SOME FEATURES OF THE UPPER ZONE OF THE SUB-ARCTIC PACIFIC OCEAN

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ABSTRACT

The upper zone is defined by the depth at " D " of the homogeneous (isohaline and isothermal) layer at the end of the cooling season (March-April). The limit " D " is defined in the logarithmic plot of the salinity structure by a marked discontinuity at the top of the halocline. The temperature and salinity at this limit persist beneath the thermocline and secondary halocline which appear in summer. They are modified slightly by entrainment and transport. These conclusions are supported by comparison of winter and summer data from the eastern sub-Arctic. Therefore it is possible, from an oceanographic survey made in the summer, to identify the extremes of temperature that existed throughout the depth (D) of the upper zone, throughout the whole region, during the previous winter, for the periods studied.

This analysis is applied to four years of summer data (1956 through 1959) and significant variations in the winter temperatures and their distribution are shown.

CONTENTS

INTRODUCTION

It has been confirmed that the salinity structure, with minor variations, is a permanent feature of the eastern sub-Arctic[1] (Dodimead, 1958). An examination of extensive data in this region

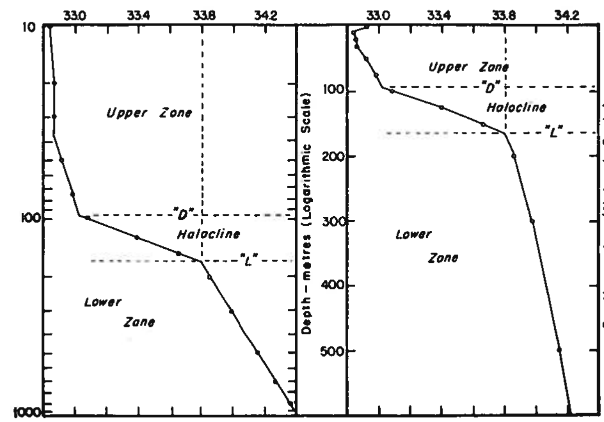

FIGURE 1.

showed that this structure could be accurately delineated by plotting salinity as a function of the logarithm of the depth (Doe, 1955; Tully and Dodimead, 1957). Such a plot (Fig. 1) leads to a definition of 3 distinct zones; an upper zone of relatively homogeneous, low salinity water, a transition zone characterized by a marked halocline, and a lower zone in which the salinity increases gradually with depth (Tully, 1957). These are separated by two marked discontinuities at the upper and lower limit of the halocline. They have been designated " D " and " L " respectively, as shown in the figure.

Recently it has been reported that the features of an estuarine system, the " entrainment " process and fresh water mechanism occur in the sub-Arctic region (Tully and Barber, 1959). In the report the significance of, and the variations at " L " (bottom of halocline) were discussed. The significance of the upper limit " D " was discussed briefly. It is now possible to propose a mechanism for the formation of the upper zone and the significance of the depth, salinity and temperature at " D ".

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1. Sub-Arctic region can generally be characterized by the presence of an upper zone and halocline in the salinity structure. The region includes the transition zone as defined in " The Oceans " (Sverdrup *et al*) which is bounded on the south by the sub-Tropic waters.

SALINITY STRUCTURES IN THE NORTH PACIFIC OCEAN

In Figure 2(b) (logarithmic plot) and Figure 2(c) (natural plot) are shown representative salinity structures in the North Pacific Ocean (positions indicated in Figure 2(a)). It is apparent that the upper zone and hence the limit "D" can always be defined, and that the salinity structure can be interpreted logarithmically within the sub-Arctic region.

As shown in Figure 2(b), the lower limit "L" is not an invariable feature of the sub-Arctic region. In areas of mixing, such as the vicinity of the Aleutian Islands and in some areas of the Bering Sea, the marked halocline deepens (Fig. 2(b), K), and the lower limit "L" becomes indefinite (Fig. 2(b), J). This latter feature has been reported previously (Dodimead, 1958) and has been demonstrated in the Strait of Juan de Fuca by Tully (1957). In extreme cases, the structure becomes nearly isohaline throughout the column (Fig. 2(b), L).

Within the transition zone, the upper zone and halocline become less pronounced (Fig. 2(c)). They both disappear in the sub-Tropic waters (Fig. 2(b), G; Fig. 2(c)).

It is noted that in the western sub-Arctic, when the lower limit of the halocline can be defined, the salinity at "L" approximates 33.8‰. This is very near the values that have been reported for the eastern sub-Arctic (Doe, 1955; Tully and Dodimead, 1957; Dodimead, 1958.)

SALINITY AND TEMPERATURE STRUCTURES AT OCEAN STATION "P"

A sequence of salinity and temperature structures (natural plot) at Ocean Station "P" (lat 50°N; long 145°W) is shown in Figure 3. In the following discussion it must be noted that the movement of water in the vicinity of Ocean Station "P" is generally slow, 1–2 miles per day. In addition the water reaching this area is subject to similar climatic conditions as that at Ocean Station "P" and can be regarded as having resided there.

In Figure 3 are shown the changes that occur in the structures from the end of the cooling period, March, through the period of heating, April to October (Tabata, 1958), and to the commencement of the next heating period. It is seen that the salinity and temperature structures are isohaline and isothermal respectively to "D" during the late cooling period. Both the salinity and temperature structures undergo changes above "D" during the period of heating. The structures again become homogeneous during the following cooling period. These changes recur from year to year. It is apparent that the upper zone is established during the period of cooling, and although it undergoes changes, it can be defined throughout the period of heating and is again re-established during the winter period. The salinity and temperature established from the surface to "D" (upper zone) will depend on the degree of cooling, strength of winds, amount of fresh water in the upper zone, and to some degree on the temperature which the water in the upper zone attained during the previous summer. It is evident that these processes do not extend below "D".

Three noticeable changes occur in the salinity structure during the period of heating. These can be related to the development of a marked thermocline within the upper zone (Fig. 3(e)) and the "entrainment" process (Tully and Barber, 1959).

First, because of the stability inherent in the thermocline, which reaches a maximum in early September, the extent of mixing under extremes of summer winds is limited. It is defined by the relatively isohaline and isothermal layer, which is generally between 10 and 30 metres in depth.

Secondly, coincident with the thermocline, a secondary halocline may develop. Fresh water added to the upper zone in summer is conserved in the region above the thermocline.

Thirdly, below the thermocline, and the secondary halocline, if present, the salinity structure, instead of being isohaline, as during the period of cooling, develops a slight gradient to "D". This change in structure can be related to the "entrainment" from the halocline, of water of higher salinity than that immediately above it (Tully and Barber, 1959). This upward transfer from the halocline is probably limited to some level within the thermocline.

