PHYSICAL OCEANOGRAPHIC INVESTIGATIONS IN THE EASTERN BERING AND CHUKCHI SEAS DURING THE SUMMER OF 1947

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ABSTRACT

New information on the physical properties of the waters in the eastern Bering and Chukchi seas is discussed. It shows that, in summer, the water masses of this area are complicated by the circulation and advective processes. In general, the southern Bering Sea water flows northward and is modified by warm low-salinity water from rivers along the Alaskan coast and from intrusions of cold high-salinity water from the western Bering Sea. This mixture of water funnels through the Bering Strait principally at the surface on the eastern side. In the Chukchi Sea this water continues northward, tending to follow the Alaskan coast, turning into Kotzebue Sound, and then heading around Cape Lisburne toward Point Barrow. Other water masses occur in the central Chukchi Sea opposite Kotzebue Sound and north of 70° N latitude. Near the Arctic ice pack boundary, unusual stratification of the water occurs, with subsurface temperature maximums in the form of tongues or pockets. This phenomenon is probably caused by mixing of water from melting ice cakes with the advected higher-salinity water from the Bering Strait.

INTRODUCTION

During a familiarization cruise on the USS Nereus to the Bering and Chukchi seas in the summer of 1947, geological, biological, and physical investigations of the sea floor and water were undertaken by oceanographers from the U. S. Navy Electronics Laboratory and the Scripps Institution of Oceanography. This paper reports studies of the physical properties of sea water; detailed results of all phases of the program have been reported elsewhere (LaFond, Dietz, Pritchard, 1949).

In the prosecution of the oceanographic programs, the ship hove to four times each day in the shallow areas of the Bering and Chukchi seas for vertical series of temperature, salinity, and other oceanographic observations. The locations of these serial oceanographic stations are shown in Fig. 1. Thirty-nine stations were located north of the Aleutian Islands, 22 of these being north of Bering Strait in the Chukchi Sea.

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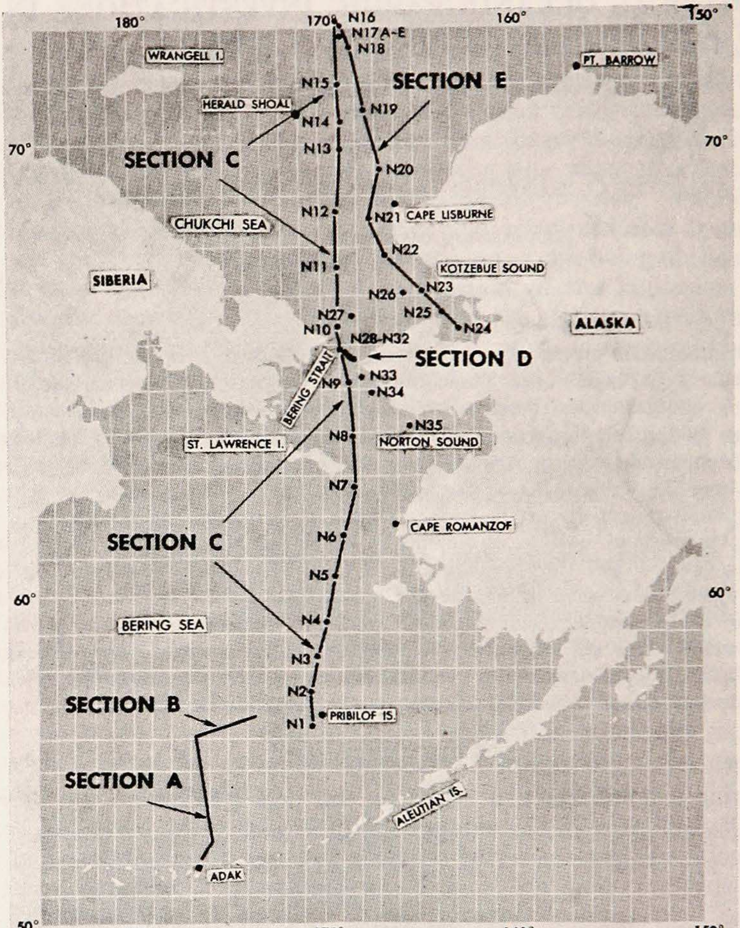

Figure 1. Bathythermograph and hydrographic stations used for vertical sections.

Several previous cruises, notably those conducted by the U. S. Coast Guard in 1934 (Barnes and Thompson, 1938) and in 1937–1938 (Goodman, Lincoln, et al., 1942), have made fairly complete investigations of the eastern Bering Sea and Norton Sound. However, relatively few data have been obtained previously in the central Chukchi Sea area. The latter cruises, in the summers of 1937 and 1938, occupied a number of stations along the Alaskan Coast from Bering Strait nearly to Point Barrow, but the data obtained were not sufficient to show the lateral distribution of the physical variables.

Sverdrup, on the MAUD (Sverdrup, 1929), obtained considerable data between Herald Shoal and Wrangell Island, but he occupied only two serial stations east of 170° W in the Chukchi Sea. Thus, the data taken during this USS NEREUS cruise in the Chukchi Sea represent a considerable increase in the oceanographic information available for this area.

Also shown in Fig. 1 is the location of the line of bathythermograms obtained from Adak north to the southern edge of the extensive shallow water area of the Bering Sea. It was in this shallow water region, north from the area of the Pribilof Islands, that all of the serial observations in the Bering Sea were taken. At each hydrographic station, vertical water temperatures were obtained from both bathythermograms and reversing thermometers. The BT observations are extremely valuable from the standpoint of description of the thermal structure, since a continuous temperature trace with depth is obtained. Because of this greater detail given by the BT observations, all vertical cross sections are based on bathythermograms, and the isotherms are in degrees F. However, the more accurate temperatures obtained from reversing thermometers simultaneously with the water samples were used for computations of density and dynamic topography.

