036	1110	1147	-44		76	2128	2280	2356
-6	70	38	1064	1140	1178	-45		77	2156	2310	2387
-7	71	39	1092	1170	1209						

*Read Col I. for determining frost degree days, base 32°F.

**Read Col.II. for determining warming degree days base 32°F.

In months where the smooth air temperature curve crosses the 32°F ordinate (see par. 3.1), approximate frost or warming degree days in that month by multiplying number of days beyond the crossing point by degree days as determined graphically at the midpoint between end of the month and the time of crossing.

curves thus constructed will be referred to as smoothed air temperature curves. All empirical relationships pertaining to formation and growth of sea ice and involving frost degree days have been established in accordance with these definitions.

Cases are described below in which it is desirable to employ the lower base of 23°F for determining degree days of frost. In such cases computations are similar to those using a base of 32°F. Table 3 facilitates determination of frost degree days employing the 23°F base from smoothed air temperatures.

USE OF TABLE 2 --

Example 1: Assume the smoothed air temperature for December is -2°F. To determine frost degree days use col. 1; read down to -2. Since December has 31 days, degree days accumulated in December total 1,054.

Example 2: Assume the smoothed monthly mean observed temperature for August of 35°F and a predicted mean of 18°F for September. The smoothed air temperature curve determined by these two temperatures crosses the 32°F ordinate on 21 August; ten days with temperatures below 32°F occur in August. On 26 August (midpoint of 21-31 August) a smoothed air temperature of 29°F indicates an average accumulation rate of three frost degree days/day. Multiplying three by ten days yields 30 frost degree days accumulated in August.

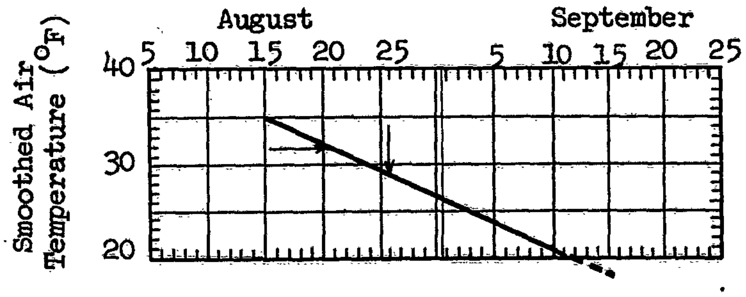

Table 3

CONVERSION TABLE: Monthly accumulated frost and warming degree days, base 23°F. from smoothed air temperature

MONTHLY MEAN SMOOTHED AIR TEMPERATURES(°F)		ACCUMULATION RATE DEGREE DAYS COL III	DEGREE DAYS IN MONTH			MONTHLY MEAN SMOOTHED AIR TEMPERATURES(°F)		ACCUMULATION RATE DEGREE DAYS COL III	DEGREE DAYS IN MONTH		
COL I*	COL II**		28	30	31	COL I.	COL II.		28	30	31
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20	26	3	84	90	93	-19	65	42	1176	1260	1302
19	27	4	112	120	124	-20	66	43	1204	1290	1333
18	28	5	140	150	155	-21	67	44	1232	1320	1364
17	29	6	168	180	186	-22	68	45	1260	1350	1395
16	30	7	196	210	217	-23	69	46	1288	1380	1426
15	31	8	224	240	248	-24	70	47	1316	1410	1457
14	32	9	252	270	279	-25	71	48	1344	1440	1488
13	33	10	280	300	310	-26	72	49	1372	1470	1519
12	34	11	308	330	341	-27	73	50	1400	1500	1550
11	35	12	336	360	372	-28	74	51	1428	1530	1581
10	36	13	362	390	403	-29	75	52	1456	1560	1612
9	37	14	392	420	434	-30	76	53	1484	1590	1643
8	38	15	420	450	465	-31	77	54	1512	1620	1674
7	39	16	448	480	496	-32	78	55	1540	1650	1705
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2	44	21	588	630	651	-37	83	60	1680	1800	1860
1	45	22	616	660	682	-38	84	61	1708	1830	1891
0	46	23	644	690	713	-39	85	62	1736	1860	1922
-1	47	24	672	720	744	-40	86	63	1764	1890	1953
-2	48	25	700	750	775	-41	87	64	1792	1920	1984
-3	49	26	728	780	806	-42	88	65	1820	1950	2015
-4	50	27	756	810	837	-43	89	66	1848	1980	2046
-5	51	28	784	840	868	-44	90	67	1876	2010	2077
-6	52	29	812	870	899	-45	91	68	1904	2040	2108
-7	53	30	840	900	930	-46	92	69	1932	2070	2139
-8	54	31	868	930	961	-47	93	70	1960	2100	2170
-9	55	32	896	960	992	-48	94	71	1988	2130	2201
-10	56	33	924	990	1023						
-11	57	34	952	1020	1054						
-12	58	35	980	1050	1085						
-13	59	36	1008	1080	116						
-14	60	37	1036	1110	1147						
-15	61	38	1064	1140	1178						
-16	62	39	1092	1170	1209						

*Read Col. I. for determining frost degree days, base 23°F.
**Read Col. II. for determining warming degree days, base 23°F.
In months where the smooth air temperature curve crosses the 23°F ordinate (see Par. 3.1), approximate frost or warming degree days in that month by multiplying number of days beyond the crossing point by degree days as determined graphically at the midpoint between end of the month and the time of crossing.

3.2 SELECTION OF STATIONS FOR DETERMINING INITIAL FORMATION OF OFFSHORE (PACK) ICE AND ATTAINMENT OF VARIOUS CONCENTRATIONS

Figure 6 shows days elapsed before initial formation of pack ice and locations where various concentrations were attained as related to accumulated frost degree days computed from smoothed air temperature using bases of 23° and 32°F. The first appearance of offshore ice and attainment of open and close pack ice was determined from aerial reconnaissance made within a 60-nautical-mile radius of the locations indicated in the figure.

Sufficient temperature data far removed from coastal stations could not be obtained for determining relationships based on the temperature regime in the environment of the pack ice further offshore. In order to determine a reliable means of relating ice formation and attainment of discrete concentrations to accumulated frost degree days, eight stations taken between 1953 and 1959, inclusive, were selected. Various types of environments were considered in selecting the eight stations. Offshore ice, removed from nearshore influences, was then assumed to behave in conformity to conditions which averaged these various influences.

Thule, Greenland, was selected as a station situated near offshore pack ice characterized by predominantly weak offshore winds and by a northerly subsurface warm current. Upernavik represents a coastal station characterized by predominantly weak offshore winds and by a strong surface current carrying warm waters in its surface and upper layers. Clyde represents a station situated close to a definite, cold, southward moving current where weak offshore winds prevail. Cape Lisburne represents an environment somewhat similar to Thule, in that a northerly subsurface warm current occurs in this locale. This location is unique in that, unlike conditions at any of the other three stations, occasional onshore drift can bring considerable masses of arctic pack or extremely ridged winter ice into the region. Kotzebue represents much more of a continental influence than do any of the other seven stations described above and below. Nome has somewhat less continental influence than Kotzebue, otherwise it is relatively unaffected by offshore currents and by unusual influx or efflux due to peculiarities of wind flow. The Nome and Kotzebue environments contain trapped ice, especially the latter, because containing currents oppose prevailing offshore winds (figure 3). Finally, Cape Romanzof and Nunivak Island represent a lower ice thickness regime. In addition to being selected for varying current and wind flow influences, the eight stations discussed above represent a good coverage of varying environments and total thickness of sea ice in areas throughout the eastern and western North American subarctic.

The period of study for the eight stations selected is shorter than desired for formulating prediction relationships. It is noteworthy that the 1953 to 1959 period contained the coldest year in Point Barrow's weather records. Air temperature data have been reported at Point Barrow on a daily basis since 1921. Furthermore, 6 of the last 40 maximum annual temperatures recorded at Point Barrow were within one-half degree of the maximum recorded at the selected stations during the study period.

3.3 PREDICTING THE INITIAL FORMATION OF ICE, NEGLECTING ICE ADVECTION:

3.31 SELECTED STATIONS WHERE PACK ICE PREDICTION IS MADE LESS THAN 60 NAUTICAL MILES OFFSHORE OR AT STATIONS WITH SIMILAR ENVIRONMENTAL REGIMES

Figure 6 emphasizes the considerable variance that occurred in days elapsed after frost degree days begin to accumulate and in the number of accumulated frost degree days attained using 23° and 32°F bases at the time ice initially forms. By studying the anticipated temperature range at any of the eight stations in figure 6, one can approximate days elapsed and frost degree days attained at time of initial ice formation. The forecaster's immediate problem is to consider whether or not ice will initially form near the eight stations or near stations which are known by comparative climatic and oceanographic study to be similar to the eight stations in environment. At any of the eight selected stations, he may be able to determine the general range of these two variables from the left half of figure 6 (32°F base). If the air temperature drops at a moderate rate, the forecaster may use accumulated degree days and/or days elapsed employing the 23°F base in a similar manner (see right half of figure 6) to predict the probability of the first appearance of the first pack ice with greater assurance of verification.

3.32 STATIONS WHERE PACK ICE PREDICTION IS MADE MORE THAN 60 NAUTICAL MILES OFFSHORE OR AT STATIONS WITH ENVIRONMENTAL REGIMES DISSIMILAR TO THOSE OF THE SELECTED STATIONS

Offshore pack ice is much less affected by strong currents and advection caused by wind stress than is nearshore ice. Therefore, the uppermost graph in figure 7, which averages the nearshore conditions of eight stations, should be useful in predicting the first appearance of pack ice on the basis of accumulated frost degree days, base 32°F, computed from smoothed temperatures extrapolated between land station data over the more central pack ice regions. The uppermost graph in figure 7 is suggested for use only if the air temperature forecast indicates slow decrease of temperatures during the prediction period and for predictions more than 60 nautical miles offshore. The curve on the extreme **left in figure** 8 is recommended as an alternative to figure 7 to indicate whether ice is likely to form on the basis of the number of days elapsed after the extrapolated smoothed temperature has reached or will reach 32°F as determined at the beginning and the end of the prediction period.

The uppermost graph in figure 9 and figure 10 (23°F base) are to be used in a similar manner for predicting initial appearance of ice on the basis of the predicted smoothed air temperature curve when temperatures are expected to decrease to values below 23°F.

3.4 PREDICTION OF THE ATTAINMENT OF OPEN PACK ICE AND CLOSE PACK ICE, NEGLECTING ADVECTION

3.41 WITHIN 60 NAUTICAL MILES OF STATION SELECTED OR AT STATIONS WITH SIMILAR ENVIRONMENT

Unless specified otherwise, WMO nomenclature is employed throughout this manual. Table 4 lists five characteristic NAVOCEANO-WMO stages of development or age of pack ice for purposes of reviewing the concentration categories.

Table 4

NAVOCEANO-WMO Concentration Categories of Pack Ice

Tenths Coverage	Categorical Term
0	Ice free
1 - 3	Very open pack ice
4 - 6	Open pack ice
7 - 9	Close pack ice
Essentially 10	Very close pack ice

Figure 11 shows the days elapsed after the smoothed air temperature curve crossed the 23° and 32°F bases and accumulated degree days for the two bases up to the time that the concentration became open pack ice. The extreme variance of the data using the 32°F base suggests advective influences so great that little is added to forecasting skill for predicting open pack concentration on the basis of days elapsed or degree-day accumulations. On the other hand, days elapsed and degree-days are computed with the 23°F base. Therefore, the 23°F base should be used exclusively for growth predictions of open pack ice. Advective considerations will be discussed below in predicting open pack and close pack coverage. Prior to this step, however, an objective determination of concentration expected on the basis of accumulated degree days should be made utilizing the 23°F base portions of figure 11 and 12.

3.42 WHERE PACK ICE IS MORE THAN 60 MILES OFFSHORE AND/OR AT STATIONS WITH ENVIRONMENTS DISSIMILAR TO THOSE OF THE SELECTED STATIONS

The following procedures are suggested for use in cases where it is desirable to predict initial attainment of pack ice greater than 4/10 concentration at locales more than 60 nautical miles offshore and/or near selected coastal stations.

(1) Use smoothed air temperatures from coastal stations to extrapolate between these coastal stations when estimating mean monthly temperature for any offshore pack ice region if the predicted temperature becomes less than 23°F.

(2) Estimate the time at which the extrapolated temperature curve will fall below 23°F.

(3) In the same manner, predict the extrapolated air temperature as required for ensuing months.

(4) Plot accumulated frost degree days on one-year-by-days paper and determine the degree days accumulated at the beginning and at the end of the forecast period.

(5) Use figure 9 with this information to determine whether open or close pack ice may be predicted.

In a similar manner, an independent prediction can be made of days elapsed after the smoothed air temperature reached 23°F. The number of days which occur at the beginning of the forecast period may thus be obtained; similarly, the number of days elapsed at the end of the forecast period may be determined. Use figure 10 with this information to determine the probability of occurrence of open or close ice.

3.5 PREDICTING THE GROWTH RATE OF ICE AFTER INITIAL FORMATION

A well-established empirical relationship* permits prediction of ice growth after initial formation anywhere in the arctic pack on the basis of frost degree days, base 32°F. This relationship is shown in figures 13 and 14. If an icebreaker traveling in the vicinity of Cape Lisburne should report 10 percent open water and 90 percent thick winter ice having an average thickness of approximately 4 feet, the procedure of extrapolating coastal land station temperature data and converting these into degree days, base 32°F, will permit the short-term ice forecaster to predict (1) the growth attained in the open water and (2) the increment of thickness that will be added to the winter ice.

Forecasts of increasing thickness can also be made on the basis of ages reported by aircraft. Table 5 equates the stage of development (age) with ice thickness according to newly adapted WMO terminology.

For example, assume no advection and 5/10 medium winter ice at the start of a 5-day forecast period. If mean air temperature over the next 5 days is 0°F, then the thickness of the medium winter ice should increase approximately 3 inches during the 5-day period (figure 13-I_o = 6 to 12", 160 DD).

* $\sum \theta_F = 1.43 I^2 + 28.6 I$

Furthermore, although the uppermost curves in figures 13 and 14 are not always satisfactory for initial stages of growth under ordinary circumstances, they are satisfactory for predicting even small thickness accumulations resulting from young ice growth in pack ice consisting of older ice types with concentrations exceeding 5/10 or 6/10. An example of predicting such young ice growth is given on page 131, appendix G.

Table 5

Usual Characteristic Stages of Development Reported in NAVOCEANO-WMO Terminology

Term	Usual Age	Usual Thickness
New ice	Days to Weeks	<2 inches
Young ice	Days to Weeks	2 - 6 inches
Medium winter	Days to Weeks	6 - 12 inches
Thick winter	Weeks to Months	>12 inches
Young polar ice	> 1 to 2 years	<7 feet
Arctic pack	> 2 years	>8 feet

In addition to use in nearshore areas, this relationship has also proved reliable in winter ice. Frost degree days computed from ARLIS II data for the 1962-63 season indicated a 67-inch thickness in one year ice adjacent to the station; verification showed 65 inches.

Frequently the ice forecaster without benefit of ship ice thickness reports will be required to make initial determinations of thickness to be encountered by icebreakers and ships on the basis of extrapolated temperature and frost-degree-day accumulation over the entire past ice growth season. Such hypothetical thickness curves are included in figure 1 for four stations in the western Arctic.

In conclusion, ice formation, attainment of discrete concentrations, and growth predictions should be predicted first and independently of advective influences. Advection should be considered according to the method outlined in chapter 4 below. The two results must then be subjectively integrated.

4. SHORT-TERM FORECASTING OF SEA ICE DRIFT AND DEFORMATION

4.1 RE-EMPHASIS OF IMPORTANCE

Polar and winter packs and ice streams normally exhibit relatively small changes in concentration of new ice (prediction described in chapter 3) and little melt (chapter 5) within the period of a short-term ice forecast. Short-term changes in ice concentration, deformational features, pressure characteristics of pack ice, and widening or narrowing of leads are the result of ice drift. The most time-consuming and laborious computations are devoted to determination of rarefaction and compaction influences. The influences cause changes in concentration, in pressure within the ice, in amount of ridging, and other deformational features. A procedure is formulated below for continual study and prediction of pack ice motions with a minimum of computations. (An example illustrating the procedures outlined in paragraphs 4.2 through 4.62 is given in appendix G).

4.2 GRID AND PROCEDURE FOR DETERMINING ICE DRIFT

4.21 BASIC VECTOR EQUATION FOR ICE DRIFT

The suggested procedure makes use of the simplified expression:

$$\vec{V}_i = \vec{V}_w + \vec{V}_c$$

where $\vec{V}_i$ represents total ice drift
$\vec{V}_w$ represents the wind drift component of total drift, and
$\vec{V}_c$ represents the current component of ice drift

The equation states simply that total ice drift is equal to the vector sum of wind drift effect and permanent or gradient current effect.

4.22 STEPS FOR DETERMINING ICE DRIFT IN 48-HOUR FORECASTS

1. Maintain a plot of the most recent ice reconnaissance data and interpolate holidays by means of historical ice information derived from H.O. Pub 705, Part 2, and by the extension of this publication contained in appendix C.

2. Employ a tabular ice drift computation sheet such as the one below and a grid covering the short-term ice forecast area similar to that shown in figure 15.

ICE DRIFT COMPUTATION SHEET

FORECAST PERIOD

FROM____________(Time-Date) TO______________(Time-Date)

Col (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Point No.	Geostrophic Flow		Wind Drift (Speed) of ice (nm/day)	Current		Sea Ice Drift	
	Direction (°T) (toward)	Wind Speed (knots)		Direction (°T) (toward)	Speed (nm/day)	Direction (°T) (toward)	Distance (nm)
1							
2							
etc.							
Extra Points							
A							
B							
etc.							

3. Draw a mean pressure chart over the portion of the grid which covers the forecast area. Make sure that the analyzed portion of the grid includes source regions of ice that may be advected into the area by winds and currents. The mean prognostic pressure chart for a 48-hour ice forecast can be completed by averaging pressure values from the latest observed surface pattern contained in the 30-hour prognostic surface weather chart or the 48-hour prognostic pressure pattern if the latter is available.

4. Contour the mean prognostic pressure chart to determine geostrophic flow.

5. Complete the ice drift computation sheet. At each point required for the forecast, enter the vectors of geostrophic flow in columns 2 and 3. By superimposing the grid shown in figure 15 on the latest ice reconnaissance chart, determine appropriate response and conversion factors from table 6. This will be accomplished by use of the most frequently reported ridging coefficient and the most frequently reported concentration in the area of prediction.

Table 6

Response and Conversion Factor (Percent) for Obtaining Wind Drift of Sea Ice (Nautical Miles Per Day) From Geostrophic Wind Speed for Varying Concentration and Ridging (Tenths)

TOTAL CONCENTRATION OF ICE (TENTHS)

EXTENT OF RIDGING AND HUMMOCKING (TENTHS)	0-1	2	3	4	5	6	7	8	9-10
0	12	10	10	7	7	5	5	5	2
1	29	24	22	19	17	14	12	10	7
2	38	36	34	24	22	19	17	14	10
3	48	43	38	34	29	26	22	17	14
4	55	55	50	43	38	34	29	24	19
5	72	62	58	53	43	38	31	26	22
6	86	79	72	65	58	50	43	34	26
>6	98	89	82	72	62	55	48	38	29

6. Multiply the geostrophic wind speed (column 3) by the appropriate response and conversion factor from table 6 and enter the result in column 4 of the ice drift computation sheet.

7. Obtain the permanent or gradient current vectors (nautical miles per day) for the points required in the short-term forecast from table 7 and enter in the appropriate columns (5 and 6) of the ice drift computation sheet.

Table 7

Recommended Currents for Use With Grid Model Shown in Figure 15

GRID POINT NO.	CURRENT	
	DIRECTION	SPEED (nm/day)
1	200	.5
2	225	.4
3	215	.5
4	230	.4
5	320	1.2
6	325	1.6
7	260	.6
8	280	.4
9	120	.6
10	335	1.1
11	310	1.1
12	300	.6
13	295	.4
14	130	.5
15 & 16	355	.9
17	60	.5
18	40	.8
19	110	.5
20	250	.9
21 & 22	340	1.0
23	-	0
24	90	1.3
25	20	.8
26 & 27	100	.4
28	70	.8
29	30	.8
30	230	.8

8. On graph paper (H.O. 2665-20 recommended), add the wind drift vector (columns 2 and 4) to the current vector (columns 5 and 6). The magnitude of the vector sum is the average ice speed in nautical miles per day.

9. The direction of the mean vector obtained in step 8 which is the direction of the total ice drift is entered in column 7.

10. For completion of the ice drift computation sheet the average ice speed must be multiplied by 2 days and entered in column 8.

The procedure described above provides the theoretical drift field, occurring in the forecast period, consisting of the points in the grid for which entries have been made in the ice drift computation sheet.

4.3 FIVE-DAY ICE FORECASTS

The same general procedures described in paragraph 4.22 are used in formulating a 5-day ice forecast. The mean pressure field over the 5-day prediction period, however, is provided by the Extended Forecast Section, U. S. Weather Bureau. At field locations such as Kodiak and Argentia, special arrangements with Fleet Weather Central, Washington, D.C., may be necessary for direct transmission of 5-day mean predicted pressure charts. The pressure chart can be transmitted by facsimile or numerical code ("canned") processes. When the 5-day prediction period is characterized by rapidly changing conditions, such as a rapidly moving cold front, the prediction period may have to be divided into two or more parts. In such cases, the prediction procedure remains the same. Caution must be exercised, however, to multiply the average ice drift speed by the appropriate number of days for entry in column 8 of the ice drift computation sheet.

4.4 PREDICTING CHANGE IN CONCENTRATION

Prediction of changes in concentration over a given period is expedited by means of an ice drift computation sheet. For example, in supporting an icebreaker through the rectangle described by points 20, 21, 24, and 25 in figure 15 in March, the prediction of change in concentration is simply a matter of superimposing the appropriate grid rectangle upon the latest ice reconnaissance chart. The change in concentration that takes place over the prediction period may be determined by computing the change in dimensions of the rectangle with a planimeter or by graphic methods. The equation for the area of a quadrilateral is used in the latter method:

$$A = 1/2\ ab \sin \theta$$

where A = area
a = a diagonal
b = the other diagonal, and
θ = either angle between the two diagonals.

The original concentrations are then multiplied by the ratio of the original area to the newly determined area to determine the predicted concentrations.

4.5 PREDICTING CHANGE IN ICE BOUNDARIES

Movement of the outer ice boundary occurring within the area of the short-term prediction is determined by a method similar to that described for the formulation of the ice drift model. Attention is again directed to the ice drift computation sheet (par. 4.22), in which several additional points chosen along the ice boundary may be labeled A, B, etc. in column 1. These points should be located within approximately 30 to 60 miles of each other, depending on the shape of the boundary. Prognostic geostrophic winds and permanent current components of the vectorial ice drift are computed and entered in the appropriate columns (2 thru 6) of the ice drift computation sheet. Total ice drift can then be determined and entered in columns 7 and 8. The ice boundaries can be moved accordingly.

4.6 PREDICTING DEFORMATIONAL CHARACTERISTICS

4.61 RIDGING AND HUMMOCKING AS INDICATED FROM THE METHOD OF PREDICTING CHANGE IN CONCENTRATION

The concentration in any particular rectangle may be determined from the method described in paragraph 4.4. If the concentration is initially close and is expected to increase rather abruptly to a value in excess of 8/10 or 9/10 or if the concentration is initially 9/10 to 10/10 and is expected to increase to 10/10 or greater, one would definitely include expectation of considerable ice pressure and/or marked increase of ridge formation in the short-term forecast.

4.62 PREDICTING DEFORMATION RESULTING FROM SHEAR

A prognostic ice drift vector chart is strongly recommended for the period of every short-term forecast. Utilize a suitable chart of the same scale (1:10 million) to serve as the mean pressure chart (par. 4.22). After the chart has been plotted, lines of equal ice drift may be contoured at intervals of one nautical mile per day. In regions where the gradients are tight and where concentrations exceed 8/10, some shear deformation should occur as a result of collisions among floes.

Extensive ridging may be expected when a considerable amount of young ice (10 to 20 percent) is present in total concentrations that are very close and where the predominant type is thick winter or polar ice. Such information should also be included in the short-term prediction.

If the predominant type is young ice with total concentration of 7/10 or greater, strong shear should result in considerable rafting of floes. This information should also be included in the short-term prediction.

4.63 ESTIMATING RIDGE THICKNESS FROM AERIAL RECONNAISSANCE DATA

For regions of arctic pack ice or heavily ridged winter ice, a useful empirical relationship between the number of ridges and the maximum thickness of the ridged ice has been formulated. This relationship is graphically shown in figure 16 for use by the short-term ice prediction activity. Some aerial ice reconnaissance reports contain ridge counts based on brief sample counts which are mathematically converted into numbers of ridges per 30 nautical miles. The ice forecaster can convert ridge counts into predictions of maximum ridge thickness. A ridge count of 300 per 30 nautical miles, for example, would indicate a maximum ridge thickness of 70 feet. If convergence is predicted according to the methods of paragraphs 4.61 and 4.62 over that area, a maximum ridge thickness greater than 70 feet would be predicted

4.64 ESTIMATING THE MEAN THICKNESS OF ARCTIC PACK ICE ON THE BASIS OF RIDGE COUNTS

Another useful relationship derived from underice data is expressed in figure 16. This relationship enables the short-term ice forecaster to approximate the mean thickness of arctic pack ice on the basis of ridge counts. For example, a ridge count of 320 per 30 nautical miles indicates a mean ice thickness of 11 feet. This information should be included in the short-term prediction.

The relationship of ice thickness to deformational processes has been recognized by Soviet and U.S. scientists. Pressure alters the crystal structure of sea ice and often causes rafting and ridging. After a considerable time, isostatic processes tend to smooth the ridges. Ice with such a history, however, would tend to be considerably thicker than expected on the basis of ordinary ice growth resulting from heat exchange among air, ice, and water.

4.7 SUBJECTIVE QUALIFICATIONS OF THE WIND DRIFT VECTOR

As previously stated, experience indicates that ice drifts along the isobars representing geostrophic wind flow, and that ice drift depends upon surface roughness and concentration as given in table 6, which shows that ice drifts more slowly relative to the wind as concentration increases. As ridging and hummocking increase, the speed of the ice relative to the wind stress increases. As illustrated by figures E-1, E-2, and E-3, the deviation angle should theoretically decrease and ice drift should increase as wind speed increases. Furthermore, for increasing thicknesses of ice, the deviation angle increases and ice speed decreases. Finally, the deviation angle tends to decrease at lower latitudes, and ice drift tends to increase relative to the wind.

A series of additional empirical rules, offered for use by the ice forecaster with increasing experience in a particular area, are based upon empirical data and theory.

(1) When the drift component perpendicular to and towards the coast is strong, the deviation angle tends to be more to the left of the isobaric flow and parallel to the coast; in addition, the drift tends to follow the direction of littoral currents. The direction of the predominant component of littoral currents is usually north along the eastern shores of seas or enclosed bays and south along the western shores of seas and enclosed bays or straits.

(2) When the drift component perpendicular to and away from the coast is strong, ice again tends to drift more to the left of the isobars; response of the ice to the geostrophic wind is decreased; and the current tends to become less effective.

(3) When ice moves toward areas of greater concentrations, the deviation angle tends to increase and the ice drifts more to the right of the isobar; response of ice to geostrophic wind tends to decrease.

(4) When ice moves towards areas of lesser concentrations, the variation in deviation angle is complex; but response of ice to the geostrophic wind tends to increase.

4.8 CURVES FOR DEVIATION ANGLE AND ICE DRIFT FOR VERY CLOSE ICE CONDITIONS

It is unusual for very close ice to be predominant over a wide area. Statements in this paragraph apply only to very close ice which is composed of more than 95 percent thick winter and polar ice. If this rather unusual ice condition exists, curves contained in appendix E may be applied—figure E-1 to regions located at approximately 54°N, figure E-2 at about 68.30°N, and figure E-3 above 76°N. Latitudinal effects between 76°N and the pole are small. Caution should be exercised in applying these curves, because they are expressed in terms of surface wind rather than geostrophic wind, as was the case in the methods recommended above for forecasting ice drift. The procedures are otherwise identical, and an ice drift computation sheet (par. 4.22) may be applied.

4.9 PREDICTING TIDAL INFLUX AND EFFLUX OF ICE FOR LIGHTERAGE AND OFFLOADING OPERATIONS

Figure 17 illustrates extreme variations of tidal range that may be characteristic of prediction areas. Zubov (1945) discusses tides and their effects on sea ice; this work is recommended reading for short-term forecasters, expecially those supporting operations which use small boats in landing arctic supplies directly on unprepared beaches and in regions where strong tidal currents may exist. The strength of littoral currents is not dependent on tidal range alone. In fact, stations which have a very mild tidal range, such as Pt. Barrow, may have considerable tidal currents which affect offloading and lighterage operations. The short-term forecaster receives situation reports describing behavior of ice in lighterage and anchorage areas. The ice generally drifts into the area on the floodtide and drifts out on the ebbtide. The main Fox site at Hall Lake, some distance to the south of Igloolik, is an example of a locale where offloading operations are considerably affected by scattered ice moving in and out of the operational area. Local bathymetric and orographic effects will cause some modification in these generalized statements.

General improvement or worsening of the tidal ice problem can be predicted. The short-term ice forecaster should prepare a daily plot of predicted times and heights of tides for periods of extensive offloading operations.

Figure 18 emphasizes daily and other short-term tidal height magnitudes. Between 11 and 14 September 1956 the forecaster at Igloolik received data reflecting a tidal ice problem. A study of Igloolik tides (figure 18) would indicate intensification of influx-efflux conditions in the following 5-day period. Conversely, if a tidal ice problem had been observed between 7 and 10 September, improvement would be indicated in the following 5-day period. The source of ice is assumed to remain relatively constant; that is, no advection changes, no marked increase in concentration owing to new formation, and no decrease in concentration occur as a result of melting. Predictions are not as accurate at stations where tidal oscillations are less intense; for example, Point Barrow. Nevertheless, the same procedure may be applied after observing the influx-efflux problem over a short period.

5. PREDICTING DRIFT OF ICEBERGS

The short-term forecaster may be required to predict movements of individual icebergs affecting operations in a particular locale. Icebergs have much greater draft than ordinary sea ice. Consideration of currents, therefore, must include currents in the deeper strata.

Budinger (1960) made a very significant study of iceberg drift. Budinger obtained the following empirical relationship by studying several bergs in the Grand Banks-Labrador Sea region:

$$V_B = K W_s$$

where V_B is the drift speed of icebergs due to wind and wind-driven current (nm/da
K is a constant depending upon the shape* of the berg and its immersion ratio (amount above water/amount below water), and
W_s is the surface wind speed. (knots)

Although the validity of currents measured during these experiments was not established to the satisfaction of the investigator, the wind-driven current effect has been integrated in the empirical relationship. The equation gives the speed of the iceberg movement along a track 50 degrees to the right of the downwind direction.

In addition to applying this relationship in eastern Arctic areas, the short-term forecaster may experimentally use it in the region northwest of Alaska in predicting the movement of fragments of shelf ice, such as ice islands ARLIS II and T-3. The difficulty in applying this relationship in the Alaskan area is that vertical density distribution and current velocity gradients may vary considerably. Therefore, caution should be used in applying the relationship in regions other than the southward moving winter ice stream in the eastern Arctic.

6. PREDICTING DISINTEGRATION OF SEA ICE

6.1 GENERAL

During the early navigation season which generally begins with

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*Values of K are 0.7 for blocky or massive bergs, 1.0 for pyramid or pinnacled bergs, and 1.4 for drydock, winged, or sailor bergs.

ice disintegration, short-term predictions of ice disintegration are relatively unimportant. At such times a terse phrase, "no appreciable melt," will suffice in the body of the ice prediction. During the period when ice is disintegrating rapidly—generally at time of peak surface ship operations—the method of predicting ice disintegration discussed below may be required frequently. On such occasions, the short-term ice forecaster should include statements concerning the decrease in concentration expected as a result of melting and the expected decrease in thickness of various ages, types, or stages of ice.

In spite of the fact that shipping operations are greater during the time when ice is melting rapidly, little scientific work has been performed on methods of predicting the quantity of sea ice disintegration in terms of known and/or predictable parameters. As a result, NAVOCEANO is engaged in considerable original research and formulation in order to correct this situation.

Referring to figure 3, winter packs and winter ice streams melt completely during the late navigational or summer season. The ability to predict melt in polar pack and polar ice streams is extremely important because these types contain considerable quantities of young and medium winter ice in all seasons as a result of divergence and shearing motions within the pack ice. The polar pack frequently is reported to contain 10 or 20 percent of medium winter ice (up to 12 inches thick). The capability of predicting quantitatively when the medium winter ice will melt is of considerable use to the ice forecaster.

Warm spells also occur suddenly in the regions of archipelagic packs from time to time. At such times the ability to predict the quantities of the younger ice types that will be melted becomes especially significant. The importance of drift has been emphasized in the foregoing chapter. Insofar as both archipelagic winter and polar packs are concerned, the ability to predict disintegration is especially important because of the characteristic of being motionless during a considerable portion of the year. For example, after the ice "sets" in Dolphin and Union Strait, no appreciable drift occurs. In the ensuing season, the decrease in concentration in such packs and their melt rates are exclusively affected by thermal interchange between water, ice, and atmosphere.

Trapped ice is also profoundly affected by thermal interchange. In Kotzebue and Norton Sounds, for example, the combination of current which tends to move the ice into these sounds and predominating wind drift which tends to move the ice out counteract one another. Melt thus becomes the primary determinant of decrease in concentration.

Areas of occasional ice, such as Cook Inlet, occur only after a sudden and prolonged severe cold spell. Melt occurs rapidly when the temperature increases.

6.2 WARMING DEGREE DAYS AND THEIR ACCUMULATION

A warming degree day is defined as a mean daily temperature of 1°F above an arbitrary base. For the purposes of this manual, the bases of 23° and 32°F have been chosen. The general reasons offered for the selection of these bases are discussed under paragraph 1.52. As in the case for frost degree days, all accumulations and computations of warming degree days are based on a monthly temperature curve drawn on a year-by-days basis. Furthermore, all empirical relationships pertaining to melt and disintegration have been related to warming degree days based on mean monthly temperatures.

Reference is directed below to tables 2 and 3 which permit quick estimation of the number of warming degree days accumulated in any particular month employing bases of 23° and 32°F.

6.3 PREDICTING THE TOTAL MELT OF SEA ICE AT A LAND STATION FROM WARMING DEGREE DAYS

Biello (1960) studied the sequential ice thickness measurements obtained from the Canadian-U.S-Danish arctic stations in North America. He related thickness decreases to the number of accumulated warming degree days. His computations were in the metric system and employed a different base from that suggested in this manual. In addition, Biello employed actual mean daily temperatures for his computations rather than daily temperatures based on mean monthly temperatures. His relationship has been converted to warming degree days on a base of 32°F in figure 19. Converting Biello's relationship reduced the correlation coefficient from .87 to .81. For simplification in the number of required procedures, figure 19 is recommended for predicting the total melt of landfast sea ice at stations within the forecast areas.

6.4 PREDICTING THE TOTAL MELT OF WINTER PACK

For a method of predicting the melting time of offshore pack ice, rather than local fast ice, the same series of widely divergent stations discussed in paragraph 3.2 were selected. NAVOCEANO aerial reconnaissance data obtained from 1953 through 1959 were employed to obtain the time of ice melt in offshore regions near various stations.

Beginning of melt, for the purposes of the study, was taken to be the time when the smoothed monthly temperature curve for the appropriate station rose above 32°F. The warming degree days for those stations and times were then determined and correlated with the hypothetical ice thickness computed for each of the appropriate stations for which adequate data were collected during the 1953-1959 period. The resulting relationship is shown in figure 20. Application of the Zubov relationship shown in figures 13 and 14 in the appropriate ice growth season served as the basis for determining maximum ice thickness. The curve in figure 20 is recommended for determining whether ice will completely melt over the period of the short-term prediction and for determining whether younger ice types (table 5) will completely melt during the forecast period.

6.5 PREDICTING THE DECREASE IN OFFSHORE CONCENTRATION RESULTING FROM ICE MELT

6.51 DAYS REQUIRED TO ATTAIN VARIOUS CONCENTRATIONS AFTER SMOOTHED AIR TEMPERATURE RISES ABOVE 23°F

It should be re-emphasized (par. 1.52) that decrease in the concentration of winter packs and drift streams is primarily attributable to thermal exchange between water, ice, and atmosphere. Since the ice deteriorates at a markedly greater rate after the ice temperature attains 23°F, this temperature was selected as the basis for formulating the prediction technique for ice disintegration.

Figure 21 illustrates the number of days that elapse after the smoothed air temperature reaches 23°F and the relationship of this period to the decrease in offshore ice concentration from very close pack ice (greater than 0.95) to close pack ice (0.7-0.9). As expected, a weak correlation coefficient of 0.5 was obtained (figure 21). During periods of high concentration and during initial stages of ice melt, advection plays the greatest part in determining concentration changes during the early melt season. Nevertheless, the method for advection of ice described in chapter 3 contributes additional skill to short-term ice forecasts. Application of the curve in figure 20 is also feasible for areas where archipelagic packs are characteristic (figure 3), in areas of trapped ice, or near any of the stations listed in figure 21.

Similarly, for any of the eight stations included in the point location codes, figures 22, 23, and 24 show the number of days required after the smoothed air temperature reaches 23°F for offshore concentrations to decrease to open pack ice, very open pack ice, or to completely disappear. It should be noted that the correlation coefficients improve steadily as the number of days required after the smoothed air temperature reaches 23°F is related to the lower concentration categories. This increase in reliability of employing days after temperature reaches 23°F indicates the importance of melt processes in lowering concentrations as the season progresses.

Figures 21 through 24 should be used for nearshore areas at the stations enumerated on each of the graphics. The four figures may also be applied in short-term prediction for locales with environmental backgrounds similar to any of the enumerated stations.

