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Sea-Ice Conditions in the Norwegian, Barents, and White Seas

E. S. Batten

A report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

Rand
SANTA MONICA, CA. 90406

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An investigation of the possible effects of climatic change on the military posture of the United States and the Soviet Union. The problem is to estimate worsening sea-ice conditions in the Norwegian, Barents, and White seas in the event of a climatic cooling during the next few decades. Future climatic conditions assumed for this study approximate the severe winters experienced during the Little Ice Age from the mid-1400s to the mid-1800s. A period of cooling in the polar regions implies a worsening of sea-ice conditions in the Arctic seas producing increased hazards to navigation. The author concludes that for a climatic state similar to the Little Ice Age, the Norwegian and Barents seas would remain open to navigation. Within the White Sea, however, under extreme conditions the duration of the ice season would lengthen to about 8 months, with maximum ice thickness reaching 70 in., Ref. (ETG)

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PREFACE

This report, prepared for the Defense Advanced Research Projects Agency, presents research results of a Rand project investigating the possible effects of climatic change on the military posture of the United States and the Soviet Union. A forthcoming companion report (R-1922-ARPA) reviews the climatic history of the earth to provide perspective on the range of possible future climatic states, and attempts to make reasonable estimates of the climatic change that might occur in Europe over the next few decades.

The present report addresses the problem of estimating possible worsening sea-ice conditions in the Norwegian, Barents, and White seas in the event of a climatic cooling during the next few decades. The future climatic conditions assumed for this study approximate the severe winters experienced during the period from the mid-1400s to the mid-1800s, known as the Little Ice Age. If recent northern hemispheric cooling trends continue, a climate of the Little Ice Age type may occur within the next half-century.

SUMMARY

An examination of climatological evidence clearly shows that climate varies on time scales of decades, centuries, millennia, and longer periods. This knowledge by itself is insufficient to permit forecasting of the future climatic state. It can be used, however, to guide us in placing reasonable limits on the range of future climates. One possible climatic state that could be attained within the next half-century can be approximated by the severe winter conditions experienced during the Little Ice Age from the mid-1400s to the mid-1800s.

The assumption of a period of cooling in the polar regions implies a worsening of sea-ice conditions in the Arctic seas producing increased hazards to navigation. This report provides estimates of sea-ice conditions in the Norwegian, Barents, and White seas following an assumed climatic deterioration.

It is concluded that, for a climatic state similar to the Little Ice Age, the Norwegian and Barents seas would remain open to navigation. Within the White Sea, however, the duration of the *average* ice season would lengthen (although by less than a month) and thickness of the ice would increase (although by only about $\frac{1}{2}$ ft). The most extreme conditions to be expected in the White Sea would have ice lasting from 8 to $8\frac{1}{2}$ months, consolidated ice from $6\frac{1}{2}$ to 7 months, and maximum ice thickness reaching 70 in. Even in this extreme case, ice-breaking operations should not be substantially more difficult than they are today.

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I. INTRODUCTION

Speculations concerning the future state of the climate are abundant in current popular and technical literature. These speculations cover the full range of possibilities from pronounced warmings leading to the possible disappearance of the Arctic ice pack to pronounced coolings with a return to full glacial conditions. A summary of past, present, and possible future climatic states was given in Batten, Rapp, and Warshaw (1976). They concluded there that *if* continued cooling is assumed, a reasonable climatic state for the next half-century or so would approximate the climatic conditions during the 400-year period from the mid-1400s to the mid-1800s.

During this period, known as the Little Ice Age, mountain glaciers advanced to their farthest forward positions in postglacial time. However, the large continental ice sheets typical of full glaciation did not exist. European winters were generally colder than today and often long and severe, but summer temperatures were not much below modern values.

A climatic deterioration to a Little Ice Age climatic state would imply worsening ice conditions, which might hinder navigation in the seas bordering the Arctic Basin. This report examines ice conditions, both past and present, in the Norwegian, Barents, and White seas (see Fig. 1 for locations) to estimate future ice conditions in the event that such a climatic deterioration occurs.

In the next section the general ice conditions in the Norwegian, Barents, and White seas are discussed. We present the argument that the oceanic and meteorological conditions are such as to make unlikely any substantial increase in ice formation in the Norwegian and Barents seas. In the White Sea, however, decreasing winter temperatures can be expected to both lengthen the ice season and increase the thickness of the ice. Section III deals exclusively with ice conditions in the White Sea and presents estimates of the seasonal pattern of ice formation, growth, and melt, assuming a return to Little Ice Age conditions.

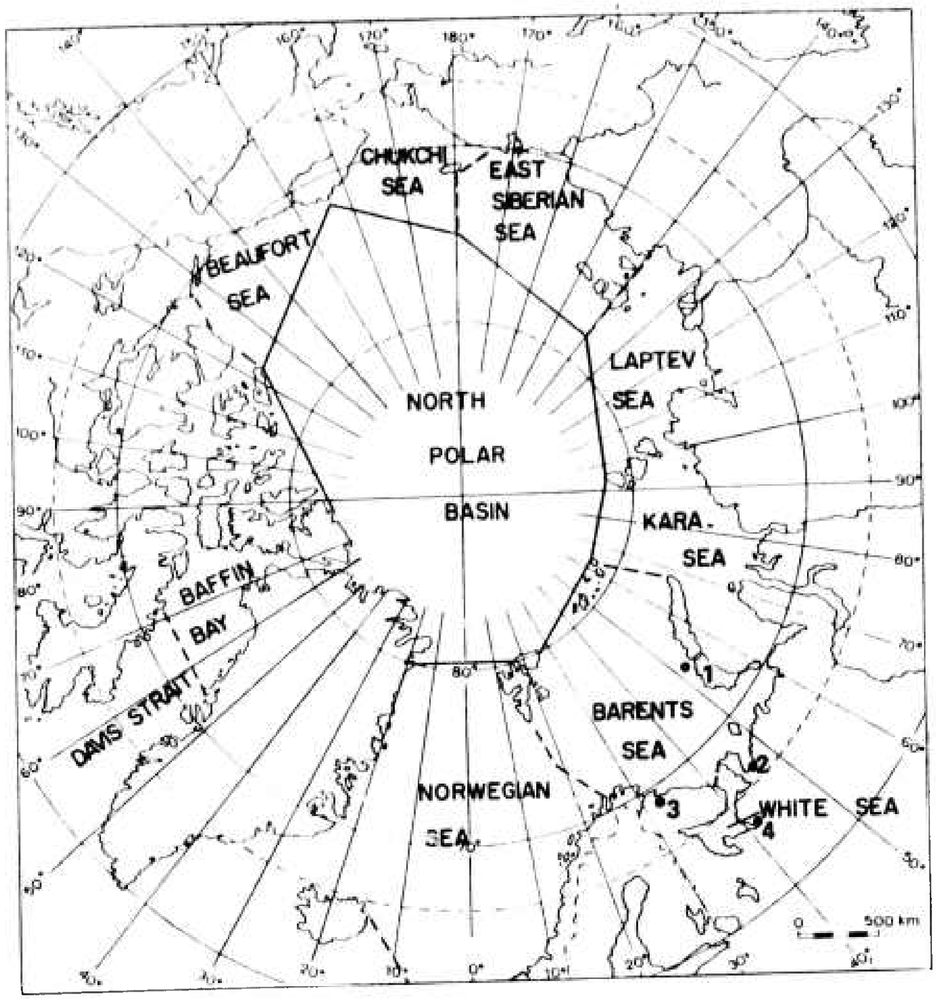


Fig. 1—The Arctic seas. Locations referred to in the text are (1) Novaya Zemlya, (2) Cheshskaya Bay, (3) Murmansk, and (4) Archangel.

II. GENERAL ICE CONDITIONS IN THE NORWEGIAN, BARENTS, AND WHITE SEAS

ICE CONDITIONS DURING THE PRESENT CENTURY

The Norwegian, North Cape, and Murman currents (see Fig. 2) (extensions of the North Atlantic drift) keep the Norwegian coast ice-free throughout the year. Ice is no hindrance to navigation as far as 400 mi seaward from the western Norwegian coast and as far as 150 mi seaward from the northern Norwegian coast. Year-long ice-free coastal waters extend along the Murman coast into the Barents Sea. In the far eastern portions of the Barents Sea, the bays and gulfs may become icebound. The maximum western extent of the 0.5 or greater fractional coverage of ice occurs in April and is near 37°E on the Murman coast (see Fig. 3).

The effect of the warm saline waters of the North Cape and Murman currents is evidenced by the lack of complete freezing in some years at locations along the southwest coast of Novaya Zemlya and a short distance east of the Cheshskaya Bay on the mainland. Murmansk (35°E), for example, in 11 years of data (U.S. Navy Hydrographic Office, 1958) never experienced complete freezing. Slush formed in only 4 of the 11 years.

The interior of the White Sea (Fig. 1) is separated from the Barents Sea by a narrow strait bounded on the west by the Kola Peninsula and on the east by the Kanin Peninsula and is thus to a large extent isolated from the effects of the warm currents. Freezing in the White Sea can start in late October in the deep bays such as Archangel. A continuous strip of fast ice usually forms along all coasts by December. The interior is filled with fields of drift ice of variable strength and thickness. The ice reaches its greatest concentration during February and March. Breakup of the fast ice begins in April. During May the drift ice in the interior of the sea melts rapidly. At Archangel the average ice period lasts from early November to early May.

