ON THE PHYSICAL OCEANOGRAPHY OF BRISTOL BAY 1969-1970

A

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ON THE PHYSICAL OCEANOGRAPHY OF BRISTOL BAY 1969-1970

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ABSTRACT

The examination of hydrographic data obtained in Bristol Bay 1969-1970 allowed oceanographic conditions in this region to be described for shorter time periods (several weeks) than previous studies (several months). This data revealed that during early spring Bristol Bay was homogeneous both vertically and horizontally in temperature and vertically in salinity. During late spring, a steep thermocline developed in the offshore regions and was present throughout summer, while the salinity structure remained vertically homogeneous. Salinity and bottom temperature contours tended to follow isobaths and indicated a cyclonic circulation in the bay. Summer surface temperature distributions are characterized by regions of cold water. These regions are believed to be maintained by upwelling of cold bottom water due to a subsurface convergence in the bottom Ekman layer. Data from 1970 showed that low temperature and high salinity water was much more extensive in that year than in 1969. This is attributed to deeper water from outer Bristol Bay surfacing in central Bristol Bay.

ACKNOWLEDGMENTS

I wish to thank the members of my committee, Dr. Robin Muench, Dr. Bill Reeburgh and Dr. Tom Royer, who were always willing to listen to problems and offer suggestions throughout my work at the University of Alaska. I would also like to thank my wife, Chris, who carefully proofread this work numerous times.

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CHAPTER ONE

INTRODUCTION

Description of Area

Locality and Bathymetry

Bristol Bay is that area eastward of a line drawn from the Kuskokwim River to Cape Sarichef, Unimak Island (Fig. 1). It is bordered to the south by the Alaska Peninsula, which isolates it from the North Pacific. The area covers roughly 200,000 sq. km and in most places it is less than 100 meters deep. For purposes of this study, the area's boundaries were taken as the region enclosed by the Alaska Peninsula to the south, longitude 165° on the west, and mainland Alaska to the east and north.

The inner, central and outer Bristol Bay are identified in Fig. 1. Inner Bristol Bay is that area east of a line from Port Heiden to Hagemeister Island. Central Bristol Bay is that area west of inner Bristol Bay and east of a line from Cape Newenham to the eastern end of Unimak Island. Outer Bristol Bay extends from its boundary with central Bristol Bay westward to 165° west. Central refers to the area defined in Fig. 1, while middle Bristol Bay will be used to distinguish the region parallel to the Alaska Peninsula between northern and southern waters in all areas of the bay.

Bathymetry of the bay is shown in Fig. 2. Isobaths form a trough which opens to the west. Depths increase gradually seaward from the

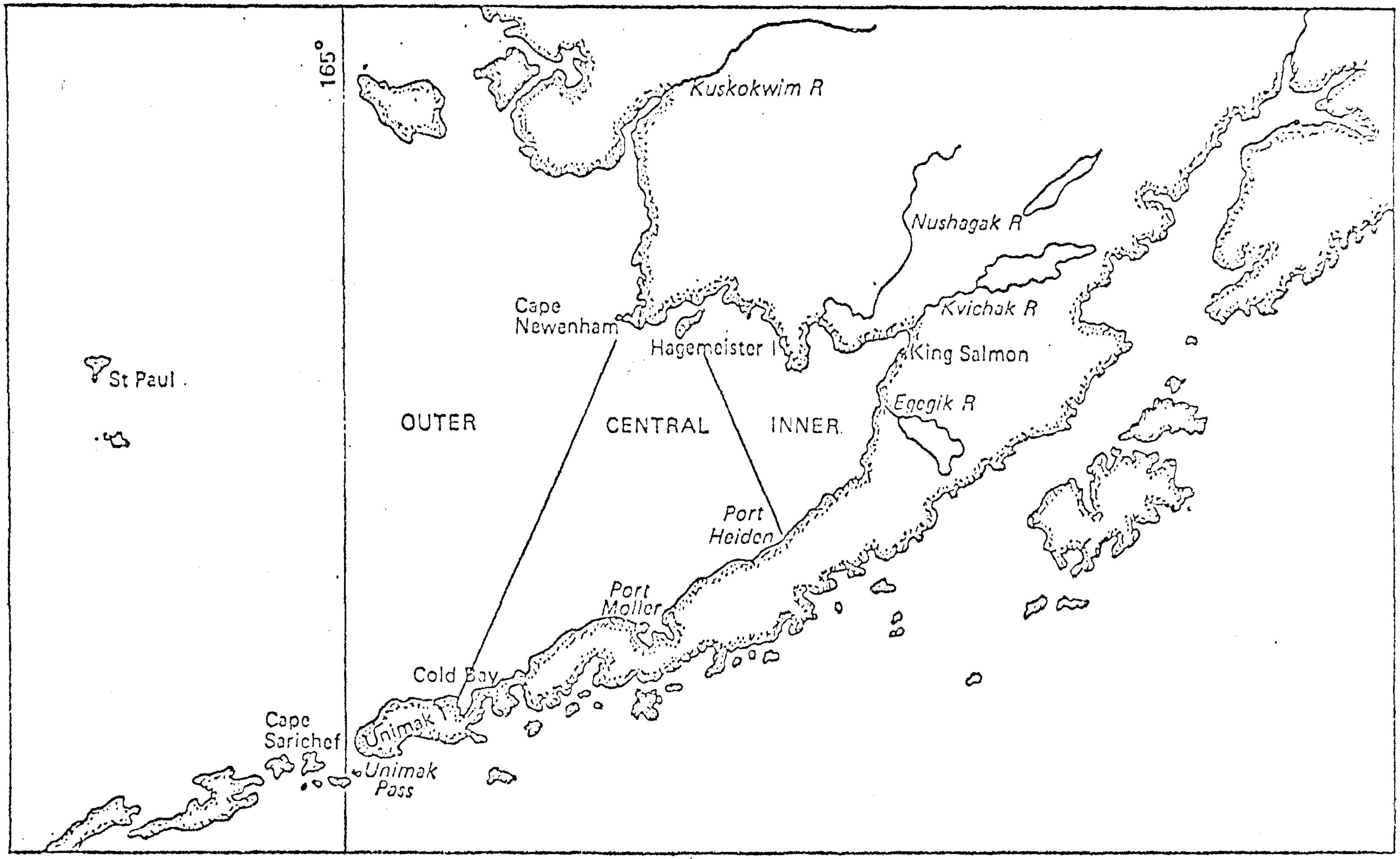


Fig. 1 Bristol Bay with place names and subdivisions used in this work.

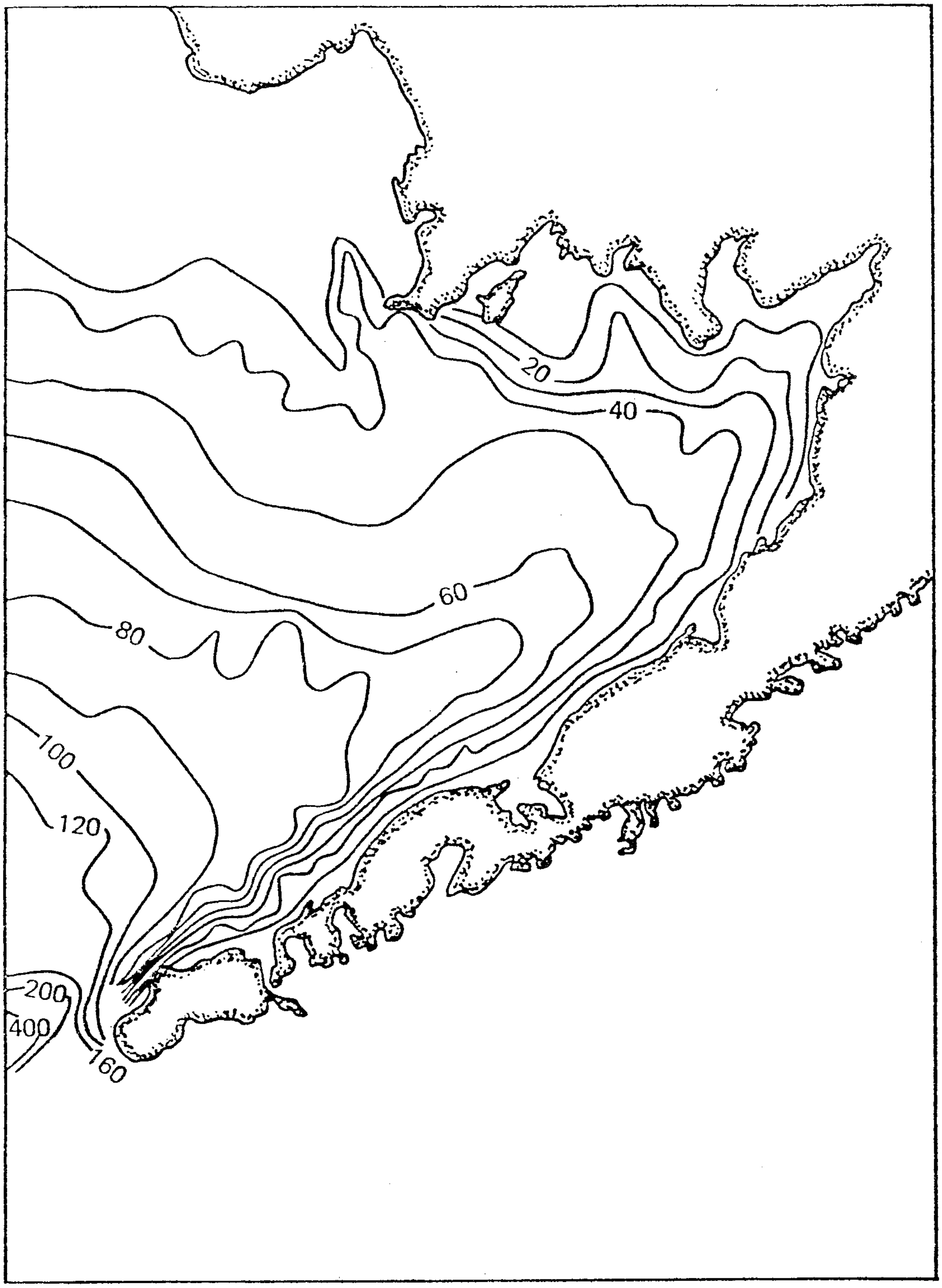


Fig. 2 Bathymetry of Bristol Bay with depth in meters.

coasts towards the mouth of the bay where depths are greater than 100 m. The bottom of Bristol Bay is essentially flat, having an average bottom gradient of 0.02°/‰ with minimal relief variations (Lisitsyn, 1966).

Climate and Weather

Bristol Bay's weather is controlled by interaction between the North Pacific High and Aleutian Low systems during the summer and winter, respectively. These interactions produce fair summer weather as compared to that in winter. The climate is characterized by cloudy skies, mild temperatures relative to the surrounding land and relatively heavy precipitation. Records from the Environmental Data Service indicate that annual precipitation in the Bristol Bay area ranges from 33 cm at Port Heiden to 86 cm at Cape Newenham. The differences in these values are due to geographical and topographical influences and should be extrapolated with caution when referring to the bay itself. Most precipitation occurs in the summer and fall from June to November. Maximum summer temperatures are in the low sixties, while temperatures approach zero in the winter.

Local wind data from the Bristol Bay area are available from the Air Weather Service, U.S.A.F., for six locations in the region: Cape Sarichef, Cold Bay, St. Paul, Cape Newenham, King Salmon and Port Moller (Fig. 1). As with the precipitation values, caution should be used in extrapolating wind data to the bay itself because of topographical influences. Generally, winds are northerly in late fall and winter and shift to southerly in late spring (Dodimead et al., 1963).

Summer winds are highly variable in direction. The wind stress curl shows a tenfold increase in the winter over that in summer (Hughes et al., 1974).

Freshwater Runoff

The area surrounding Bristol Bay provides an extensive watershed. Major freshwater inputs into the bay include the Kuskokwim, Egegik, Nushagak, and Kvichak rivers (Fig. 1), as well as hundreds of smaller rivers and streams. Discharge records available from the United States Department of the Interior (1974) gave the average discharge of the Kvichak as 480.9 $m^3 sec^{-1}$ over the past 7 years and Kuskokwim as 1,232 $m^3 sec^{-1}$ over the past 23 years. These records showed that the peak period of runoff is from May to October. This spring and summer freshwater input, in conjunction with extensive ice formation in the winter, results in a considerable range of oceanographic conditions for Bristol Bay (Dodimead et al., 1963).

Ice Conditions

One of the most characteristic features of Bristol Bay is its extensive winter ice cover (Fig. 3). The extent of winter ice is dependent on the severity of winter temperatures. Ice formation begins as early as November and persists into April (Dodimead et al., 1963). The ice is locally formed (Tabata, 1974) and dissipates in place, usually by the middle of May. The duration of the ice cover may be dependent on local winds during spring. Konishi and Saito (1974) found that the ice cover in Bristol Bay was more persistent when winds tended to be northerly during May to June 1971. In 1967, when ice cover was

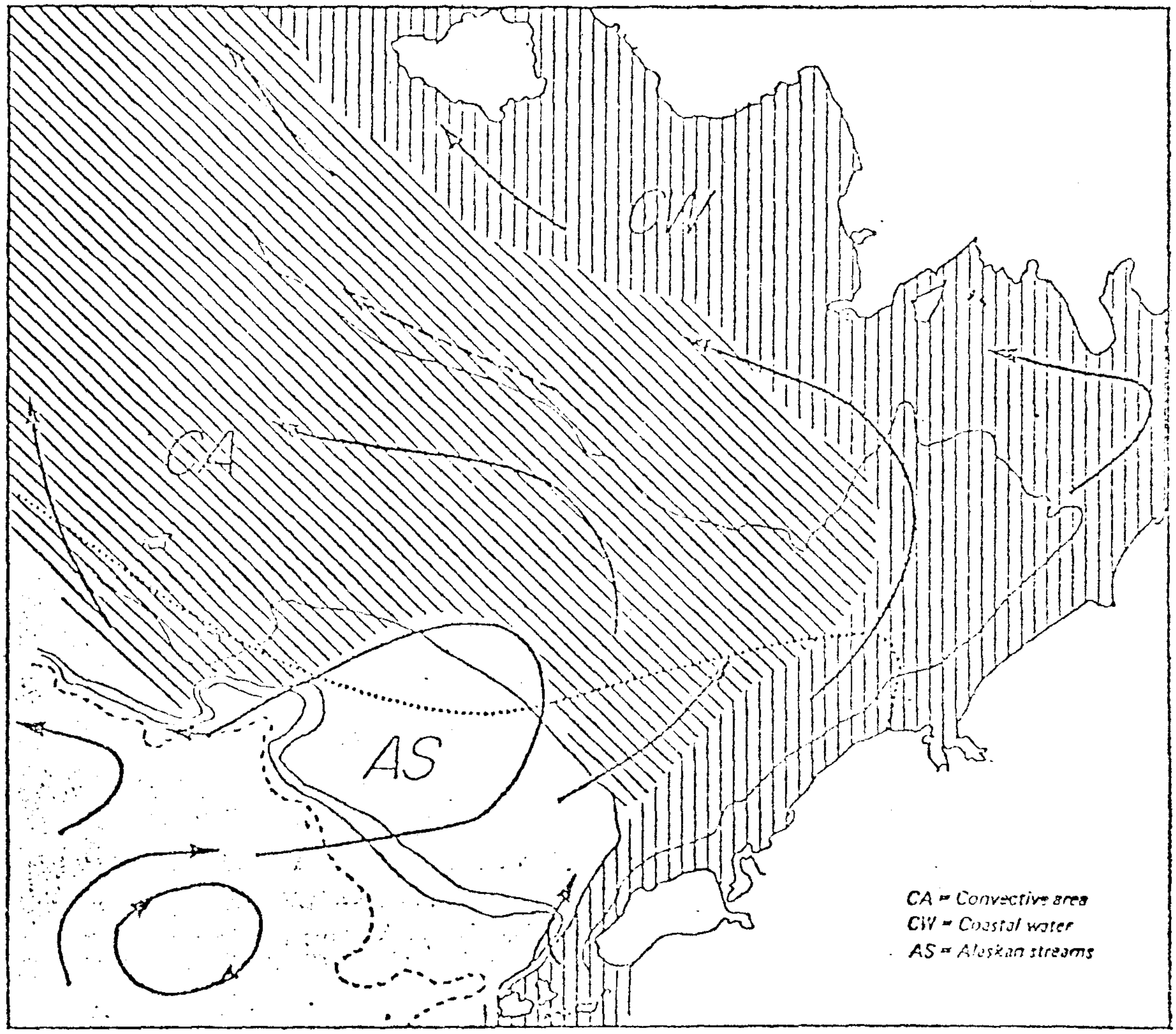


Fig. 3 Water massas of Bristol Bay according to Takenouti and Ohtani (1974). Dotted line is approximate ice edge in winter.

less persistent, winds were more southerly in direction. Satellite photographs of the Bering Sea for 1974 showed Bristol Bay was ice covered from January to April except for an area north of Unimak Island (Muench and Ahlnas, 1976). The open area north of Unimak Island is thought to be due to the advection of warm water in a northeast direction along the Bering Sea side of the Aleutian Chain, thus preventing ice formation north of the island (Muench, personal communication).

