



TECHNICAL REPORT

CLIMATOLOGY OF THE ICE POTENTIAL
AS APPLIED TO
THE BEAUFORT SEA AND ADJACENT WATERS

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U. S. NAVY HYDROGRAPHIC OFFICE
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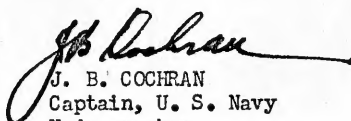
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A B S T R A C T

The techniques of ice potential climatology are methods for summarizing ice potential calculations on an areal basis. These techniques involve the use of an assumed constant total heat loss in water columns, from which charts of potential ice thickness, depth of convection, and stability are produced. The use of ice potential climatological techniques in forecasting involves recognition of the different characteristics of the areas being studied. These techniques are applied to the Beaufort Sea and adjacent waters. Eight areas with different potential ice thickness and stability are delineated, and their properties and probable causes are discussed.

FOREWORD

The Hydrographic Office is engaged in a continuing study of ice conditions affecting ship movements in the Arctic Basin. As an essential preface to improving the techniques of ice forecasting, it has been necessary to formulate theories concerning the large-scale movements of ice in the Arctic Basin. Application of the techniques of ice potential calculation as described in this report will aid in understanding the causes for the large annual fluctuations in amounts of ice and the persistence of areas of heavy and light concentrations of ice.


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A. INTRODUCTION

For the past several years the Hydrographic Office has been developing techniques of observing and forecasting sea ice conditions. Much of the effort in this program has been directed toward means of predicting the movements of ice on a short-range basis. Within the past two years, methods have been developed and used to make forecasts of ice formation and growth covering periods of several months. Extension of these methods of ice forecasting to large-scale phenomena, such as the Alaskan shore lead, has proved to be difficult. The recent development of theories of the ice potential allows further extension of ice potential calculations into the field described in this report.

The terminology of the ice potential theory and the method of calculating the ice potential are explained by Lee and Simpson (1954). The ice potential may be viewed as a measure of the stability of sea water, since it describes the existing vertical distributions of salinity and density. As a result of the development of analytical methods of calculating the ice potential (Brown, 1954), it has become possible to obtain machine listings of the ice potential calculations for all oceanographic station data in any desired area. The concept of ice potential climatology has been developed to formalize the presentation of this ice potential data.

B. TECHNIQUES OF ICE POTENTIAL CLIMATOLOGY

The ice potential indicates the stability of the water at a single place and time. In order to examine the relative stability of a number of different water samplings, a method of areal presentation has been devised. This method is called, by analogy with climatic maps, ice potential climatology.

There are several possible ways of contouring the ice potential. Some of these have no physical significance, but others are useful and provide important insights into the physical processes that influence the occurrence, growth, and disintegration of sea ice. Principal chart forms may be listed as follows:

- (1) Constant Heat Loss
- (2) Constant Depth of Convection
- (3) Depth of Convection Associated with Constant Heat Loss
- (4) Stability Index

1. Charts of Constant Heat Loss over an Ocean Area

The most useful basis for drawing climatological charts of the ice potential is to postulate a constant heat loss over an area. By finding the potential ice thickness associated with a given heat loss, isoline charts are drawn by connecting points of equal ice potential. The calculation of the ice potential and the associated sensible heat loss is described by Lee and Simpson (1954). The total heat loss consists of

the sensible heat plus the latent heat of formation of ice. The procedure for drawing ice climatological charts consists of two parts. First, the total heat loss for a given ice potential and sensible heat loss (assuming the cross section of the water column to be 1 cm.²) is found by adding 72 gm. cal./cm³ of potential ice to the sensible heat loss. The quantity 72 gm. cal./cm³ is derived by assuming the latent heat of sea ice to be 80 gm. cal./gm. and the density of sea ice to be 0.9. Second, it is necessary to postulate a heat loss which is realistic in relation to the annual heat budget of the chosen area. After these two factors are determined, the chart is readily drawn. An example of this type chart is shown in figure 1, which presents isolines for the Beaufort Sea derived from data collected in summer 1951. Detailed discussion of all charts will be found in the following section.

Limitations of this type chart are found in the requirement that the ice potential be determined for open water areas where the effects of advection are relatively minor, and in the often unrealistic assumption that total heat loss is constant over a large area. Since the ice potential calculation assumes negligible advective changes, it is necessary to use hydrographic stations made in deep water away from inshore runoff. However, in the Beaufort Sea, it is difficult to navigate inside the Polar Pack, and most available data are inevitably derived from observations made in shallow inshore areas. As a practical matter, it has proved necessary to use a minimum depth of 50 meters in order not to restrict the information unduly. Where more data are available, the minimum depth could be increased to 100 meters or even to 200 meters, with a consequent increase in reliability. The assumption that heat loss is constant over the area is nearly correct when applied to the Beaufort Sea, since its latitudinal extent is only 5 degrees. However, if a similar study were made for Baffin Bay, for example, different heat losses might be required for different latitudes since the bay extends over a relatively wide range of latitude.

The choice of a standard heat loss is made on the basis of a reasonable heat loss, which will give average ice thickness values corresponding to the total growth during a winter. The reason for choosing a large heat loss is to make sure that convection proceeds long enough to penetrate into layers which are sufficiently deep to eliminate local temperature variations, leaving only water mass variations. When a total heat loss of 20 kg. cal./cm.² is used as in figure 1, thicknesses range from a maximum of 220 cm. to a minimum of -10 cm.¹ According to Zubov (1938), average annual ice growth in the Arctic is about 200 cm. Thus, the total heat loss used is reasonable, although arbitrary.