In Figure 4 are shown the early stages of reestablishment of the upper zone. During the period, October through November, the thermocline deepens and is partially destroyed by mixing. At the same time the secondary halocline deepens, and it is difficult to differentiate the secondary and primary halocline (Fig. 4(b), (c)). As a result a relatively shallow isohaline and isothermal upper zone is formed. As the season advances both the top of the halocline and thermocline deepen. This process continues through the cooling period until the waters become homogeneous to a depth defined in the salinity struc-

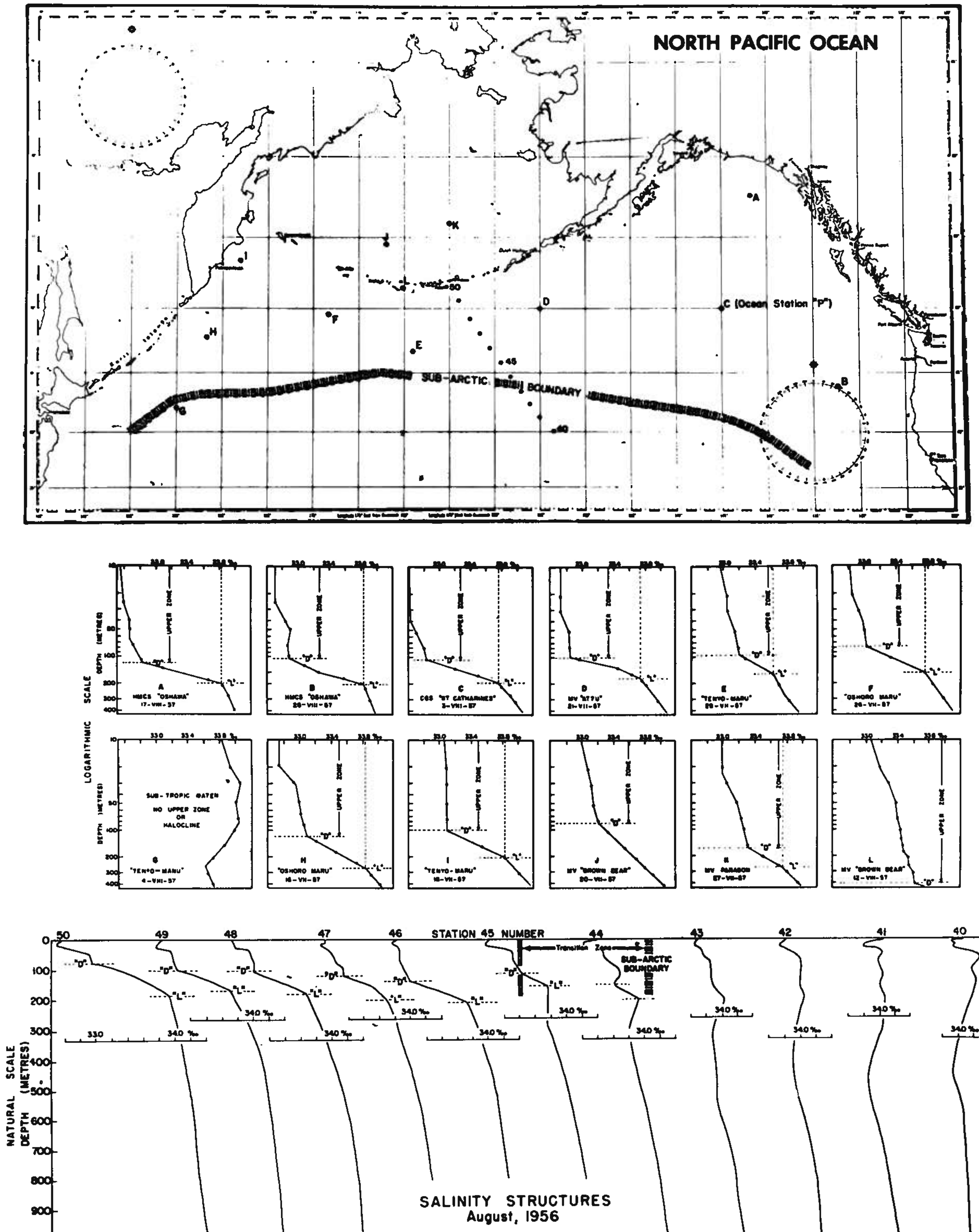

NORTH PACIFIC OCEAN
C (Ocean Station "P")
SUB-ARCTIC BOUNDARY
UPPER ZONE
SUB-TROPIC WATER
NO UPPER ZONE
OR
HALOCLINE
LOGARITHMIC SCALE
DEPTH (METRES)
STATION NUMBER
Transition Zone
SUB-ARCTIC BOUNDARY
NATURAL SCALE
DEPTH (METRES)
SALINITY STRUCTURES
August, 1956

FIGURE 2. a, b, c

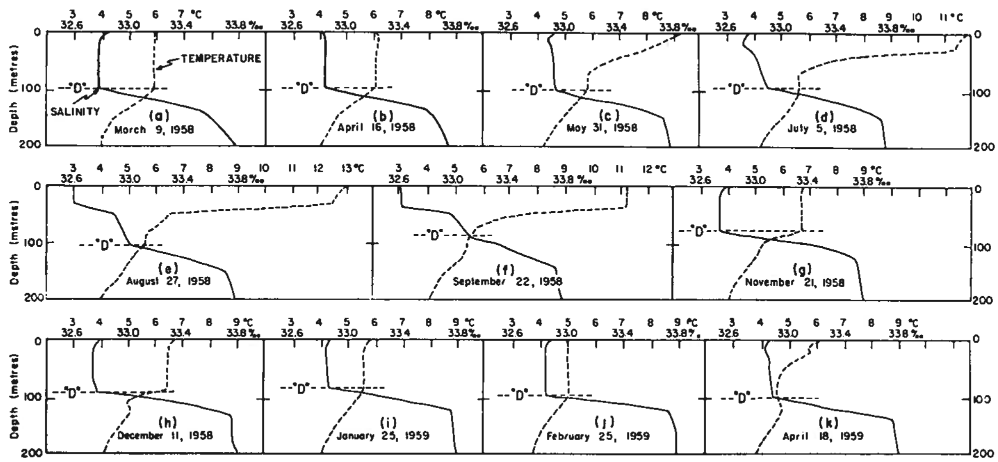


FIGURE 3. **Salinity (–) and temperature (– –) structures at Ocean Station " P " (lat 50°N, long 145°W) March 1958–April 1959.**