Circulation and Water Masses - Previous Works

The first extensive investigation into the Bristol Bay area took place in 1938, 1939, 1940 and 1941 aboard the U.S.C.G.T. Redwing. Data from this period have been summarized by Favorite et al., (1961). Drift stick measurements made during June 1939 were insufficient to delineate the mean flow because of dominant northeast-southwest tidal fluctuations (Dodimead et al., 1963). A cyclonic circulation was deduced from the temperature and salinity distributions (Dodimead et al., 1963).

An investigation of mean and tidal currents was carried out in Bristol Bay in June 1957 (Hebard, 1959). These Ekman current meter records at four anchor stations showed water movement into Bristol Bay along the Alaska Peninsula and a cyclonic circulation within the bay itself with speeds of less than .5 m sec^{-1}. Rotary tidal currents elongated in the northeast-southwest direction were found with speeds ranging from .05 to .86 m sec^{-1}.

Takenouti and Ohtani (1974) used water mass analysis to derive a circulation scheme for the Bering Sea. Their results showed that

Bristol Bay is mainly made up of coastal water and a convective area with the intrusion of Alaska Stream water in the extreme outer southwest portion of the bay (Fig. 3). Table 1 summarizes water characteristics of these Bristol Bay waters. The cyclonic circulation about inner Bristol Bay conforms with that found by Hebard (1959) and Dodimead et al., (1963). A major difference between Takenouti and Ohtani's scheme and that of previous works is the small cyclonic gyre-like feature found southeast of the Pribilofs.

More recent works have agreed with a general concept of a cyclonic circulation within Bristol Bay (Coachman, 1975; Myers and Muench, 1975), but finer details of the flow field remain incomplete.

Data - Objectives

Little is known about the regional oceanography of Bristol Bay. Extensive station coverage and hydrographic data collection has taken place during only two time periods. The first of these was the summer cruises of the U.S.C.G.T. Redwing, which have previously been mentioned. The second took place in the spring and summers of 1969 and 1970 aboard various ships. The data gathered during this period are available from the National Oceanographic Data Center (NODC). NODC data contain temperature, salinity and (when available) dissolved oxygen values at standard depths.

Previous studies of Bristol Bay have described oceanographic conditions with time scales on the order of several months. One major objective of this thesis is to describe conditions for shorter time periods with time scales varying from 1 to 5 weeks, depending on the

TABLE 1

Characteristics of Bristol Bay waters according to Takenouti and Ohtani (1974)

Region	Layer	Vertical distributions of temperature and salinity Summer	Winter
AS	Upper	0-20 m 8C, 32-32.6°/₀₀	deepening 2 to 3°C
	Thermocline	20-50 m, .2/m	vanish
	Halocline	20,30-100 m, .01/m	vanish on shelf
	Lower	4°C, 33-33.2°/₀₀	
CA	Upper	0-20,30 m 7°C, 31-32.5°/₀₀	
	Thermocline	10,20-30 m, > .3/m	isothermohaline
	Halocline	20-30 m, < .2	0 to 2°C
	Lower	.3°C	
CW	Surface	0-10 m, 5,6-3,4°C	isothermohaline
	Bottom	3-4°C, < 31.6°/₀₀	= 1.7 to 0°C

AS Alaskan Stream Water
CA Convective Area
CW Coastal Water

data. The time periods and number of stations are listed in Table 2. Included in the list is a 1968 cruise of the Institute of Marine Science (IMS), University of Alaska. Station locations for each period are shown in Appendix. 1.

TABLE 2

Time periods and number of stations used in this work

Year	Time Period	Number of Stations
1968	June 17 - July 3	50
1969	April 11 - 30	69
	May 1 - June 6	73
	June 15 - July 5	112
	July 5 - 31	89
	August 1 - 27	64
1970	March 29 - 31	18
	April 1 - 26	35
	May 22 - 30	40
	June 7 - July 3	49
	August 10 - 26	45
	September 16 - 21	41

CHAPTER TWO

DESCRIPTION OF CONDITIONS 1969-1970

Temperature

March (1970 only) and April were the earliest months for which data were available for this study. As would be expected for late winter, most of the bay displayed low temperatures and the water column was nearly homogeneous. It was well mixed from winter convection. Water in inner, central and northern outer Bristol Bay was homogeneous or showed a slight (.1 to .3°C) temperature increase from surface to bottom. Minimum temperatures for the water column found at the surface in these regions were probably due to the winter ice cover. The ice cover would affect temperature changes in the water column in relation to heat input. Heat input to the surface layers, principally from solar radiation, would be utilized, in part, to melt the ice (heat of fusion). Heat input at depth, from the advection and diffusion of warmer water into these regions, could be used totally to warm the water. Supporting this concept is that in southern outer Bristol Bay, which is ice free during winter (Fig. 3), maximum temperatures were found at the surface.

During March and April of 1969 and 1970, inner and central Bristol Bay had temperatures between 0 and 1°C. The warmest water found in Bristol Bay for this time of year was in the southwest corner just inside Unimak Pass. Here, surface temperatures reached almost 3°C during 1969 and were between 1.5 and 2°C for 1970. Higher temperatures in this region may be attributable to the advection of warm water into this area from two outside sources: Bering Sea water flowing northeasterly along the northern side of the Aleutian Chain, and Alaska Stream water intruding through Unimak Pass. Upwelling along the shelf break may also bring warm water to the surface in this region at this time of year. These processes will be pursued further in relation to conditions observed in the southwest corner of Bristol Bay.

During May, surface waters had started to warm and the conditions present throughout much of the bay during March and April were confined to the northern regions of central and outer Bristol Bay and coastal areas. Southern portions of the bay showed thermal stratification as opposed to the more northerly regions, and a distinct temperature front existed between these two areas. The separation of warmer southern stratified water and colder northern homogeneous water was evident from a temperature cross section of central Bristol Bay for 1970 (Fig. 4). The surface temperature decreased from 3°C to less than 1°C over a distance of roughly 30 km. Surface water south of this temperature front was between 2 and 3°C during 1969 and greater than 3°C during 1970. North of the front, temperatures were generally less than 1°C both years. The temperature front was not as pronounced during 1969, but was still evident. This may have been due to the fact that the May 1969 data was obtained throughout the month while May 1970 data was obtained during one week. Since considerable heating of Bristol Bay occurs during May, the 1970 data may have provided a more synoptic picture.

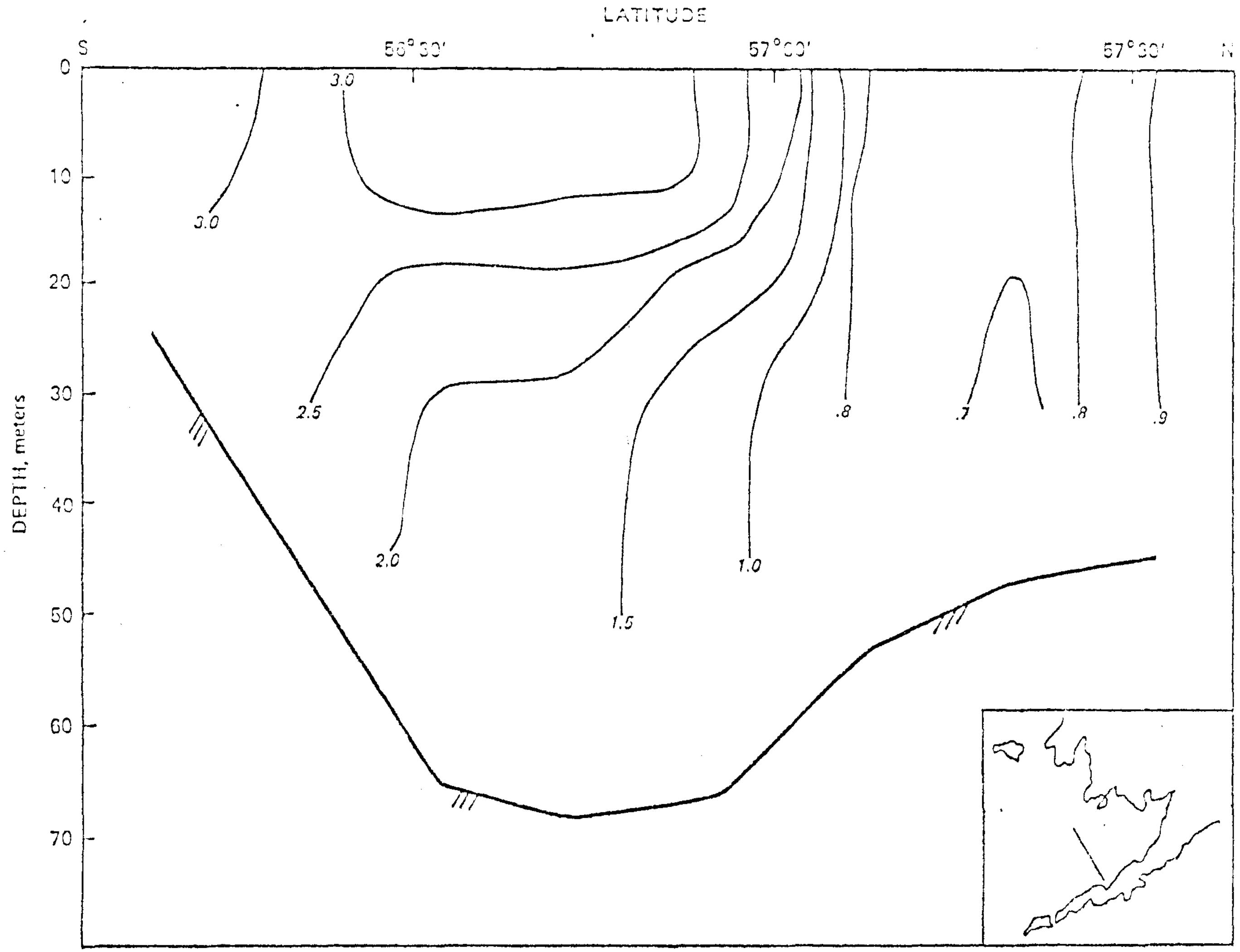


Fig. 4 Vertical temperature section across central Bristol Bay May 22-30 1970.

The horizontal temperature front observed during May may reflect the later melting of ice in northern Bristol Bay compared to southern Bristol Bay. This would cause a lag in heating of the north waters compared to water in southern Bristol Bay. An alternate explanation is that this front, located in water of approximately 60 m depth, may represent a dynamic boundary established by a current (in roughly the east-west direction) running through this region. Such a current, existing roughly along the 50 m isobath in northwestern Bristol Bay, was suggested by Muench (1976).

Inner bay water during May was vertically homogeneous. Temperatures at different stations throughout inner Bristol Bay varied between 1.5 and 2.5°C during 1969 and between 2 and 3°C during 1970. As in April, temperatures in the southwest corner of the bay were relatively high compared to the rest of the bay with surface temperatures approaching 4°C in 1969 and between 4 and 5°C in 1970. Relatively warm water was also found along the shallow coastal perimeter of the bay where temperatures were between 3.5 and 4.5°C and the water was vertically homogeneous apparently having been well mixed from winds and tides.

Continued warming of Bristol Bay surface layers persisted throughout June and July, while bottom waters in central and outer Bristol Bay showed less warming tendency. Uniform heating of the entire water column takes place in inner Bristol Bay, leading to a homogeneous water column. This is due to the effective tidal and wind mixing which takes place throughout this entire shallow water column. The decreased warming of bottom water in central and outer Bristol Bay (decreased warming moving outward in the bay) leads to the development of a seasonal thermocline whose magnitude increases toward the mouth of the bay.

The general temperature pattern observed during June and July was increased temperatures at the coasts and lower temperatures towards the middle of the bay. This pattern is shown in several temperature cross sections for inner, middle and outer Bristol Bay for this period (Figs. 5-8). Doming of the isotherms towards the middle of the bay was observed for all three regions. Water temperatures in the middle of inner Bristol Bay were between 5 and 5.5°C while temperatures greater than 6°C were found along the coast (Fig. 5). A section across central Bristol Bay from Port Moller in the south towards Hagemeister Island up to 58° N (Fig. 6) showed a double domed structure. Water temperatures in the middle of central Bristol Bay were around 7°C. To the north of this warm water, a pronounced doming of isotherms was observed. In this region a surface temperature of 3.6°C was found which was the lowest observed in the bay for June and July of 1969 and 1970. A less pronounced dome structure was found to the south of the warm middle bay water. In this region, temperatures were below 6°C. The double dome temperature structure in central Bristol Bay was also evident in June 1968 in a section between Port Moller and Cape Newenham (Fig. 7). Remarkably similar conditions were displayed in 1968 and 1969. During both years, the more pronounced dome structure was evident in northern Bristol Bay between 57°30' and 58° and the lowest surface temperature was 3.6°C. The less pronounced, more southerly, warmer structure was also present during both years. Cooling towards the middle of outer Bristol Bay between

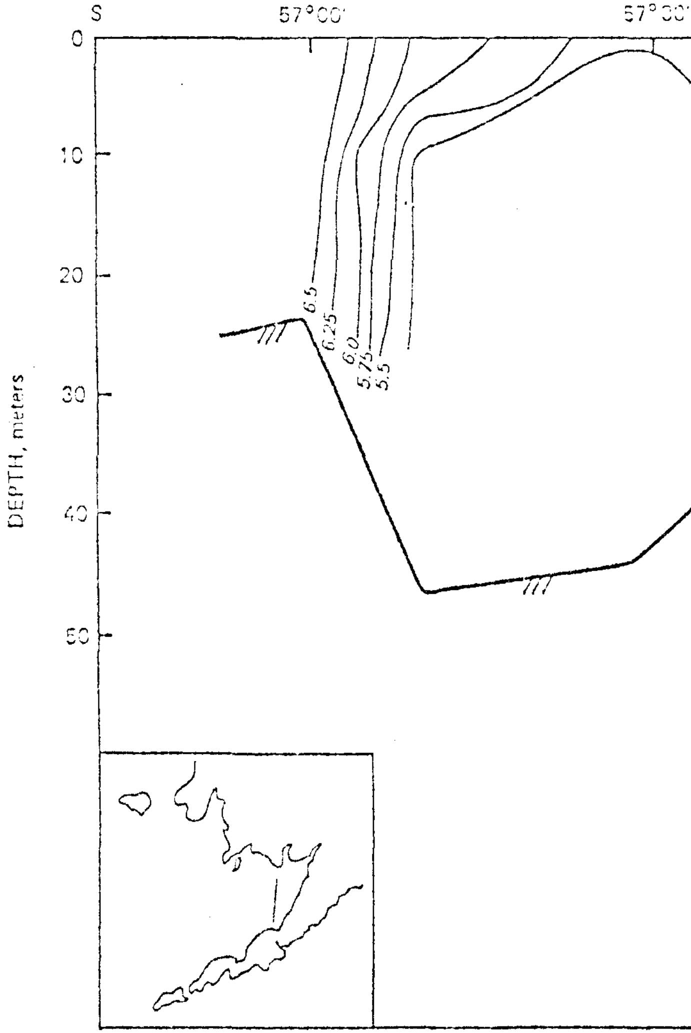
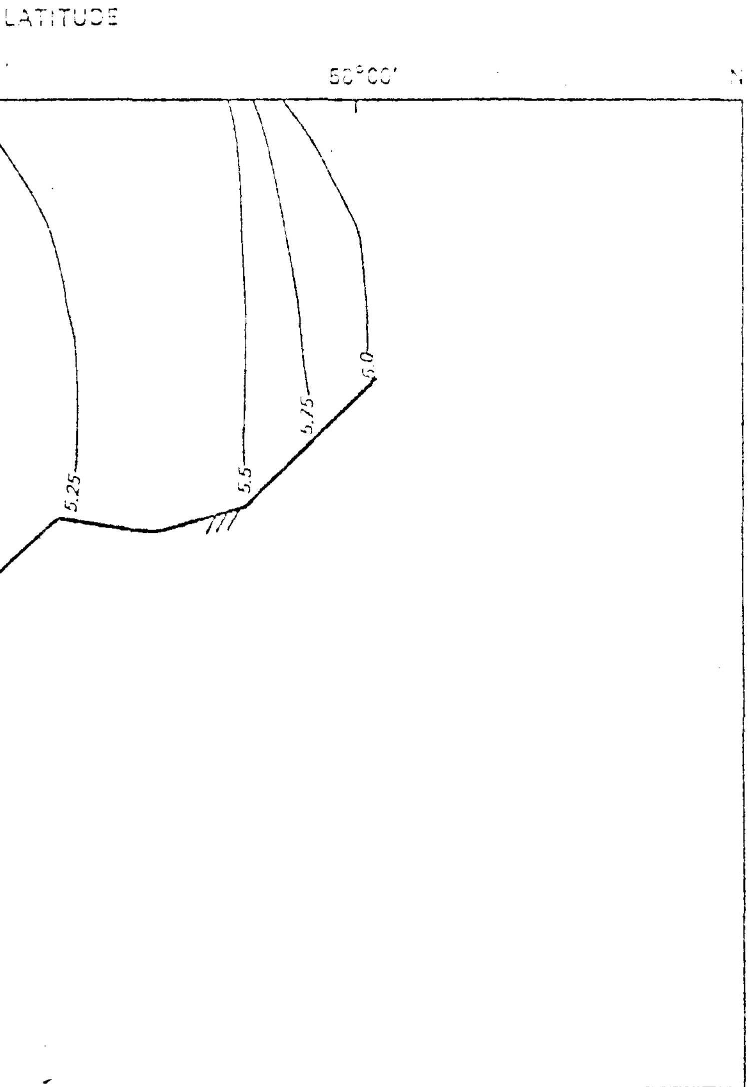