¹ Negative ice potentials are purely formalistic mathematical expressions indicating that insufficient heat has been lost to produce ice formation.

No assumptions have been made as to the mechanism of heat loss. Actual rate of heat loss may vary in winter from perhaps 100 gm.cal./cm²./day from an ice surface to perhaps 500 or 600 gm. cal./cm.²/day from open water. Therefore, figure 1 is not a forecasting chart and does not indicate when ice will form in the various areas.

2. Charts of Potential Ice Thickness Associated with Constant Depth of Convection

By the nature of the ice potential calculations, every value of ice potential and heat loss has associated with it a depth of mixing by thermohaline convection. Charts showing the potential ice thickness associated with a constant convective depth would seem to be useful as indicating the effect of mixing the water to a given level. However, since the vertical gradients of temperature and salinity in the surface layers differ from place to place, it is not realistic to compare two water masses by assuming equal thermohaline convective activity. In actuality, water masses differ in the amount of energy necessary to produce convection. Hence, charts showing ice thickness associated with a constant mixed layer depth are meaningless physically.

3. Charts showing Depth of Convection Associated with Constant Heat Loss

While it is not realistic to draw charts based on a constant depth of mixing, it is useful to consider charts which are based on a constant heat loss over an area and show the depth of mixing associated with the given heat loss. In effect, such a chart shows the stability of the water. The greater the depth to which convection reaches, the less stable the water mass.

Figure 3 shows depths of convection associated with a standard total heat loss of 20 kg. cal./cm.²

4. Stability Index

The data presented in figures 1 and 3, representing potential ice thickness and depth of convection associated with a constant total heat loss, may be combined into a stability index. This index measures the average potential addition of ice in units of potential centimeters of ice per meter of convection when thermohaline convection is extended downward. Thus, the stability index shows potential ice thickness as a percentage of the depth of convection. A high percentage indicates high stability and a low percentage low stability. However, the percentages are only relative, so that negative percentages may occur without implying actual overturn of the water. Figure 4 is an example of

a chart of stability index.

5. Effect of Time of Observation Upon the Ice Potential

Before discussing the ice potential climatology of the Beaufort Sea in detail, it is necessary to consider the effect on the climatology of the time of the oceanographic data collection. Since the ice potential reflects the actual heat content and stability of the water mass at the time water samples are collected, it is dependent on the heat budget of the water. If the potential ice thickness is calculated at intervals while the water is gaining heat, the sensible heat loss necessary to form a specified amount of ice will increase. Conversely, during the time when the water is losing heat, the potential ice thickness will steadily increase. The time of reversal of the heat budget in the Beaufort Sea is not known with certainty. Separation of the available data into those secured before and after 31 August did not show any noticeable time differences on an area-wide scale, although in some individual cases where oceanographic stations were repeated at intervals of a month or more, there was considerable variation in the potential ice thickness.

G. ICE POTENTIAL CLIMATOLOGY OF THE BEAUFORT SEA AND ADJACENT WATERS

The Beaufort Sea area has been selected to illustrate the use of the ice potential climatological techniques described above. This area has been one of the least known water areas of the world, but within the past few years the area has been extensively surveyed. The large-scale factors influencing the ice of the Beaufort Sea have been considered previously by the author (Corton, 1954).

1. Ice Potential in 1951

Figure 1 shows the potential ice thickness associated with a uniform heat loss of $20 \text{ kg. cal./cm.}^2$ in summer 1951, assuming that observations were taken simultaneously at a time near the neutral point between heat gain and heat loss in the water column. A small area near Point Barrow shows a negative ice potential of some 40 cm. At this location a heat loss of $20 \text{ kg. cal./cm.}^2$ is not sufficient to form ice. In an area north of Barter Island the potential ice thickness amounts to 200 cm., whereas the center of the polar basin shows potential ice thicknesses greater than 220 cm. A second area of low ice potential is found in the entrance to Amundsen Gulf, with increases to the east and northwest of this center.

There is a large subjective element in figure 1 in drawing lines covering such a large area with comparatively sparse data. Since the observations are made in water at least 50 m. in depth, the isolines are estimated near shore. Also, since ice conditions limit the operations of ships, the geographical coverage of the area is not uniform.

2. Mean Ice Potential

Figure 1, which shows the potential ice thickness areally for summer of a single year, is comparable to a chart of mean weather conditions over a period of perhaps two or three months. The next logical step is the construction of mean charts of the ice potential by averaging the data covering a number of years. Such a chart is presented as figure 2. By drawing mean charts of the ice potential, the average stability for every location can be examined to find areas of persistent high or low potential ice thickness. It is natural that the high and low values of ice potential should be found in nearly the same locations year after year, because the data reflect the quasi-permanent water currents and the regular annual nearshore cycle of freezing and melting and surface runoff.

As can be seen from figure 2, the main features of the chart for 1951, figure 1, are characteristic for the five-year period, 1950-1954. The area of greatest potential ice thickness is the center of the Beaufort Sea, with an extension southward to the Alaskan coast between Barter and Herschel Islands. In the coastal area east of Point Barrow the ice potential is small and increases eastward. A second area of low ice potential is located outside the entrance to Amundsen Gulf, between 125° and 130°W and 70° to 73°N. This area is evidently of dynamic origin, which is quite unlike that around Point Barrow.