The relationships for days elapsed as a function of initial ice thickness permits determination of a family of curves showing the average number of days after the smoothed air temperature exceeds 23°F when offshore ice concentration may be expected to decrease. Figure 25 depicts this family of curves for forecasting ice concentrations more than 60 nautical miles offshore. These curves are to be applied on the basis of extrapolated smoothed air temperatures from coastal stations for the open pack.

Figure 25 may also be applied to estimate the number of days required to predict ice concentrations during the melt season at points not similar to the stations described in figures 21 through 24. For example, assume a report of ice 5 feet thick at an offshore location where 40 days have elapsed since the extrapolated air temperature reached 23°F. At the end of a 5-day forecast period, the concentration should be 0.5, representing a total decrease of 0.1.

6.52 PREDICTING THE DISINTEGRATION RATE ON THE BASIS OF ACCUMULATED WARMING DEGREE DAYS, BASE 23°F

Figures 26 through 29 are scatter diagrams similar to those discussed in paragraph 5.51 depicting the initial pack ice thickness and accumulated warming degree days, base 23°F. These diagrams show the warming degree days required after the smoothed air temperature rises above 23°F for very close pack to change to, (1) close pack (figure 26), (2) open pack (figure 27), (3) very open pack (figure 28), or (4) to completely disappear (figure 29). These relationships should be employed only when predicting pack ice disintegration within 60 nautical miles of the listed stations or at stations with similar environmental influences.

It was desirable to establish correlation coefficients and to formulate a family of curves for the short-term ice forecaster's use in relating accumulated warming degree days to ice disintegration involving concentration decreases in all coverage categories. Means of warming degree days and hypothetical initial ice thicknesses were computed for each of the stations and correlated. Figures 30 through 33 depict these correlations. These relationships permit formulation of the decrease in any discrete concentration as a function of warming degree days, base 23°F (figure 34). For example, assume an accumulation of 500 warming degree days at the time of initiation of a particular forecast and hypothetical ice thickness (or ice thickness report by icebreaker) of 5 feet. Assume further that 100 warming degree days accumulate during the prediction period. Then, from figure 34 the short-term ice forecaster would predict the concentration to decrease from 5 tenths to 4 tenths within the prediction period. Another illustration of the use of figure 34 is given on page 135, appendix G.

It will be noted in figure 34 that a given number of degree days during the time when ice concentrations are high appear to result in more melt than is the case when concentrations are low. The result appears to be inconsistent with physical reality; however, the apparent inconsistency results from the fact that initial thermal interchange between the atmosphere and ice results in melt of the young and relatively level portions of the ice. As the season progresses the proportion of heavily ridged pressure ice becomes greater relative to the total quantity of pack ice present. Thus, a greater quantity of warming degree days are required to melt the thick, heavily ridged ice after the smoother and larger portions of the pack ice have completely disintegrated.

Latest temperature and degree day plots for 23° and 32°F bases at selected stations throughout the area of interest should be maintained by the local forecasting activity. A recapitulation of these charts suggested to be regularly maintained is given in appendix H.

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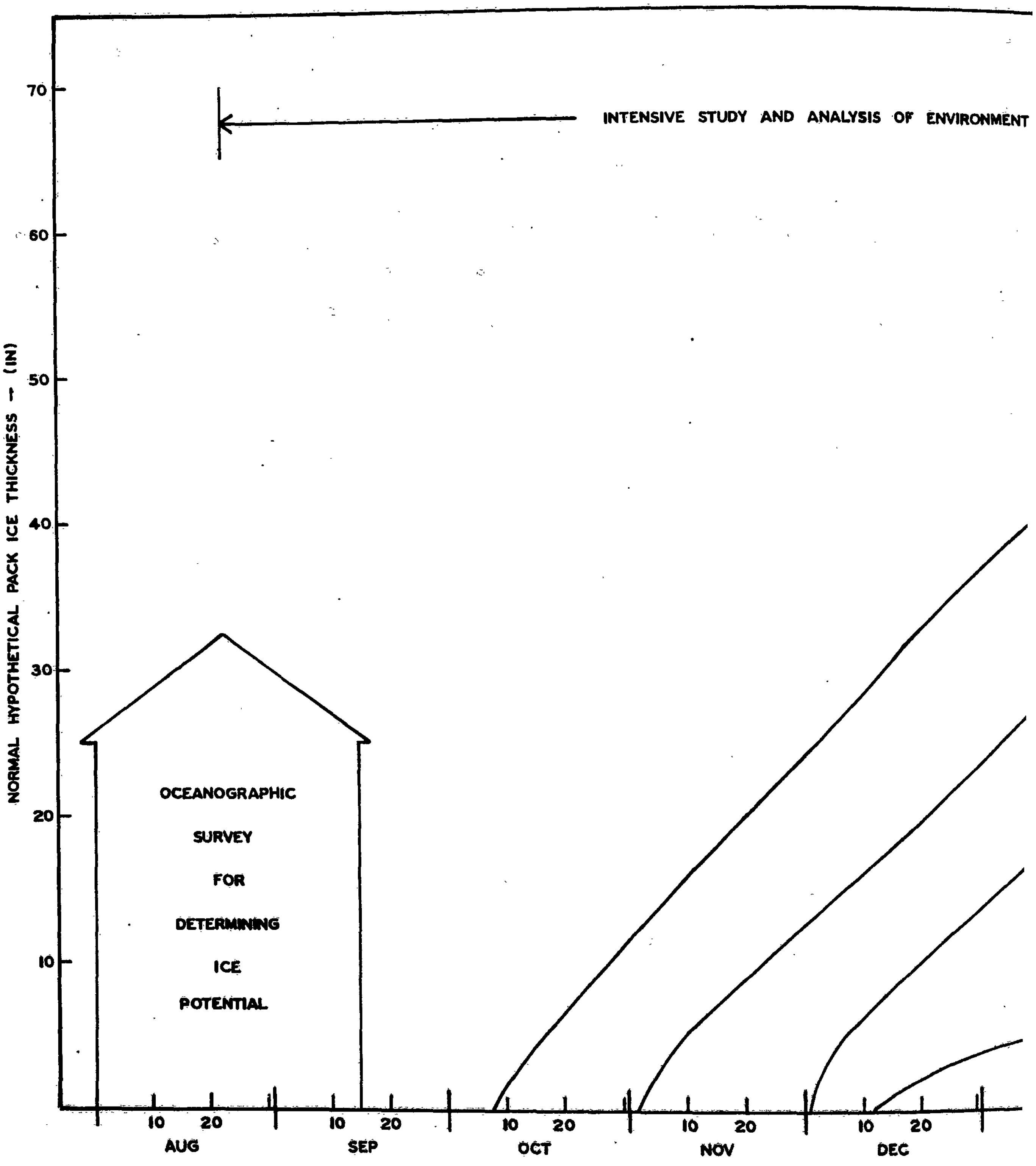
1

LEGEND
SOLID LINE = HYPOTHETICAL GROWTH CURVE, OFFSHORE PACK
DASHED LINE = HYPOTHETICAL MELT CURVE, OFFSHORE PACK



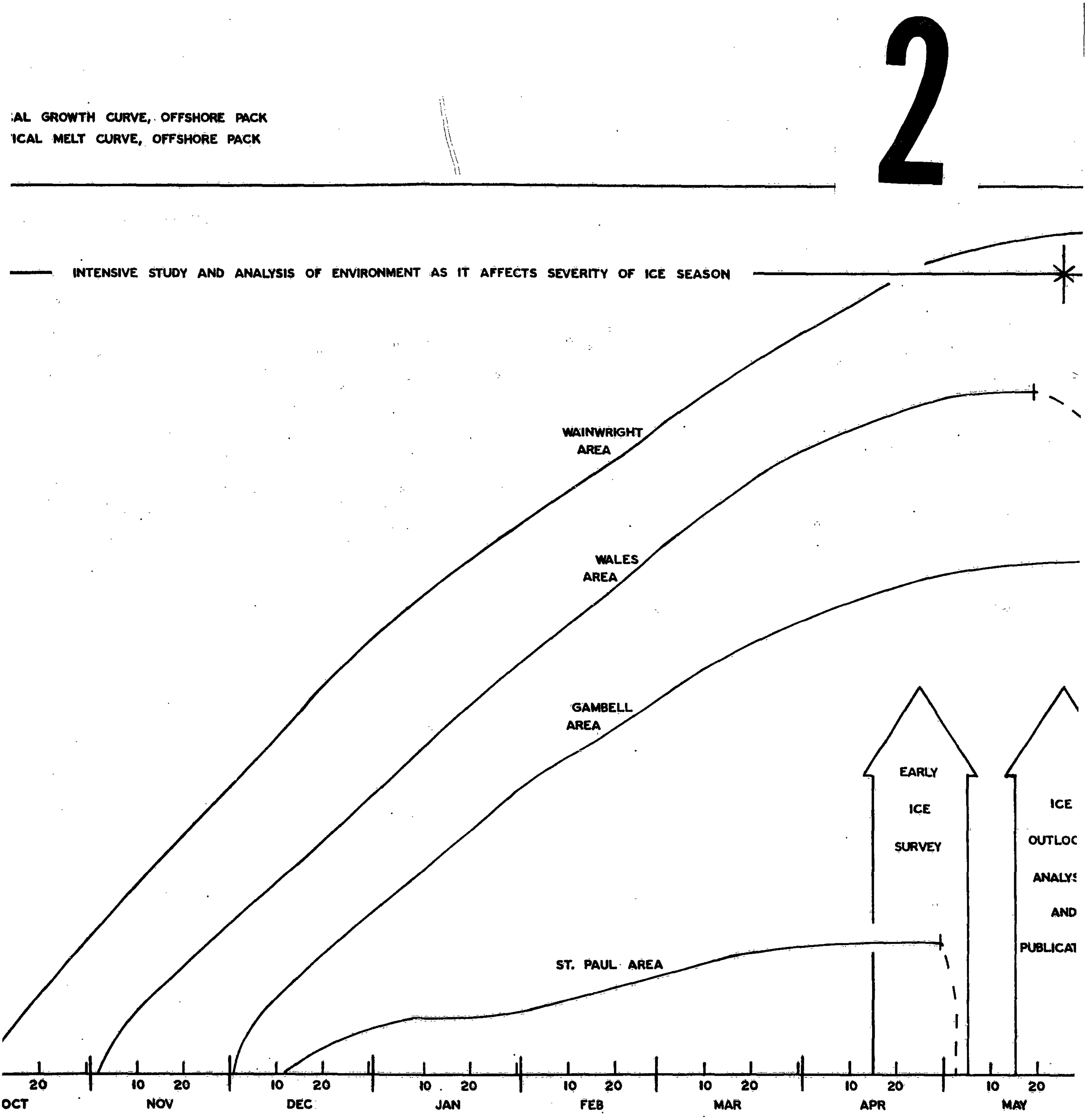
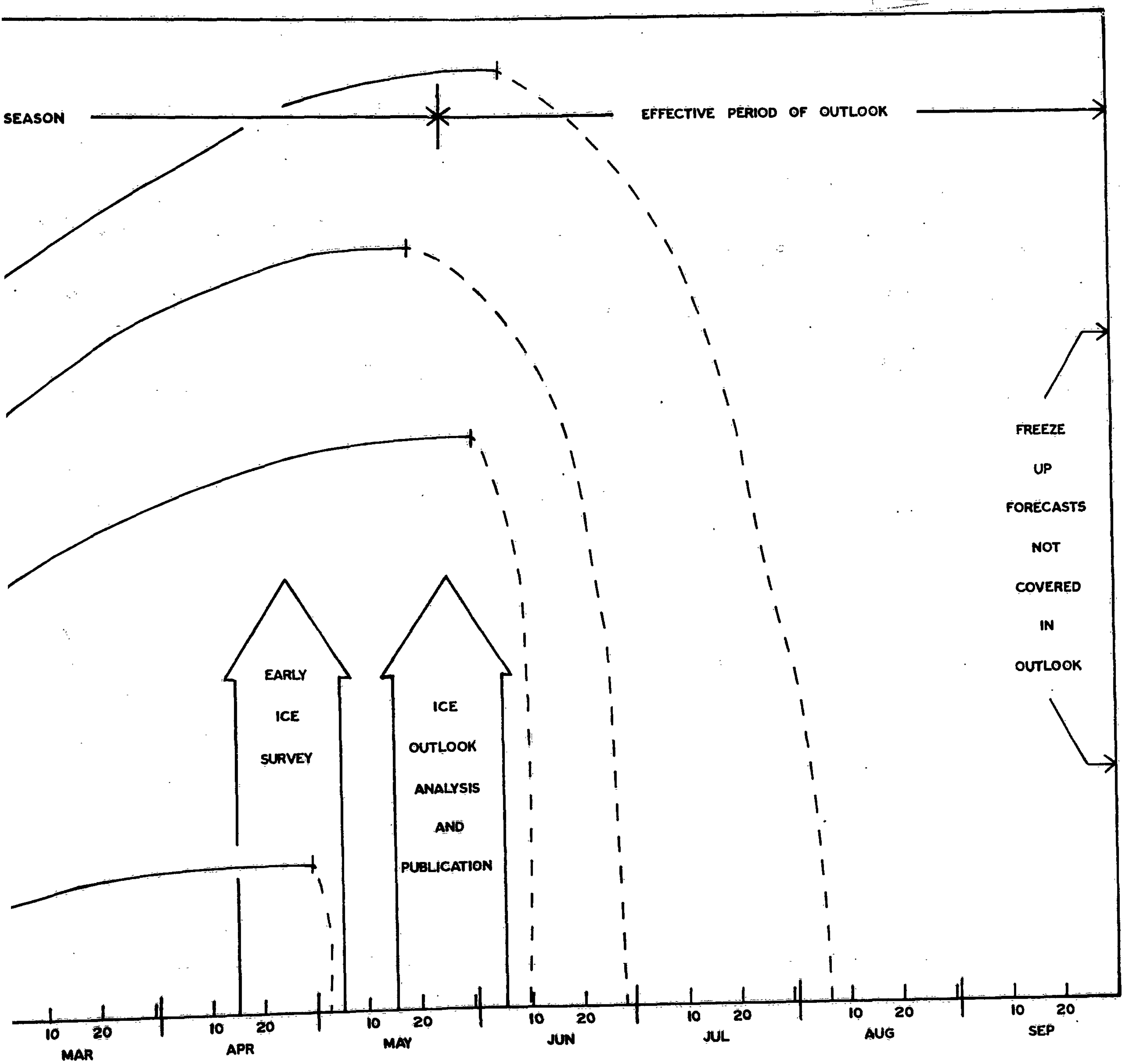


FIGURE I BASIC CONCEPT OF LONG-RANGE OUTLOOK

3



LONG-RANGE OUTLOOK

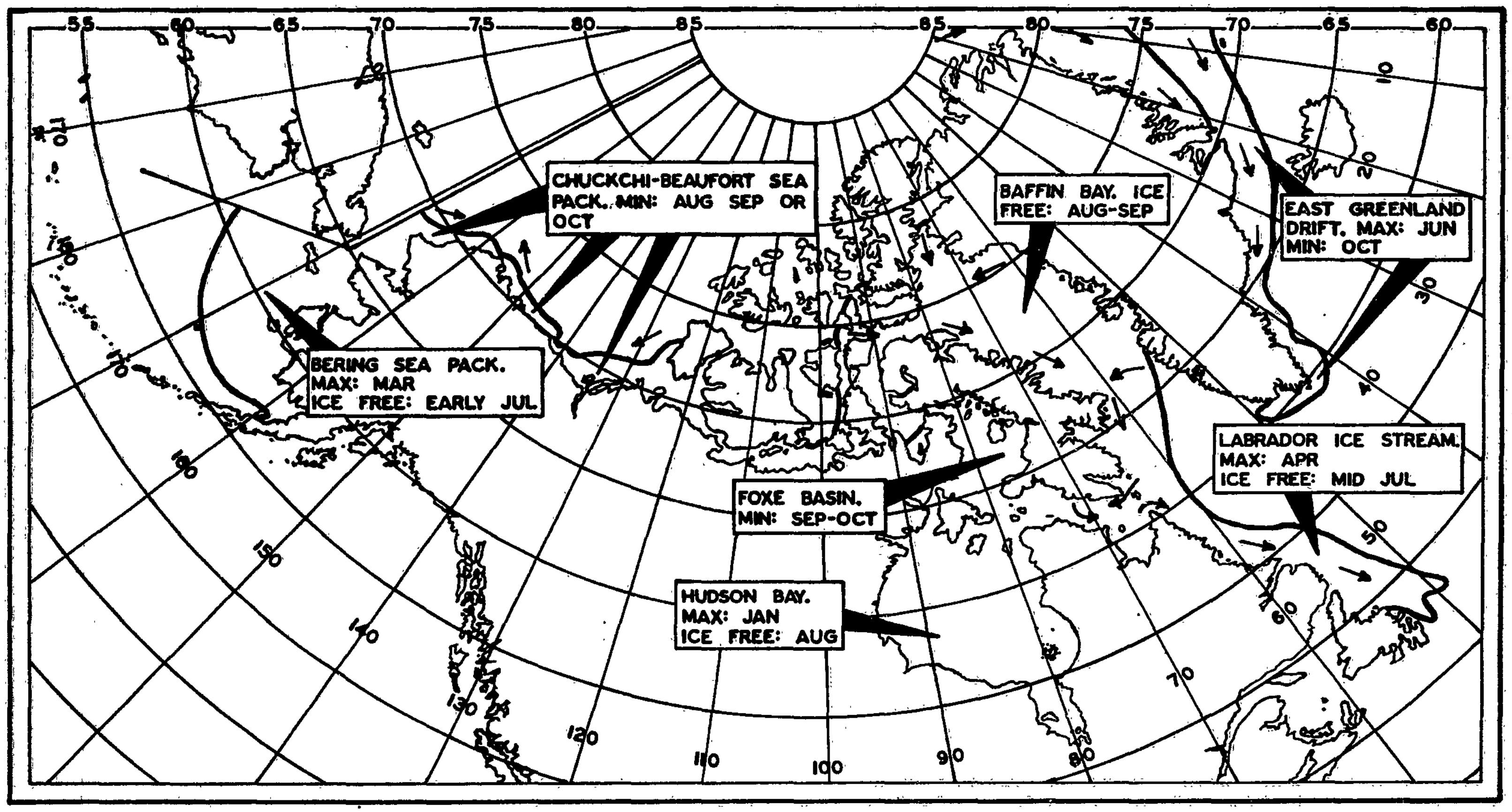


FIGURE 2 SEASONAL MAXIMUM AND MINIMUM EXTENT OF SEA ICE

1

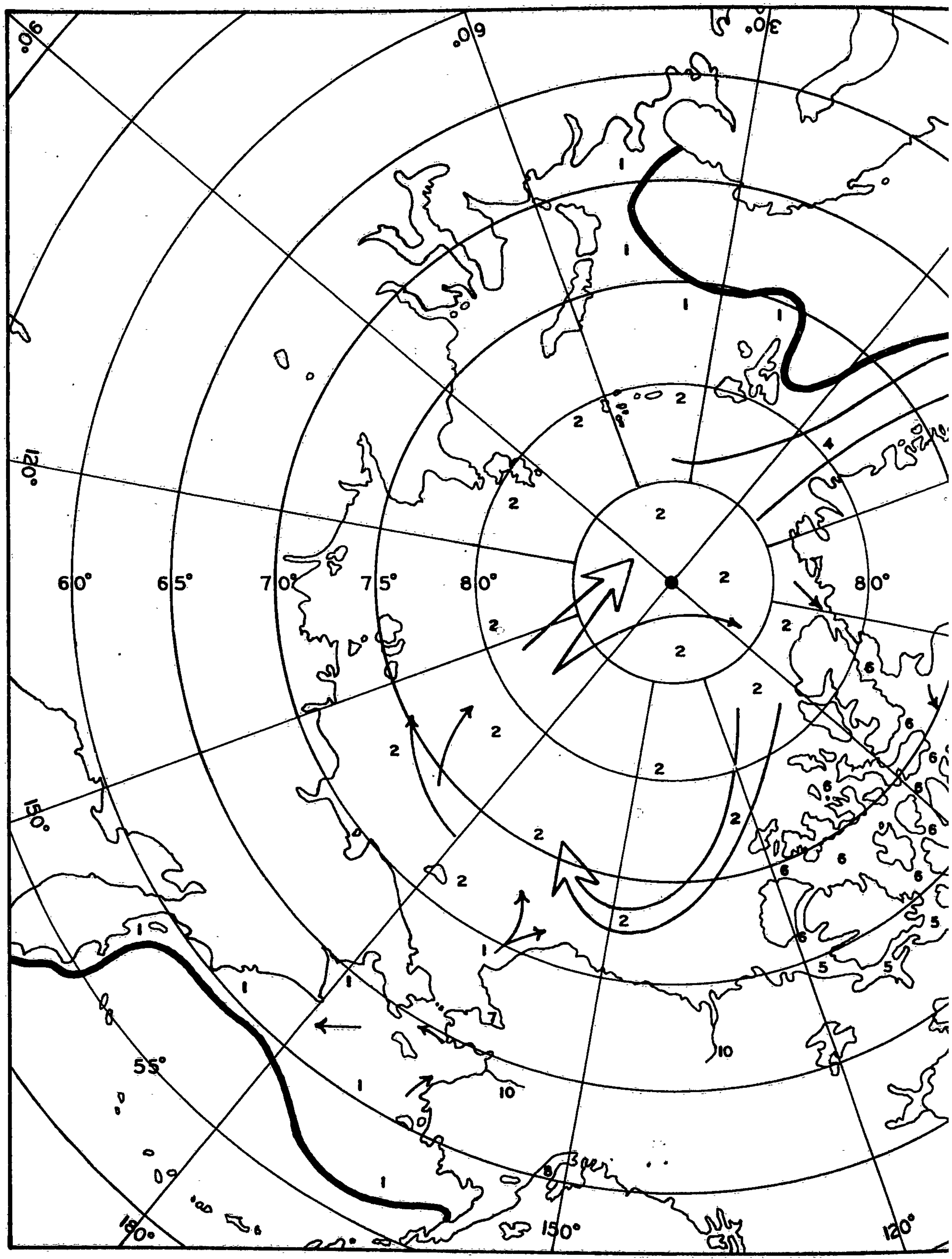


FIGURE 3 TYPE

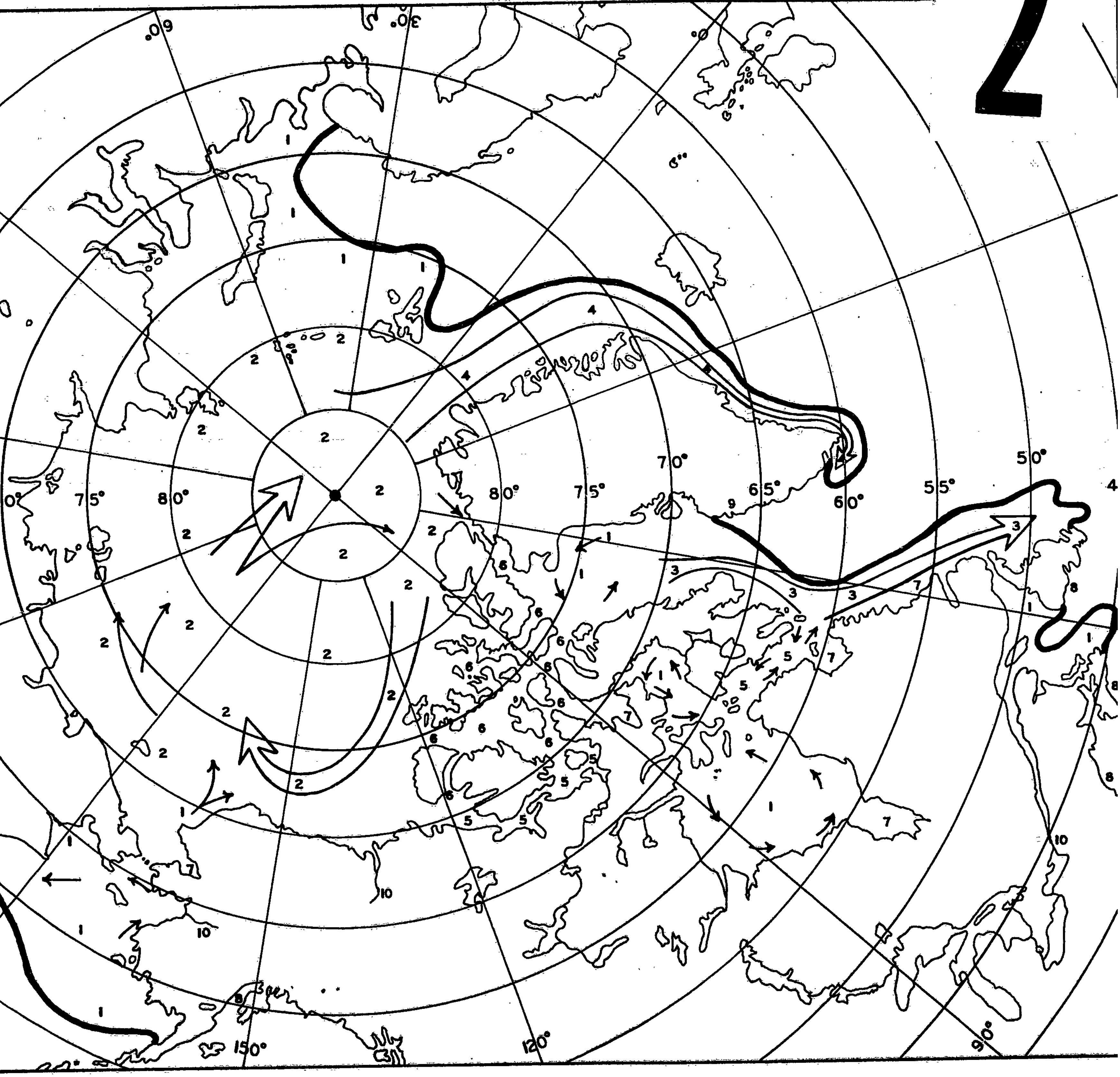
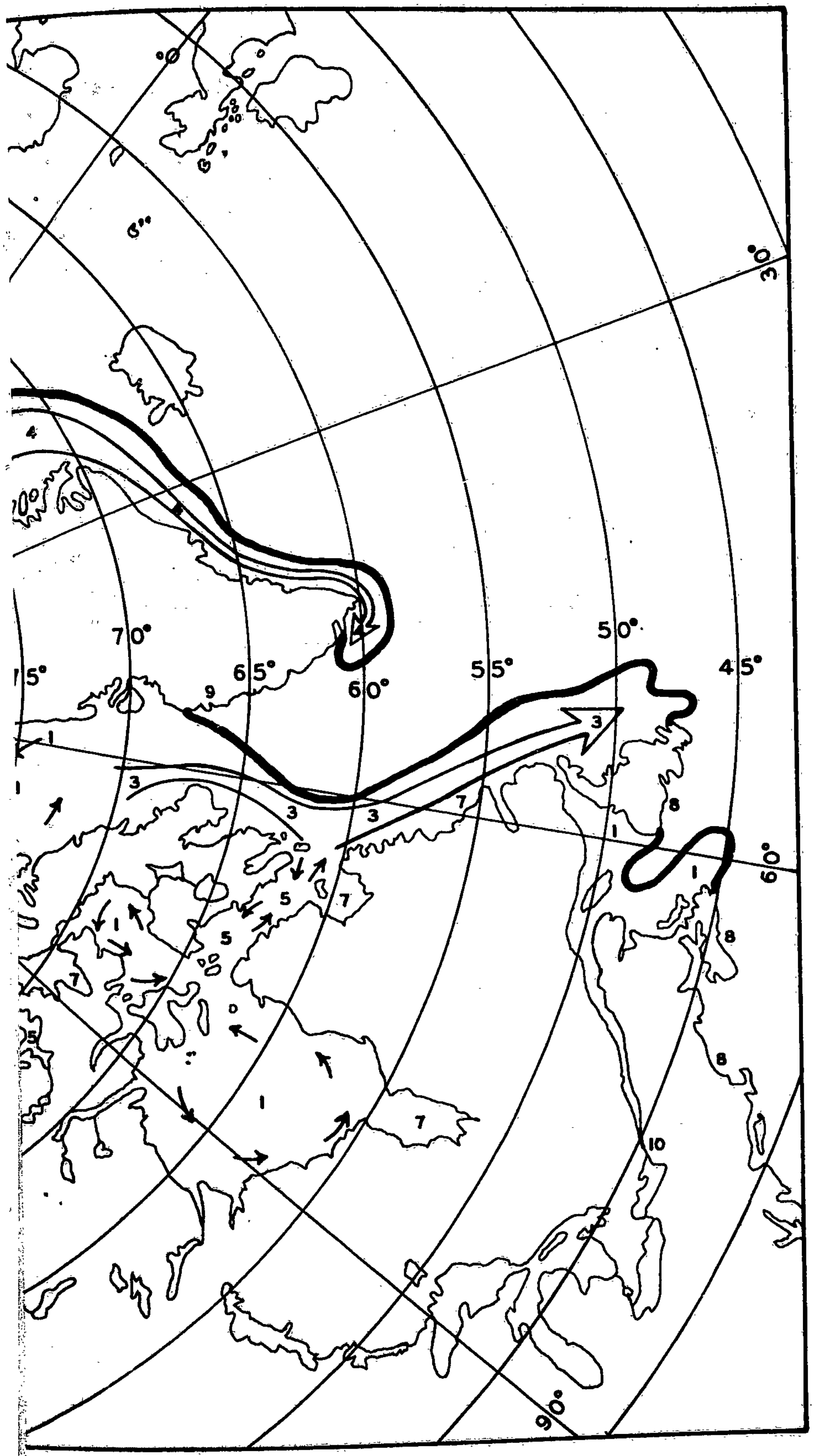


FIGURE 3 TYPES OF SEA ICE

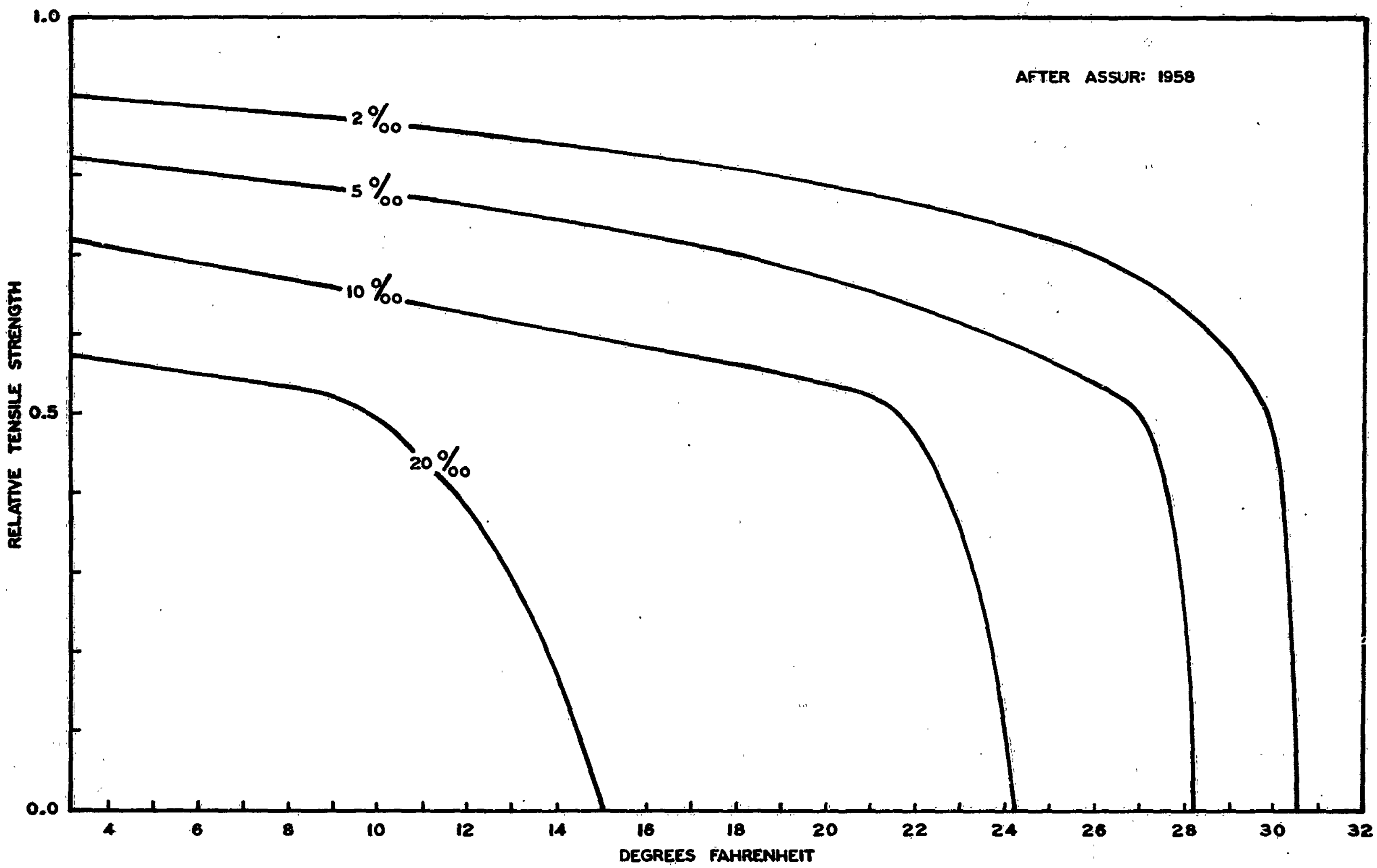


LEGEND

1. WINTER PACK
2. POLAR PACK
3. WINTER ICE STREAM
4. POLAR ICE STREAM
5. ARCHIPELAGIC WINTER PACK
6. ARCHIPELAGIC POLAR PACK
7. TRAPPED ICE
8. OCCASIONAL ICE
9. FIORD ICE
10. RIVER ICE

3

S OF SEA ICE



NOTE
SALINITIES IN PARTS PER THOUSAND CORRESPOND APPROXIMATELY TO THE FOLLOWING TYPES:
2 POLAR ICE
5 WINTER ICE
10 FIRST FORMATION OF YOUNG ICE
20 SALT ICE PRODUCED BY FLOODING

FIGURE 4 TENSILE STRENGTH OF SEA ICE RELATIVE TO FRESH-WATER ICE AS A FUNCTION OF TEMPERATURE AND SALINITY

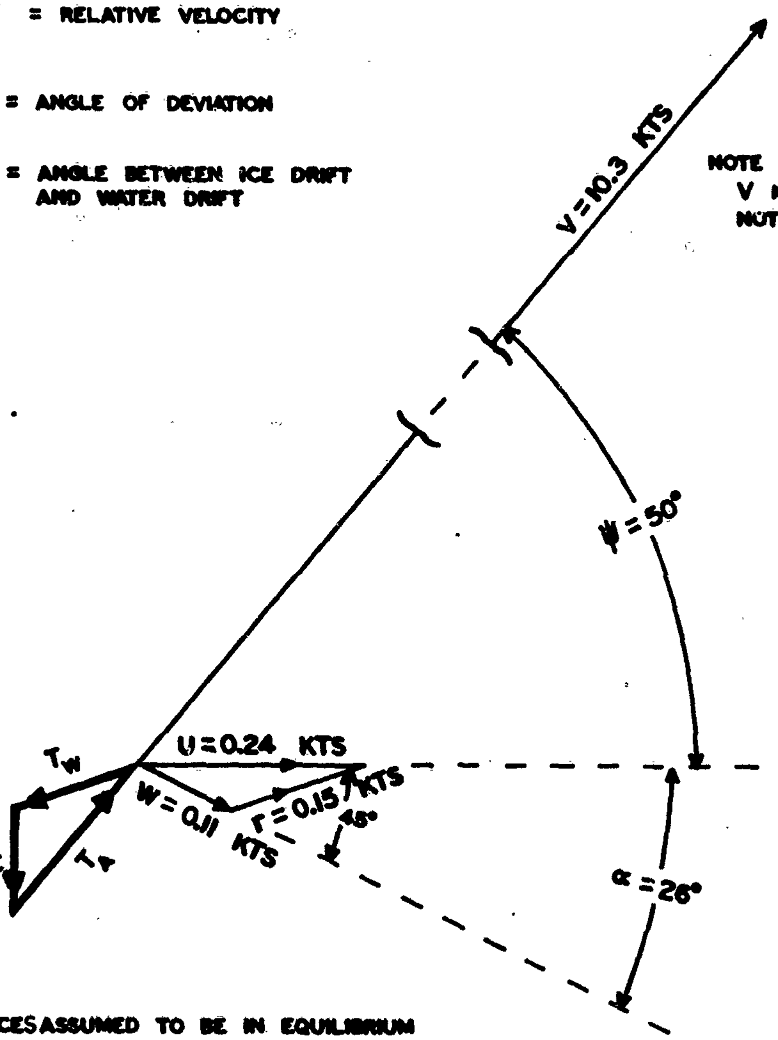
VELOCITY VECTORS

V = WIND VELOCITY
U = ICE DRIFT VELOCITY
W = WATER DRIFT VELOCITY
T = RELATIVE VELOCITY

ψ = ANGLE OF DEVIATION

α = ANGLE BETWEEN ICE DRIFT AND WATER DRIFT

AFTER SHULEIKIN: 1963



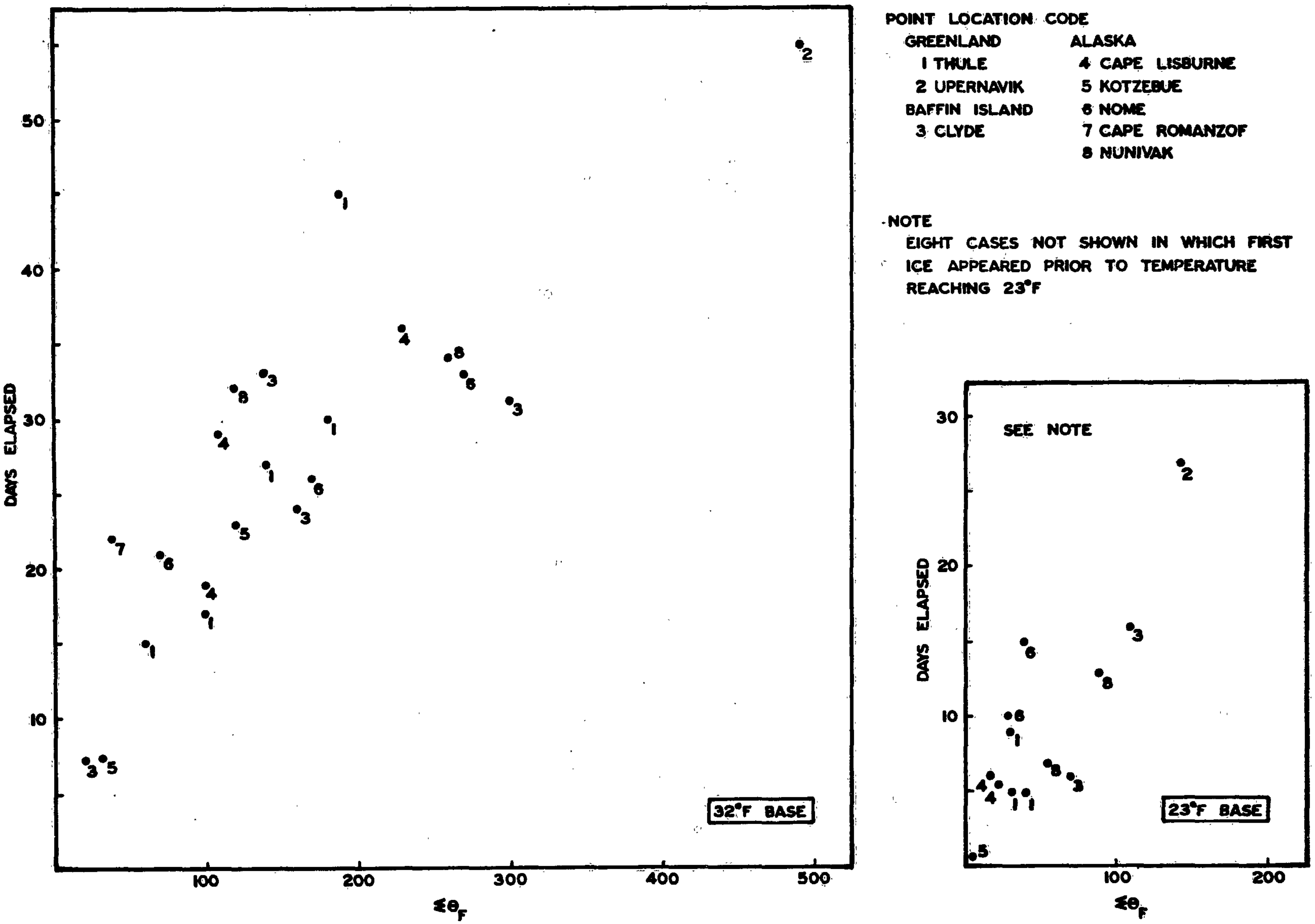
NOTE
V MUCH LARGER THAN OTHER VELOCITIES.
NOT DRAWN TO SCALE

FORCES ASSUMED TO BE IN EQUILIBRIUM

T_A = WIND STRESS ACTING ON TOP OF ICE APPROXIMATELY IN DIRECTION OF V
T_W = STRESS BETWEEN ICE AND WATER ACTING ON UNDERSIDE OF ICE IN DIRECTION OPPOSITE OF Γ
C = CORIOLIS FORCE PER UNIT AREA ACTING ON THE ICE AT 90° TO THE RIGHT OF U