Fig. 5 Vertical temperature section
1969.



across inner Bristol Bay June 15 - July 5

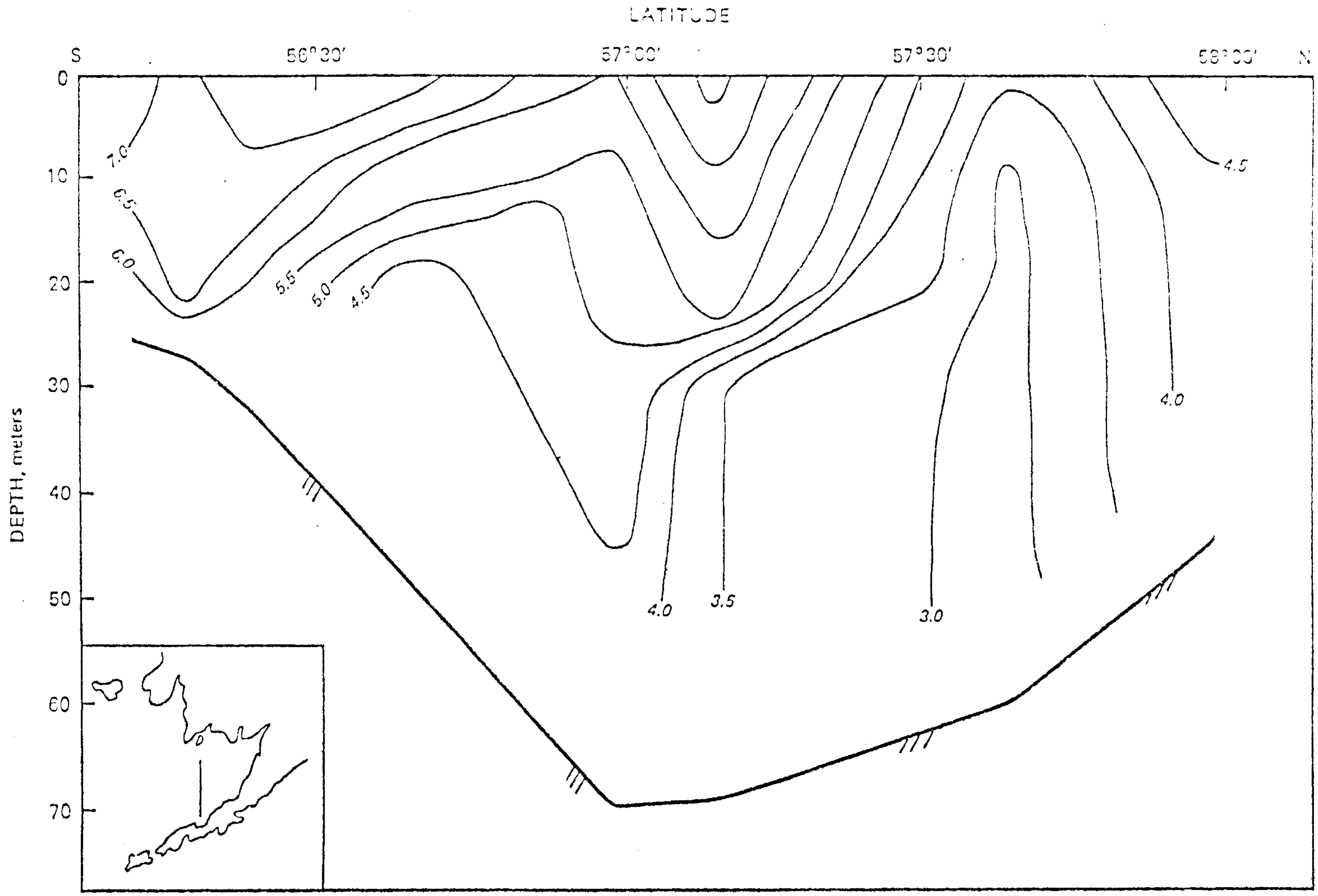


Fig. 6 Vertical temperature section across central Bristol Bay June 15 - July 5 1969

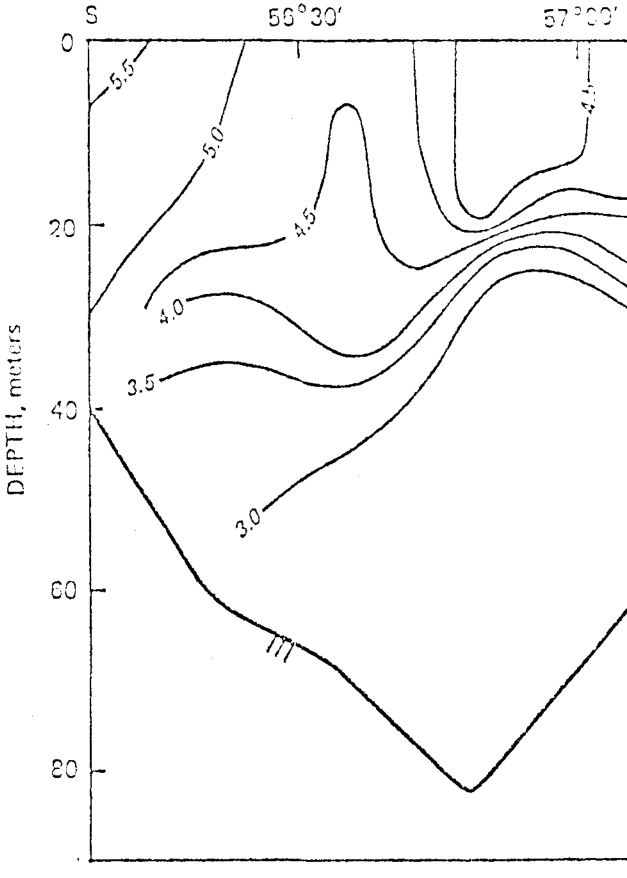
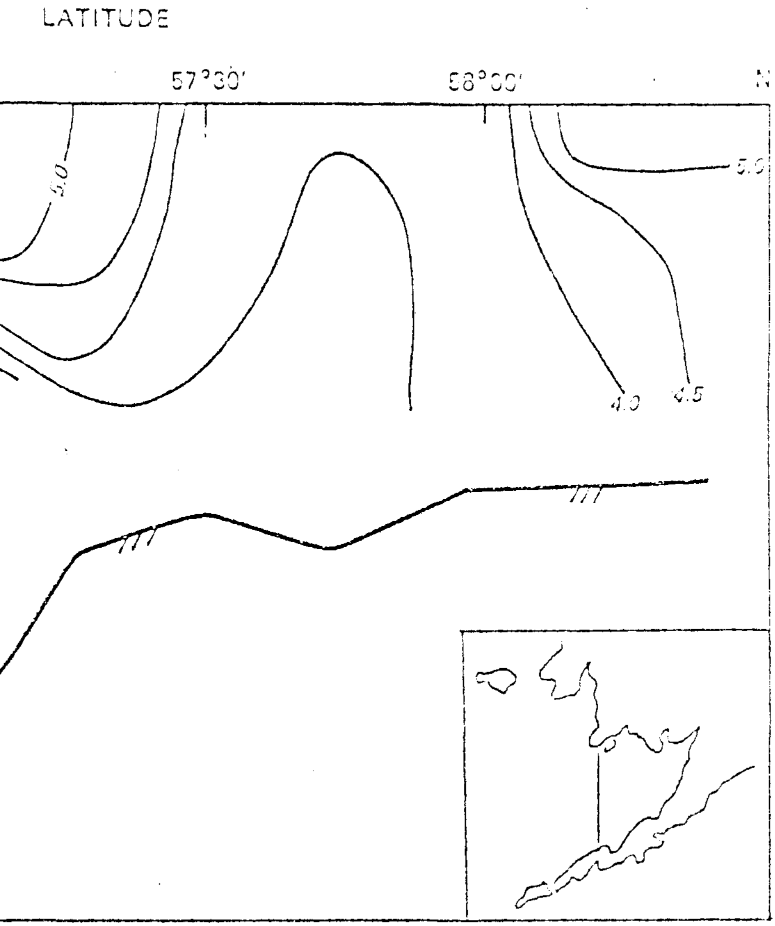


Fig. 7 Vertical temperature sect
1968.



ion across central Bristol Bay June 17 - July 3

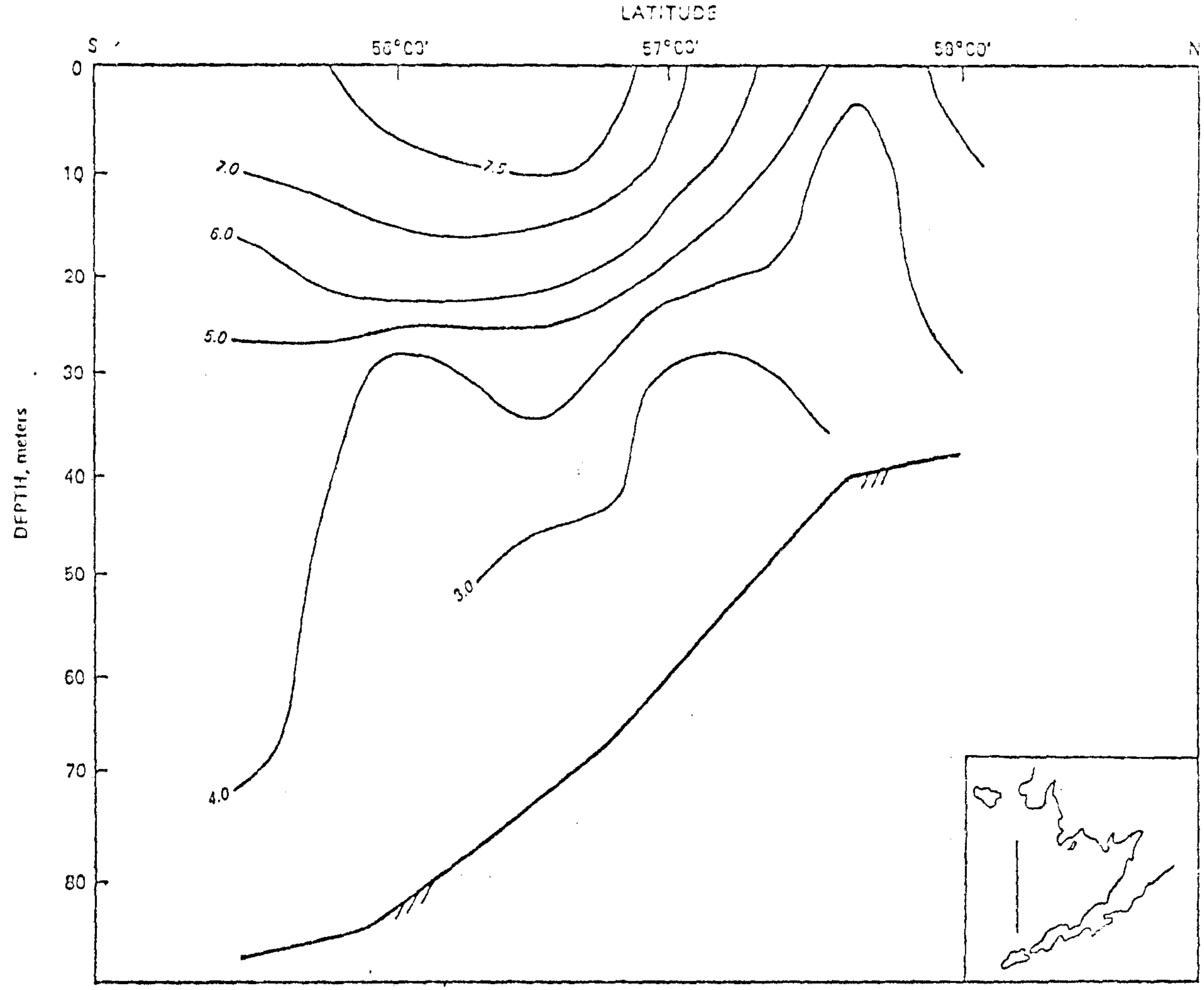


Fig. 8 Vertical temperature section across outer Bristol Bay June 15 - July 5 1969.

57° and 58° N was observed in a cross section taken along longitude 164° (Fig. 8). Temperatures were around 7.5°C in southern outer Bristol Bay and decreased to between 4 and 5°C in middle outer Bristol Bay.

Water temperatures during June and July of 1970 were lower than those in 1969 in all regions of central and outer Bristol Bay. This was especially true for the offshore regions of central and outer Bristol Bay, where temperatures during 1970 were roughly 2 to 3°C lower than in the same areas during 1969. Other regions of the bay displayed similar temperatures or showed temperatures 1 to 2°C lower during 1970 than in 1969.

Surface temperature distributions during June and July were characterized by localized regions of cold water. Surface contours were consequently more irregular when compared with bottom contours. This seemed to be true for Bristol Bay throughout the entire study period. This feature is exhibited in the surface and bottom temperature distributions for July 1969 (Figs. 9, 10). The surface distribution (Fig. 9) showed cold areas (<7°C) surrounded by water with temperatures between 7 and 8°C. The intrusion of warm water of 10 to 11°C from the southwest was also evident. Bottom temperature distribution (Fig. 10) for the same time period showed a much more regular pattern. Bottom isotherms displayed temperatures which decreased towards outer Bristol Bay. Bottom temperatures ranged from 8°C in inner Bristol Bay to 3°C in outer Bristol Bay. Isotherms exhibited roughly the same pattern as isobaths (troughs opening to the west).