In view of the incomplete knowledge of currents and water masses in the Beaufort Sea area at this time, only tentative postulates may be made as to the origin of the areas of high and low ice potential shown in figure 2. The great potential ice thicknesses indicated in the center of the polar basin are characteristic of the extremely cold surface waters of that area. The extension of the great potential ice thicknesses to the shore near the Alaskan-Yukon border may be caused by an onshore eddy which may curve counterclockwise along the coast and across Mackenzie Bay. This surface eddy was apparent in examining ice movements during the summer of 1954. The area of low ice potential around Point Barrow is probably the result of advection of warm water from Bering Strait. Some portion of this current of warm water apparently proceeds eastward along the Alaskan coast, losing heat as it moves eastward and accounting for the increase in ice potential from Point Barrow eastward.

The most interesting feature of figure 2 is the area of low ice potential southwest of Banks Island. A priori, this area should not be much different from the area around Barter and Herschel Islands, for there is no known source of warm currents in this part of the Arctic. However, the area of low ice potential is evident for each of the five years from 1950 to 1954 and, therefore, must be regarded as a normal feature. It is believed that this feature is of dynamic origin rather than advective in nature like the area around Point Barrow. It is possible that the bottom topography of the eastern Beaufort Sea and Amundsen Gulf causes tidal phenomena which could change the ice potential of the surface waters in that area. Tidal range throughout the area is small, amounting to less than 2 feet nearly everywhere. Dec-

pite the small tidal range, there is much horizontal transport of water by the tides entering Amundsen Gulf from the Beaufort Sea. The bottom topography shows a sill located between Cape Bathurst and Thesiger Bay, averaging 200 to 250 meters in depth, and over which a large quantity of water is transported by tides, creating a large-scale tidal rip. The effect of this tidal phenomenon is to decrease the ice potential by causing upwelling over the sill between the Beaufort Sea and the Amundsen Gulf basin; therefore, the area of low ice potential is formed.

The above theory seems reasonable until it is considered that the actual thickness of the surface layer involved in the ice potential (about 20 to 25 meters) is only about a tenth of the depth involved in the horizontal tidal transport. In addition, the location of the low ice potential is northwest of the sill. There is evidently some other unknown source of unstable water which causes the low ice potential in this area.

3. Depth of Convection in 1951

As explained previously, a depth of convection is determined whenever a fixed total heat loss is used. A chart showing these convective depths for a total heat loss of 20 kg.cal./cm.² is given for 1951 (fig. 3) and may be used in conjunction with figure 1. Figure 3 shows less regularity than figure 1. There are several centers of shallow and deep convection evident on the chart. In general, the depth of convection induced by the fixed heat loss is greatest to the north and least toward the south. Convective depths of over 50 meters are found north of 76°N, whereas depths of less than 10 meters are found in Mackenzie Bay. Since a shallow depth of convection is caused by stratification, the area affected by the runoff of the Mackenzie River contains the most stratified surface water of any area on the chart. In some cases, high ice potential values are associated with deep convection, while in other cases, the opposite association is found. For example, in the area of high ice potential north of Barter Island the convective depths are less than 20 meters, although the same amount of potential ice thickness (200 cm.) accompanies convection reaching a depth of 45 meters near 76°N 170°W. Also, the area of low potential ice thickness at the entrance to Amundsen Gulf is not evident on the flat isoline field in figure 3.

Because of the nature of the available data, it was not possible to present a mean chart of convective depth for the period 1950 to 1954. Inasmuch as the mean chart for ice potential (fig. 2) resembles the chart for 1951 (fig. 1) in most respects, it is felt that a mean chart of convection would nearly duplicate the main features shown on figure 3.

4. Stability Index for 1951

By combining the data shown in figures 1 and 3, an index of stability related to ice formation is obtained by finding the average potential ice thickness per unit of depth of convection. Since potential ice thickness is given in centimeters and convective depth in meters, the ice potential

stability index of centimeters of potential ice thickness per meter of convection is expressed as a percentage. A high percentage denotes relatively high stability, since the vertical stratification of the water mass is great when a large increase in potential ice thickness accompanies a small increase in depth of convection (section B 3). Similarly, a low percentage indicates relatively low stability.

Figure 4 shows the stability index for 1951 as derived from figures 1 and 3. A feature of the chart is the wide range of index levels from below zero to over 26 (an index below zero denotes so-called negative ice potential or lack of ice formation after the fixed heat loss has taken place). The greatest stability is found in the area north and northeast of Mackenzie Bay, where the runoff from the Mackenzie River is an influence. A second small area of high stability to the south of Banks Island may also represent runoff. Two interesting areas of relatively low stability exist near Banks Island. To the southwest of the island in the same area as the low potential ice thicknesses in figure 2, the stability is low. This area is shown by good data to be definitely cut off on the north at about 73°N . It thus forms a small pocket of unstable water between the stable waters of the runoff area to the southwest and the area along the southern coast of Banks Island. A second very small area of low stability of unknown origin is found in the southern part of Amundsen Gulf, centered at 120°W .

5. Areas with Similar Ice Potential and Stability

The charts discussed above, figures 1 through 4, share to some extent a common difficulty in ready analysis. As a summary and combination of the above figures, figure 5 is presented to indicate the various areas in the Beaufort Sea and adjacent waters within which ice potentials and stability index readings are similar. In the figure the locations of the areas and their relative size are immediately apparent. Shapes and sizes of the areas are approximate.