TEMPERATURE AND SALINITY

Adak to the Pribilof Islands. BT observations were made every hour along a section from Adak northward to 56° 03′ N, 176° 38′ W and then along a section east northeastward to 56° 36′ N, 173° 39′ W. These sections (Fig. 1, A and B) are over the eastern end of the deep Bering Sea basin, with the depth running at about 2100 fathoms at most stations. The BT, therefore, suffices in obtaining data on only a relatively small portion (300 to 400 feet) of the vertical thermal structure of this region. It has been shown, however, that the temperature and salinity structures of the Bering Sea basin below 100 m are very similar to those in the subarctic region of the North Pacific (Sverdrup, Johnson, and Fleming, 1946: 732–733). The mean flow is northward through the channels of the Aleutian chain, and the BT traces characteristic of most of these obesrvations in the southern Bering Sea are not unlike those found in the subarctic water south of the Aleutians.

The horizontal temperature structure at the surface, at 25 m and also at 40 m, is shown in Figs. 2, 3, and 4. It indicates the existence of a clockwise eddy at about 55° N, 175° W.[2] A study of the data

[2] A discussion of the relationship between thermal structure and currents is given by Sverdrup, et al., 1946: 394.

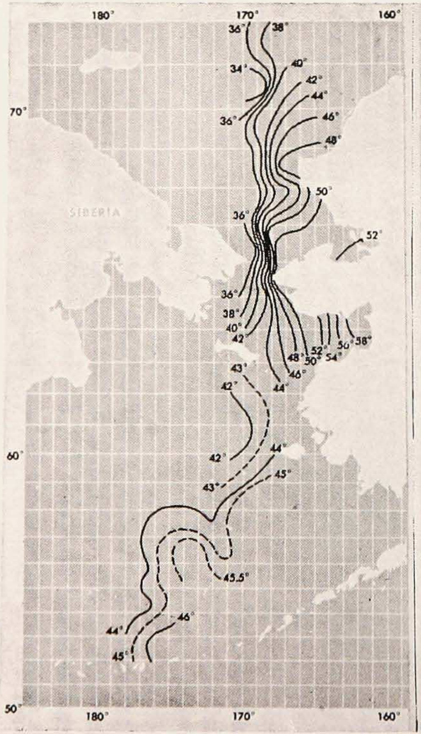

Figure 2. Horizontal distribution of temperature (°F) in Bering and Chukchi seas, at the surface.

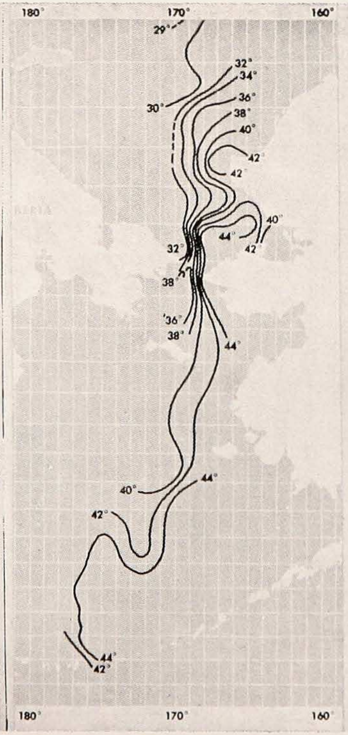

Figure 3. Horizontal distribution of temperature (°F) in the Bering and Chukchi seas, at a depth of 25 meters.

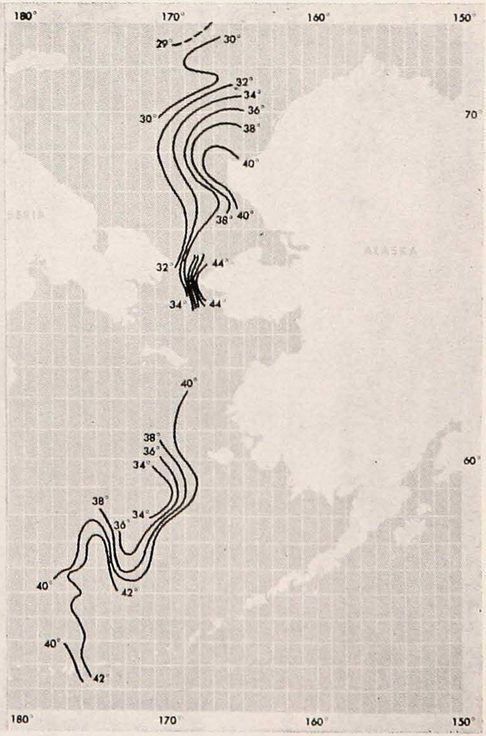

Figure 4. Horizontal distribution of temperature (°F) in the Bering and Chukchi seas, at a depth of 40 meters.

presented as a vertical section (figure not shown) further emphasizes the existence of this clockwise eddy.

The Bering Sea from the Pribilof Islands to Bering Strait. Nine hydrographic stations were occupied along a line running from a point just south of the Pribilof Islands to the eastern side of St. Lawrence Island and then north to Bering Strait; three more stations were occupied on a line southeast from Cape Prince of Wales toward Norton Sound (see Fig. 1).

