OCEANOGRAPHIC STRUCTURE IN THE BERING SEA

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Contents

I. Introduction

1. *Preface*

The Bering Sea had been considered as a mere marginal sea of the Pacific Ocean till recent years; however, the importance of the Bering Sea is noticed on fisheries and oceanography for it has a high concentration of nutrients and high biological productivity. A vast amount of marine life is produced in the sea and a part of the production is used for fisheries, and that provides an important source of the albuminous food for humankind. The Bering Sea is moreover regarded as the source of the Oyashio Current which is cold but rich in oxygen and nutrients, and also has high biological productivity.

The purpose of this paper is to explain the mechanism of formation for various structural types of the shelf waters or the process of transformation from the

Pacific waters to the new Bering Sea waters, showing the oceanographic structures of the sea, and to make a summary of the characteristics and a role of the Bering Sea in the Subarctic Circulation, those having influence on marine life as a physical environment.

2. *Subarctic Region*

The water masses and current system in the Subarctic Region of the northern North Pacific Ocean were summarized by Dodimead *et al.*[1] They classified the region into five domains for the upper zone and into three for the lower one from the regional characteristics of distribution of properties. The Bering Sea Basin Waters belong to the Western Subarctic Domain except for the narrow area along the Aleutian Islands, and the waters of the shallow area around the Bering Sea Basin belong to the Coastal Domain.

The characteristics of the Subarctic Region are generally explained with the stratified vertical structures of temperature and salinity. The vertical salinity structure is classified into three parts which are the upper zone, the halocline and the lower zone.[2] In winter, the temperature of the upper zone falls down below that at the top of the lower zone, while in summer, temperatures near the surface rise up rapidly due to the heating of the surface, therefore a distinct dichothermal stratum is formed in the Western Subarctic Domain, as shown in Fig. 1.[3] On the other hand, winter cooling is not so much to be found in the eastern Subarctic Pacific, and the temperature of the upper zone is maintained higher than that of the lower zone, therefore no dichothermal stratum is formed in this region, as shown in Fig. 2.[4]

The current system in the Subarctic Region is shown as a close circulation. The Alaskan Stream which is an only westward flow in the Subarctic Pacific Region, comes from the Gulf of Alaska along the Aleutian Islands as an extension of the Alaska Current, transporting dilute surface water and relatively warm water at depths to the Western Subarctic Region.[5] Most of the Alaskan Stream Waters come into the Bering Sea through the Amchitka Pass and the straits west of Attu Island, while the East Kamchatka Current coming from the Bering Sea flows southwestward along the Kamchatka Peninsula, having the typical characteristics of the Western Subarctic Waters. Relative transport in the Subarctic Region is schematically shown in Fig. 3. The Bering Sea acts on the Subarctic Circulation as a terminal pool of the Alaskan Stream and as a source of the East Kamchatka Current.[6]

The waters on the continental shelf in most parts of the eastern Bering Sea and along the Siberian Coast have characteristics different from those of the deep Basin Waters. The discontinuous zone of the properties in a water column is formed between them along the continental slope. The shelf waters are under

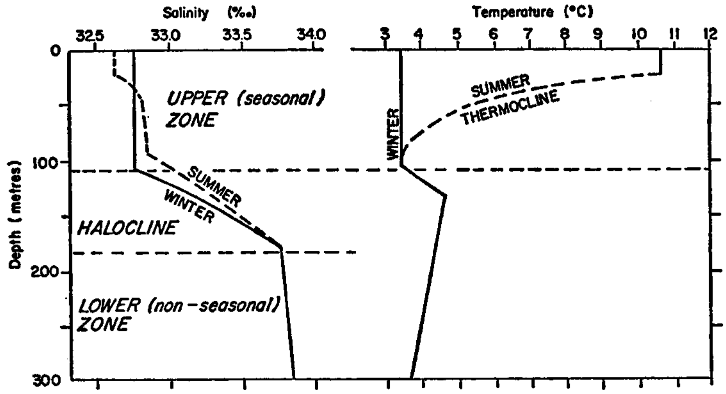


Fig. 1. Schematic structures in the Western Subarctic Pacific Region (Dodimead, 1967).

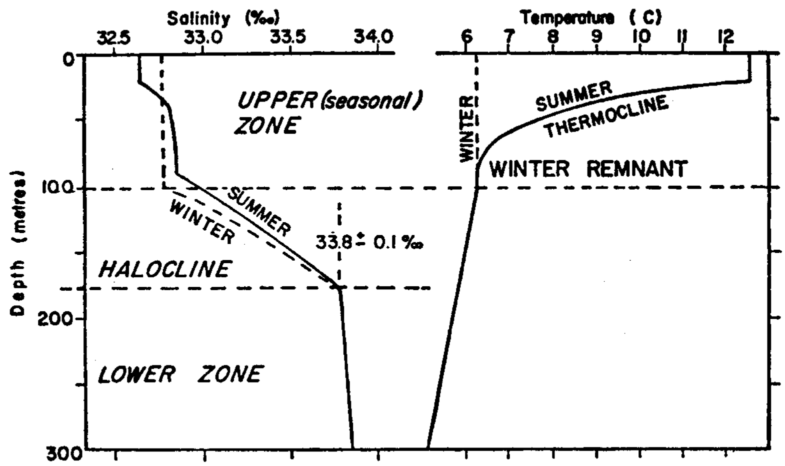


Fig. 2. Schematic structures in the eastern Subarctic Pacific Region (Dodimead & Pickard, 1967).

the influence of fresh water discharge from the land and drift ice, or of the strong tidal current, and largely receive the winter cooling into the shallowness of the bottom configuration. Therefore various types of oceanographic structures are formed on the shelf corresponding regionally in some degree to these influences.[7]

3. *Sources of data*

Most of the oceanographic data in summer were obtained on board the Oshoro Maru and the Hokusei Maru of the Faculty of Fisheries, Hokkaido University.[8],[9],[10],[11],[12],[13],[14] Other data, especially the winter measurements, were obtained by American research ships belonging to Scrips Institution of Oceanography, Fish and Wildlife Service and U.S. Coast Guard, those data are obtained through

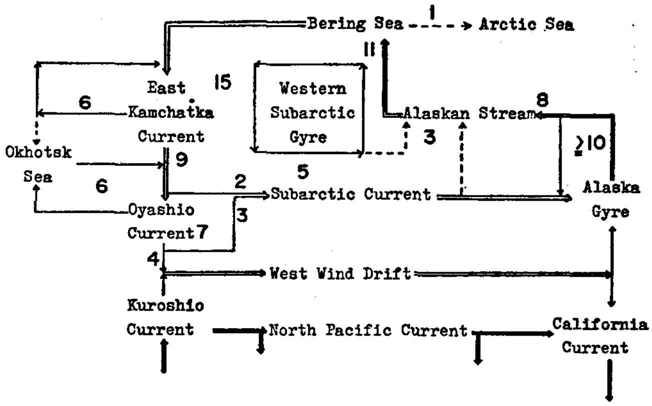


Fig. 3. Schematic diagram of relative transport in the northern North Pacific Ocean in winter. Numerals indicate volume transport ($\times 10^6$ m^3/sec) in reference to the 1,000-m. level.

Table 1. *Sources of data.*

On the continental shelf

Year	Month	Ship	Institution	WDC Catalogue Number
1962	9	Northwind	U.S. Coast Guard	139.16 B-1
1963	6	Oshoro Maru	Hokkaido Univ.	124.2 B-9
1964	7-8	——	——	124.2 B-12
1965	7	——	——	124.2 B-16
1966	7	——	——	124.2 B-21

In the Bering Sea Basin

Year	Month	Ship	Institution	WDC Catalogue Number
1959	6-7	Oshoro Maru	Hokkaido Univ.	124.2 B-3
1961	6-7	——	——	124.2 B-6
	6	Marine View	Fish & Wildlife Service	139.10 W-1
	6	Paragon	——	139.10 V-2
	7	Hokusei Maru	Hokkaido Univ.	124.2 A-7
1962	6-7	Oshoro Maru	——	124.2 B-7
	7	Northwind	U.S. Coast Guard	139.16 B-1
1963	6-7	Oshoro Maru	Hokkaido Univ.	124.2 B-9
1964	6-8	——	——	124.2 B-12
1965	6-7	——	——	124.2 B-16
1966	2-3	G.B. Kelez	Fish & Wildlife Service	139.10 X-1
	1-2	Argo	Scripps Inst. of Oceanogrpahy	139.8 I-10

Japanese Oceanographic Data Center from WDC.[15),16)] Sources of data used for this study are shown in Table 1.

4. *Bottom configuration*

The Bering Sea is isolated from the Pacific Ocean by the Alaska Peninsula – the Aleutian to the Komandorski Islands chain. A cross-sectional area and still depths of major passes or straits through the Aleutian — Komandorski Islands chain were

Table 2. *Cross-sectional areas and sill depths of major passes or straits through the Aleutian Islands (Favorite, 1967).*

Location	Pass or Strait	Area ($m^2 \times 10^6$)	Max. sill depth (m)
163°W–165°W			
Alaska Peninsula to Krenitzin Islands	1 False	0.1	35
	2 Unimak	0.9	60
	3 Ugamak	0.2	45
165°W–170°W			
Tigalda Island to Herbert Island	4 Derbin	0.1	50
	5 Avatanak	0.4	80
	6 Akun	0.1	10
	7 Akutan	0.2	70
	8 Unalga	0.1	45
	9 Umnak	0.2	50
	10 Samalga	3.9	200
	11 Chuginadak	1.0	210
170°W–175°W			
Hebert Island to Atka Island	12 (Herbert)	4.8	275
	13 (Yunaska)	6.6	457
	14 Chagulak	0.3	65
	15 Amukta	19.3	430
	16 Seguam	2.1	165
	17 Amlia	0.1	25
175°W–180°			
Atka Island to Amchitka Island	18 Atka	0.2	35
	19 (Oglodak)	0.1	5
	20 Fenimore	0.2	35
	21 Tagalak	0.1	35
	22 Chugul	0.6	85
	23 Umak	0.1	20
	24 Little Tanaga	0.1	30
	25 Kagalaska	0.1	25
	26 Adak	0.5	60
	27 Kanaga	0.1	30
	28 Tanaga	3.6	235
	29 (Ogliuga)	0.1	10
	30 (Kavalga)	0.3	55
	31 Amchitka	45.7	1155
180°–173°E			
Amchitka Island to Attu Island	32 Oglala	0.8	25
	33 (Rat)	0.6	15
	34 (Kiska)	6.8	110
	35 Buldir	28.0	640
	36 Semichi	1.7	105
173°E–163°E			
Attu Island to Kamchatka Peninsula	37 (Near)	239	2000
	38 Komandorski	3.5	105
	39 Kamchatka	335.3	4420

given by Favorite,[5] as shown in Table 2. Sill depths of most passes are shallower than 200 meters, and sill depths exceeding 1,000 meters are confined within three passes which are the Amchitka, the Near and the Kamchatka. Somewhat deeper sill depths are found in the Amukta, the Yunaska and the Buldir; however, these

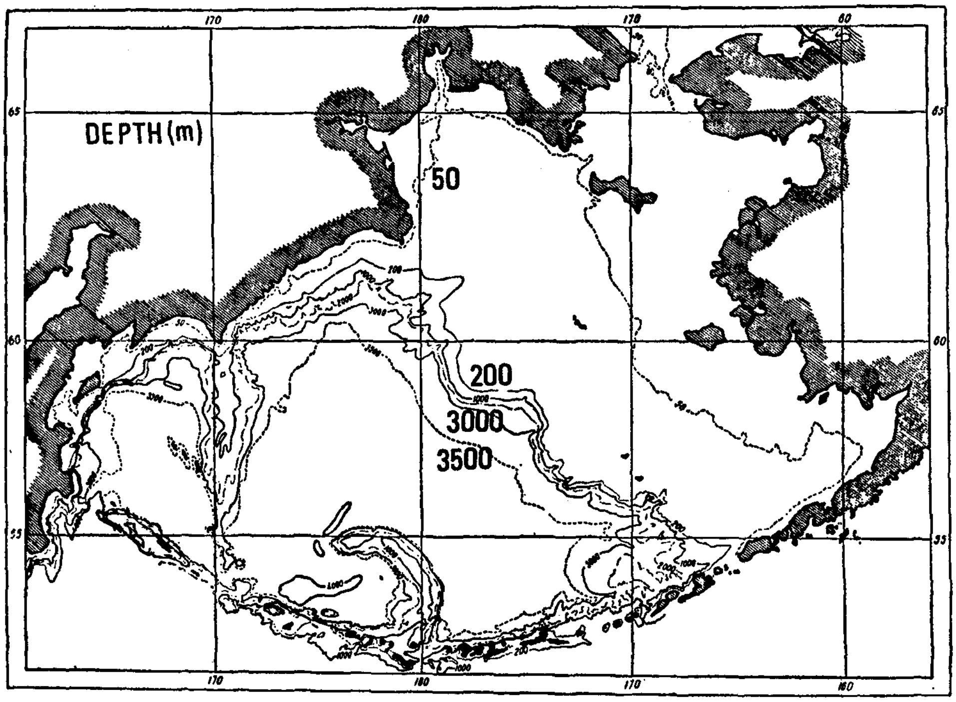


Fig. 4. Sea-bed relief of Bering Sea (Boichenko, from Zenkevitch, 1963).

depths are within the order of 400 to 600 meters.

A bathymetric chart of this region is shown in Fig. 4.[17] The northeastern part of the Bering Sea bounded between Cape Navarin and Unimak Island is extensively covered by the continental shelf, while the deep region is subdivided into two basins by the ridge continuing from Cape Olyutorskii to the south along the 170°E meridian. The Bowers Bank Arc with a crest depth less than 200 meters is continuous at depths shallower than 1,000 meters from Kiska Island to the north, thereafter to the northwest. The Bering Sea is connected with the Arctic Sea through the Bering Straits; however, the sill depth of the Straits and depths of the north of St. Lawrence Island are shallow and around 50 meters. The continental shelf along the Siberian Coast is relatively narrow.

