The Monthly and Extreme Limits of Ice in the Bering Sea*

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Abstract

The main features of ice conditions in the Bering Sea are sketched and mean monthly limits of ice, based on reconnaissance data, are presented.

The factors controlling the extreme limit of ice in this area, which coincides rather closely with the edge of the continental shelf, are discussed. It is concluded that while there may be several contributing oceanographic and meteorological factors, the chief one is probably heat transport into the area by the Pacific Current, which at this season has been shown to flow along the edge of the continental shelf.

An attempt is made from available observations to show whether there has been any noticeable change in the severity of ice conditions over the past century. Evidence is inconclusive, but suggests that whereas the extreme limit of ice may not have changed appreciably, the retreat of the ice in spring is earlier now than it was in the period 1870–1900.

I. Introduction

The Bering Sea is of interest among the ice-covered waters of the world in that it is a boundary area. Only about half of the sea develops an ice cover. As such it is one of a group of Northern Hemisphere seas that also include the Sea of Okhotsk and Sea of Japan on the Pacific side of the Arctic and the Barents and Greenland seas, Denmark Strait, Davis Strait, and the Labrador Sea and Gulf of St. Lawrence on the Atlantic side. The ice regimes of these boundary seas are very different one from another, but all share the fact of the boundary itself and the question of the balance of component factors which dictates its precise position, whether as a mean value or at a specific time. It is the purpose of this paper to examine this question for the Bering Sea.

II. Annual Cycle of Ice Conditions

Shorefast ice begins to form in the bays of the northwest coast of the Bering Sea in early October (Leonov, 1960, Chapter 1, Bering Sea, pp. 32–185). On the east side it is perhaps little later, but the first ice has formed in the Norton Sound area by mid or late October. Pack ice follows the same pattern, appearing in the Gulf of Anadyr' in October and in Norton Sound in November. It builds outwards from the coasts and southward from Bering Strait, reaching a maximum in February or March, and retreating northward again through April and May. On the Alaska side the last pack ice disappears in June, but off the Siberian coast it is sometimes apparently found well into July (U.S.S.R., 1926–36). Fast ice, which is the last to go, may also linger into July, especially

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on the Siberian side. Virtually all this ice is of local formation and of one year's growth, and most of it melts within the Bering Sea, so it is a relatively simple situation. Polar ice enters the Bering Sea in the fall on the west side of Bering Strait, but usually in small quantities and not every year. It seldom penetrates beyond Provideniye Bay (Meilakh, 1958).

Figures 1 and 2 show the mean extent of ice cover for each month. The solid lines, covering the eastern part of the sea, are based on aerial reconnaissance charts of the United States Navy (U.S.N. Hydrographic Office, 1955–65) for the years 1954–65. In the early years of this period flights were made at least once a week, but in the later years only twice a month, and as observations are often restricted by cloud cover, the means must be regarded as approximations based on incomplete data. Observations for November and December are particularly scarce. Nevertheless the data are very much more complete than any that have existed before, and their consistency for January to April suggests that for this period at least they are reasonably reliable. In May and June the patterns become more variable and complex and the means correspondingly less realistic. In June the remaining pack ice tends to be in scattered patches, and these are sometimes to be found south of St. Lawrence Island, though they are more usually limited to the area north of it.

The dashed lines in Figs. 1 and 2, covering the west side of the Bering Sea, are

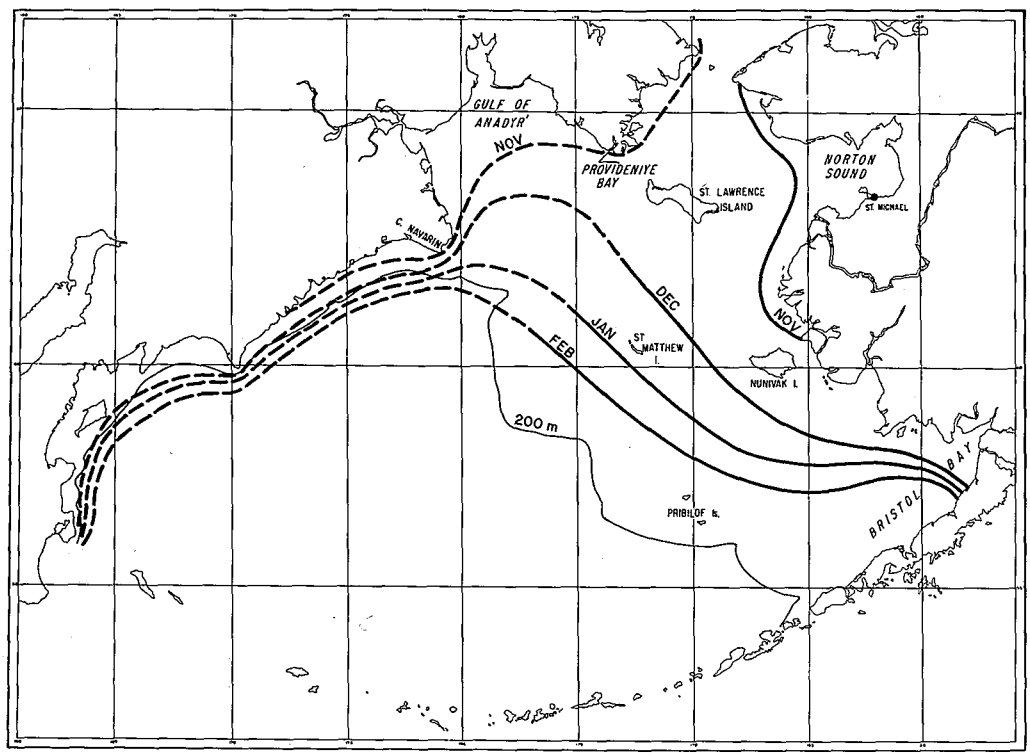

Fig. 1. Mean monthly limits of 0.1 concentration of ice for November-February, based on United States Navy reconnaissance data (solid lines) and typical limits for the same months after Bulgakov 1965 (dashed lines)

