PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY OF THE SEAS TO THE WEST AND NORTH OF ALASKA

E. C. LaFond*

ALASKA, with the north Pacific Ocean to the south, a transition zone through the Bering and Chukchi seas to the west, and the Arctic Ocean to the north, is exceptionally well situated for studies in oceanography. These diverse water masses contain a variety of ecological environments, and different physical and geological conditions. However, owing to problems of transportation and lack of facilities, relatively little oceanographic work has been done in the seas around Alaska.

Most information on soundings, currents, and ice conditions in the area has come from commercial ships engaged in whaling and shipping. Even much of the information on physical oceanography and marine geology has been obtained incidental to other operations. The main studies of the physical and chemical structure of the water were made by U.S. Coast Guard vessels staffed with University of Washington oceanographers during the summers of 1933, 1934, 1937, and 1938. On these cruises serial stations, making oceanographic sections, were occupied throughout the eastern Bering Sea and Bering Strait, and along one line to Point Barrow. Another prewar cruise was made by the *Maud* which obtained considerable data between Herald Shoal and Ostrov Vrangelya (Wrangel Island) (Sverdrup, 1929).

During the war the principal oceanographic work carried out consisted of bathythermograph observations in the southern part of the Bering Sea. Postwar investigations consisted of scattered bathythermograph observations and oceanographic stations from icebreakers running through the Bering and Chukchi seas to Point Barrow in 1946, 1948, and 1950. These investigations were made by personnel of the U.S. Coast Guard, Scripps Institution of Oceanography, University of Washington, and U.S. Hydrographic Office. In 1947 a U.S. naval ship staffed with U.S. Navy Electronics Laboratory and Scripps observers occupied stations through the Bering and central Chukchi seas to a latitude of 72°N. In 1949 both Canadian and United States naval ships investigated the southern and eastern Bering Sea and the eastern Chukchi Sea to a latitude of 73°N.

Although the number of cruises in this area appears impressive, it must be remembered that all the data were taken in midsummer. During this season significant week-to-week changes take place in the physical properties of the water. Furthermore, additional duties or programs of the ships made it impossible to locate or time stations to the best advantage for adequate coverage.

*U.S. Navy Electronics Laboratory, San Diego, California.

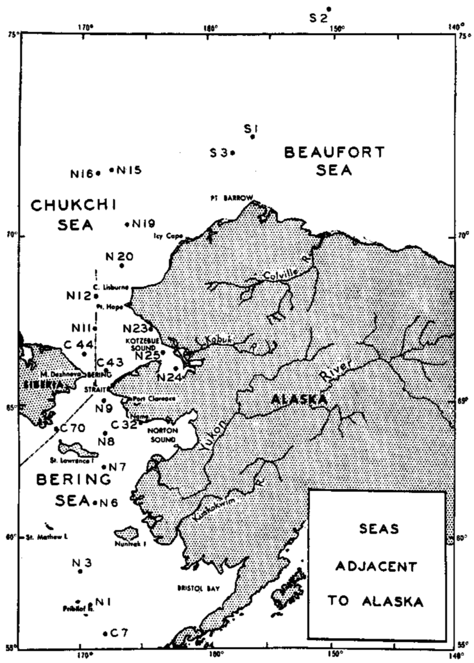

Fig. 1. Seas adjacent to Alaska showing location of oceanographic stations.

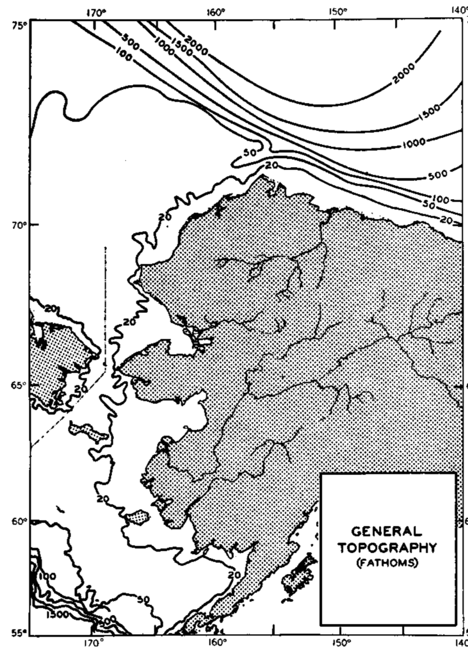

Fig. 2. General submarine topography around Alaska.