As shown by the horizontal distribution of temperature and salinity at various depths (Figs. 2–7), the major change in these variables occurs in an east-west direction rather than along the line of stations running from the Pribilof Islands to the Bering Strait. In general, the warmer and less saline water is found near the Alaskan coast. The isotherms tend to run southwest-northeast in the region of the four southernmost stations; however, the ridge extending out from Cape Romanzof appears to deflect the warm coastal water west, so that the isotherms run southeast-northwest in the region south of St. Lawrence Island.

The isotherms and isohalines for the southernmost four stations are not parallel; the isohalines run from southeast to northwest, while the isotherms run approximately southwest-northeast. The protrusion of the isohalines to the west in the region of Cape Romanzof occurs somewhat south of the same protrusion of the isotherms. North of St. Lawrence Island the isotherms and isohalines run approximately parallel, converging toward Bering Strait.

The highest surface temperatures, 58° F, were encountered in Norton Bay. The lowest surface temperature obtained south of Bering Strait was 41° F, although the trend of the isotherms indicates that much lower temperatures exist off the Siberian coast opposite Seward Peninsula.

A study of temperature-salinity relationships provides a convenient method for determining water mass characteristics and origin. T-S diagrams, therefore, were plotted for all stations in the Bering Sea except for those in Norton Sound (see Fig. 8). Included in Fig. 8 is the T-S relationship for the upper layers of the subarctic water found to the south of the Aleutians, as given by the upper 100 m of CARNEGIE St. 120 (47° 02′ N, 166° 20′ E). The T-S curves for NEREUS Sts. N1, N2, and N3 are similar in shape to that at CARNEGIE St. 120 but are 1‰ lower in salinity at equivalent temperatures. The shape of the T-S relationship remains about the same, but the average salinity decreases northward (Sts. N4, N5, N6, N7) to the region between St. Lawrence Island and Bering Strait. Here the water has a higher

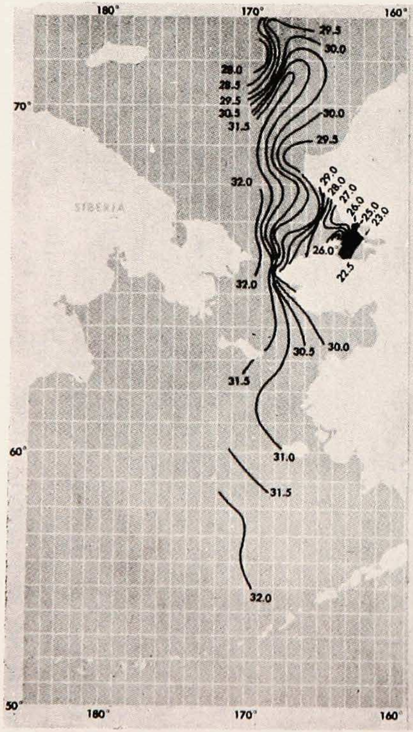

Figure 5. Horizontal distribution of salinity (°/₀₀) in the Bering and Chukchi seas, at the surface.

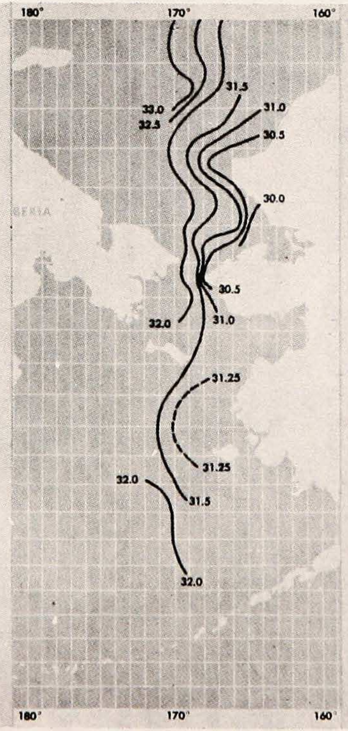

Figure 6. Horizontal distribution of salinity (°/₀₀) in the Bering and Chukchi seas, at a depth of 25 meters.

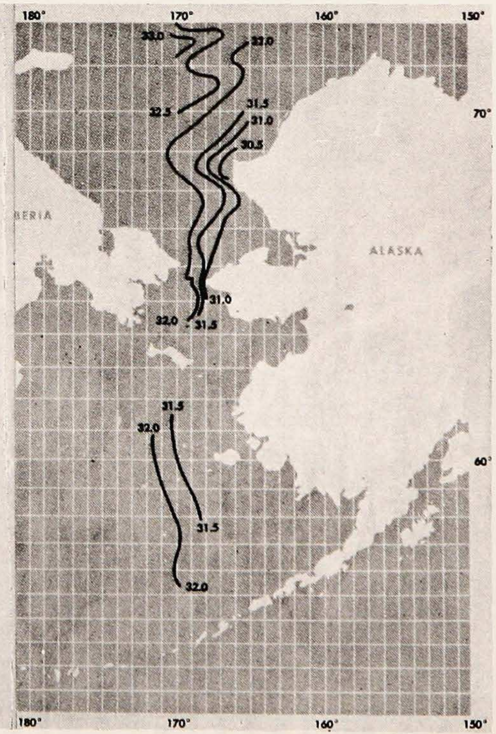

Figure 7. Horizontal distribution of salinity (°/₀₀) in the Bering and Chukchi seas, at a depth of 40 meters.