The latest months in the year for which data were available were

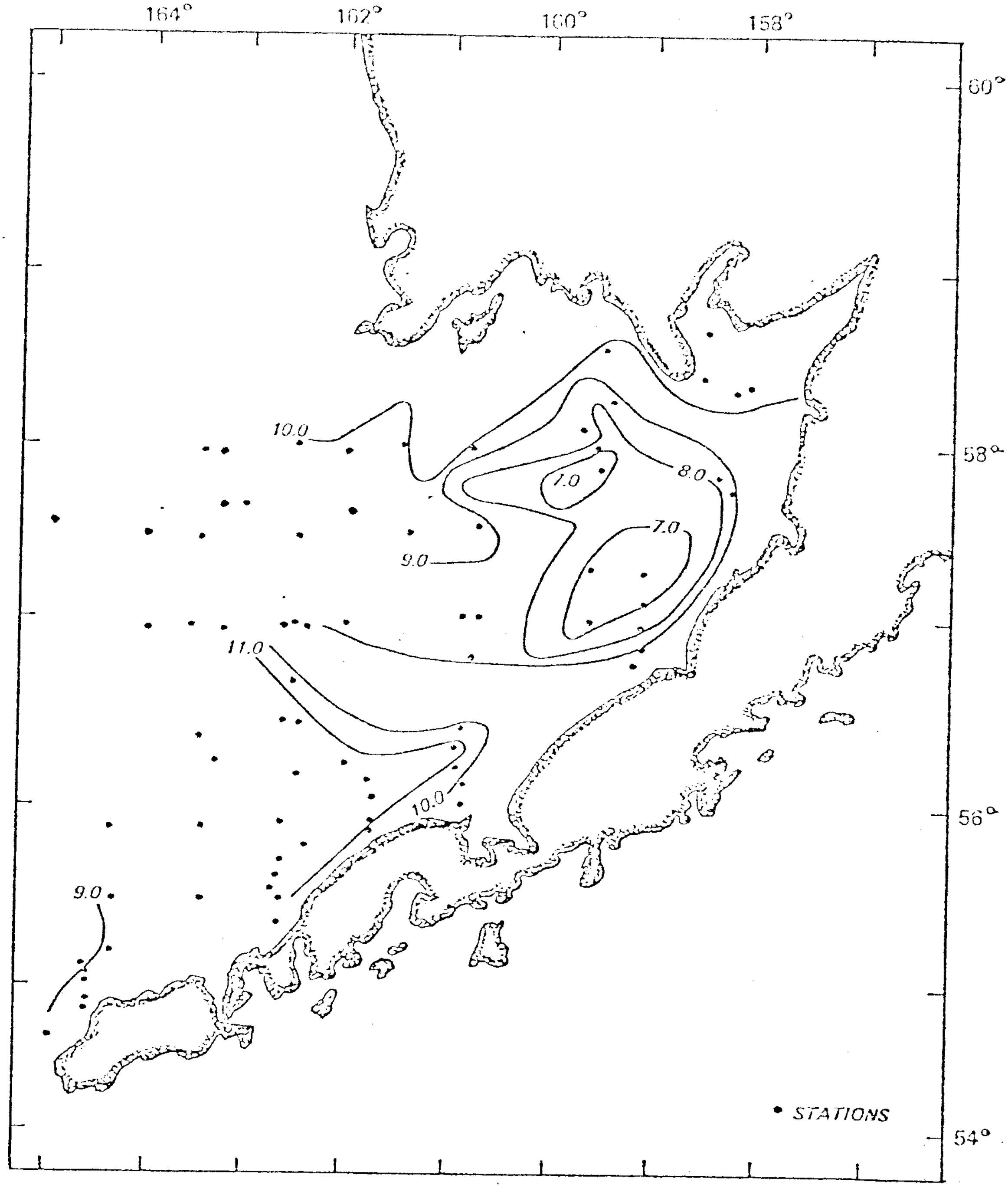


Fig. 9 Surface temperature distribution July 5-31 1969.

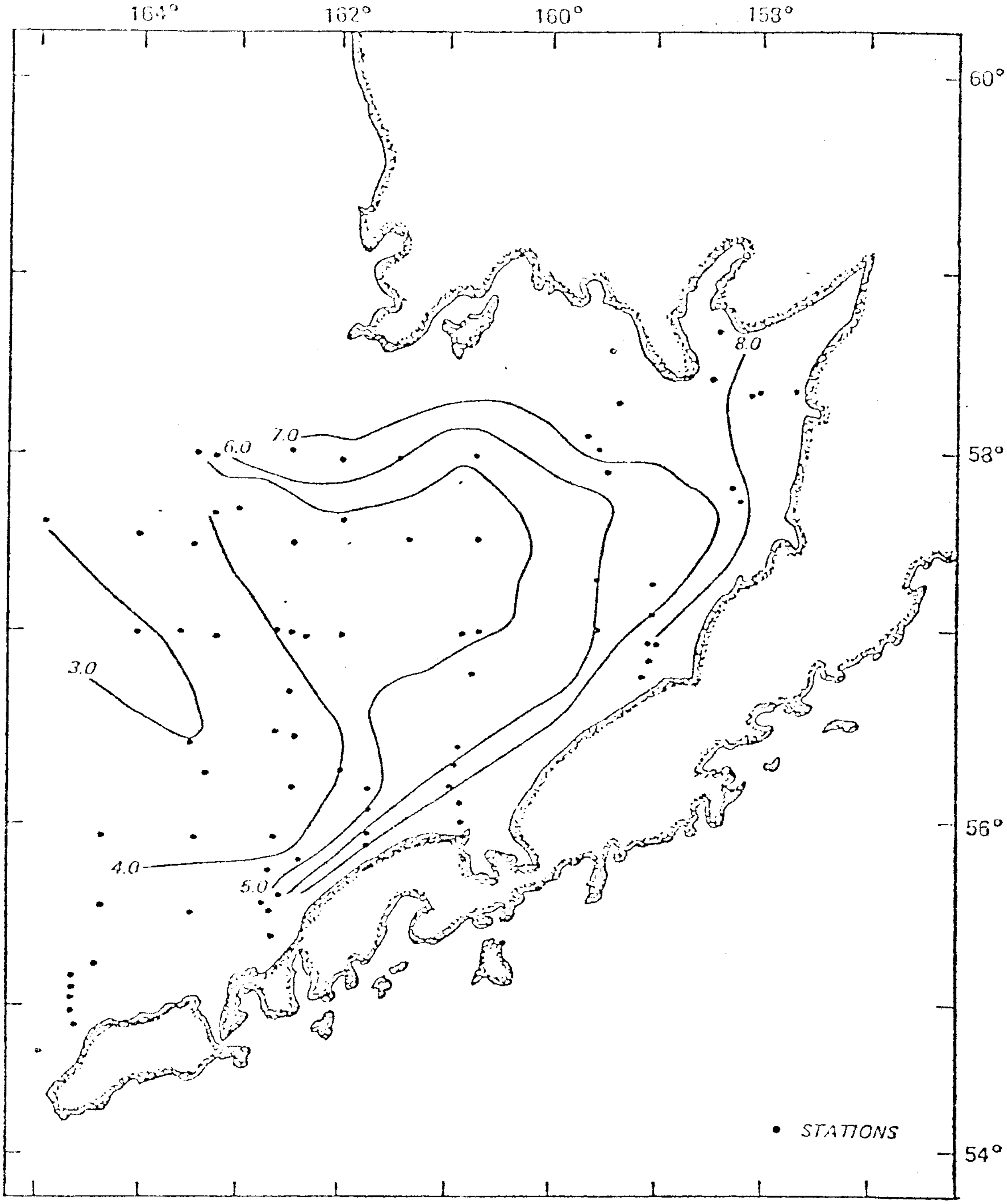


Fig. 10 Bottom temperature distribution July 5-31 1969.

August in 1969 and September in 1970. During August, heating of the bay continued, but at a decreased rate. Examination of the 1970 data showed that water temperatures were maximum during August and decreased slightly by September. The highest water temperatures in the bay were found off the Kvichak River in the innermost portions of Bristol Bay. Temperatures there were greater than 12°C in 1969 and between 11 and 11.5°C in 1970. Inner Bristol Bay displayed vertical homogeneity as in previous months with temperatures ranging between 10 and 12°C. Coastal water temperatures around the perimeter of the bay were between 9 and 10°C during 1969 and 1970. Surface water temperatures in central Bristol Bay were between 9 and 10.5°C in 1969 and between 8 and 9°C in 1970. The cold regions in the middle of the bay, present in June and July, still existed during August with temperatures below 9 and 8°C in 1969 and 1970, respectively.

Bottom temperature distributions showed the same pattern as in previous months, with isotherms roughly paralleling isobaths. This is demonstrated in the bottom temperature distribution for August 1970 (Fig. 11). Also apparent from the August 1970 bottom distribution was the steady, gradual decrease in bottom temperatures towards the mouth of the bay. Temperatures decreased from 9 to 4°C from inner to outer Bristol Bay.

Most of outer Bristol Bay showed features similar to those of the central bay with similar surface temperatures found in both regions during August. Surface water temperatures north of Unimak Island were 1 to 3°C lower than the surrounding water to the north and east. The area

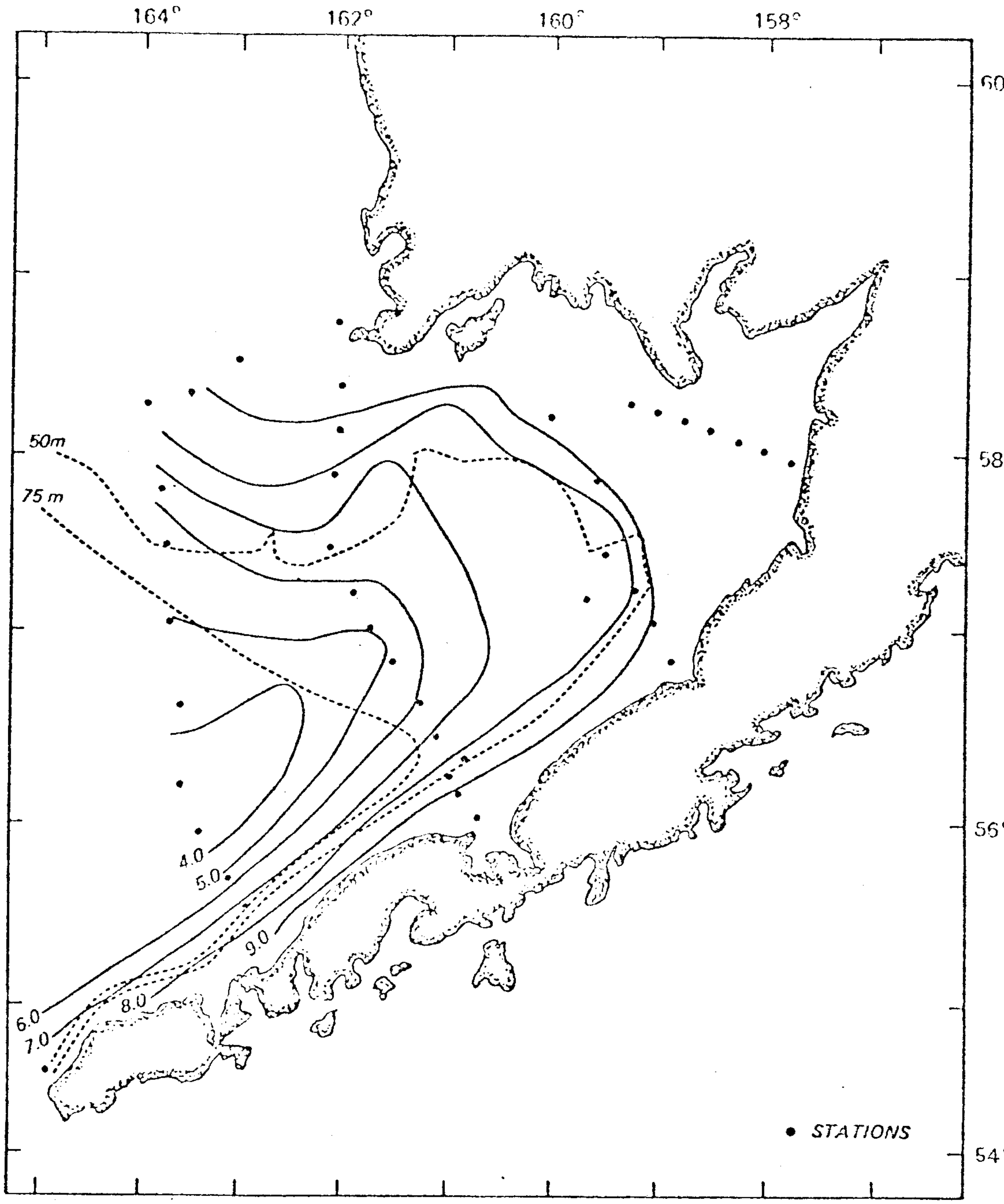


Fig. 11 Bottom temperature distribution August 10-26 1970.

north of Unimak Island is the same region where relatively high temperatures (compared to the rest of the bay) were found during March, April and May. It may be that the same processes (advection or upwelling) responsible for increased temperatures from March to May were now acting to cool water in this region during August. Bottom temperatures did not vary as much in outer Bristol Bay as compared to central Bristol Bay. Bottom temperatures in the outer bay were approximately the same as the coldest water found in central Bristol Bay (3 to 4°C).

Salinity

During the early part of the study period, Bristol Bay, except in the extreme outer portions, was characterized by a homogeneous water column with respect to salinity and denser water than later in the year. Conditions present in March, April and May showed little monthly variation and steadily increased salinities were observed from inner to outer Bristol Bay. In 1969 salinities increased from 31.6°/₀₀ in inner Bristol Bay to 32.2°/₀₀ in the outer bay (Fig. 12). During 1970, from March to July, water in middle central Bristol Bay was approximately .1 to .3°/₀₀ more saline than that present in 1969. Salinities in middle Bristol Bay were roughly 32°/₀₀ and decreased to around 31.3°/₀₀ at the coasts during April and May 1970 (Fig. 13).

The Unimak Pass region (where warm areas were found in early spring and cold areas in late summer) displayed lower salinities in 1970 compared to 1969. During 1969 salinities in the upper 50 meters in this area were around 32°/₀₀ while during 1970 salinities in the same region were between 31.5 and 31.7°/₀₀. The fresher water observed

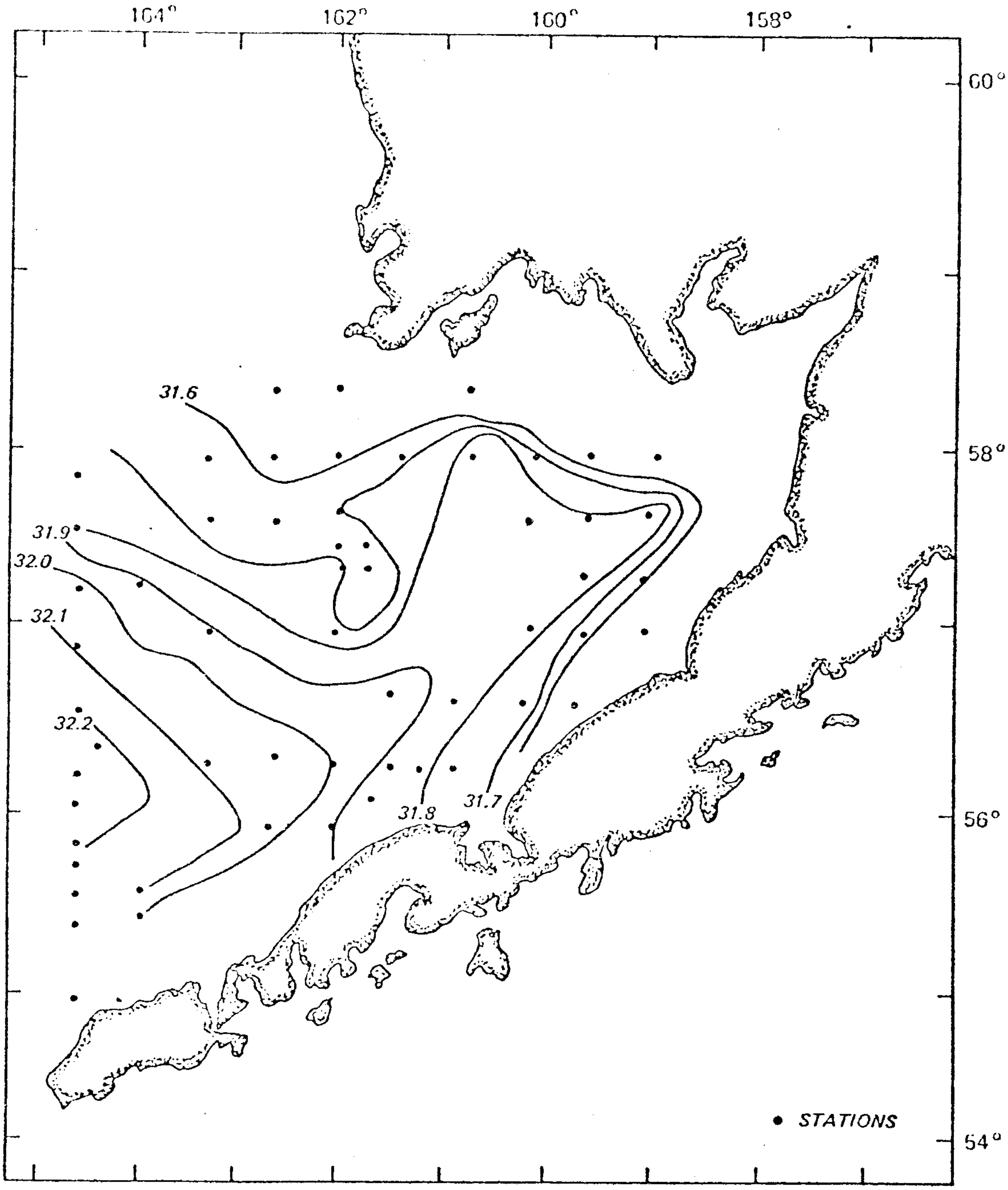


Fig. 12 Surface salinity distribution May 1 - June 6 1969.