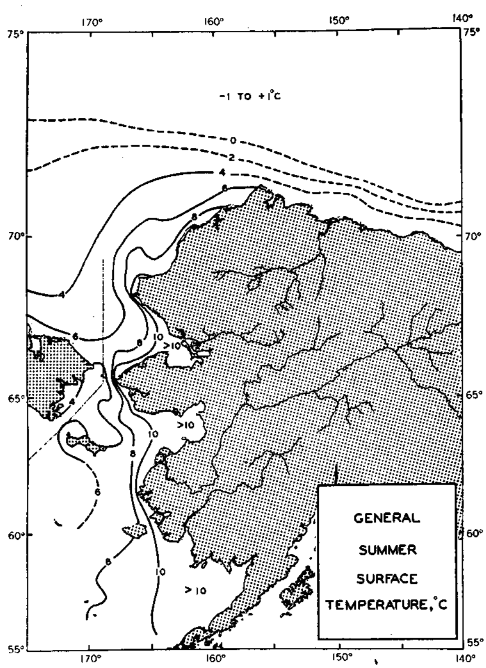

Fig. 3. General summer sea surface temperature around Alaska.

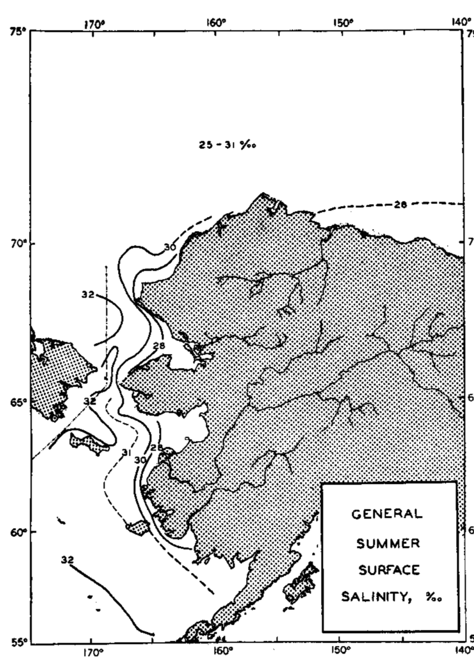

Fig. 4. General summer sea surface salinity around Alaska.

Submarine topography

The Bering Sea is bounded on the south by the Aleutian Island arc, and on the north by Siberia and Alaska (Figs. 1 and 2). In the southwest it is an abyssal ocean basin; the deepest part, around 2,100 fathoms (not shown on Fig. 2), has a rather flat floor. A steep slope connects this basin to the shallow continental shelf that extends throughout the northern and eastern Bering Sea, Bering Strait, and most of the Chukchi Sea. This shelf is remarkably level and smooth. It has an average slope of 3 to 4 inches a mile, and is believed to be flatter than any land feature of comparable area (Buffington *et al.*, 1950, p. 2).

The floors of the northern Chukchi and Beaufort seas fall off steeply into the Polar Basin, to depths of over 2,000 fathoms (Emery, 1949). Just north of Point Barrow a depression, the Barrow Sea Valley, crosses the continental slope to the northeast.

Sediments

Bottom sediments collected by various expeditions indicate that the floor of the Bering Sea is mainly sandy, with some large areas of mud or sandy mud west of 170°W., and sand and gravel on the edge of the continental shelf. The muddy area appears to stretch north into the Anadyrskiy Zaliv (Gulf of Anadyr) which receives the outflow of several large Siberian rivers. Gravel and rock were found in spot samples taken near the islands, particularly along the edge of the continental shelf south of the Pribilof Islands, and certain areas along exposed coastlines, such as near Seward Peninsula. Coarse sediments are also found in Bering Strait. In the Chukchi Sea nearshore areas are sandy with occasional gravel patches, and sediments, in general, become progressively finer in texture northwards to a zone of mud and sand. North of Alaska the bottom appears to be largely mud. In all areas occasional isolated patches of mud, sand, and gravel are found.