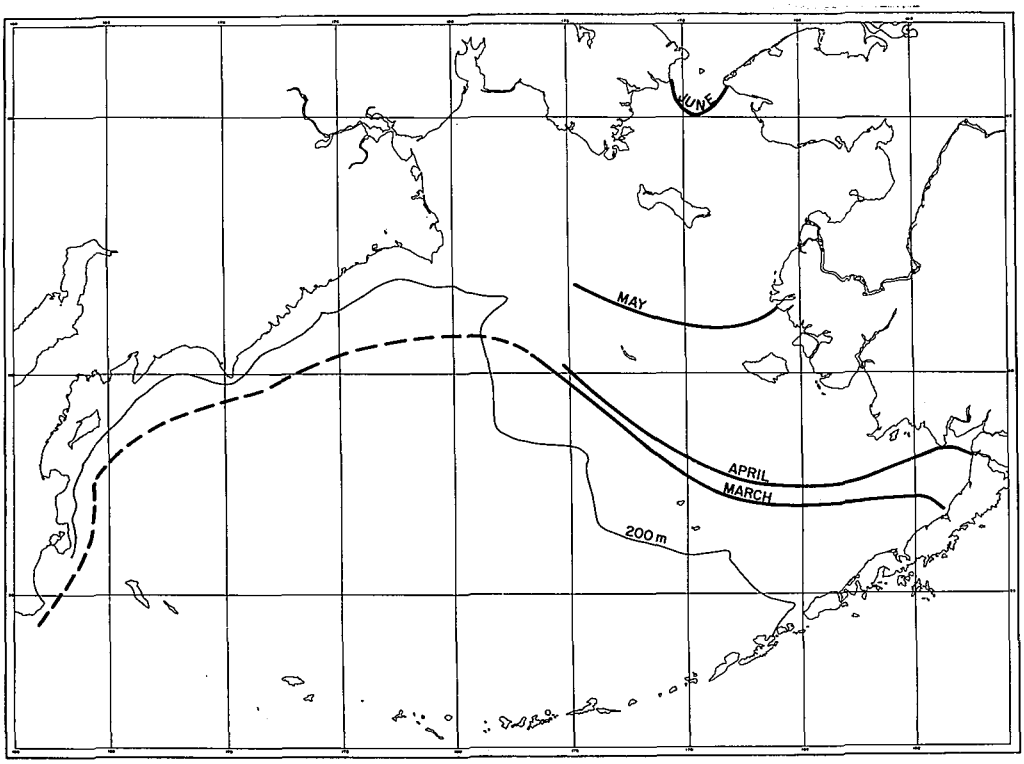

Fig. 2. Mean monthly limits of 0.1 concentration of ice for March-June, based on United States Navy reconnaissance data (solid lines) and typical limits for March after Bulgakov 1965 (dashed lines)

taken from Bulgakov (1965). They represent not mean positions but what he describes as "one possible pattern". Although he does not actually say so I have assumed that the pattern he has chosen is a fairly typical one. It certainly is in agreement with the few observations available to me for this part of the area, among them Figs. 5 to 7, satellite photographs from ESSA-I and TIROS-VIII. Figures 5 and 6 show an ice edge almost identical to Bulgakov's line for the same month, while Fig. 7 shows rather less ice.

Figures 3 and 4 show the extent of variation of the mean ice limits for February and March respectively over the period 1954-65. It will be seen that both the mean maximum and the extreme observed limits are a little farther south for February than for March, but that whereas in February the means in most years fall in the upper half of the range, those in March fall mainly in the lower half. March may therefore in general be regarded as the month of maximum ice, though in any given year the maximum extent may occur in February. This situation is reflected in Figs. 1 and 2, where the March line is only very slightly below the February line.

III. Drift

The movement of the ice cover is dictated, as in other areas, by wind and current, the wind being generally accepted as the dominant force. The Bering Sea is strongly

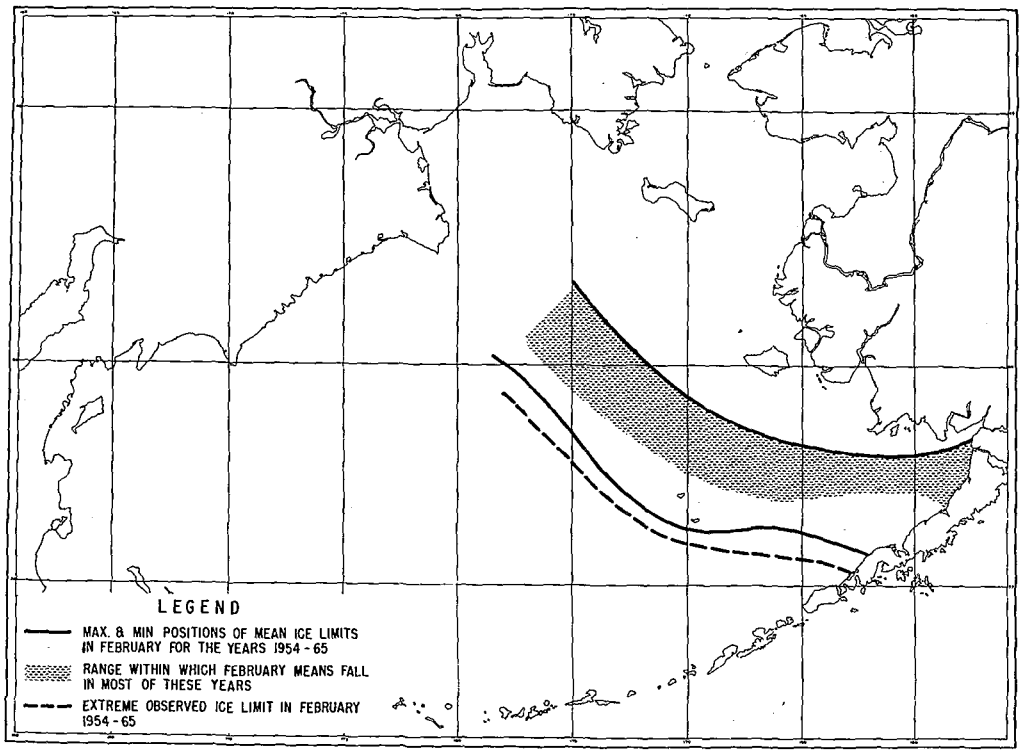

Fig. 3. Range of 0.1 ice limits for February for the years 1954–65

influenced in winter by the Aleutian Low, which tends to give predominantly northerly winds in the north and west, and northeasterly and easterly winds near the east coast. Near the southern boundary of the ice the winds are more variable but still with a slight predominance of northerlies. In spring the Aleutian Low decreases in intensity and by the end of June the winds have become predominantly southerly. The northerly flow is reestablished in September.