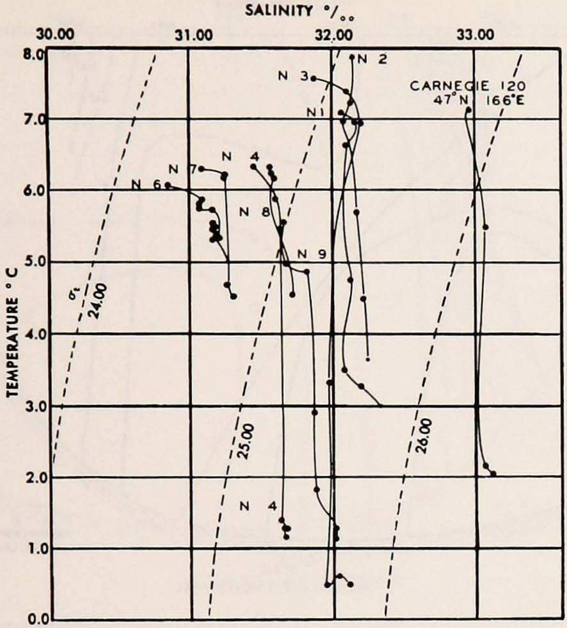

Figure 8. Temperature-Salinity diagrams from stations in the Bering Sea (see Fig. 1).

salinity because of the mixing with more saline water which apparently flows northward to the west of the line of the NEREUS stations (Goodman, Lincoln, et al., 1942).

Bering Strait. Five hydrographic stations were occupied across the eastern half of Bering Strait. Very large horizontal gradients of the physical variables were encountered here, the most extreme gradients occurring along the Alaskan side of the Strait. In this location, a surface temperature drop of 10° F in 30 miles was observed; 8° of this change occurred in the 10 miles between the two stations nearest to the Alaskan coast. The corresponding salinity change was 2.5 °/oo.

Vertical cross sections of temperature and salinity have been constructed for the five stations across the eastern part of Bering Strait. The temperature section (Fig. 9) shows the change from cold water on the western side of the section to relatively warm water near the Alaskan coast at all depths. The warm water overruns the cold water in the middle, producing fairly large vertical gradients in temperature. The salinity section (Fig. 10) shows the decrease in salinity from west to east. The greatest horizontal change at all depths occurs between the two stations nearest to the Alaskan coast. There the low-salinity

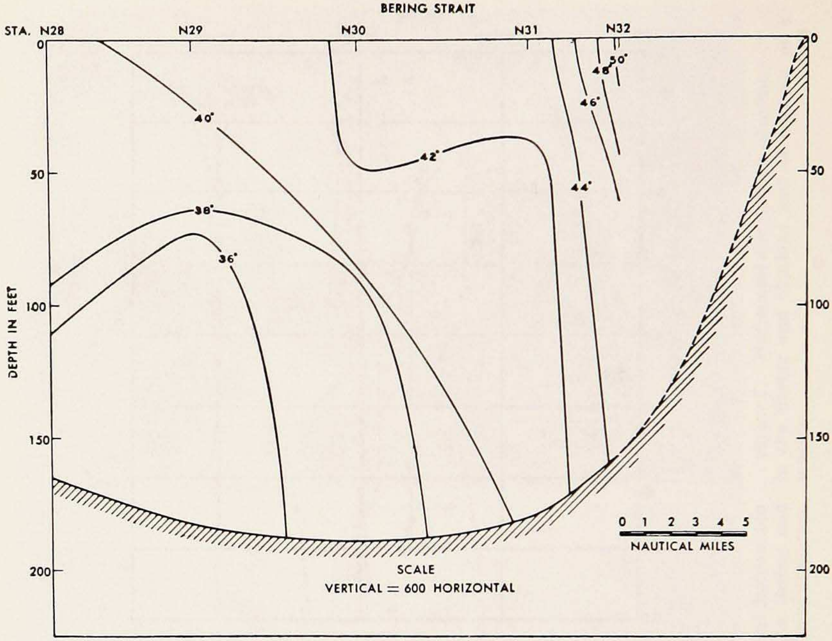

Figure 9. Vertical temperature section D (°F) across the eastern side of Bering Strait (see Fig. 1).

water is apparently related to runoff from Alaskan rivers. The mass field, as indicated by the distributions of temperature and salinity, must be associated with a relatively strong current running northward through Bering Strait.

The depth of the thermocline decreases from west to east, with the greatest gradients in the thermocline occurring at the central station. The vertical temperature gradients below the thermocline are small. The vertical salinity gradients increase from west to east. The layer of maximum vertical salinity gradient occurs just below the thermocline.

The T-S diagrams for this area are shown in Fig. 11. The stations on the western and middle portions of the section show the same T-S characteristics as those shown by the stations in the central Bering Sea (N28 to N30). However, St. N32, on the far eastern side of the Strait, shows water of different character. This water is warmer and less saline with a considerable salinity gradient. St. N31 is apparently a mixture of the western and eastern waters in the Strait. As will be seen later, the T-S relation at St. N32 is very similar to that of the