Sediments in this area are mainly derived from the large rivers entering the Bering and Chukchi seas from the Alaskan and Siberian coasts, which deposit large amounts of silt and clay, especially towards the north in the Chukchi Sea, and from ice rafting. Material carried by rivers flowing under ice freezes to the under surface, and ice freezing to the bottom and banks picks up sediment. In the spring break-up the ice may be carried out to sea and the accumulated sediment may be scattered anywhere in the area.

Horizontal temperature and salinity structure

The horizontal temperature distribution in the surface water to the west and north of Alaska is shown in Fig. 3. Relatively warm surface water is found in the southern and eastern part of the Bering Sea (Goodman *et al.*, 1942, pp. 125–6). Currents move this water across the slope and shelf of the Bering Sea in a northwesterly direction. In summer warmer waters are found near the Alaskan coast, the temperatures decreasing with distance from the coast (LaFond and Pritchard, 1952, p. 72). Thus isotherms, in general, tend to follow the coast bending into Norton Sound, Kotzebue Sound, and

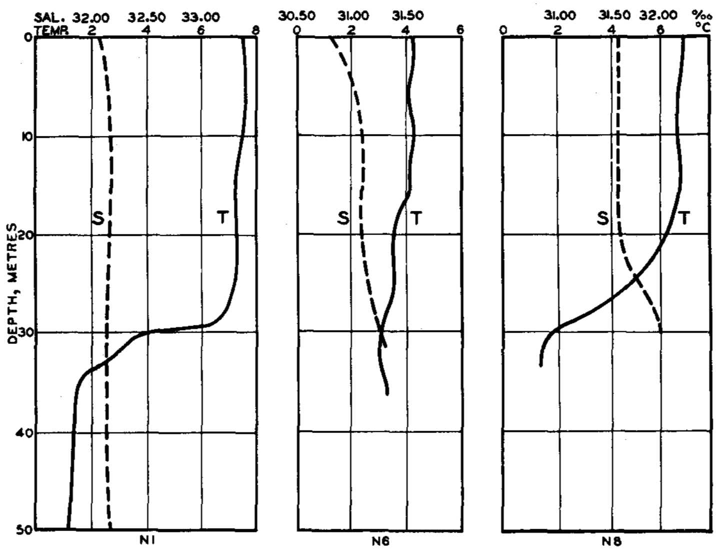

Fig. 5. Examples of vertical temperature and salinity in Bering Sea in summer (*see* Fig. 1 for location of stations).

around Cape Lisburne, with highest temperatures in the inner parts of Norton Sound and Kotzebue Sound. Colder water appears to come from the western side of the Bering Sea, especially just north of St. Lawrence Island. Colder water is also found in the Chukchi Sea; it apparently originates just north of, and along, the Siberian coast. North of 70°N. surface temperatures fall abruptly at the boundary of the ice pack. During the summer the temperatures sometimes drop to less than -1°C, and usually vary between +1° and -1°C within the scattered ice.

Changes in horizontal salinity distribution also occur in an east–west direction (Fig. 4). In general, less saline water is found along the Alaskan coast, particularly in the inner parts of Norton and Kotzebue sounds, and the isohalines in the southeastern Bering Sea tend to run southeast–northwest, then eastward past St. Lawrence Island, bending into Kotzebue Sound. In the northern Chukchi Sea and to the north of Alaska the surface salinity is difficult to forecast as it is largely determined by the southern limit of the ice pack. Readings ranging from 25 to 31 parts per thousand in summer have been obtained.