COMPUTED FOR ϕ = 71°30'N

FIGURE 5 EXAMPLE OF VECTOR RELATIONSHIP BETWEEN WIND VELOCITY AND ICE DRIFT VELOCITY



NOTE
EIGHT CASES NOT SHOWN IN WHICH FIRST ICE APPEARED PRIOR TO TEMPERATURE REACHING 23°F

FIGURE 6 DAYS ELAPSED VERSUS FAHRENHEIT FROST DEGREE DAYS ACCUMULATED FROM TIME SMOOTHED AIR TEMPERATURE REACHED BASE UNTIL FIRST APPEARANCE OF OFFSHORE ICE

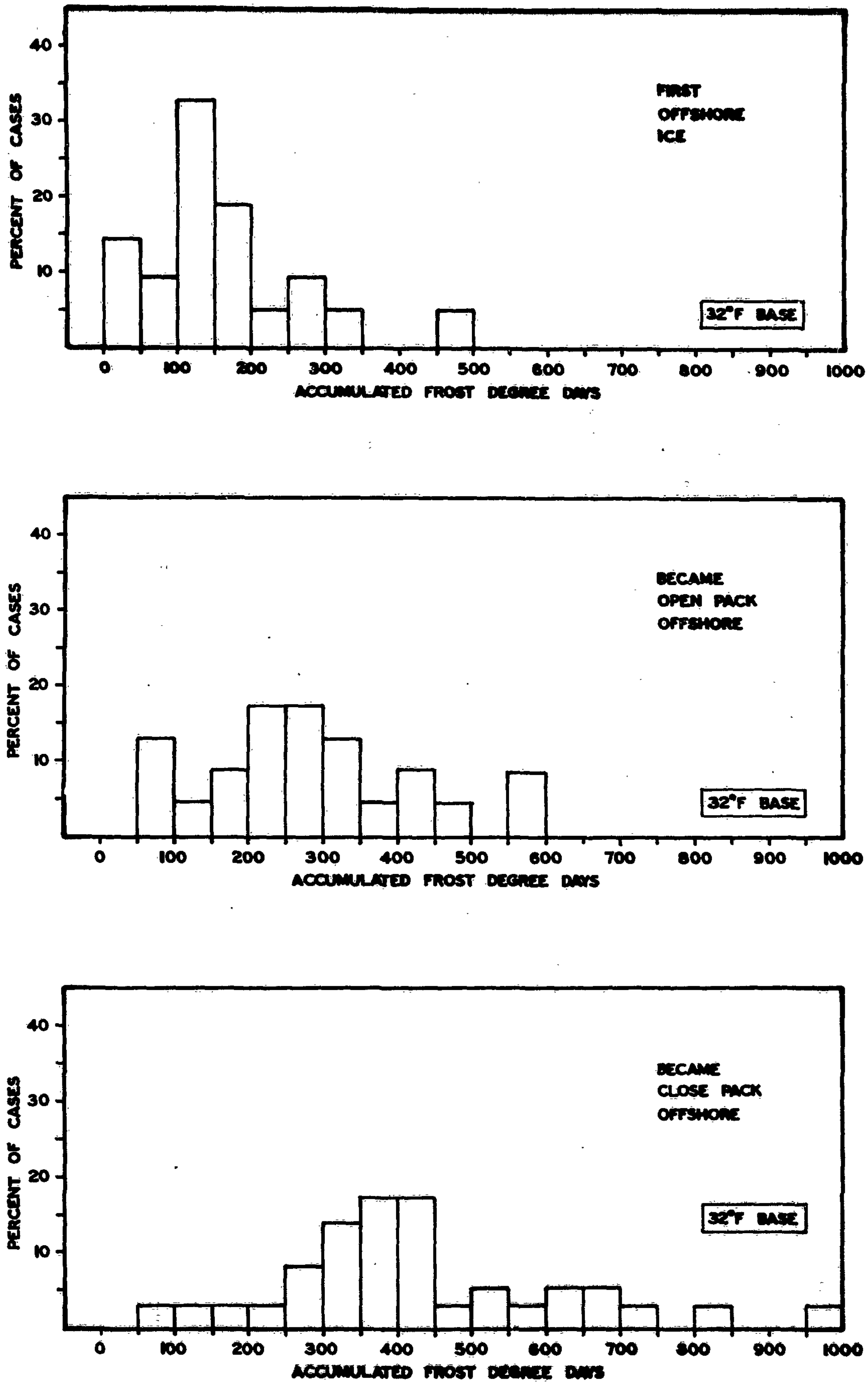


FIGURE 7 VARIATION IN ACCUMULATED FAHRENHEIT FROST DEGREE DAYS REQUIRED TO REACH CONCENTRATION CATEGORIES INDICATED

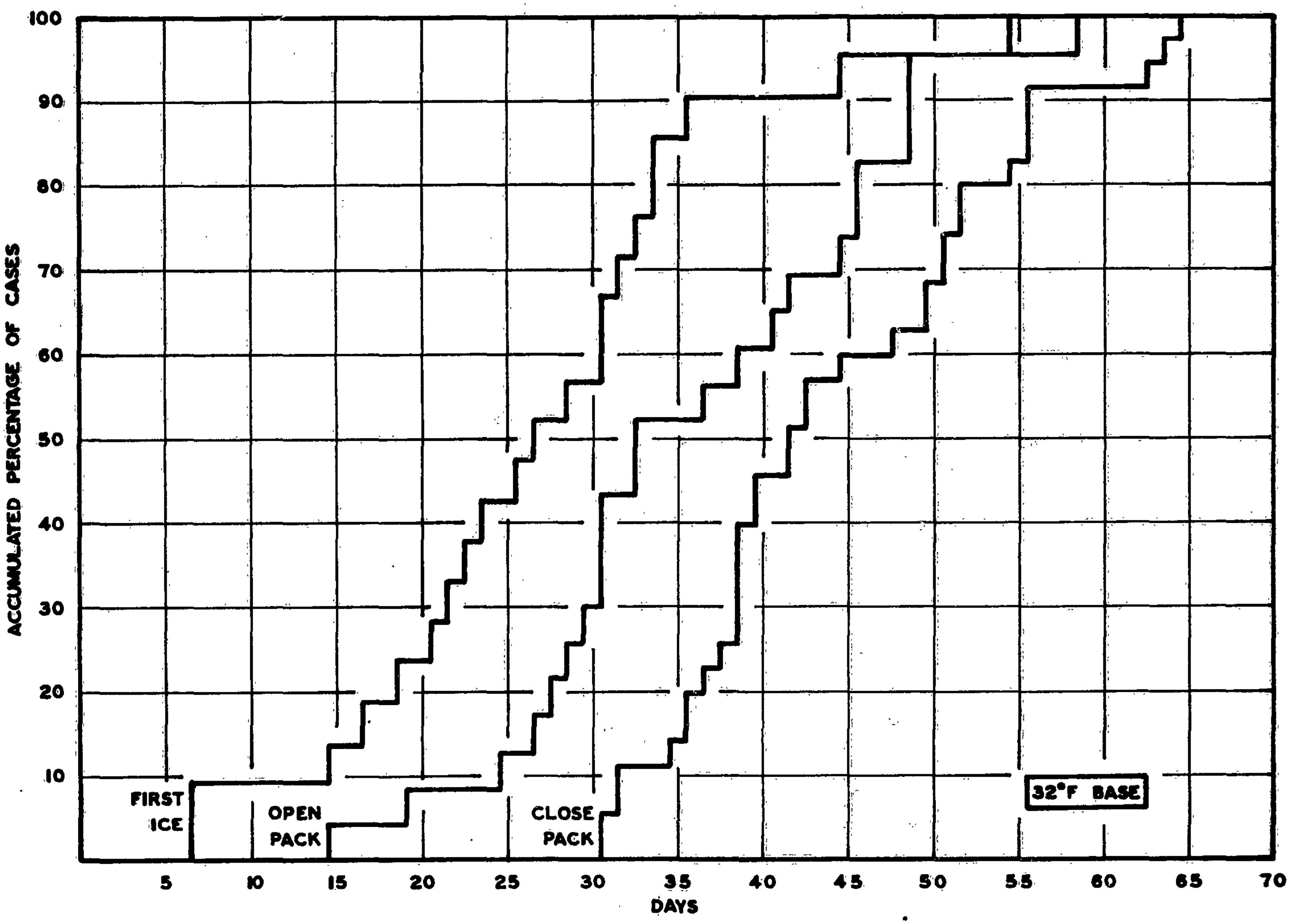
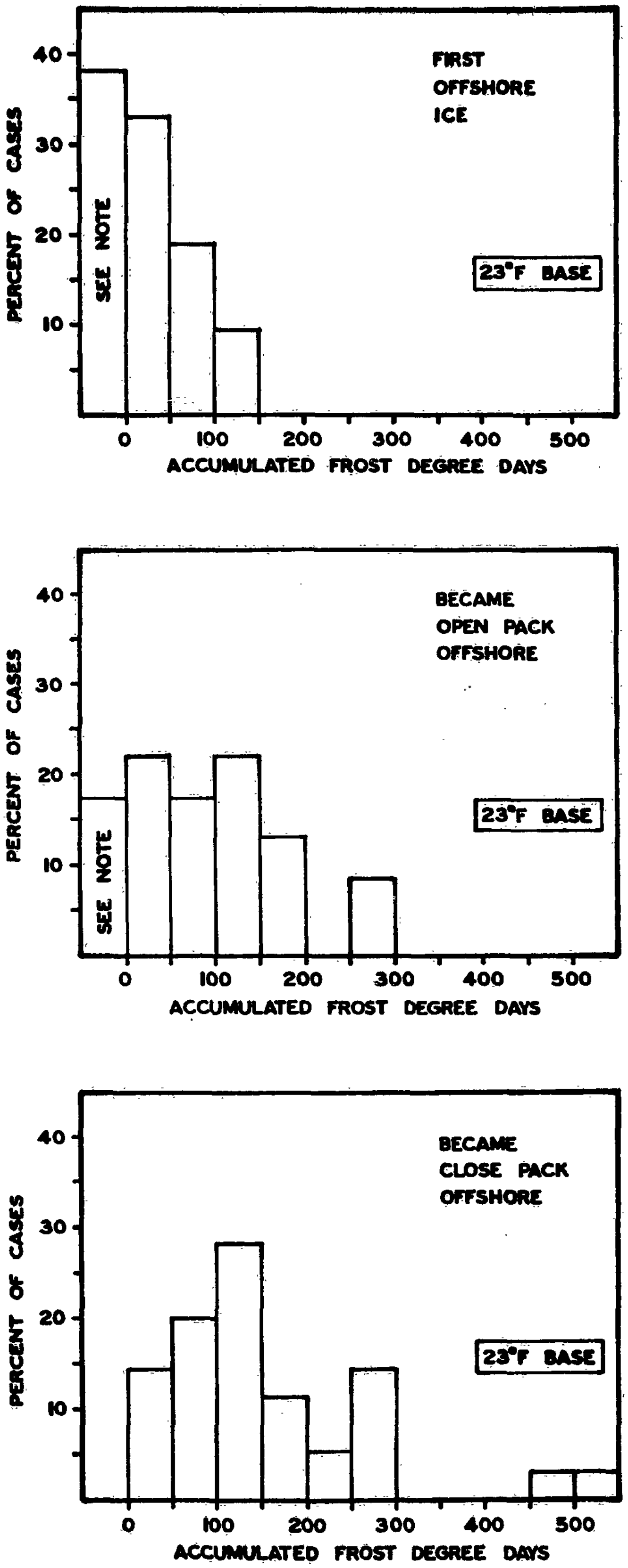


FIGURE 8 DAYS ELAPSED AFTER SMOOTHED AIR TEMPERATURE REACHED 32°F UNTIL OFFSHORE CONCENTRATION BECAME CATEGORY INDICATED



NOTE
THESE CASES
OCCURRED
PRIOR TO AIR
TEMPERATURE
REACHING 23°F

FIGURE 9 VARIATION IN ACCUMULATED FAHRENHEIT FROST DEGREE DAYS REQUIRED TO REACH CONCENTRATION CATEGORIES INDICATED

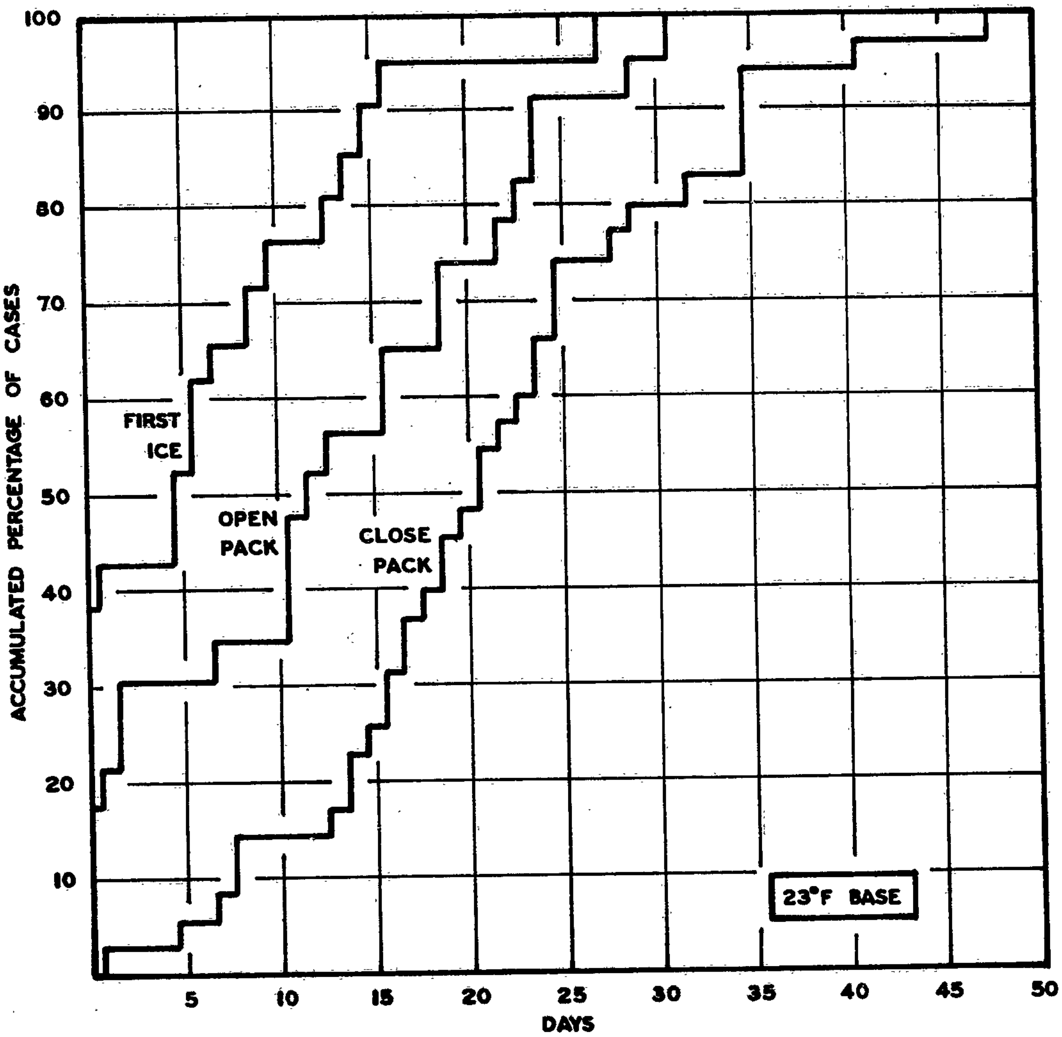
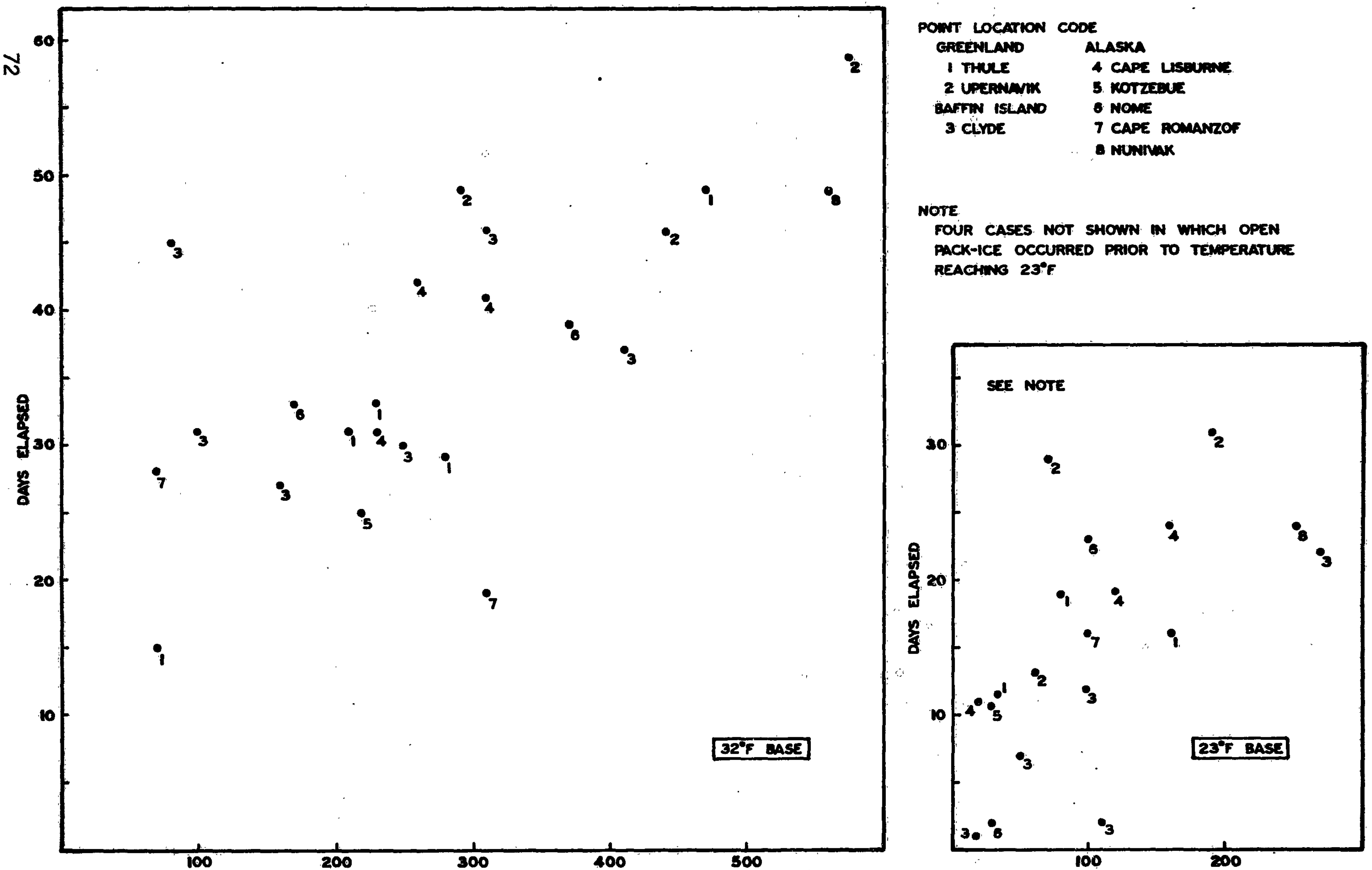


FIGURE 10 DAYS ELAPSED AFTER SMOOTHED AIR TEMPERATURE REACHED 23°F UNTIL OFFSHORE CONCENTRATION BECAME CATEGORY INDICATED



NOTE
FOUR CASES NOT SHOWN IN WHICH OPEN PACK-ICE OCCURRED PRIOR TO TEMPERATURE REACHING 23°F

FIGURE 11 DAYS ELAPSED VERSUS FAHRENHEIT FROST DEGREE DAYS ACCUMULATED FROM TIME SMOOTHED AIR TEMPERATURE REACHED BASE UNTIL OFFSHORE CONCENTRATION BECAME OPEN PACK-ICE

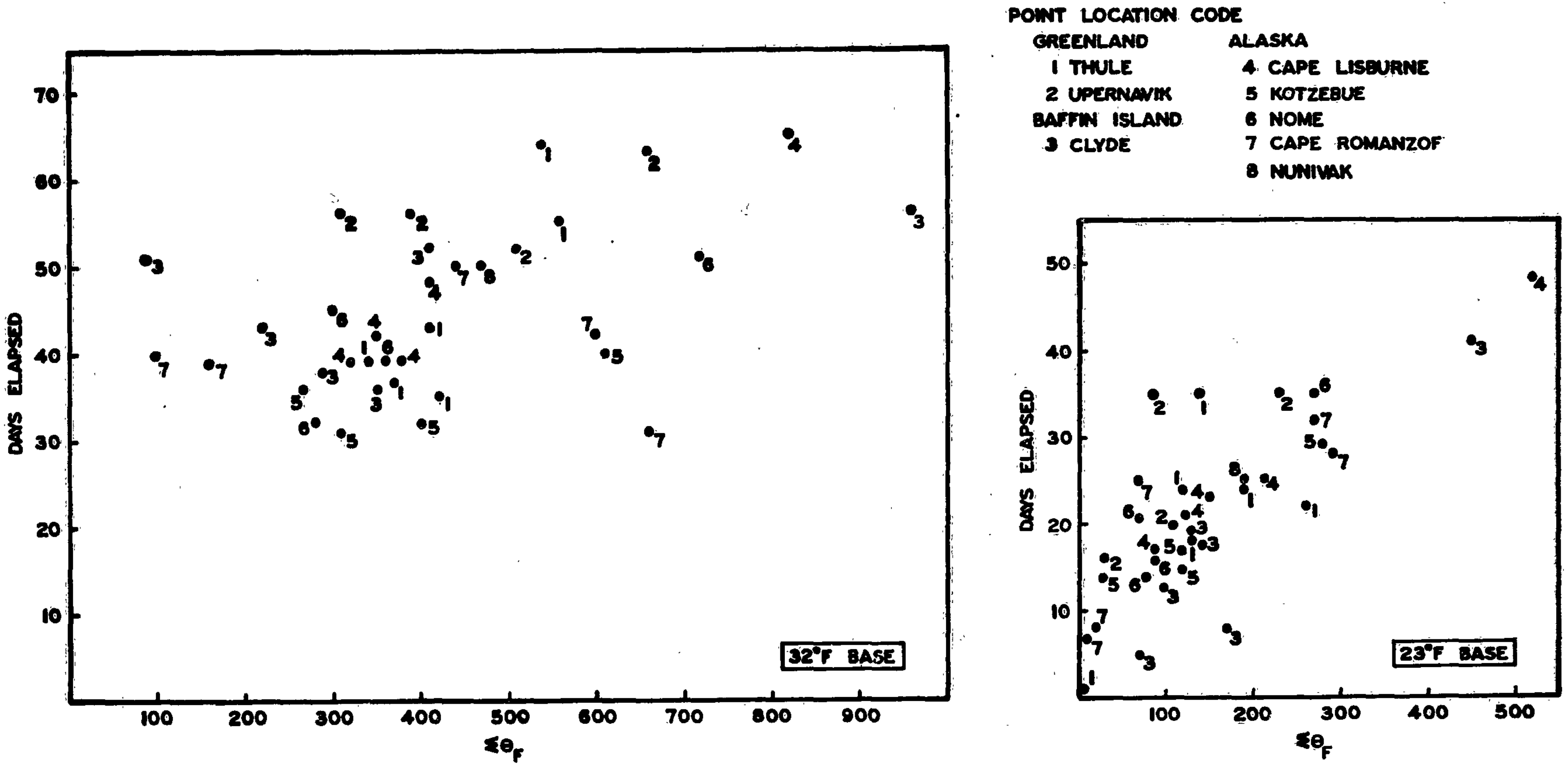


FIGURE 12 DAYS ELAPSED VERSUS FAHRENHEIT FROST DEGREE DAYS ACCUMULATED FROM TIME SMOOTHED AIR TEMPERATURE REACHED BASE UNTIL OFFSHORE CONCENTRATION BECAME CLOSE PACK-ICE

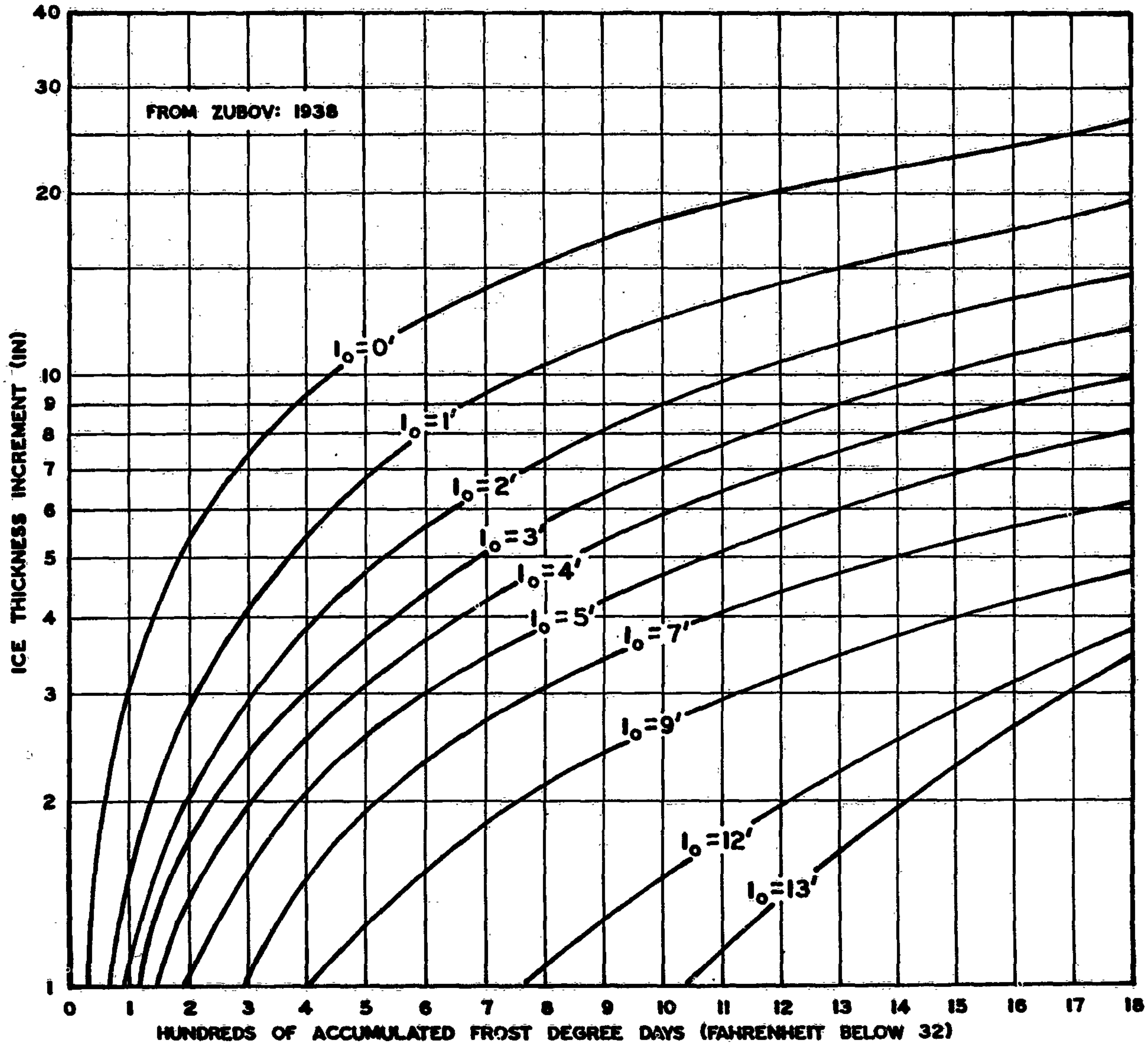


FIGURE 13 RELATIONSHIP BETWEEN ACCUMULATED FROST DEGREE DAYS AND ICE GROWTH FOR VARYING INITIAL ICE THICKNESSES (SMALL "DD" ACCUMULATIONS)

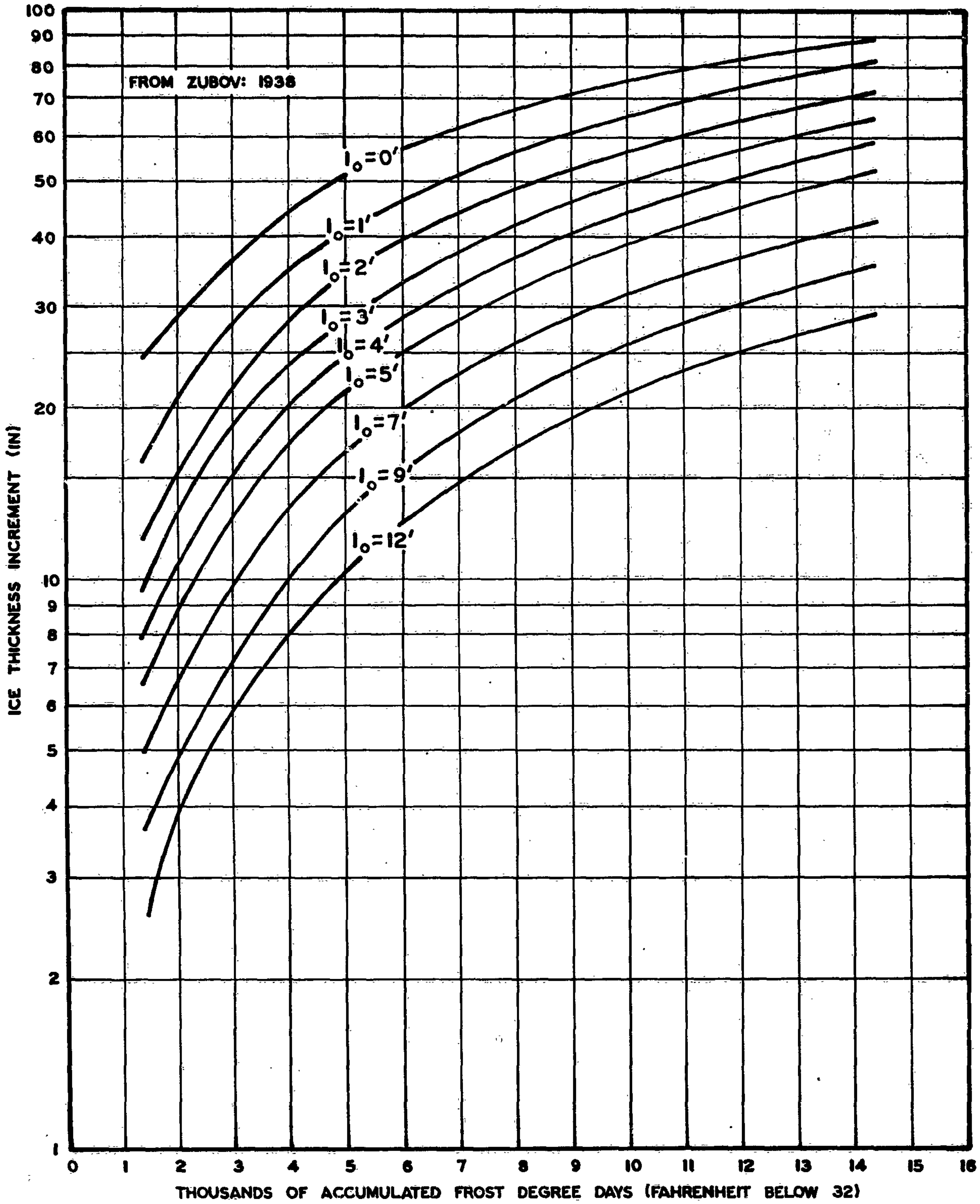


FIGURE 14 RELATIONSHIP BETWEEN ACCUMULATED FROST DEGREE DAYS AND ICE GROWTH FOR VARYING INITIAL ICE THICKNESSES (LARGE "DD" ACCUMULATIONS)