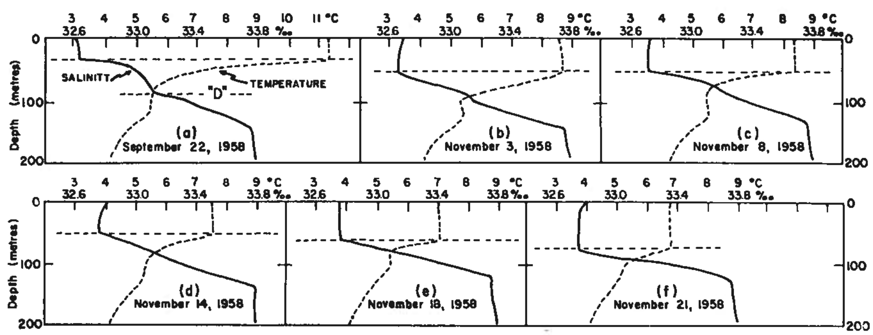
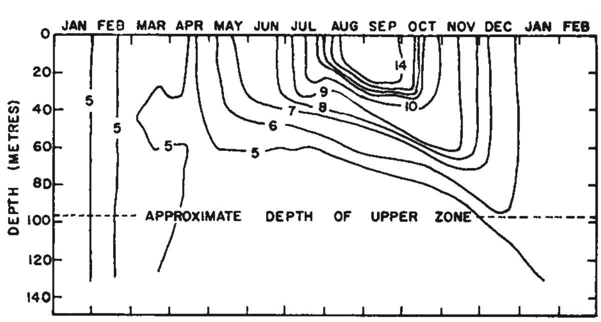
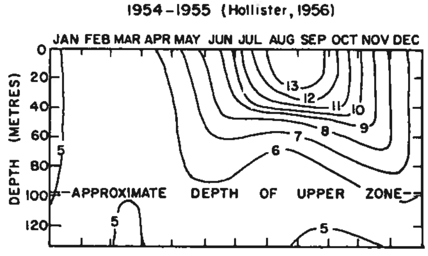


FIGURE 4.



TEMPERATURES (°C) AT OCEAN STATION "P" (lat 50°N, long 145°W) 1954–1955 (Hollister, 1956)



TEMPERATURES (°C) AT OCEAN STATION "P" (lat 49°N, long 148°W), 1943–1949 (Robinson, 1957)

FIGURE 5.

ture by the point " D " (Fig. 3(j)).

During the early period of heating and especially during the early period of cooling, warm water penetrates to greater depths within the upper zone than during mid-summer. This feature is shown in Figure 5 (Hollister, 1956; Robinson, 1957). The latter period is one of maximum winds, the former being one of moderate winds (Tabata, 1959). Because of the penetration of warm water to moderate depths in the upper zone, it is suggested that the mixing to homogeneity and the establishment of the depth " D " must be due primarily to wind action.

Further evidence in support of wind action is found in the depth of the upper zone calculated from Ekman's emperical relation

$$D = \frac{7.6\,W}{\sqrt{\sin \varphi}} \quad \text{(Sverdrup } et\ al\text{, 1942)}$$

This expression gives a value of 112 metres for wind speeds of 25 knots which are average in the region during the cooling period (Tabata, 1959). The calculated value is near that observed at Ocean Station " P " (95–105 metres).

Under more extreme conditions of winds, the homogeneous zone would probably deepen to some greater depth where the stability inherent in the halocline would retard further deepening of the upper zone.

TEMPERATURE STRUCTURES

It has been shown that the upper zone is established during the period of cooling and that the temperature structure is isothermal in this zone. By the end of the cooling period, two extremes of temperature structure are found in the sub-Arctic region; an isothermal layer to " D " and a negative thermocline (Fig. 3); and an isothermal layer to " D " and a positive thermocline (Fig. 6(a)). In either case the winter thermoclines lie in the halocline. Between these extremes the water column may be nearly isothermal throughout the upper zone and halocline. These structures are primarily dependent upon the extent of cooling and the temperature of the water in the halocline.

As a result of surface heating and the development of a thermocline within the upper zone in summer, two primary temperature structures are found. The first are those shown in Figure 3 for the summer months. The second has a subsurface minimum at " D " and a maximum in the halocline (Fig. 6(b)). This structure is very common in the western and to a lesser extent in the eastern sub-Arctic. The subsurface minimum has been reported as " dichothermal " water by Uda (1935) who considered it to be formed by cooling during the previous winter. It has not been associated with the depth " D " defined in the salinity structure. It is now evident that the temperatures of the water at " D " extended to the surface during the winter months.

The upward mixing processes, " entrainment ", that change the salinity structure in the vicinity of " D " during the summer months will alter the temperature structure slightly. In the

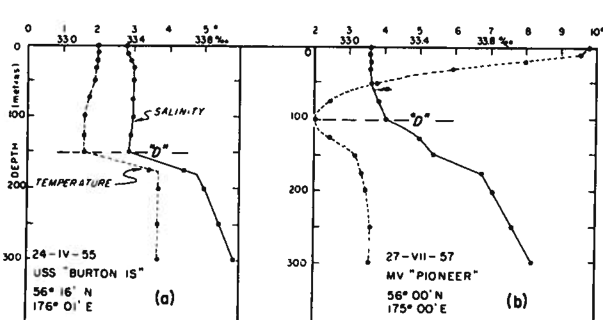


FIGURE 6.

case of the " dichothermal " structure, temperatures of the waters at " D " in summer will probably be slightly higher than those established in winter, since the waters above and below " D " are warmer than those at " D ". In the other structure, the temperature established at " D " in winter will probably be similar to that observed in the summer, since the temperature gradient in the vicinity of " D " is generally small.

It is now apparent that the extremes of temperature and salinity of the water established in the homogeneous upper zone during the winter persist within small limits and can be recognized at the depth " D " through the following spring and summer. It is further proposed that the winter distributions can be recognized in the summer data. This is discussed in the following sections.