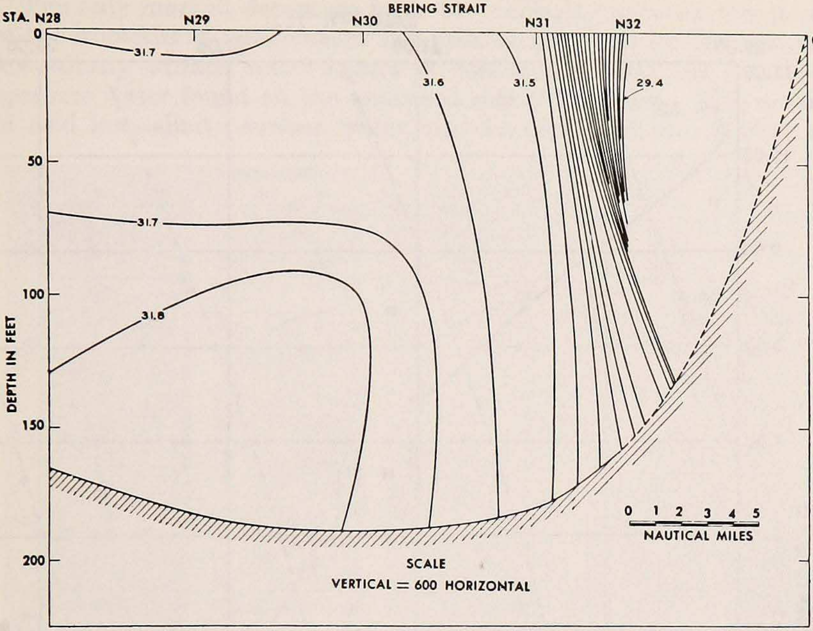

Figure 10. Vertical salinity section D (°/oo) across the eastern side of Bering Strait (see Fig. 1).

Alaskan coastal Sts. N33, N34, and N35 extending into Norton Sound, and to Sts. N26 and N27 in the Chukchi Sea, northeast of Bering Strait.

Chukchi Sea. Twenty-two serial stations were occupied north of Bering Strait in the Chukchi Sea: Seven in a north-south line from Bering Strait to the edge of the pack ice just north of 72° N; five stations, occupied over a 24-hour period while the ship was drifting southeastward, in the immediate vicinity of the ice pack; another eight stations from the ice pack into Kotzebue Sound, together with the two stations between the Sound and Bering Strait. These stations provide the most extensive data yet obtained in this area of the Chukchi Sea and provide a good network for the study of the distribution of physical properties.

The over-all distribution of temperature and salinity in the Chukchi Sea leads to horizontal contour charts which are remarkably similar for the various depths and for both temperature and salinity. Warm low-salinity water is found at all depths on the Alaskan side of the Chukchi Sea. The isopleths of both temperature and salinity tend to follow the contours of the coastline (Figs. 2–7).

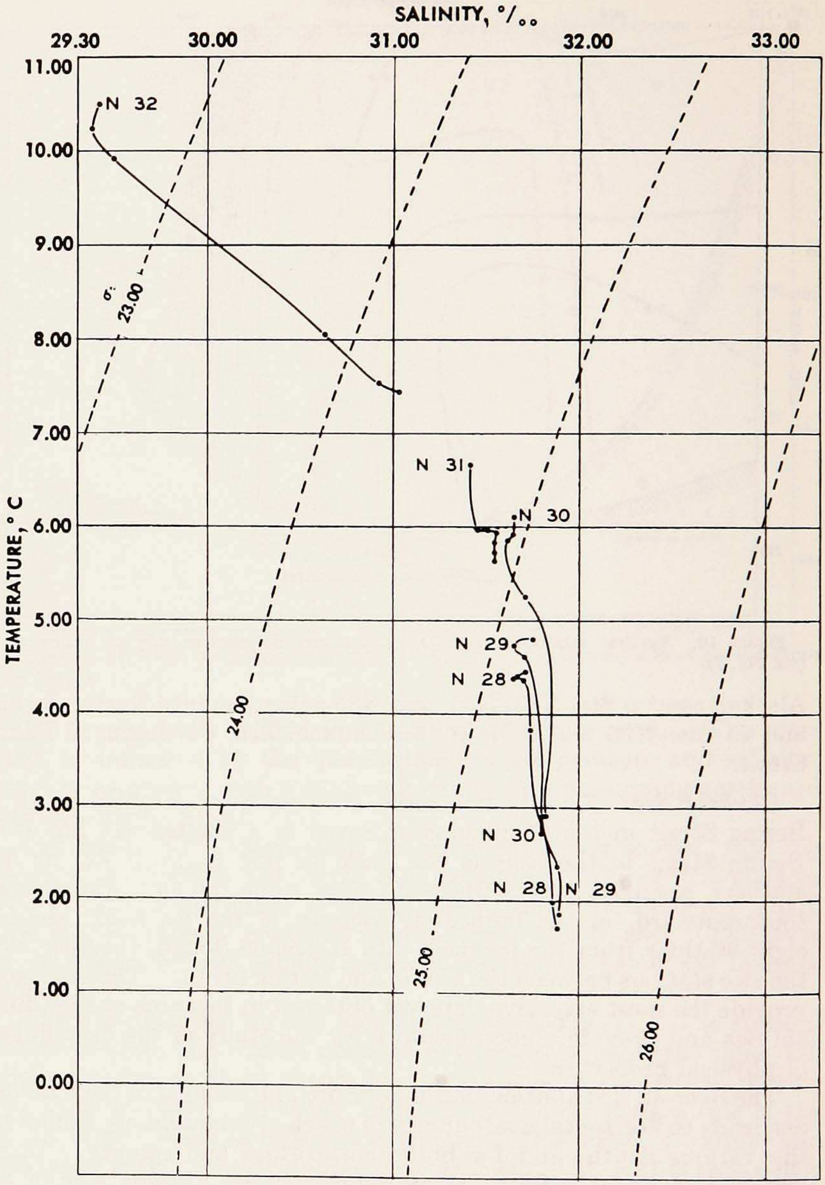

Figure 11. Temperature-Salinity diagrams from stations across the eastern side of Bering Strait (see Fig. 1).