The areas in figure 5 are determined by classifying the main areas of figures 2 and 4 into six classes by arbitrarily dividing the potential ice thicknesses into two categories, less than 140 cm. and greater than 140 cm. In addition, the stability index is divided into three categories, less than 8 percent, from 8 to 16 percent, and greater than 16 percent. These categories are referred to as low or small, moderate, and high or great. Although there are six possible classes, only four are found to exist.

Area A in figure 5 is characterized by low ice potential and low stability. In this region the convective depths as shown in figure 3 are so great that in winter the thermohaline mixing reaches to the bottom in shallow waters, while the total amount of ice formed by the given heat loss is small.

In area B of figure 5 the potential ice thickness is great, and the stability is low. This area includes the cold water of the central Arctic, which has low stability because the surface layer remains close to the freezing point during the summer. The area has two small offshoots toward the shore, one between areas A and C, and the other between areas C and D.

The western stub, area B1, is transitional between the area of low ice potential and low stability to the west and the area of high ice potential and moderate stability to the east. Area B2 comprises a small area of low stability between the more stable waters to the west and east. A speculative cause for the presence of this area is the cold cyclonic current which is presumed to set eastward along the coast between 142° and 138°W.

Area C of figure 5 is a small area in which the stability is moderate while the ice potential is great. This area contains water which is similar to that of the central Arctic in that potential ice thickness is great but is distinguished from that area because stability has been increased by surface runoff.

Area D in figure 5 is similar to area C in having moderate stability and high ice potential. It is transitional between the mid-Arctic area and the inshore area E described below.

Area E in figure 5 is unique in having extremely high stability along with high ice potential. The surface water of this area contains much runoff water even as far as 150 miles offshore; hence it is highly stratified. Surface salinities are below 24‰ in most of the area. Due to the stratification, once the heat loss is large enough to cause ice formation, a small amount of further convection increases the ice thickness greatly.

Area F in figure 5 resembles area A in having low ice potential and low stability. However, a typical T-S diagram from area F should not be expected to be identical with one from area A, since the ice potential calculation uses the average values of temperature, salinity, and density in the water column rather than those at each individual level. The fact that two areas are similar in their capacity for ice formation does not necessarily connote their similarity in other respects. As indicated above, the reason for the existence of area F is not known.

Area G in figure 5 is like areas C and D in having high ice potential and moderate stability. It contains some surface runoff like the other two similar areas. Because of its small size, the area of very high stability near DeSalis Bay, shown in figure 4, has been ignored in delineating area G.

The remaining area in figure 5 is area H, which is like area B in having low stability and high ice potential. Its presence in the southern part of Amundsen Gulf can be inferred from historical ice reports. As summarized in figures 6 and 8 through 12 in H.O. Technical Report 25 (1955) summer ice conditions in the southern part of Amundsen Gulf are usually worse than those in the northern part of the gulf. This may possibly be an area of upwelling in which cold subsurface water replaces the warm layer that causes higher stability in area G.

D. USE OF ICE POTENTIAL CLIMATOLOGY IN FORECASTING

The above discussion of figures 1 through 5 has implied the use of the techniques of ice potential climatology in ice forecasting. The major point is that surface ice conditions are related to the physical properties of the surface layer involved in the ice potential calculations. An illustration has been given in the discussion of figure 5 with respect to area H in southern Amundsen Gulf. As long as average ice thickness is the criterion and not the transitory conditions induced by wind movements, the ice potential climatology provides an accurate guide to mean ice conditions. However, the ice potential climatology must be used with the knowledge that the observed ice conditions depend on actual heat loss and not on the postulated constant heat loss. More information needs to be collected as to the heat budget over ice and water in the Arctic.

While all of the figures are of use in forecasting, the most immediate use is seen in figure 5. By subdividing the Beaufort Sea into areas, it is possible to utilize each area as a forecasting indicator. The forecaster should be aware that conditions in each area are different, and that data from each area are necessary for making a complete analysis. As for oceanographic data necessary for calculating the ice potential each year, the delineation into areas as in figure 5 makes an effective collection of data much easier, since the number of hydrographic stations to be studied can be kept to a minimum. Aerial reconnaissance data can be used in conjunction with the ice potential climatology by using areas as indicators. Within such areas as A and F, formation of leads should be common throughout the winter season, while within areas B and H, few leads should be noted, and so on for the other areas according to their ice potential and stability. Thus, planning for routes to be covered by aerial reconnaissance should include consideration of the areas involved. Similarly, the results of aerial reconnaissance can be used as verification of the ice potential patterns observed in previous oceanographic data.

It is not the purpose of this report to give detailed rules for ice forecasting by means of ice potential climatology. The aim is to point out some broad categories of information which are of use in ice forecasting, either on a short- or long-range basis. An example of the former is the use of figure 2 to deduce the relative proportions of winter and polar ice in the various parts of the Beaufort Sea. Figure 2 indicates that there may be great differences from place to place in the average age of the ice and the percentages of winter and polar ice. Since flees made up of winter and polar ice have different physical characteristics, they respond differently to environmental factors and hence affect the application of techniques of ice forecasting.