The most important factor controlling the ice formation along the northwestern coasts of Europe is the intrusion of warm North Atlantic waters into the area. The maintenance of this branch of the North

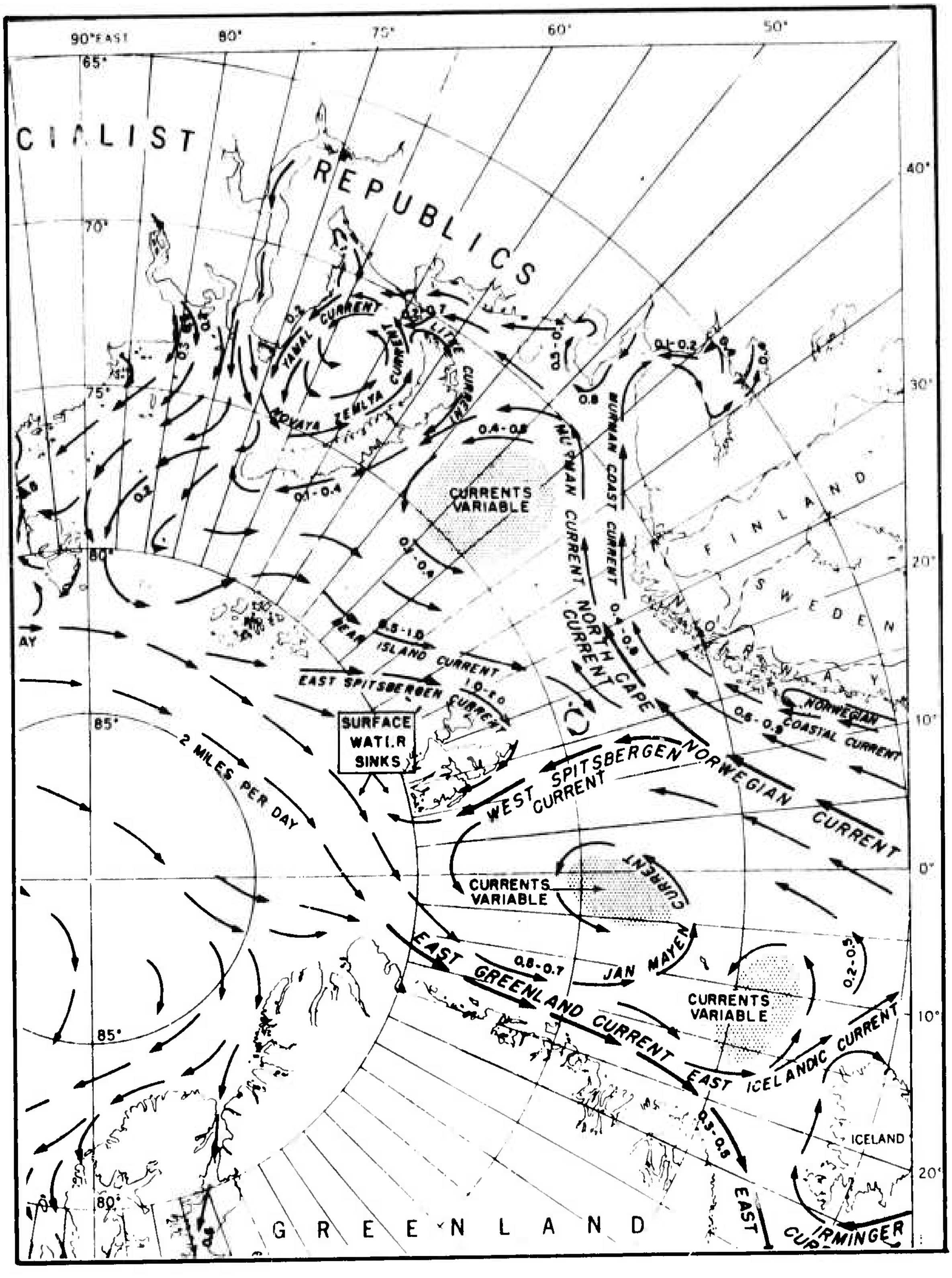


Fig. 2 — Ocean currents in the Norwegian, Barents, and White seas (from U.S. Navy Hydrographic Office, 1958)

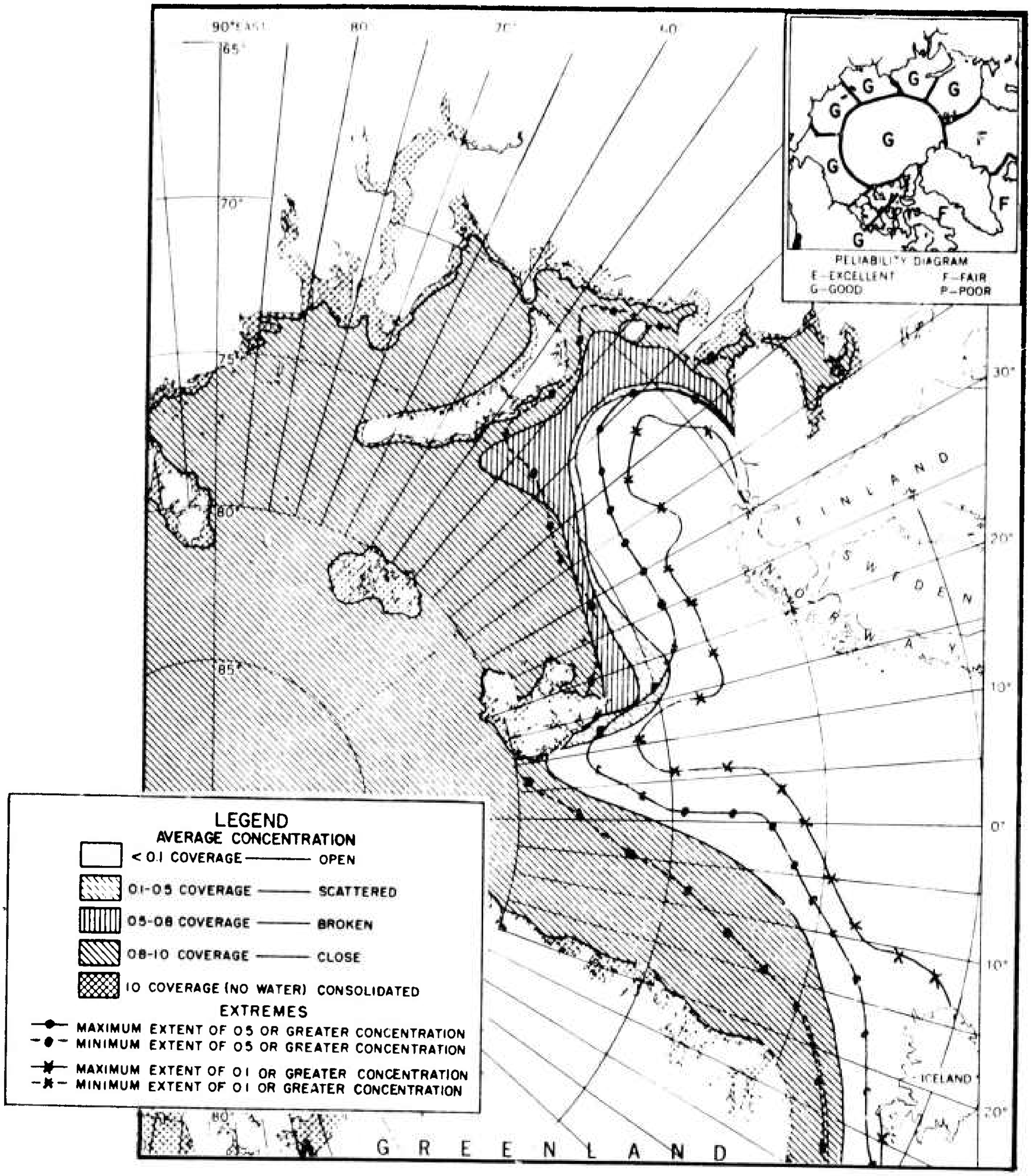


Fig. 3—Average concentration and extremes of ice conditions for April (from U.S. Navy Hydrographic Office, 1958)

Atlantic Ocean circulation is described by Worthington (1970). He estimates that the total *outflow* of water from the Arctic region is approximately 10×10^6 m^3/sec, mostly in the form of dense deep-ocean outflows into the North Atlantic. The outflow must be matched by an *inflow*, or the Arctic Ocean would suffer a drop in sea level of 6 cm/day. Only 10 percent of the outflow is made up by surface inflow through the Bering Strait. Most of the northward flux of water (8×10^6 m^3/sec), required by continuity of mass, takes place through the channel between the Faeroe and Shetland islands, forming the Norwegian, North Cape, and Murman currents. The temperature of the water in these currents is well above freezing throughout the year. As long as this ocean circulation is maintained, the climate of northwestern Europe will remain moderate and the Norwegian and Barents seas will remain relatively ice-free.

ICE CONDITIONS DURING THE LITTLE ICE AGE

Within the last 600,000 years (the Quaternary period) at least four major glacial advances have occurred. Periods with substantially warmer temperatures, the interglacials, separated the periods of major glaciation. At the present time, the earth is experiencing an interglacial epoch, the Holocene, which began about 10,000 years ago. The present interglacial was marked with shorter period temperature variations of smaller amplitude. During the Little Ice Age (1430-1850 AD), the climate was colder and more severe than today, but it did not approach the severity of the climate experienced during full glaciation. Kellogg (1975) has suggested that, during the full glacial periods of the late Quaternary, ice covered the Greenland and Norwegian seas at least in winter. However, although sea ice increased between Iceland and the Faeroe Islands during the Little Ice Age, apparently caused by changes in atmospheric circulation (Bjerknes, 1965), the channel between the Faeroe and Shetland islands remained open. Warm currents were still able to flow along the northern coasts. Drift ice undoubtedly increased in the Norwegian and Barents seas, but the waters remained open.

With the assumption of a climate deterioration to Little Ice Age conditions, historical evidence indicates that we should not anticipate major advances of the ice pack into the Norwegian and Barents seas.

However, in the White Sea, where the ice forms and melts annually, continued climatic cooling can be expected to result in increased ice formation. The extent to which ice conditions in the White Sea might worsen is the subject of the remainder of this report.

III. ESTIMATES OF ICE GROWTH IN THE WHITE SEA

The task of this section is to estimate the seasonal pattern of ice formation, growth, and melt within the White Sea that might accompany a cooling trend during the next few decades. The climatic conditions we wish to approximate are those experienced during the Little Ice Age.

Some notion of the seasonal variation of the fraction of the sea covered by ice can be obtained from oceanographic charts such as those found in the *Oceanographic Atlas of the Polar Seas* (U.S. Navy Hydrographic Office, 1958) or from the *Monthly Ice Charts* compiled by the British Meteorological Office. By itself, this kind of information cannot be used to extrapolate ice conditions in a future climatic state. Further, they provide very little useful information on ice thickness. However, used jointly with an appropriate model of ice formation and growth, they can be used to guide such an extrapolation.