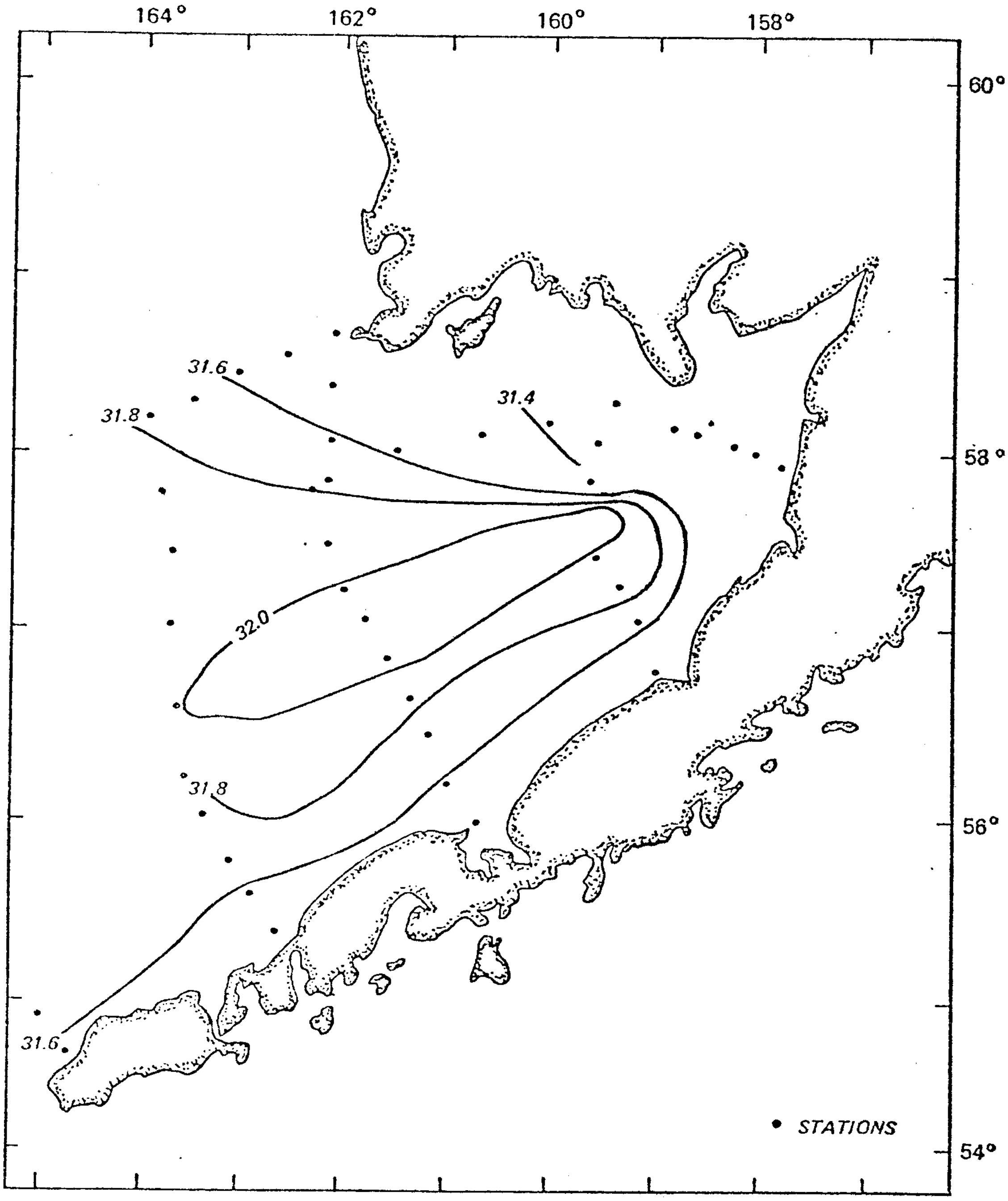


Fig. 13 Surface salinity distribution May 22-30 1970.

during 1970 was probably attributable to advection through Unimak Pass from the south. Two facts supported this idea. First, while spatial coverage around Unimak Pass was sparse, temperature and salinity values found during 1970 north of Unimak Island correlated with those found south of Unimak Island. Second, conditions in the bay, in the absence of intrusion of lighter water from some outside source, would have shown increasing salinities towards the mouth of the bay. This was observed in 1969 data which displayed steady increased salinities towards outer Bristol Bay (Fig. 12). The 1970 data showed a break in this pattern with the low salinity area (31.6°/₀₀) bordered by higher salinity water (31.8°/₀₀) to the north and east.

The dense water found in the middle of the bay from March to May 1970 was still evident in late June, in contrast with the conditions observed in June and July 1969. Salinities in late June 1970 were around 31.9°/₀₀ for the middle bay and decreased toward the coasts where salinities were generally 30 to 31°/₀₀ (Fig. 14). During 1969 salinities were 31.3°/₀₀ in inner Bristol Bay and increased to greater than 32°/₀₀ in outer Bristol Bay (Fig. 15). The Unimak Pass region, which had lower salinities during March to May 1970 as opposed to 1969, continued to display the lower salinities during June and July 1970.

During June and July most of the bay still displayed the vertically homogeneous conditions found earlier in the study period. The inner and northern portions of the bay deviated from these conditions and showed slight stratifications (.1 to .3°/₀₀) between surface and bottom layers. Stratification in the inner and northern areas of the bay was due to the

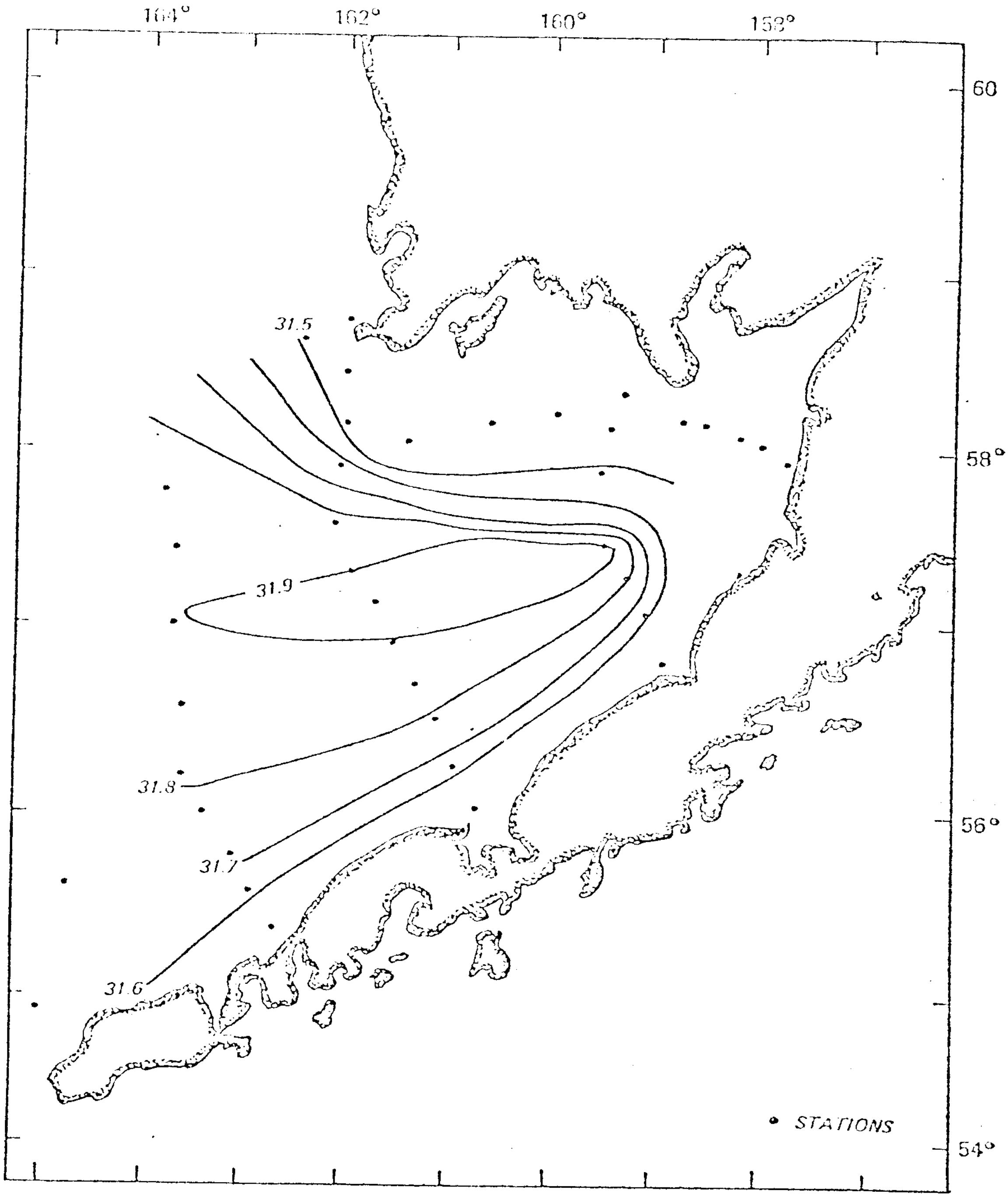


Fig. 14 Surface salinity distribution June 7 - July 3 1970.

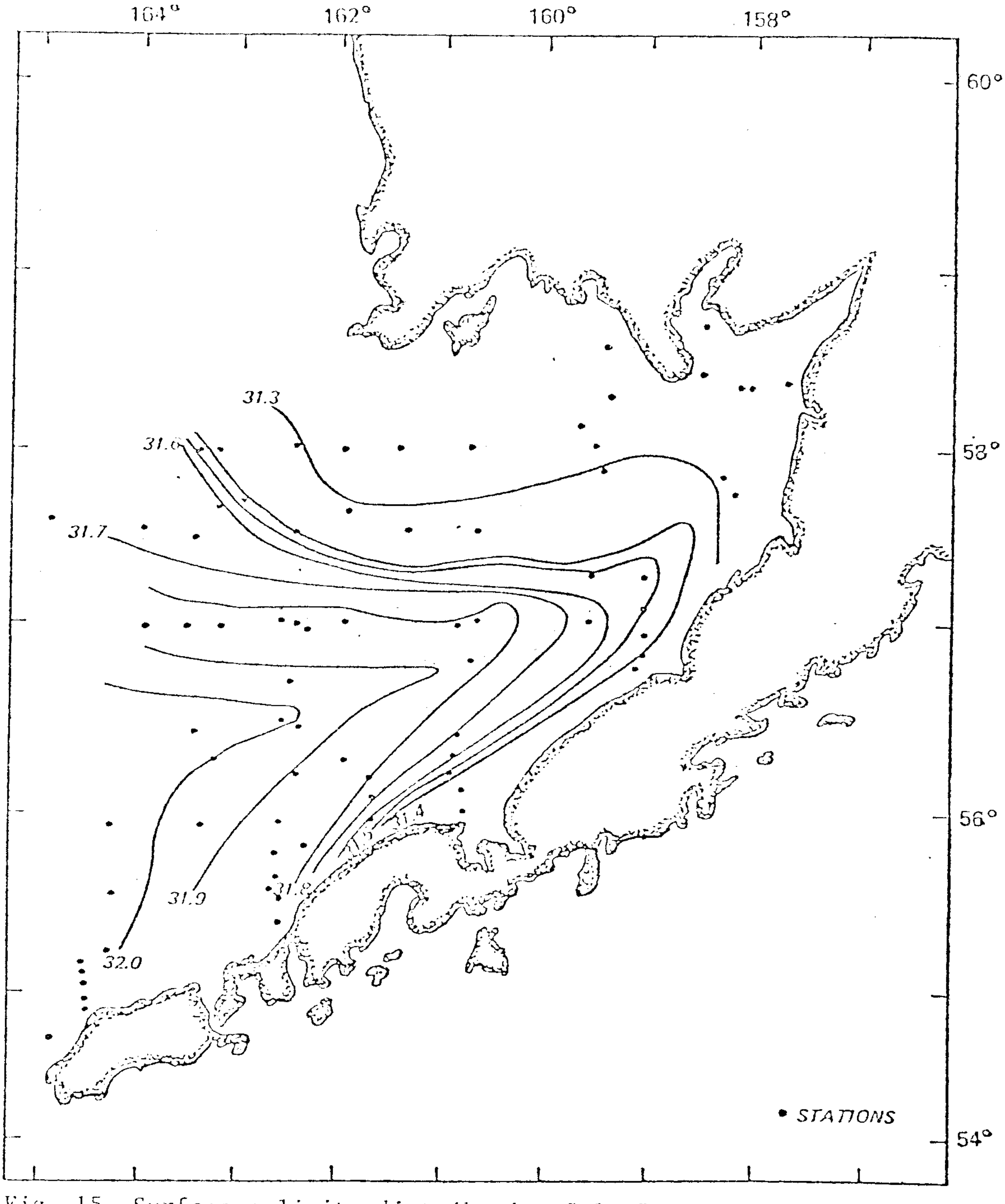


Fig. 15 Surface salinity distribution July 5-31 1969.

freshening of surface layers in these regions by several major freshwater sources (Kvichak, Nushagak and Egegik rivers). The influence of these freshwater inputs may be observed in the surface salinity distribution for July 1969 (Fig. 15). The freshening of surface water in inner and northern Bristol Bay leads to a narrow tongue-like distribution for surface isohalines. A comparison of surface and bottom distributions (Figs. 15, 16) for this same time of year reveals that this narrow tongue-like feature was confined to surface layers with bottom isohalines resembling (in configuration) surface isohalines but being wider spaced. The bottom isohalines paralleled isobaths, a feature displayed also by the bottom isotherms.