SUMMARY OF DATA

The results of the analysis from the salinity *vs.* logarithm of the depth plot are shown in Figures 7 through 12 for 1956, 1957, 1958 and 1959. The summer distributions were obtained using mainly July-August data, made available by the oceanographic and fisheries agencies in Japan (12, a, b), United States (13, a, b, c), and Canada (14). The only winter data available were from the eastern sub-Arctic. In some areas, where salinity data were lacking, or the depth intervals of the observations were not sufficient to define the structure, the temperature at " D " was determined from the temperature structure alone if a marked " dichothermal " structure existed. This method is not always possible, since in some regions, especially the eastern sub-Arctic, small inversions of temperature occur which are not a result of previous winter cooling, but may be a remnant from cooling two winters previous, or due to lateral intrusion of water in or below the halocline.

DEPTH OF UPPER ZONE

The depth of the upper zone is shown in Figures 7 and 8. Over the eastern sub-Arctic (east of longitude 160°W), the average depth was of the order of 90 to 95 metres, with little evidence of seasonal variation from winter to summer. In the Alaska Gyral, " D " was generally found at depths less than 75 metres and is associated with the dome (anticline of lower zone water, Tully and Dodimead, 1957) and the anticlockwise circulation in this region. Near the Canadian coast and southward the depth at " D " was generally less than 75 metres. This is a region of relatively warm brackish water. In

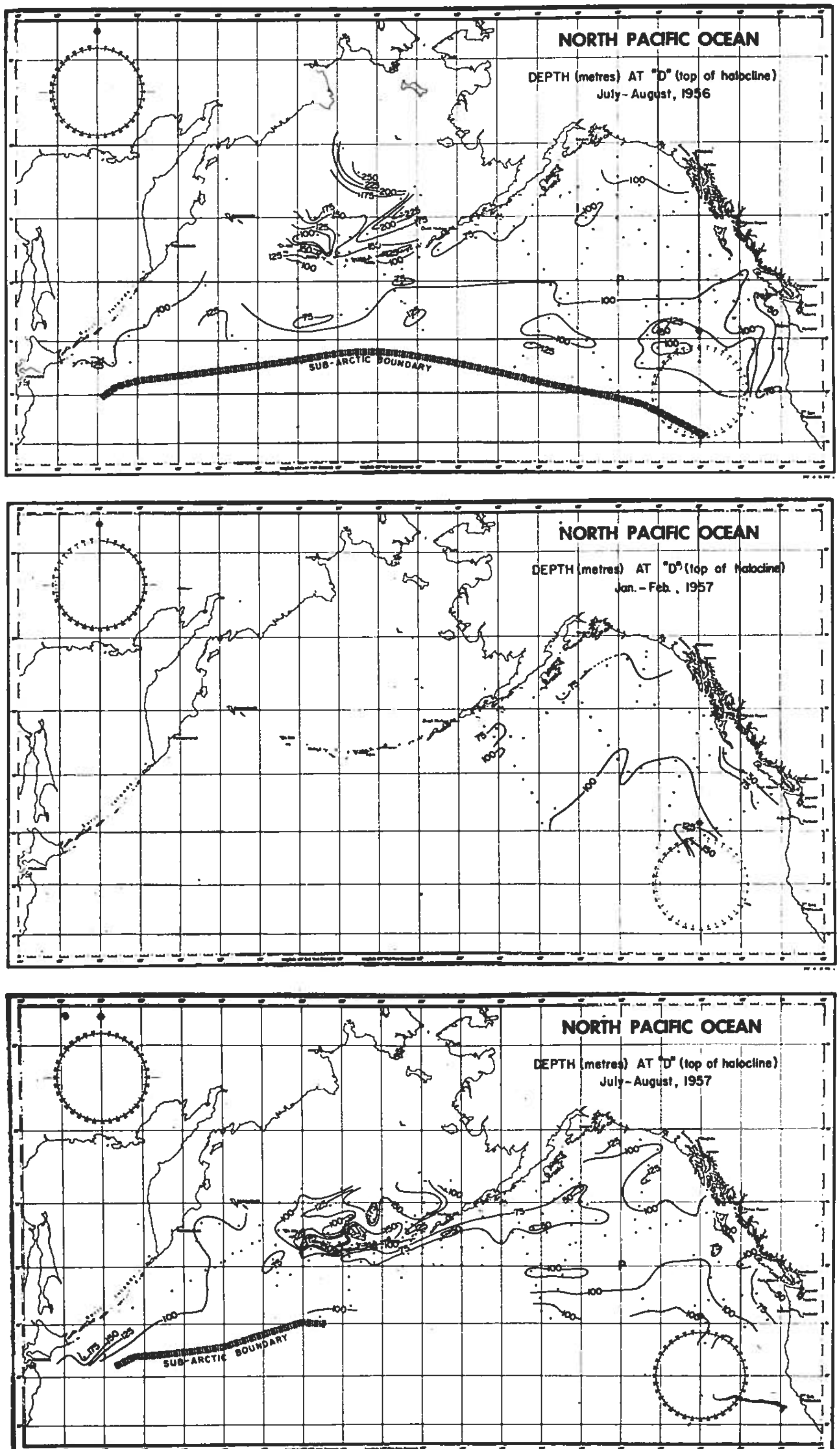

NORTH PACIFIC OCEAN
DEPTH (metres) AT "D" (top of halocline)
July-August, 1956
SUB-ARCTIC BOUNDARY
NORTH PACIFIC OCEAN
DEPTH (metres) AT "D" (top of halocline)
Jan.-Feb., 1957
NORTH PACIFIC OCEAN
DEPTH (metres) AT "D" (top of halocline)
July-August, 1957
SUB-ARCTIC BOUNDARY

FIGURE 7.