Detailed models of ice growth (see, for example, Maykut and Untersteiner, 1971) are available. However, these models require the specification of heat fluxes to and from the upper and lower boundaries of the ice sheet. The heat flux data are not routinely measured and must be derived from detailed heat budget studies of the earth-atmosphere-cryosphere system. A simpler model, requiring input data available from historical records, is thus more appropriate.

Lengthy historical records of the surface air temperature are available for Archangel located at Dvinskaya Bay in the eastern White Sea (see Fig. 4). These data may be used with one of the several existing empirical or theoretical models relating ice growth to surface air temperature. In the appendix to this report we postulate that an approximation to the upper limit of the thickness of ice that forms during a winter season may be derived from the accumulated negative degree days.* This approximation is used with climatological data at

*The accumulated negative degree days indicate the progress of seasonal cooling and may be defined as the sum of the number of degrees Celsius (centigrade) below zero experienced each day during the period of below-zero temperatures.

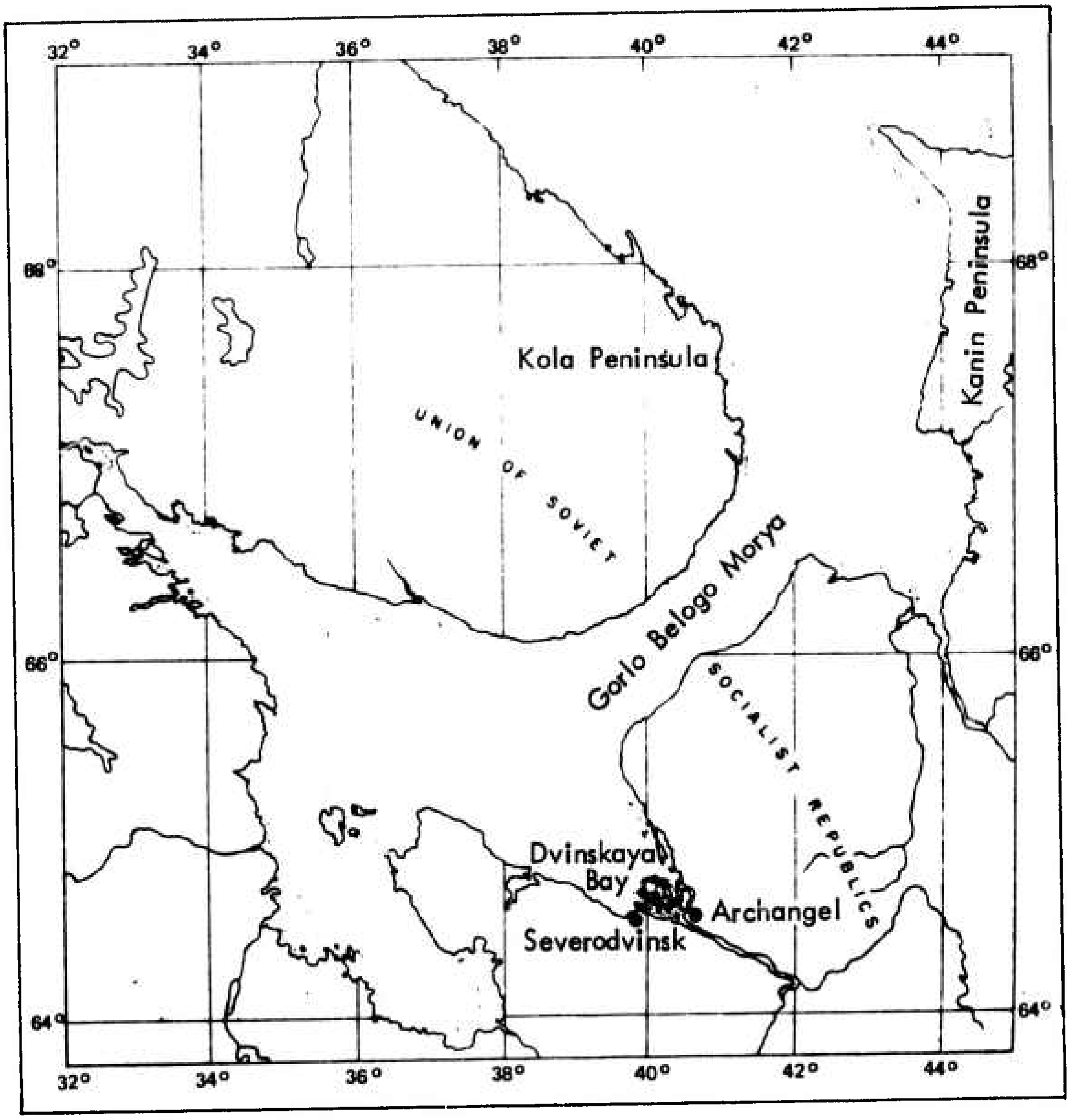


Fig. 4—The White Sea

Archangel for the years 1891-1973 and with observed ice conditions in the White Sea obtained from monthly ice charts for the years of 1962-1969 and 1972-1973 to estimate the following conditions:

1. Generalized rules for the *seasonal* pattern of ice formation, ice growth, and ice melt at Archangel in terms of accumulated negative degree days.
2. The *seasonal* patterns of ice formation, ice growth, and ice melt for past extreme years at Archangel.

3. General conditions in the northern approaches to the Archangel area.
4. The *secular* and *inter-annual* variation of maximum ice thickness in the Archangel area for the period 1891-1973.
5. Future conditions resulting from a cooling trend.

The generalized rules in item 1 are obtained from the observed ice conditions and the monthly mean air temperatures during the years 1962-1969 and 1972-1973. These rules are used together with the ice growth model in the appendix to formulate a method of reconstructing ice conditions in the White Sea area from historical temperature data (items 2 and 3) and from temperatures for an assumed future climatic state (item 5). The reconstructed extreme ice states provide us with a notion of the range of ice extents and thickness experienced in the White Sea area during the recent past. It is also desirable to estimate the magnitude of the year-to-year variability of the maximum ice thickness and the magnitude of the longer trends in ice thickness presumably caused by climatic warmings or coolings. These estimates may be obtained from the historical temperature record at Archangel and the ice growth model (item 4). Finally, possible future ice conditions resulting from an assumed cooling trend are inferred from the results of items 1 through 4.

SEASONAL PATTERN OF ICE FORMATION

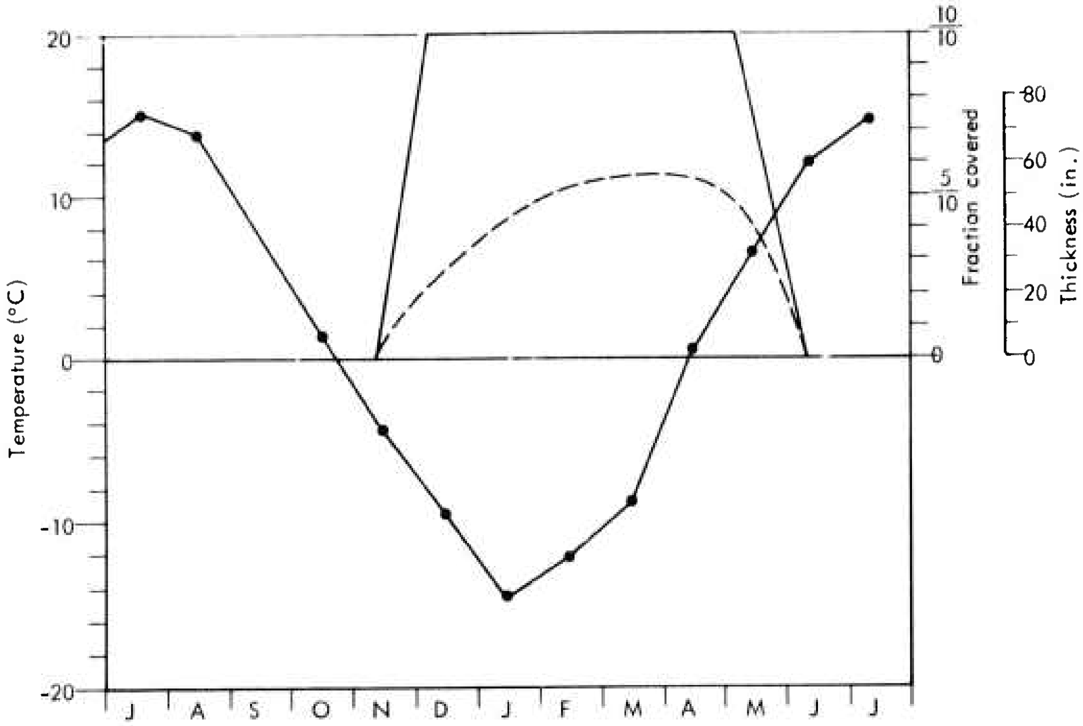
We used monthly ice charts, when available, from the British Meteorological Office to examine the seasonal pattern of ice formation in the White Sea and Archangel area. The ice charts give the extent and concentration of ice at the end of each month. The concentration is specified by five categories: new or degenerate ice, very open pack ice (1/10 to 3/10 covered), open pack ice (4/10 to 6/10 covered), close or very close pack ice (7/10 to 9/10 covered), and land-fast or continuous field ice (10/10, no open water). During the years studied, the duration of ice in any concentration around Archangel ranged from 5 to 8 months. The duration of complete coverage (10/10) ranged from 4 to 6 months. The earliest formation was observed in October and the latest complete melt was in June. The earliest complete coverage was November and the latest start of breakup was May.

Using data from the ice charts and curves of the intra-annual variation of temperatures, as given by the monthly mean temperatures observed at Archangel, we determined some general rules relating ice formation and melt to the onset of *below*-freezing temperatures, the accumulated negative or positive degree days, and the onset of *above*-freezing temperatures:

1. Ice begins to form within 15 to 30 days following the start of below-freezing temperatures.
2. Complete ice coverage (10/10) is observed following the accumulation of 200 ($\pm$60) negative degree days.
3. Complete ice coverage (10/10) remains for 15 to 30 days following the return to above-freezing temperatures.
4. Ice is completely removed after the accumulation of 300 ($\pm$180) positive degree days.