The current pattern is rather less clear. Direct measurements are still scarce and computed schemes are many and vary considerably in detail, but until recently all have shown a basically cyclonic circulation, with Pacific water entering the Bering Sea through the straits of the Aleutian chain, some of it continuing into the Chukchi Sea through Bering Strait and some swinging west to join a well-marked southward-flowing current down the Siberian coast. In winter the Bering Strait outflow is cut by about three-quarters (Coachman and Barnes, 1961). I will have more to say about these currents shortly.

Observations of ice drift show a strongly prevailing southerly drift off the coast of Siberia south of Cape Navarin (U.S.S.R., 1926–36) where prevailing wind and current coincide. A number of winter cruises by United States icebreakers in the eastern part of the sea have all reported a close correlation between wind direction and ice drift, the latter following the direction of the former with a time lag of only a few hours. Soviet vessels in Bering Strait and the western Bering Sea have reported the same (U.S.S.R.,

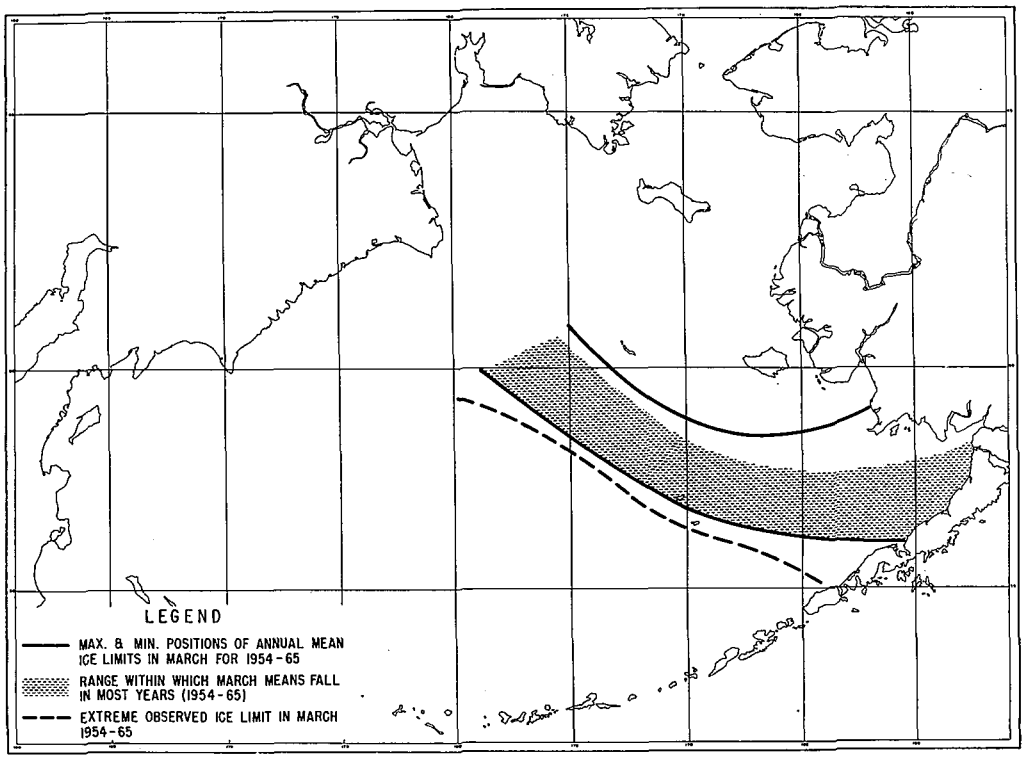

Fig. 4. Range of 0.1 ice limits for March for the years 1954–65

1926–36). Since the prevailing wind direction in the winter months is quite strongly northerly over the northern and western parts of the Bering Sea and slightly northerly in the southern part, it follows that notwithstanding the northward-flowing Pacific Current, the net ice drift must have a southerly trend. Leonov (1960) disagrees with this, stating that in the eastern part of the sea the ice drift is northerly, and that up to 10% of the ice of the Bering Sea is transported into the Chukchi Sea during the winter. This opinion is not however borne out by the icebreaker observations, and it seems very doubtful that the north-flowing current in this area does more than slow down and reduce the effect of the wind. Nevertheless the situation appears to be complex. In 1955 the USCGC Northwind took up a station in the ice northeast of St. Lawrence Island and drifted from 22 March to 5 April. With winds in the northerly sector throughout, except for one day of southerly winds, the drift was generally south, but there were variations that do not relate to wind direction, and which were attributed to tidal currents (U.S.N. Hydrographic Office, 1958). Presumably currents of some kind were exerting an influence, but the salient fact remains that in an area with a net northward current the net drift was southward, reconfirming the predominant influence of winds.

Figures 5, 6 and 8, satellite photographs taken by ESSA–I in March 1966, show the effect of a northeasterly circulation on the ice conditions. The dark areas outlining the south- and west-facing coasts of Alaska indicate open leads offshore, and Nunivak

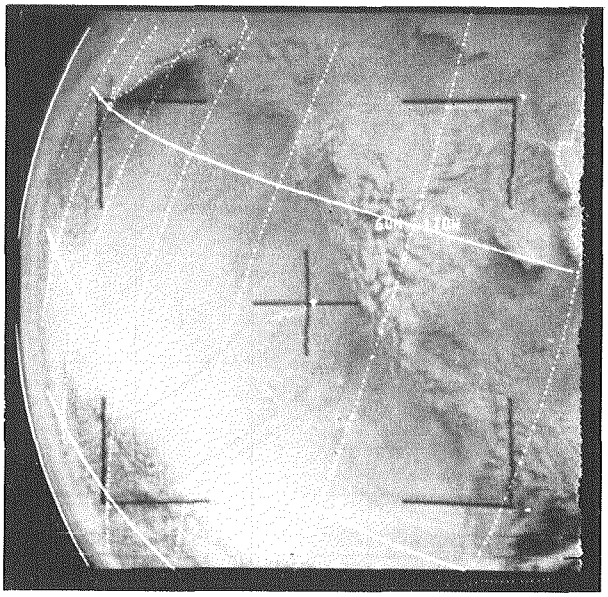

Fig. 5. Satellite photograph from ESSA-I, taken on 24 March 1966, showing ice edge running from Bristol Bay (bottom right) to Cape Navarin (top left centre) and open water south of Nunivak Island (right centre) St. Lawrence Island (top right) and St. Matthew Island (centre just north of 60°N) and east of the Alaskan coast. The white tone south of the ice edge is cloud. (This and other ESSA-I photographs courtesy U.S. Environmental Science Services Administration)