The only marked departure from the similarity between the trend of the isopleths of temperature and salinity occurs at St. N15, where low-salinity surface water occurs in conjunction with the low-temperature water found on the westward side of the area. This region of cold low-salinity surface water may be explained as a pocket of

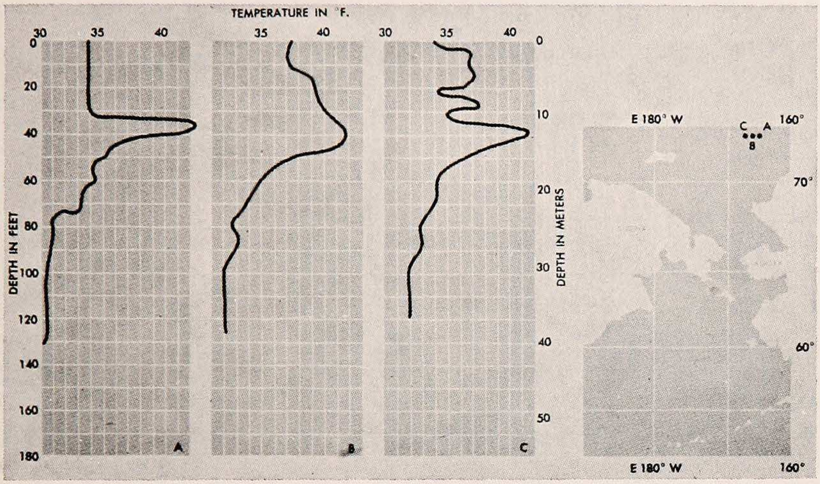

Figure 12. Bathythermograms taken in the ice pack region.

melt water which had drifted down from the ice area under the influence of the northwest winds which prevailed at this time. The similarity of St. N15 to the stations occupied in the ice area will be noted further in the discussion of the T-S relationship.

Several unusual features of these structures were shown by the BT observations. At several stations a subsurface maximum in temperature was observed. These maximums and their associated positive gradients were frequently observed north of 70° N near the boundary of the ice. Fig. 12 gives observations made in the region of the ice pack; these show pronounced positive gradients. The temperature in the warm subsurface layer was up to 9° F higher than the overlying isothermal layer (Fig. 12A). Repeated observations show that the layer may take on different characteristics. For example, the isothermal layer may be completely lacking, and a positive gradient may extend almost to the surface (Fig. 12B). In some cases multiple layers of positive temperature gradients were observed (Fig. 12C). The subsurface maximum occurred most often at a depth between 30 and 45 feet, and in all cases it occurred at a depth of less than 50 feet. In most cases the salinity gradient is large enough to counteract the temperature gradient, and the vertical stability is maintained (Fig. 13A). At some stations, however, the increase in salinity in the layer of positive temperature gradients was not sufficient to compensate for the decreasing density caused by the temperature change, thus creating a condition of vertical instability. In some cases instability was ob-

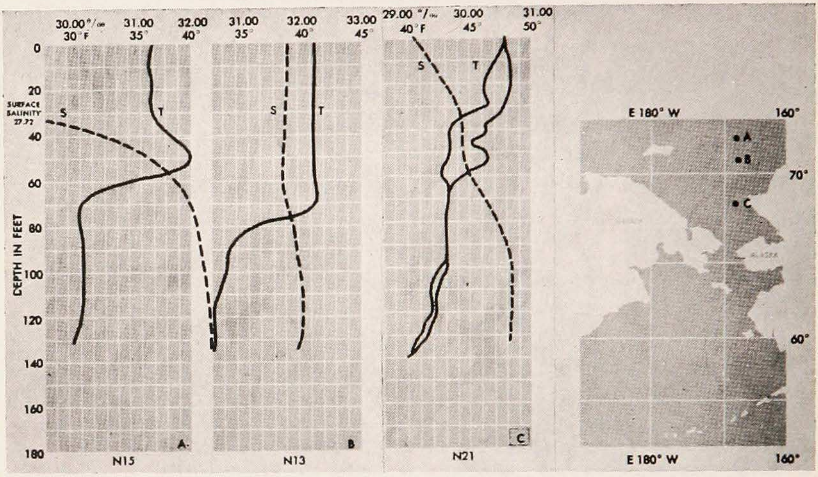

Figure 13. Bathythermograms (T) and salinity traces (S) taken in the eastern Chukchi Sea. Double trace in C represents the observed temperature when lowering and retrieving the bathythermograph.

served to be a result of vertical salinity gradients alone. At St. N13 (Fig. 13B), for example, the surface layers are isothermal, but the salinity decreases slightly with the depth in the upper 20 m.

The presence of instability is further substantiated by the bathythermogram at St. N21 (Fig. 13C). One of the traces shown is that made by the instrument while it was sinking through the water; the other trace was made by the instrument while it was being hauled in. If only one such bathythermogram had been obtained, it could be supposed that there was something wrong with the instrument; however, two BTs were lashed together at most of these stations, and nearly identical traces were obtained from both instruments. The rapid change in the thermal structure indicated here (the difference in time between the two traces is but 1 or 2 minutes) may well be explained as the result of vertical convection set up by recently established instability. Typical examples of vertical temperature and associated salinity plots (Fig. 13) indicate that the vertical gradients increase with increasing latitude. The layers near the bottom, especially at the northern stations, show low temperatures of approximately

29° F and high salinities of about 33 °/oo. A possible explanation of the formation of this bottom water is given in the discussion of the T-S relationships below.