II. Waters Coming into the Bering Sea from the Pacific Ocean

Barnes & Thompson[18] first reported with oceanographic observations that the Pacific waters came into the Bering Sea through the passes near Tanaga Island. These Pacific waters are now known as the Alaskan Stream having a volume transport of about 8×10^6 m^3/sec in reference to the 1,000-meter level. One half of this westward transport comes into the Bering Sea through the Amchitka Pass, and this northward flow was reported by Arsen'ev[19] and also estimated by

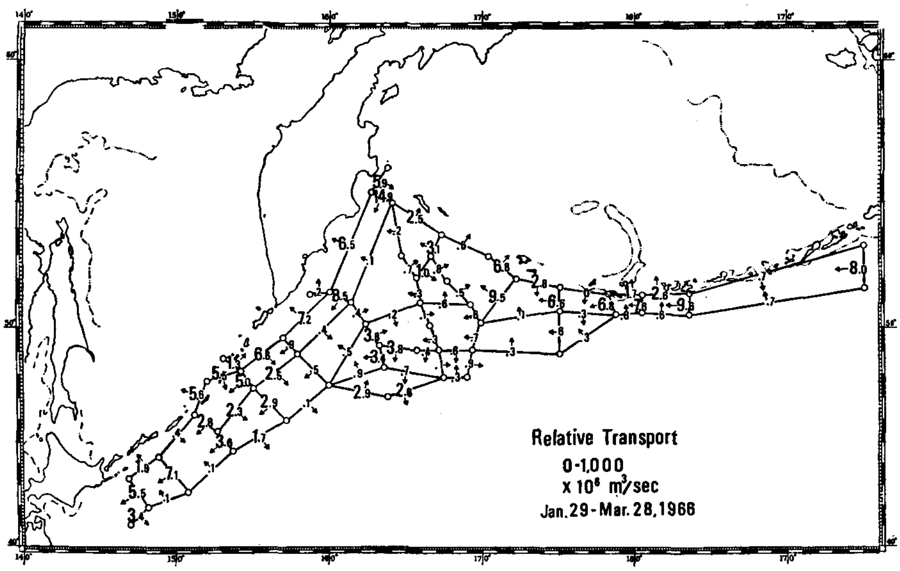


Fig. 5. Relative transport ($\times 10^6$ m^3/sec) in the northwestern Subarctic Region.

Favorite[20] to be of the order of 5×10^6 m^3/sec of transport. The remainder reaches as far westward as the 170°E long. where it also flows into the Bering Sea through the straits west of Attu Island. The waters of the Subarctic Current and the Western Subarctic Gyre join this northward flow from the south between the 165°W long. and the 170°E. Consequently, the amount of net transport into the Bering Sea from the Pacific Ocean is estimated to be of the order of 11×10^6 cm^3/sec. Three quarters of transport coming into the Bering Sea originate from the Alaskan Stream, and a quarter is coming from far south. Relative transport in this region is shown in Fig. 5.[6]

The Western Subarctic Waters are characterized by a conspicuous stratification with low temperature and relatively high salinity of the upper layer in winter, or a distinct dichothermal layer around the 100-meter depth in summer, and relatively low temperature in the mesothermal layer. Vertical structures of the Western Subarctic Gyre and the Subarctic Current show these characteristics mentioned above as shown in Fig. 6.

On the other hand, the Alaskan Stream has a rather complicated structure. Vertical distribution of its temperature and salinity are quite different across the stream. Along the southern boundary of the stream, between the 165°W long. and the 170°E, a very sharp halocline is found at all stations, as shown in Fig. 7. The simple homogeneous upper layer in winter and the clearly stratified salinity structure indicate a typical characteristic in the Subarctic Region. The salinity of the upper layer increases downstream from the east to the west; however, the

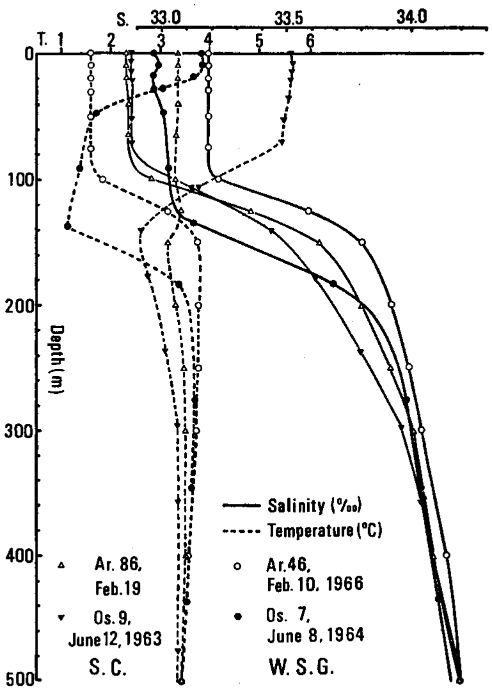


Fig. 6

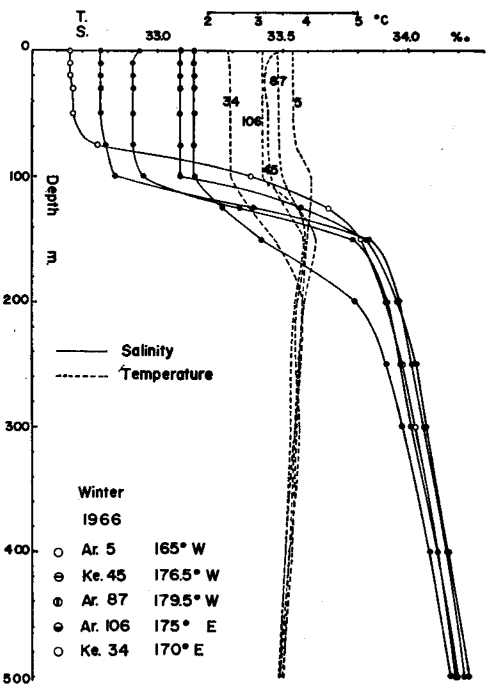


Fig. 7

Fig. 6. Typical vertical distribution of temperature and salinity in the Western Subarctic Gyre and in the Subarctic Current.

Fig. 7. Vertical distribution of temperature and salinity along the southern boundary of the Alaskan Stream in winter.

salinity at the bottom of the halocline, namely at the top of the lower layer indicates a same value of 33.8‰. The temperature structure is also simple, the temperature of the upper layer in winter is slightly lower than that at the bottom of the halocline, and temperature differences between them increase toward the west although they are small. Whereas in the lower layer, vertical distributions of temperature at each station are identical.

Along the center of the stream, the stratified structure is disturbed, as shown in Fig. 8. The diluted surface water in the upper layer at the eastern observations of Ar. 3 and Ke. 42 disappears at Ar. 88.

Along the northern boundary of the stream near the Aleutian Islands, no stratified structure is observed although the diluted surface waters remain at Ar. 2 and Ke. 39, as shown in Fig. 9. At the stations of Ar. 88, Ke. 39 and Ar. 89, the vertical profiles of salinity show a homogeneous gradient, and no appreciable thermocline is observed in the temperature profiles. The western observations of Ke. 20 and Ke. 25 indicate a reformation of the homogeneous upper layer by cool-

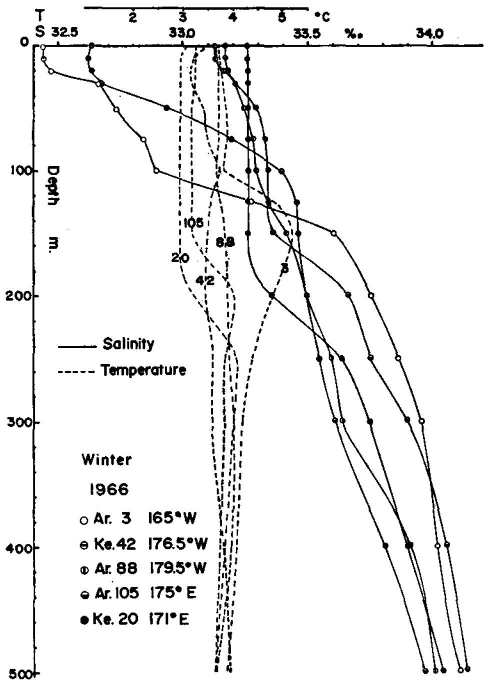


Fig. 8. Vertical distribution of temperature and salinity along the center of the Alaskan Stream in winter.

ing from the surface, though the halocline is very loose.

The temperature of the surface layer is, in general higher and higher upstream, while salinity is decreasing. Entering the Bering Sea, the waters of the Alaskan Stream lose their stratified structure, but still maintain the high temperature of the mesothermal layer, a characteristic in the eastern Subarctic Region.

The location of the stations used in this chapter shown in Fig. 12.

III. Current Pattern in the Bering Sea

The general cyclonic circulation in the Bering Sea Basin is recognized by many authors, e.g., Koto & Fujii[21], Dodomead et al.,[1] Favorite,[22] Arsen'ev,[19] but in detail, there are considerable differences between these current patterns. In this study, a dynamic topography of a 100-decibar surface ovre 1,000 decibars is used for representing the current pattern of the upper layer, since it may be considered that an upper layer is flowing uniformly in the region. Although the data are obtained for different years, the values of dynamic height are generally in a good agreement, as shown in Fig. 10, suggesting that the current pattern is stable from year to year.

The general cyclonic circulation is indicated by the isohypse of 0.90 dyn. m.

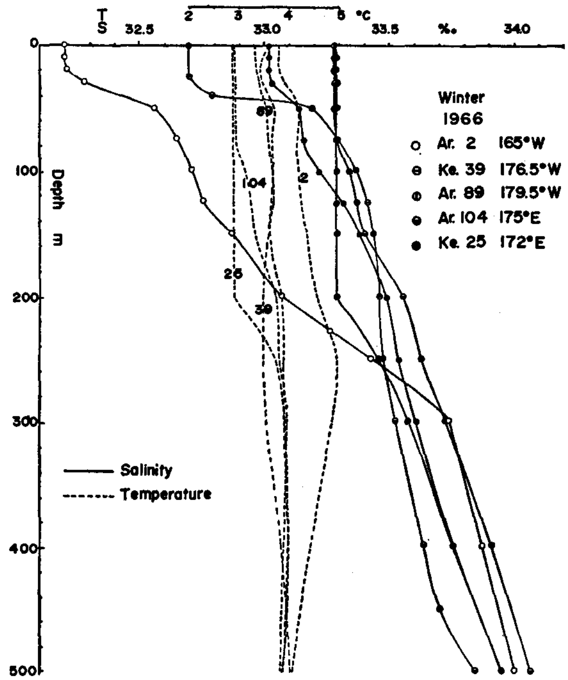


Fig. 9. Vertical distribution of temperature and salinity along the northern boundary of the Alaskan Stream in winter.

continuing from the Pacific through the west of Attu Island. In the western basin, a small cyclonic circulation is indicated by the isohypse of 0.85 dyn.m., which corresponds to the southern boundary of the Alaskan Stream. The isohypse of 0.95 dyn. m. along the continental slope in the eastern basin indicates continuity from the Alaskan Stream through the Amchitka Pass. Another one along the Kamchatka Peninsula suggests the source of the cold upper waters of the East Kamchatka Current.

Small clockwise eddies are found near Attu Island, Adak Island and two others near the continental shelf. These eddies are considered to be of a permanent nature, because the high values of dynamic height are constantly obtained in these regions, irrespective of the year of observation, although the position of their centers and their sizes may vary from year to year.

The current speed in the Bering Sea Basin is, in general, a few cm/sec, except along the continental slope and the coast of Kamchatka and also in of some the eddies, where speeds of 10 to 15 cm/sec may be attained, according to dynamic calculations. Thus the Alaskan Stream Waters, having once entered the Bering Sea, remain there more than one year before flowing out into the Pacific Ocean.

On the continental shelf in the eastern Bering Sea, a strong tidal current is

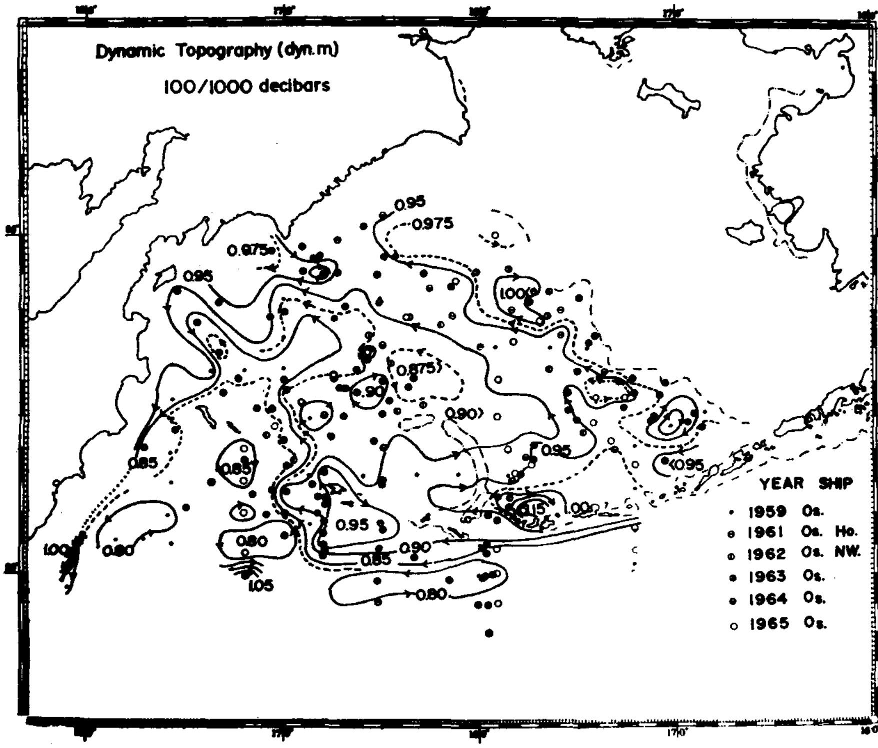


Fig. 10. Dynamic topography, 100/1,000 decibars.

dominant. Its speed was obtained by the current meter measurement or the drifting rod experiment to be 1.5 knot off Cape Chaplina, about 1 knot near the coast of Alaska[18] and 2 or 3 knots in the Bristol Bay[1]. In the Bering Straits, 80 or 95 cm/sec and 20 or 70 cm/sec of northward currents were observed at the east and west sides of the straits, respectively.[23]

In general, the steady current is, however, very weak on the shelf, and its speed may be estimated a few cm/sec. The dynamic topography of the surface over 50 decibars is shown in Fig. 11. In these shallow regions, the dynamic calculation does not represent the current speed; however, it may be considered that the distribution of isohypses suggests a flow pattern. The isohypses are generally parallel to the isobaths and towards the northwest except for the Gulf of Anaduir and north of St. Lawrence Island. Almost all the waters on the shelf flow toward northwest from the Unimak Pass and the Bristol Bay, and turn their direction toward the northeast off the Gulf of Anaduir and then come into the Arctic Sea through the Bering Straits. This northward volume transport was estimated about 1.4×10^{6} m^{3}/sec in summer[23]. The southwestward flow from the Gulf of Anaduir through the south of Cape Navarin, which was supposed by various

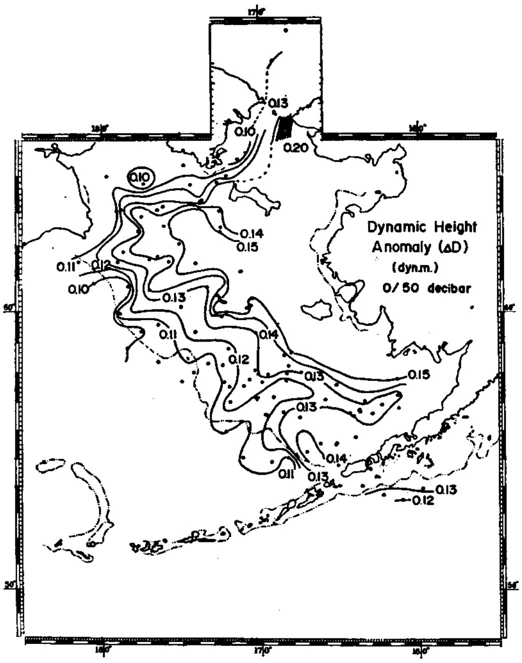


Fig. 11. Dynamic topography, 0/50 decibars.

authors as providing the extreme cold waters to the upper layer of the coastal waters along the coast of Siberia in the western Bering Sea, is not indicated in this topography, and neither in Fig. 10.