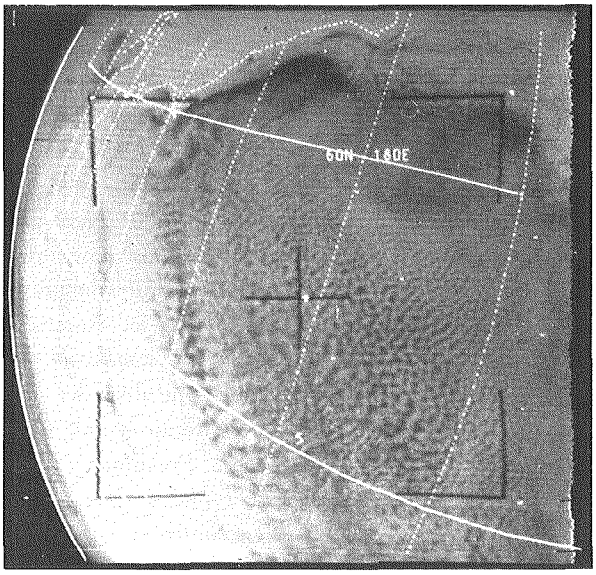

Fig. 6. ESSA-I picture slightly to the west of Fig. 3, taken the day before, showing the ice edge (top) and the quite narrow strip of ice running down the Siberian coast from Cape Navarin (top right centre). Open lead (polynya) south of Cape Navarin

and St. Lawrence Islands can be identified by the open water to the south of them, as can even the little St. Matthew Island, which without the polynya would not show at all. Similar polynyas are to be found very frequently on the south side of the Chukotskiy Peninsula and Cape Navarin, and on the north sides of all the large Siberian bays (Kupetskiy, 1958). In Fig. 6 one can be seen south of Cape Navarin. The more constant the northerly winds the more stable are these polynyas.

IV. Position of the Southern Boundary

In the Bering Sea the extreme limit of ice has a special quality, in that it coincides to a remarkable degree with the edge of the continental shelf. This characteristic is shared in the Pacific area by the Sea of Japan (Bulgakov, 1965). Figure 9 shows the extreme observed limit for the eastern part of the sea, as reported by U.S. ice reconnais-

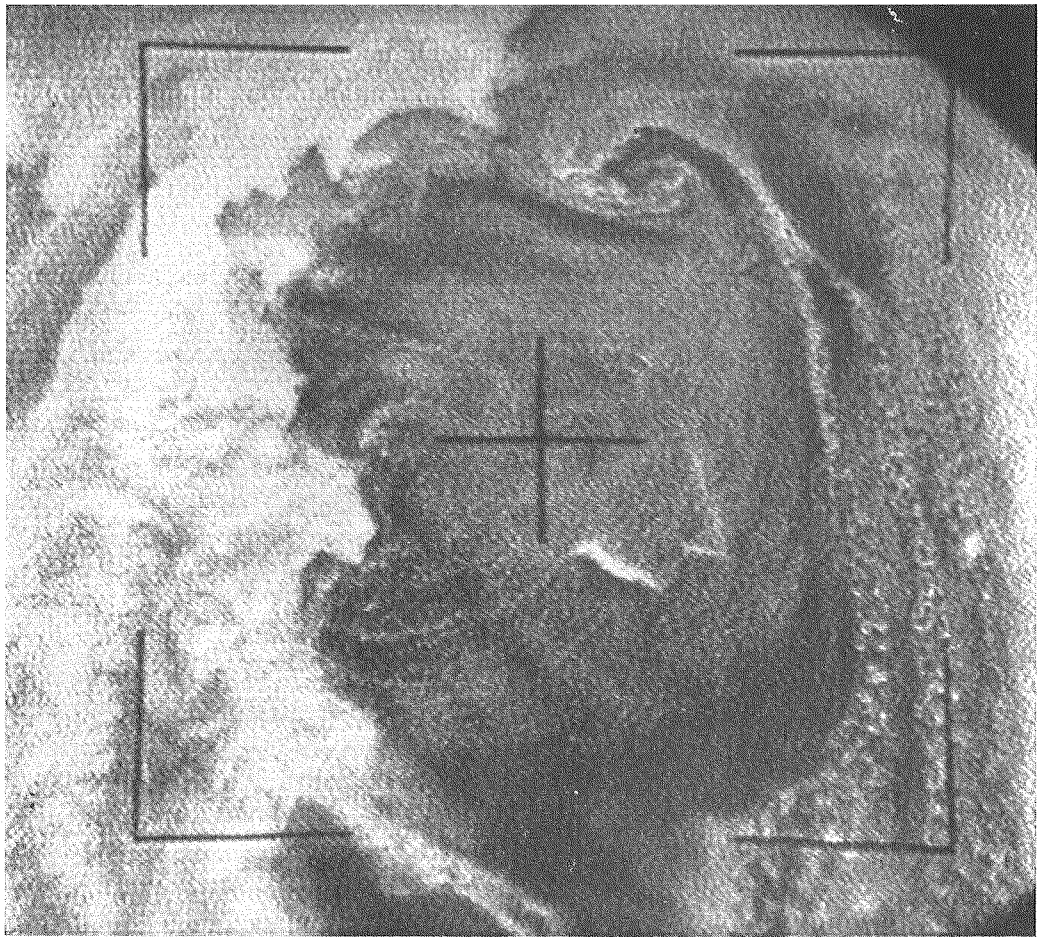

Fig. 7. Western Bering Sea showing the Kamchatka Peninsula (left) and Bering Island (right of centre). Taken from TIROS-VIII on 1 March 1964. Ice is limited to the large bays and a quite narrow area off the coast. The cyclonic eddy is a cloud pattern. (Photograph courtesy U.S. National Aeronautics and Space Administration)

sance flights in the period 1954–65. Owing to the spacing of the flights, it cannot be definitely claimed that this is the absolute limit reached by ice in this period, but it is not likely to be far off it. Also shown is a line taken from Bulgakov (1965) which he calls the line of probability of encountering zero ice in March. It is computed from observations over an unspecified number of years and he regards it as also the line of maximum ice cover in severe seasons. These lines show a close correlation with the 200 m depth contour for the eastern part of the sea. In the west the correlation is much less marked, but the more typical line in Fig. 2 follows the 200 m contour fairly closely, as do the ice edges observed by TIROS and ESSA satellites in the last three years (Figs. 5 to 7). It seems fair to say that for most of the sea not only does no ice form south of the shelf, but ice drifting into the deep water with the prevailing northerly winds is quickly melted.