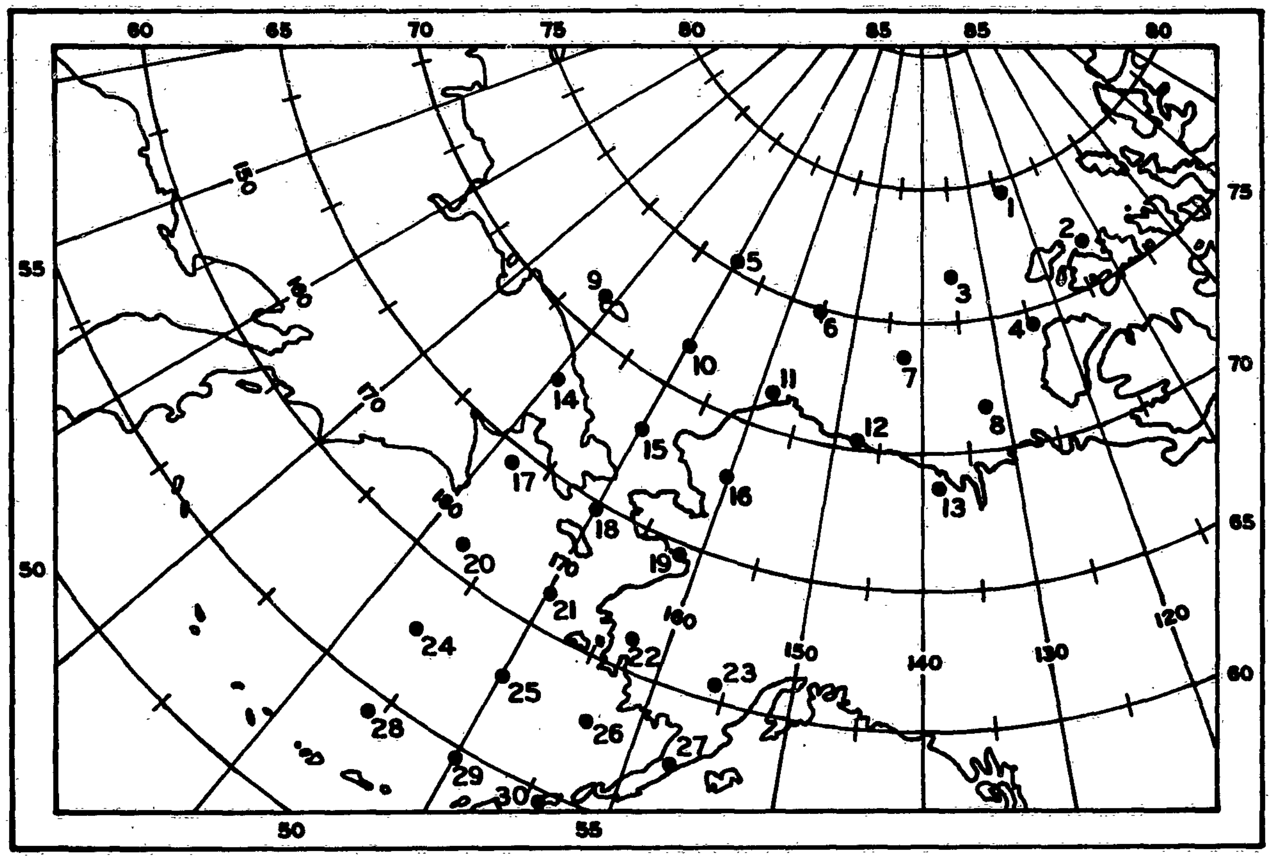


FIGURE 15 SUGGESTED GRID MODEL FOR PREDICTING ICE DRIFT

NOTE
TO BE USED ONLY FOR ARCTIC PACK ICE.
EMPIRICALLY DETERMINED FROM SUBMARINE PROFILE DATA

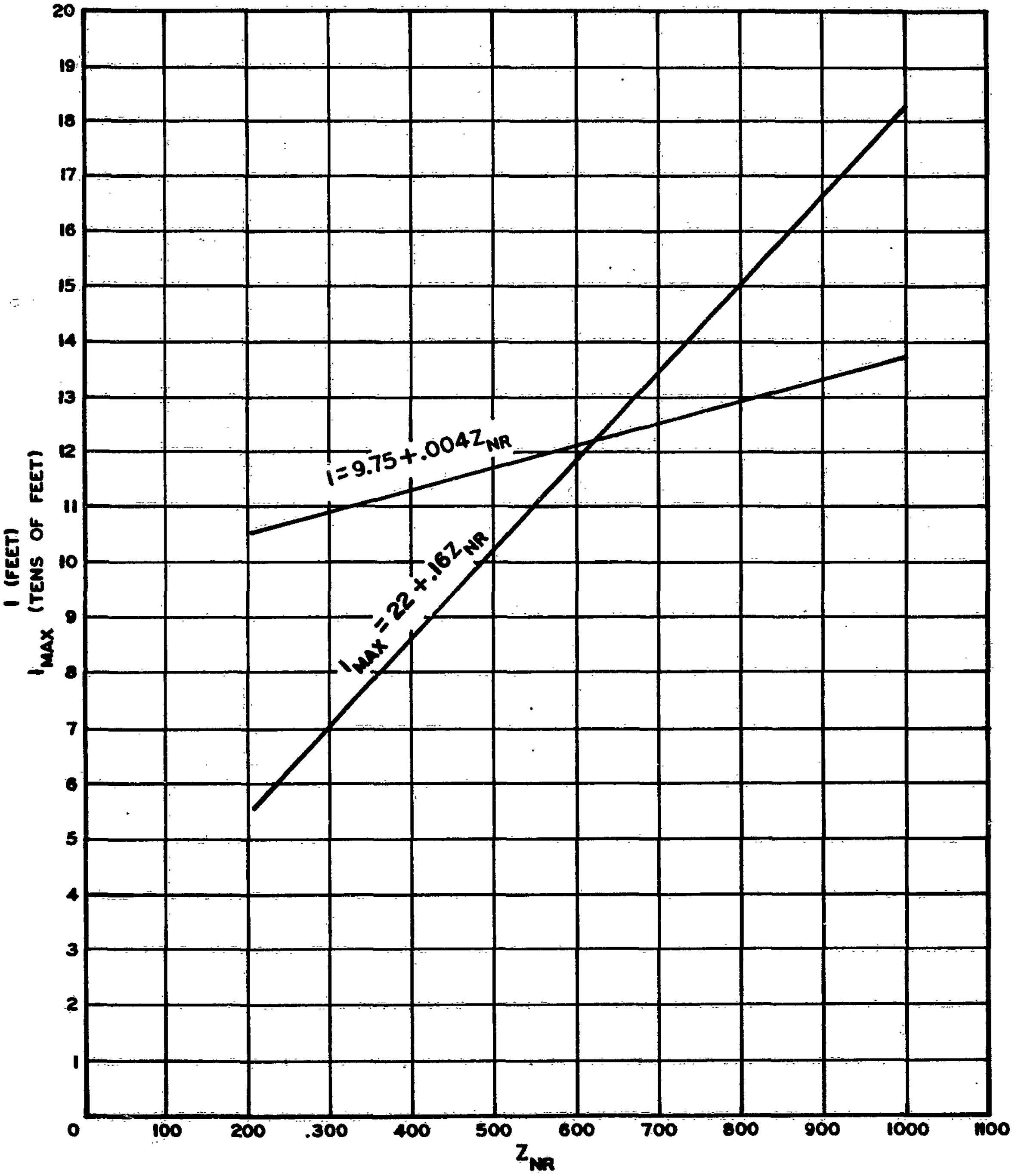


FIGURE 16 ICE THICKNESS (I) AND MAXIMUM THICKNESS THROUGH RIDGES PER 30 NAUTICAL MILES (I_{MAX}) EXPRESSED AS FUNCTIONS OF MEAN NUMBER OF RIDGES PER 30 NAUTICAL MILES (Z_{NR})

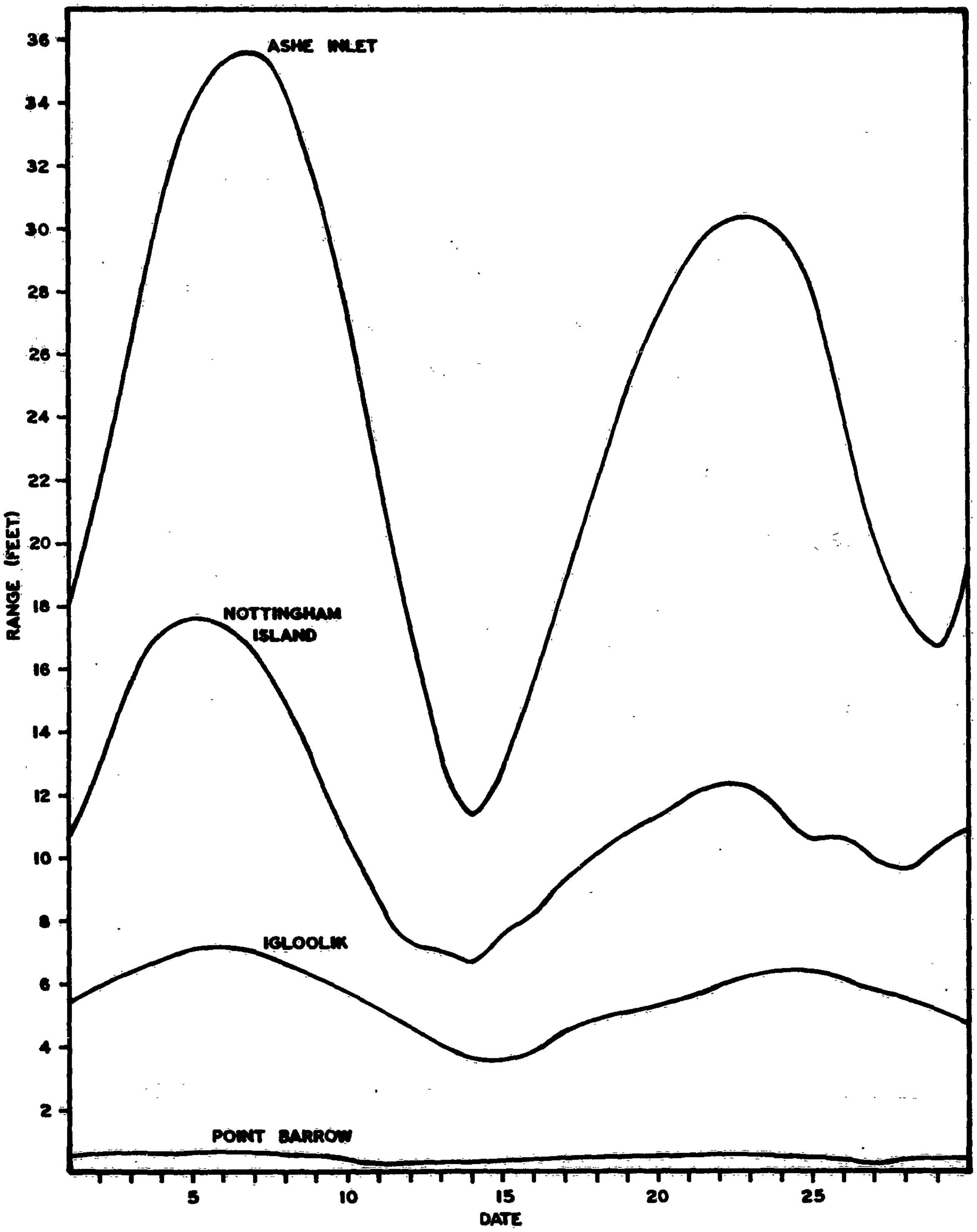
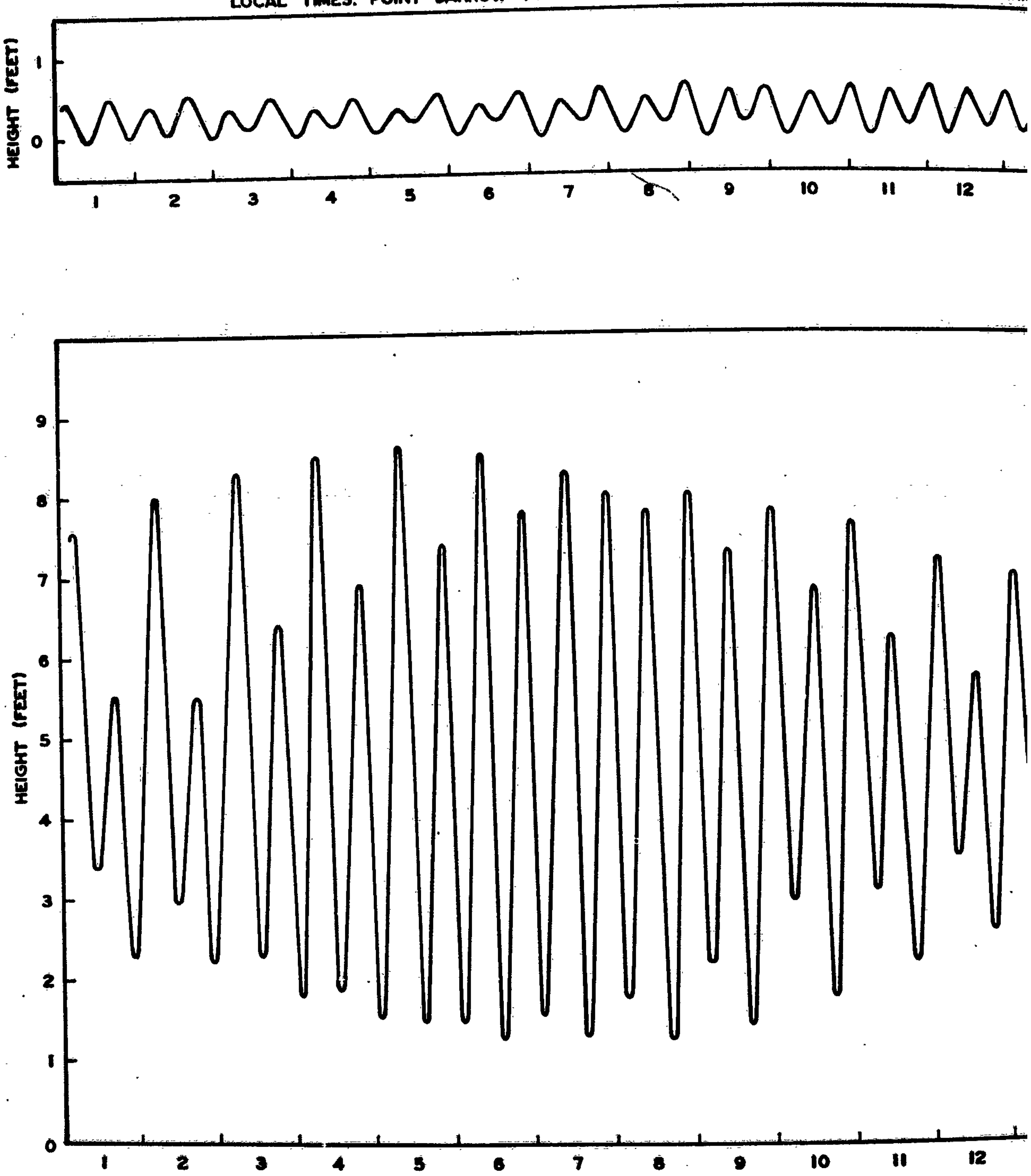


FIGURE 17 COMPARISON OF PREDICTED DAILY TIDAL RANGES FOR SEPTEMBER 1956

NOTE
LOCAL TIMES. POINT BARROW TIME MERIDIAN: 165°W (PLUS 10). IGLOOLIK TIME MERI



1

FIGURE 18 PREDIC

2

OINT BARROW TIME MERIDIAN: 165°W (PLUS 10), IGLOOLIK TIME MERIDIAN: 75°W (PLUS 5)

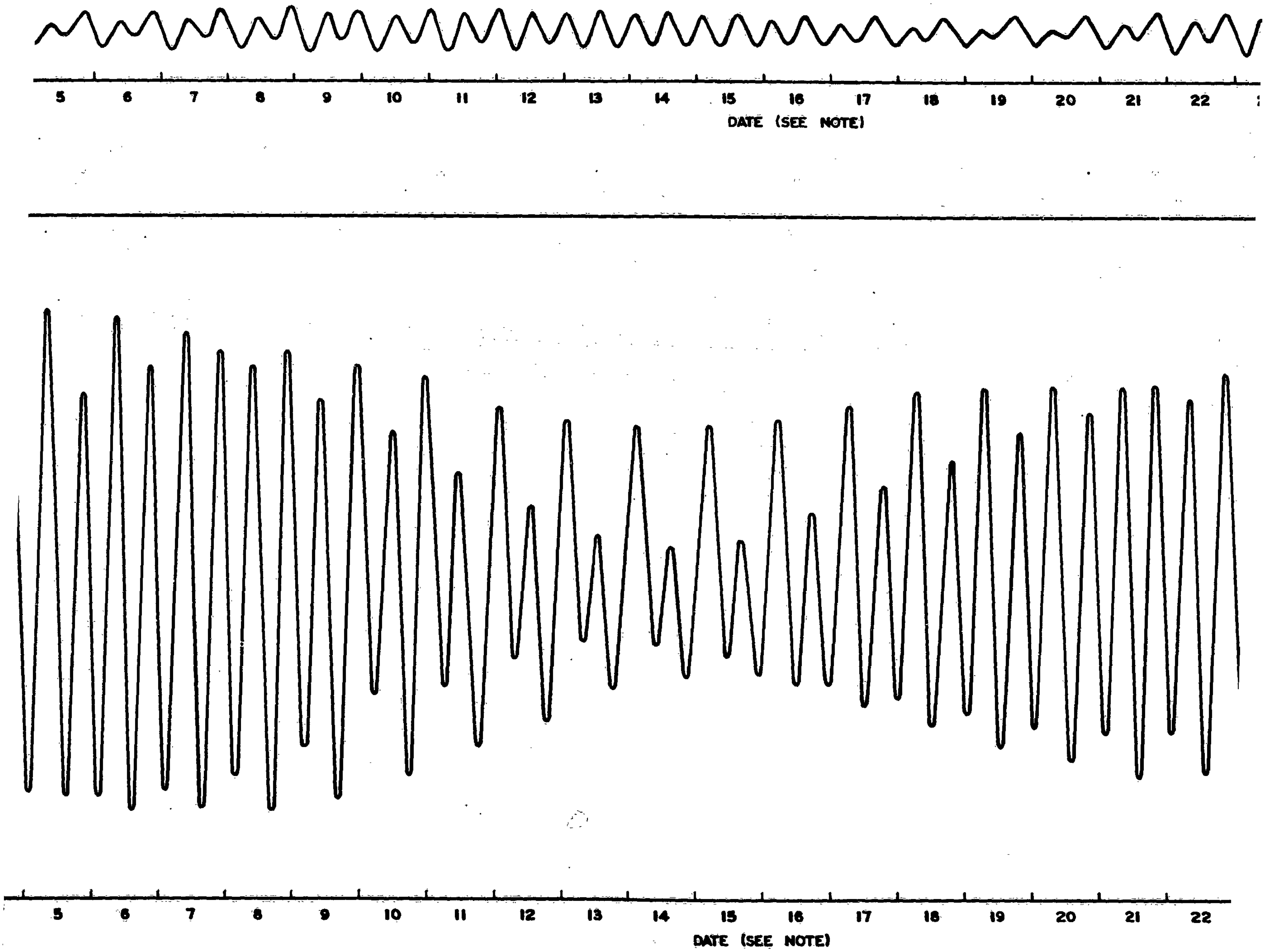
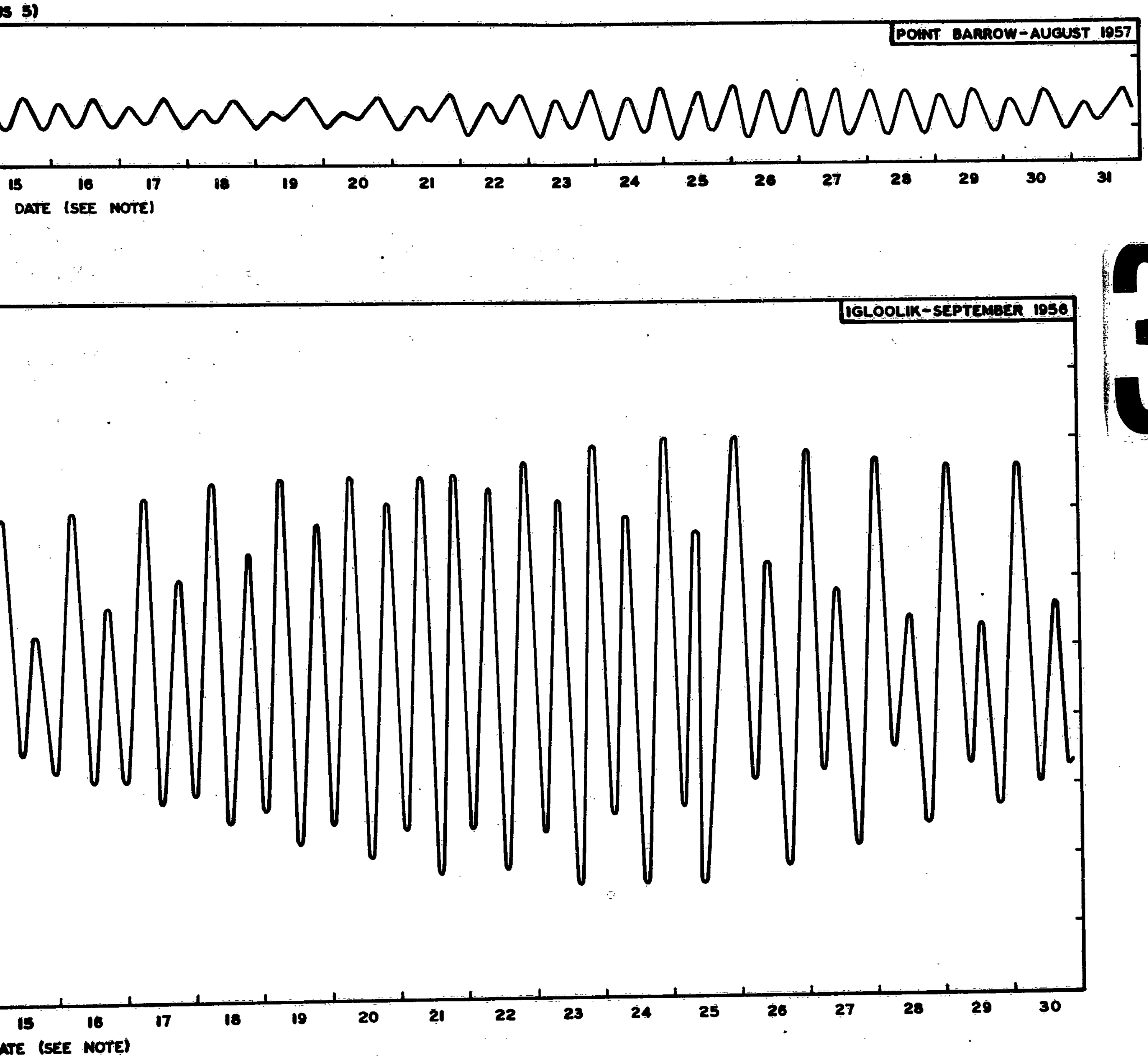