IV. Waters in the Bering Sea Basin

1. *Vertical structure of the basin waters*

One of the characteristics of the waters in the Bering Sea Basin is, in general, represented in a thermal vertical structure which has distinct dichothermal waters at the bottom of the upper layer, namely on top of the halocline, in summer. Near the Aleutian Islands and the continental slope in the southeastern Bering Sea, however, the Alaskan Stream waters are directly coming into the basin; accordingly, a dichothermal stratum is not clear in these regions. The boundary between the Alaskan Streatm waters and the Bering Sea Basin waters or and the Subarctic Current waters is evidently indicated in the thermal transection by a horizontal discontinuity of temperature. The transection across the Aleutian Islands and the Alaskan Stream (S. 1) is shown in Fig. 13, and the location of the section is shown in Fig. 12. The dense vertical isotherms at the depth corresponding to the dichothermal waters, near St. 14–2 and St. 10 respectively indicate the boundaries between them.[24] The domelike isohalines at St. 10, caused by

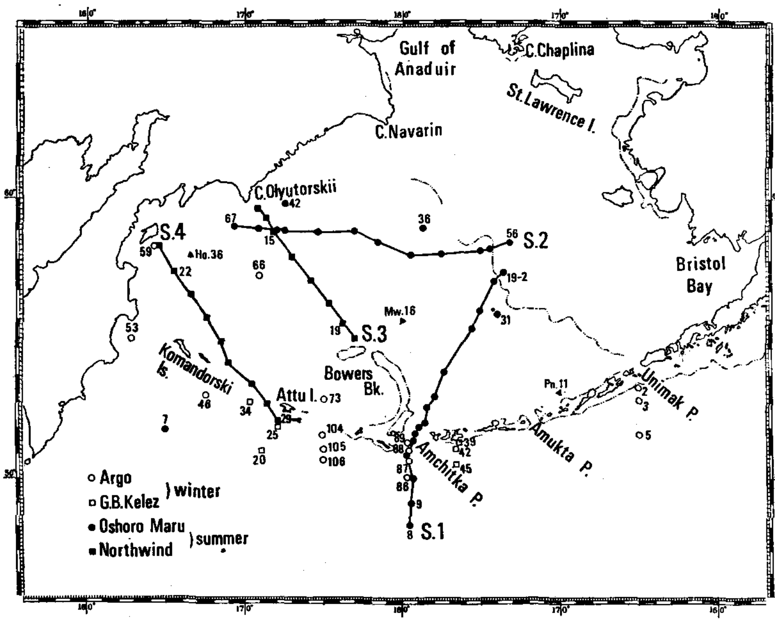


Fig. 12. Location of the stations and sections used in this chapter.

upwelling, also indicate the boundary between the Alaskan Stream and the Subarctic Current.[5,25]

The dichothermal waters lie above the halocline in the Bering Sea, while those of the Subarctic Current lie within the halocline, nevertheless both dichothermal waters are found at the same depth of about 150 meters, indicating a difference in the process of the formation of dichothermal waters.[21] A gradient of the halocline is relatively loose in the Bering Sea, and the isohalines deepen near the Aleutian Islands and the continental slope. Relatively warm waters more than 4°C at St. 20 indicate the intrusion of the Alaskan Stream waters, along the continental slope through the near passes, into the upper layer of the Basin waters. Isotherms of 3.8°C also indicate the continuity of the mesothermal waters from the Alaskan Stream through the Amchitka Pass.

A similar profile is found in the latitudinal transection of the northern part of the Basin (S. 2), as shown in Fig. 14. Though the temperatures in the dichothermal layer are decreasing toward the west, the warm mesothermal waters are successively found at the bottom of the halocline which is relatively loose even in the western part. The isohalines under the dichothermal layer also deepen toward both sides of the section. The thickness of the upper layer becomes larger than the former section, and reaches about a 200-meter depth. Diluted waters from the coast and the shelf spread over the surface layer of both sides of the section.

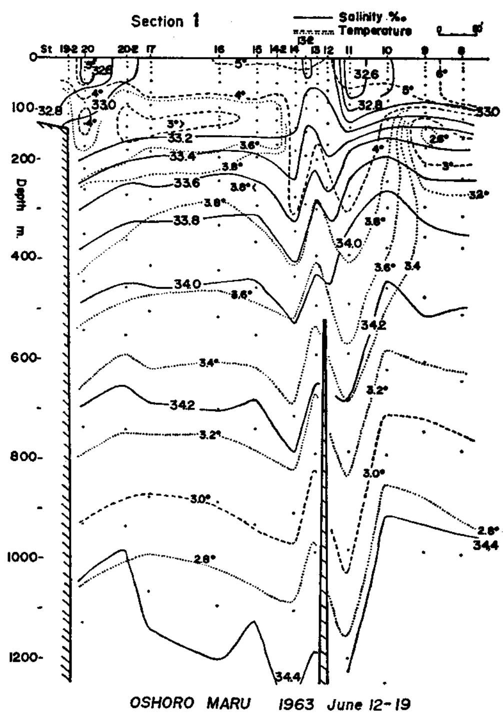


Fig. 13

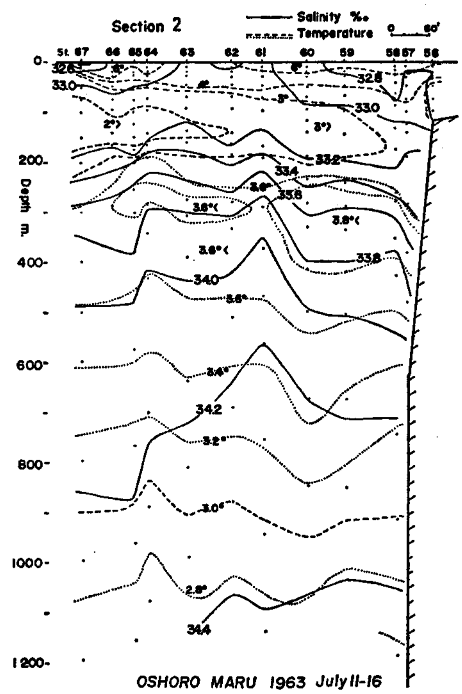


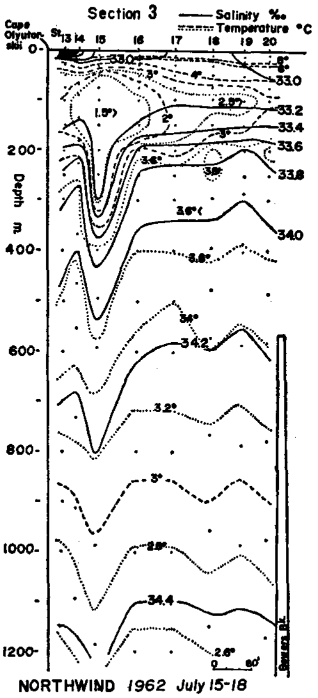
Fig. 14

Fig. 13. Vertical sections of salinity and temperature across the Alaskan Stream and the southeastern part of the Bering Sea Basin. Locations of sections are shown in Fig. 12.

Fig. 14. Vertical sections of salinity and temperature across the northern part of the basin.

The transection between Cape Olyutorskii and the Bowers Bank (S. 3) is shown in Fig. 15. In the western part of the basin, these profiles show a little change, a gradient of the halocline steepens and the thickness of the upper layer becomes shallower than the former two sections except for St. 15. The temperatures in the dichothermal layer decrease toward the northwest and are colder than those of the former two sections. The temperature of the mesothermal waters also decreases below 3.8°C in the northwestern part. An unusually thick upper layer at St. 15 may be caused by sinking with a strong anticyclonic eddy southeast of Cape Olyutorskii, as indicated in Fig. 10.

The southwesternmost transection of the Basin between Karaginskii Island and Attu Island (S. 4) is shown in Fig. 16. The halocline and the dichothermal stratum are very distinct and shallow except at the east of St. 28. The temperatures in the dichothermal layer are, as a whole, the coldest in these sections, their values at St. 21 appear below 1°C, and those in the mesothermal layer moreover appear



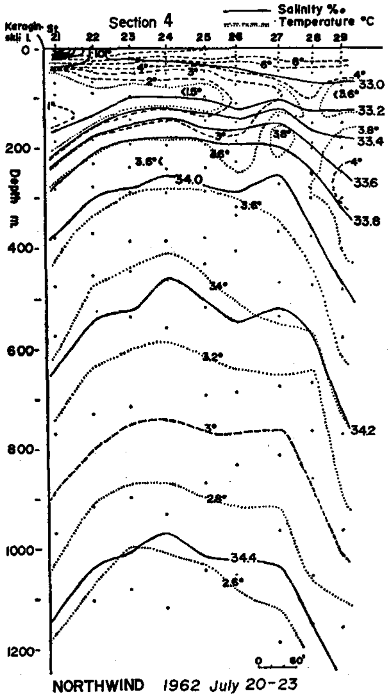


Fig. 15 Fig. 16

Fig. 15. Vertical sections of salinity and temperature between Cape Olyutorskii and Bowers Bank.

Fig. 16. Vertical sections of salinity and temperature between Karaginskii Island and the south of Attu Island.

below 3.7°C. It indicates at the western terminus of the Alaskan Stream that there are a loose halocline, a weak dichothermal stratum and warmer mesothermal waters over 4°C at St. 29. The domelike isohalines and isotherms under the upper layer suggest that there is a cyclonic circulation, causing the lower waters to upwell, in the western basin.

The thickness of the upper layer or of above the 33.2‰ surface corresponding to a salinity at the bottom of the upper layer is larger in the circumferential regions than in the central region of the basin, as shown in Fig. 17. The difference in thickness between them reaches more than 50 meters, the shallower one is below 125 meters, while the deeper one is over 175 meters.

The minimum temperatures in the dichothermal layer are decreasing for more than 3°C from the Alaskan Stream in the Pacific through near the Aleutian Islands and the continental slope to less than 2°C from the coast of Siberia and to less than 1°C from the East Kamchatka Current, corresponding with the flow pattern. Such a geographical distribution of the minimum temperature suggests a degree

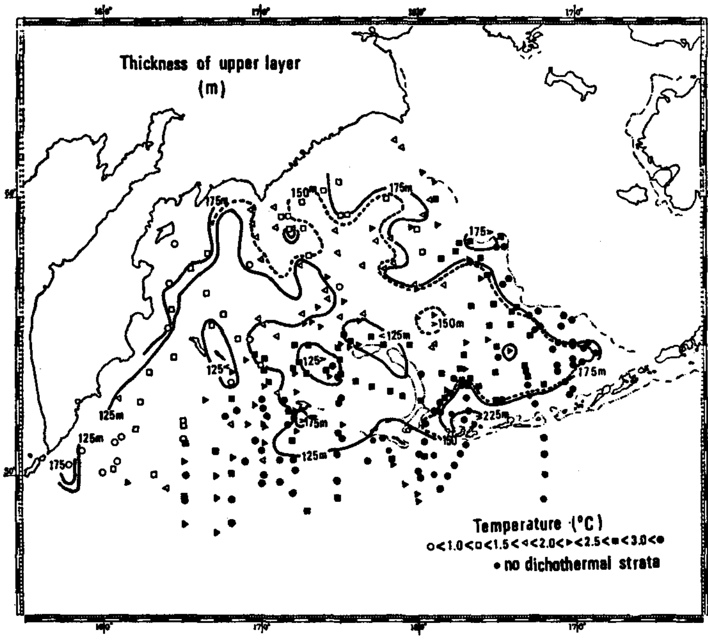


Fig. 17. Thickness of the upper layer, and temperature at the bottom of the upper layer or on the surface of salinity of 33.2‰.