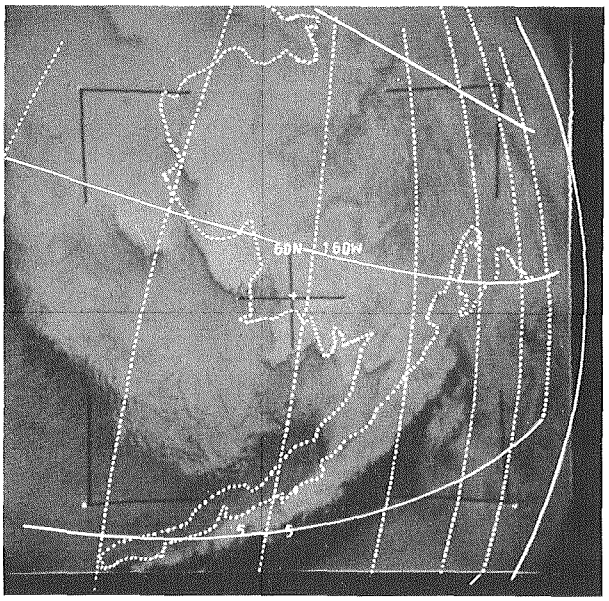

Fig. 8. Ice in the eastern Bering Sea, from ESSA–I, 21 March 1966. The darker patches represent ice of lower concentration and the dark lines off the coasts and in the pack are open leads

The waters of the wide shelf area that forms the northern half of the Bering Sea are very shallow, most of the shelf being under 100 m and much of it under 50 m (Fig. 9). In the winter this water has been shown to be isothermal and isohaline over most of the shelf (U.S.N. Hydrographic Office, 1958; Dodimead *et al.*, 1963) with a horizontal temperature distribution increasing from north to south. Mixing thus continues to the bottom and freezing proceeds from north to south to the line where the accumulation of freezing degree-days is not sufficient to cool the water layer to freezing point. This line will vary from year to year, and as will be seen from Figs. 3 and 4, in many years it does not in fact reach the edge of the shelf. Kniskern and Potocsky (1965) have computed frost degree-day and ice thickness curves for a number of stations in the

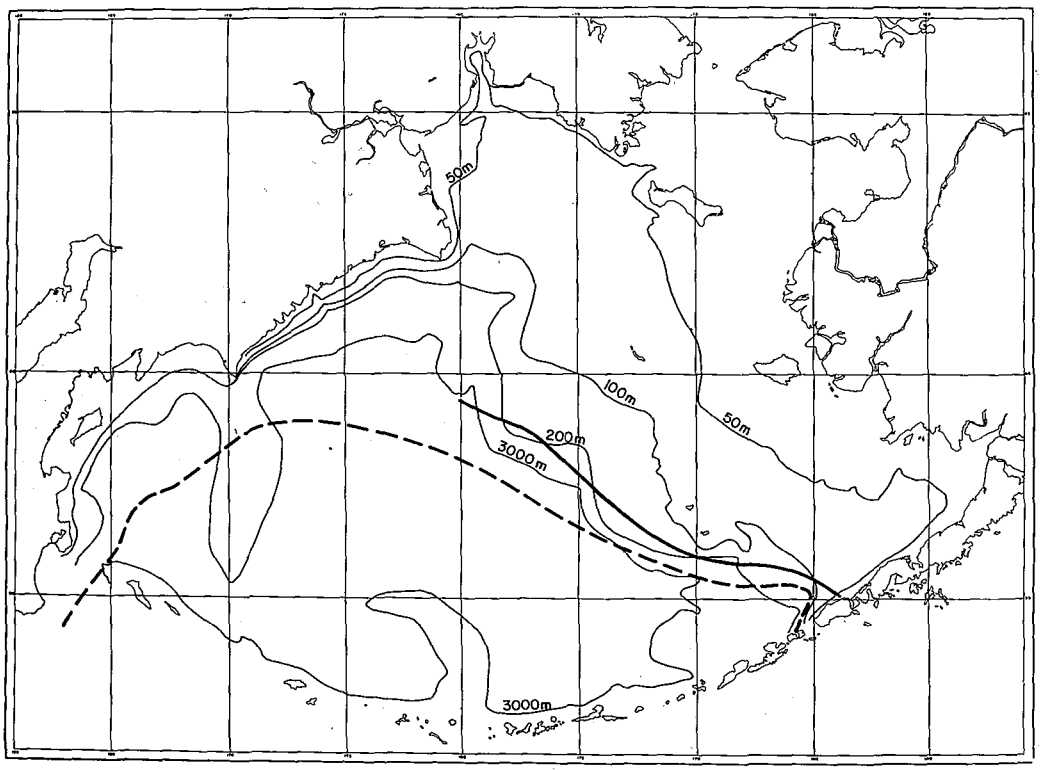

Fig. 9. Extreme observed limit of ice in the years 1954–65, based on United States Navy reconnaissance data (solid line) and "line of probability of presence of zero ice" for March, after Bulgakov (dashed line)

Bering Sea, of which the most southerly is St. Paul Island in the Pribilofs. The figures from this station show accumulation of from 250 to 1400 frost degree-days (F) (139–778 degree-days C) and a theoretical ice growth of 16 inches (40 cm). These figures presumably apply to the harbour, where conditions for ice formation are most favourable. It is thus not surprising to find that there is often no ice in the open sea in this area.

At the edge of the shelf the oceanographic structure is more complex. Observations made across the slope in March and April of 1955 (U.S.N. Hydrographic Office, 1958) show sharp horizontal surface gradients of temperature, salinity and density in the region of the ice boundary on all sections. Near the Pribilof Islands, where the ice boundary at the time of observation coincided closely with the continental slope and where the shelf is shallow, the vertical structure was isoclinal right to the edge of the shelf, the edge being marked by a sudden change to a layered structure. There is thus a sharp change in physical and chemical properties of the water column (Dodimead *et al.*, 1963), and consequent lack of mixing between the shelf and slope water.

In some areas, notably west of the Pribilofs, where the depths near the edge of the shelf are rather greater, the 1955 observations recorded a slightly different situation. Here in the shelf water the same steep horizontal surface temperature gradient was accompanied by warmer and more saline water underneath, indicating some intrusion of

Pacific water below the surface. The influence of this intrusion on the temperature and salinity gradients persisted for more than 250 nautical miles on to the shelf. Off the edge of the shelf there was in both cases a sharp rise in surface temperature from around 0°C on the shelf to values in the order of 2°C.