E. SUMMARY

Ice potential calculation, which has hitherto been discussed on the basis of individual hydrographic stations, is placed on an areal basis

by means of the techniques of ice potential climatology. These techniques are applied to the Beaufort Sea and adjacent waters. After discussion of the climatological charts of the potential ice thickness and the depth of convection, a special type of stability index is derived. Several regions of varying ice potential and stability are described as a means of gaining insight into the complex causes of synoptic and mean ice conditions in the Beaufort Sea. Finally, some aspects of the use of ice potential climatology as a forecasting tool are discussed.

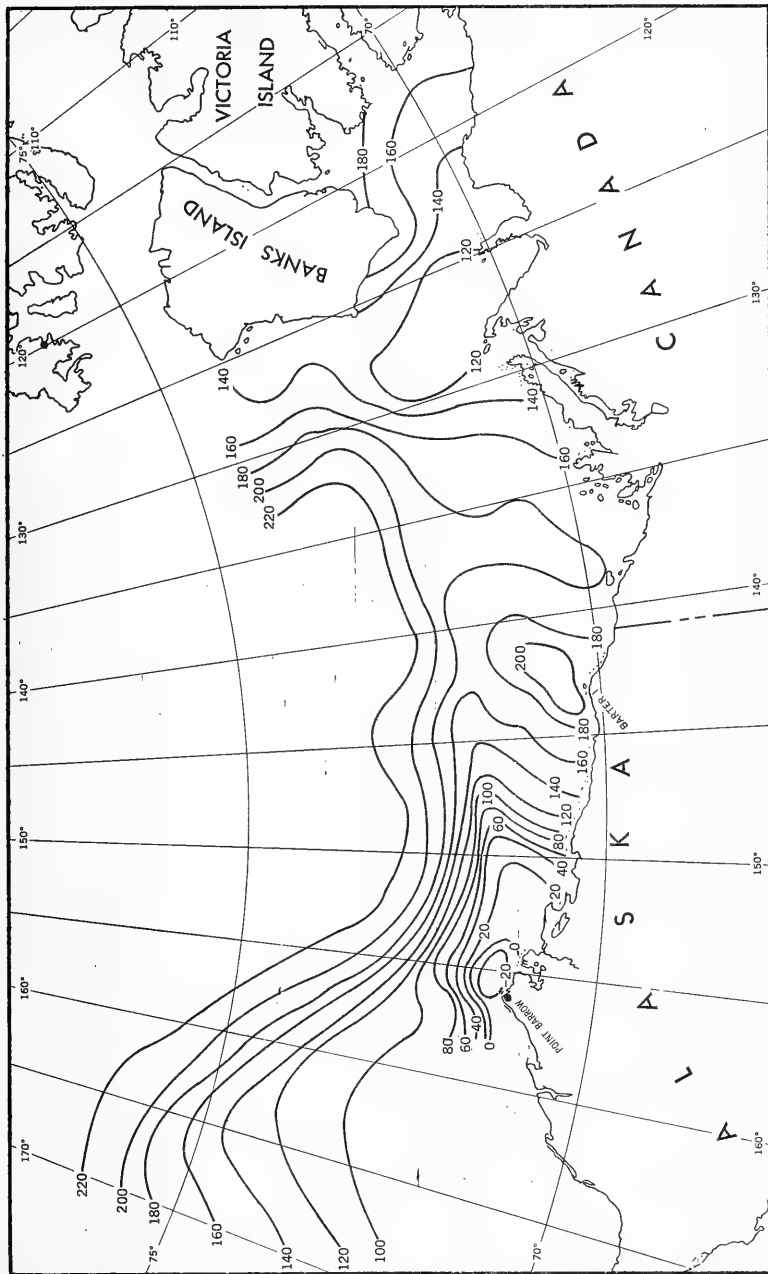


FIGURE 1. POTENTIAL ICE THICKNESS (CM.) ASSOCIATED WITH TOTAL HEAT LOSS OF 20 KG. CAL./CM², 1951