A marked change in conditions from previous months was evident in examining salinity distributions for August and September. The region of high salinities found in the middle of the bay from March through June was no longer present in August 1970. The salinity distribution for August 1970 corresponded to that found in August 1969. During August of both years salinities in central Bristol Bay were between 31 and 31.8°/₀₀ (Fig. 17). The freshening of northern and inner bay water, similar to that found in June and July, was also evident in the August surface salinity distributions. Surface salinities in northern portions of Bristol Bay were generally less than 31°/₀₀. The lowest salinities during August and September were found in the innermost portions of the bay. Here, low salinities between 27 and 30°/₀₀ can be mainly attributed to dilution from the freshwater input of the Kvichak River. Another change observed during August and September 1970 was that surface waters around Unimak Pass did not appear as an anomalous

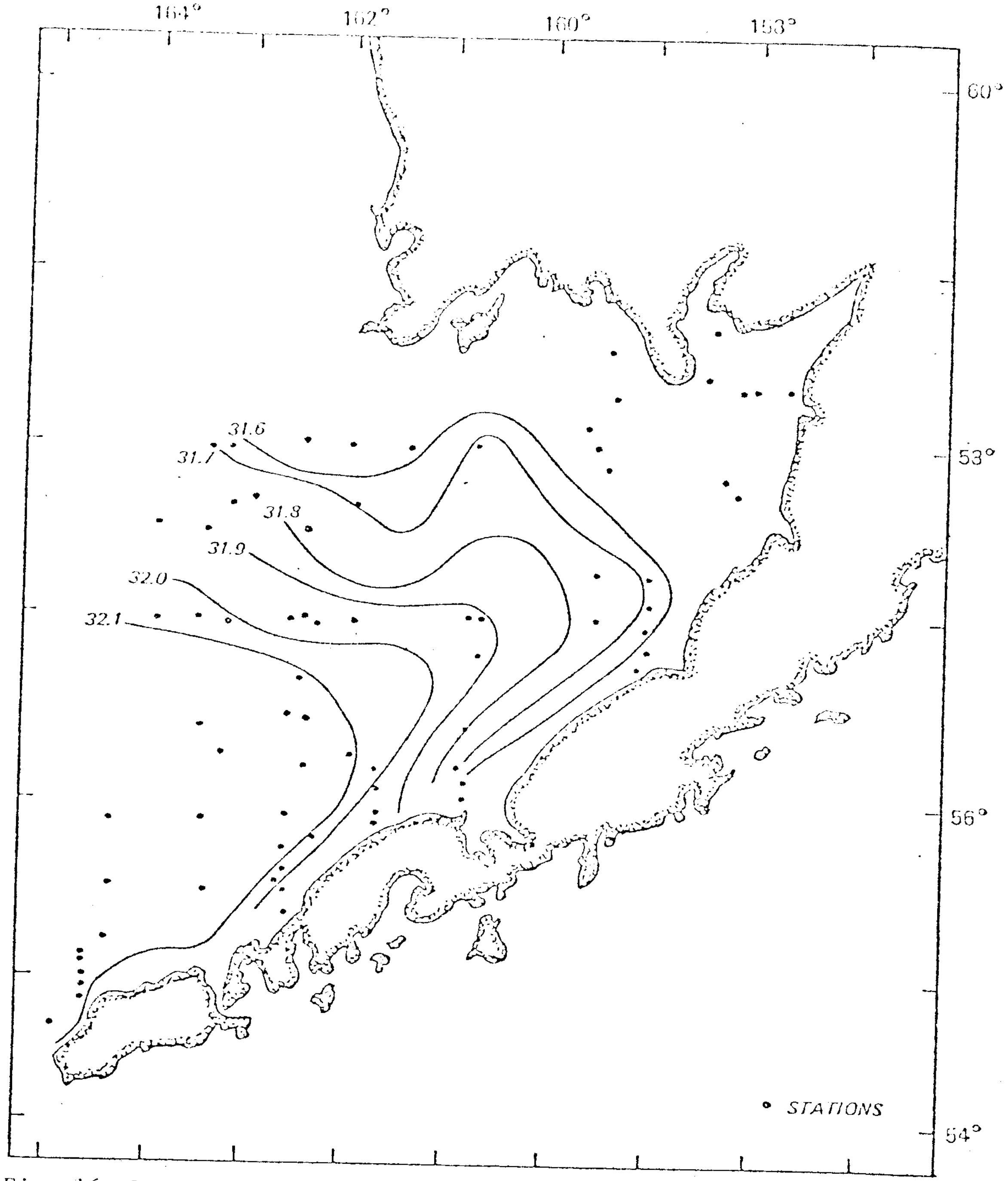


Fig. 16 Bottom salinity distribution July 5-31 1969.

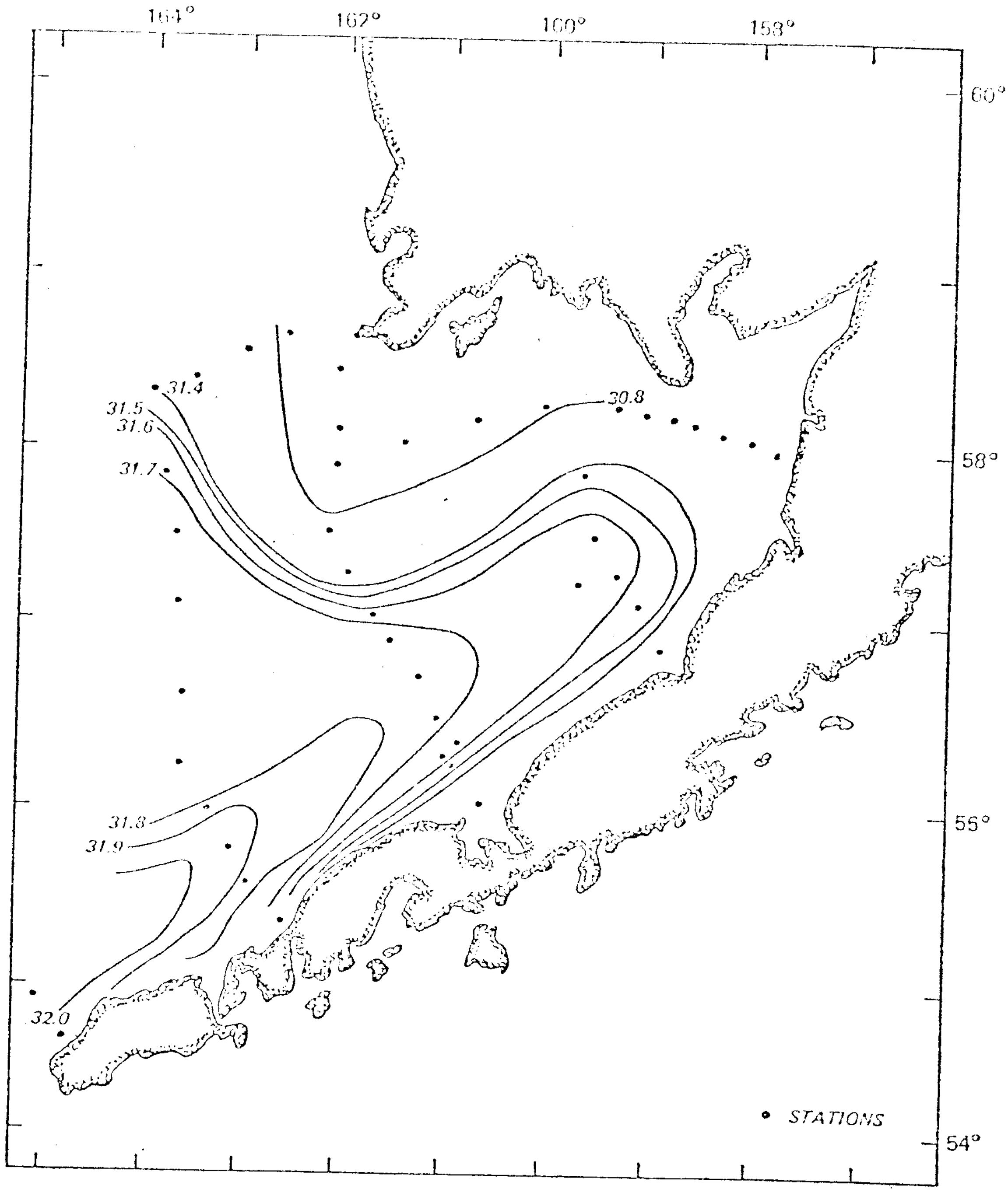


Fig. 17 Surface salinity distribution August 10-26 1970.

region of low salinities. Instead, surface salinity distribution was analogous to that exhibited by the bottom distribution which showed increased salinities towards the southwest.

Summary of Hydrographic Data

Several characteristic features were observed in the vertical distributions of temperature, salinity and sigma-t for the three subdivisions of Bristol Bay at different times during the study period (Figs. 18, 19, 20). Vertical temperature profiles showed the presence of a steep thermocline between 20 and 30 meters in outer and central Bristol Bay during June. This can be attributed to the heating of surface water several degrees in these regions while temperatures in the bottom layer were more stable and increased only slightly. The low bottom temperatures (1 to 3°C) present in outer and central Bristol Bay is due to the presence of a pynocline which results in low heat transfer from the surface to the bottom layers. Later in the year, in August, a thermocline between 10 and 30 meters was present but was less abrupt than the June thermocline, due to the increased temperatures of bottom water.

Freshening in all regions of the bay occurred throughout the spring and summer. This was displayed in both the salinity and sigma-t profiles (Figs. 19, 20). The vertically homogeneous conditions present in inner Bristol Bay throughout the study period were evident in the temperature, salinity and sigma-t profiles. The density and salinity structure showed their greatest deviation from these homogeneous conditions for inner Bristol Bay during May, when a slight freshening of surface water was

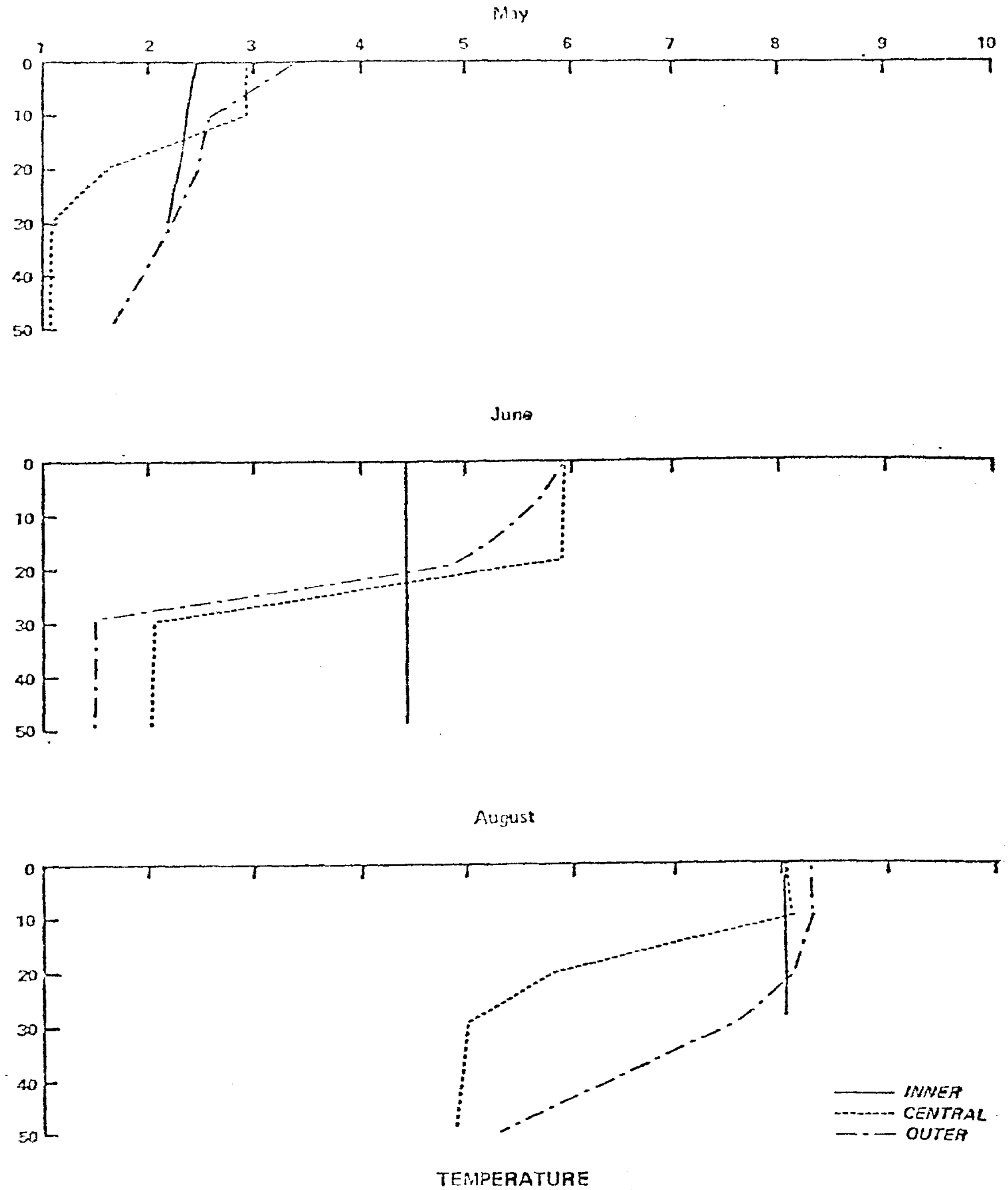


Fig. 18 Representative temperature vs. depth profiles for different times of the study period.

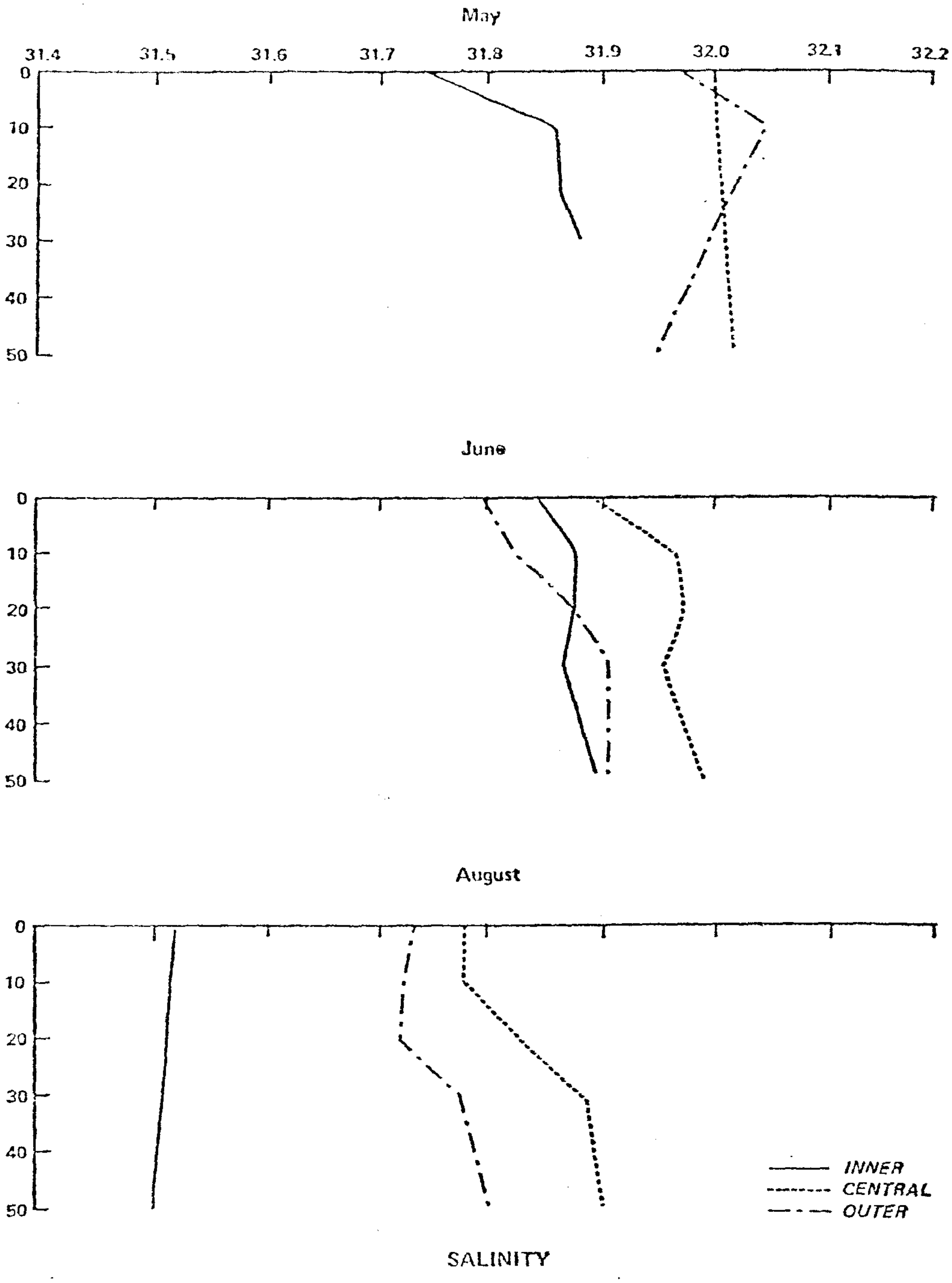


Fig. 19 Representative salinity vs. depth profiles for different times of the study period.