The T-S relationships for Sts. N10–N15 are shown in Fig. 14. The T-S diagrams for N10, N11, N12, and N13 show characteristics similar

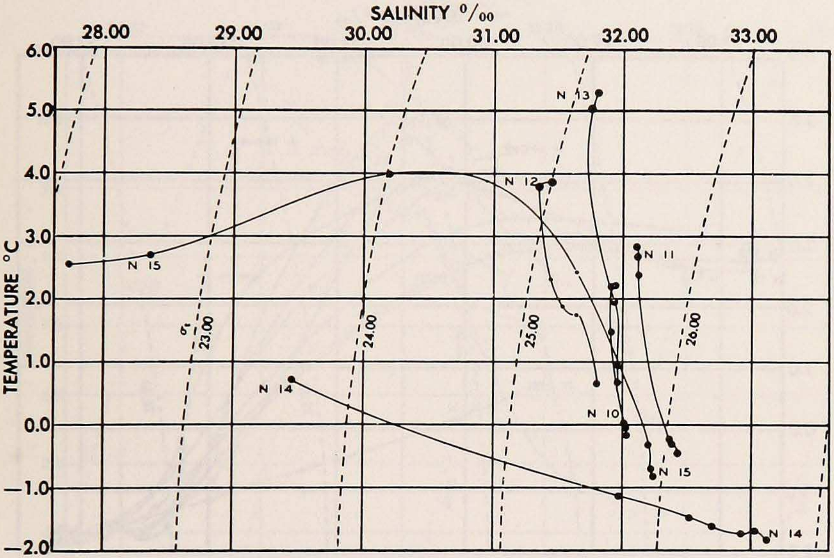

Figure 14. Temperature-Salinity diagrams from stations in the central Chukchi Sea (see Fig. 1).

to those found at the central Bering Sea stations, though the temperatures at the Chukchi Sea stations are somewhat colder. It would seem apparent from this similarity in T-S relationship that the water at these Chukchi Sea stations results from a northerly flow at all depths from the Bering Sea.

The marked change in the T-S relationship at N14 and N15 is indicative of a change from water whose recent origin is the Bering Sea to water resulting from the melting of the ice in the northern Chukchi Sea. The elongation of the T-S relation for N14 and N15 toward low salinity in the surface layers is indicative of melt water.

The T-S relationships for N16, N17 (A–B), N18, and N19 appear in Fig. 15 with a repetition of the diagrams for N14 and N15. These stations show fairly similar T-S curves. The low-salinity surface water indicative of melting is present to a greater or less degree on all curves. The spread of the curves in the central portion of the diagram is related to the amount of mixing between the low-salinity melt water and the more saline water. The more saline and relatively warm water found at mid-depths seems to have originated in the Bering Sea, and in this locality it appears as a wedge between the surface melt water and the uniform bottom water that is found on all of these T-S plots. The cold and relatively high-salinity water (33 °/₀₀), found on

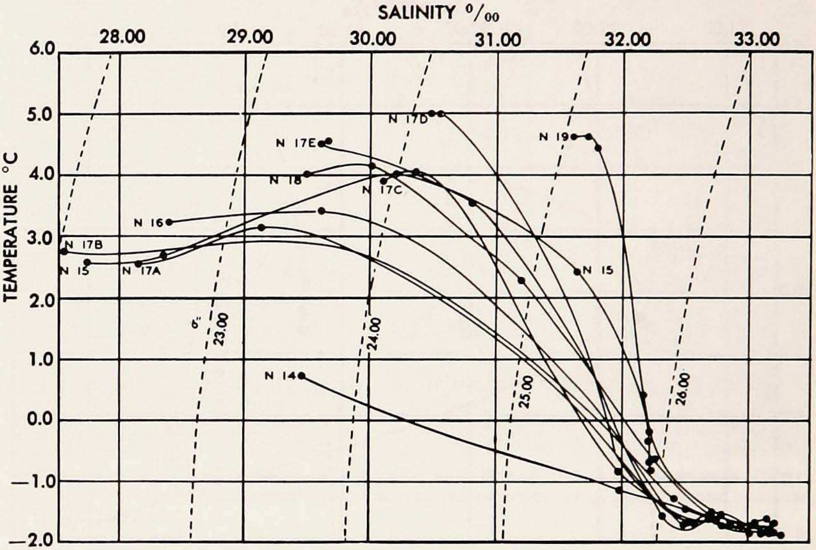

Figure 15. Temperature-Salinity diagrams from stations in the northern Chukchi Sea near ice pack (see Fig. 1).

the bottom at all of these stations, is probably the result of winter freezing. Because of the lower freezing point of salt water, relatively fresh water freezes first, especially when the rate of freezing is slow. Hence the water just below the freezing layer becomes more saline, and, since it is also being cooled, it becomes heavier than the underlying water and sinks to the bottom. Since this bottom water is probably formed in winter throughout the Chukchi Sea (probably in the northern part of the Bering Sea also), the failure of this high-salinity bottom water to appear farther south than N14 is indicative of a northward transport along the bottom at the stations in the southern and central Chukchi Sea.

Nearer the Alaskan coast the T-S plots show higher temperatures and lower salinities, as can be seen from the data for N20, N21, and N22 in Fig. 15. Also shown are the T-S relationships for N26 and N27, in the southeastern part of the Chukchi Sea, and for N33, N34, and N35, located along the Alaskan coast south of Bering Strait and in Norton Sound. The similarity of the T-S plots between these latter stations in the northeastern Bering Sea and the stations in the southeastern section of the Chukchi Sea can be used to confirm the pattern of flow which will be discussed.