FIGURE 18 PREDICTED TIME AND HEIGHT OF HIGH AND LOW DAILY TIDES



3

ID HEIGHT OF HIGH AND LOW DAILY TIDES

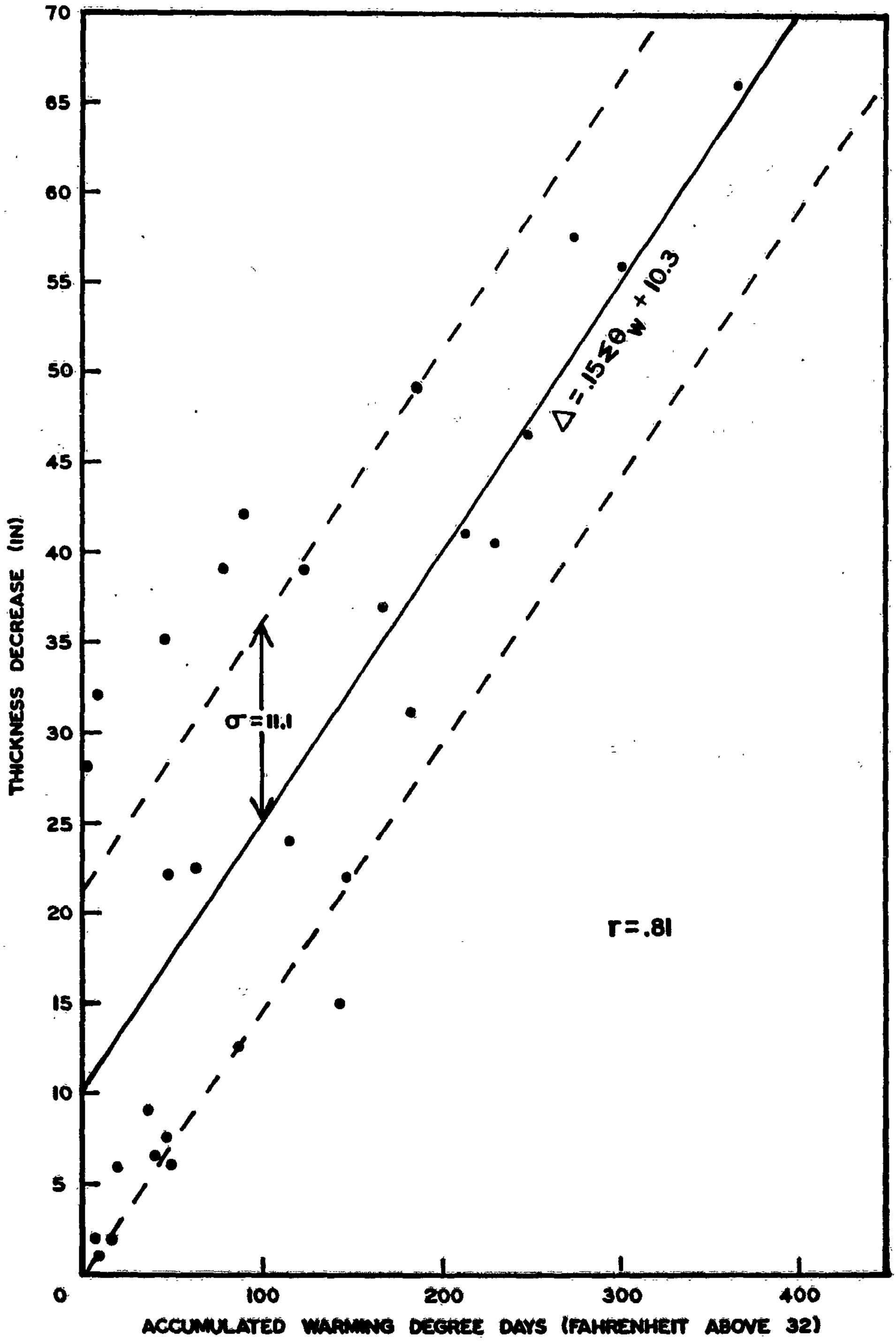


FIGURE 19 RELATIONSHIP BETWEEN DECREASE IN LANDFAST ICE THICKNESS AND ACCUMULATED WARMING DEGREE DAYS

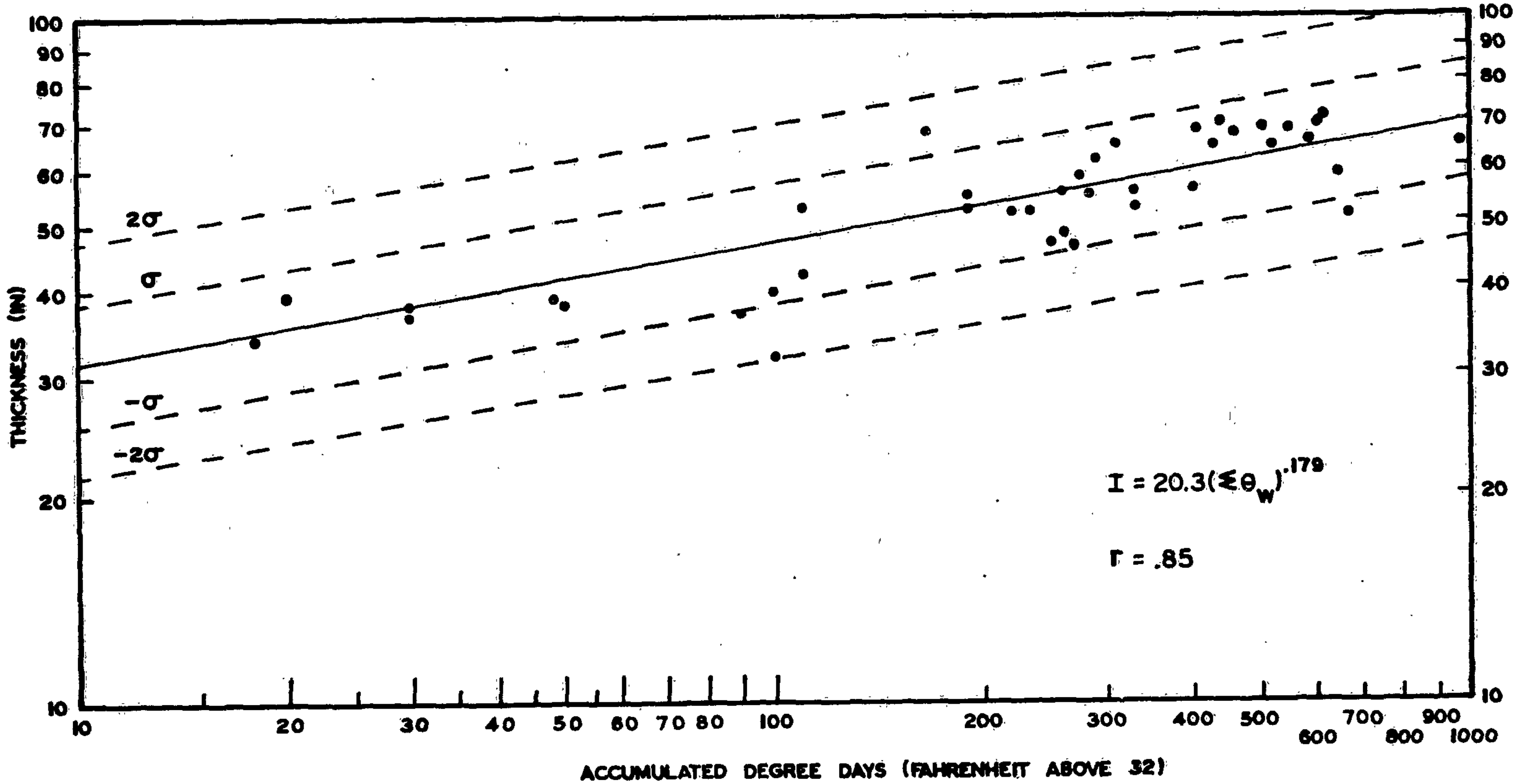


FIGURE 20 MAXIMUM THICKNESS OF OFFSHORE PACK ICE WHICH WAS COMPLETELY MELTED FOR VARIOUS WARMING DEGREE DAYS

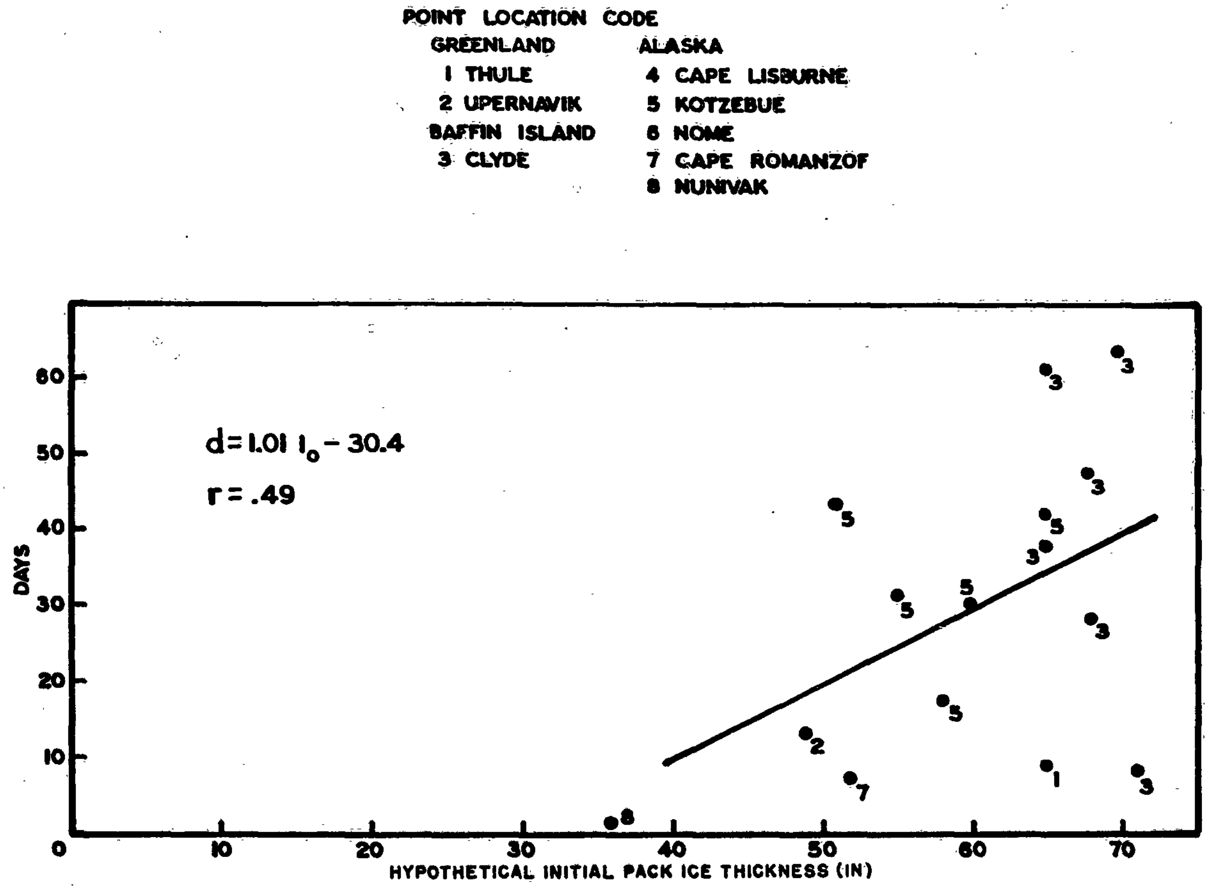


FIGURE 21 DAYS AFTER SMOOTHED AIR TEMPERATURE REACHED 23°F TO DECREASE OFFSHORE CONCENTRATION TO CLOSE PACK ICE

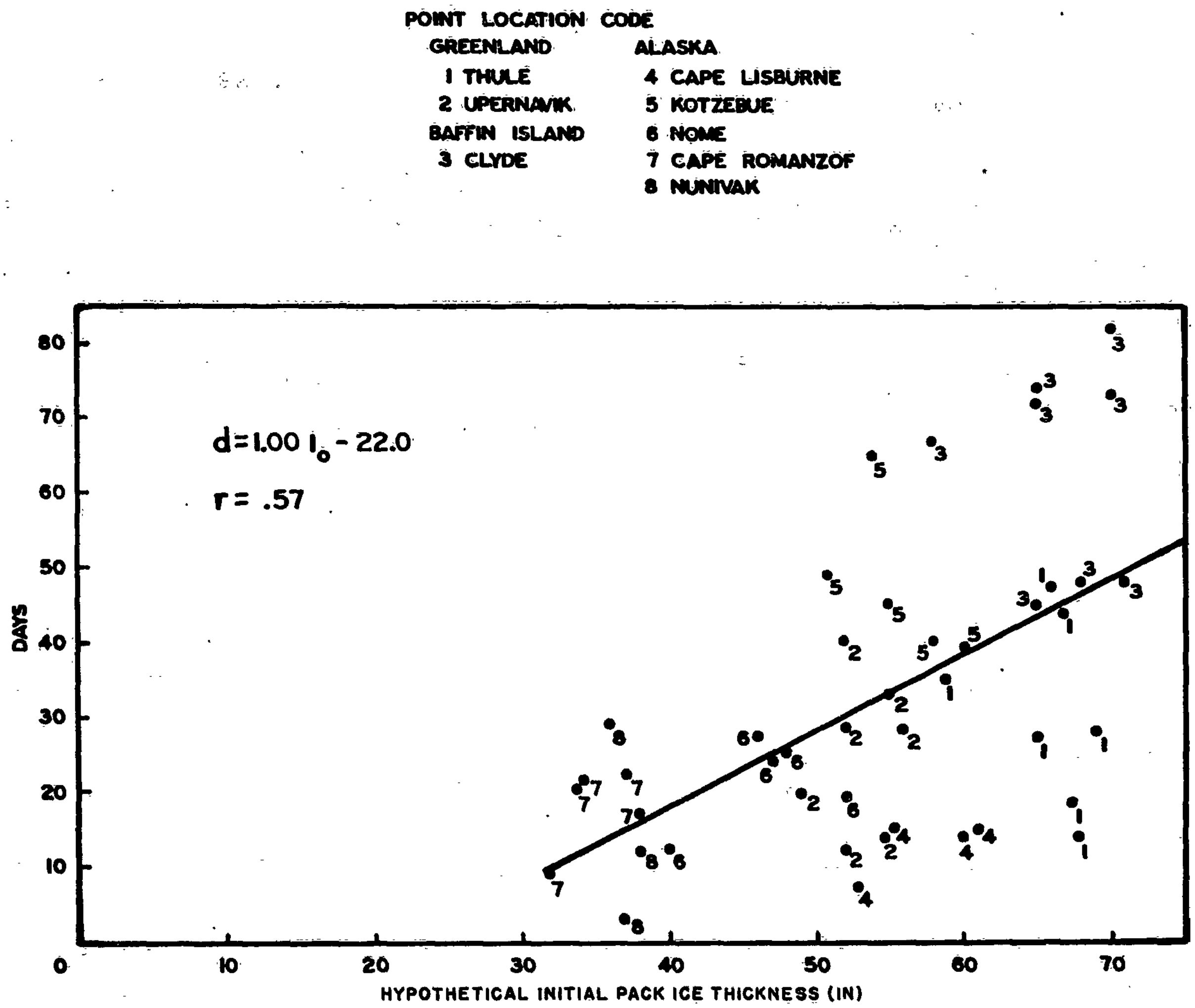


FIGURE 22 DAYS AFTER SMOOTHED AIR TEMPERATURE REACHED 23°F TO DECREASE OFFSHORE CONCENTRATION TO OPEN PACK ICE

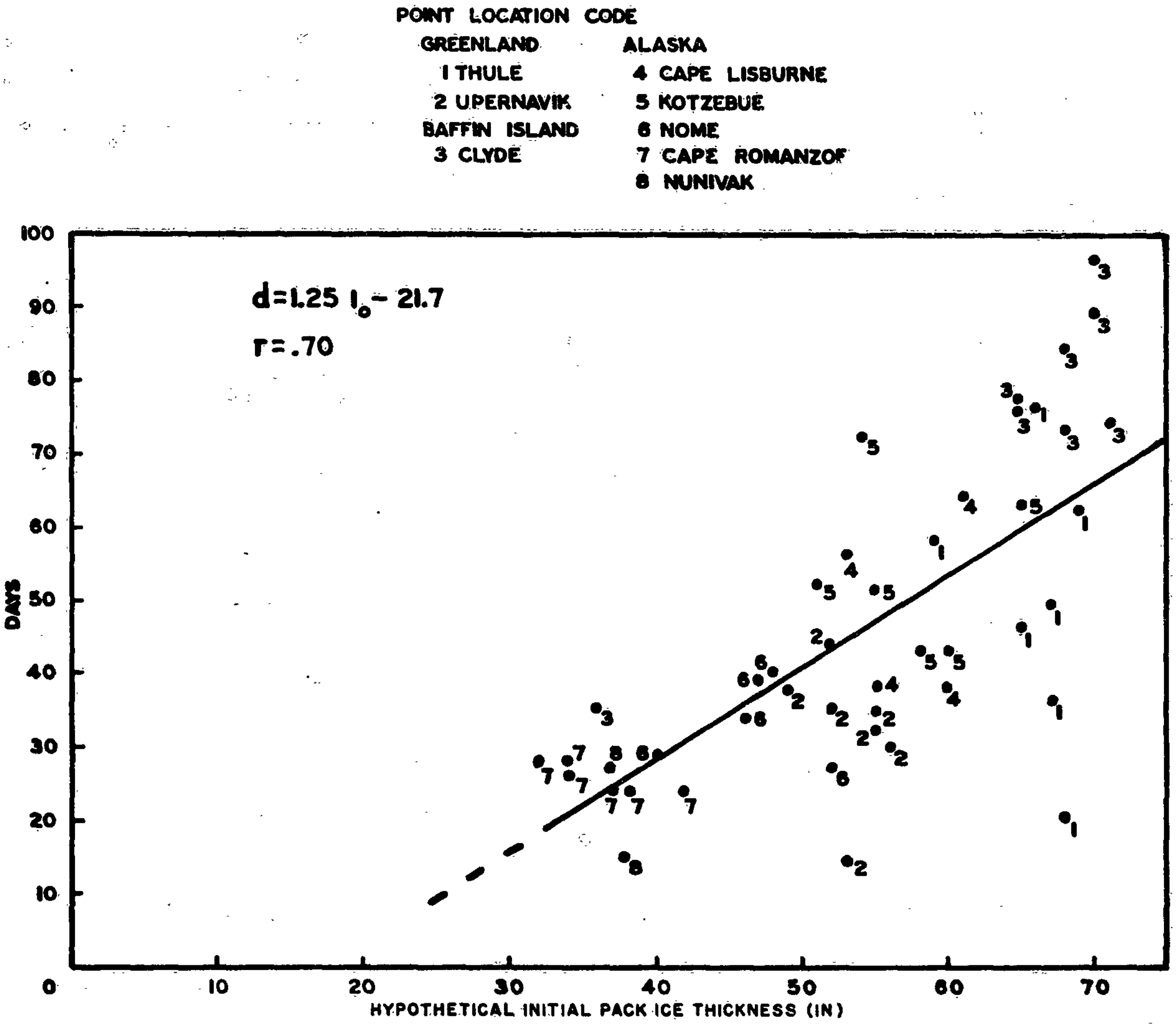


FIGURE 23 DAYS AFTER SMOOTHED AIR TEMPERATURE REACHED 23°F TO DECREASE OFFSHORE CONCENTRATION TO VERY OPEN PACK ICE

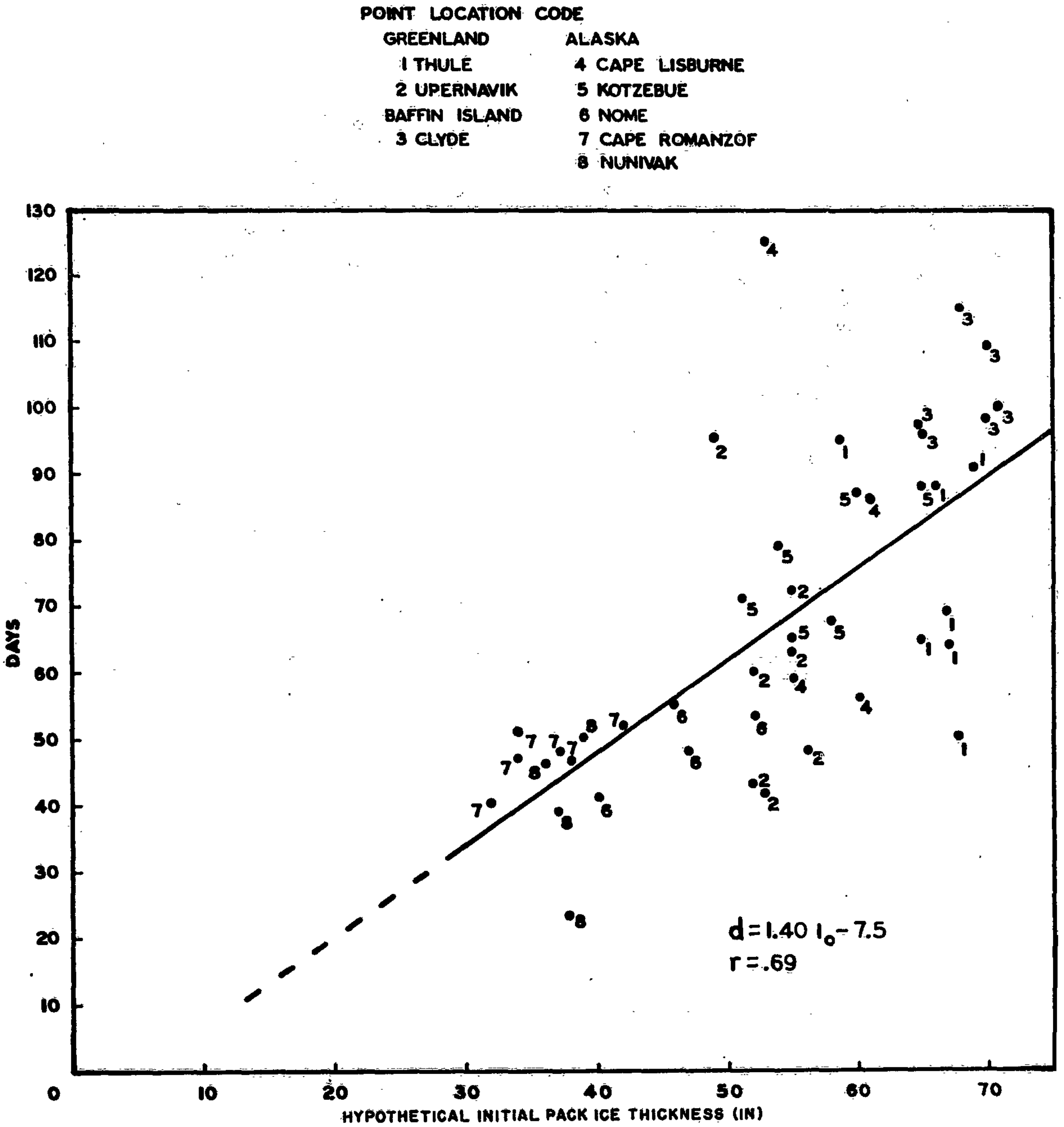


FIGURE 24 DAYS AFTER SMOOTHED AIR TEMPERATURE REACHED 23°F TO COMPLETELY MELT OFFSHORE PACK ICE

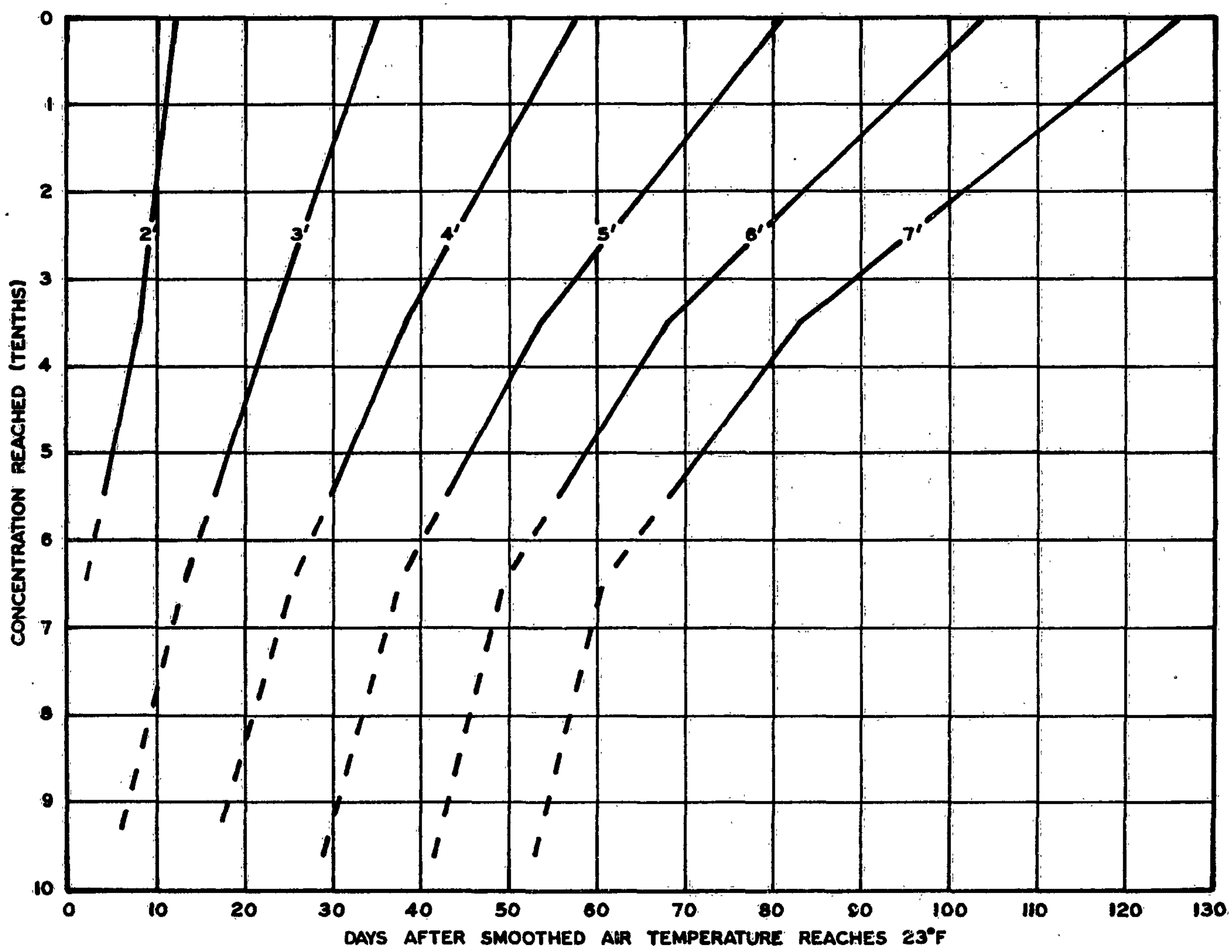


FIGURE 25 FORECASTING AID FOR OFFSHORE CONCENTRATION USING DAYS AFTER SMOOTHED AIR TEMPERATURE EXCEEDS 23°F FOR VARYING INITIAL ICE THICKNESSES

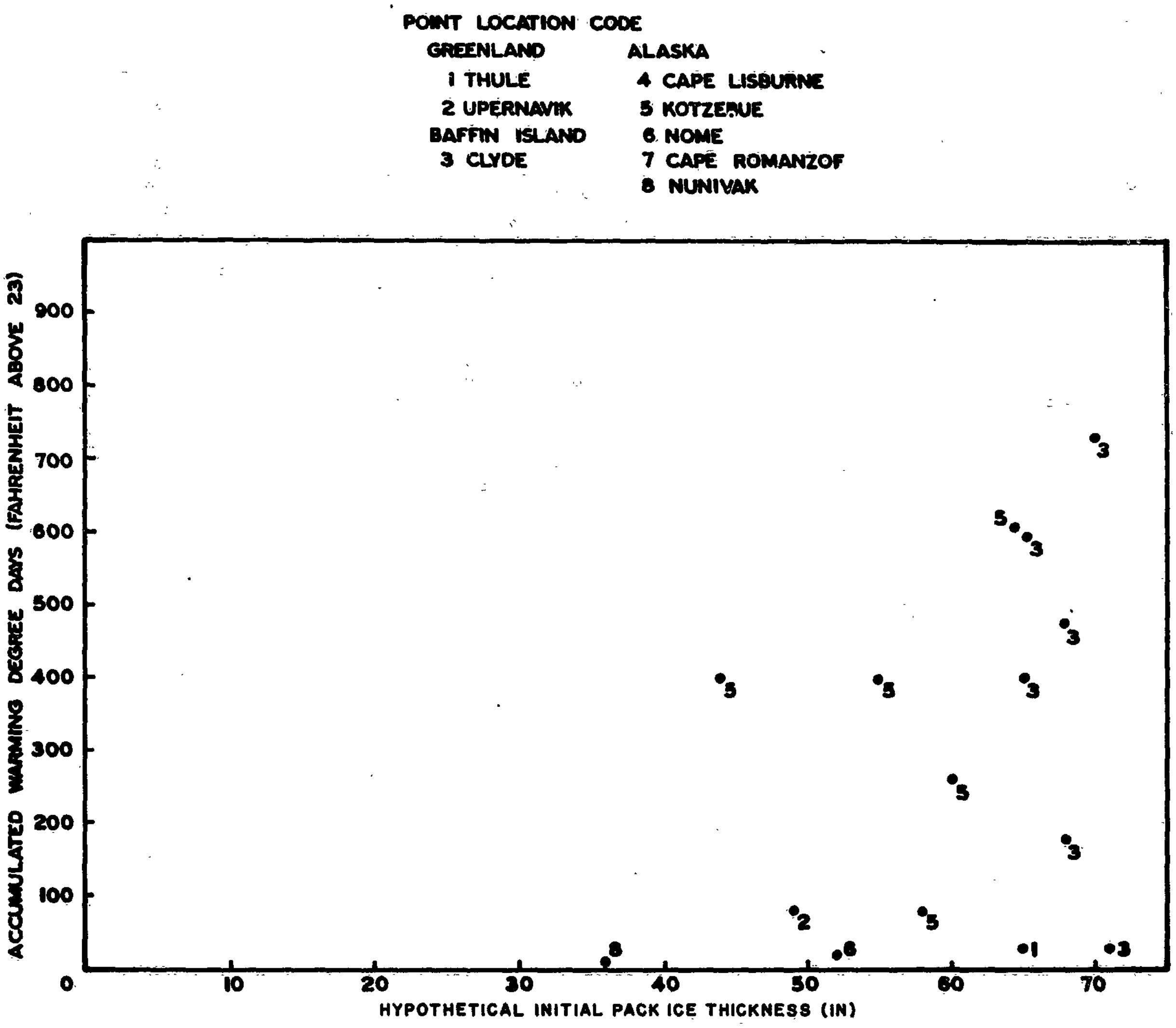


FIGURE 26 ACCUMULATED WARMING DEGREE DAYS ASSOCIATED WITH CONCENTRATION DECREASE TO CLOSE PACK ICE

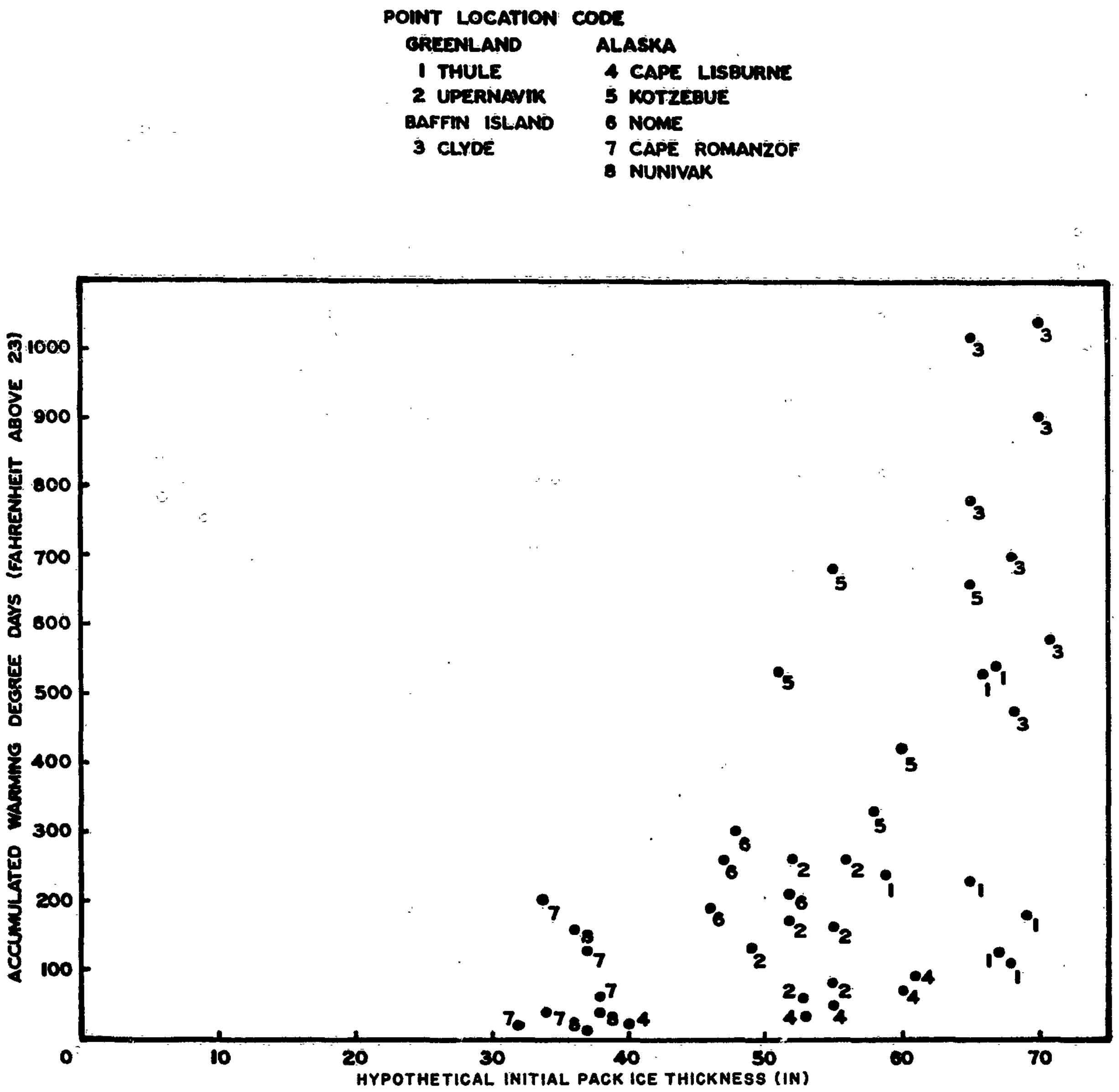


FIGURE 27 ACCUMULATED WARMING DEGREE DAYS ASSOCIATED WITH CONCENTRATION DECREASE TO OPEN PACK ICE

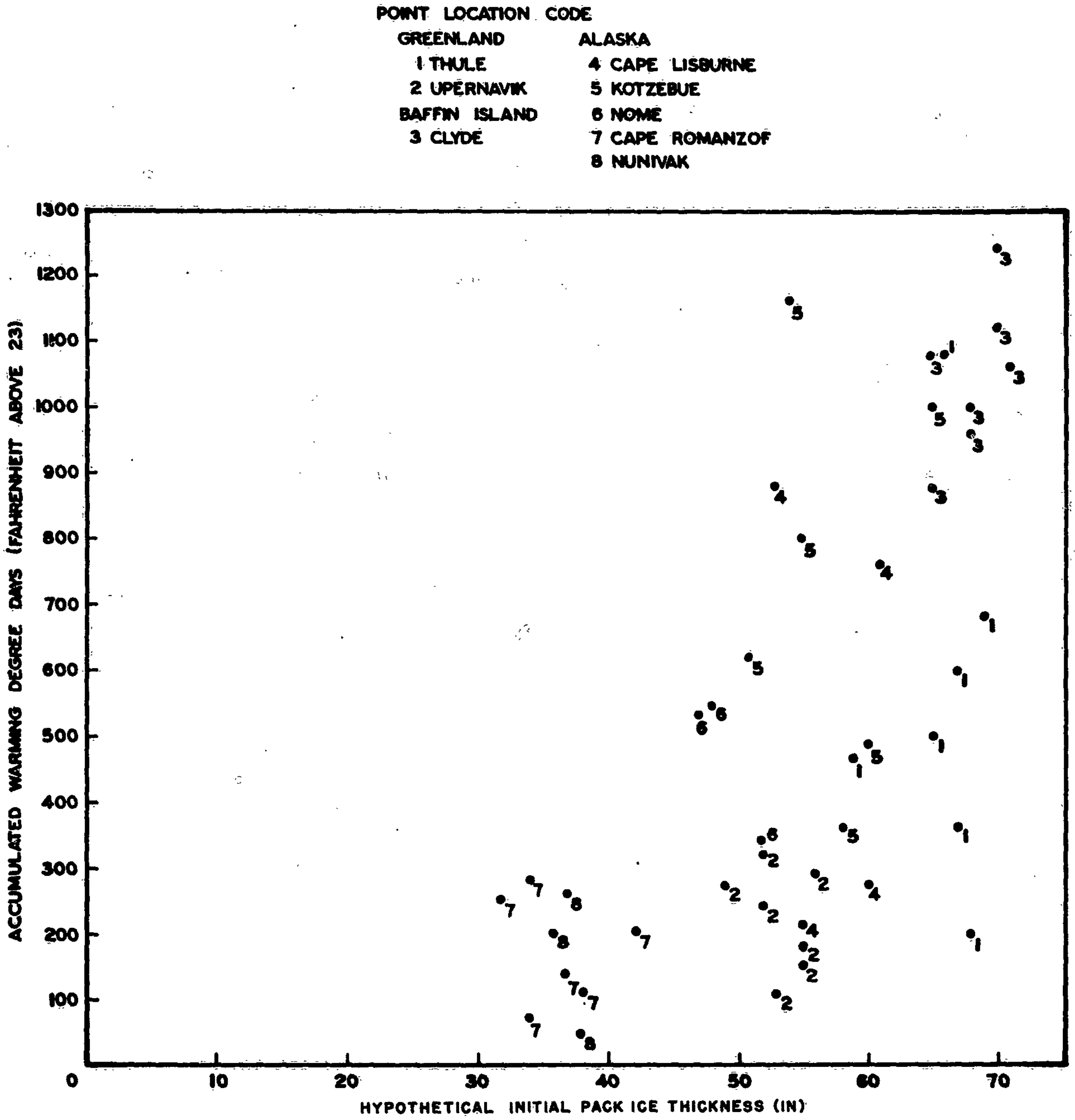


FIGURE 28 ACCUMULATED WARMING DEGREE DAYS ASSOCIATED WITH CONCENTRATION DECREASE TO VERY OPEN PACK ICE

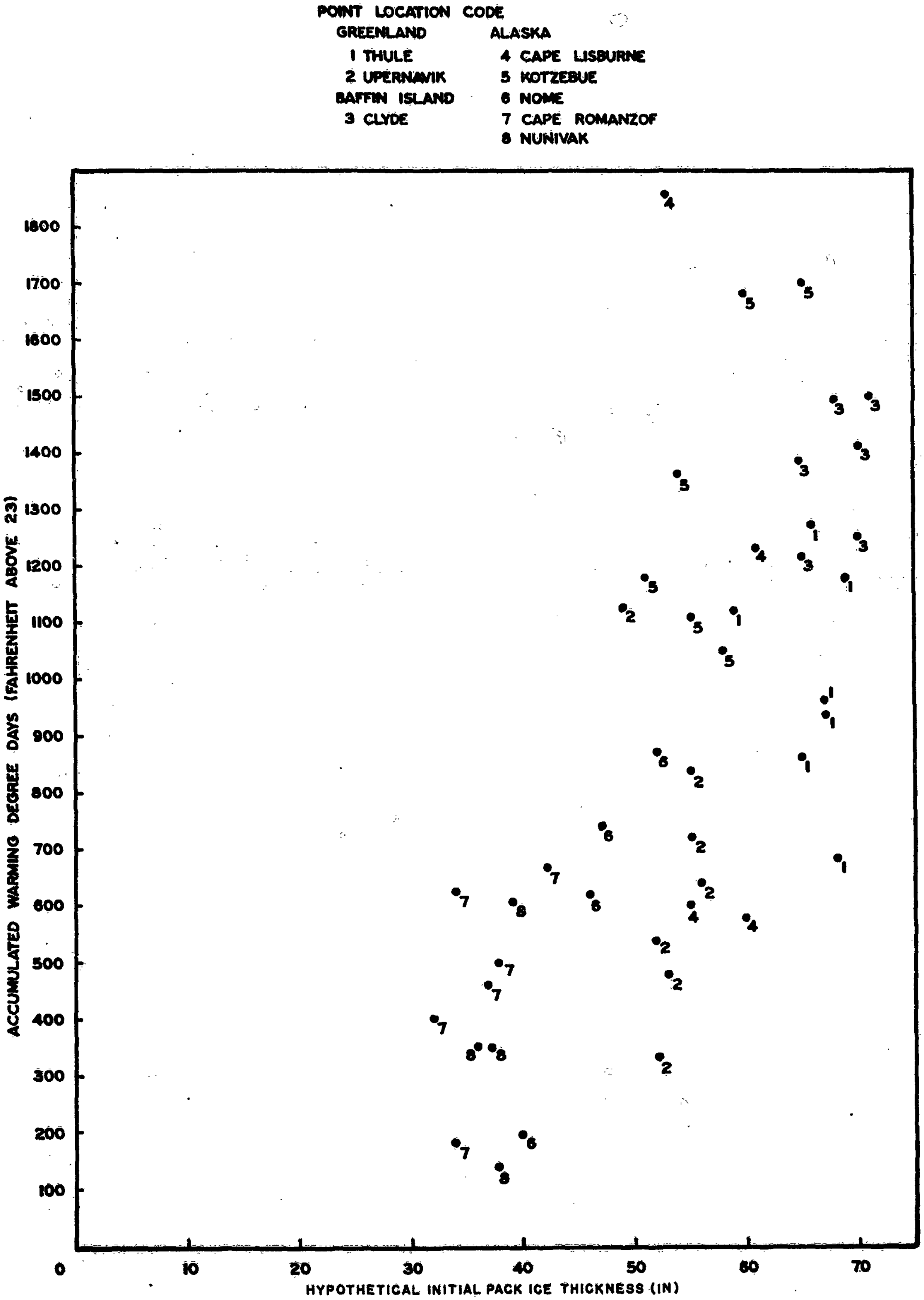


FIGURE 29 ACCUMULATED WARMING DEGREE DAYS ASSOCIATED WITH FINAL DISAPPEARANCE OF OFFSHORE PACK ICE

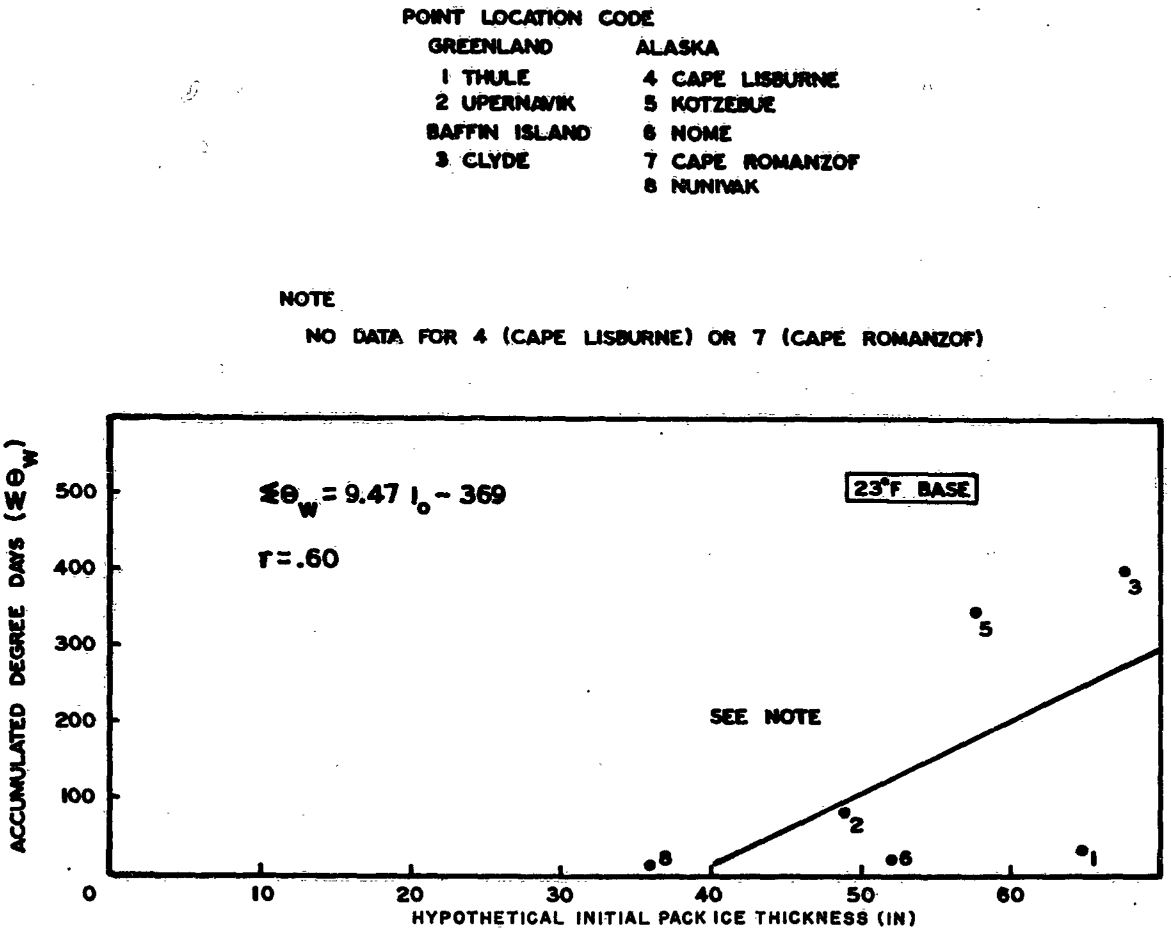


FIGURE 30 ACCUMULATED WARMING DEGREE DAYS REQUIRED TO DECREASE OFFSHORE CONCENTRATION TO CLOSE PACK ICE PLOTTED AS MEANS FOR EACH LOCATION

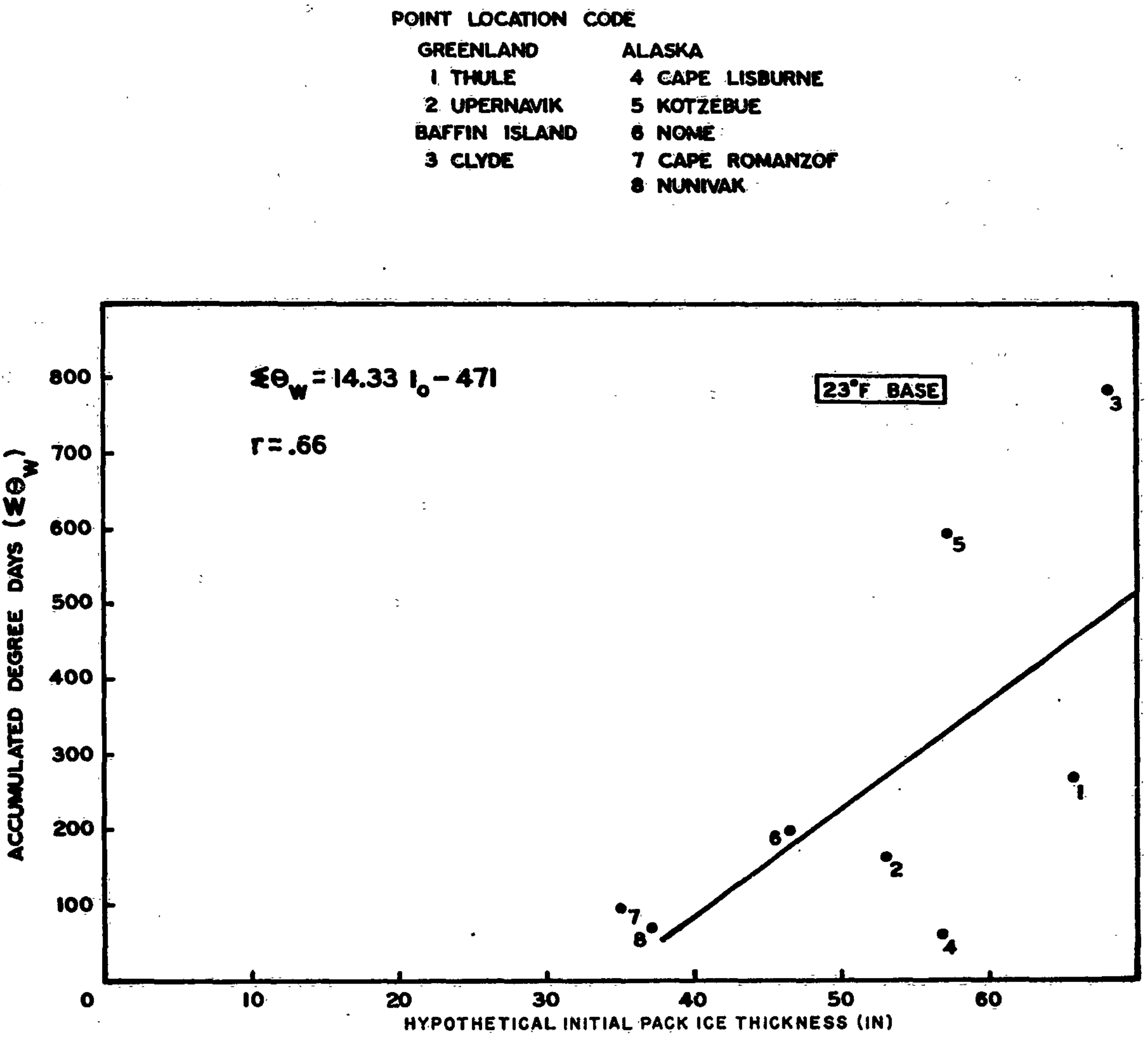


FIGURE 31 ACCUMULATED WARMING DEGREE DAYS REQUIRED TO DECREASE OFFSHORE CONCENTRATION TO OPEN PACK ICE PLOTTED AS MEANS FOR EACH LOCATION

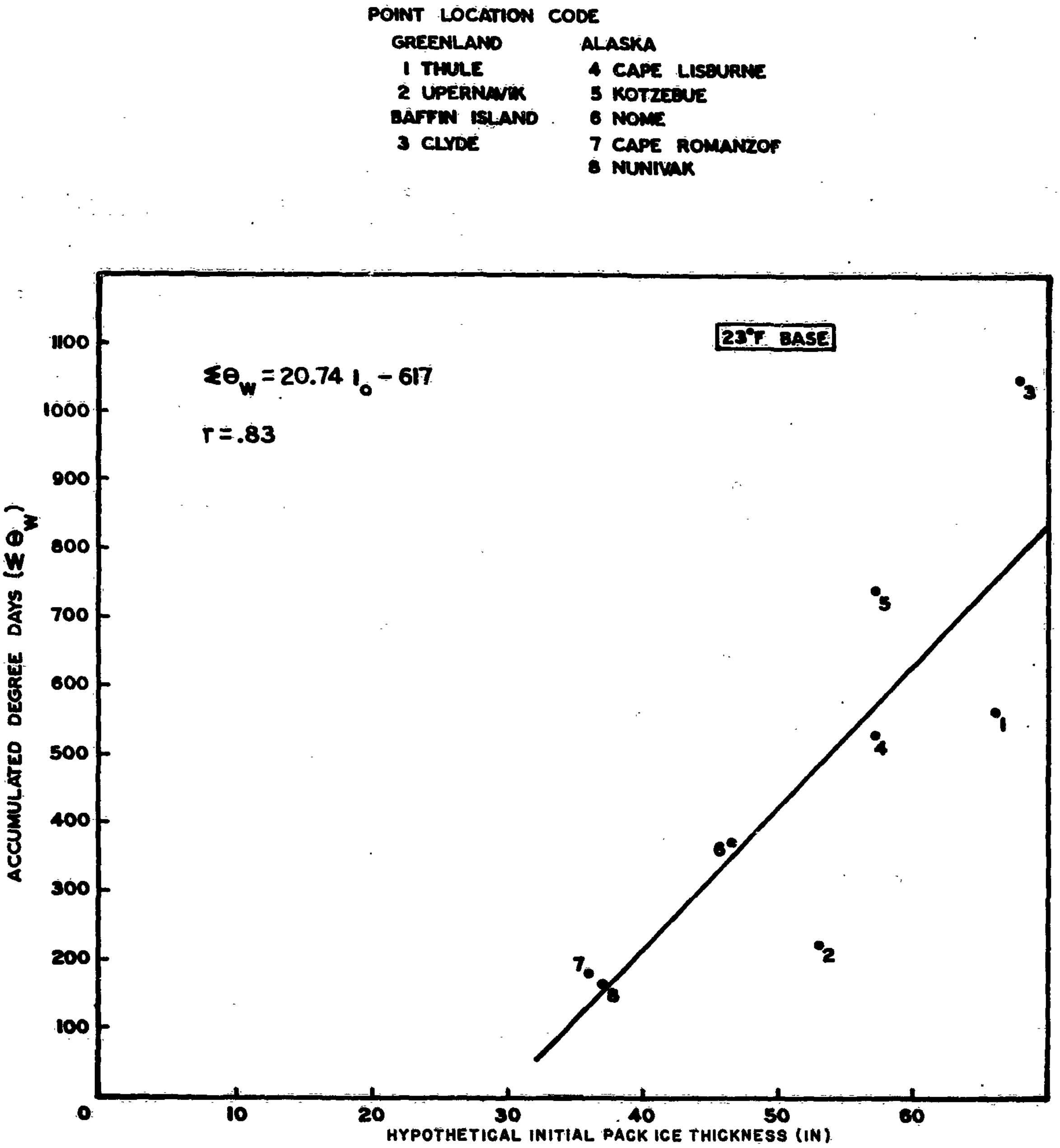


FIGURE 32 ACCUMULATED WARMING DEGREE DAYS REQUIRED TO DECREASE OFFSHORE CONCENTRATION TO VERY OPEN PACK ICE PLOTTED AS MEANS FOR EACH LOCATION