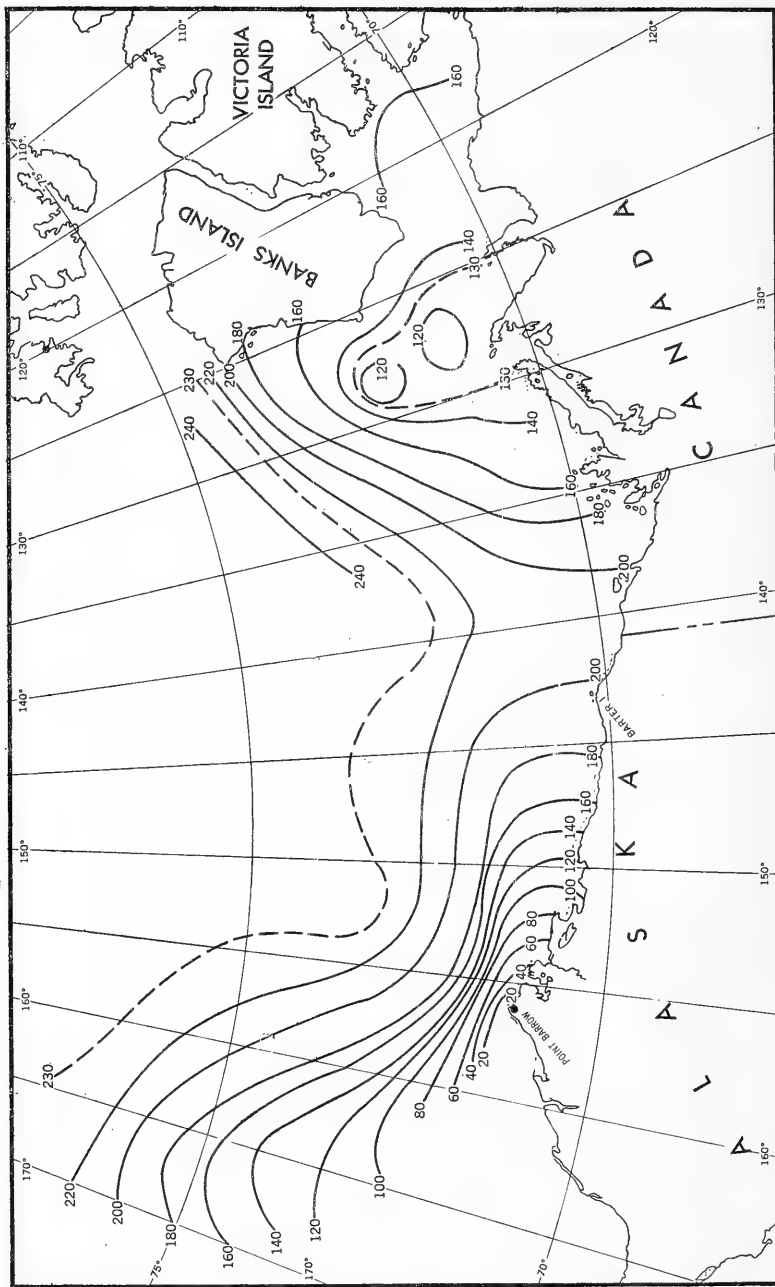


FIGURE 2. POTENTIAL ICE THICKNESS (CM.) ASSOCIATED WITH TOTAL HEAT LOSS OF 20 KG. CAL./CM², MEAN 1950-54

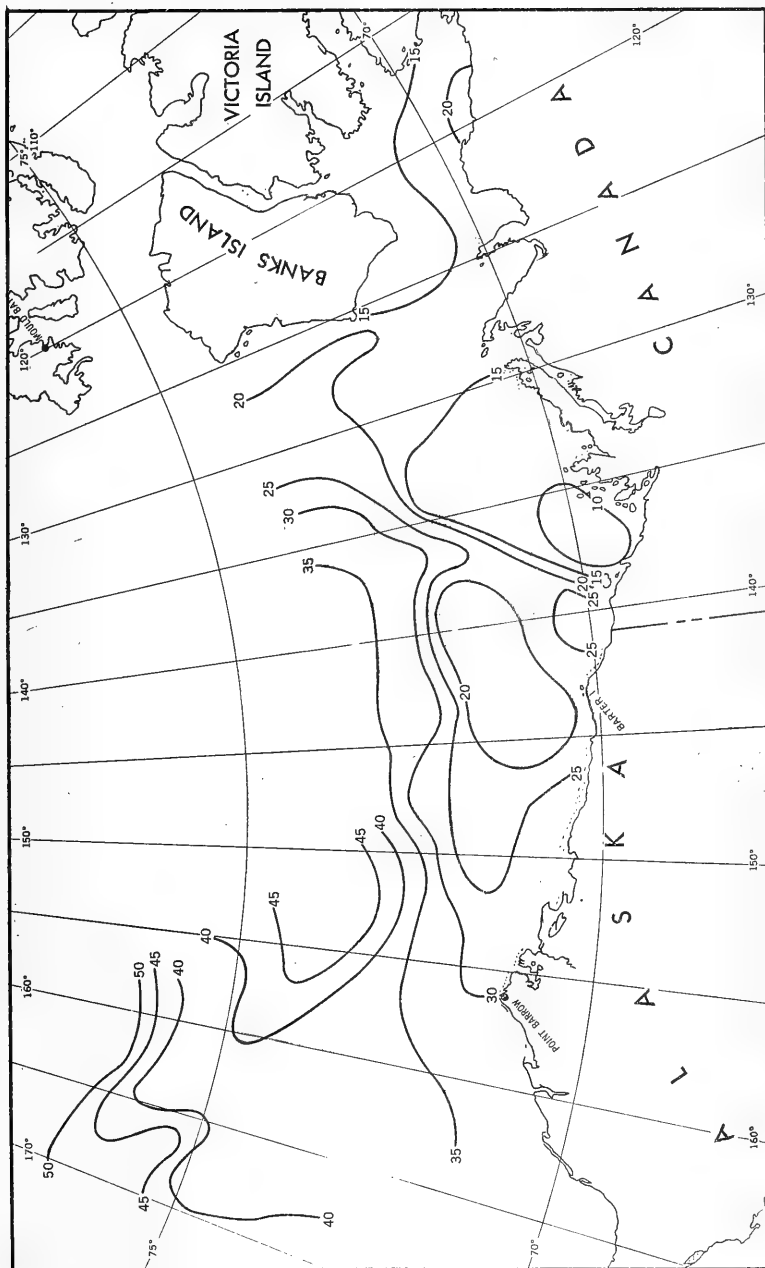


FIGURE 3. DEPTHS OF CONVECTION (M) ASSOCIATED WITH TOTAL HEAT LOSS OF 20 KG. CAL./CM², 1951

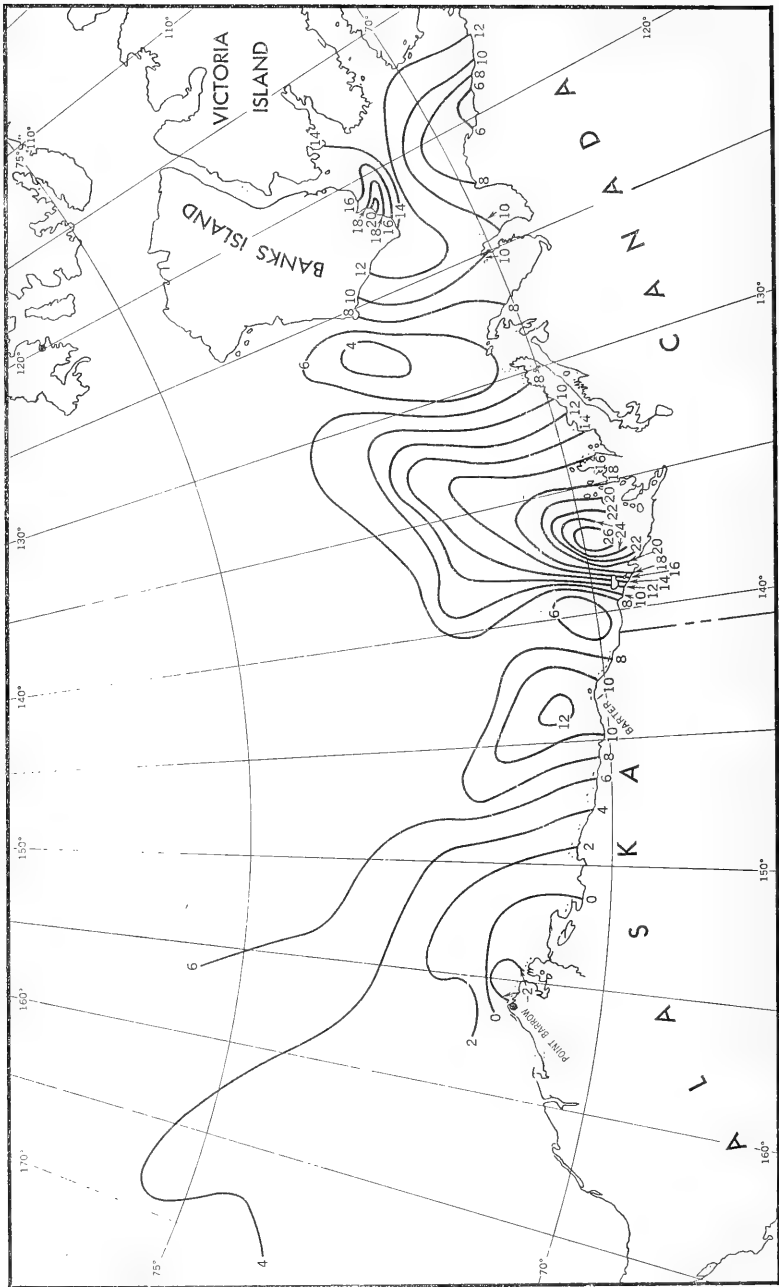


FIGURE 4. STABILITY INDEX FOR 1951 (CM./M. FOR TOTAL HEAT LOSS OF 20 KG. CAL./CM.²)