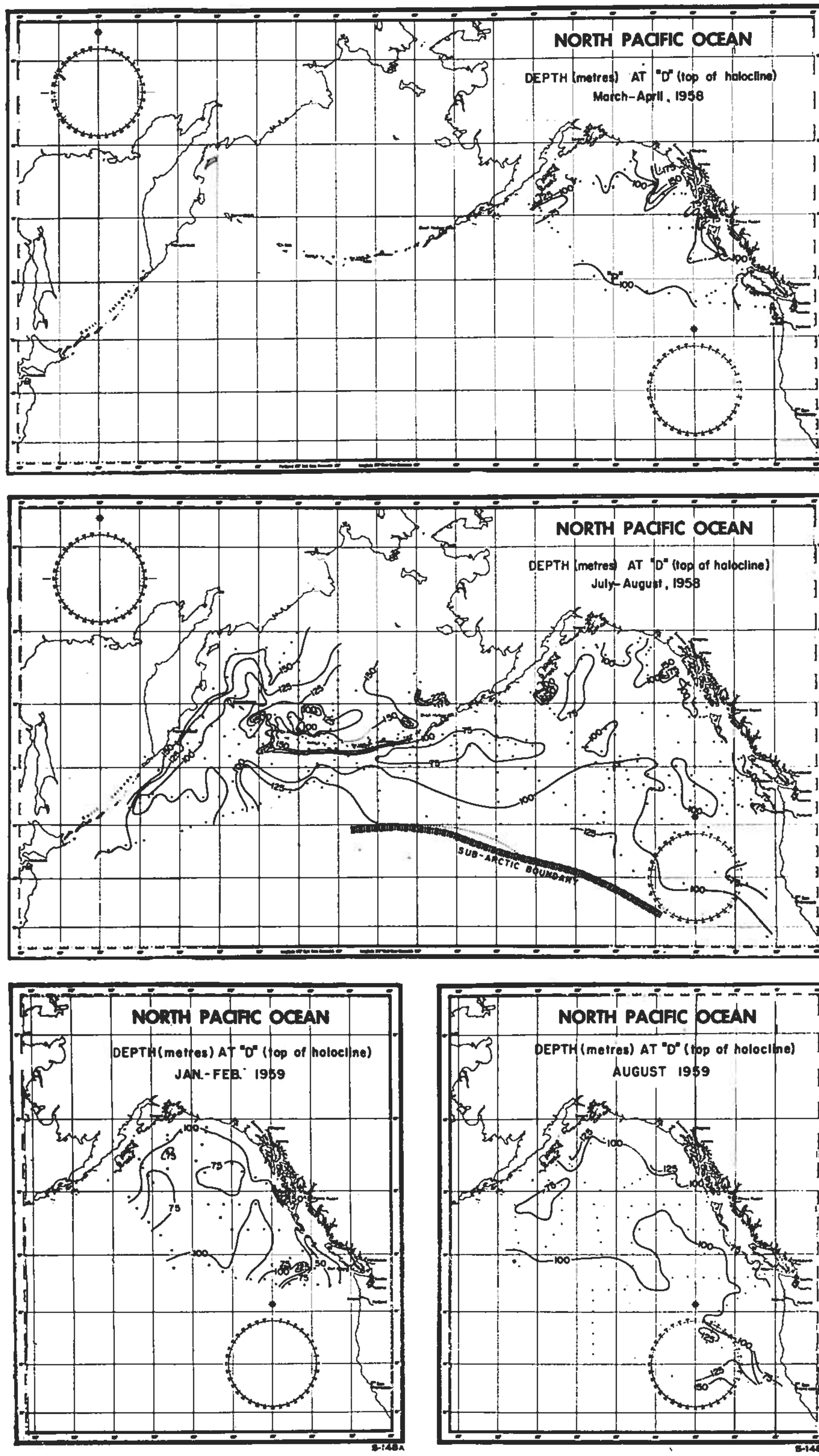

NORTH PACIFIC OCEAN
DEPTH (metres) AT "D" (top of halocline)
March-April, 1958
NORTH PACIFIC OCEAN
DEPTH (metres) AT "D" (top of halocline)
July-August, 1958
SUB-ARCTIC BOUNDARY
NORTH PACIFIC OCEAN
DEPTH (metres) AT "D" (top of halocline)
JAN.-FEB. 1959
NORTH PACIFIC OCEAN
DEPTH (metres) AT "D" (top of halocline)
AUGUST 1959

FIGURE 8.