Vertical temperature and salinity structure

Examples of the vertical temperature structure from bathythermograms and the vertical salinity structure from oceanographic stations (Fig. 1) are illustrated in Figs. 5, 6, and 7. Near the Pribilof Islands (Fig. 5, N1), the typical summer temperature structure shows a sharp layering with no appreciable salinity gradients. Farther north, between St. Lawrence and Nunivak islands (Fig. 5, N6), both the salinity and temperature are nearly uniform with depth. North of St. Lawrence Island (Fig. 5, N8), sharp vertical gradients again appear. In Bering Strait the warmer, less saline water near the Alaskan coast, causes large gradients of temperature and salinity near the

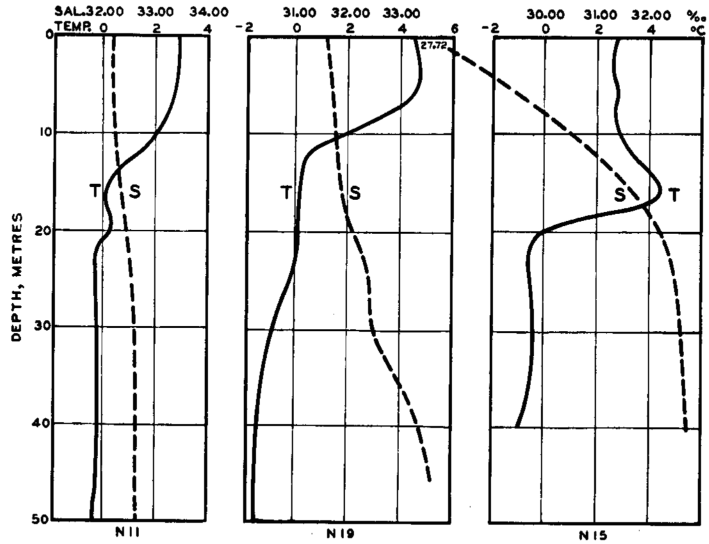

Fig. 6. Examples of vertical temperature and salinity in Chukchi Sea in summer (*see* Fig. 1 for location of stations).

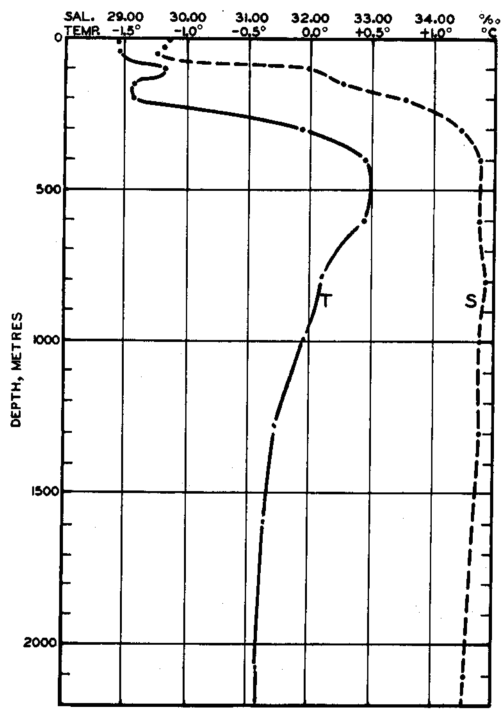

Fig. 7. Example of vertical temperature and salinity in Beaufort Sea in spring (*see* Fig. 1 for location of station).

surface on that side of the channel. In the Chukchi Sea the vertical temperature structure is more variable in summer. Just north of Bering Strait and off Cape Lisburne, shallow seasonal thermoclines and relatively weak salinity gradients are found. Near the boundary of the ice pack there is a pronounced maximum around 15 metres with very irregular temperature structures above and in the main thermocline, and the salinity is low due to meltwater. The high temperature maximum below the surface is attributed to warm water of higher salinity brought into the area through Bering Strait, which sinks on meeting the cold, but low-salinity, meltwater from the ice pack.

The vertical distribution of temperature and salinity in the Beaufort Sea in spring is shown in Fig. 7 (Worthington, 1953, p. 545). The temperature is near freezing to a depth of 200 metres. Below this depth a subsurface maximum occurs around 500 metres. This relatively warm layer is believed to be drawn into the region from the Atlantic Ocean, though some modification must take place as the salinity is lower than that of the North Atlantic.

The temperature and salinity curves of the Bering and Chukchi seas are typical of summer observations (Figs. 5 and 6). Speculations on the temperature structure for other seasons based on previous observations in the southern Bering and northern Chukchi seas are shown schematically in Figs. 8 and 9 by superimposing a heavy temperature–depth curve for each season on a block of ocean.