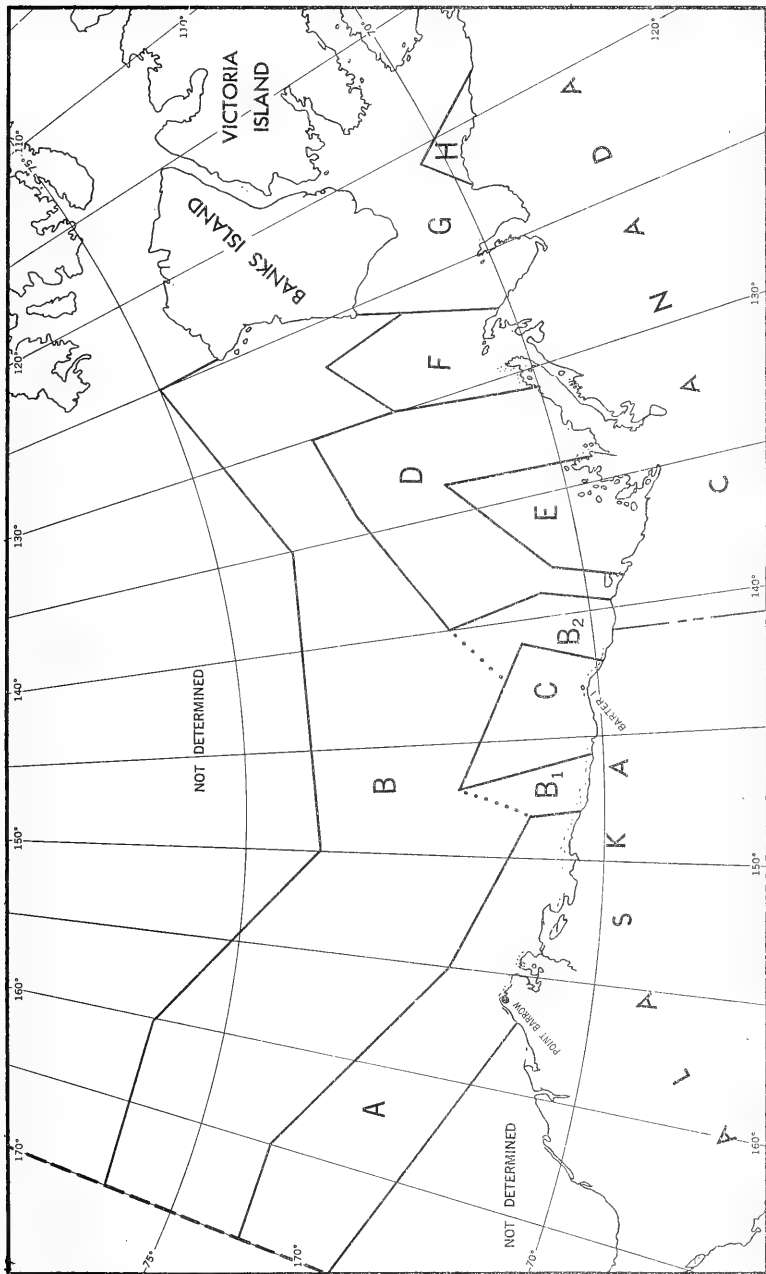


FIGURE 5. ICE POTENTIAL CLIMATOLOGICAL AREAS OF THE BEAUFORT SEA AND ADJACENT WATERS

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1. Sea Ice - Forecasting
 2. Sea Ice Potential
 3. Oceanography
 4. Beaufort Sea - Sea Ice
 5. Amundsen Gulf - Sea Ice
 6. Convection
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- ii. author: Edward L. Corton
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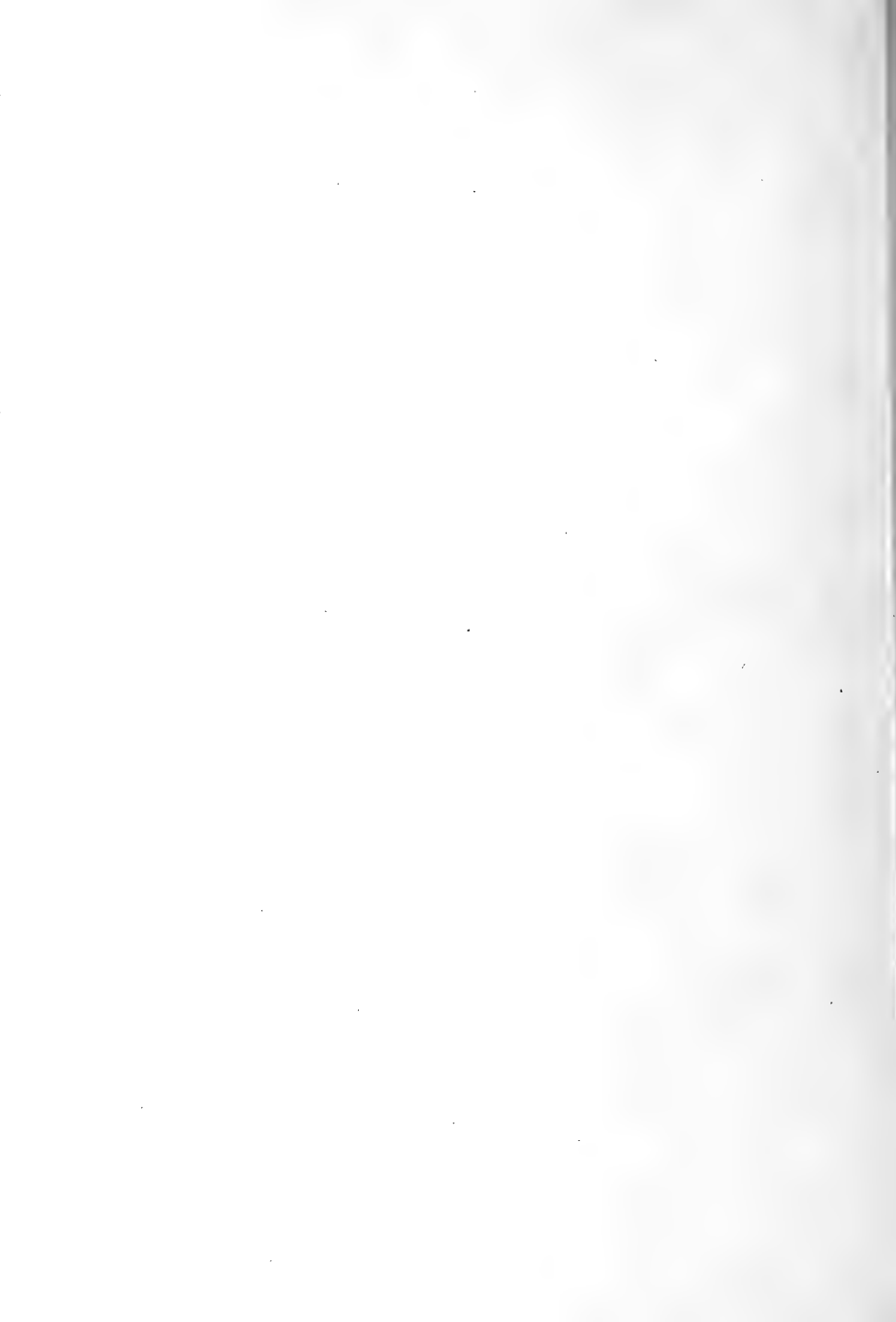
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