These rules were used to construct a composite model of the formation, growth, and melt of ice for the years with ice data. The model is shown in Fig. 5. Included in the figure is the intra-annual variation of temperature, the fraction of ice coverage, and the growth and decay of ice thickness. The onset and disappearance of ice are based on the four rules above, and the thickness curve is based, with some modifications, on Eq. (6) in the appendix. This equation predicts that the formation and growth of ice begin with the onset of below-freezing temperatures. However, ice is observed to form 15 to 30 days later. Thus, the thickness curve was adjusted to match the formation date as given by rule 2 above. Further, Eq. (6) does not predict the ablation of ice during the melting period, so the thickness curve was extrapolated from the date of maximum thickness to date of complete melt as given by rule 4 above.

In this model ice year, ice conditions start in early November and last for 7 months with complete coverage for 5 months (early December through early May). The ice grows to a maximum in April of slightly less than 5 ft and then decreases, completely disappearing by mid-June.



Gorlo Belogo Moryo Stroit	4/10–6/10	7/10–9/10	7/10–9/10	10/10	7/10–9/10	1/10–3/10
Northern White Seo	1/10–3/10	4/10–6/10	7/10–9/10	7/10–9/10	4/10–6/10	1/10–3/10

Fig. 5—Composite of sea-ice conditions at Archangel reconstructed from monthly ice charts for the years 1962-1969 and 1972-1973. The solid "step" curve gives the fraction of water covered with ice, the dashed curve gives ice thickness, the dots give monthly temperatures, and the table lists the fraction of the area covered with ice at two other locations in the White Sea.

SEASONAL ICE FORMATION FOR EXTREME YEARS

Applying the same procedure used for the model year, we can obtain reconstructed ice formation patterns for extreme years (maximum and minimum ice formation) from the Archangel data. The choice of years with maximum or minimum ice formation was based on two factors: the length of below-freezing temperatures and the value of the accumulated negative degree days for the year.

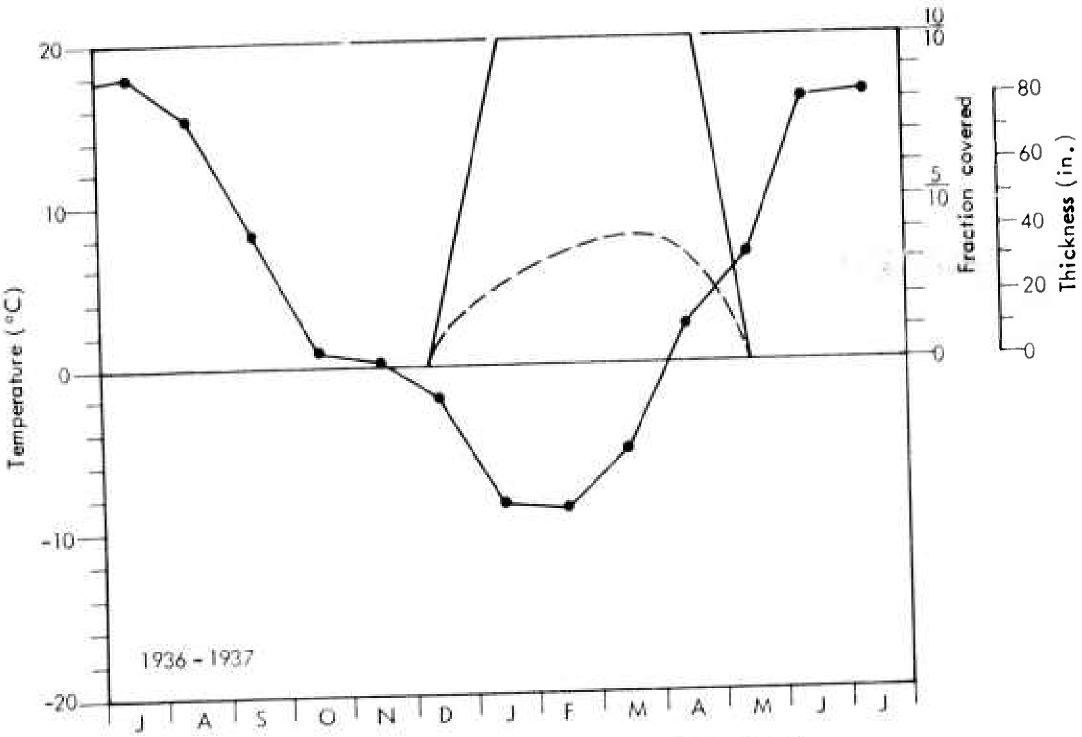
We judged that the least ice formed during the winter of 1936-1937. The reconstructed pattern of ice formation for this winter is shown in Fig. 6. The duration of ice in the 1936-1937 winter was about two months shorter than the model year, forming a month later and disappearing a month earlier. Maximum ice thickness reached 40 in. at the end of March, about $1\frac{1}{2}$ ft less than the model year.

The greatest amount of ice formed during the winter of 1901-1902 (Fig. 7). The duration of ice was approximately $2\frac{1}{2}$ months longer than the 1936-1937 winter, but one-half month longer than the model year. The cold year ice thickness exceeded that of the warm year by more than 2 ft and exceeded the model year by less than a foot.

The similarity between the model year and the 1901-1902 winter can be understood in terms of the secular variations of temperature to be discussed later (see Fig. 10, p. 20). It can be noted from Fig. 10 that the temperature conditions in the 1960s were similar to the late 1800s and early 1900s. In fact, two of the winters (1965-1966 and 1968-1969) used in constructing the model year approached the severity of the 1901-1902 winter. The observed conditions for those years are shown in Figs. 8 and 9.

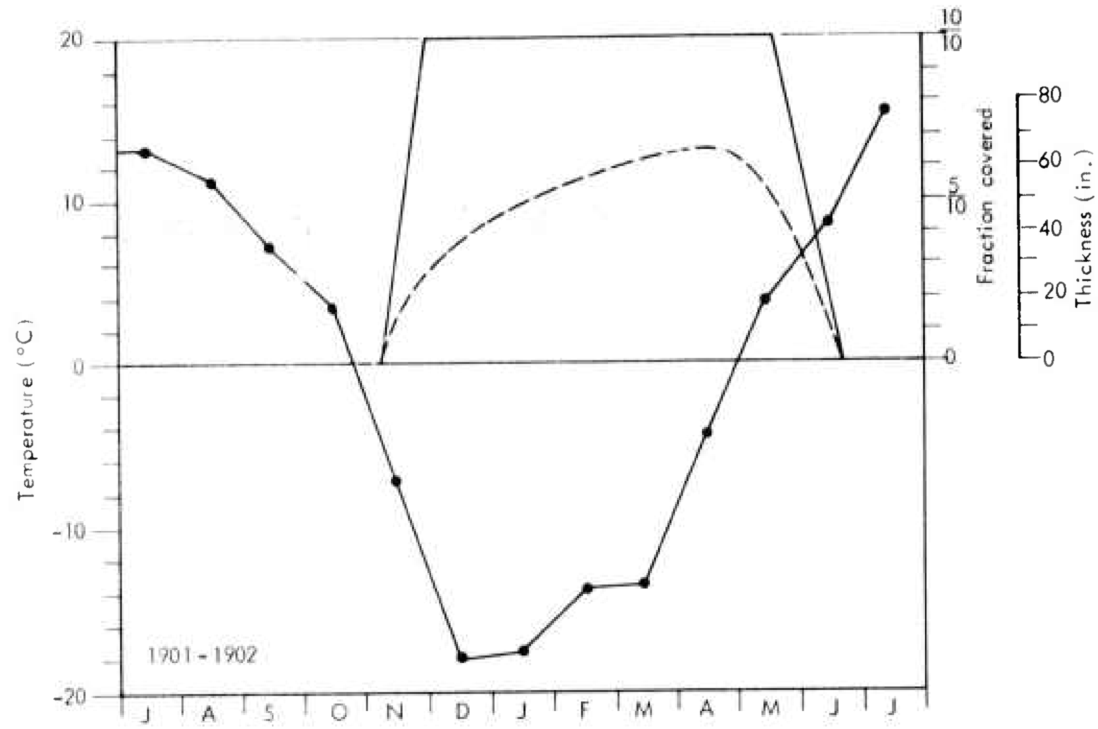
ICE CONDITIONS IN THE NORTHERN APPROACHES TO THE ARCHANGEL AREA

The discussion until now has concentrated on conditions near Archangel, which can be considered representative of the coastal regions of Dvinskaya Bay. Some comments are in order concerning ice conditions in the Gorlo Belogo Morya Strait (the strait along the Kola Peninsula separating the northern and southern portions of the White Sea) and the area near the entrance of the White Sea. Ice conditions for these two areas taken from ice maps in the U.S. Navy Hydrographic Office (1958)



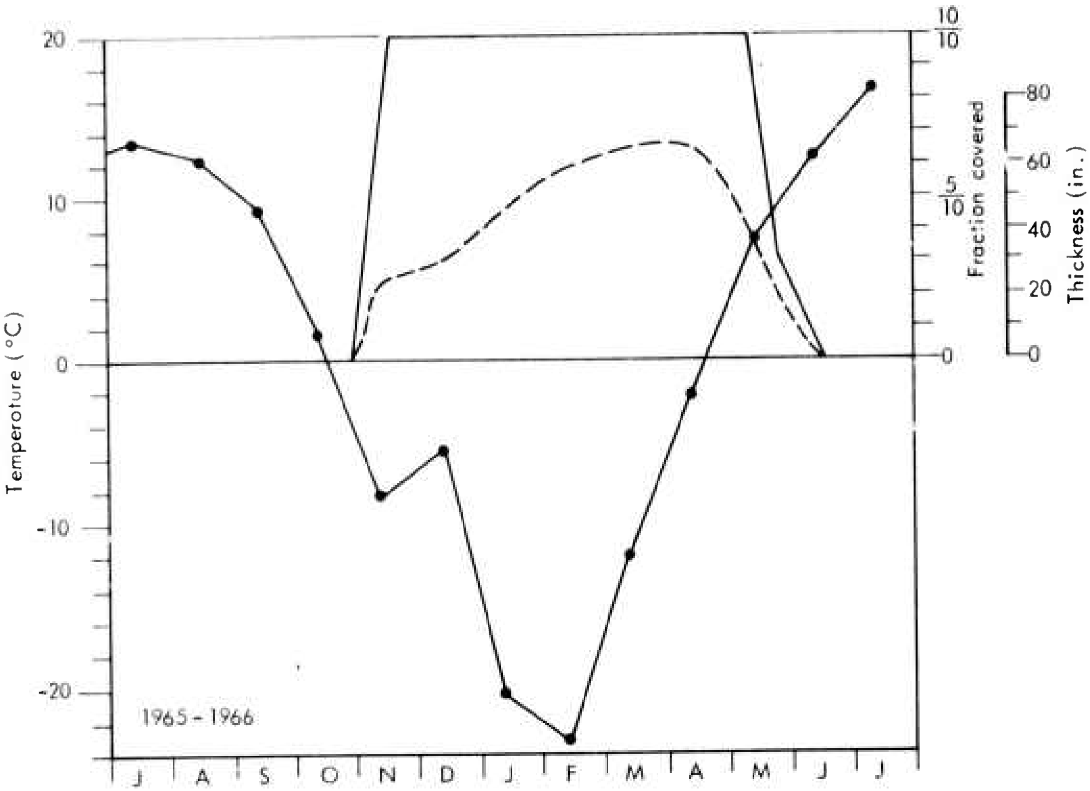
Gorlo Belogo Moryo Stroit	0	1/10 - 3/10	4/10 - 6/10	4/10 - 6/10	1/10 - 3/10	0
Northern White Sea	0	0	1/10 - 3/10	4/10 - 6/10	1/10 - 3/10	0