It thus appears that there is little or no mixing of shelf and slope water, although slope water penetrates the shelf along the bottom at some points. It remains to ascertain the nature of the surface mixing layer off the edge of the shelf. The depth of this layer has seldom been found to exceed 200 m and is mostly between 100 and 150 m (Natarov, 1963; Dodimead *et al.*, 1963), or much the same at the mixing depth on the outer parts of the shelf. In summer surface heating of the shelf water removes the sharp temperature difference between shelf and slope observed in winter (Dodimead *et al.*, 1963) but even at the end of the summer warming period the temperature difference between the lower shelf waters and the slope waters at the same depth persists, and the salinity and density differences remain throughout the water column. At the beginning of the cooling period, therefore, the lower parts of the mixing layer in the slope water are warmer than the shelf water and there is a greater reserve of heat to be given off before ice can form.

Zubov (1945) introduced a concept, used in forecasting the onset of ice formation, which he called the critical depth of vertical circulation, or the depth to which convective mixing must continue, for a water column of given TS structure, before ice will form. From this is derived the freezing index, or amount of heat that must be given off by the water column before ice will form. Bulgakov (1965) has calculated this critical depth for a variety of points in the Bering Sea. He computes the depths with and without a factor to account for the compressibility of sea water, and finds that for stations in the deep water of the Bering Sea the inclusion of this factor increases the critical depth in most cases to the bottom, or to values in the order of 3 000~4 000 m. He thus suggests that in theory at least mixing could continue to the bottom before ice would form. However even without the compressibility factor the values he found for the same stations were all greater than the actual mixing layer and would thus in any case account for the failure of ice to form.

The calculation of critical depth does not take into account the advection of heat

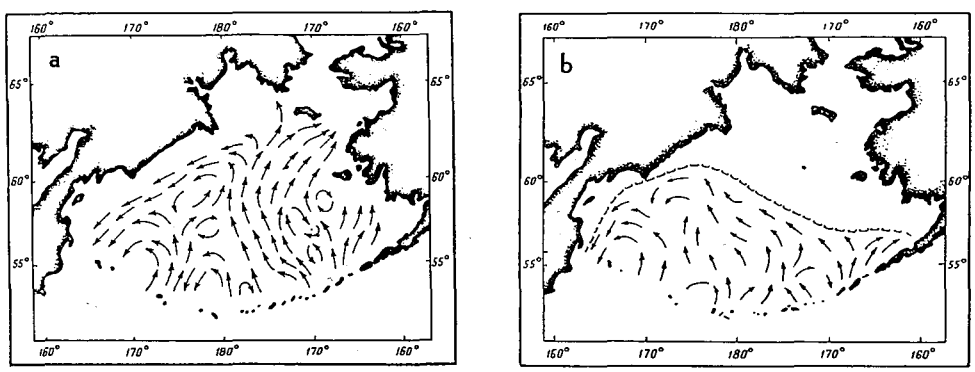

Fig. 10. Surface water circulation, based on dynamic charts of surface/1 000 db, according to Natarov (1963). (a) Summer 1959. (b) Winter 1961.

by currents after the time at which the critical depth is determined, and it would appear that this may be an important factor in limiting the ice in the Bering Sea. As stated earlier the current structure of the Bering Sea is still not clearly established, but there are some recent papers in this field that appear to be significant. Natarov (1963) presents

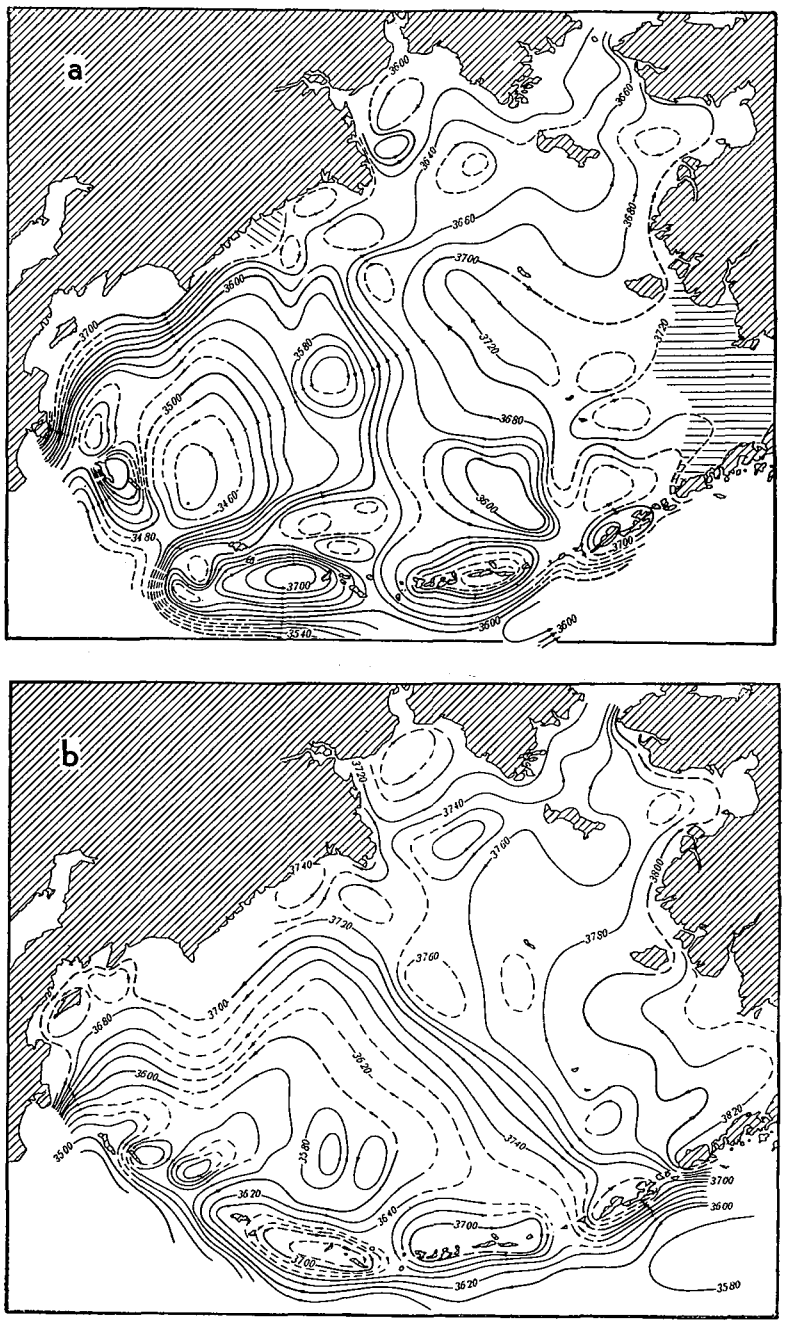

Fig. 11. Dynamic relief 10 db/1 000 db according to Arsen'ev (1965). (a) June; (b) August