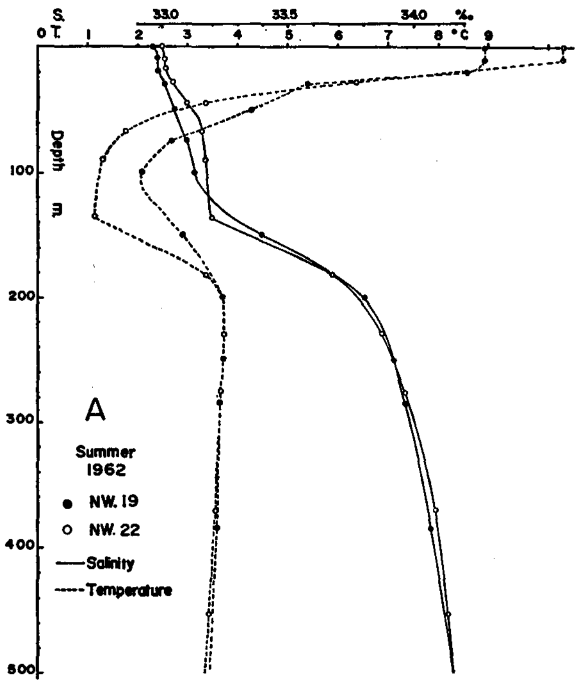


Fig. 18. Salinity and temperature curves of Type A in summer.

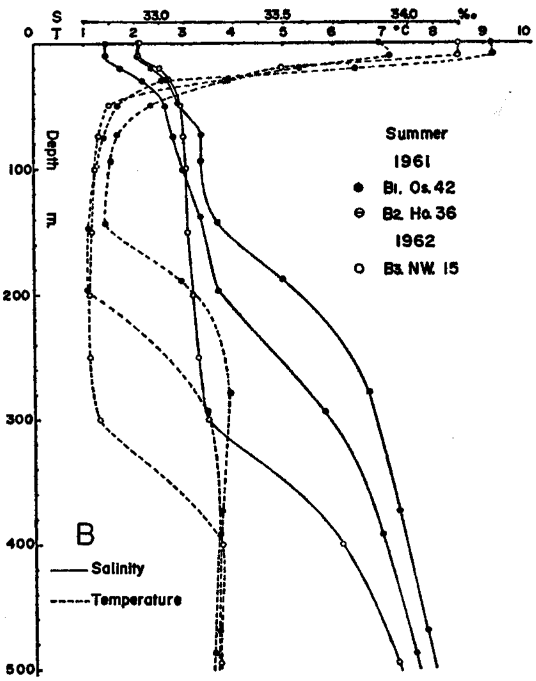


Fig. 19. Salinity and temperature curves of Type B in summer.

of winter cooling and also a path of the warm waters from the Pacific.

2. *Types of vertical distribution of salinity and temperature*

In the Bering Sea Basin, the salinity structure varies widely from a significant stratification to a homogeneous gradient in the upper 500-meter layer. It is possible to divide it into five different types of vertical distribution, as shown in Fig. 18, 19, 20 and 21. In winter, the upper layer becomes homogeneous and the characteristics are simplified because of the strong vertical mixing due to cooling and atmospheric disturbances. Winter examples are also shown in Fig. 22.

The geographical distribution of these types of vertical distribution and the depth of the isohaline surface of 33.8‰ which represents the bottom of the halocline, are shown in Fig. 23. The Distribution of types corresponds with the current pattern in Fig. 10 and with the distribution of dichothermal temperatures in Fig. 17. Type A, which has a distinct halocline and cold dichothermal waters in the shallow upper layer, is found in the western basin where a cyclonic circulation is indicated. Type D, which has a homogeneous salinity gradient and a relatively weak dichothermal stratum, is found along both sides of the Aleutian Islands and the margin of the continental shelf, indicating continuity and influence from the Alaskan Stream Waters. Type C is found in the central part of the

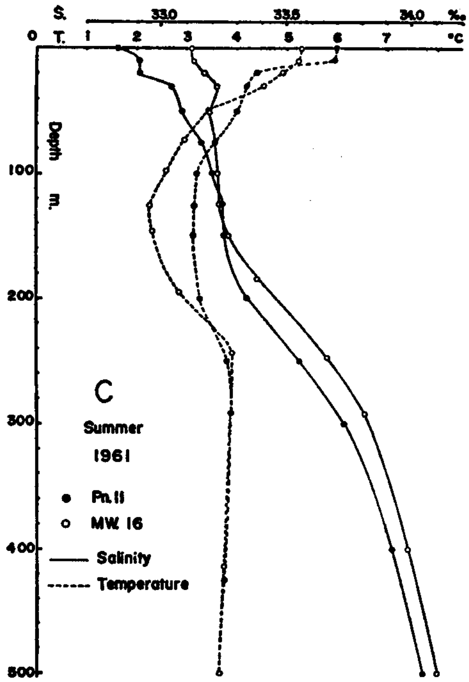


Fig. 20

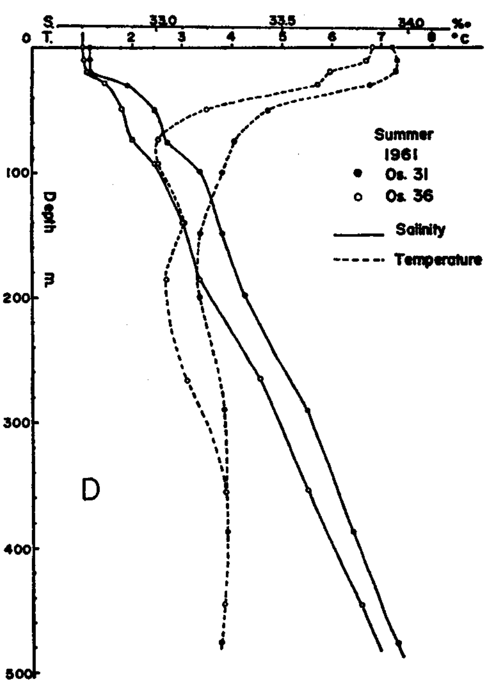


Fig. 21

Fig. 20. Salinity and temperature curves of Type C in summer.
Fig. 21. Salinity and temperature curves of Type D in summer.

eastern basin, and Type B is spreading over the Siberian Coast continuing from Types D and C. Type E is restrictedly found in a clockwise eddy near an island or a coast where strong vertical mixing or sinking occur.

3. *Process of formation of various Types*

Correspondence between the geographical distribution of Types and the current pattern or the others indicates a process of transformation from the northeastern Pacific waters to the Western Subarctic Waters, as schematically illustrated in Fig. 24.[26] Flowing westward along the Aleutian Ridge like the Alaskan Stream, or entering the Bering Sea through shallow and narrow passes between islands, a strong vertical and horizontal turbulence is generated by the topographical effects of the complicated bottom configuration of the island chain. Such strong mixing never occurs in mid-oceans. The typical structure of the Subarctic Waters, the marked salinity stratification, are thus destroyed and homogeneous salinity gradient is formed. Type D on both sides of the Aleutian Islads and near the continental shelf is formed from the Alaskan Stream Waters by strong mixing while flowing along the Aleutian Ridge and the continental slope. That vertical mixing may

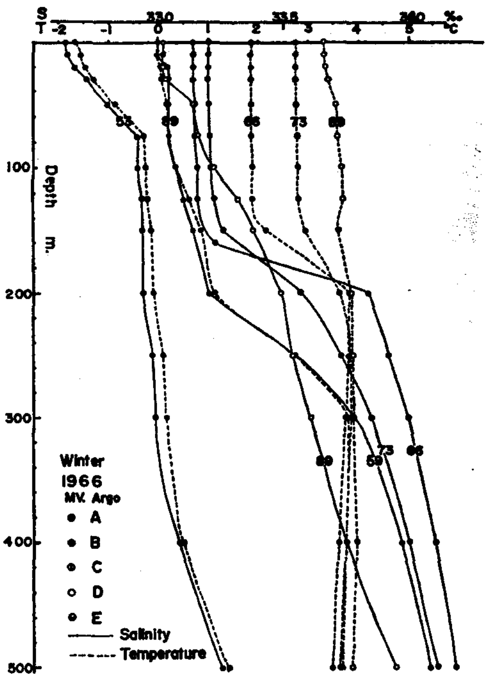


Fig. 22. Salinity and temperature curves of the five Types in winter.

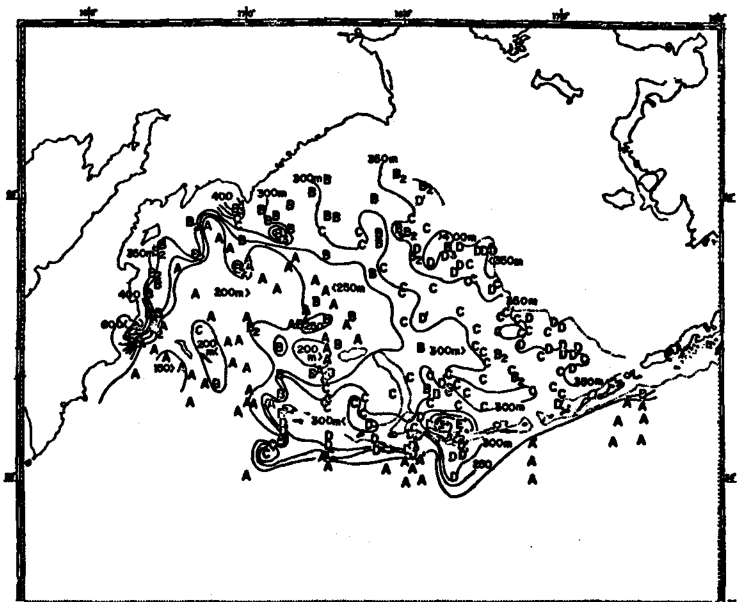


Fig. 23. Distribution of Types and the depth of salinity of 33.8‰ surface indicating the top of the lower layer.

take place across a stable pycnocline, the increase of potential energy is supplied mainly by the dissipation of tidal energy.[27]

Type C is found in an innermore region than Type D, apart from the Aleutian Ridge or the continental shelf, and it always has a dichothermal layer above the halocline having a relatively small gradient. For Type C, the mechanism mentioned above could not be applicable. During winter, Type D is cooled from the surface and an upper layer of uniform salinity and temperature is formed by thermal convection, this process is indicated by winter observation of Ke. 25, as shown in Fig. 9. In addition, the upwelling of more saline waters of the lower layer, associated with anticlockwise circulation, increases the salinity gradient underneath the upper layer. During summer, the temperature near the surface increases, but the warming does not reach the bottom of the upper layer where the cold waters remain as a dichothermal layer.

Type B is distinguished from Type C by the low salinity of the surface layer, the colder dichothermal waters and the larger salinity gradient of the halocline although the salinity at the bottom of the halocline is the same for both Types B and C. These characteristics and the distributions of both types suggest that Type B is formed by a mechanism similar to that of Type C, but with the intrusion of less saline shelf waters over the surface layer and by more intense cooling reaching more deeply than Type C. In regions of strong clockwise eddies and to the right of strong currents flowing along the coast or the continental shelf, sinking occurs in the upper layer, thus modifying Type B until it has a thick upper layer. The Type B waters modified are denoted by a suffix 2 or 3, depending on the thickness of the upper layer (Fig. 19).

Type B waters flow from the Bering Sea southwestward along Kamchatka like the East Kamchatka Current and then along the Kuril Islands, with a volume transport of 9×10^6 m^3/sec. The cold and less saline Okhotsk waters mix laterally with the East Kamchatka Current waters near the Kuril Islands, forming typical Western Subarctic Waters. Part of the latter turns eastward and flows parallel to the West Wind Drift as the Subarctic Current, while the other part flows farther southwest as the Oyashio.

The waters occupying the southwestern part of the Bering Sea Basin have a vertical structure similar to that of Type A of the Alaskan Stream. The former, however, has a mesothermal layer beneath the halocline, while the latter has a considerably warmer mesothermal layer within the halocline. The thermosteric anomaly of the former is about 110 cl/ton, while for the latter it is about 125 cl/ton or more. The rather low temperature of the mesothermal layer of the Western Subarctic Gyre probably results from the lateral mixing with the cold waters of the Okhotsk Sea origin.

The process of forming Type B from Type D, i.e., the increse of the salinity

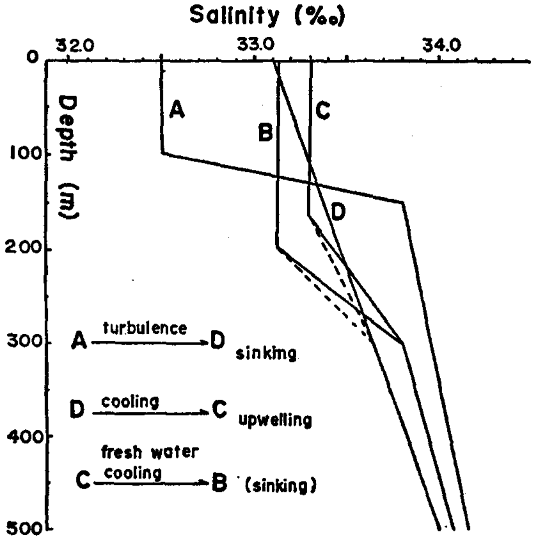


Fig. 24. Schematic representation of transformation from Type A through Type D to Type C and Type B.

gradient resulting from upwelling, also tends to transform Type B into Type A. Judging from the detailed vertical structures, Type A in the western part of the Bering Sea comes from the Western Subarctic Gyre.

V. Waters on the Continental Shelf

1. Horizontal distribution of salinity and temperature

The surface waters in the Bering Sea are, as a whole, diluted by the precipitation or melting water of drift ice in summer, the shelf waters are moreover diluted by fresh waters from the land. Horizontal distribution of salinity at the surface is shown in Fig. 25. The surface salinity on the whole shelf is less than 32.5‰, and the isohalines are almost paralleled to the isobaths except for those in the Gulf of Anaduir and in the Norton Sound, with decreasing value toward the coast. In the region north of St. Lawrence Island and in the Bering Straits, the surface salinity of the western side is higher than that of the eastern side. The isohaline of 31.0‰ indicates an extension of diluted waters from the Alaskan Coast toward the southwest of St. Lawrence Island, then after toward the Arctic Sea through the pass east of St. Lawrence Island and the Bering Straits.