North of the Aleutian Islands the temperature during winter is virtually the same from the surface to depths greater than 120 metres (Fig. 8) (Pattullo *et al.*, 1950). Slightly higher temperatures around 150 metres are attributed to subsurface advection and are believed to be characteristic of the region. By spring the temperature–depth curve begins to show steps indicating successive heating and mixing of the water. By summer these steps become large and merge into the seasonal thermocline. Frequent winds in this region cause the surface layer to remain at the same temperature even though heat is being added to the water. In the fall the isothermal layer becomes deeper as a result of increased mixing and cooling.

In the northern Chukchi Sea (Fig. 9) the surface is ice-covered in winter. The cooled surface water develops vertical convection currents which produce isothermal surface layers. By spring the ice becomes thicker and the water remains in isothermal layers. Minor gradients are the result of subsurface advection. In summer the surface layer is heated; in addition, warm water is brought into the region from the south at a subsurface level, creating a

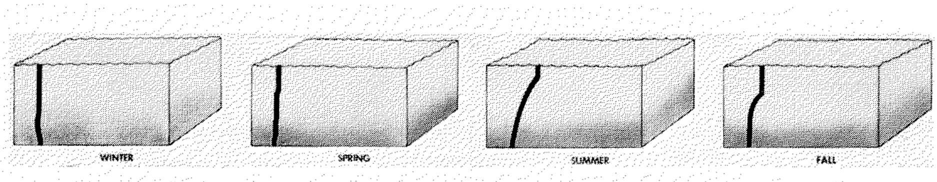

Fig. 8. Schematic seasonal changes in vertical temperature structure in southern Bering Sea. (Vertical scale about 0–150 m., horizontal temperature scale –1 to 30°C).

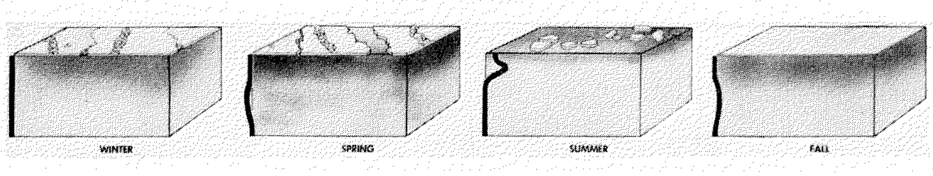

Fig. 9. Schematic seasonal changes in vertical temperature structure in northern Chukchi Sea. (Vertical scale about 0–150 m., horizontal temperature scale –1 to 30°C).

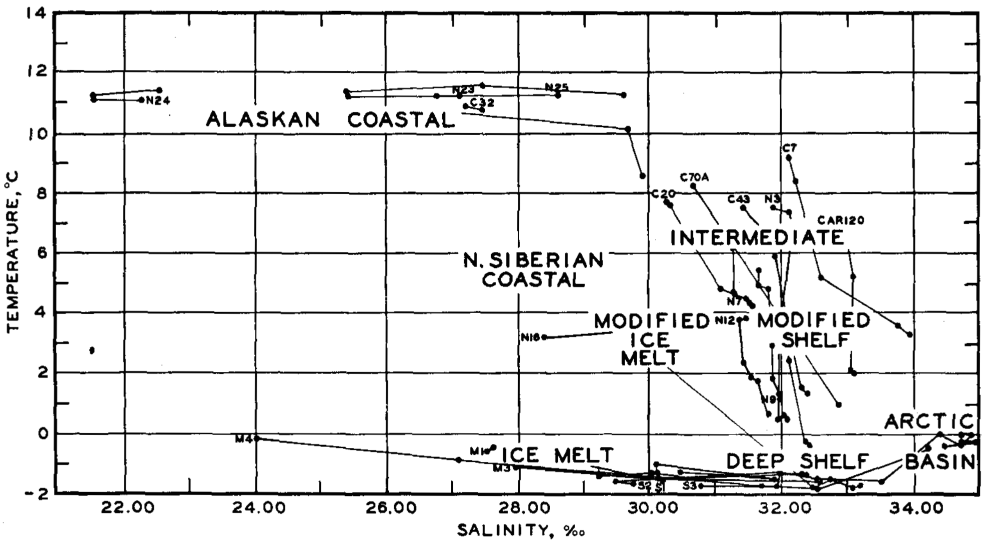

Fig. 10. Water masses of the seas adjacent to Alaska, based on observed temperature and salinity relation. Dots and fine connecting lines are observed T–S data.

subsurface temperature maximum. By fall the surface again freezes and the cooling and mixing processes create an isothermal layer over a slightly negative gradient.