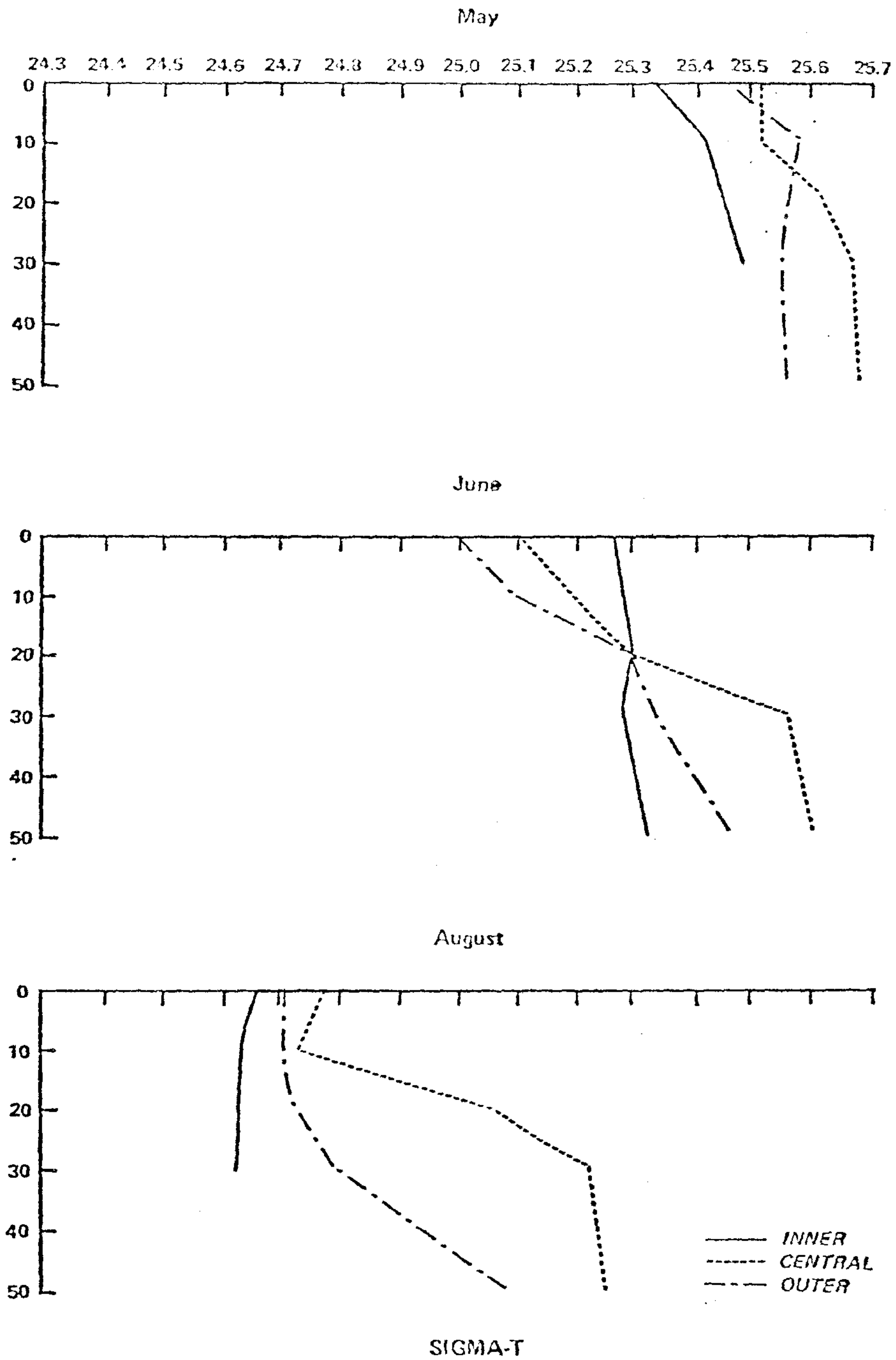


Fig. 20 Representative sigma-t vs. depth profiles for different times of the study period.

evident. This may be qualitatively attributed to the melting of ice and river input in this region at this time of year.

Several large scale temperature and salinity features observed in 1969 and 1970 were identical to those found during the Redwing cruises 30 years earlier. Salinity and bottom temperature contours showed the same general pattern during both periods of the study. Isohalines and bottom isotherms were parallel to isobaths and formed troughs which opened towards the west (Figs. 10, 11, 12, 15, 16, 17, 21, 22).

This tongue-like distribution supports two flow possibilities (Sverdup and Fleming, 1941). Flow may be around the tongue parallel to property isolines or along the axis of the tongue towards the tip. The former would correspond to the hypothesized cyclonic circulation and was supported by the strong correlation (.95) of the mean bottom layer temperature of the southwestern shelf and the degree days of frost of the previous winter (Coachman, unpublished manuscript). This correlation tends to substantiate that cold bottom water was winter formed locally and the tongue-like distributions were shaped by advection around the bay. Also evident from both the 1969-1970 and 1939-1941 studies were the areas of cold surface water in the middle of the bay (Figs. 9, 23) and the freshening of surface water in northern and inner Bristol Bay in summer.

Temperatures observed in 1969 and 1970 compared with those found in other years for Bristol Bay showed temperatures in 1969 were several degrees higher than normally found and 1970 temperatures were about the same. McClain and Favorite (unpublished document) reported on anomalously cold air and sea surface temperatures observed in the southeastern

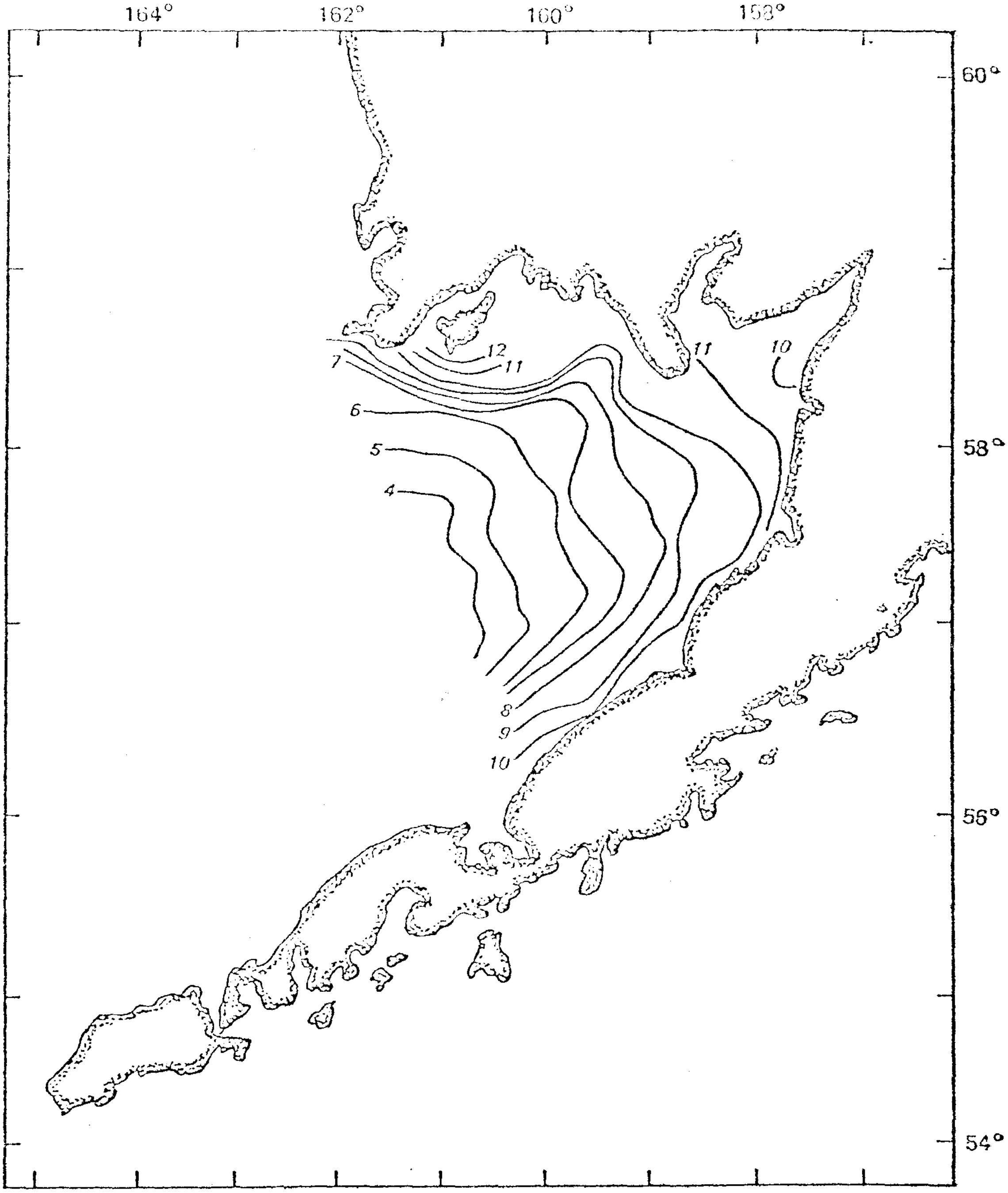


Fig. 21 Bottom temperature distribution August 1939 from Dodimead et al. (1963)

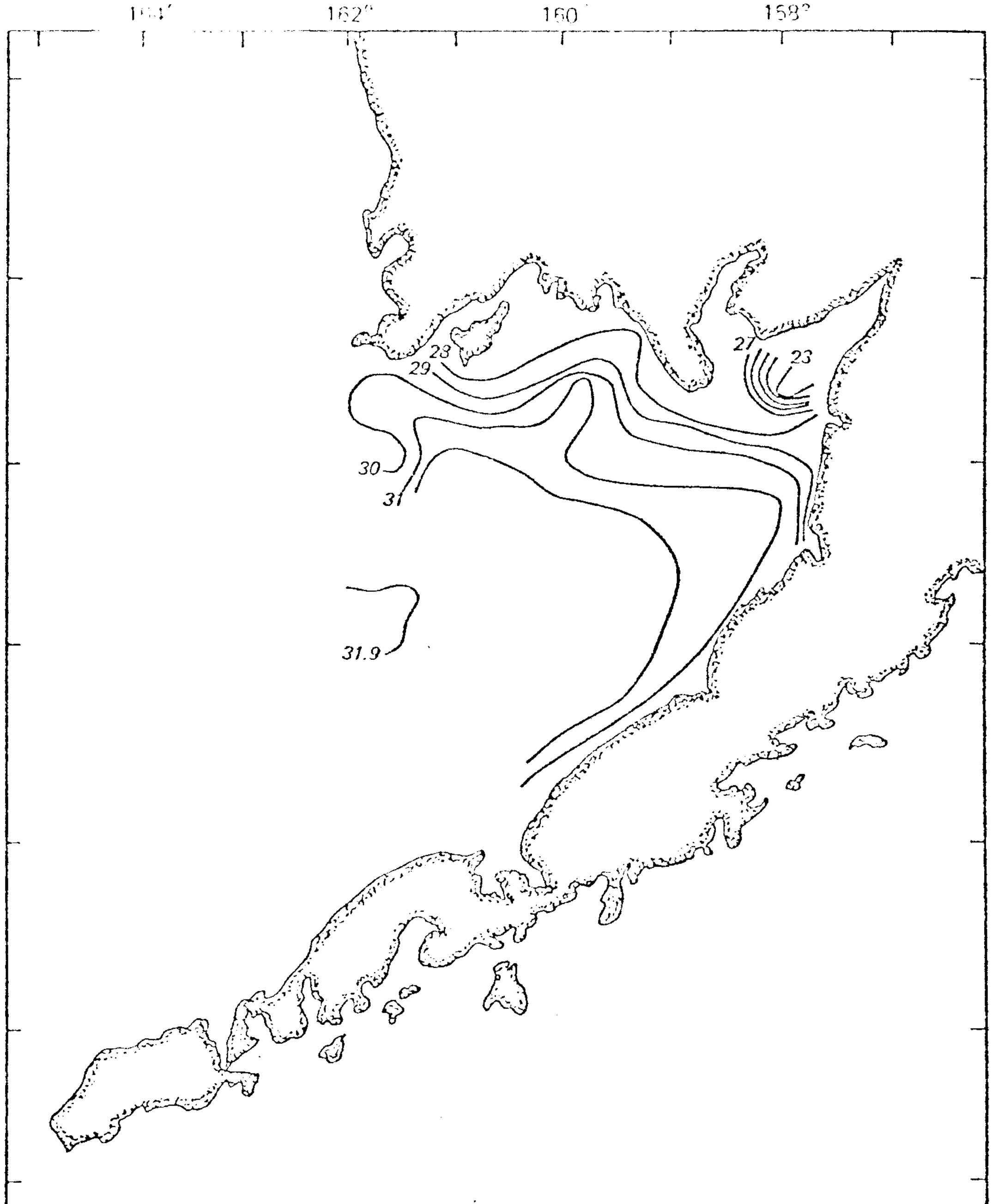


Fig. 22 Bottom salinity distribution August 1939 from Dodimead <u>et al.</u> (1963).

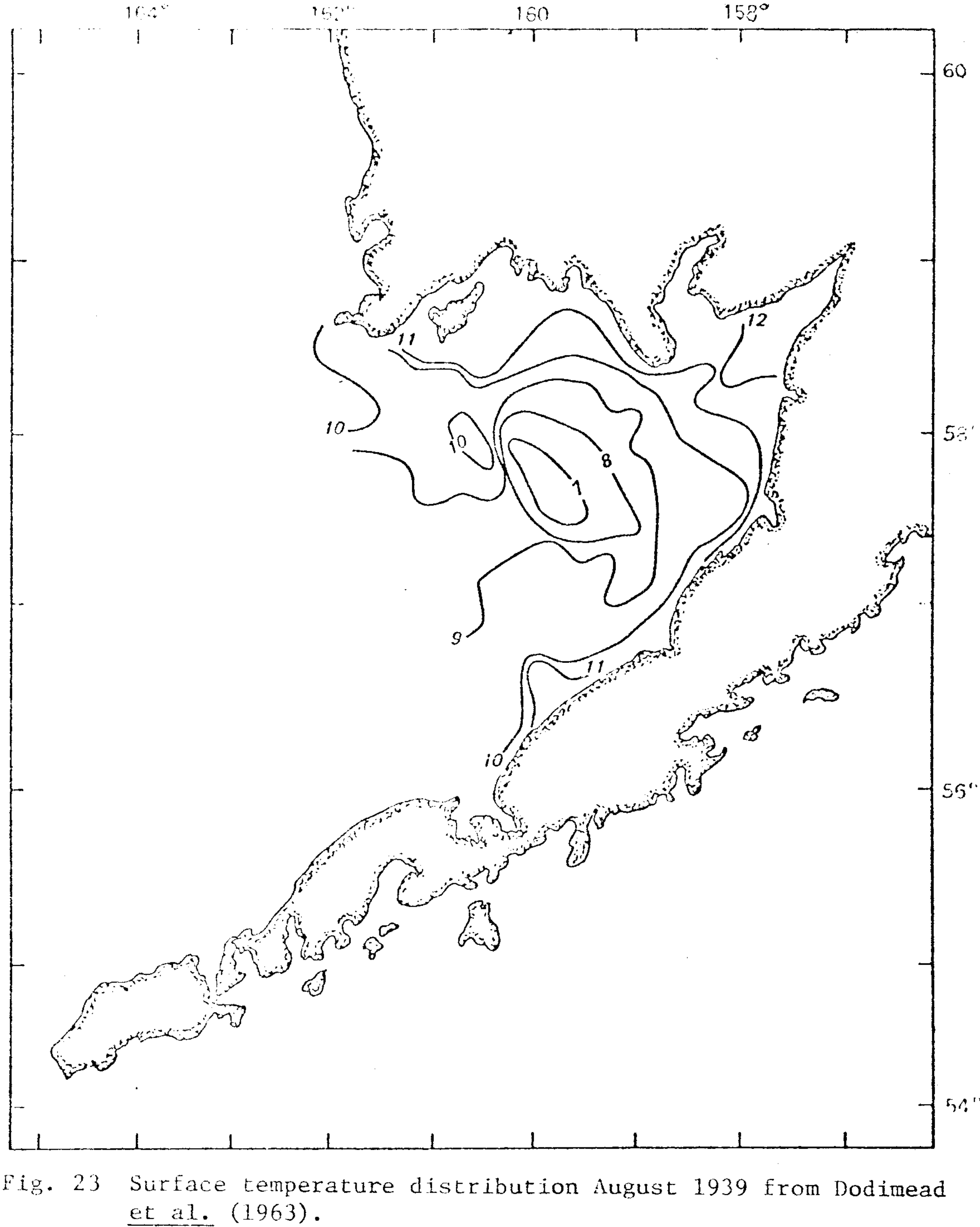


Fig. 23 Surface temperature distribution August 1939 from Dodimead <u>et al.</u> (1963).