The detailed observation in the Gulf of Anaduir done by the Northwind of the U.S. Coast Guard in September 1962, obviously indicated discontinuity between the diluted surface waters in the Gulf of Anaduir and those at the southwest of St. Lawrence Island, as shown in Fig. 26. The surface waters in the Gulf of Anaduir are extremely diluted by the land waters discharging from the Anaduir

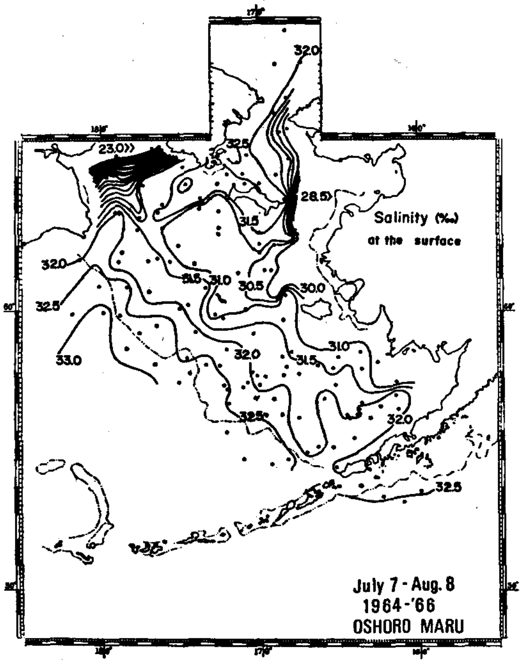


Fig. 25. Horizontal distribution of salinty at the surface on the shelf in summer.

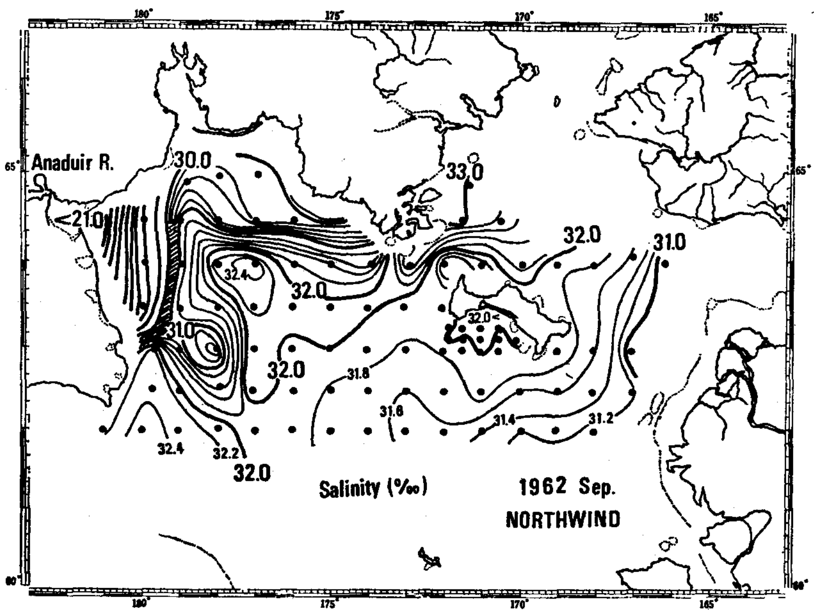


Fig. 26. Horizontal distribution of salinity at the surface in the Gulf of Anaduir in autumn.

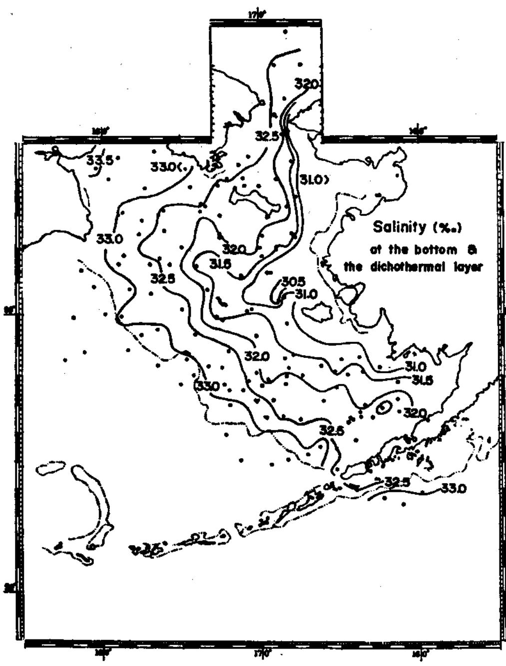


Fig. 27. Salinity distribution at the bottom on the shelf in summer.

River and others, and these diluted waters are within the confines of the gulf. It must be noticed that less saline water below 24.7‰ is spreading along the western coast of the gulf from the mouth of the Anaduir River, because the waters below 24.7‰ of salinity freeze on the surface like fresh waters, in winter.

The pattern of salinity distribution at the bottom is almost identical with that at the surface except for the Gulf of Anaduir, as shown in Figs. 27 and 28. The isohalines are drawn similar to the isohypes of Fig. 11, indicating the flow pattern. In the Gulf of Anaduir, the salinity of the lower waters is very high in contrast with the surface waters and more than 33.0‰ of the saline waters spread over most of the gulf. The 33.0‰ isohaline, continuing from the basin along the margin of the shelf into the gulf, indicates an intrusion of the basin waters of the upper layer into the gulf underneath the diluted surface waters through the east of Cape Navarin, and also a continuity of these waters from the basin into the Arctic Sea through the south of Cape Chaplina and the western side of the Bering Straits.

The salinity difference between the surfce layer and the lower one is a little less than 0.2‰ in the region south of Lat. 60°N and near the coast of Alaska, while in the region southwest of St. Lawrence Island, this value exceeds 0.2‰ and amounts to 0.8‰. In the Gulf of Anaduir, the salinity difference is remarkably

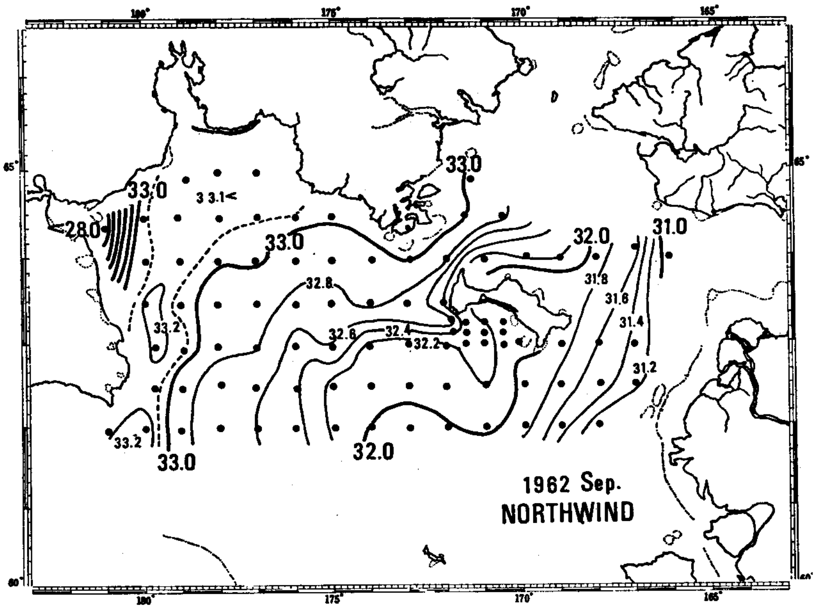


Fig. 28. Salinity distribution at the top of lower layer in the Gulf of Anaduir in autumn.

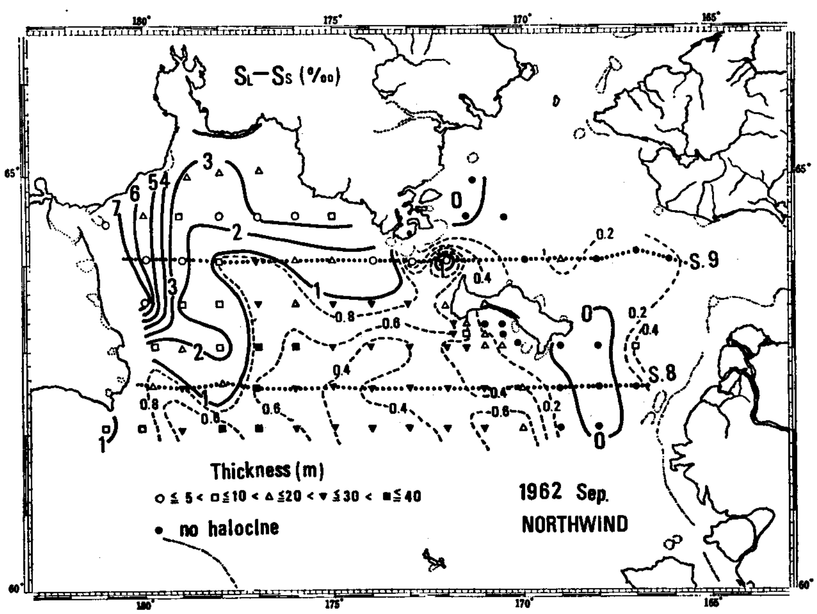


Fig. 29. Salinity difference between the surface layer and the lower one in the Gulf of Anaduir in autumn. Marks indicate the thickness of the surface layer.

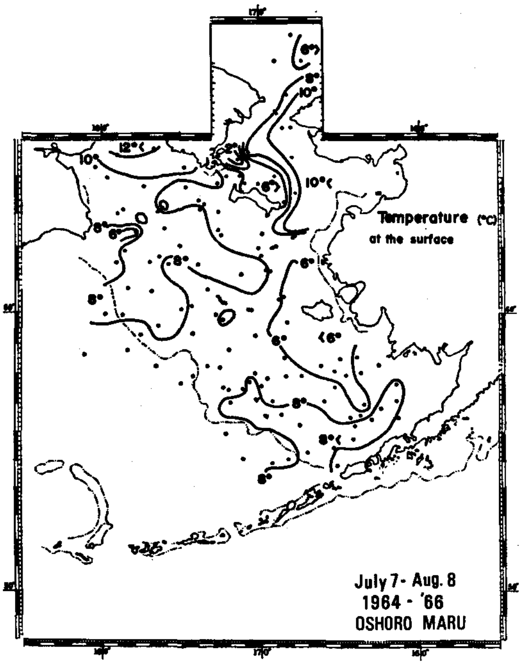


Fig. 30. Horizontal distribution of temperature at the surface in summer.

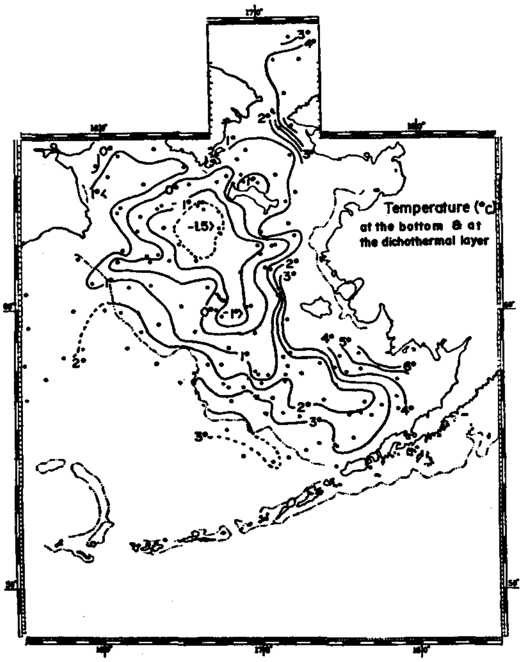


Fig. 31. Temperature distribution at the bottom in summer.

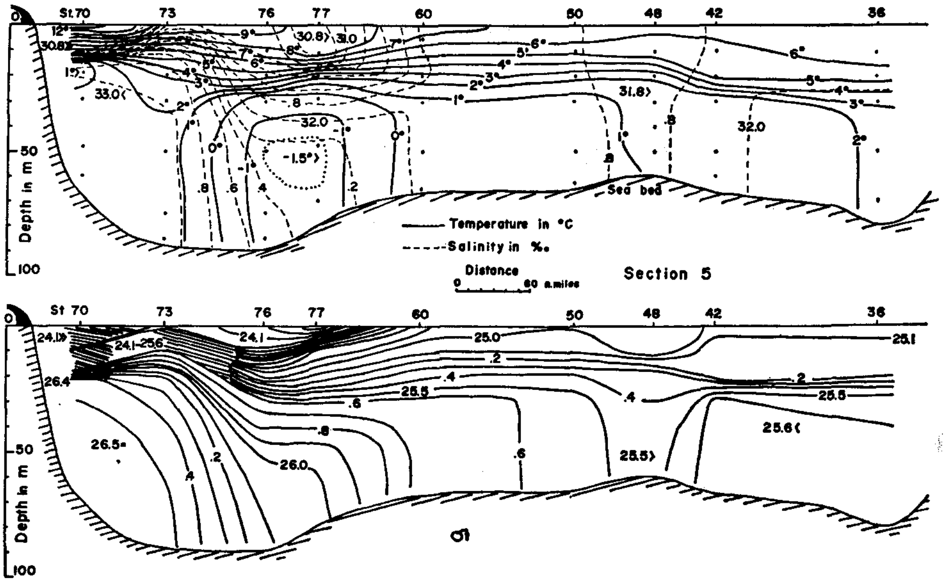


Fig. 32. Vertical sections of temperature, salinity and σ_t between the Gulf of Anaduir and the Alaska Peninsula on the shelf, locations of sections are shown in Fig. 41.

large, its value of the whole Gulf exceeds 1.0‰ and the largest value comes to 7.0‰ or more, as shown in Fig. 29.

The thickness of the surface layer is shallower than 20 meters in the gulf, while in the region out of the gulf, its value exceeds 20 meters. These conditions suggest the degree of facility of the ice formation.

It is a characteristical feature of temperature distribution on the shelf in summer that the extreme cold waters, having a center at the southwest of St. Lawrence Island, is extensively remaining beneath the surface layer, though the surface temperature rises up to 6–8°C in the southern part of the shelf or to more than 10°C in the restricted region of the northern part, as shown in Figs. 30 and 31. Although these cold bottom waters are spreading over the central part of the shelf from the southwest of St. Lawrence Island toward the southeast, they do not indicate a flow pattern or an origin of the cold waters.