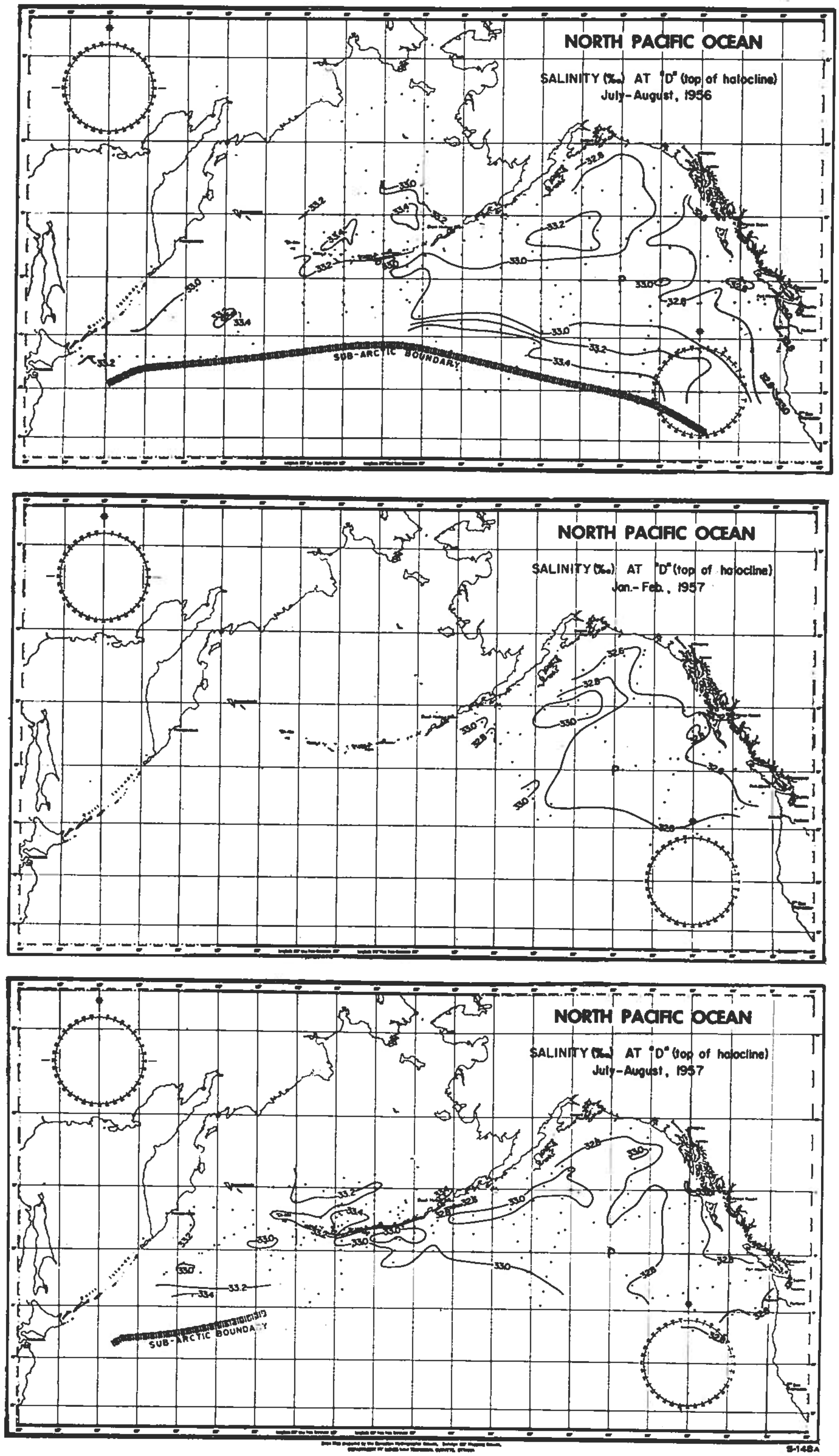

NORTH PACIFIC OCEAN
SALINITY (‰) AT "D" (top of halocline)
July-August, 1956
SUB-ARCTIC BOUNDARY
NORTH PACIFIC OCEAN
SALINITY (‰) AT "D" (top of halocline)
Jan.-Feb., 1957
NORTH PACIFIC OCEAN
SALINITY (‰) AT "D" (top of halocline)
July-August, 1957
SUB-ARCTIC BOUNDARY
S-148A

FIGURE 9.

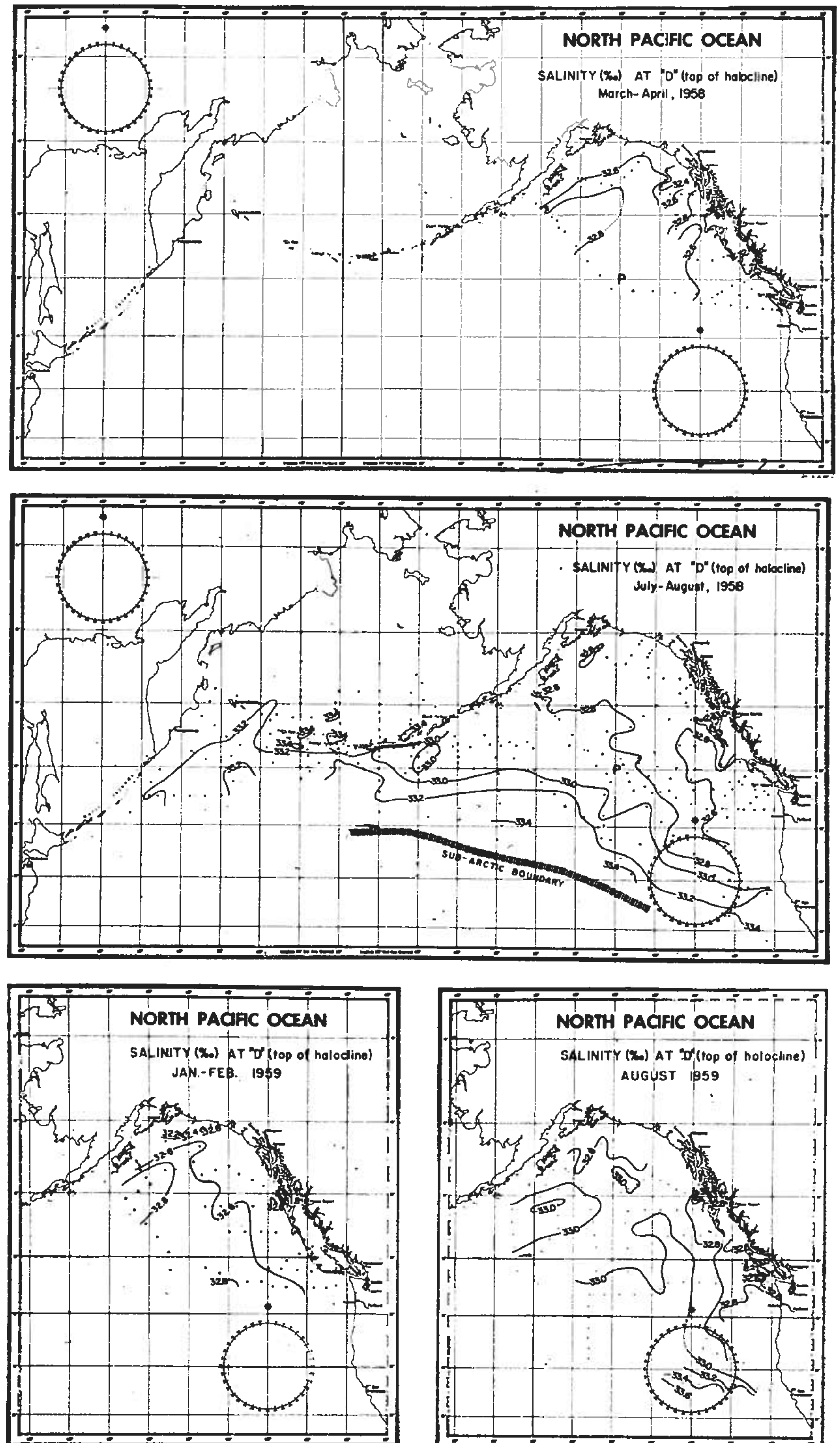

NORTH PACIFIC OCEAN
SALINITY (‰) AT "D" (top of halocline)
March- April, 1958
NORTH PACIFIC OCEAN
SALINITY (‰) AT "D" (top of halocline)
July- August, 1958
SUB-ARCTIC BOUNDARY
NORTH PACIFIC OCEAN
SALINITY (‰) AT "D" (top of halocline)
JAN.-FEB. 1959
S-148A
NORTH PACIFIC OCEAN
SALINITY (‰) AT "D" (top of halocline)
AUGUST 1959
S-148A

FIGURE 10.