Water masses

The study of temperature–salinity (T–S) relationship provides a convenient method for determining the characteristics, origin, and movements of water masses (Sverdrup *et al.*, 1942, pp. 739–45). The temperature and corresponding salinity at the surface and each subsurface observation level for various oceanographic stations in the seas to the west and north of Alaska (Fig. 1) are plotted in Fig. 10. The individual T–S values are shown by a dot and those for a complete (vertical series) station are connected by a fine line. The source of data are indicated: Nereus (N), Chelan (C), Maud (M), Skijump (S), and Carnegie (CAR). For these summer data a certain consistency in the T–S relationships of this shallow water Alaskan region was maintained. Because of this consistency it has been possible to establish eight water masses having a definite T–S value as shown in Fig. 10. The *Alaskan Coastal* water for example, is characterized by high temperatures (10–12°C) and low salinity (<30 o/oo). It is found along the western coast of Alaska as far north as Point Barrow and attributed largely to the river runoff of warm fresh water. The *Ice Melt* water is found in the region of arctic pack and has low salinity from the melting of relatively fresh (low salinity) sea ice, but the temperature still remains just above freezing. The *Deep Shelf* water in the Bering and Chukchi seas is probably the result of winter freezing at the surface creating low temperatures below the ice, combined with higher salinity. This water mass persists near the bottom in summer throughout most of the Bering and Chukchi seas with the exception of the Bering Strait region. Deep *Arctic Basin* water is relatively cold but of still higher salinity. As mentioned previously this water must come from the Atlantic Ocean. Another source of water in the Chukchi Sea is believed to be from the west, along the Siberian coast. This *North Siberian Coastal* water has a relatively low salinity due to fresh water from the large rivers in this region. Its temperatures run lower than that of *Alaskan Coastal* water coming from the Bering Sea. Where two or more water masses mix the modified water masses are termed *Modified Shelf*, *Intermediate*, and *Modified Ice Melt* water. *Modified Shelf* is merely the summer-heated winter *Deep Shelf* water; *Intermediate* results from mixing of *Modified Shelf* and *Alaskan Coastal* water; and *Modified Ice Melt* appears to be largely a surface mixture of *Ice Melt* and *Intermediate* water. By means of these established water masses it is usually possible to determine the origin and direction of flow from the continuity in the measured T–S relation.

Currents

The general flow of surface water in the area around Alaska during the summer has been studied. There is a general northerly flow from southeastern Bering Sea through Bering Strait (Fig. 11) (Barnes and Thompson, 1938, p. 162). The flow of the Alaskan coastal water tends to follow the contours of the coast, deflecting into Norton Sound, closely hugging the Alaskan side of Bering Strait, deflecting into Kotzebue Sound, continuing north around major promontories, and finally flowing north from Point Barrow. In this region the current is believed to combine with water from the east in the Beaufort Sea. The two types of water merge and after flowing north, appear

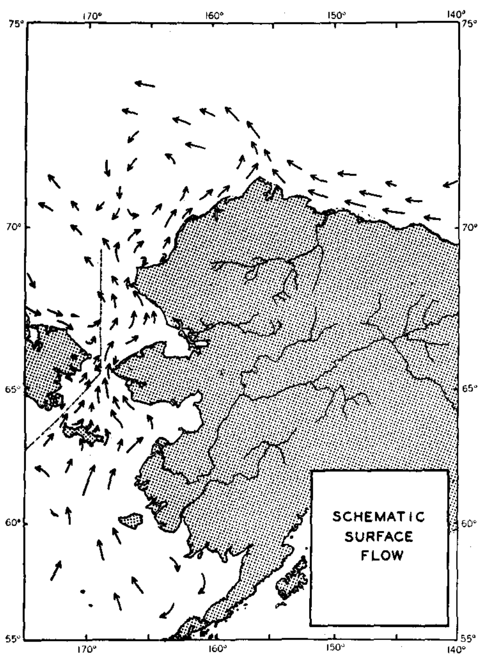

Fig. 11. Schematic surface currents around Alaska in summer.