An isohaline of 33.0‰ in Fig. 27 and the isotherms of 1°–3°C in Fig. 31 along the margin of the shelf indicate an intrusion from the basin water of the upper layer; therefore the thermal front is perpetually formed between the cold self waters and the warm basin waters along the margin of the shelf. On the other hand, a bottom temperature of the shallow region along the Alaskan Coast is immediately raised in summer by a great vertical heat transfer from the surface due to the strong tidal current, while the vertical heat transfer is relatively small in the deep region, especially the large halocline in the northern region, as shown in Fig. 29, preventing a heat transfer from the surface layer to the lower one.[28] Therefore a thermal front is also formed between them along the isobath of about 30 meters, and the cold bottom waters are represented as a beltlike or tonguelike shape.[7] These thermal fronts formed in the lower layer on the shelf influence upon the migration path of some kind of demarsal fish.[28),29),30]

2. *Vertical section*

Vertical section along the center of the beltlike cold bottom waters from the Gulf of Anaduir to off Bristol Bay (S. 5) is shown in Fig. 32. In the section of southeast of St. 60, salinity distribution is almost homogeneous vertically and horizontally, though a thermocline is formed at about a 30-meter depth, and temperature under the thermocline gradually increases toward southeast. In contrast with the foregoing, the remarkable halocline with a distinct thermocline is indicated in the section northwest of St. 77. At St. 76 and St. 77, extreme cold waters, near the freezing point, are shown at the bottom of the halocline, and they present a dichothermal stratum. In the Gulf of Anaduir northwest of St. 73, a large but shallow halocline with a distinct thermocline is also formed; however, the salinity and the temperature of the lower waters under the surface layer are relatively high, therefore a discontinuity of these properties with the cold waters mentioned above is clearly indicated between St. 73 and St. 76. Consequently, the pycnocline between the surface layer and the lower one is weak in the southern area, larger

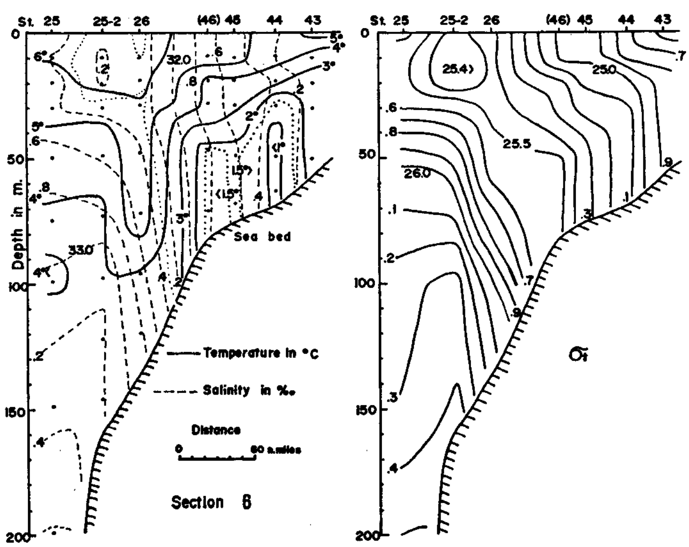


Fig. 33. Vertical sections of temperature, salinity and σ_t in the southern part of the shelf.

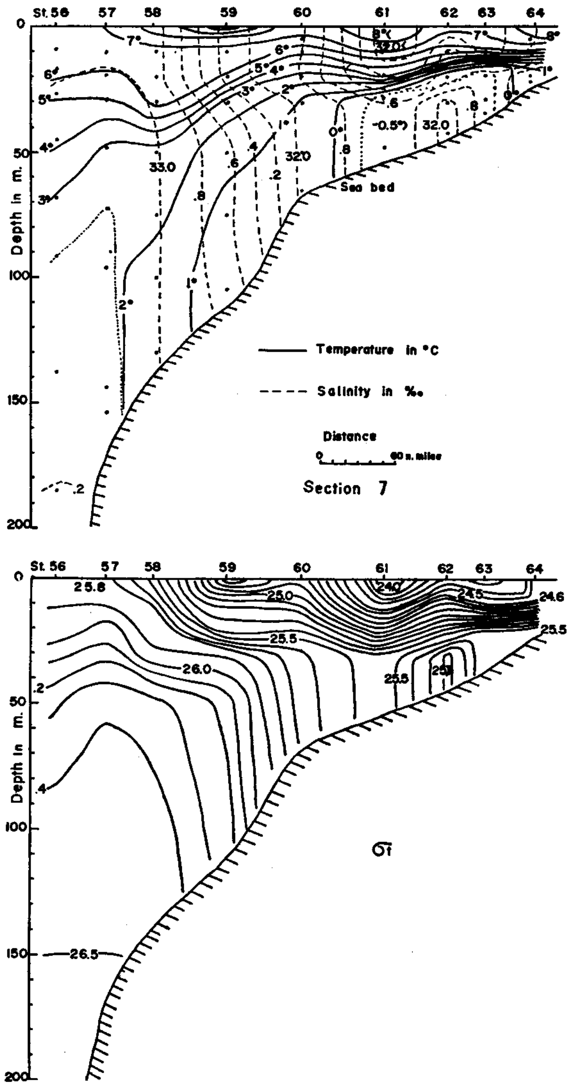


Fig. 34. Vertical sections of temperature, salinity and σ_t in the northern part of the shelf.

in the northern area and largest in the Gulf of Anaduir.

Vertical transections across the former section are shown in Figs. 33 and 34. On the southern section (S. 6) of Fig. 33, a halocline with a loose thermocline is weak and the isohalines are standing vertically crossing with the isotherms on the whole shelf, whereas at the margin of the shelf, the isotherms deepen down and become parallel to the isohalines. At St. 25, a salinity increases with depth and the temperature is relatively high. These distributions of properties indicate the intrusion of the warm and less saline Pacific waters from the Alaskan Stream

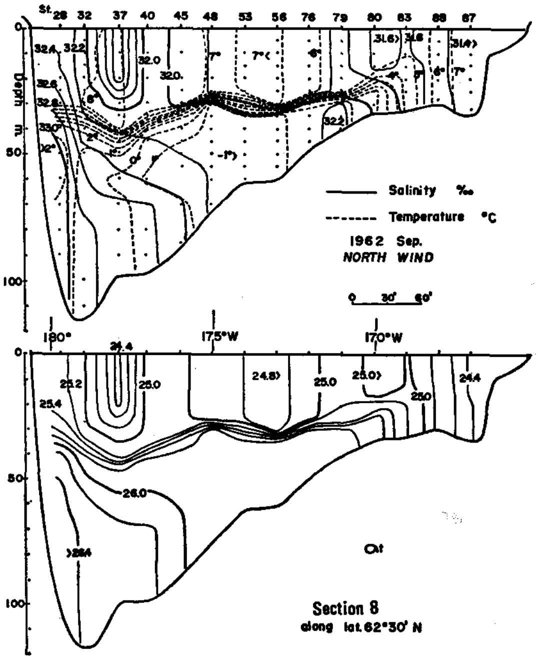


Fig. 35. Vertical sections of temperature, salinity and σ_t at the entrance of the Gulf of Anaduir. Locations of Sections are shown in Fig. 29.

through the Unimak Pass and others. Isopycnals of 26.0 and 25.6 indicate the sinking of these warm basin waters at St. 26.

In the northern section (S. 7) of Fig. 34, the basin waters along the shelf from the Alaskan Stream lose their characteristics of warmth and a vertical salinity gradient, and they are transformed into cold and saline homogeneous waters as stated in preceding chapter. The isohalines are also standing vertically, though having a large halocline corresponding with a thermocline in the marginal region of the shelf, whereas in the shallower region, the isohalines are lying horizontally with a remarkable halocline, and extremely cold waters remain on the sea bottom under the halocline with a remarkable thermocline. Therefore the difference of density between the surface layer and the lower one is conspicuously large on the shelf.

The discontinuity of the properties between the basin waters and the shelf waters, as shown in Figs. 33 and 34, is clearly indicated along the whole margin of the shelf, and this characteristic is maintained from the surface to the bottom, therefore the whole waters on the shelf are lighter in density and less in salinity than the basin waters, except for the lower waters in the Gulf of Anaduir.

A similar discontinuity is also found between the lower waters in the Gulf of Anaduir, though situated on the shelf, and the southernly extremely cold bottom

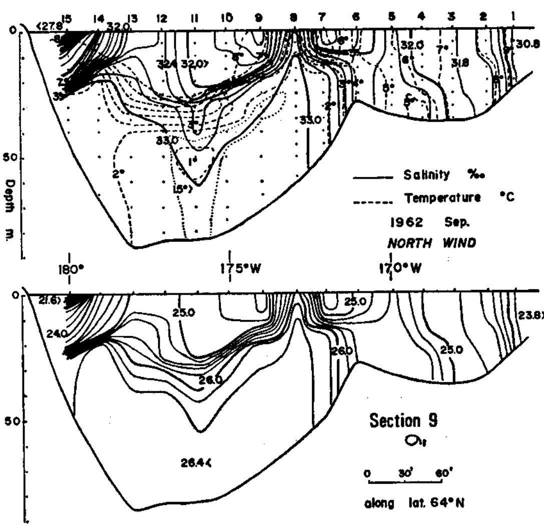


Fig. 36. Vertical sections of temperature, salinity and σ_t in the Gulf of Anaduir.

waters, as shown in Figs. 32, 35 and 36. At the entrance to the gulf (S. 8), in Fig. 35, the saline basin waters intruded on the shelf are restricted within a narrow limit of Cape Navarin under the thermocline with a halocline by the extremely cold waters below 0°C; however, a part of these saline waters intrudes under the cold waters on the sea bottom. In a central region of the gulf (S. 9), the saline basin waters are extensively spreading over the gulf under a large halocline and thermocline, as seen in Figs. 27 and 28. Therefore a remarkable but shallow pycnocline is formed between the lower saline basin waters and the upper diluted waters, especially along the western coast of the gulf where discharged waters from the Anaduir River are flowing; the density difference exceeds σ_t of 5.0. It suggests a major clockwise circular current in the gulf that the pycnocline deepens down at St. 11. At St. 8, a strong upwelling is indicated by these isolines. This upwelling is also indicated by a horizontal salinity distribution at the surface, in Figs. 25 and 26, near the coast of Cape Chaplina. East of St. 7, isolines are standing vertically indicating strong vertical mixing.

3. *Classification to type of vertical structure*

Though the depth of the shelf region, in general, is shallower than 100 meters, there are different types in vertical salinity and temperature structures to be found. These shelf waters are bounded within the basin waters by a discontinuous zone of horizontal distribution of properties along the continental slope, as stated before. One part of the basin waters (A.S.) being relatively warm and having a less saline surface coming from the Alaskan Stream through the Unimak

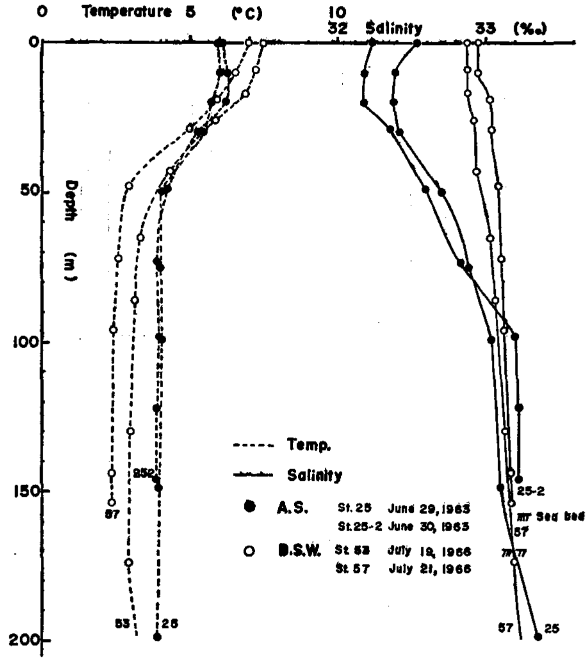


Fig. 37. Typical temperature and salinity structures in A.S. and B.S.W. regions.

Pass or adjacent passes, joins with the shelf waters at the southeastern margin of the shelf. Whereas along the northern margin of the shelf, another part of the basin waters (B.S.W.) being relatively cold and having a uniform upper layer in salinity (Type C or Type B in Chapter IV), also joins with the shelf waters. Typical vertical structures of these basin waters are shown in Fig. 37.

In the southeastern region on the shelf (C.A), the salinity structure is uniform or has a small halocline less than 0.2‰; however, the temperature structure has an apparent thermocline between the isothermal surface layer and the isothermal bottom one at a depth of about 30 meters. In the shallow region less than 30 m. deep along the coast of Alaska (C.W.), salinity and temperature structures are almost uniform vertically, and these values are relatively low. The isothermal bottom layer of C.A. and this are caused by extreme vertical mixing due to a strong tidal current.[28] Typical structures of these shelf waters are shown in Fig. 38.

In the Gulf of Anaduir (A.G.) and Norton Sound (N.S.), the surface layer is under the effect of fresh waters strongly discharging from the land, therefore the thin surface layer is extensively covered by extremely less saline waters, as shown in Fig. 39. In the Gulf of Anaduir, the waters of the lower layer show a high salinity more than 33.0‰ and a relatively warm temperature more than 1°C, that is the same for the waters in the upper layer of the B.S.W. waters.

In the region southwest of St. Lawrence Island (I.F.A.) surrounded by these

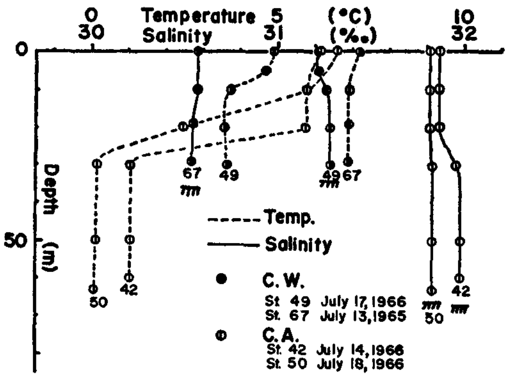


Fig. 38. Typical temperature and salinity structures in C.A. and C.W. regions.