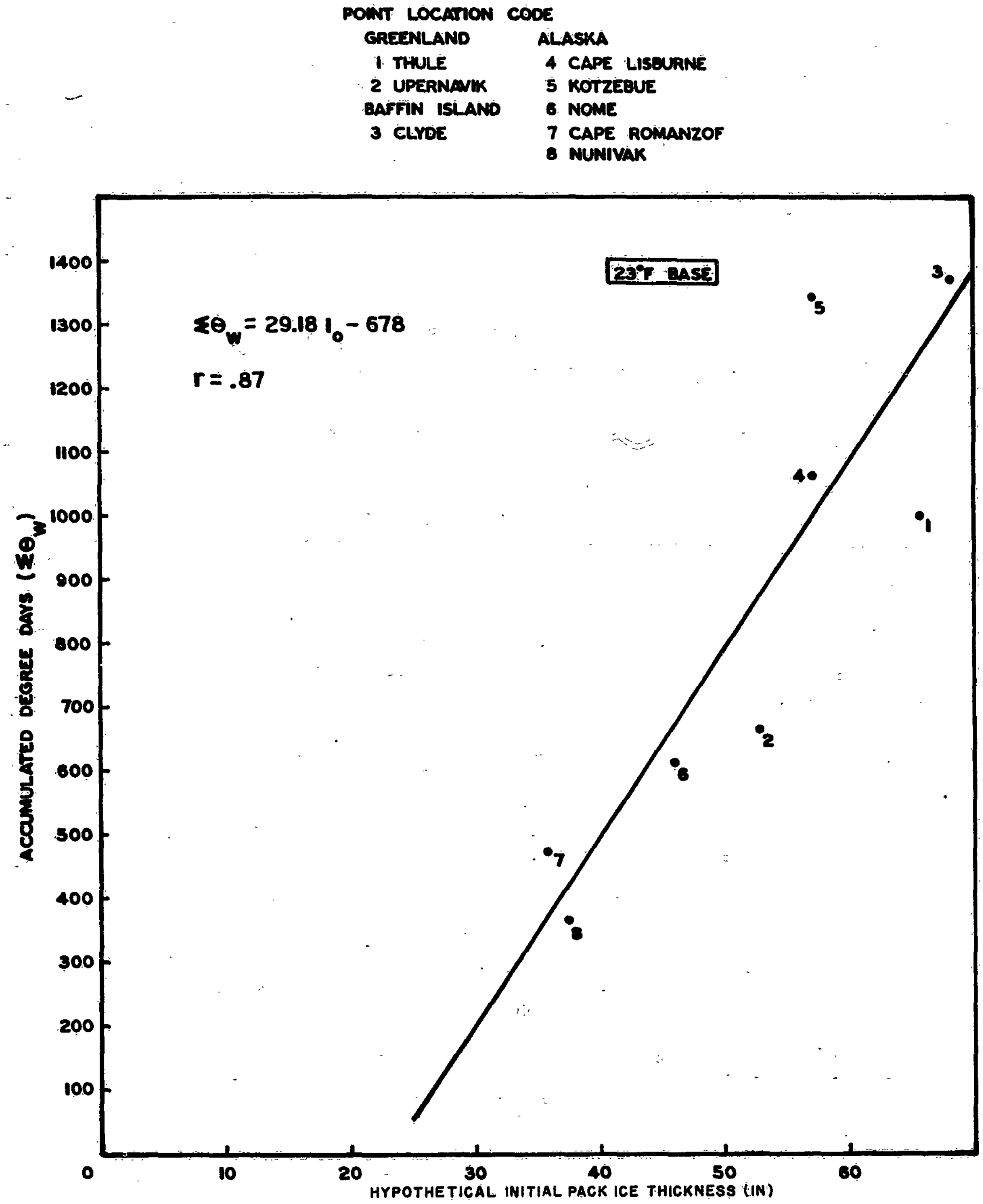


FIGURE 33 ACCUMULATED WARMING DEGREE DAYS REQUIRED TO COMPLETELY MELT OFFSHORE PACK ICE PLOTTED AS MEANS FOR EACH LOCATION

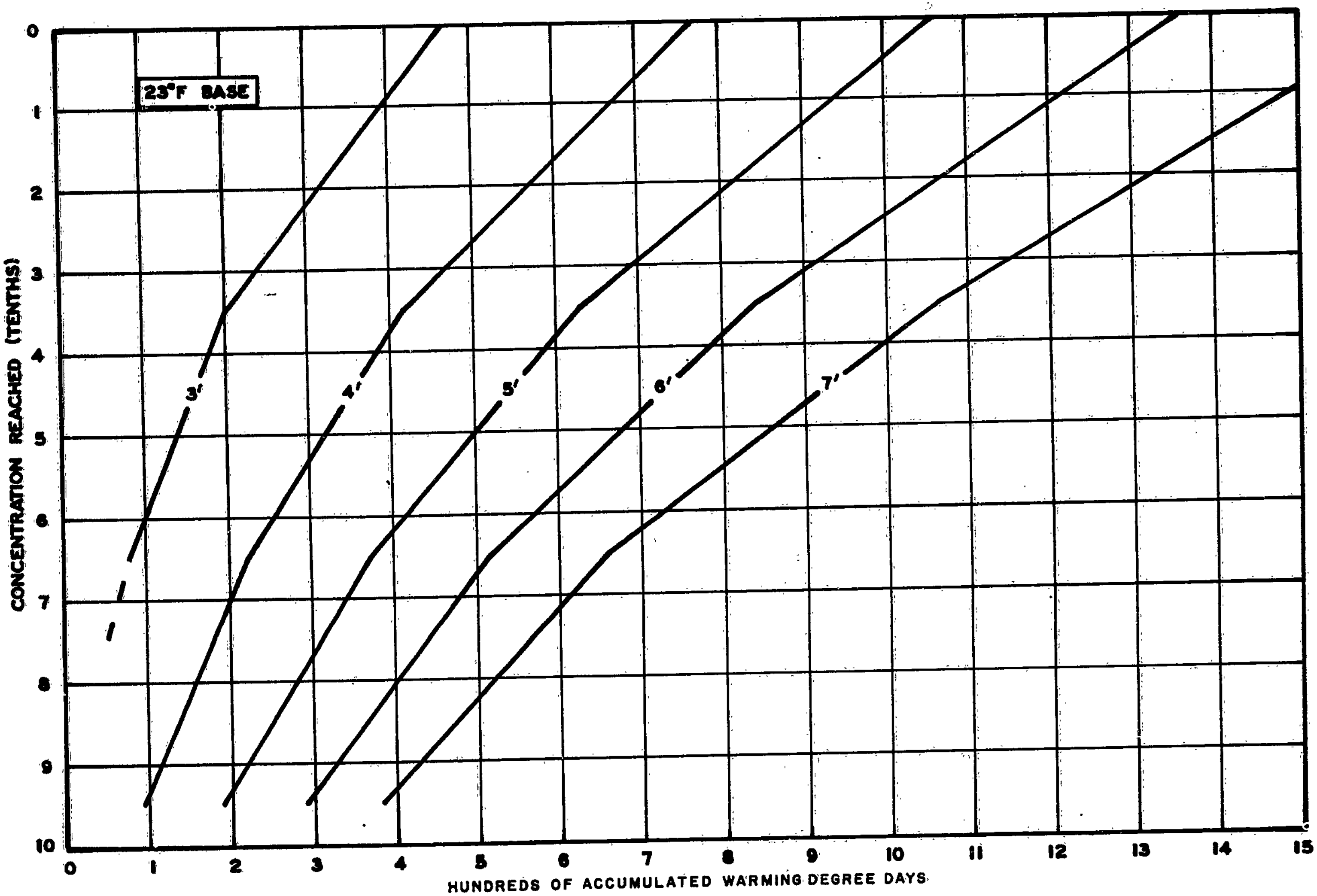


FIGURE 34 FORECASTING AID FOR OFFSHORE CONCENTRATION USING ACCUMULATED WARMING DEGREE DAYS FOR VARYING INITIAL ICE THICKNESSES

APPENDIX A

Operational References

Experience gained in the Arctic is recorded mainly in various operational reports. A partial list of the reports available at the Naval Oceanographic Office is included in this appendix.

A few specific ice forecasting comments from these reports are summarized below:

1. Planning of the operation should be flexible enough so that changes can be made in execution as suggested by ice conditions. It is recommended that an experienced ice forecaster be available to the operational commander aboard the flagship in order to make optimum use of predicted ice conditions. The 5- and 30-day ice forecasts furnished by NAVOCEANO are considered valuable for planning but are too general to be used as a guide for day-to-day decisions.

2. Emphasis on facsimile transmission of ice condition charts was unanimously recommended. Criticism was made of the small scale of these charts (4). Some commands recommended supplementary word messages for filling gaps caused by poor facsimile reception. One command recommended repeating the facsimile charts when reception had improved.

3. Several reports distinguished between two types of ice forecasts: offshore ice conditions for the benefit of shipping and ice in the anchorages and grounded on the beaches for the benefit of offloading operations. Difficulties have been reported in handling this second type of forecast by someone other than a forecaster on the scene.

4. Several reports mention annual differences in ice conditions. One report (1) criticized strict adherence to a prearranged reconnaissance schedule which neglected the ship operating areas at the time the ships were there.

5. The same report mentioned drifts of as much as 40 miles in a 15-hour period by ships beset in ice near Point Barrow. Several reports mentioned that the current in the vicinity of Point Barrow generally flowed northeastward at 1 to 2.5 knots. However, in 1955 and 1957, a southerly set was observed during several periods in August.

6. In some cases, lack of an ice prediction service in areas where ice conditions were more severe than anticipated resulted in expressed desirability of such a service (2).

7. A discussion of the eastward escape route for Pacific ships which might be trapped by the closing of the polar pack onto Point Barrow is given in a COMSTS report (3). A maximum tidal current of 7 knots was observed in Bellot Strait (5).

8. Importance of tides in eastern areas where the range is significant is shown by the following quotation from the USS ATKA report (6). "On numerous occasions during the transit of Smith Sound, ice conditions were so acute that to batter and ram the hard polar pack was futile and only produced hull and propeller damage. Under these conditions, patience proved to be the wiser solution, as it soon became evident that a few hours' wait meant a change in the tides resulting in shifting of the pack and the relief of pressure."

9. In early years of the forecasting program (1953), there was considerable criticism of the optimism in ice forecasts along the northern Labrador coast. Subsequent to opening of Hopedale and Saglek to shipping one year, southward drifting ice caused severe problems.

10. The danger of planning an operation on the sole basis of ice conditions experienced in several past seasons is cited in several reports. In briefing, ice forecasters should emphasize annual and seasonal variability in ice conditions.

Western North American Arctic

COMMANDER AMPHIBIOUS GROUP ONE (CTG 5.1) Post Operation Report, Commander Joint Task Group WEST (Project 572), by RADM F. C. Stelter, Jr. 6 September 1957. CONFIDENTIAL.

COMMANDER TASK GROUP 93.8 Post Operation Report, 1959 DEWLINE SEALIFT OPERATIONS, by CAPT W. C. Foster. USCGC STORIS (WAG-38), September 1959. Annex B is CONFIDENTIAL.

COMMANDING OFFICER, USCGC NORTHWIND (WAGB-282). Report of 1961 Fall Arctic Cruise, by CAPT R. R. Waesche. 6 December 1961. UNCLASSIFIED.

1. COMMANDING OFFICER, USS BURTON ISLAND (AGB-1). Operation Report of Icebreaker and Hydrographic Operations, summer 1960, by CDR G. C. Evans, Jr., 1960. UNCLASSIFIED.

COMMANDING OFFICER, USS STATEN ISLAND (AGB-5). Post Operation Report of Icebreaker and Hydrographic Operations, by CDR W. L. Larson. 22 September 1961. UNCLASSIFIED.

2. COMMANDING OFFICER, USS STATEN ISLAND (AGB-5). Post Operational Report of Arctic Operations WEST-Icebreaker and Hydrographic Operations, by CDR W. L. Larson. 14 September 1959. UNCLASSIFIED.

Combined Western and Eastern North American Arctic

COMMANDER MILITARY SEA TRANSPORTATION SERVICE. Post Operation Report of MSTS Arctic Operations 1955, by VADM F. C. Denebrink. Washington, D.C. 16 February 1956. CONFIDENTIAL.

-------. Report of MSTS Arctic Operations 1957, by VADM J. M. Will. Washington, D.C., 25 March 1958. UNCLASSIFIED.

Eastern North American Arctic

COMMANDER, MILITARY SEA TRANSPORTATION SERVICE, ATLANTIC AREA. Post Operation Report of MSTSLANT Arctic Operations 1957, by RADM D. T. Eller. 20 December 1957. UNCLASSIFIED.

3. -------. Post Operation Report of MSTS Arctic Operations EAST 1958, by RADM D. T. Eller. 22 December 1958. UNCLASSIFIED.

-------. Post Operation Report of MSTS Arctic Operations EAST 1959, by RADM D. T. Eller. December 1959. UNCLASSIFIED.

4. -------. Post Operation Report of MSTS Arctic Operations EAST 1961, by CDR Griffith C. Evans, Jr. 3 November 1961. UNCLASSIFIED.

5. COMMANDER TASK GROUP 6.5. Operation Bellot, by CAPT T. C. Pullen. HMCS LABRADOR, 23 September 1957. UNCLASSIFIED.

6. COMMANDING OFFICER, USS ATKA (AGB-3). Lake Hazen-Polaris Promontory Post Operation Report, by CDR W. H. Reinhardt. 4 November 1958. UNCLASSIFIED.

General

Arctic Institute of North America. The Arctic Basin, coordinated by John E. Sater. Washington, D. C., 1963

Tait, A. J. "The Operational Concept for Sea Ice Reconnaissance and Forecasting Program Conducted During Arctic Operations," in Arctic Sea Ice. Washington, D.C., 1958. pp. 265-267 (NAS-NRC Pub. 598)

U.S. Navy Department. Naval Arctic Operations Handbook Part I and II, prepared by the Arctic and Cold Weather Coordinating Committee of the Office of the Chief of Naval Operations 1949. 2nd edition, 1950. Washington, D.C. 484 pp.

U.S. Navy Hydrographic Office. (U.S. Naval Oceanographic Office) Manual of Ice Seamanship, 1950. 128 pp. (H.O. Pub 551)

APPENDIX B

Sea Ice Distribution References

Canadian Hydrographic Service Surveys and Mapping Branch Department of Mines and Technical Surveys. Pilot of Arctic Canada, Vols. I, II, and III, reprinted 1960.

German Hydrographic Institute. Atlas der Eisverhaltnisse des Nordatlantischen Ozeans und Ubersichtskarten der Eisverhaltnisse des Nord- und Sudpolargebietes, Hamburg, 1950. (Pub No. 2335)

Schule, J. J., Jr., and W. I. Wittmann. "Comparative Ice Conditions in the North American Arctic, 1953 to 1955, Inclusive," AM GEOPHYS U T 39. pp 409-419, 1958.

U.S. Navy Hydrographic Office (U.S. Naval Oceanographic Office). Distribution of Ice, Amundsen Gulf to Shepherd Bay. March 1955, 47 pp. (Technical Report No. 25)

------. Distribution of Ice in Baffin Bay and Davis Strait, by H. S. Kaminski. February 1955, 31 pp (Technical Report No. 13)

------. Ice Atlas of the Northern Hemisphere. 1946a, 106 pp. (H.O. Pub 550)

------. Ice Conditions in Baffin Bay and the Labrador Sea Relevant to Proposed Cable Tracks and Cable Operations, by W. I. Wittmann. 1961 (Informal Manuscript No. 16-61). Unpublished.

------. Local Environmental Factors Affecting Ice Formation in North Star Bugt Greenland, by R. J. McGough. January 1953, 40 pp. (Technical Report No. 23)

------. Local Environmental Factors Affecting Ice Formation in Søndre Strømfjord Greenland, by J. R. D. Tapager. November 1956, 25 pp. (Technical Report No. 22)

------. Local Environmental Factors Affecting Ice Formation in Terrington Basin, Labrador, by O. S. Lee. December 1955, 20 pp. (Technical Report No. 24)

------. Oceanographic Atlas of the Polar Seas, Part II, Arctic. 1957, 149 pp. (H.O. Pub 705)

------. Proposed Arctic Drift Ship Station Study, by W. I. Wittmann. 1961, (Informal Manuscript No. 19-61). Unpublished

------. Report of Ice Observations and Forecasting for the Season, 1953. (H.O. Misc. 15869-1953)

------. Report of the Ice Observing and Forecasting Program, 1954. (Technical Report No. 49)

------. Report of the Ice Observing and Forecasting Program, 1955. (Technical Report No. 50)

------. Report of the Ice Observing and Forecasting Program, 1956. (Technical Report No. 51)

------. Report of the Ice Observing and Forecasting Program, 1957. (Technical Report No. 52)

------. Report of the Ice Observing and Forecasting Program, 1958. (Technical Report No. 66)

------. Report of the Ice Observing and Forecasting Program, 1959. (Technical Report No. 69)

------. Report of the Ice Observing and Forecasting Program, 1960. (Special Publication No. 70(60))

------. Report of the Ice Observing and Forecasting Program, 1961. (Special Publication No. 70(61)), (in preparation).

------. Report of the Ice Observing and Forecasting Program, 1962. (Special Publication No. 70(62)), (in preparation).

------. Report of Ice Operations Labrador Sea, Baffin Bay, and Canadian Arctic Summer 1952. (H.O. Misc 15721-52)

------. Sailing Directions for Northern Canada. 1946b. 775 pp. (H.O. Pub 77)

APPENDIX C

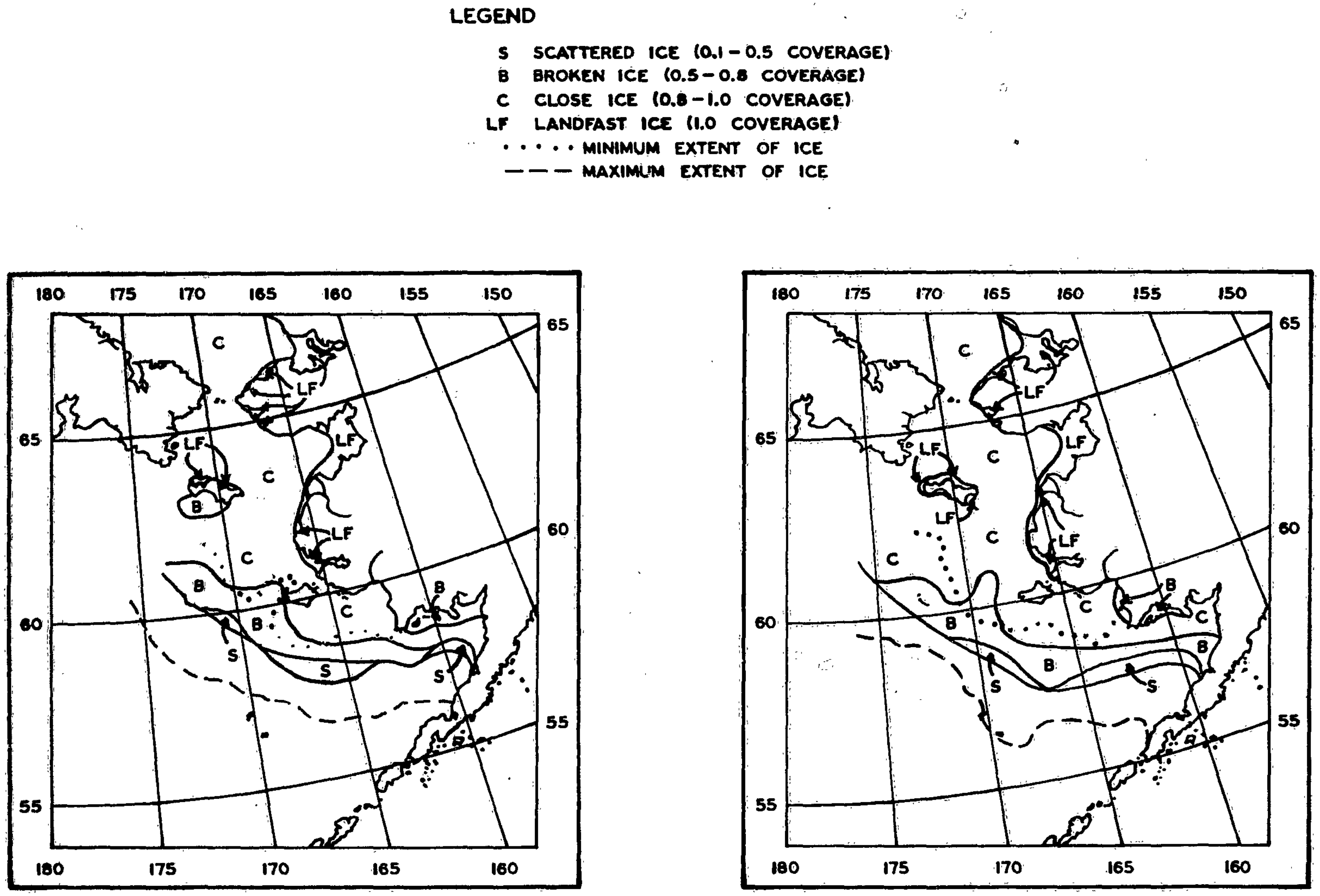
Supplemental Sea Ice Distribution Charts to H.O. Pub 705, Part II

Half-monthly average concentrations and extremes of sea ice conditions for the Bering Sea are presented in figures C-1 through C-12. Data were compiled from reports of the Ice Observing and Forecasting Program for the years 1954 through 1959 (TR-49, 50, 51, 52, 66, and 69) published by the Oceanographic Office.

Data are presented for 6-day periods throughout the ice season in these reports. The mid-monthly period (13th through 18th) is included in each half-monthly chart for determining average concentrations and extreme conditions. Scattered, broken, and close concentrations were weighted equally in the averaging process. Open water concentrations (< 0.1 coverage) were considered to be ice free.

The maximum and minimum boundaries of sea ice shown in figures C-1 through C-12 do not represent specifically observed anomalous conditions but are envelopes of the lowest and highest latitudes at which ice was observed in the data.

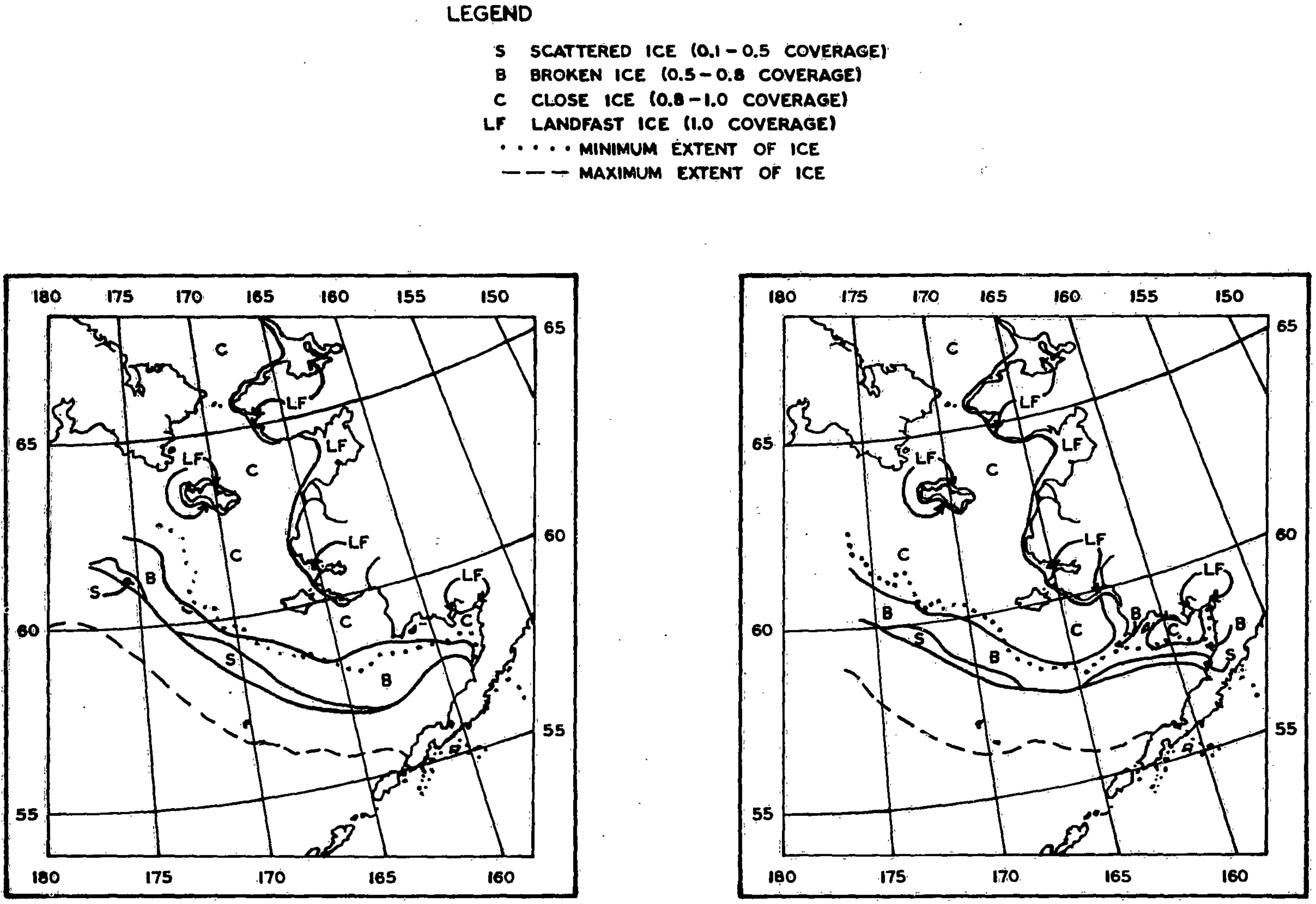
Averages and extremes for December were interpolated mainly from November and January data.



1-15 JANUARY

16-31 JANUARY

FIGURE C-1 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS



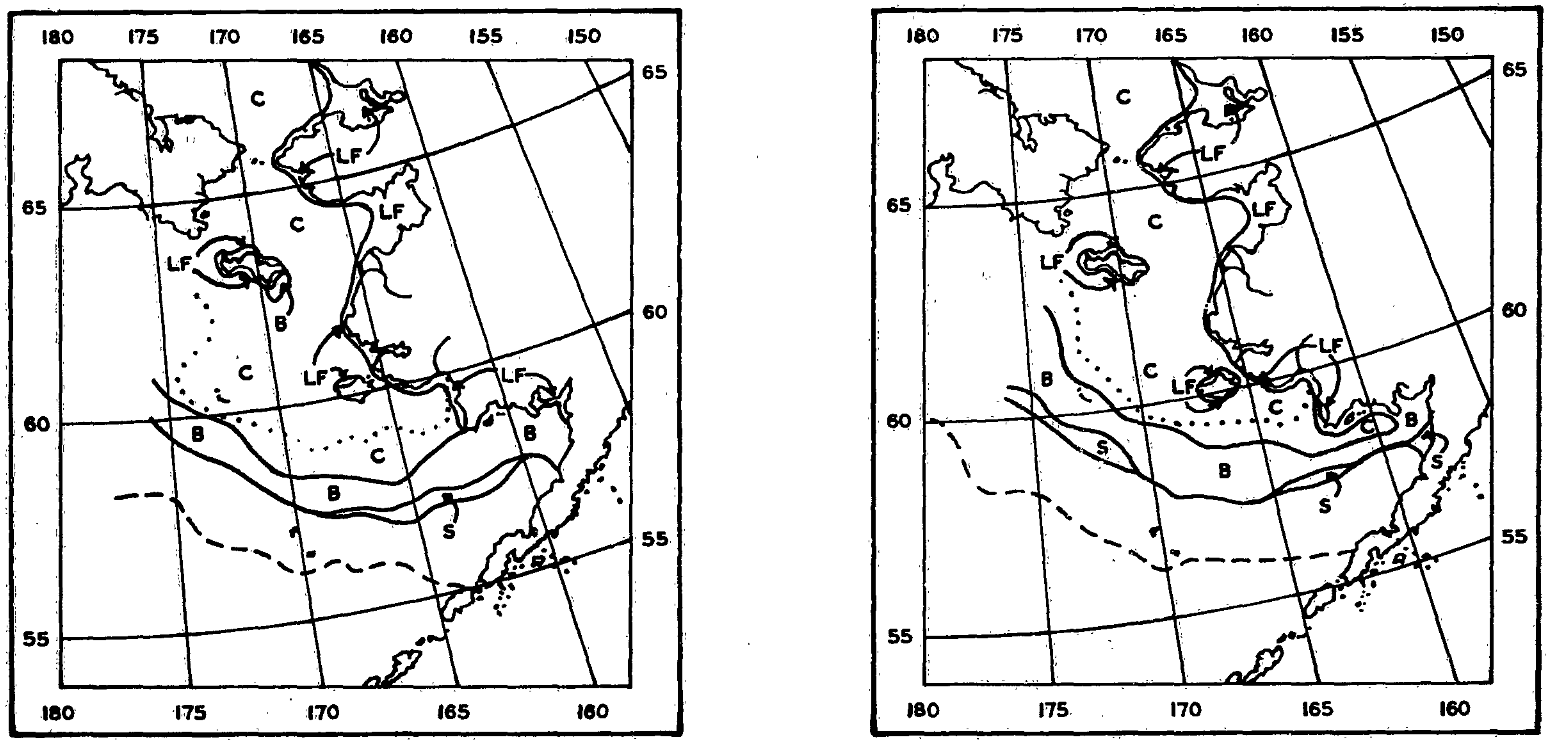
1-15 FEBRUARY

16-28 FEBRUARY

FIGURE C-2 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS

LEGEND

S SCATTERED ICE (0.1 – 0.5 COVERAGE)
B BROKEN ICE (0.5 – 0.8 COVERAGE)
C CLOSE ICE (0.8 – 1.0 COVERAGE)
LF LANDFAST ICE (1.0 COVERAGE)
• • • • • MINIMUM EXTENT OF ICE
— — — MAXIMUM EXTENT OF ICE



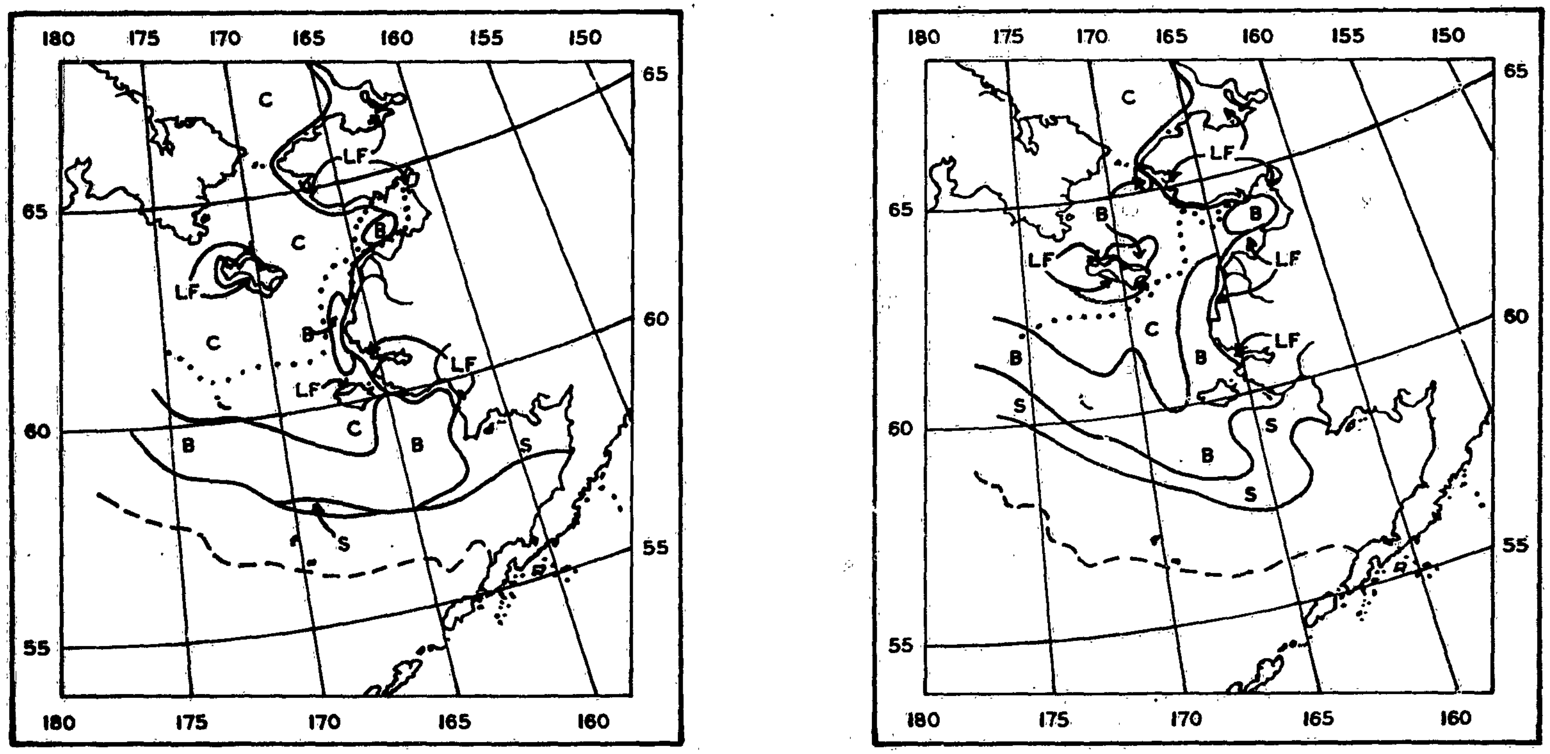
1-15 MARCH

16-31 MARCH

FIGURE C-3 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS

LEGEND

S	SCATTERED ICE (0.1 – 0.5 COVERAGE)
B	BROKEN ICE (0.5 – 0.8 COVERAGE)
C	CLOSE ICE (0.8 – 1.0 COVERAGE)
LF	LANDFAST ICE (1.0 COVERAGE)
• • • • •	MINIMUM EXTENT OF ICE
— — —	MAXIMUM EXTENT OF ICE



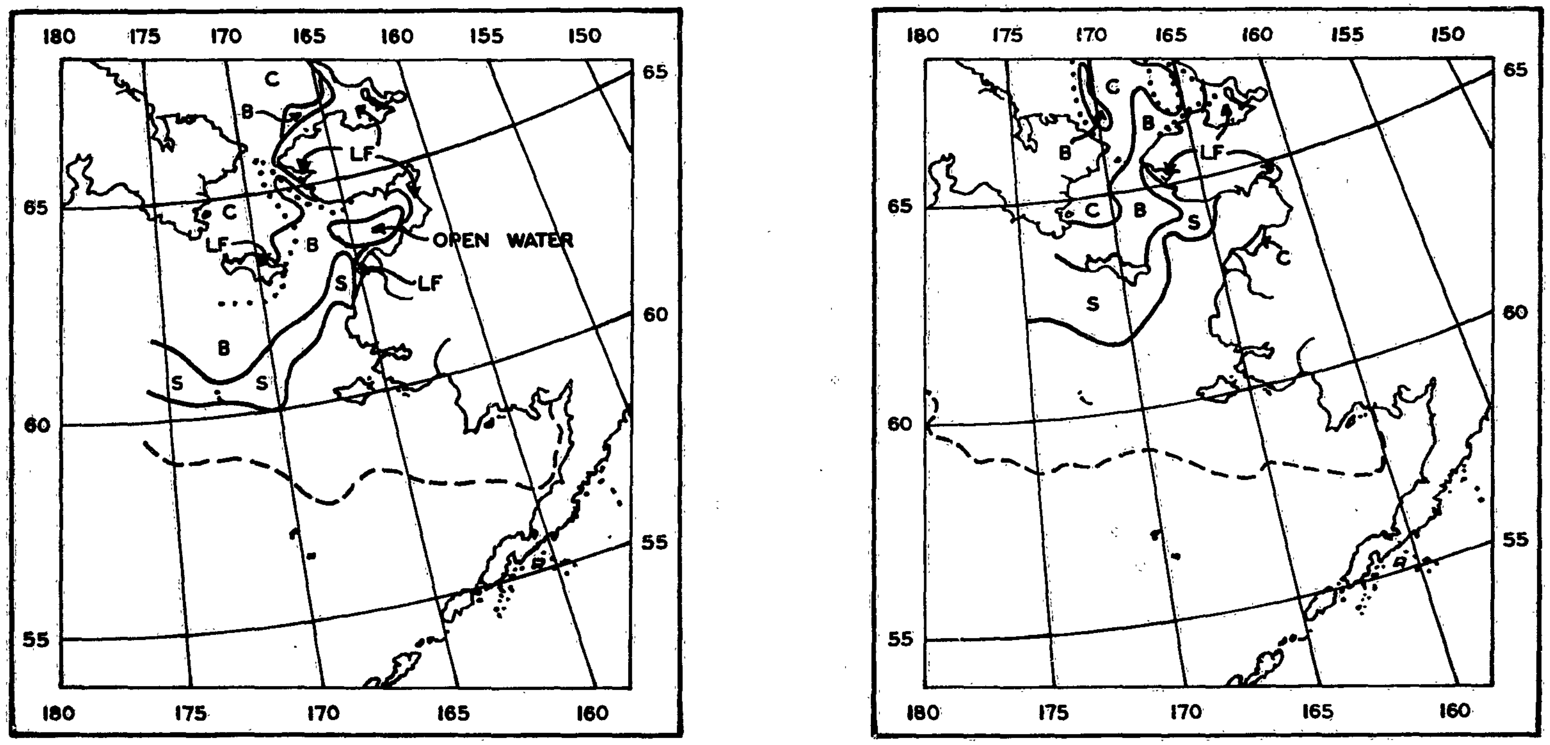
1-15 APRIL

16-30 APRIL

FIGURE C-4 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS

LEGEND

S SCATTERED ICE (0.1 – 0.5 COVERAGE)
B BROKEN ICE (0.5 – 0.8 COVERAGE)
C CLOSE ICE (0.8 – 1.0 COVERAGE)
LF LANDFAST ICE (1.0 COVERAGE)
• • • • • MINIMUM EXTENT OF ICE
— — — MAXIMUM EXTENT OF ICE