current charts for summer and winter seasons (Fig. 10) constructed by the dynamic method from data gathered on cruises covering almost the entire Bering Sea in 1959 and 1961. He states that in winter there appears to be little Pacific water penetrating the central section of the shelf area, but that the current runs northwest along the edge of the shelf. Arsen'ev (1965) goes further, postulating that the cyclonic circulation is even in summer limited to the deep-water part of the sea, and that the shelf has a separate and basically anticyclonic circulation (Fig. 11). His dynamic charts for June, July, August and October are based on over 6 000 stations dating from 1874 to 1959, and considerably modify the author's own previously published work (Dobrovol'skiy and Arsen'ev, 1959, 1961).

An examination of these charts shows that in fact they are very similar. Although Natarov talks of the conventional cyclonic circulation his summer chart does not in fact show it except for the deep-water part of the sea. His winter chart shows a simplification of this circulation and a sharp reduction of water entering the shelf area at 175–180°W. Current observations in the ice-covered part of the sea in winter are unfortunately lacking, but the known reduction in the flow through Bering Strait in winter would be in keeping with a reduced flow of Pacific water on to the shelf.

It would seem that a current such as this, moving along the edge of the shelf at speeds of 8~15 cm/sec (Natarov, 1963) and penetrating the shelf only to a limited extent and that below the surface, would in itself be enough to account not only for the absence of ice formation but for the rapid melting of any ice that drifts over the edge of the shelf. The heat constantly transported by the current is presumably sufficient to balance that lost to the atmosphere and in melting the ice.

Finally the important meteorological factor must not be ignored. With a general east-west isotherm structure the line must inevitably be reached south of which the frost degree-day accumulation is not sufficient for ice to form, and as has been pointed out already this line is in fact frequently well north of the continental slope. It is quite possible, though without weather stations in the sea area hard to prove, that even without oceanographic differences ice would not form much farther south than it does now. However it would seem rather a coincidence that the limiting boundary should be so closely associated with the edge of the shelf, and it would be hard to account for the northward swing of the boundary towards Cape Navarin, in an area where both air and sea temperatures tend to be lower rather than higher.

The importance of heat transport by current is emphasized by McQuain (1954), who remarked on a spring cruise that year that the break-up, which was early, appeared to be due to warm water rather than air temperature or radiation. He based this statement on scarcity or absence of puddles on the ice surface, which are always the first sign of melting by radiation. This observation might support the current scheme of Natarov, the onset of melting being associated with the changeover from winter to summer pattern and the accompanying increase in Pacific water invading the shelf.

A word should be said about the area in the western part of the sea where the extreme ice edge as given by Bulgakov (Fig. 9) projects far beyond the shelf, so that the identity with the continental slope appears to break down. There are two factors which have a bearing on this. One is that Bulgakov does not state how far back the

observations go on which his line is based, and the question of climatic change may be significant. I shall return to this point later. The second is that this is an area of strongly marked southerly drift, and where, according to Natarov, the temperature of the surface mixing layer is lower than farther east, while the current speeds along the edge of the slope slacken from 8~15 to 3~5 cm/sec. This combination could cause ice to accumulate here in extreme seasons and to melt more slowly than farther east. It is very unlikely that any ice forms in this area.

V. Historical Evidence

In view of the well-established warming of the climate that has taken place in the Northern Hemisphere over the first half of this century, it is of interest to speculate on whether this has had any effect on the limit of ice in the Bering Sea.

That the Bering Sea area did not escape the warming has been amply established by many writers. Air temperatures at many stations have risen, fishes have moved northward, and it has been shown that the 1920 s and 30 s saw an intensification of the Aleutian Low, probably accompanied by an increased flow of Pacific water into the Bering Sea (Pokrovskaya, 1946).

Unfortunately direct evidence of changes in the ice conditions and in the position of the ice limit is very scarce and not very reliable. However one valuable source exists in the records of the whalers who frequented the area in the nineteenth century. Whales

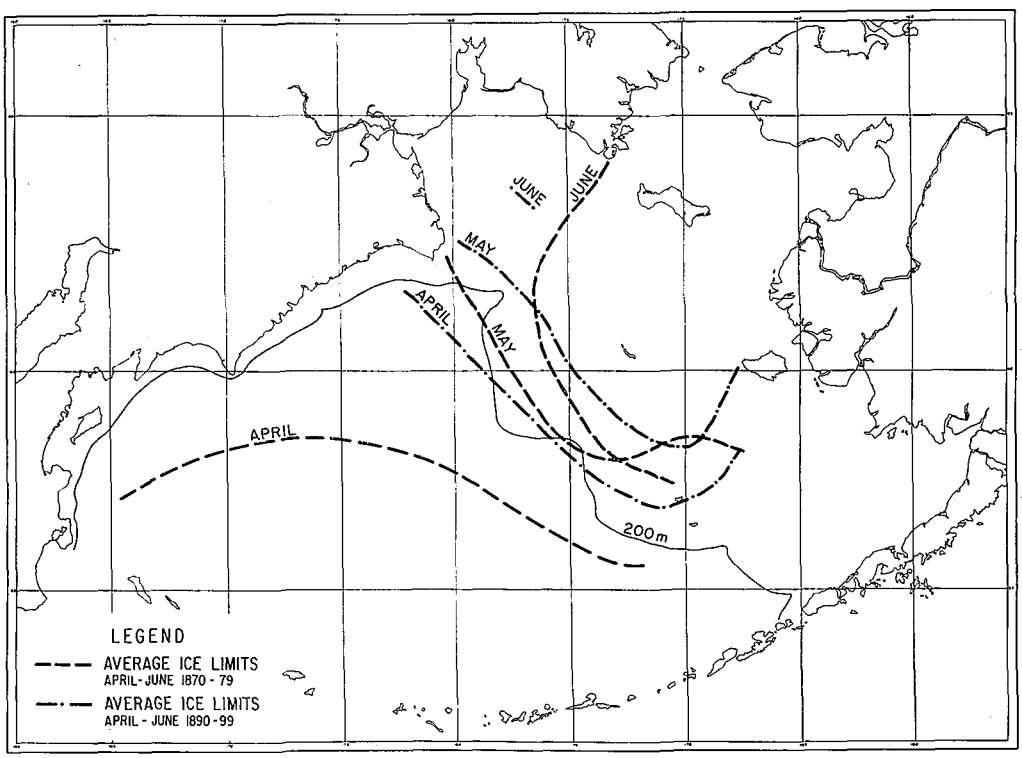

Fig. 12. Average ice limits in the 1870 s and 1890 s, based on data of Dall and Page