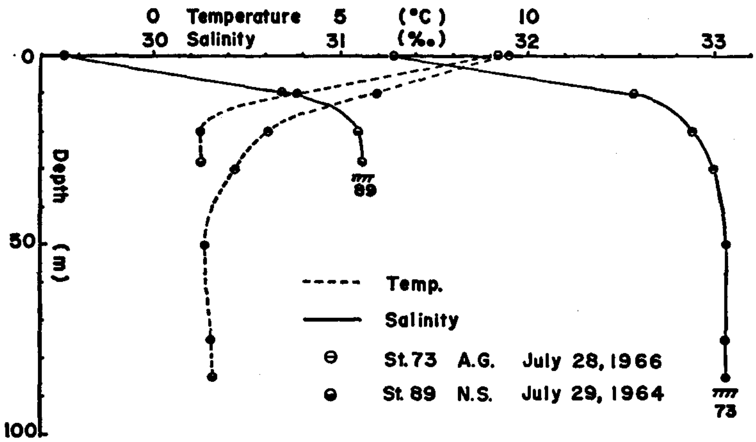


Fig. 39. Typical temperature and salinity structures in A.G. and N.S. regions.

waters mentioned above, vertical profiles show two or three stratified structures, as shown in Fig. 40. The temperature under the shallower halocline is extremely cold as it is near the freezing point, while that under the deeper one becomes warmer again toward the bottom.

A geographical distribution of the patterns of vertical structures is shown in Fig. 41, including the location of vertical sections and oceanographic stations used in this chapter.

In the Subarctic Region, the upper layer is altered from the stratified structure in summer into homogeneous strata in winter by vertical mixing due to thermal convection and wind stirring under the cold and severe weather.[31] Zubov[32] defined the critical depth that vertical circulation in winter could reach to a depth without ice formation. The critical depths of the shelf waters are shown in Fig. 42. In the southeastern part and the coastal region of the shelf, vertical circula-

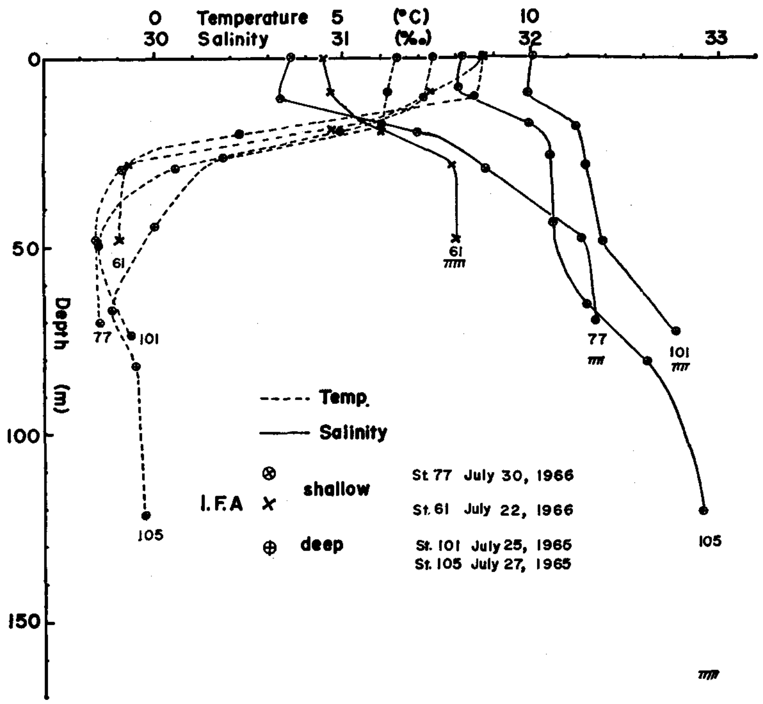


Fig. 40. Typical temperature and salinity structures in I.F.A. region

tion can reach the bottom and homogeneous waters from the surface to the bottom can also be formed by winter cooling, C.A. and C.W. waters are formed by this process. Whereas in most regions of the northern part of the shelf, thermal convection is restricted within the surface layer because of the large halocline between the surface layer and the lower one.

Zubov[32] also defined the amount of heat given off from the water column till the temperature fell down to the freezing point by winter cooling as a freezing index which indicated facility for ice formation. The freezing indexes are small in the northern part of the shelf but are large in the southern part and along the margin of the shelf, as shown in Fig. 43. Since the amount of heat given off from the basin waters in winter is estimated by a difference of thermal profile from the dichothermal temperature to be of the order of 25 Kg-cal/cm^2 [7], it may be concluded that the sea ice can be formed in the northern part and the coastal region only, as shown by small freezing index in Fig. 43 and shallow critical depth in Fig. 42.

In the process of ice formation, a salinity of the convective surface layer increases with the increase of amount of freeze, and it causes an increases of density in the surface layer. The depth of the convective layer is accordingly deepened in compliance with the process of ice formation, and vertical circulation finally attains to the lower layer in consequence of the disappearance of the large halo-

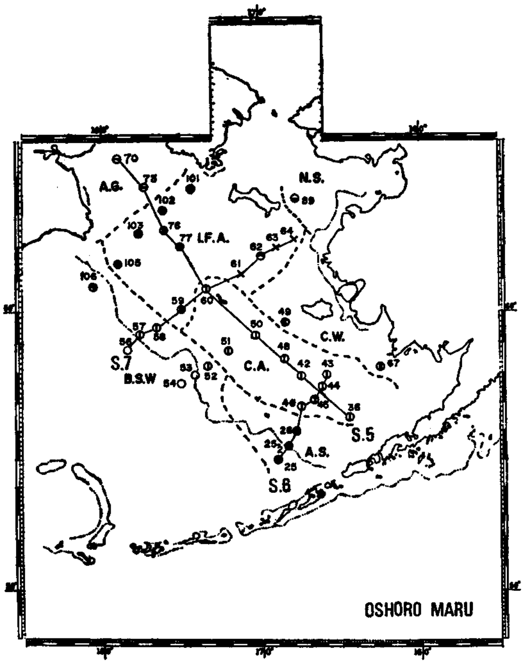


Fig. 41. Location of vertical sections and regions.

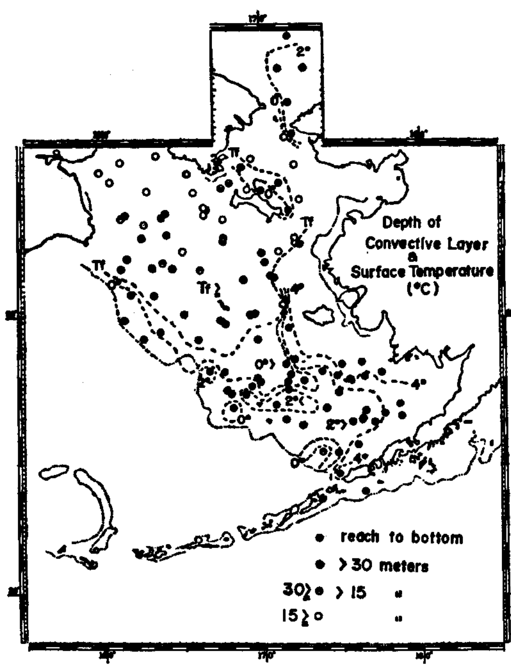


Fig. 42. Depth of convective layer and surface temperature at the point reaching the critical depth of vertical circulation in winter.

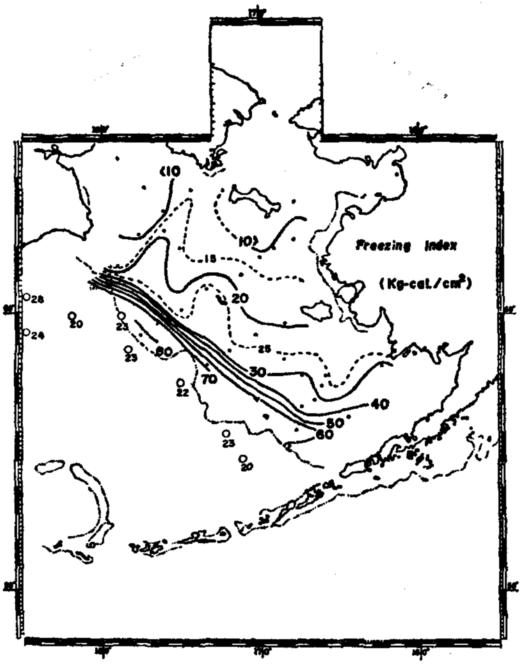


Fig. 43. Freezing indexes for the stations on the shelf and amount of heat given off by the water column in the deep region in winter estimated from the summer observations.

cline in summer, then the extremely cold waters are formed below the sea ice.

The water in the region southwest of St. Lawrence Island is isolated from the flow toward the Bering Straits from the north of the basin through the pass near Cape Chaplina, as shown in Fig. 11. Consequently, the extremely cold waters in the I.F.A. region remain at that place till summer all the while being preserved by a large halocline from summer heating, as a remnant in process of ice formation in winter.

The amount of sea ice produced in this region is estimated at about 120 cm of thickness from the difference of salinity between the surface layer and the lower one at St. 77, then a sum of latent heat given off by freezing and a value of the freezing index is also estimated as 24.2 Kg-cal/cm^2 [7]. This value is equivalent to the order of 25 Kg-cal/cm^2 of the basin waters estimated above. In the open sea, the concentration of salinity of the surface layer caused by ice formation is consequently considered to be within 1‰ in the I.F.A. region or a few ‰ even in the Gulf of Anadiur. Though Arsen'ev[19] indicated saline waters over 34‰ at depths exceeding 100 meters in one of the inlets with a deep threshold of about 20 meters in the Gulf of Anadiur, the amount of such cold and saline waters may be small and are not able to transform the characteristics of the lower waters of the Gulf of Anadiur as a whole.

VI. Interaction between the Shelf Waters and the Basin Waters

Vertical circulation in the process of ice formation in situ reaches a depth of 100 meters in the Okhotsk Sea Basin[33], whereas on the continental shelf of the sea, cold and saline waters more than 33.6‰ are formed by ice formation and these waters spread toward the south in a mid layer of depths 200 to 600 meters[34]. In the eastern Bering Sea, however, vertical circulation by this process is confined within about 60-meter depth and inside the continental shelf. A density of the whole of the shelf waters, even of the extremely cold waters of which salinity is concentrated by ice formation, is smaller than that of the basin waters in the upper layer, as those vertical sections can be seen in Fig. 33 and 34, and distribution of σ_t at the bottom is shown in Fig. 44. The isopycnal of 26.4, which represents the density of the basin waters near the bottom of the upper layer, indicates the intrusion of the basin waters beneath the lighter shelf waters at the margin of the shelf and in the Gulf of Anaduir. The beltlike cold waters, as shown in Fig. 31, lie between the isopycnals of 26.0 and 25.0 or less, therefore the influence of the shelf waters upon the basin waters is limited within the upper layer of the basin waters. In the northeastern part of the Bering Sea Basin, a double dichothermal stratum is formed by lateral mixing under the effect of the

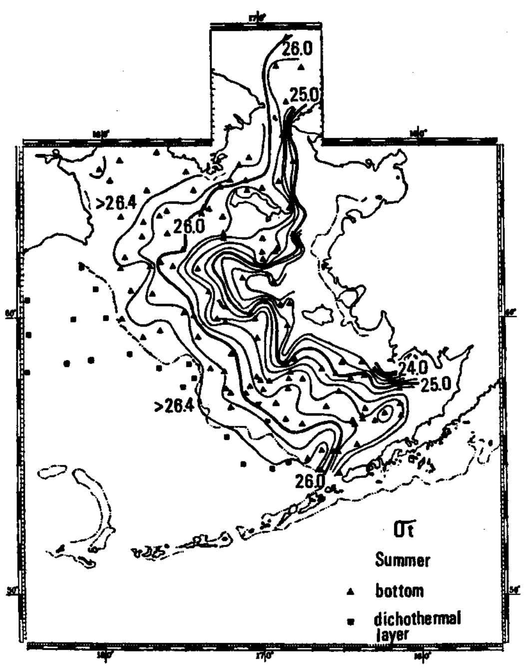


Fig. 44. Distribution of σ_t at the bottom of the shelf and of the dichothermal water in the basin.

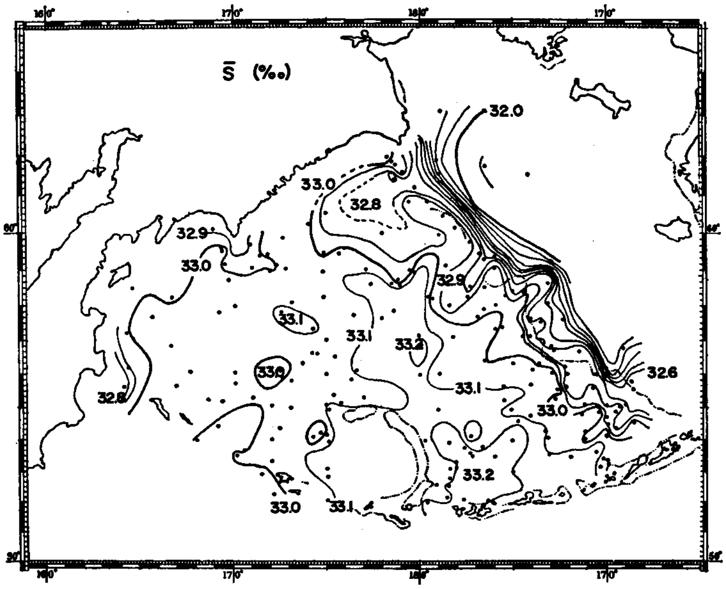


Fig. 45. Distribution of mean salinity in the layer from the surface to 100-meter depth.

cold bottom waters of the shelf[21], however, this double dichothermal structure is also confined within the adjacent region to the continental shelf.

A degree of extension of the shelf waters upon the basin waters may be indicated by the mean salinity of a water column from the surface to a depth, because the influence of dilution in the surface layer by precipitation in summer for the whole sea can be removed away by mixing on calculation, whereas the regional dilution caused by the intrusion of the less saline shelf waters or by the melting waters of drift ice originated on the shelf moreover remains in the difference of the mean salinity. A geographical distribution of the mean salinity from the surface to 100-m. depths is shown in Fig. 45. Since the mean salinity of most of the basin is in excess of 33.0‰, we may take a value of 33.0‰ as the standard mean salinity of the basin waters in the upper layer. We presume the salinity of the shelf waters extending toward the basin as the maximum value of 32.6‰ and the minimum value of 32.0‰, the former corresponding to the salinity of the surface waters from the Alaskan Stream in A.S. region and the latter to the surface salinity along the southwestern boundary of the cold bottom waters on the shelf. Then a diminution of the mean salinity of 0.1‰ from the standard value in the basin area means the joining of the shelf waters having a thickness of 25 m. of the former or of 10 m. of the latter, respectively, that is also corresponding to the joining of fresh waters of 30 cm in height per unit area.