Fig. 6 — Estimated sea-ice conditions at Archangel for the best year in the historical record (for explanation of curves, see Fig. 5)



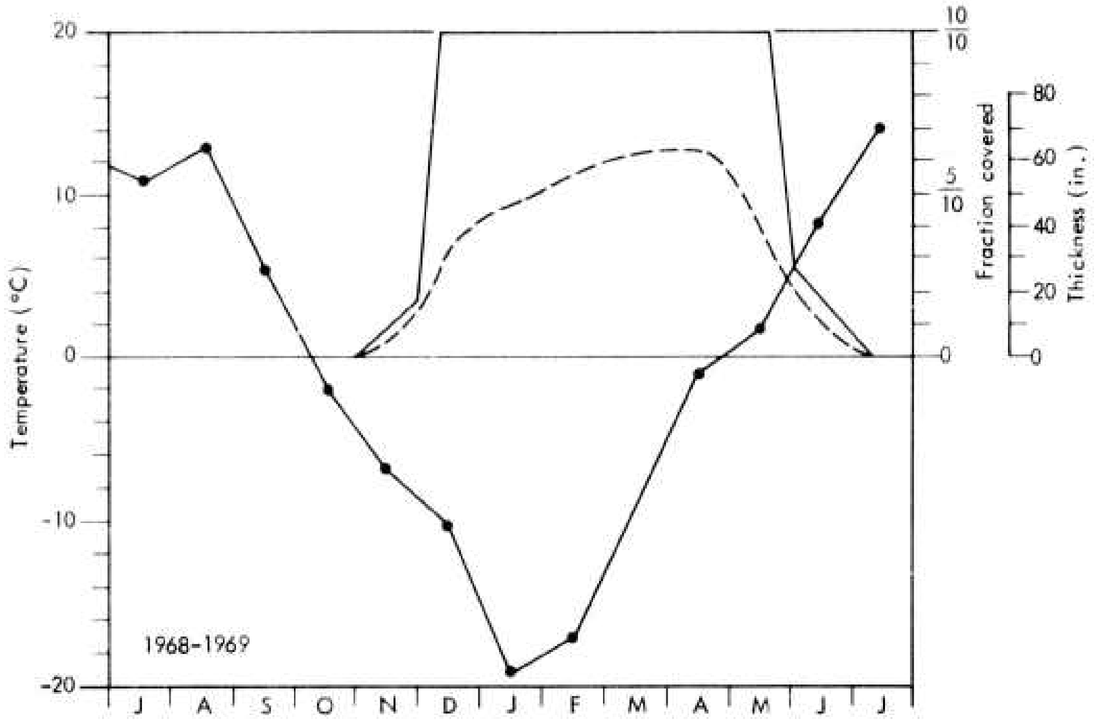
Gorlo Belogo Morya Strait	1/10-3/10	4/10-6/10	7/10-9/10	10/10	10/10	10/10	4/10-6/10	1/10-3/10
Northern White Sea	0	4/10-6/10	7/10-9/10	7/10-9/10	10/10	7/10-9/10	4/10-6/10	0

Fig. 7— Estimated sea-ice conditions at Archangel for the worst year in the historical record (for explanation of curves, see Fig. 5)



Gorlo Belogo Morya Strait	4/10 - 6/10	7/10 - 9/10	10/10	10/10	10/10	1/10 - 3/10	0
Northern White Sea	4/10 - 6/10	7/10 - 9/10	10/10	7/10 - 9/10	7/10 - 9/10	7/10 - 9/10	0

Fig. 8—Sea-ice conditions reconstructed for Archangel from monthly ice charts for the 1965 - 1966 winter (for explanation of curves, see Fig. 5)



Gorlo Belogo Morya Strait	0	7/10-9/10	7/10-9/10	7/10-9/10	7/10-9/10	7/10-9/10	4/10-6/10	1/10-3/10
Northern White Sea	0	7/10-9/10	7/10-9/10	7/10-9/10	7/10-9/10	7/10-9/10	7/10-9/10	1/10-3/10

Fig. 9—-Sea-ice conditions reconstructed for Archangel from monthly ice charts for the 1968-1969 winter (for explanation of curves, see Fig. 5)

are given in Table 1. These data summarize information available before 1957. According to this source, ice begins to form about a month following the start of ice formation in Dvinskaya Bay and disappears approximately at the same time that it does in the Bay. Ice cover never becomes complete in the northern White Sea, but does reach "consolidated" (10/10) conditions for four months (January through April) in some portions of the Strait. Winds, tides, and currents probably inhibit the formation of land-fast ice in these areas. Also, one might expect that an upward heat flux below the ice pack, aided by relatively warm water from the Murman coast current, would reduce the maximum ice thickness predicted by the equation used for Archangel.

Table 1

WHITE SEA ICE CONDITIONS

Month	Gorlo Belogo Morya Strait	Northern White Sea
November	Scattered	Scattered
December	Close	Scattered to broken
January	Consolidated	Close
February	Consolidated	Close
March	Consolidated	Close
April	Consolidated	Close
1-15 May	Broken	Broken
16-31 May	Broken	Broken
1-15 June	Scattered	Scattered
16-30 June	Clear	Clear

SOURCE: *Oceanographic Atlas of the Polar Seas, Part II, Arctic*, U.S. Navy Hydrographic Office, H.O. Pub. No. 705, Washington, D.C., 1958.

NOTE: Fraction of area covered with ice: scattered = (0.1-0.5); broken = (0.3-0.8); close = (0.8-1.0); consolidated = (1.0).

Data from the monthly ice condition charts for the years 1962-1969 and 1972-1973 indicate slightly different conditions. Ice formation in the Strait and the northern White Sea was first observed in December or January, a month to two months after the start of ice in Dvinskaya Bay. Consolidated conditions were observed in only two of the years in the

Strait (for a duration of two and three months) and in only one month of one year in the northern White Sea. The average conditions obtained from the monthly ice charts are given in Table 2.

Table 2

WHITE SEA ICE CONDITIONS DURING THE YEARS 1962-1969 AND 1972-1973

(In fraction of area covered with ice)

Month	Gorlo Belogo Morya Strait	Northern White Sea
November	Clear	Clear
December	1/10-3/10	1/10-3/10
January	7/10-9/10	4/10-6/10
February	7/10-9/10	7/10-9/10
March	7/10-9/10	7/10-9/10
April	4/10-6/10	4/10-6/10
May	1/10-3/10	1/10-3/10
June	Only one year with 1/10-3/10 coverage	

The data in Tables 1 and 2 were used to estimate conditions in the Strait and northern White Sea for the model year and the extreme years. The results are given at the bottom of Figs. 5, 6, and 7. Observed conditions are shown in Figs. 8 and 9.

THE SECULAR AND INTER-ANNUAL VARIATIONS OF ICE THICKNESS

With the aid of the ice growth model in the appendix, it is possible to relate the maximum ice thickness attained during a winter season to a suitably chosen 12-month mean temperature. The usual annual mean based on a calendar year is not appropriate for this study because it includes data for months from two different winter seasons. To maintain the integrity of each individual winter season, the 12-month mean temperatures used in this report are computed from the months of July through June of the following year.

The 12-month mean temperatures at Archangel (see Fig. 4 for location) for the years 1891-1973 are shown in Fig. 10. In addition to