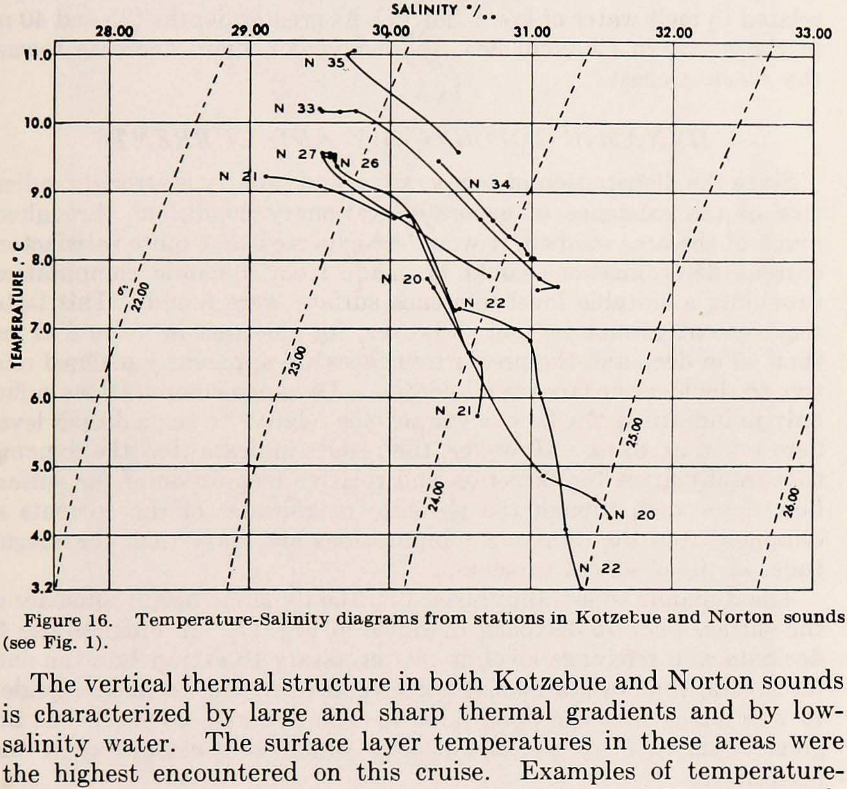

Figure 16. Temperature-Salinity diagrams from stations in Kotzebue and Norton sounds (see Fig. 1).

The vertical thermal structure in both Kotzebue and Norton sounds is characterized by large and sharp thermal gradients and by low-salinity water. The surface layer temperatures in these areas were the highest encountered on this cruise. Examples of temperature-depth and salinity-depth curves from Kotzebue and Norton sounds are shown in Fig. 16.

DENSITY

Because of the close relationship between the isopleths of temperature and salinity, contours of σ_t are very similar to the isotherms and isohalines. The general parallel character of the isopleths of these physical variables indicates that in general the conditions are stationary and that the current will flow parallel to the isolines of temperature, salinity, and density.

South of Point Hope the isopycnals run approximately parallel to the depth contours. The lower-density water is found at all depths along the Alaskan coast; very low-density water (σ_t = 16.8) is found in Kotzebue Sound. In the northern Chukchi Sea, regions of low density occur in the surface layer to the west of the line of stations (away from the Alaskan coast). This area of low surface density is related to melt water of low salinity. At greater depths (25 and 40 m) in the northern Chukchi Sea, the isopycnals again decrease toward the Alaskan coast.

DYNAMIC TOPOGRAPHY AND CURRENTS

Since the distribution of temperature and salinity is strongly indicative of the existence of generally stationary conditions throughout much of the area studied, it would be expected that quite satisfactory current determinations could be made from dynamic computation, providing a suitable level reference surface were found. This latter requirement cannot be met, however, for the area in general is less than 50 m deep and the pressure surfaces are apparently inclined relative to the level surfaces at all depths. Dynamic computations suffice only in indicating the flow of the surface relative to some deeper level, here taken at 45 m. However, the results indicate that the dynamic topography gives the direction and relative magnitude of the surface flow quite well, though the absolute magnitudes of the currents as obtained from the dynamic computations are lower than the magnitudes of the observed currents.

The dynamic topography, based on the dynamic height anomaly of the surface over 45 decibars, is shown in Fig. 17. In order to use 45 decibars as a reference level, it was necessary to extrapolate the data for several shallow stations, using several reference stations as guides. It was found that the final value for the dynamic anomaly was not greatly affected by the manner in which this extrapolation was performed.

The solid arrows on Fig. 17 show the direction of drift of the USS Nereus during several periods when the ship was allowed to drift with the current and the wind. Because the vessel has a high freeboard, it is likely that the drift is greatly affected by the wind. This is seen most clearly at the drift stations taken at the edge of the ice pack, where the ship drifted southeastward at about ½ knot although the dynamic topography indicates a northerly flow. This drift of the ship was related to the observed northwest wind of about 7 knots, for the drift was observed to be southward relative to the pieces of floating ice which surrounded the ship at the beginning of the drift.

Figure 17. Dynamic height contours (0/45 dynamic meters) in dynamic centimeters observed in the Bering and Chukchi seas with direction of calculated current flow indicated by arrowheads along the contours of dynamic height. Observed drift of ship is indicated by short heavy arrows.

The observed velocities of drift at Sts. N8, N9, and at the five stations in Bering Strait, gave directions which were very close to the direction of flow indicated by the dynamic topography. However, in every case the computed velocities were much smaller than the observed velocities (approximately 1/10 as large). This is to be expected since the bottom waters also have a northerly motion. Some of the difference between observed and computed currents in Bering Strait can be related to wind drift of the ship, for the wind was blowing at an average speed of 17 knots from the south during this period of observation.

For the southern Bering Sea region the current streamlines, as deduced from the distribution of temperature alone, are shown on Fig. 17 as dashed lines. Previous investigators (Goodman, Lincoln, et al., 1942) have reported the existence of eddies similar to the one depicted here in this region of the Bering Sea.

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