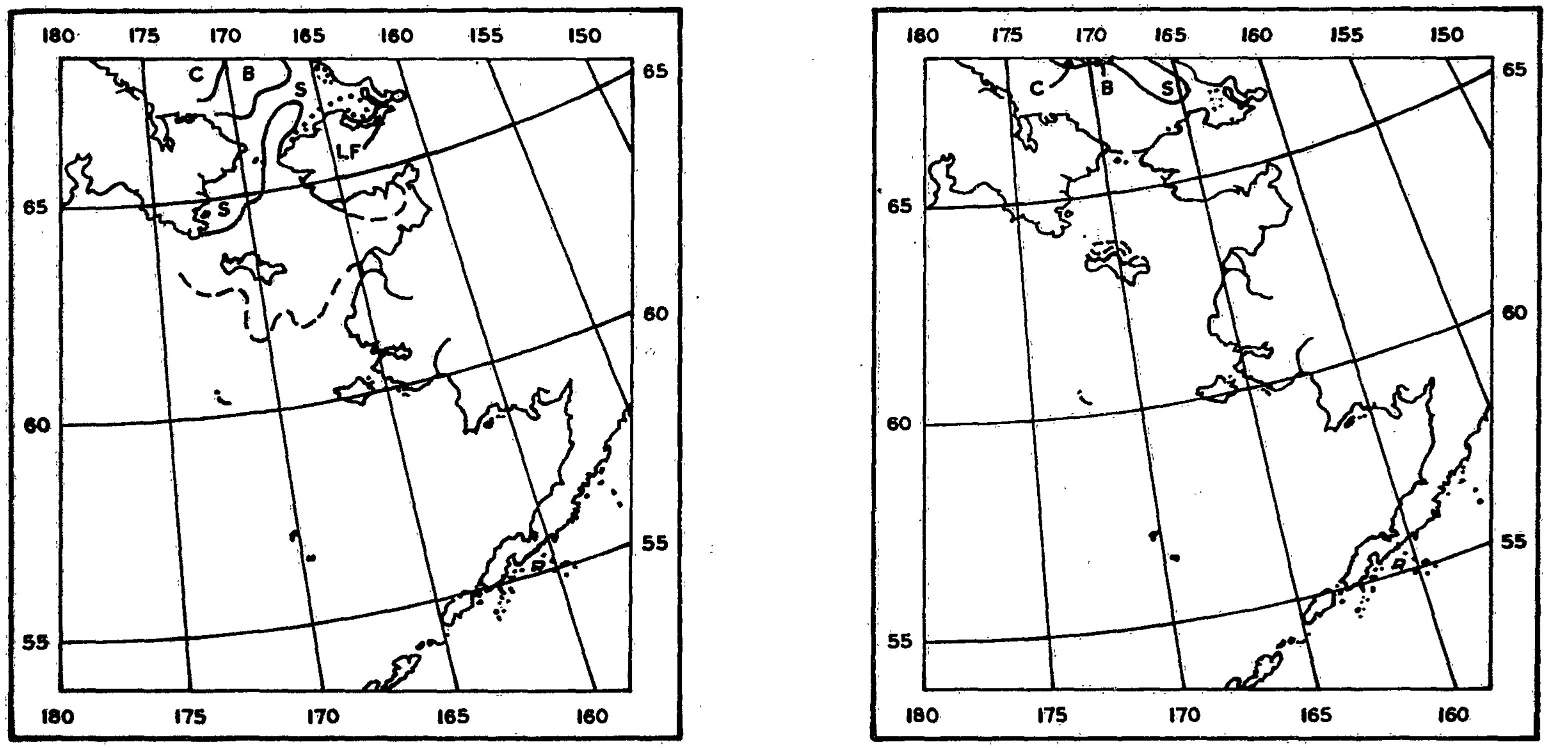
1-15 MAY

16-31 MAY

FIGURE C-5 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS

LEGEND

S SCATTERED ICE (0.1 – 0.5 COVERAGE)
B BROKEN ICE (0.5 – 0.8 COVERAGE)
C CLOSE ICE (0.8 – 1.0 COVERAGE)
LF LANDFAST ICE (1.0 COVERAGE)
• • • • • MINIMUM EXTENT OF ICE
— — — MAXIMUM EXTENT OF ICE



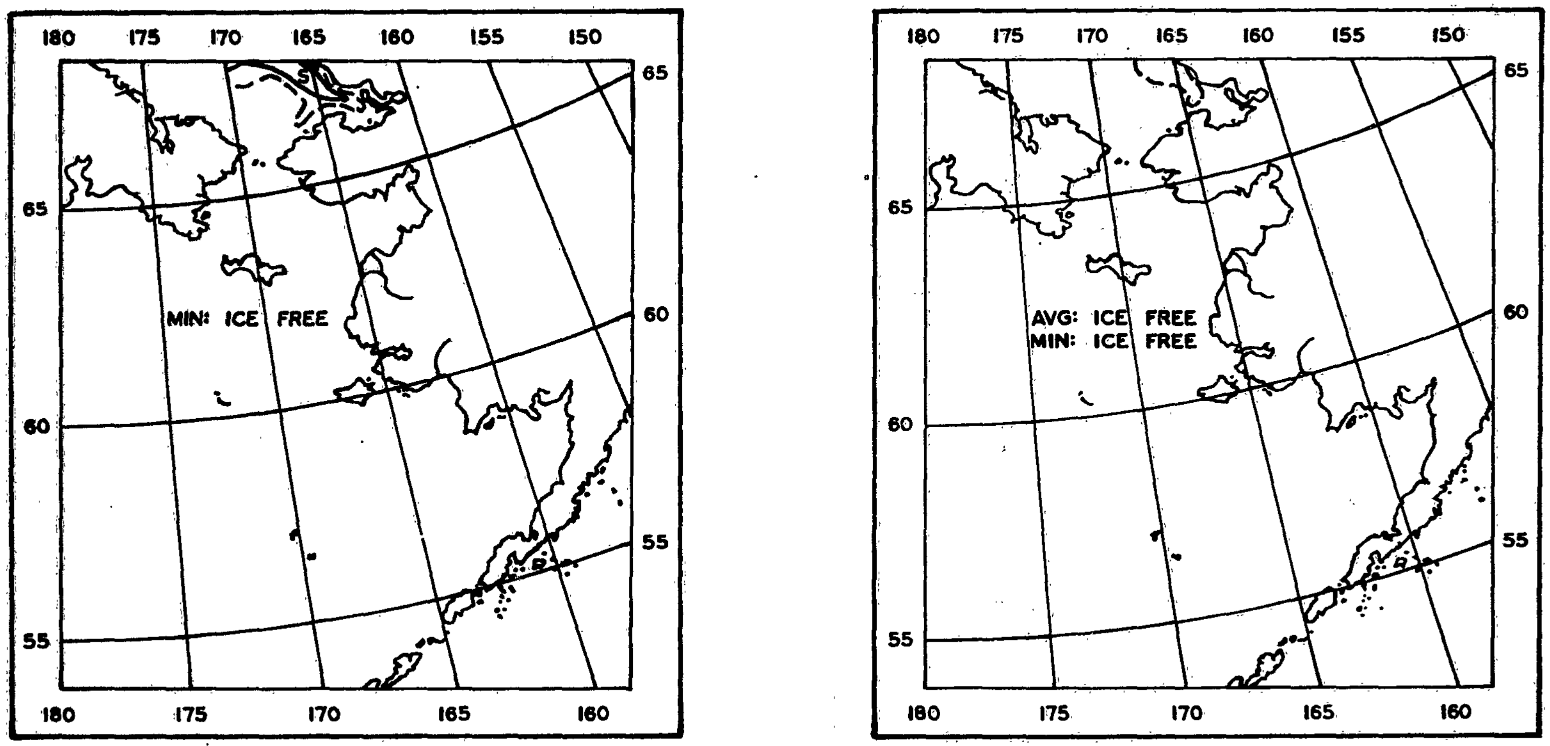
1-15 JUNE

16-30 JUNE

FIGURE C-6 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS

LEGEND

S SCATTERED ICE (0.1 – 0.5 COVERAGE)
B BROKEN ICE (0.5 – 0.8 COVERAGE)
C CLOSE ICE (0.8 – 1.0 COVERAGE)
LF• LANDFAST ICE (1.0 COVERAGE)
• • • • • MINIMUM EXTENT OF ICE
— — — MAXIMUM EXTENT OF ICE



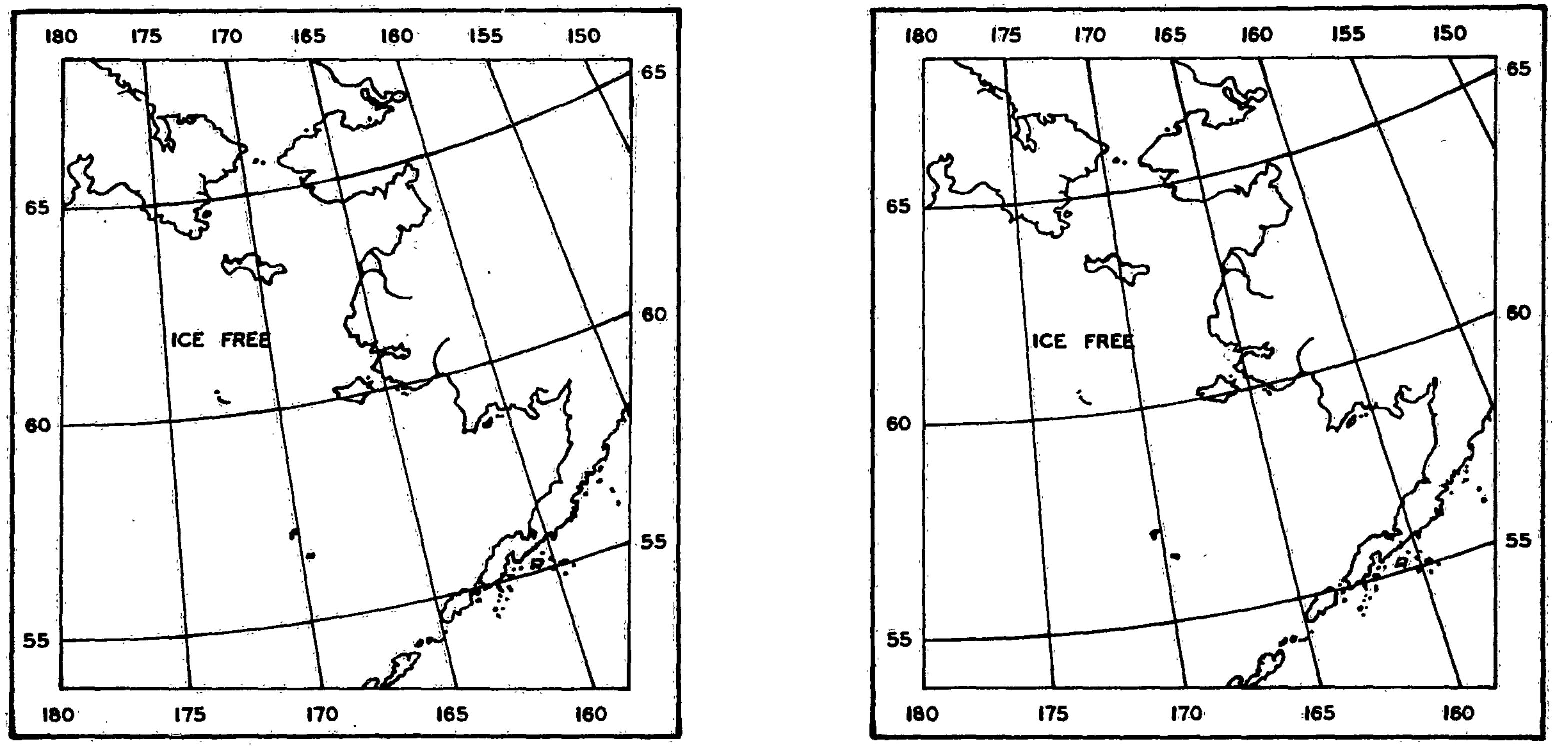
1-15 JULY

16-31 JULY

FIGURE C-7 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS

LEGEND

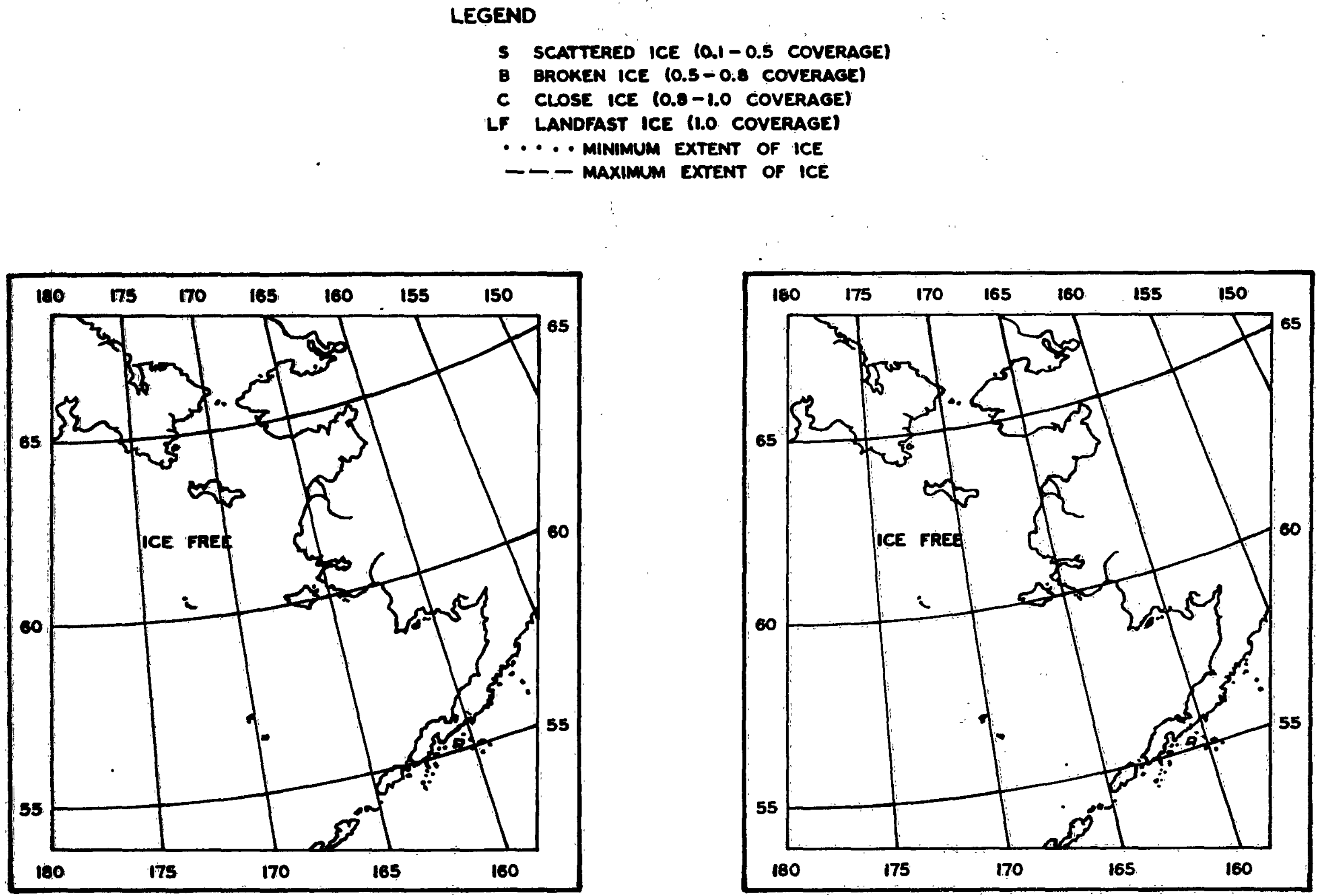
S	SCATTERED ICE (0.1 – 0.5 COVERAGE)
B	BROKEN ICE (0.5 – 0.8 COVERAGE)
C	CLOSE ICE (0.8 – 1.0 COVERAGE)
LF	LANDFAST ICE (1.0 COVERAGE)
• • • • •	MINIMUM EXTENT OF ICE
— — —	MAXIMUM EXTENT OF ICE



1-15 AUGUST

16-31 AUGUST

FIGURE C-8 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS



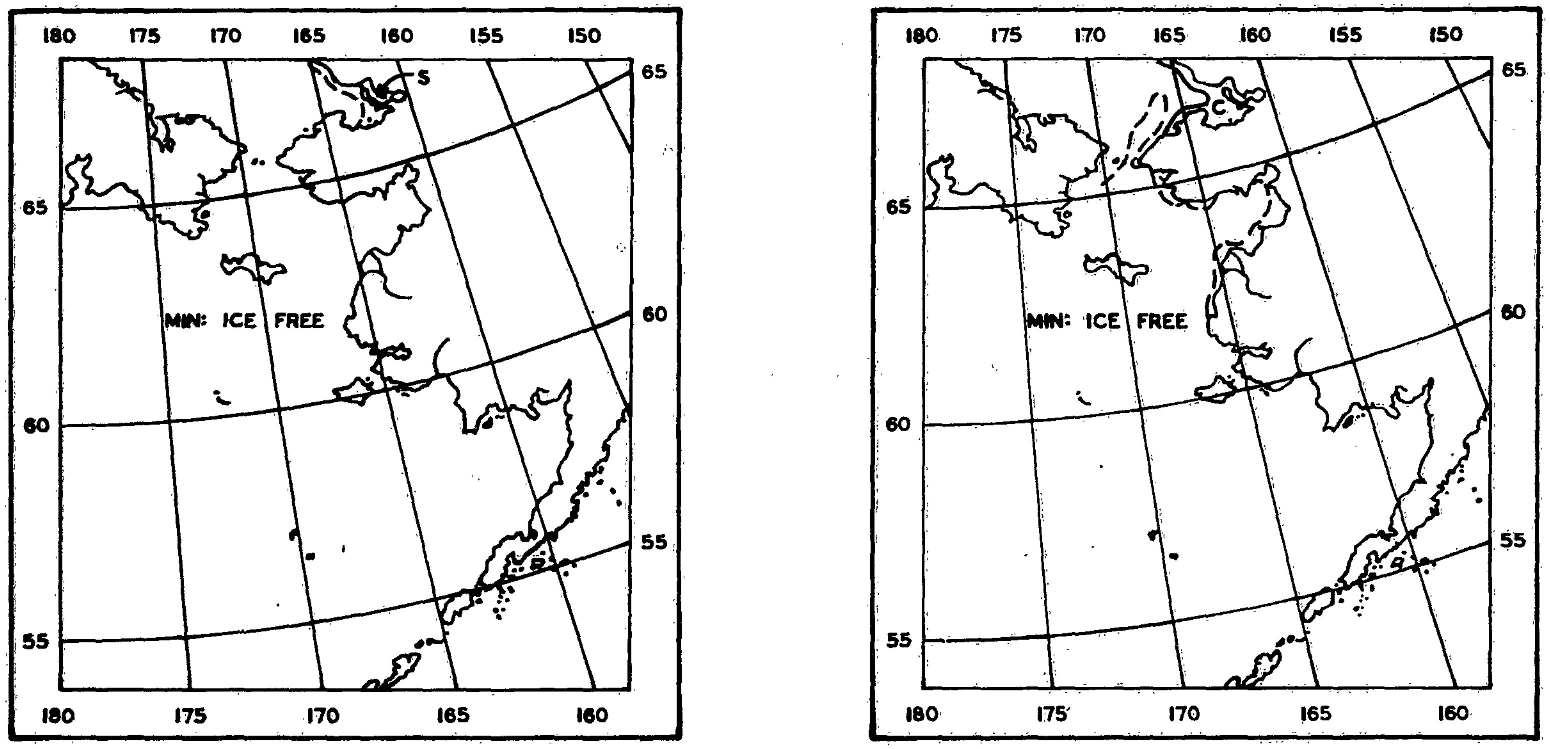
1–15 SEPTEMBER

16–30 SEPTEMBER

FIGURE C-9 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS

LEGEND

S SCATTERED ICE (0.1 – 0.5 COVERAGE)
B BROKEN ICE (0.5 – 0.8 COVERAGE)
C CLOSE ICE (0.8 – 1.0 COVERAGE)
LF LANDFAST ICE (1.0 COVERAGE)
• • • • • MINIMUM EXTENT OF ICE
— — — MAXIMUM EXTENT OF ICE



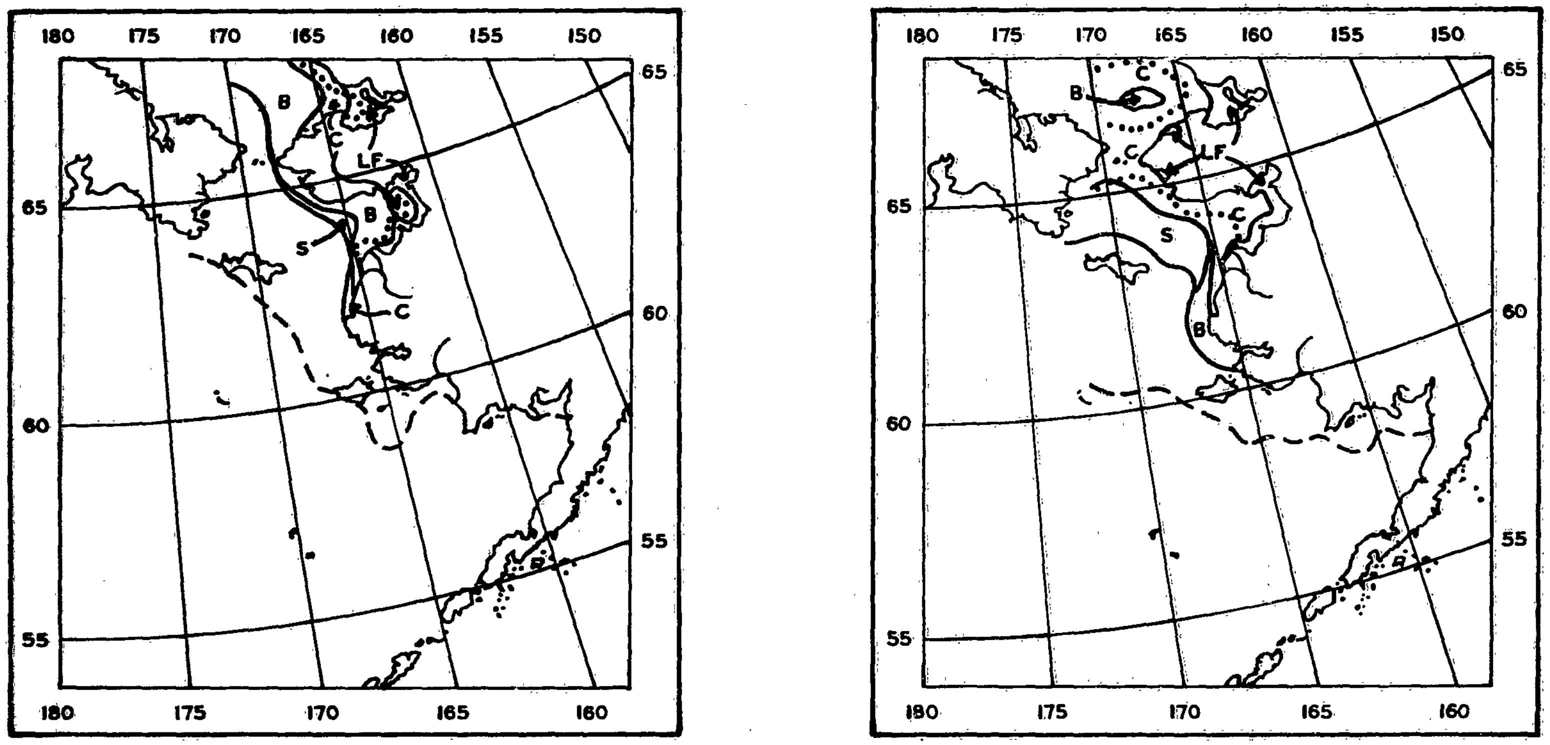
1-15 OCTOBER

16-31 OCTOBER

FIGURE C-10 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS

LEGEND

S SCATTERED ICE (0.1 – 0.5 COVERAGE)
B BROKEN ICE (0.5 – 0.8 COVERAGE)
C CLOSE ICE (0.8 – 1.0 COVERAGE)
LF LANDFAST ICE (1.0 COVERAGE)
• • • • • MINIMUM EXTENT OF ICE
— — — MAXIMUM EXTENT OF ICE



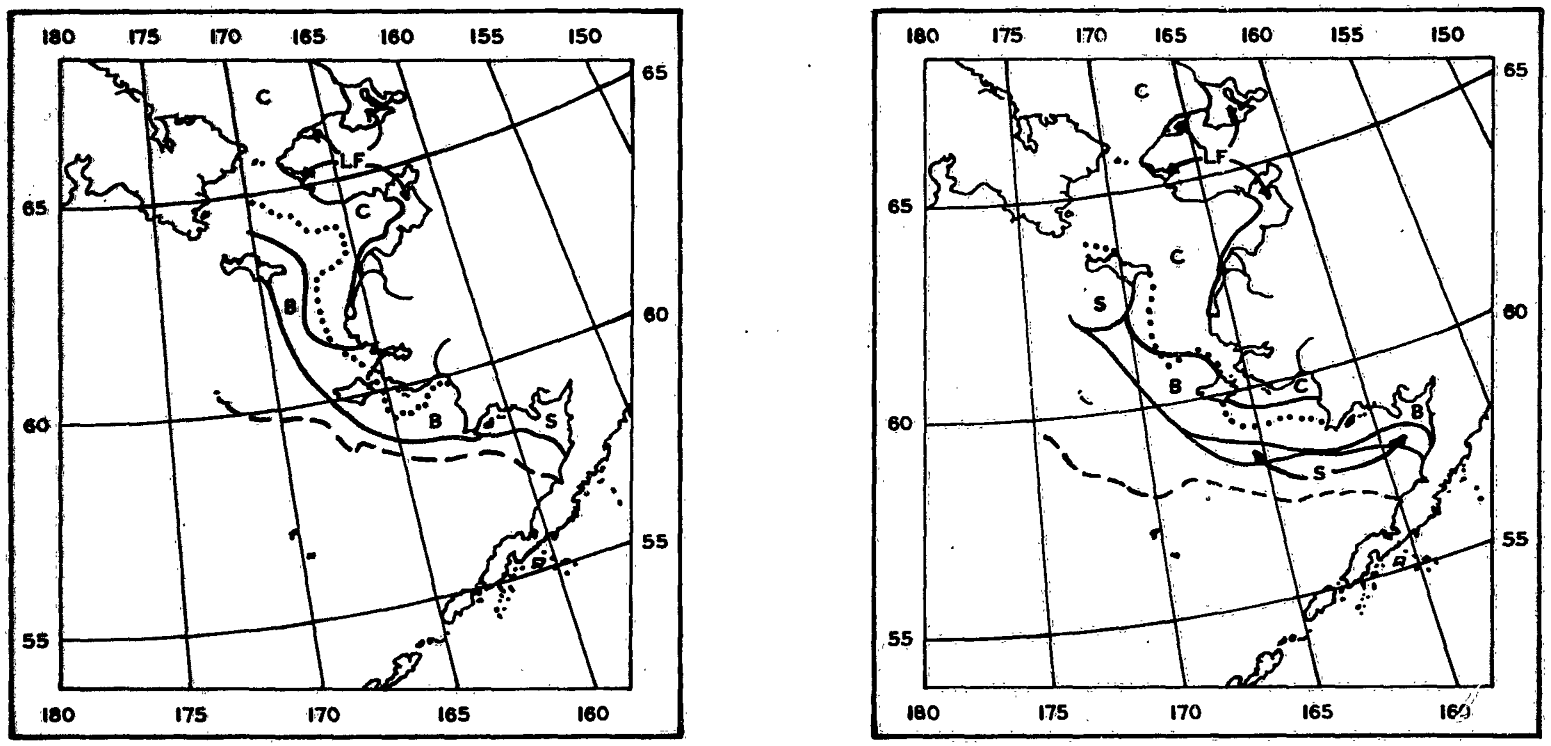
1-15 NOVEMBER

16-30 NOVEMBER

FIGURE C-11 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS

LEGEND

- S SCATTERED ICE (0.1 – 0.5 COVERAGE)
- B BROKEN ICE (0.5 – 0.8 COVERAGE)
- C CLOSE ICE (0.8 – 1.0 COVERAGE)
- LF LANDFAST ICE (1.0 COVERAGE)
- • • • • • MINIMUM EXTENT OF ICE
- — — — MAXIMUM EXTENT OF ICE



1-15 DECEMBER

16-31 DECEMBER

FIGURE C-12 AVERAGE CONCENTRATION AND EXTREMES OF ICE CONDITIONS

APPENDIX D

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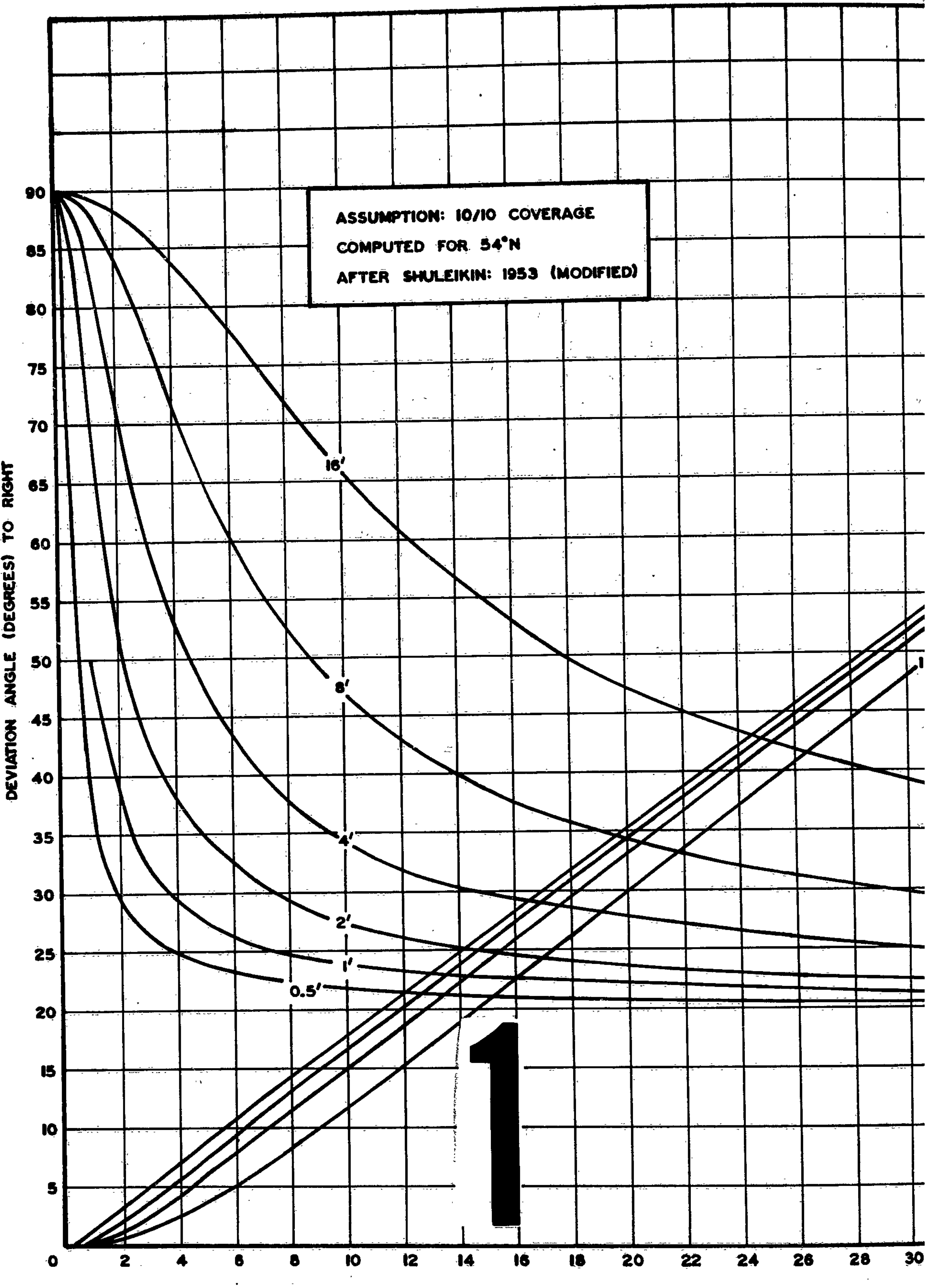
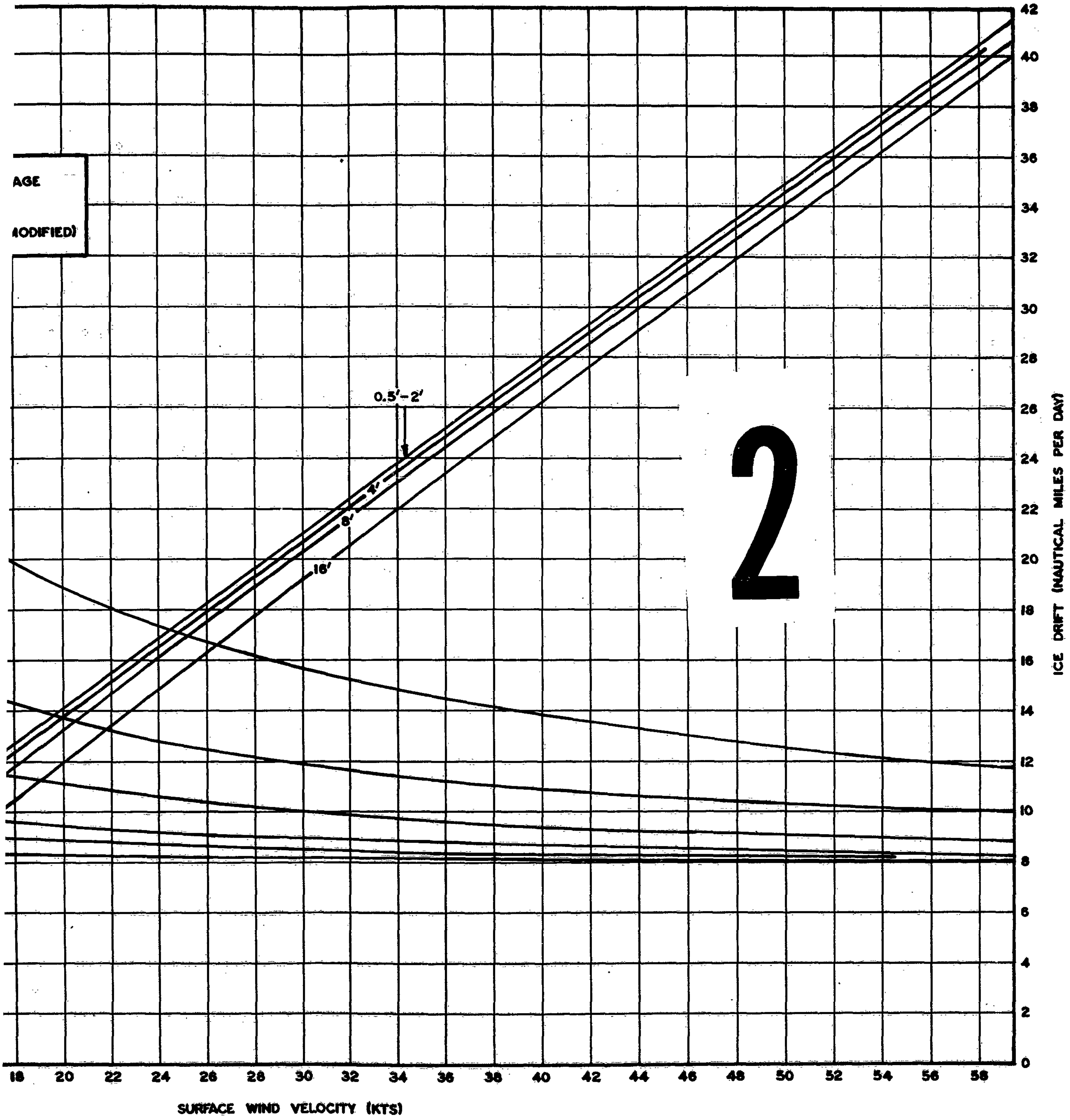