are found at the ice edge and in open water areas within the ice, therefore the whalers tended to follow the ice edge as it retreated northward, and their log-books and journals are a rich source of information for anyone with the time and energy to track them down. I have not been able to do this, but luckily Dall (1882) and Page (1900) have compiled a good deal of information for the 1870 s and 1890 s respectively. I have plotted all their data and from them drawn average ice limits for April, May and June in the two decades in question. These are shown on the map in Fig. 12.

As an indication of comparative conditions this map is interesting, though it would be a mistake to place too much reliance on it. In the first place the sampling is not very large, though there are some data for almost every year; secondly it is taken from secondary sources, which are more liable to copying error than original data; and thirdly it is subject to misinterpretation. For instance the extreme northward curves at the west end of the line for June in the 1870 s and at the east end for April and May in the 1890 s are probably indicative of the eagerness of the whalers to get north through leads in these areas to the good whaling grounds northwest of St. Lawrence Island, where open water developed early, and do not necessarily mean that there was no ice south or inshore of these lines. However this latter kind of error can work only one way—it can make the ice appear to be less than it was but cannot make it appear more.

A comparison of the map with Fig. 2 reveals quite a considerable difference. Mean limits in all three months are noticeably farther north in Fig. 2 than for either period in Fig. 12, and the difference becomes greater as the season advances. However only the April line for the 1870 s is below the present outside limit of ice. Unfortunately there are no observations for February or March, but it is interesting to note that both Page (1900) and a similar but unsigned report written ten years earlier (U.S. Hydrographic Office, 1890) describe the normal outer limit of ice as almost exactly the same as it is today. Page even goes so far as to remark on its coincidence with the 100-fathom (200 m) curve. Both state that the ice stays around this maximum limit until the end of April. Dall puts his general limit for the west part of the sea farther south, in keeping with the line for April (1870 s) in Fig. 12, but for the eastern part of the sea his limit is actually a little to the north of the other two.

From this slight evidence it would appear quite probable that break-up in the 1870 s and the 1890 s was later than it is today by about a month. Whether the southern limit of ice has changed is less clear. The evidence of the Hydrographic Office reports (U.S.H.O., 1890; Page, 1900) suggests that it has not changed materially since 1890. It must be remembered that their observations in February and March were probably mainly limited to shore stations on the Alaskan and Siberian coasts and the Pribilof Islands and the limit may actually have been farther south than they realized. However for the Bristol Bay area at least shore stations can give a fairly accurate picture, and in this area there seems to have been little change.

The evidence of Dall suggests a considerable extension of the southern limit in the 1870 s for the west side of the sea only. His apparently anomalous line for April is worth further comment. It is based not on one or two observations but on about a dozen, made in two separate years, so its position is unlikely to be due to errors of calculation or plotting. It is also quite close to Bulgakov's line of zero ice (Fig. 9) and

indeed the same observations may have been among those used by Bulgakov. If so, and if it does indeed indicate a more severe condition than exists today, it would help to explain why Bulgakov's line is so extreme. The presence of this southerly extension could be explained by the same mechanism described on page 699, and indeed rather supports this explanation, as given a colder climate, a less developed Aleutian Low and less advection of heat by the Pacific Current, the rate of melting in this coldest part of the deep basin of the Bering Sea might be expected to be slower than it is today, and the ice limit therefore farther south. Along the eastern part of the slope the advection, even though reduced, might still have been enough to melt the ice. It does not necessarily follow that ice formation extended any farther south than it does today, and it apparently did not do so in the Bristol Bay area.

Additional evidence of a change in break-up dates is given in Table 1, which shows dates of opening of navigation at St. Michael, in Norton Sound, since 1880, based on annual data kindly made available by the United States National Weather Records Center. Here again too much reliance cannot be placed on the information. A second source of what purports to be the same data for part of the period (Weightman, 1941) has some quite considerable differences. Much of the information was provided to the Weather Bureau by commercial shipping sources, and it is never quite clear whether the data given is the actual date of break-up or the date of arrival of the first ship, which might

Table 1. Dates of opening of navigation at St. Michael, Alaska

	Earliest	Latest	Mean	Remarks
1880–89	June 4	June 30	June 13–14	
1890–99	June 5	June 25	June 15	
1900–09	June 1	July 3	June 11	
1910–19	May 19	June 16	June 4	
1920–29	May 26	June 19	June 5	
1930–39	May 24	June 10	June 1	6 yrs. missing
1940–49	May 21	June 10	June 2	1 yr. missing
1950–59	May 10	June 6	May 26–27	2 yrs. missing

Table 2. Dates of closing of navigation at St. Michael, Alaska

	Earlist	Latest	Mean	Remarks
1880–89	Oct. 10	Dec. 7	Nov. 15	
1890–99	Oct. 25	Dec. 7	Nov. 10	
1900–09	Oct. 22	Nov. 22	Nov. 5	
1910–19	Oct. 26	Nov. 17	Nov. 9	
1920–29	Oct. 21	Nov. 23	Nov. 6	1 yr. missing
1930–39	Nov. 3	Nov. 22	Nov. 11	6 yrs. missing
1940–49	Oct. 25	Nov. 18	Nov. 7	1 yr. missing
1950–59	Oct. 25	Nov. 30	Nov. 7–8	4 yrs. missing

be considerably later. However, with these reservations, the figures do show a clear trend to earlier opening which continues right into the 1950 s.

The dates of closing of navigation (Table 2) show no such trend, and in fact no significant change of any sort. This negative result, like the positive one in Table 1, may be due to inadequate data. However, it is perfectly possible that both are quite valid and that the warming makes itself felt only in spring. Certainly the descriptions of freeze-up given by Page and the 1890 report, unlike their descriptions of break-up, quite closely reflect present conditions.

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