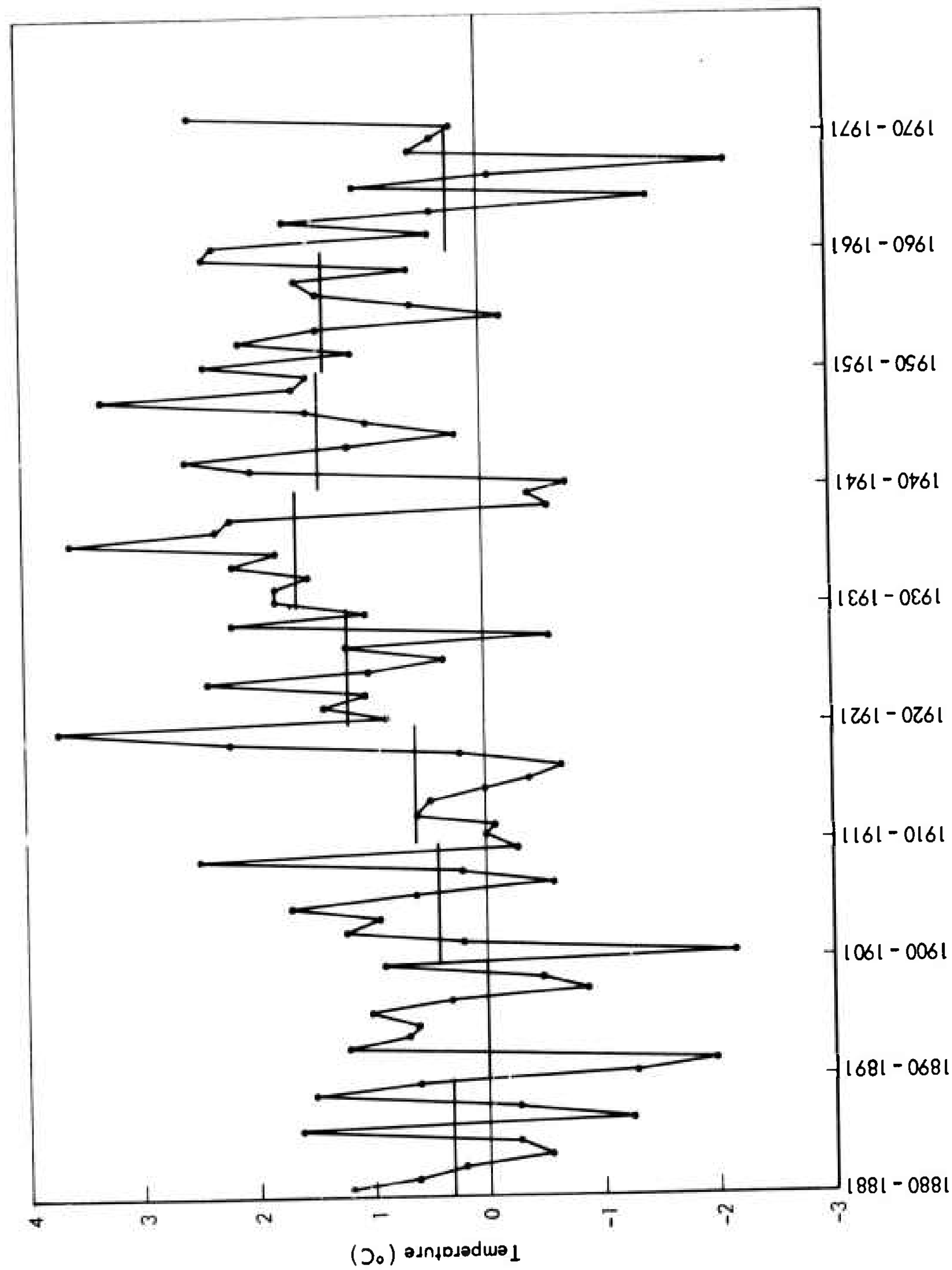


Fig. 10—Variation of the 12-month (July-June) mean temperature at Archangel

the means for each 12-month period, ten-year mean temperatures are indicated by the horizontal bars. The long period temperature trends for the northern hemisphere from the late 1800s to the 1970s discussed by Batten, Rapp, and Warshaw (1976) are clearly indicated in the Archangel data. The temperature increased from the 1890s to a peak in the 1930s and 1940s, then decreased in the 1960s. Another interesting feature of the data in Fig. 10--one especially pertinent here--is the clear demonstration that changes between 12-month periods can be larger than the difference between the warmest and coldest decades. This suggests that the year-to-year variation of maximum ice thickness may be more important than the slow secular changes that occur within a few decades.

The accumulated negative degree days were computed for the years displayed in Fig. 10, and the maximum ice thickness for each winter was estimated using the relationship derived in the appendix. The results are shown in Fig. 11. The ice thickness for each winter is shown, together with the decadal mean indicated by the horizontal lines. As discussed above, the ice in the White Sea forms and melts annually; thus, the lines connecting the individual winter values should not be interpreted as depicting a pattern of continuous growth and decay. The lines were inserted merely to aid the reader in discerning differences between individual winter seasons.

As was the case for the 12-month mean temperatures in Fig. 10, the winter-to-winter changes in ice thickness can be larger than the difference between extreme decades. From one winter to the next, the ice thickness as estimated may differ by as much as $1\frac{1}{2}$ ft. The difference between extreme decades is only 7 in. Clearly, even with continuous cooling during the next few decades, future ice conditions during some winters may not be as severe as those experienced during recent winters.

Merely extrapolating ice conditions to some future *average* state will not adequately define the potential effects of a climatic cooling. Some estimate of the possible year-to-year variability is also needed. We may estimate the year-to-year variability from the climatological record at Archangel. If year-to-year temperature changes for the year

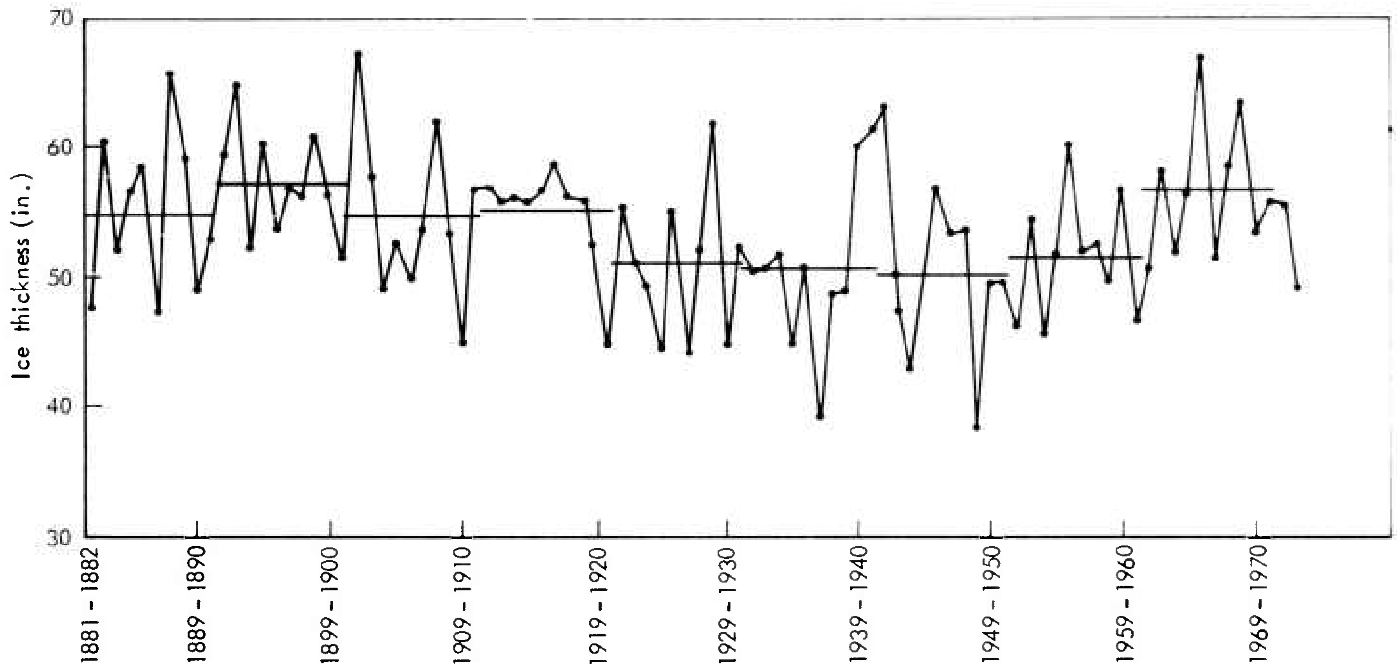


Fig. 11—Variation of the maximum annual ice thickness estimated from data for negative degree days for Archangel

as a whole are similar to those for the winter season, the 12-month mean temperature should be highly correlated with the accumulated negative degree days. Indeed, the correlation coefficient for the Archangel data was found to be -0.91. The regression line relating the 12-month mean temperature to the accumulated negative degree days is given in Fig. 12. Given on the right of Fig. 12 are the corresponding maximum ice thicknesses computed by the formulas given in the appendix. Due to the approximate nature of the ice thickness formula and the high correlation between the winter-centered 12-month mean temperatures and the

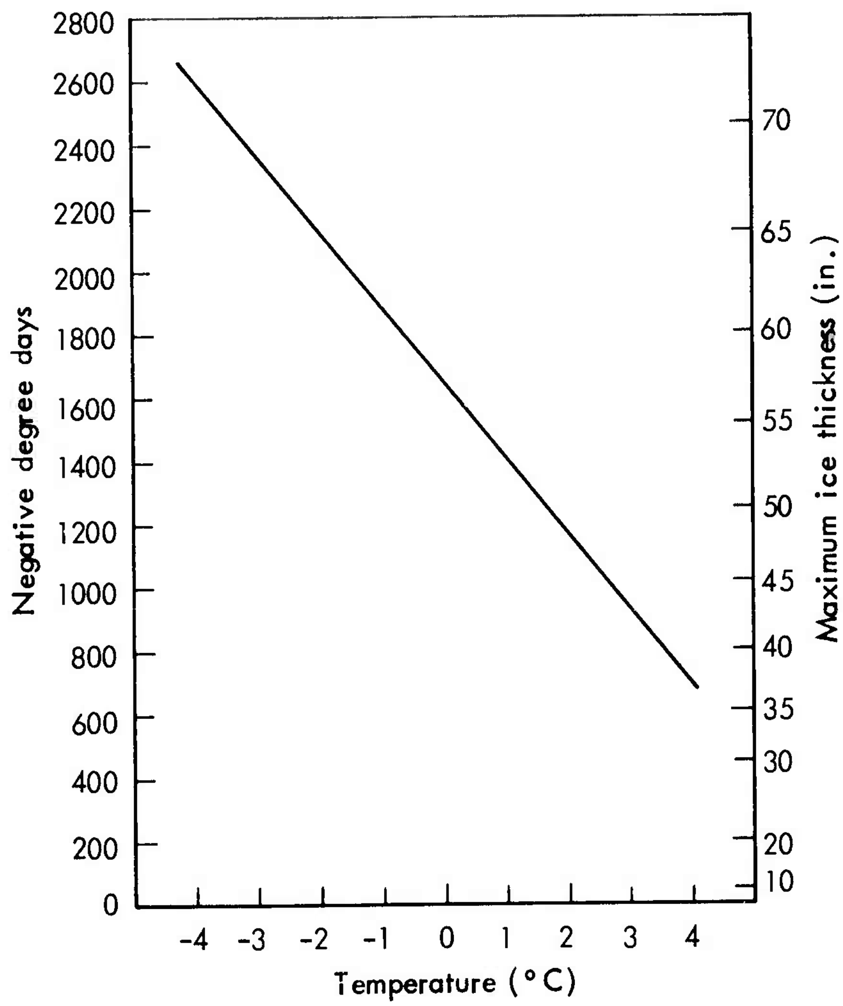


Fig. 12 — Relation between the 12-month mean temperature at Archangel, negative degree days, and maximum ice thickness

accumulated negative degree days, we may, without degrading the results to any palpable degree, use the mean temperatures as a measure of maximum ice thickness. We estimate the variability of ice thickness from the actual distribution of the mean air temperature at Archangel.