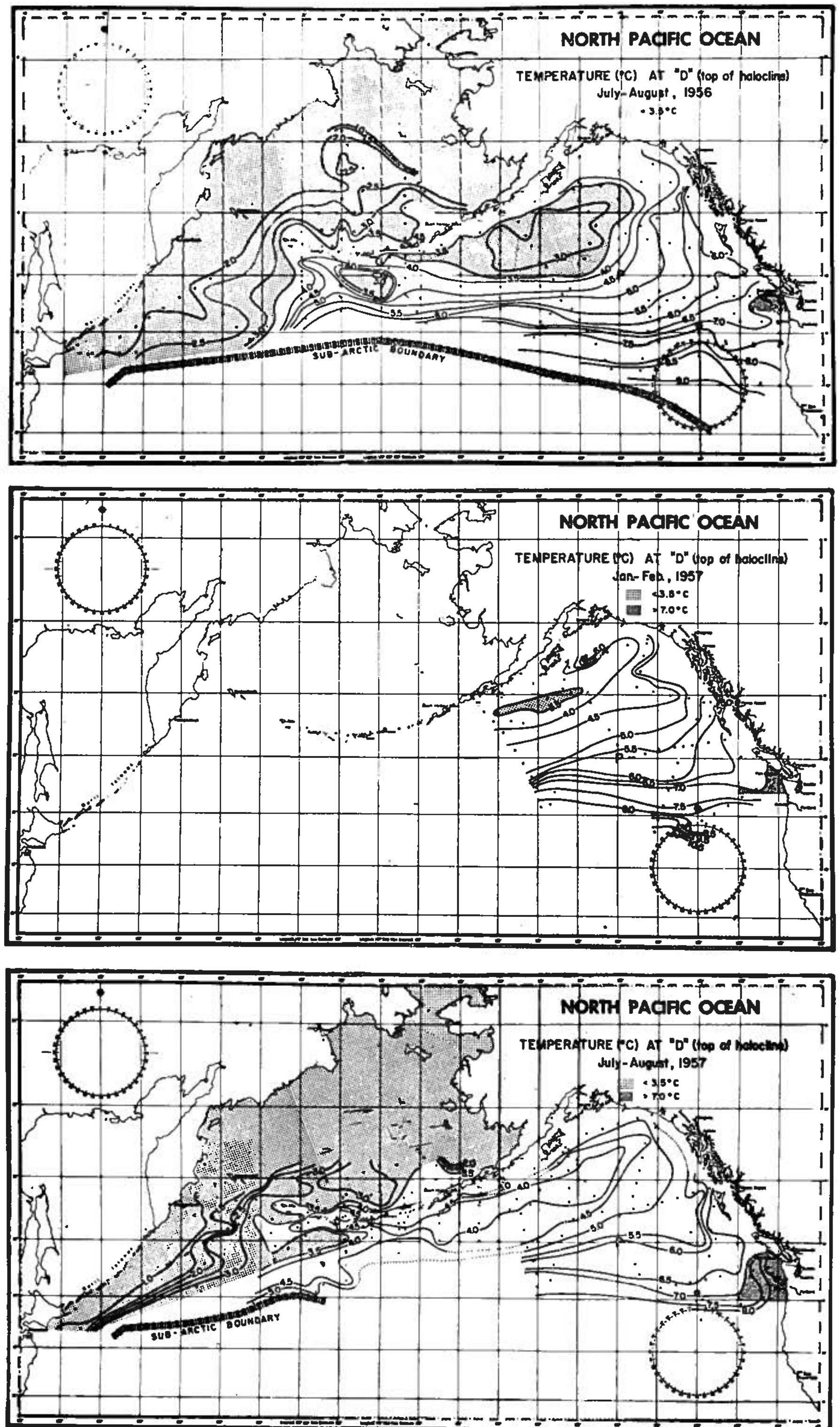

NORTH PACIFIC OCEAN
TEMPERATURE (°C) AT "D" (top of halocline)
July-August, 1956
SUB-ARCTIC BOUNDARY
NORTH PACIFIC OCEAN
TEMPERATURE (°C) AT "D" (top of halocline)
Jan-Feb, 1957
<3.5°C
>7.0°C
NORTH PACIFIC OCEAN
TEMPERATURE (°C) AT "D" (top of halocline)
July-August, 1957
<3.5°C
>7.0°C
SUB-ARCTIC BOUNDARY

FIGURE 11.