One of the isohalines of the mean salinity of 33.0‰ is drawn apart from the continental slope from the Unimak Pass toward the northwest with a gradual increase of distance from the shelf, and turns its direction toward the northeast along the Siberian Coast to Cape Navarin. Another one is drawn from Cape Olyutorskii toward the southwest along the Kamchatka Peninsula. The continuity between them is not evident. Considering the flow pattern and distribution of the drift ice in winter[35], it may be concluded that the extension of the shelf waters toward the basin is confined within the adjacent region along the shelf and the northeasternmost of the basin, therefore the less saline waters along the Kamchatka are not originated from the eastern shelf waters but are formed in the adjacent coastal region.

The vertical circulation caused by winter cooling is restricted within the upper layer even in the process of ice formation on the shelf, therefore the cold intermediate waters, as seen in the Okhotsk Sea[34], are never formed in the Bering Sea, except for a little amount of the saline waters in the closed inlets.

VII. Discussion

In general, as mentioned in foregoing chapters, the upper waters in the Bering Sea are under the strong influence of winter cooling, then the homogeneous upper layer is formed; on the other hand, since the concentration of salinity in the process of ice formation on the shelf does not exceed the salinity of the basin waters, new intermediate waters are never formed in the Bering Sea. Therefore the warmth of the mesothermal waters from the Alaskan Stream is preserved in the lower layer slightly decreasing the temperature with an anticlockwise circulation in the basin.

Though various types of vertical distribution of properties are found in the Bering Sea Basin, those are thus indicating a pattern in the process of transformation of a water mass, namely from the Alaskan Stream Waters originating in the eastern Subarctic Pacific to the Western Subarctic Waters. One of the important factors on transformation is the remarkable vertical mixing along the Aleutian Islands caused by a strong tidal current. Such strong vertical mixing which never occurs in the open sea, causes the transport of nutrients from the deep waters up to the surface layer; consequently the region around the Aleutian Islands is moreover rich in nutrients in the Subarctic Region[16]. Vertical mixing due to thermal convection in winter reaches the basin more deeply because of a loosed halocline by the foregoing mixing; consequently oxygen content is also rich at depths along the circumference of the basin. These conditions may be considered as one of the reasons causing a high production of marine life in the Bering Sea.

Along the Aleutian Islands and the continental slope in the eastern Bering Sea, warm waters from the Alaskan Stream may provide a profitable environment in winter for some kind of fish spawning, or may shelter the fry from the winter cooling.

A discontinuous zone of the properties distribution is formed between the Type D waters coming through the Amchitka Pass and the other, it has been suggesting that this boundary might have influence on the migration route of the sockeye salmon returning to natal streams in the Bristol Bay[36,37].

VIII. Summary

Three quarters of the waters in the Bering Sea are provided by the Alaskan Stream from the Pacific Ocean mainly through the Amchitka Pass and the pass west of Attu Island, the other quarter comes from the Western Subarctic Gyre. On the other hand, the Eastern Kamchatka Current comes from the Bering Sea through the Pass between Kamchatka and Komandorskii, and provides waters to the Okhotsk Sea and the Oyashio.

In the Bering Sea, vertical structures are classified into various types of vertical distribution of properties for the basin waters and also the shelf waters. Verious types of the basin waters indicate a pattern in the process of transformation of a water mass, which is caused by a remarkable vertical mixing due to the tidal current along the Aleutian Islands, winter cooling and the upwelling of lower waters due to anticlockwise circulation in the basin; therefore the thickness of the upper layer is larger at the circumference of the basin than in the central region, and temperature is higher along the Aleutian Islands and the continental slope than along the north and the west of the basin.

Various types of the shelf waters are also formed under the influence of the joining of fresh waters from the land and drift ice, of the strong tidal current and of the winter cooling upon the shelf. The beltlike distribution of the cold bottom waters found in summer does not indicate an origin of the cold waters and advectional effects, but the remains of the cooled water in winter in situ; therefore the meteorological conditions of the preceding winter largely influence the oceanic conditions on the shelf of the following summer.

Sea ice in the Bering Sea can be formed within the regions of I.F.A., A.G., N.S., a part of C.W. and in some parts of the bay along Kamchatka; however, the increase in density of the shelf waters due to the concentration of salinity in the process of ice formation is never beyond the basin waters, the influence of the shelf waters upon the basin waters is accordingly restricted within the upper layer and the adjacent region along the shelf. On the other hand, the basin waters of the upper layer along the shelf penetrate into the margin of the shelf and into the Gulf of Anadiur under the shelf waters, then enter the Arctic Sea afterwards.

A geographical distribution of various types of vertical structures and flow pattern of shallow waters are schematically represented in Fig. 46.

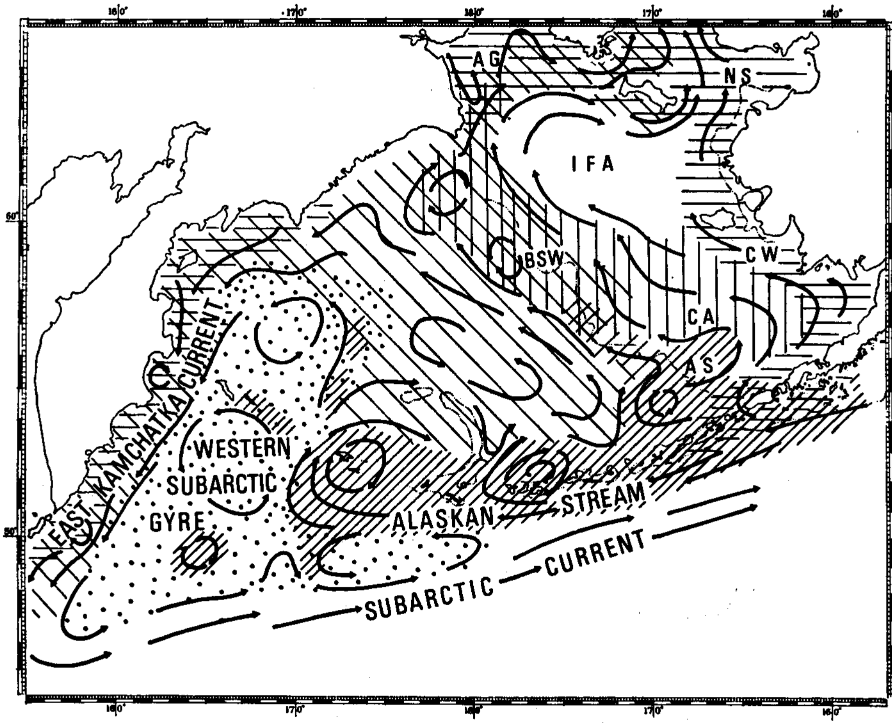


Fig. 46. Schematic representation of flow pattern of shallow waters and extension of type of vertical structure on the shelf.

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References

1) Dodimead, A.J., F. Favorite and T. Hirano (1963). Salmon of the North Pacific Ocean-II, Review of oceanography of the Subarctic Pacific region. Bull. Int. North Pacific Comm., 13, 195.
2) Tully, J.P. and F.G. Barber (1960) An estuarine analogy in the Subarctic Pacific Ocean. Jour. Fish. Res. Bd. Canada, 17, 91–112.
3) Dodimead, A.J. (1967). Winter oceanographic conditions in the central subarctic Pacific. Int. North Pacific Comm., Doc. 999, 14.
4) Dodimead, A.J. and G.L. Pickard (1967). Annual changes in the oceanic-coastal

waters of the eastern Subarctic Pacific. Jour. Fish. Res. Bd. Canada, 24 (11), 2207–2227.
5) Favorite, F. (1967). The Alaskan Stream. Bull. Int. North Pacific Comm., 21, 1–20.
6) Ohtani, K. (1970). Relative transport in the Alaskan Stream in winter. Jour. Oceanogr. Soc. Japan, 26, 271–282.
7) Ohtani, K. (1969). On the oceanographic structure and the ice formation on the continental shelf in the eastern Bering Sea. Bull. Fac. Fish., Hokkaido Univ., 20, 94–117. (in Japanese with English abstract).
8) Faculty of Fisheries, Hokkaido University (1960). Data Record of Oceanographic observations and Exploratory Fishing, No. 4.
9) Faculty of Fisheries, Hokkaido University (1962). Data Record of Oceanographic observations and Exploratory Fishing, No. 6.
10) Faculty of Fisheries, Hokkaido University (1963). Data Record of Oceanographic observations and Exploratory Fishing, No. 7.
11) Faculty of Fisheries, Hokkaido University (1964). Data Record of Oceanographic observations and Exploratory Fishing, No. 8.
12) Faculty of Fisheries, Hokkaido University (1965). Data Record of Oceanographic observations and Exploratory Fishing, No. 9.
13) Faculty of Fisheries, Hokkaido University (1966). Data Record of Oceanographic observations and Exploratory Fishing, No. 10.
14) Faculty of Fisheries, Hokkaido University (1967). Data Record of Oceanographic observations and Exploratory Fishing, No. 11.
15) Japanese Oceanographic Data Center (1967). George B. Kelez, February 1-April 6, 1966, South of Komandorsky and south of Adak Island. Prelim. Data Rep. CSK, No. 34.
16) Scrips Institution of Oceanography, University of California (1966). Boreas Expedition, SIO reference 66–24, 153. (JODC, Prel. Data Rep. CSK, No. 36, 1967)
17) Zenkevitch, L. (1963). Biology of the Seas of the U.S.S.R. 955p. John Wiley & Sons Inc., George Allen & Unwin Ltd. London.
18) Barnes, C.A. and T.G. Thompson (1938). Physical and chemical investigations in Bering Sea and portion of the North Pacific Ocean. Univ. Washington, Publ. Oceanogr., 3 (2), 35–79 and App. 1–164.
19) Arsen'ev, V.S. (1967). The current and water masses of the Bering Sea. (Translated from the Russian by Pearson, S., 1968), 146 p. Biol. Lab. Bureau of Comm. Fish., Seattle.
20) Favorite, F. (1972). On flow into Bering Sea through the Aleutian island passes. Preprints of international symposium for Bering Sea study, 1–2. Jan. 31-Feb. 4, 1972, at Hakodate.
21) Koto, H. and T. Fujii (1958). Structure of the waters in the Bering Sea and the Aleutian region. Bull. Fac. Fish., Hokkaido Univ., 9, 149–170.
22) Favorite, F. (1966). Bering Sea. p. 135–140. In Fairbridge, R.W. (ed.), *The Encyclopedia of Oceanography*. 1021p. Reinhold Publishing Corporation, New York.
23) Coachman, L.K. and K. Aagaard (1966). On the water exchange through Bering Strait. Lim. Oceanogr., 11 (1), 44–59.
24) Ohtani, K. (1965). On the Alaskan Stream in summer. Bull. Fac. Fish., Hokkaido Univ., 15, 260–273. (in Japanese with English abstract).
25) Uda, M. (1963). Oceanography of the Subarctic Pacific Ocean. Jour. Fish. Res. Bd. Canada, 20, 119–179.
26) Ohtani, K. (1971). Oceanographic characteristics of the Bering Sea. Bull. Japanese Soc. Fish. Oceanogr., 19, 158–172. (in Japanese).
27) Ohtani, K., Y. Akiba and A.Y. Takenouti (1972). Formation of Western Subarctic Water in the Bering Sea. p. 31–44. In Takenouti, A.Y. (ed.), *Biological Oceanography of the Northern North Pacific Ocean*. 626 p. Idemitsu Shoten, Tokyo.

28) Koto, H. and T. Maeda (1965). On the movement of fish shoals and the change of bottom temperature on the trawl-fishing ground of the eastern Bering Sea. Bull. Japanese Soc. Sci. Fish., 31, 769–780. (in Japanese with English abstract).
29) Maeda, T., T. Fujii and K. Masuda (1967). Studies on the trawl fishing grounds of the eastern Bering Sea-I. On the oceanographical condition and the distribution of the fish shoals in 1963. Bull. Japanese Soc. Sci. Fish., 33, 713–720. (in Japanese with English abstract).
30) Maeda, T. (1971). Subpopulations and migration pattern of the Alaska pollack in the eastern Bering Sea. Bull. Japanese Soc. Fish. Oceanogr., 19, 15–32. (in Japanese).
31) Tabata, S. (1961). Temporal changes of salinity, temperature and dissolved oxygen content of the water at Station "P" in the northeast Pacific Ocean, and some of their determining factors. Jour. Fish. Res. Bd. Canada, 18, 1073–1124.
32) Zubov, N.N. (1945). Mixing of the waters in the Ocean. In *Ice of the Arctic Sea.* (Translated from the Russian by Suzuki, Y., 1961), 26 p. Inst. Low Temp. Sci. Hokkaido Univ., Sapporo. (in Japanese).
33) Tabata, T. (1960). On the formation and growth of sea ice in the southern part of the Okhotsk Sea. Low Temperature Science, Ser. A, 19, 175–186. (in Japanese with English résumé).
34) Kitani, K. (1973). Studies on the dichothermal water and the transitional water in the Okhotsk Sea. Doctral Thesis. Hokkaido University, Hakodate, 118 pp. (in Japanese).
35) Dunbar, M. (1967). The monthly and extreme limits of ice in the Bering Sea. p. 687–703. In Oura, H. (ed.), Physics of Snow and Ice, Proc. Int. Conf. Low Temp. Sci., 1. Inst. Low Temp. Sci., Hokkaido Univ., Sapporo.
36) Ohtani, K. (1966). The Alaskan Stream and the sockeye salmon fishing ground. Bull. Fac. Fish., Hokkaido Univ., 16, 209–240. (in Japanese with English abstract).
37) Favorite, F. and W.J. Ingraham, Jr. (1972). Influence of Bowers Ridge on circulation in Bering Sea and influence of Amchitka Branch, Alaskan Stream, on migration paths of sockeye salmon. p. 13–29. In Takenouti, A.Y. (ed.), *Biological Oceanography of the North Pacific Ocean.* 626 p. Idemitsu Shoten, Tokyo.