Figure 13 gives the distribution of mean temperature computed from the Archangel climatological data. The 12-month mean temperatures are indicated on the left-hand ordinate with corresponding inferred maximum ice thickness on the right. The abscissa indicates the probability of mean temperature less than, or maximum ice thickness greater than, a given value. The upper curve was determined from the 1891-1973 Archangel data. The lower curve, which will be discussed below, represents a distribution with the same standard deviation but a mean 1.5°C lower.

FUTURE ICE CONDITIONS

At the present time, a comprehensive theory of climate change does not exist. Indeed, explanations for the past climatic variations outlined by Batten, Rapp, and Warshaw (1976) are highly speculative. Outlooks for the future vary with the explanation, ranging from a plunge into extensive glaciation to continued cooling for the next one to two decades followed by an uninterrupted warming. The veracity of these prognostications will neither be supported nor challenged here. For our present purposes--those of evaluating extreme ice conditions in the Norwegian, Barents, and White seas--it is sufficient to assume a continued cooling trend and to choose a reasonable thermal state for the Archangel area. To this end we will assume a future state approximating Little Ice Age conditions.

An inspection of historical records for Iceland (see Batten, Rapp, and Warshaw, 1976, for a summary) indicates that temperatures there during the height of the Little Ice Age averaged less than 1°C colder than those of the past century. Considering that Archangel has a higher degree of continentality and is to some degree sheltered from the moderating influence of Atlantic maritime air, it might not be too unreasonable to assume that the difference between present and Little Ice Age conditions exceeded 1°C. Therefore, in keeping with the philosophy of exploring reasonable extremes, we will assume that the

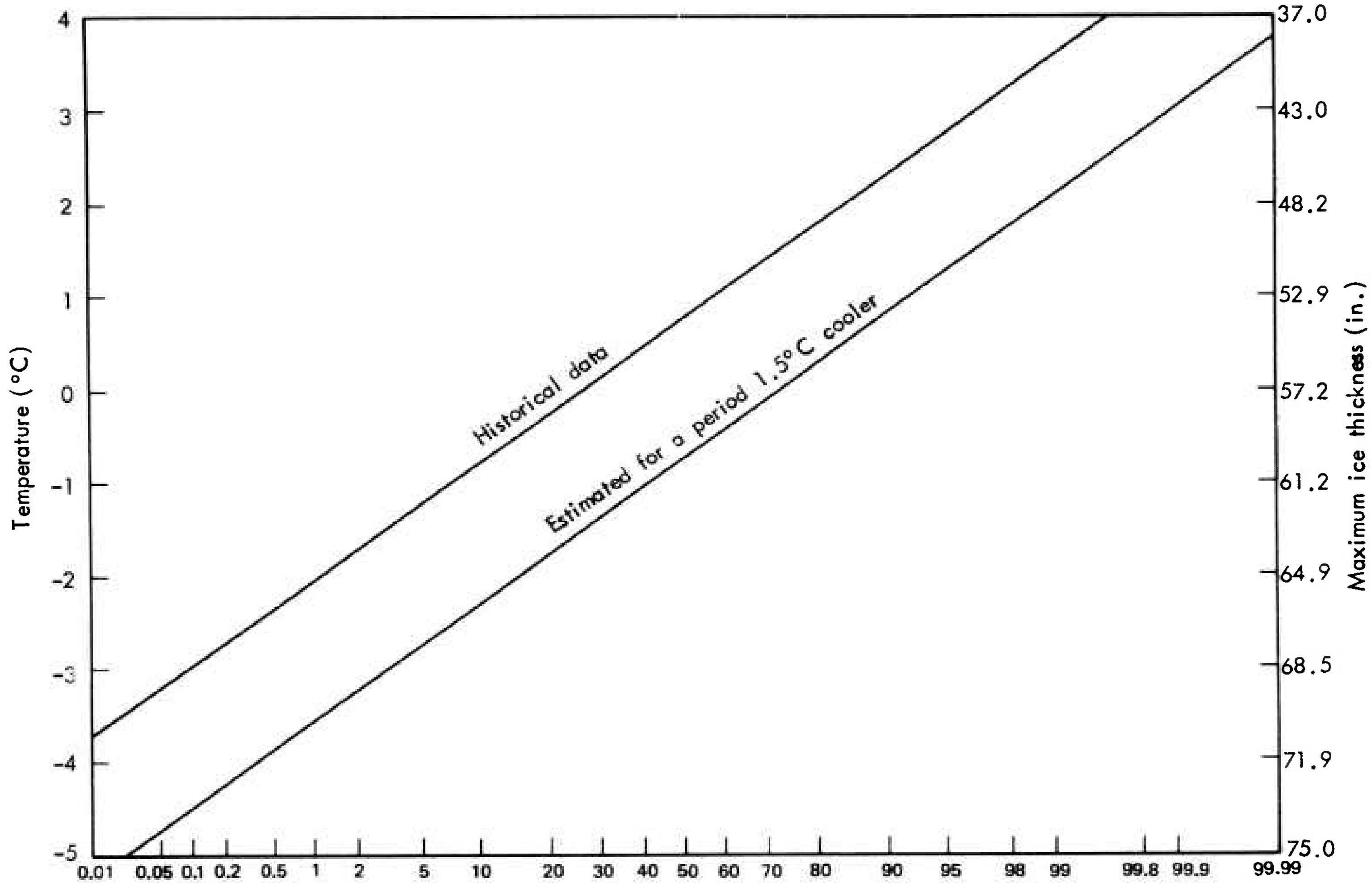


Fig. 1? — Distribution of actual 12-month mean temperatures and inferred ice thickness for Archangel from historical data (1881 - 1973) and the estimated distribution for a period with a mean 1.5°C lower temperature at Archangel during the Little Ice Age averaged 1.5°C below the value observed during the last century. Further, we will assume that the standard deviation of temperature can be estimated by the value obtained from the Archangel data. Some justification for this assumption is given by Batten, Rapp, and Warshaw (1976), who show that for two other locations, Basel and Edinburgh, there are no significant trends in the variance of January air temperature in a 200-year climatic record.

The lower curve in Fig. 13 represents the assumed temperature distribution during the Little Ice Age. Accordingly, the mean temperature for the coldest year (Fig. 7) was -2.3°C. (Similar conditions existing in the 1960s are shown in Figs. 8 and 9.) From Fig. 13 we note that conditions as severe or more severe than these would occur only 10 percent of the time (or one year in ten) if the average temperature dropped 1.5°C. One year in a hundred can be expected to have temperatures averaging less than -3.5°C, which equates to an ice thickness of 70 in. The correlation between 12-month mean temperatures and the duration of ice in Dvinskaya Bay, as indicated by the monthly ice charts, is only fair (correlation coefficient = -.69). However, one can estimate that in years averaging -3.5°C ice would last for 8 to $8\frac{1}{2}$ months with consolidated ice lasting for $6\frac{1}{2}$ to 7 months. In other words, the ice season in this extreme cold would be extended only one month, and the ice thickness would increase by only 5 in. over the extreme observed during the last century.

The apparently small change in ice conditions for such a large change in climate results in part from the insulating effect of the ice sheet itself. As the ice grows in thickness, the flux of heat through the ice required to remove the latent heat of fusion is decreased and the rate of growth of the ice slows. Another factor to consider is reflected in the seasonal nature of the White Sea ice. The ice melts and reforms annually. This is to a large extent the result of the modifying influence of the warm currents along the Murman coast and Kola Peninsula. With the return of the summer sun, these warm currents contribute substantially to removal of ice from the western Barents and the Kara seas. In addition, summer temperatures at White Sea latitudes throughout Europe and the USSR attain values far above freezing. (The July 60°F (15.5°C) isotherm runs west to east nearly along 65° north latitude.) Even with a drop of 1.5°C in the mean annual temperature, above-freezing temperatures can be expected for the summer months. During the Little Ice Age, for example, the winters were cold, long, and severe, but the summer temperatures were not much below modern values.

It would appear, then, that in order to substantially increase the severity of ice conditions in the Barents and White Sea areas, the warm extensions of the North Atlantic must be removed and summer temperatures reduced to near-freezing values or below. Under such conditions ice growth could be maintained for periods longer than a winter season. These conditions have existed only during periods of full glacial advance when ice covered the sea between Iceland and the coast of Norway and continental glaciers formed over northern Europe and western Russia.

IV. SUMMARY AND CONCLUSIONS

Ice conditions in the White Sea were estimated using 92 years of climatological data from Archangel and 10 years of monthly ice charts. A simple model was used to estimate the growth of ice thickness from the accumulated negative degree days. All of the major factors neglected in this simple model act to reduce the growth of ice and thus *the estimates of ice thickness presented here should represent an upper limit.*

The formation, growth, and decay of sea ice in the White Sea during the past century are summarized by reconstructed ice conditions for two extreme years. During the best year (least amount of ice), as shown in Fig. 6, ice lasts for five months (mid-December through mid-May) with maximum thickness less than $3\frac{1}{2}$ ft. During the worst year (greatest amount of ice), as shown in Fig. 7, ice lasts for $7\frac{1}{2}$ months (early November through late June) with maximum thickness of about $5\frac{1}{2}$ ft. This extremely cold year was approached by two years in the 1960s, for which observed data were available. The observed conditions for the winter of 1965-1966 and 1968-1969 are shown in Figs. 8 and 9. Figures 7, 8, and 9 would thus represent conditions presenting the greatest stress to operations in the White Sea if the climate were to remain similar to that observed during the past century.