to create an anti-clockwise circulation in the northwest. Currents along the northwestern side of the Bering Sea are weaker and more variable; occasionally they have been known to flow to the south. However, the predominant drift is to the north and enters the strait on the western side. Another current flows into the southern Chukchi Sea from the north coast of Siberia (Ratmanov, 1937, p. 111), and, after bending around in Kotzebue Sound, turns back to the northwest. Local winds tend to affect the circulation and consequently the flow shown in Fig. 11 must be considered as schematic.

Ice

The ice conditions in the Bering and Chukchi seas are not only dependent on the season but also show year-to-year variations. For example, the southern limit of the arctic pack in the Chukchi Sea was 72°N. in the late summers of 1947 and 1948, while in 1950 it was 73°N. If the wind is from the south, the pack is concentrated or blown to the north. If the wind is from the north or west, however, ice can extend to the coast of northern Alaska. In winter the Chukchi Sea and the Bering Sea freeze over up to the region of the continental slope. The thickness of the ice and the amount of hummocky-ice depend upon the severity of the winter weather and changes in wind direction and strength. In the Bering Sea the ice thickness varies from a few inches to a few feet. Off northern Alaska the water freezes to a depth of 5 to 8 feet, but hummocking will increase this depth several fold.

References

Barnes, C. A. and T. G. Thompson. 1938. 'Physical and chemical investigations in Bering Sea and portions of the north Pacific Ocean'. *Univ. Wash. Publ. in Oceanography,* Vol. 3, No. 2, pp. 35–79, and Appendix pp. 1–164.

Buffington, E. C., A. J. Carsola and R. S. Dietz. 1950. 'Oceanographic cruise to the Bering and Chukchi seas: summer 1949. Part 1. Sea floor studies'. Lab. Report NEL No. 204, 26 pp., December 1950. (U.S. Navy Electronics Lab. Report 204).

Emery, K. O. 1949. "Topography and sediments of the Arctic Basin". *J. Geol.* Vol. 57, No. 5, pp. 512–21.

Goodman, J. R., J. H. Lincoln, T. G. Thompson, and F. A. Zeusler. 1942. 'Physical and chemical investigations: Bering Sea, Bering Strait, Chukchi Sea during the summers of 1937 and 1938'. *Univ. Wash. Publ. in Oceanography,* Vol. 3, No. 4, pp. 105–69, and Appendix pp. 1–117.

LaFond, E. C. and D. W. Pritchard. 1952. "Physical oceanographic investigations in the eastern Bering and Chukchi seas during the summer of 1947". *J. Marine Research,* Vol. 11, No. 1, pp. 69–86.

Pattullo, June G., John D. Cochrane and Wayne V. Burt. 1950. 'Sea temperature in the Aleutian Island area'. SIO Report No. 24, April 1950. (Manuscript).

Ratmanov, G. E. 1937. 'Explorations of the seas of U.S.S.R.'. Hydrological Publ. No. 25, Leningrad, pp. 1–175.

Sverdrup, H. U. 1929. 'The waters on the North-Siberian shelf'. *The Norwegian North Polar Expedition with the "Maud" 1918–1925, Scientific Results,* Vol. 4, No. 2. Bergen: 131 pp. + 75 pp.

Sverdrup, H. U., M. W. Johnson and R. H. Fleming. 1942. 'The Oceans'. New York: Prentice-Hall, 1,087 pp.

Worthington, L. V. 1953. "Oceanographic results of Project Skijump I and Skijump II in the Polar Sea, 1951–1952'. *Trans. Amer. Geophys. Un.* Vol. 34, No. 4, pp. 543–51.