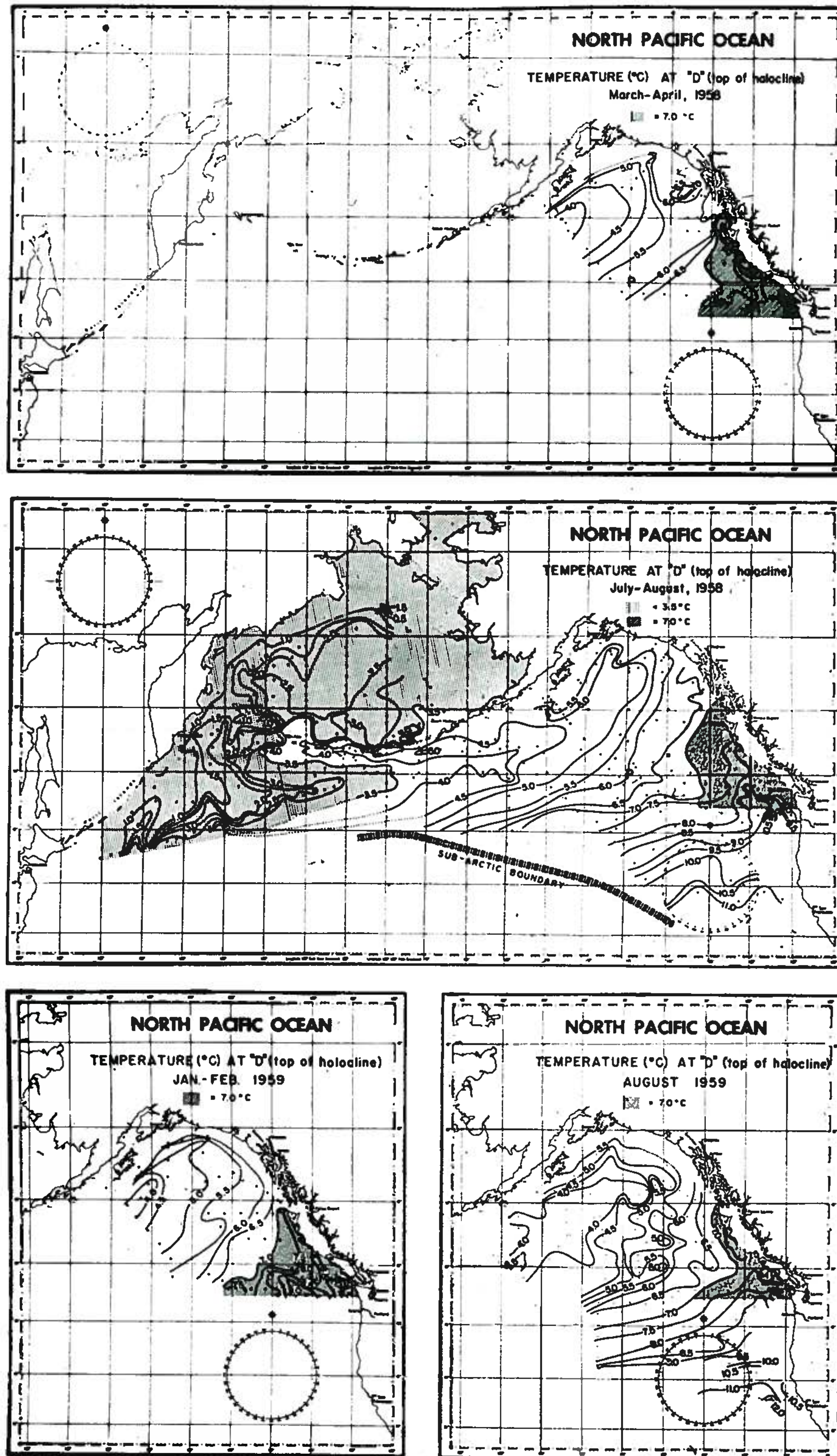

NORTH PACIFIC OCEAN
TEMPERATURE (°C) AT "D" (top of halocline)
March-April, 1958
= 7.0 °C
NORTH PACIFIC OCEAN
TEMPERATURE AT "D" (top of halocline)
July-August, 1958
< 3.5°C
= 7.0°C
SUB-ARCTIC BOUNDARY
NORTH PACIFIC OCEAN
TEMPERATURE (°C) AT "D" (top of halocline)
JAN.-FEB. 1959
= 7.0°C
NORTH PACIFIC OCEAN
TEMPERATURE (°C) AT "D" (top of halocline)
AUGUST 1959
= 7.0°C

FIGURE 12.

the northeastern part of the Gulf of Alaska, the upper zone was generally deeper than 100 metres.

The largest variations in the depth of the upper zone were found in the vicinity of the Aleutian Islands and in the Bering Sea. These are areas of marked vertical mixing. Near the Asian coast, the upper zone was relatively deep. This is an area of extreme cooling. In other areas of extreme cooling (eastern and northern Bering Sea), the stability of the upper zone, due to fresh water influence, limits the depth of vertical mixing.

SALINITY DISTRIBUTIONS AT "D"

The salinity distributions at "D" are shown in Figures 9 and 10. The highest salinity water was found in the vicinity of the Aleutian Islands, the Bering Sea and in the transition zone (33.2–33.4‰). Relatively high salinity water was present in the Alaska Gyral (33.0–33.2‰). As expected, there appears to be some seasonal variation (winter to summer) in the salinity at "D", higher values occurring during the summer than during the previous winter. The variations were generally less than 0.2‰ within a locality. Yearly variations were of the same order of magnitude. The most marked changes occurred during 1958. In the Gulf of Alaska, salinities at "D" were lower than those observed in the previous periods. At the same time in the Bering Sea salinities were higher than previously.

TEMPERATURE DISTRIBUTIONS AT "D"

Temperature distributions (Figs. 11 and 12) are most interesting because of the marked year to year variations that have occurred. The stippled areas represent water of temperatures less than 3.5°C. In August, 1956, cold water (less than 3.0°C) was present in the Alaska Gyral. After this period the water, generally, became progressively warmer to the summer of 1958. The disappearance of cold water from this area was accompanied by an increase in the temperatures of the waters between Ocean Station "P" and the coast, and northward into the eastern part of the Gulf of Alaska. This is indicated by the crosshatched areas of water greater than 7.0°C. This phenomenon is not solely associated with the degree of cooling and heating since it has been shown that an intrusion of warm water below the depth of seasonal influence occurred during these periods (Tully *et al*, 1959). Following the summer of 1958, the waters in these areas have become colder at "D". This suggests a dissipation or a retreat of the warm water intrusion.

South of the Aleutian Islands, the water was relatively warm (warmer than 3.5°C) during the summer 1956, except for a small relatively cold cell in the vicinity of 180° longitude, and the extension of the tongue of cold water from the Alaska Gyral. A slight change is noted in the summer 1957. The main body of cold water appears to have intruded further east than previously. A marked change is noted in the summer 1958. The waters were generally cold (colder than 3.5°C) further eastward and southward in this region than in the two previous periods. Thus it is seen that when relatively warm conditions appeared in the eastern sub-Arctic, relatively cold conditions prevailed in the western sub-Arctic.

It is noted that the temperature distributions at "D" in the eastern sub-Arctic were generally the same from winter to the following summer, except in the Alaska Gyral, for the periods 1956 and 1958 (Figs. 11 and 12). In this area, the water at "D" was slightly warmer in summer (0.2 to 0.5°C) than in the previous winter. This warming can be attributed to mixing resulting from "entrainment", as this is generally an area of dichothermal structure.

To casual inspection it appears that the summer distribution of temperature at "D" is not as representative of the actual winter distribution at "D" for 1959 (Fig. 12) as was the case for the previous periods.

The discrepancy between these two periods can be explained. First, there was fairly marked cooling after the completion of the winter survey (January 1959). This was not the case in the other winter surveys (Fig. 13). Thus the

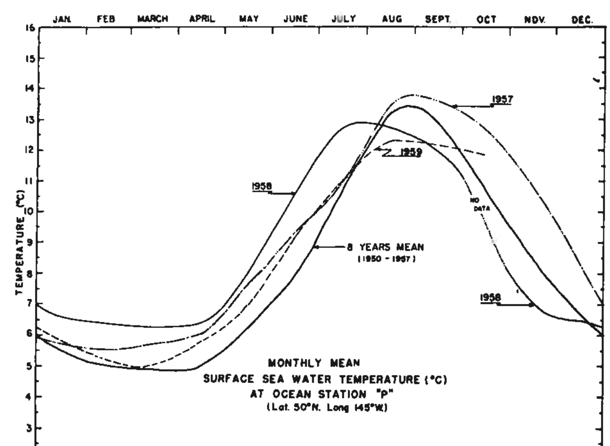


FIGURE 13.

minimum of the winter conditions was not observed. Secondly, it is suggested that there has been a change in the general trend of warming which has occurred from 1955 through 1958. This is discussed by Tully *et al* (1959). It is associated with the change in the circulation in this region. Thus it appears that the circulation was returning to the situation observed during 1956. These two factors can account for the differences observed.

CONCLUSIONS

It can be concluded that for the eastern sub-Arctic, the temperature and salinity distributions at " D " during the summer are indicative of those during the previous winter, providing minimum winter conditions were observed. It follows that each summer distribution reflects very closely that of the previous winter for the whole of the upper zone. It is proposed that these conclusions are applicable for the whole of the sub-Arctic region for these periods.

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