FIGURE E-1 ICE DRIFT SPEED AND DIRECTION FOR



DRIFT SPEED AND DIRECTION FOR VARYING WIND SPEEDS AND ICE THICKNESSES

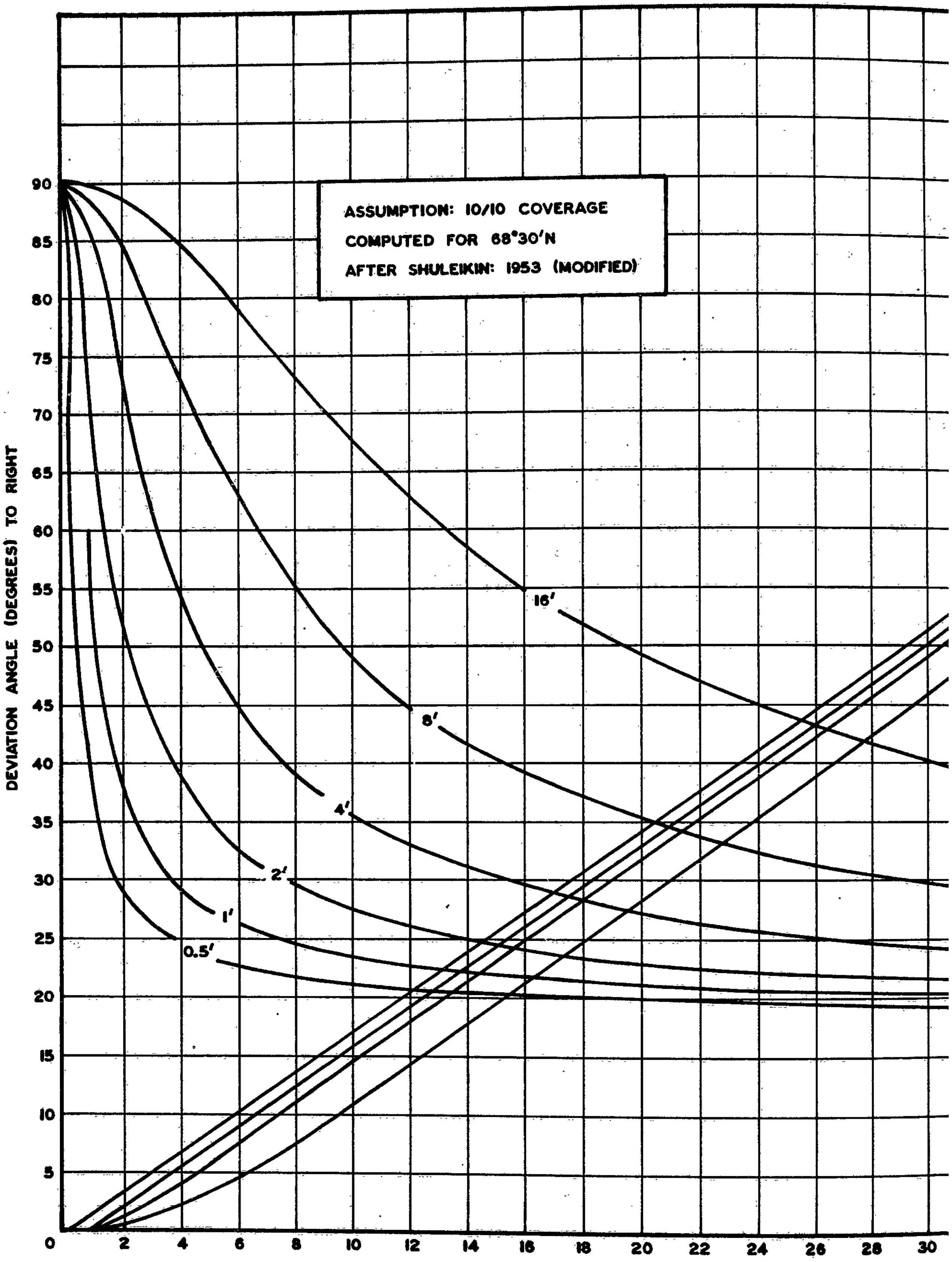
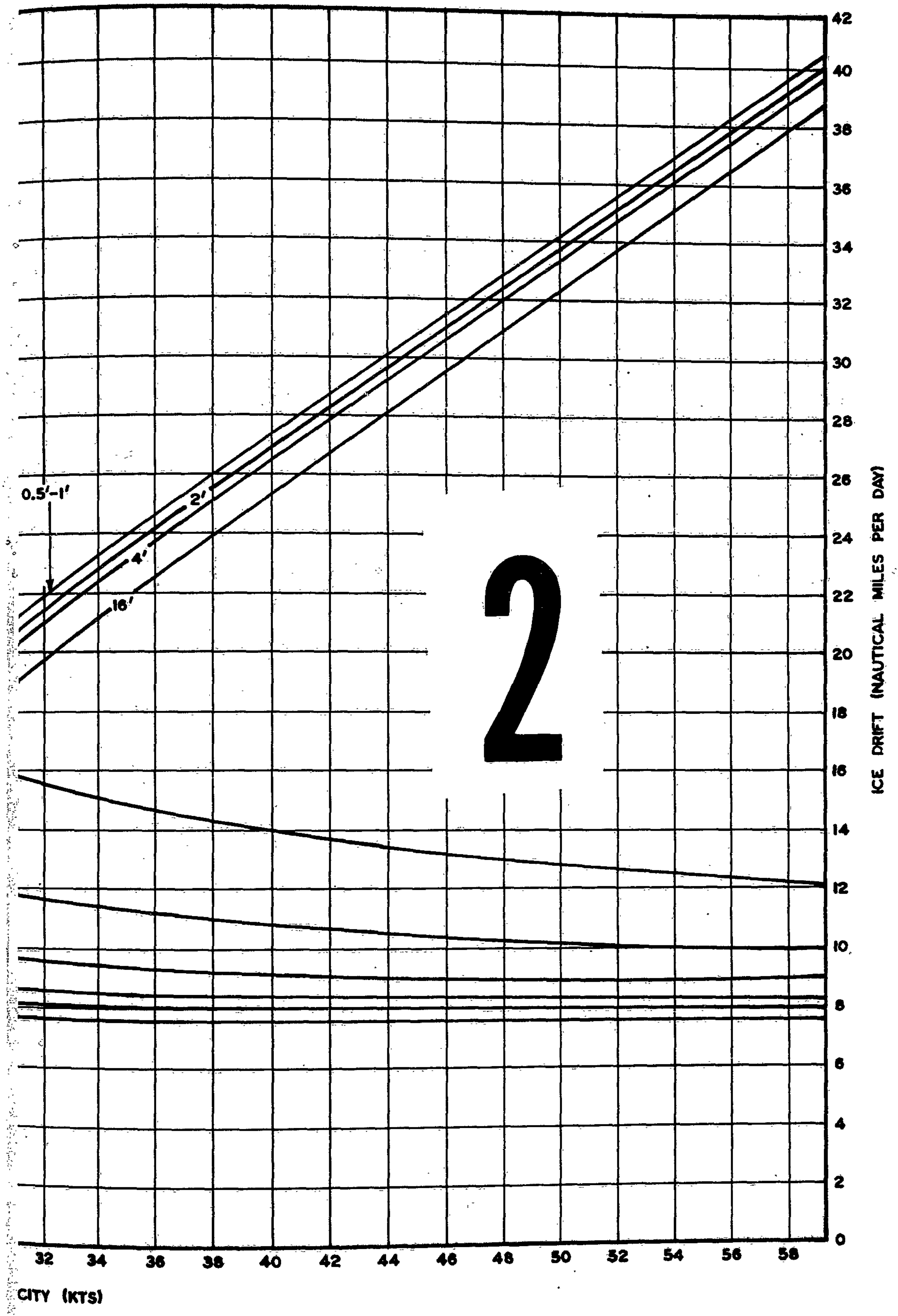
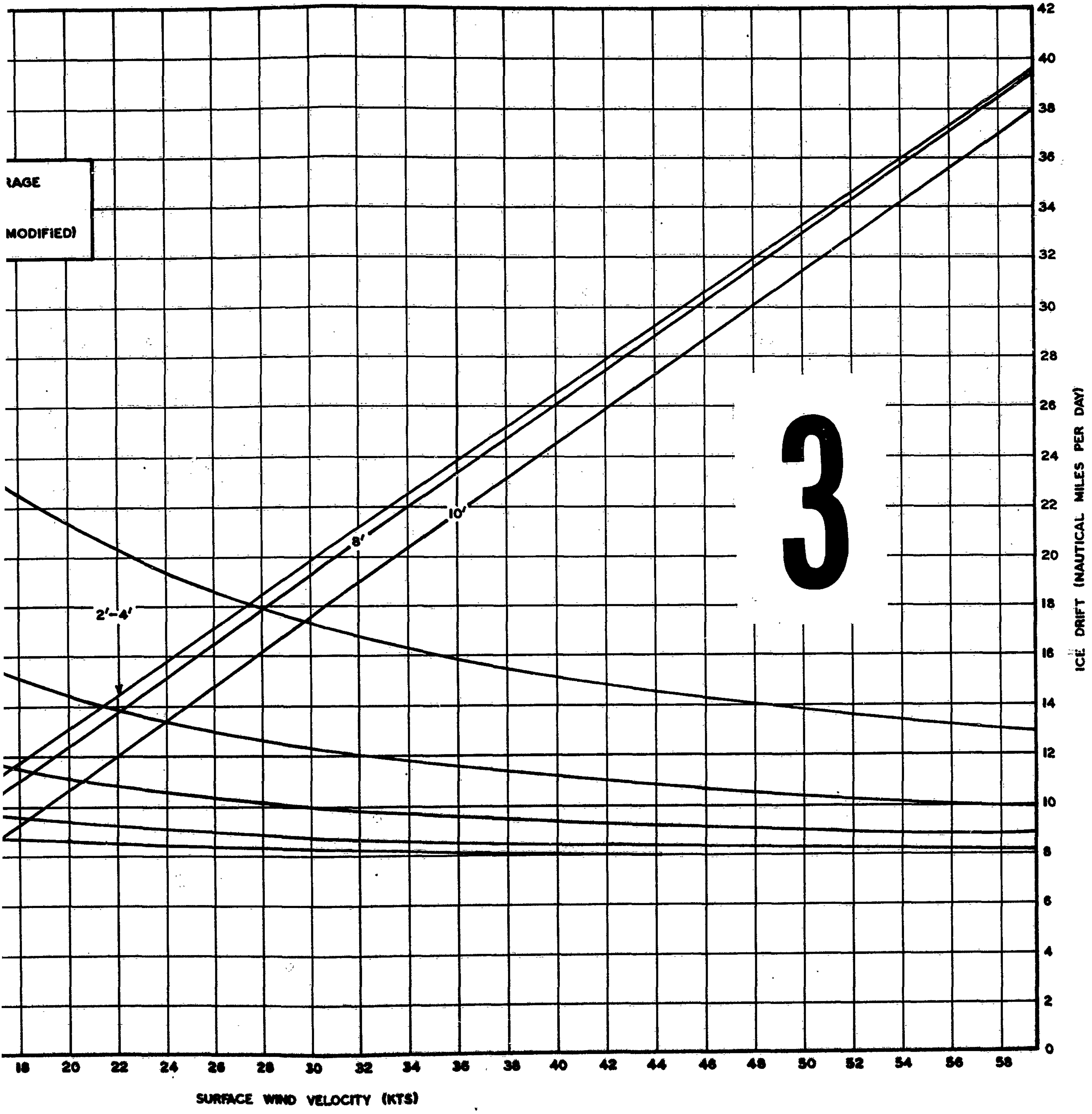


FIGURE E-2 ICE DRIFT SPEED AND DIRECTION FOR



VARYING WIND SPEEDS AND ICE THICKNESSES



E DRIFT SPEED AND DIRECTION FOR VARYING WIND SPEEDS AND ICE THICKNESSES

APPENDIX F

USWB Long-Range Forecasting Techniques

The results of applied research on methods for preparing a 5-day forecast are given by Namias (1947).

A comprehensive summary of research background and description of methods used in preparing USWB 30-day forecasts is given in his meteorological monograph (1953). As with daily forecasts, prognostic mean monthly pressure charts are constructed with kinematic techniques modified by statistical aids and physical reasoning. Machine methods permit inclusion of larger amounts of statistical data and observations than would otherwise be possible.

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APPENDIX G

Hypothetical Short-Term Ice Forecasts

A realistic example of an ice forecasting problem and its solution are outlined below in order to illustrate application of the methods described in this manual.

1. Five-Day Ice Forecast in the Northern Chukchi Sea

a. Current Ice Situation

Figure G-1(A) depicts hypothetical ice conditions in waters northwest of Icy Cape and Point Barrow on 28 August. Prior to this time ice had been alternately drifting toward and away from the coast.

During the periods of onshore drift, shipping convoys to Point Barrow and to some of the DEW sites were hampered by concentrations of very open to open ice between Icy Cape and Point Barrow. Pack ice in these shipping lanes was largely composed of disintegrating polar floes containing considerable ridged and hummocked ice. Winter ice and young ice types in this region had almost completely melted away.

On 28 August a BIRDS EYE flight provided good coverage of the ice conditions in the offshore waters. Local routine reconnaissance by P2V aircraft added details on the boundaries of the close pack, the open pack, and the very open pack, and the ice-free shore lead. Shore ice had severely hampered lighterage operations in the harbors and anchorages. This ice has recently moved out, however, and only a few grounded floes remained on 28 August.

b. Operational Situation

The task group command (CTG) anchored off Point Barrow on 28 August. During the next 5 days several convoys consisting of LSD's, LST's, and AKA's—with two wind-class icebreakers standing by for convoy duty—are scheduled to advance from the vicinity of Icy Cape to the Point Barrow anchorage area. One icebreaker is to advance to 73N,165W to occupy oceanographic stations and to conduct a 24-hour scientific program. At Icy Cape, Wainwright, and Point Barrow offshore unloading operations will be continued, if feasible, between 28 August and 2 September. CTG also desires to move one icebreaker northeastward beyond the area covered by this forecast to assist in a more severe ice problem which is predicted to persist.

c. Considerations of Long-Range Ice Outlook and Forecasts

Since the outlook was issued, sea surface temperatures have been plotted continuously. In the area shoreward of the ice-free boundary shown in figure G-1(A) ship reports of sea surface temperatures ranged between 28.7° and 32.0°F until 27 August, after which a series of nearshore bucket temperature readings of 33° to 35°F were reported by an LST between Icy Cape and Point Barrow. Table I, page 25, indicates that little melt is expected to result from heat interchange between ice and water of the remnant pressure ice of which the fringe pack is largely composed.

The last 30-day ice outlook, issued for the period 15 August through 15 September, indicated sporadic onshore drift due to an easterly progression of lows across the Bering Sea. The onshore drift was expected to decrease toward the end of the period. Recent weather maps indicate development of a high pressure center north-northeast of Point Barrow. Although this high pressure center is 600 nautical miles removed from the forecast area, it is blocking progression of lows, keeping them somewhat further south than had been anticipated.

d. Considerations of New Ice Formation and Development

Monthly mean temperatures recorded in degrees Fahrenheit by the Ice Forecast Central, Kodiak, are

	May	June	July	August	September
Point Barrow	16.6	34.5	40.4	42.5 (estimated)	33.8 (predicted)
ARLIS II	6.7	27.5	30.2	27.8 (estimated)	15.1 (predicted)

Computations of frost degree days, base 32°F, (paragraph 3.1, page 26) indicate that new ice is not likely to form either in open water between Point Barrow and Icy Cape or in the open ice areas westward of the open water.

Very thin ice may form in the leads deep within the pack ice. Using 15 July as a starting date, 210 frost degree days, base 32°F, (figure 13, page 74) are likely by 2 September on the basis of known and predicted temperatures for ARLIS II (82N,167W). Since this yields 5.5" of ice, only 2" or 3" of new ice growth are likely to have formed by the end of the forecast period in the vicinity of the oceanographic station to be occupied at 73N,165W, assuming no ice movement. Considerable ice movement in the vicinity of the oceanographic station, as seen below in discussing figure G-1(B), will tend to further restrict ice development.

e. Considerations of Drift and Deformation

Using currents (table 7, page 40) and the 5-day geostrophic flow pattern in figure G-1(B),columns 1, 2, 3, 5, and 6 were completed on an ice drift computation sheet (table G-1). Geostrophic winds were computed for points 5, 6, 10, and 11 on the grid section for the forecast area (figure 15, page 76) from the 5-day mean prognostic chart furnished by the USWB Extended Forecast Section. Points A through H were selected along various boundaries separating ice of different concentrations; geostrophic winds for these points were determined in a similar manner.

TABLE G-1: ICE DRIFT COMPUTATION SHEET

FORECAST PERIOD

FROM 28 August (Time-Date) TO 2 September (Time-Date)

Col (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Point No.	Geostrophic Flow		Wind Drift (Speed) of ice (nm/day)	Current		Sea Ice Drift	
	Direction (°T) (toward)	Wind Speed (knots)		Direction (°T) (toward)	Speed (nm/day)	Direction (°T) (toward)	Distance (nm)
5	344	7.6	1.3	320	1.2	333	13.0
6	334	4.5	.8	325	1.6	328	11.5
10	301	11.0	3.2	335	1.1	310	20.0
11	302	13.2	5.7	310	1.1	303	34.0
A	301	14.0	7.7	323	1.3	304	43.5
B	302	14.2	7.8	325	1.1	305	43.0
C	301	11.9	6.5	331	1.0	305	36.5
D	302	11.9	3.5	331	1.0	308	22.5
E	304	14.2	4.1	325	1.1	308	25.5
F	301	14.0	4.1	323	1.3	306	27.0
G	301	14.0	2.4	323	1.3	308	19.0
H	304	14.0	2.4	335	1.1	314	17.0

At points 5, 6, G, and H, geostrophic winds were multiplied by a factor of 17 percent (table 6, page 39), since concentration is 8/10 and ridging is 3/10 in the vicinity of these points (figure G-1(A)). At points 10, D, E, and F, 5/10 concentration and 3/10 ridging values are utilized according to ice reconnaissance data (figure G-1(A)). These values applied to table 6, page 39, yield a factor of 29 percent for determining ice drift speed in nautical miles per day from the geostrophic wind in knots. Similar determinations of ice concentration and ridging values are derived by applying a factor of 43 percent to the geostrophic wind at point 11 and a factor of

55 percent at points B and C. Thus, column 4 is determined for all points in the forecast area.

Columns 7 and 8 are determined by vector addition of ice drift and current drift described in paragraphs 4.1 and 4.2, page 37. After addition of the wind drift vector component (columns 2 and 4, table G-1) to the current component (columns 5 and 6), care must be exercised to multiply the speed by 5 prior to entry in column 8, since a 5-day movement is required. The information contained in table G-1 is now ready for analytical application.

The 5-day resultant ice drift vectors are plotted in figure G-1(B); ice concentration boundaries are included for clarity. The next step in construction of figure G-1(B) is careful measurement of the quadrilaterals described by points 5, 6, 10, and 11 at the start of the forecast period (solid lines) and at the end of the period (broken lines). Applying the method of paragraph 4.4, page 41:

$$A = 1/2 \text{ ab } \sin\theta$$

Letting A_o equal the initial area and A_e equal the area at the end of the forecast period, then by actual measurements:

$$A_o - A_e = \frac{(330)(321)(.99619)}{2} - \frac{(328)(334)(.99985)}{2} = 2{,}005 \text{ nm}^2$$

which represents a decrease in area of 3.7 percent.

Since operational interest lies mainly in the southeast portion of the quadrilateral, the change in the area (1/2 base x altitude) represented by points 6, 10, and 11 should be examined. The areal difference in triangles formed by these points at the beginning and at the end of the period is

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tendency for ice under such influences to increase concentration are not adequately considered by the method described. Figures G-1(B) and G-1(C), however, show that the very open ice should move into an area equal to approximately one-half its original size. Therefore, the objective estimate should be tempered to reflect a pattern similar to that in figure G-1(D). It should be noted that the very open ice is no longer indicated in figure G-1(D); and, in the northeast extremity of the forecast area, the objectively predicted open ice boundary (II in figure G-1(C)) has merged with the predicted close ice boundary (III in figure G-1(C)). The above reasoning would only apply if expected disintegration is inconsequential.

g. Considerations of Disintegration

According to the methods described in chapter 4 and from temperatures known and predicted in paragraph d above, the following warming degree days, base 23°F, should accumulate.

	May	June	July	August	September
Point Barrow	5	350	890	1495	1765
ARLIS II	0	85	295	400	400
Forecast Area	2	172	488	757	846

Values for the forecast area are roughly interpolated by weighting the ARLIS II values twice. This interpolation appears legitimate since the thermal regime within the pack ice should more closely approximate that of ARLIS II than that of Point Barrow. According to figure 34, page 96, the estimated warming degree days indicate that if the winter ice had grown to a thickness of 7 feet in the forecast area, the concentration on 28 August would be 61/100 (725 warming degree days, base 23°F, interpolated for 28 August) — fairly good agreement with that observed throughout the area. At the end of the forecast period, only another .03 of ice should have disintegrated (58/100 concentration corresponding to 763 warming degree days, base 23°F, interpolated for 2 September). Thus, melt within the prediction area should be inconsequential.

h. Pressure Ridge Draft Considerations

From the ridge counts shown by reconnaissance observations in figure G-1(A), figure 16, page 77, shows that ridges having a total thickness of 78 to 88 feet (based on ridge counts of 350 and 400) would be expected frequently and that ridges having a total thickness of 120 feet (based on ridge counts of 600) would be expected occasionally.

i. Unabbreviated Final Forecast Message

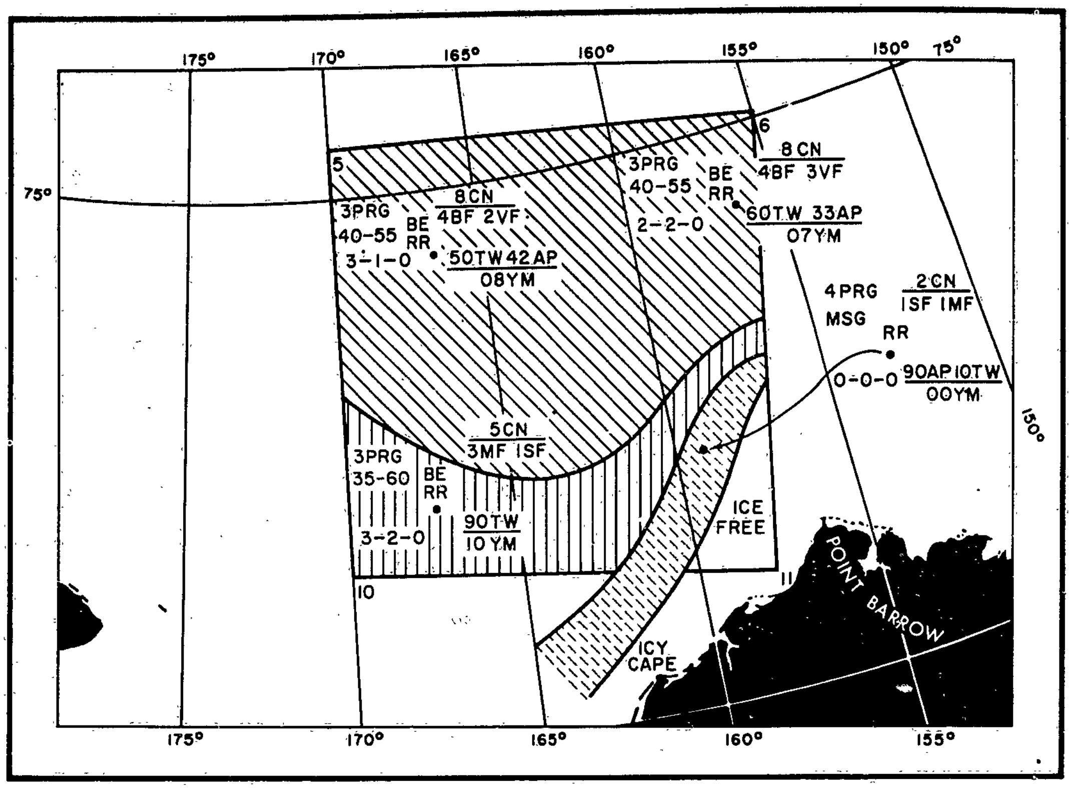
Based on all above considerations the following 5-day ice forecast message is suggested.

NAVOCEANO FIVE DAY ICE FORECAST. ALASKAN COASTAL AREA, ICY CAPE TO POINT BARROW AND WESTWARD TO 73N,165W.

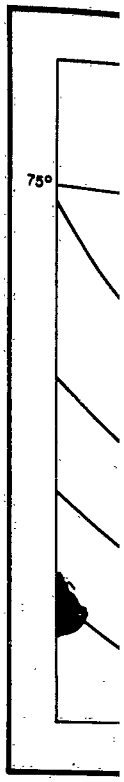
1. EXPECT WIDENING SHORE LEAD WITH STEADY WESTWARD DRIFT ICE. BY END PERIOD EXPECT ICE FREE DASH CLOSE ICE BOUNDARY FROM 73°34'N 156°12'W TO 73°18'N 158°30'W. EXPECT OPEN ICE DASH ICE FREE BOUNDARY FROM 73°18'N 158°30'W TO 71°20'N 163°00'W. EXPECT OPEN ICE DASH CLOSE ICE BOUNDARY FROM 73°18'N 158°30'W TO 72°25'N 165°00'W, THEN CURVING TO THE WEST AND NORTHWEST TO 73°00'N 170°00'W. IN ALL CASES HEAVIER ICE EXPECTED TO NORTHWEST. EXPECT NEARSHORE SHIPPING LANES

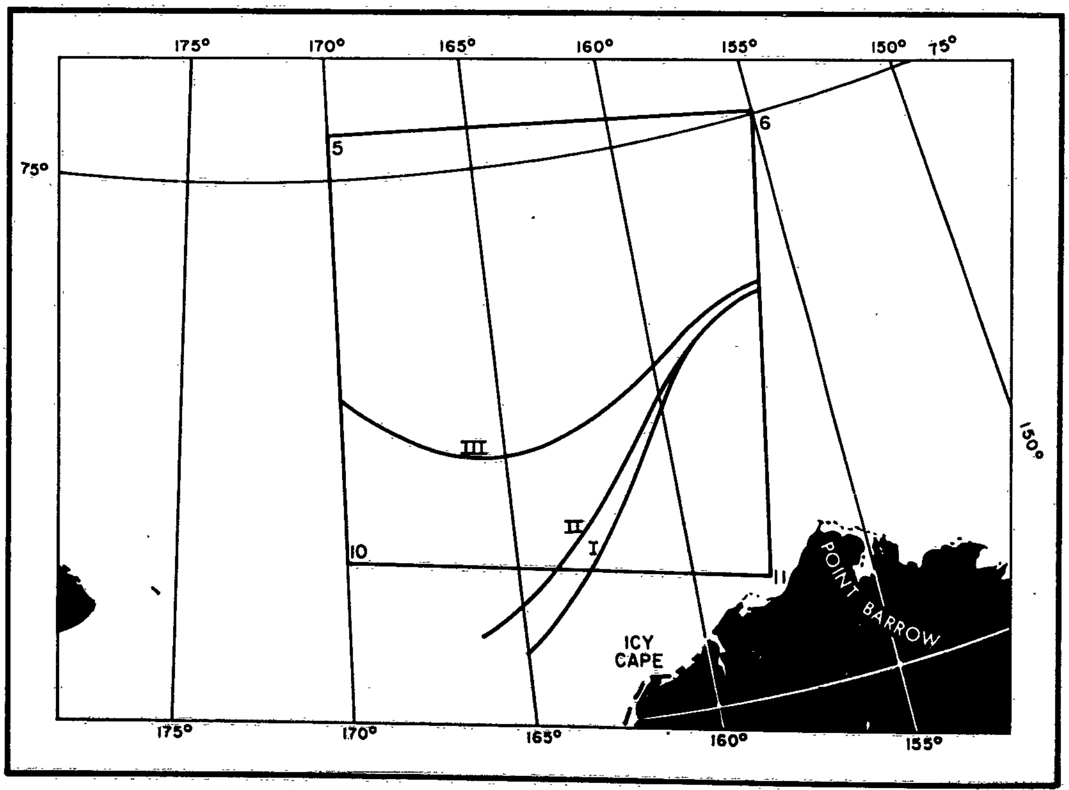
BETWEEN ICY CAPE AND BARROW TO CONTINUE ICE FREE WITH NO RECURRENCE OF SHORE ICE PROBLEM AT ICY CAPE, WAINWRIGHT, AND POINT BARROW BEACHES.

2. SUGGESTED ICEBREAKER ROUTE TO MINIMIZE HEAVIER CONCENTRATION AND TAKE ADVANTAGE OF ICE DRIFT. ICE FREE FROM 71°25'N 156°30'W TO OPEN PACK 71°56'N 161°36'W TO CLOSE PACK 72°28'N 164°00'W TO STATION 73N 165W. IN OPEN PACK: OCCASIONAL NARROW BELTS OF ICE OF CLOSE CONCENTRATION WITH LITTLE PRESSURE EXPECTED, ICE 3/10 RIDGED WITH TOTAL THICKNESS THRU RIDGES USUALLY 70 FEET OCCASIONALLY 120 FEET. USUAL THICKNESS FLOES THIS REGION 3 TO 5 FEET. SOME NEW ICE IN CLOSE PACK OF THICKNESS LESS THAN 2 INCHES. PRESSURE IN CLOSE PACK LIGHT TO MODERATE EXCEPT MODERATE TO SEVERE IN VICINITY OF 73N 165W. EXPECT 3/10 PRESSURE ICE WITH THICKNESS THRU RIDGES USUALLY 88 FFET OCCASIONALLY 120 FEET IN CLOSE PACK. USUAL THICKNESS OF FLOES 5 to 8 FEET. NO SIGNIFICANT MELT OF PACK ICE ALONG ENTIRE TRACK THRUOUT PERIOD.



A. ICE RECONNAISSANCE CHART: 28 AUGUST





C. OBJECTIVE PROGNOSTIC CHART FOR ICE BOUNDARIES

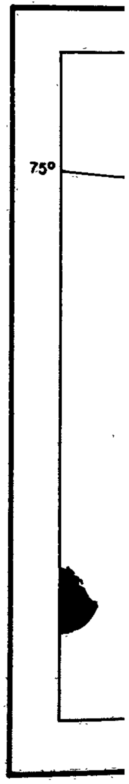
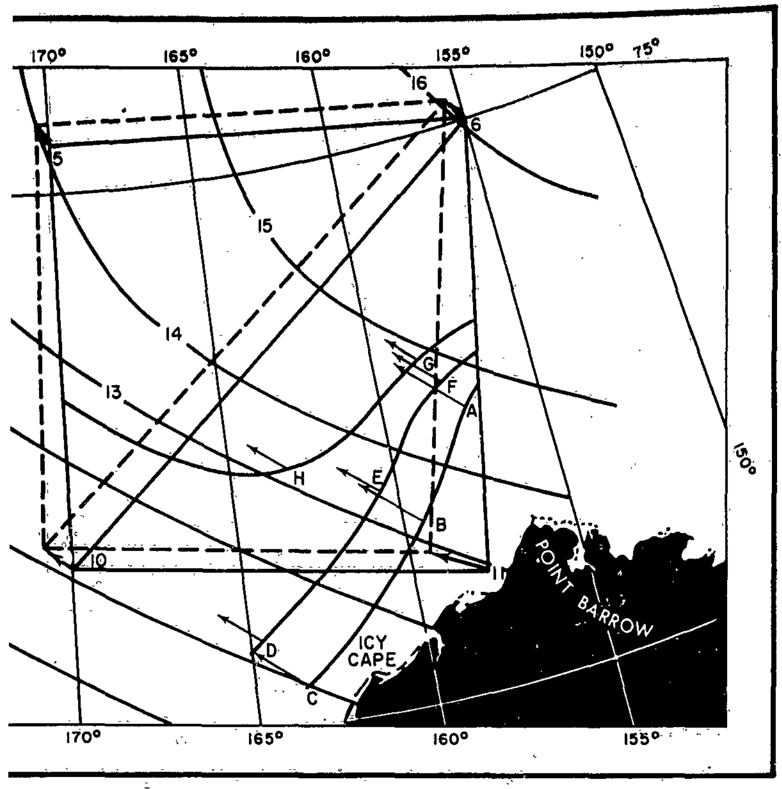
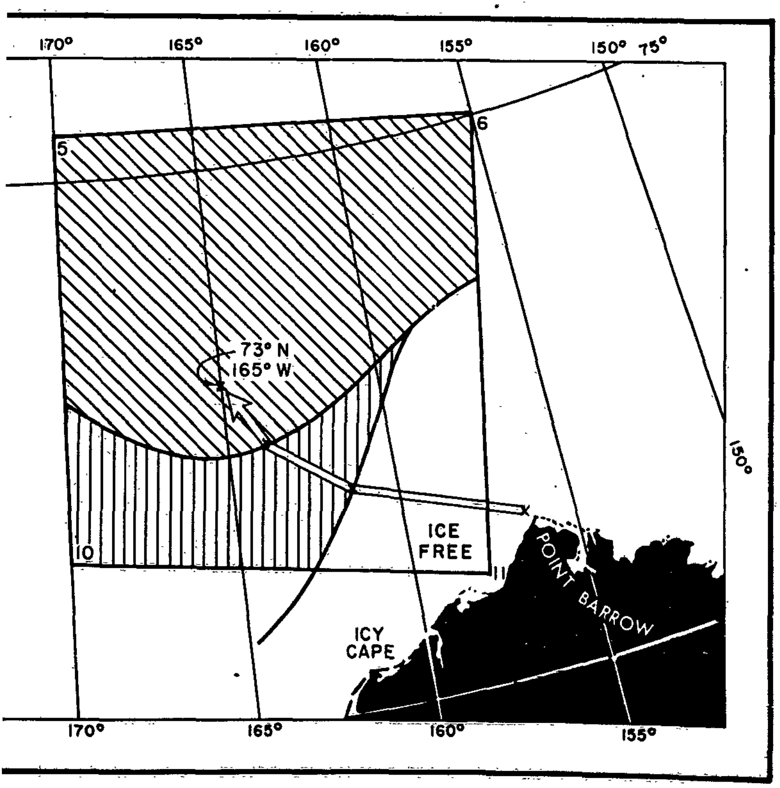


FIGURE G-1 SUGGESTED CHARTS TO AID IN FORECAST OF MOVEMENT, D



B. FIVE-DAY ICE DRIFT VECTOR CHART



FINAL PROGNOSTIC CHART: 2 SEPTEMBER

N, AND CHANGE IN CONCENTRATION

LEGEND FOR FIGURE G-1

Type of Observation (plotted above observation point)

x	Point of Grid
•	Point of Observation
BE	BIRDS EYE Observation
RR	Routine Reconnaissance

Concentration by Form (plotted to NE of observation point)

CN	Concentration (tenths of sea ice cover)
BF	Big Floe (in tenths)
MF	Medium floe (in tenths)
SF	Small floe (in tenths)
VF	Vast floe (in tenths)

Categorical Concentration

▧	Close pack, ice cover 7/10 to 9/10
▥	Open pack, ice cover 4/10 to 6/10
▨	Very open pack, ice cover 1/10 to 3/10
□	Ice Free

Pressure Ridging (plotted to NW of observation point)

PRG	Tenths of ice covered by pressure ridges
NN-NN	Mean and maximum number of pressure ridges in tens per 30 nautical miles

Stage of Development (plotted to SE of observation point)

TW	Thick winter ice (percent of sea ice observed)
AP	Arctic pack and young polar ice (percent of sea ice observed)
YM	Young and medium winter ice (percent of sea ice observed)

Puddling (plotted to SW of observation point)

N-N-N	Tenths of superficial puddles, burnt puddles, and refrozen puddles on ice in that order
MSG	Not reported

I	Very open ice-ice free boundary
II	Very open ice-open ice boundary
III	Open ice-close ice boundary

⇐ Suggested best route Point Barrow to 73N,165W

2

APPENDIX H

Recapitulation of Suggested Charts and Maps Regularly Maintained

It is suggested that the following maps and charts be regularly displayed, plotted, and/or maintained by the short-term ice forecasting activity.

Forecasts for Continuity Study

1. Monthly Prognostic Ice Chart covering local area and effective period of short-term forecast (from NAVOCEANO Long-Range Ice Outlook).

2. Latest 30-Day Prognostic Ice Chart (from 30-day NAVOCEANO ice forecast covering total area and effective time of forecast).

3. Last 5-Day Forecast prepared by short-term ice forecasting activity.

Latest Ice Information For Local Forecast Area

4. Latest Historical Ice Information from HO 705, Appendix C of the Manual, or NAVOCEANO IMR 16-61 (as appropriate).

5. Ice Reconnaissance Chart showing latest observed ice conditions with portions of the area precluded from reconnaissance interpreted by the ice forecaster (exemplified by Figure G-1(A).

Operational Information

6. Latest Operational Information including ship situation reports, and recent and proposed ship movements.

Environmental Data

7. Sea Surface Temperature Chart (should contain plot of ice - no ice line from ice potential study if included in long-range ice outlooks).

8. Latest Temperature and Degree Day Plots at all regularly reporting stations near the forecast area. Approximately 12 to 20 stations would usually suffice for either Kodiak or Argentia ice forecasting activities. These graphs are regularly maintained regardless of actual commitments in order to maintain continuity with the ice and thermal regimes prevailing in any season. (Maintain plots of both 23° base and 32°F base warming and frost degree days after the procedures described in paragraphs 3 and 6 of the manual).

9. Ice Drift Vector Charts (to be plotted only for areas where an actual ice forecasting commitment exists; exemplified in figure G-1(B)).

Short-Term Forecasting Prognostic Charts

10. As required to formulate ice prediction (exemplified by figure G-1(C) and G-1(D) in appendix G).

Note: If iceberg frequencies are a problem, if the drift of an ice station through the forecast area occurs, or if other specialized conditions prevail, appropriate additional charts should be maintained.

8. Latest Temperature and Degree Day Plots at all regularly reporting stations near the forecast area. Approximately 12 to 20 stations would usually suffice for either Kodiak or Argentia ice forecasting activities. These graphs are regularly maintained regardless of actual commitments in order to maintain continuity with the ice and thermal regimes prevailing in any season. (Maintain plots of both 23° base and 32°F base warming and frost degree days after the procedures described in paragraphs 3 and 6 of the manual).

9. Ice Drift Vector Charts (to be plotted only for areas where an actual ice forecasting commitment exists; exemplified in figure G-1(B)).

Short-Term Forecasting Prognostic Charts

10. As required to formulate ice prediction (exemplified by figure G-1(C) and G-1(D) in appendix G).

Note: If iceberg frequencies are a problem, if the drift of an ice station through the forecast area occurs, or if other specialized conditions prevail, appropriate additional charts should be maintained.

U. S. Naval Oceanographic Office
MANUAL OF SHORT-TERM SEA ICE FORECASTING,
by Walter I. Wittmann and Gordon P. MacDowell,
May 1964. 142 pp. including 50 figs. (SP-82).

Bibliography
Appendixes

This manual represents an initial attempt to systematically present recommended methods of ice prediction. All methods are based completely on regularly collected and continually disseminated environmental data readily available at field stations such as Kodiak, Alaska, and Argentia, Newfoundland. Illustrations include an extension of the treatment of Arctic ice conditions in H.O. Pub 705 into the Bering Sea area.

1. Forecasting Manual
2. Sea Ice Forecasting
3. Arctic Sea Ice
4. Bering Sea Ice Conditions
5. Degree Day Relationship to Sea Ice Conditions

i. title: Manual of short-term sea ice forecasting
ii. authors: Walter I. Wittmann and Gordon P. MacDowell
iii. SP-82

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