Assuming the climate will revert to Little Ice Age conditions in the future, a new climatological distribution of temperature was estimated for the White Sea area. This distribution is assumed to have a mean 1.5°C lower than, and a standard deviation equal to, those observed during the past century. From this extrapolation we note that the worst conditions observed during the past century would be equalled or exceeded only 10 percent of the time. The most extreme conditions, in a climate similar to the Little Ice Age, would have ice lasting for 8 to $8\frac{1}{2}$ months, with consolidated conditions for $6\frac{1}{2}$ to 7 months, and ice thicknesses reaching a maximum of 70 in.

The moderate deterioration of ice conditions represented by these results does not appear to present a major impediment to operations in the White Sea. Even after a cooling of 1.5°C, average ice duration would be extended by less than a month and ice thickness increased by about one-half foot. According to *Jane's Fighting Ships* (1974-1975), nuclear-powered ice breakers of the Lenin type are capable of opening a 100-ft-wide swath while moving continuously at 3 to 4 kn through solid pack ice 8 ft thick. Thus, ice-breaking operations should not be substantially impeded. Reformation of ice by freezing after a path is clear is relatively slow. We may estimate the reformation using a formula based on a simple model similar to the one presented in the appendix. The results are given in Fig. 14. Here it is assumed that

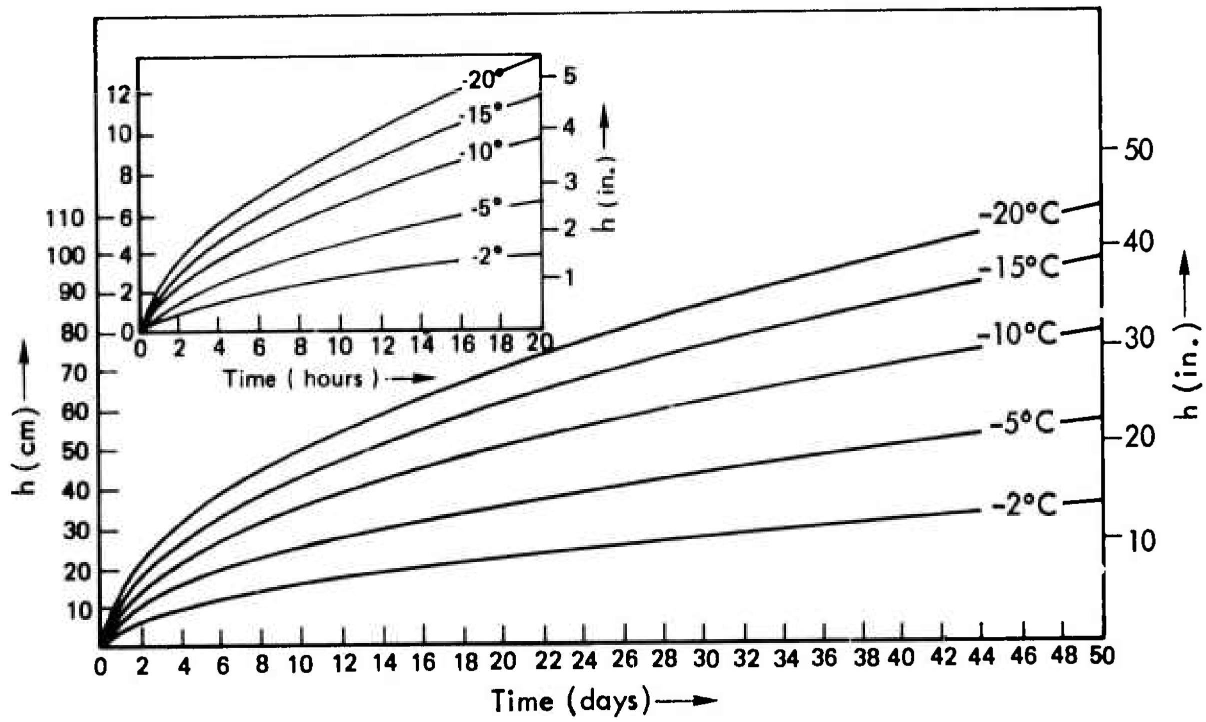


Fig. 14— Growth of thickness, h, of ice with time at different frost temperatures (after Neumann and Pierson, 1966)

the air temperature remains at the values given on the curves. For the specified temperature, the abscissa gives the time required to obtain a given ice thickness. For example, with a prevailing air temperature of -20°C (a cold temperature for the area), about 6 in. of ice would reform in 24 hr, and it would take more than a month for the ice to grow to 3 ft. (The once-cleared path might, of course, close up again due to wind-caused movement of the ice.)

Because continued deterioration of climate can be expected to result in only minor increases in the duration and thickness of ice, one must conclude that operations could be maintained with only minor adjustments to ice-breaking procedures.

Appendix

A SIMPLIFIED MODEL FOR ESTIMATING ICE THICKNESS

A detailed model of ice growth was developed by Maykut and Untersteiner (1971) in which they considered a time-dependent vertical diffusion process acting within the ice and an overlying layer of snow. The ice sheet grows and decays in response to heat fluxes at the upper and lower surfaces. The modifying effects of internal heating caused by penetrating solar radiation and storage of heat in brine pockets were also included.

A model of this type requires the specification of heat fluxes to the upper and lower boundaries of the ice. Maykut and Untersteiner used the Central Arctic heat budget given by Fletcher (1965) to make parametric studies of their ice model. Their results are not directly applicable to problems addressed in this report, nor is their model, which requires input data not commonly measured or available from historical records. However, the results of their study are useful for evaluating the assumptions of the simplified model adopted here.

The fluxes of energy at the upper boundary of the snow or ice surface include incoming long-wave radiation from the atmosphere, incoming solar radiation, outgoing long-wave radiation from the surface, sensible and latent heat fluxes to or from the surface, and heat conduction to the surface from below. The balance of these energy fluxes determines the temperature of the snow or ice surface.

At the bottom of the ice, the energy fluxes include the turbulent flux of heat from the ocean below and the conduction of heat in the ice. The temperature at the lower boundary is maintained at the freezing point of the sea water.

To estimate the growth of an ice sheet, we will use Stefan's model (Neumann and Pierson, 1966, pp. 85-87). The upper boundary conditions are simplified by specifying the temperature of the ice surface as the surface air temperature in lieu of specifying the heat flux. In addition, we ignore the accumulation of snow on the surface. At the lower boundary, the turbulent flux of heat from the ocean is neglected, and the freezing temperature of the sea water is taken to be 0°C. This model is based on the assumption that the rate of release of latent heat of freezing at the bottom of the growing ice sheet is equal to the upward flux of heat at the bottom of the ice. In other words, the ice thickness will increase as long as the heat released during freezing can be transported away from the bottom of the ice.

Clearly, by neglecting the turbulent heat flux from the ocean we will overestimate the ice thickness. The heat supplied by the underlying ocean will retard the accumulation of ice at the lower boundary (Maykut and Untersteiner, 1971). The effect of neglecting the accumulation of snow on the upper boundary is more difficult to assess. It is generally assumed that a snow layer on the ice acts as an effective insulating cover, thus decreasing the flux of heat away from the lower boundary and retarding the growth of ice. This viewpoint is supported by observations at Point Barrow by Holtsmark (1955), which showed that when an area was kept free of snow the ice grew to a thickness of 176 cm, while ice beneath a natural snow cover of 27 cm grew to only 155 cm. Further, in areas where the snow cover was induced to reach a depth of 67 cm the ice grew to only 133 cm thick, and in areas where the snow cover was built up to a depth of 2 m the ice grew to only 117 cm thick. However, the theoretical calculations of Maykut and Untersteiner indicate that after snow reaches a depth of 70 cm other factors dominate the ice growth, and the ice thickness increases rapidly with increasing snow cover. They point out, however, that the typical snow cover for the Central Arctic is 40 cm. In this range of snow depth, the cover does act to reduce the maximum thickness of the ice. It seems likely, with reasonable snow depths, that neglecting the accumulation of snow on a forming ice sheet will result in overestimates of the growth of ice.

Because both of the major assumptions in the model adopted in this report lead to an overestimate of ice growth, we may take the results of our model as a measure of the upper limit of ice thickness attained during a winter season.

The upward flux of heat through the ice is given by

$$F = -\kappa \frac{dT}{dz} , \tag{1}$$

where κ is the coefficient of thermal conductivity and dT/dz is the temperature gradient in the ice sheet. If ρ_i is the density of ice, λ_i the latent heat of fusion, and dh the increase of thickness during the time increment dt, then the heat released during ice growth is given by

$$W = \rho_i \lambda_i \frac{dh}{dt} . \tag{2}$$

Equating the flux evaluated at the bottom of the ice sheet at depth h to W, we get

$$\frac{dh}{dt} = - \frac{\kappa}{\lambda_i \rho_i} \left(\frac{dT}{dz}\right)_h . \tag{3}$$

We assume that $(dT/dz)_h$ can be approximated by a linear gradient given by $(T_A - T_f)/h$, where T_A is the prevailing air temperature at the surface and T_f is the freezing temperature of the water (taken to be 0°C). Then Eq. (3) becomes

$$\frac{dh}{dt} = \frac{\kappa}{\lambda_i \rho_i} \frac{T_A}{h} ,$$

which may be integrated to give

$$h = \sqrt{\frac{2\kappa}{\lambda_i \rho_i} \psi} , \tag{4}$$

where

$$\psi = \int_{t_1}^{0} T\, dt \tag{5}$$

is defined as the "cold sum," or the accumulated negative degree days. For our purposes ψ may be estimated from the mean temperature for each month.

Taking $\kappa = 0.0055$ cal deg^{-1} cm^{-1} sec^{-1}, $\lambda_i = 80$ cal g^{-1}, and $\rho_i = 0.9168$ g cm^{-3}, Eq. (5) becomes

$$h \approx 3.58 \sqrt{\psi} \text{ cm}$$

or

$$h \approx 1.41 \sqrt{\psi} \text{ in.} \tag{6}$$

Using values of T_f, κ, λ_i, and ρ_i typical of pure water introduces the additional assumption of zero salinity. This assumption may not be too faulty since Eq. (6) will be applied to coastal waters where runoff from the land maintains low salinities. In fact, calculations by Maykut and Untersteiner (1969) show that fresh ice grows to greater thickness than does sea ice. This assumption is thus consistent with the assertion that this model provides an estimate of the upper limit of ice thickness.

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