Bering Sea from 1971 through 1975. In their investigation, ice cover during winter and early spring was shown to play a dominant role in establishing water temperatures observed in the following months. When the ice cover in Bristol Bay remained for a longer period during any given year, a consequence of more persistent northerly winds from March to May of that year (Konishi and Saito, 1974), lower water temperatures were observed during that particular year. During 1969 and 1970 ice conditions were approximately the same according to satellite data issued by the National Oceanic and Space Administration (McClain and Favorite, 1974). Ice cover during these years (and also 1968) was the least extensive and persistent in Bristol Bay during the period from 1968 to 1975. The higher temperatures found in Bristol Bay in 1969 reflected the decreased ice cover in early 1969. This may be contrasted to 1970 when, as mentioned, temperatures were approximately the same as in other years.

CHAPTER THREE

UPWELLING IN CENTRAL BRISTOL BAY

Evidence

Evidence from previous studies (Dodimead et al., 1963; Myers and Muench, 1975) led to the conclusion that upwelling was responsible for observed conditions in central Bristol Bay. The aforementioned works touched upon this subject lightly. The former interpreted the cooling of surface water in central Bristol Bay as the result of the vertical movement of water intruding into the bay from over the shelf between Unimak Island and the Pribilofs. In the latter work, the authors observed cold regions in surface temperature distributions of central Bristol Bay and attributed these to upwelling produced by a bottom Ekman layer convergence.

Several features, which are evident in the distribution of temperature and salinity described in the previous chapter, reinforced the idea that upwelling can occur in central Bristol Bay. Vertical sections running approximately north-south across the bay for June and July (Figs. 5, 6, 7, 8) showed thermal doming which is characteristic of upwelled regions. Also evident in the surface temperature distributions were regions of cold water (Fig. 9). These cold surface water regions were present throughout the summer. By late summer (August), surface water in Bristol Bay has had adequate time to be heated by isolation, and maintenance of cold surface regions would require a source of cold water. This source could be the cold bottom layer of the convective area in central Bristol Bay or deeper water from the eastern Bering Sea.

While upwelling-like features were observed in the temperature distributions for 1969 and 1970, salinity data for that time does not support as strongly the existence of upwelling regions. This is due to the vertically homogeneous salinity structure found for the bay. Because of this homogeneous character with respect to salinity, vertical movement of subsurface water to the surface would not alter the salinity distributions.

High salinity regions were observed intermittently in central Bristol Bay. High salinity water (31.9-32°/₀₀) was observed from March to August 1970 and was absent from April to September 1969 and in August 1970 (Figs. 12, 13, 14, 15, 17). The penetration of high salinity water into Bristol Bay from March to August 1970 was much greater than is normally observed. This was inferred from comparisons of the salinity distributions for this time to the distributions given by Ingraham (1937). In Ingraham's work, mean maps of temperature and salinity (surface and bottom) were generated by using all available data for 1 x 1° squares for the entire eastern Bering Sea. The May and June distributions of Ingraham showed water of 32°/₀₀ salinity confined to outer Bristol Bay (similar to that observed in 1969 of this work), while in May and June of 1970, water of 31.9 to 32°/₀₀ was found throughout middle central Bristol Bay (Figs. 13, 14).

Salinity and temperature data, when used together, may aid in the description of an upwelling area through location of the source of upwelled water by use of T-S methods. Results from T-S analysis must be interpreted cautiously when applied to a shallow coastal area such as

Bristol Bay. Surface water in the middle of central Bristol Bay displayed T-S characteristics in May and June 1970 which corresponded with those of deeper water found to the southwest in middle outer Bristol Bay. In May 1970, temperatures between 2 and 3°C and salinities between 31.9 and 32°/₀₀ were observed for surface water in middle central Bristol Bay. These values corresponded with those found in water between 10 and 35 meters depth in middle outer Bristol Bay. A month later in middle central Bristol Bay, surface temperatures were between 4.5 and 5.5°C and salinities were between 31.9 and 32°/₀₀ which corresponded to temperatures and salinities of water in middle outer Bristol Bay at 20 to 30 meters depth. These results support the conclusion that deeper water from southwest Bristol Bay was surfacing in central Bristol Bay (Dodimead et al., 1963).

Hypothesis

In a shallow region such as Bristol Bay, it is expected that friction plays a significant role in governing physical processes. To explain observed conditions in central Bristol Bay during spring and summer of 1969 and 1970 it is hypothesized that bottom friction acting in conjunction with the earth's rotation, produces a horizontal sub-surface convergence in the cyclonic circulation which results in upwelling (Fig. 24). The degree of upwelling would depend on the magnitude of the cyclonic circulation, with upwelling being intensified during periods of increased circulation.

The statement of this hypothesis leads to a number of questions concerning the physical processes taking place in Bristol Bay. These include questions concerning the cyclonic circulation, friction and

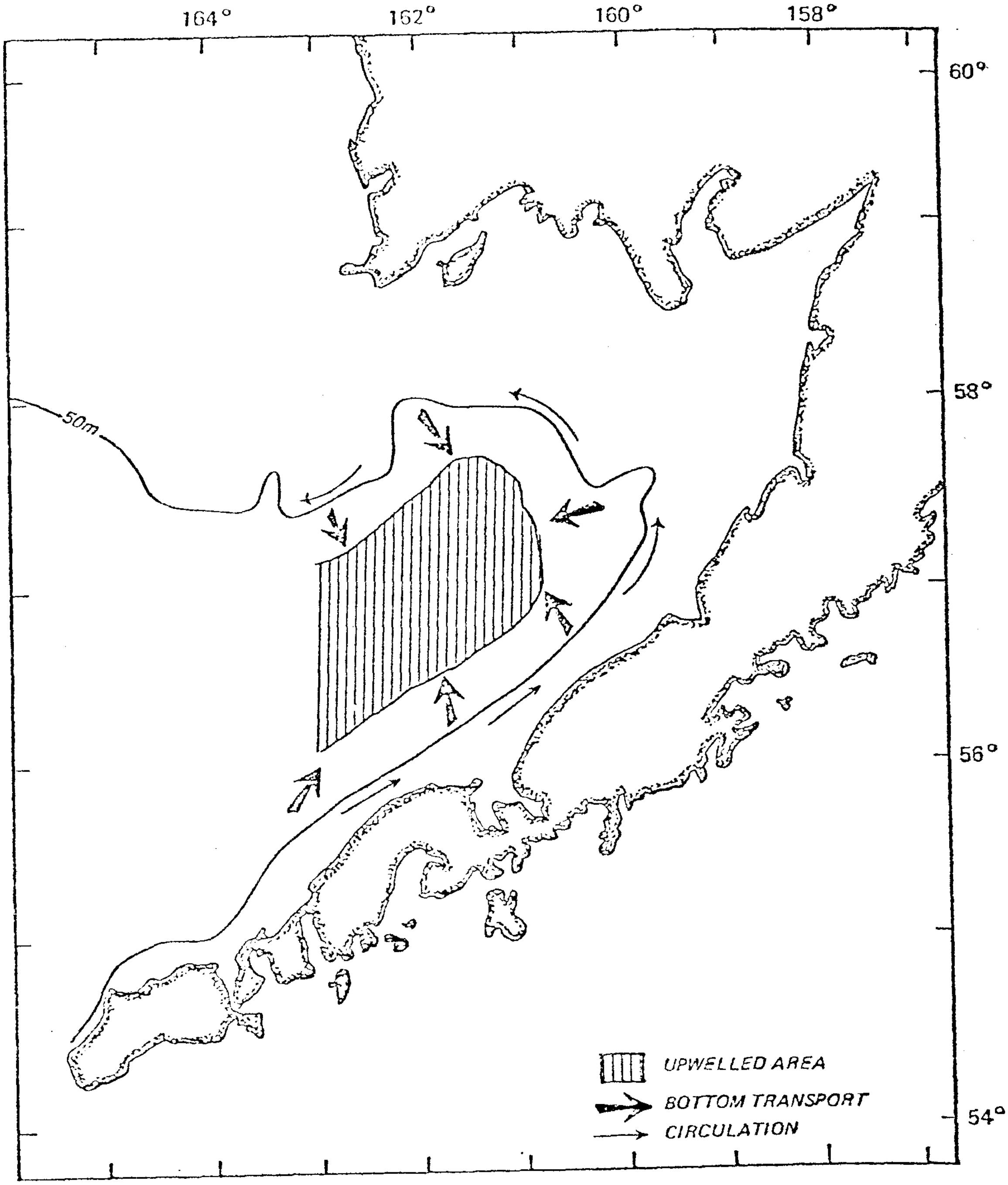


Fig. 24 Proposed upwelling mechanism.

energy considerations. Each of these will now be pursued further in hope of a better understanding of the physical processes that govern observed conditions.

Cyclonic Circulation

The first subject which must be dealt with in discussing the upwelling hypothesis is the cyclonic circulation in Bristol Bay. In relation to the hypothesis such a circulation must exist near the bottom of Bristol Bay. Evidence of the cyclonic circulation extending to the bottom is given by the shape of bottom temperature and salinity contours which tend to follow isobaths. This idea has been dicussed in the previous chapter.

While the cyclonic circulation in the bay seems to be vaguely confirmed, the spatial distribution of the flow remains uncertain. The circulation may exist as a steady flow sweeping throughout most of the bay, or as a concentrated current. The proposed upwelling mechanism would be more compatible with the latter. While either of the circulation schemes are possible, existing evidence seems to support the existence of a concentrated current. The large lateral temperature gradients observed during May 1969 and 1970 of this work and in other studies (Muench, 1976; Takenouti and Ohtani, 1974) were more indicative of a concentrated current. Further evidence supporting a concentrated current may be gained from current meter records which only recently became available (Schumacher and Coachman, unpublished document). These current meters were positioned in several locations in Bristol Bay during fall of 1975. Their records showed that mean flow in the central bay was slow, while major events occurred as pulses in the mean flow. Most speeds reported for the mean flow ranged from several tenths to several cm sec^{-1}. Moreover during the pulses, which lasted several days, speeds greater than 20 cm sec^{-1} were common. The current meter records also showed that the flow roughly paralleled the 50 m isobath in northern Bristol Bay.

Dynamic calculations, using August 1974 data for an area stradding the 50 m isobath, gave slow speeds of the same magnitude (several cm sec^{-1}) as those recorded by current meters located in the same vicinity during fall 1975. The 50 m isobath is the approximate boundary between warm, fresh coastal water and the denser, colder convective area described by Takenouti and Ohtani (1974). The corresponding speeds and directions resulting from dynamic calculations and current meters indicate a slow steady baroclinic current existing along the boundary between fresher coastal water and the denser convective area.

Friction

Friction, in a shallow area such as Bristol Bay, is considered to play a vital role in governing physical processes. The degree to which friction controls processes is difficult to assess because of the ambiguity of eddy viscosity coefficients. The role of friction, in relation to upwelling in Bristol bay is to produce a subsurface convergence. This is accomplished by bottom friction acting in conjunction with the rotation of the earth to deflect the cyclonic circulation toward the center of the bay (Fig. 23). Consequently, the deep layer in Bristol Bay corresponds to the bottom Ekman layer (depth of frictional influence) in Ekmàn's elementary current system (Ekman, 1905).

The thickness of the bottom layer of frictional influence is given by Equation (1):

$$(1) \qquad D^* = \pi\sqrt{\frac{A}{\rho\omega \sin \phi}}$$

where

D^* = thickness of layer (cm)
A = eddy viscosity (gr sec^{-1} cm^{-1})
ρ = water density (gr cm^{-3})
ϕ = latitude (degrees)
ω = Earth's angular velocity (sec^{-1})

Choosing representative values for ρ(1.02 gr cm^{-3}) and ϕ (58°) and assuming an eddy viscosity of 10^2 gr cm^{-1} sec^{-1}, which is in the range given by Sverdup (1926) for water between 0 and 60 meters on the North Siberian shelf, a value of 40 meters is obtained for D^*. This depth is approximately the same as that of central Bristol Bay. Ekman's equations for transport and velocity assumed an infinite ocean depth, but it was found that deviations in these equations are small when the depth of frictional influence is approximately the same as the water depth.

By using Ekman's equation for transport (Neumann and Pierson, 1966) and assuming an area over which upwelling takes place, the upwelling velocity may be estimated from continuity requirements. This estimated upwelling velocity, when compared to velocities found in other upwelling regions, may help in substantiating or negating an Ekman subsurface convergence as a viable upwelling mechanism. Assuming a cyclonic circulation around the 50 m isobath in Bristol Bay of 3 cm sec^{-1}, an inward transport of 5.6 x 10^{10} cm^3 sec^{-1} is obtained. By assuming an upwelling area of 10^4 km^2 (the regions of high salinity found in 1970 were around 1.5 x 10^4 km^2) an upwelling of 1.3 x 10^{-3} cm sec^{-1} is obtained.

This value is on the same order as that reported by Swift and Aagard (1976) for upwelling due to a subsurface convergence and tends to support the Ekman subsurface convergence mechanism.

Energy Considerations

While the upwelling velocity calculated from continuity requirements was a reasonable value, important dynamical considerations such as vertical friction and buoyant forces were neglected. Because of the difficulty in assessing vertical friction, its existence will merely be mentioned and this section will deal primarily with the energy necessary to overcome buoyant forces and drive upwelling.

The energy necessary to overcome buoyant forces and maintain dense surface water in central Bristol Bay may be calculated from sigma-t values. Using June and July sigma-t values it was found that approximately 10^{13} ergs sec^{-1} are required to bring a volume of bottom water 20 m thick with a horizontal surface area of 10^4 km^2 to the surface (raise this water 30 m in the water column) at the calculated upwelling velocity. Calculations of the kinetic energy flow around the upwelling region can be performed if a speed and spatial extent of the flow are assumed. Assuming that the current exists across 50 km and within 20 m of the bottom, it is found that a flow of 3 cm sec^{-1} provides only .1% of the energy required for upwelling. A flow of 13 cm sec^{-1} would provide just enough energy to drive upwelling and a flow of 30 cm sec^{-1} would provide 20 times the necessary energy.

These energy calculations indicate that large scale upwelling produced by a bottom Ekman layer convergence is possible during periods of increased circulation. Winter conditions would seem to be more favorable for upwelling by this mechanism for two major reasons. First the water column is less stratified due to winter convection; this reduces the energy required to overcome buoyant forces. Second, the increased wind stress in the winter, acting as a driving force, may increase circulation in the eastern Bering Sea and also in Bristol Bay.

Wind Data for 1969 - 1970

In a shallow area such as Bristol Bay, wind may serve as a dominant physical driving force. This was demonstrated by Kihara (1971) who found that the penetration of "Alaskan Stream Extension" water ($S > 32°/_{oo}$ and $1° < T < 6°$) into Bristol Bay from 1963 to 1969 (February to July) correlated with the northern component of wind at Unimak Island. Kihara found that as the cumulative northward component (for any given year) increased, so did the penetration of Alaskan Stream Extension" water into Bristol Bay. The increased winds from the south would also tend to increase the Ekman transport of water into Bristol Bay along the Alaska Peninsula. Such an increased transport could act to intensify the circulation, and thus, upwelling produced by a subsurface convergence of this circulation.

Because of the wind's apparent importance as a physical driving force, wind data from Cold Bay and St. Paul (Fig. 1) were examined for 1969 and 1970. The U. S. Weather Bureau obtains mean wind speeds and resultant directions for each day for these stations. Cold Bay was selected principally because of its proximity to Unimak Pass. Data from St. Paul were examined in addition to Cold Bay data because it was felt winds from St. Paul were less likely to be influenced by topographical and continental features.

Using the daily climatological values, a mean wind stress was calculated for each day from April to September for 1969 and 1970 using Equation (2):

$$(2) \qquad \vec{\tau} = C_D \, \rho_a / \vec{U}_a / \vec{U}_a$$

where

τ = wind stress vector (dyne cm^{-2})
ρ_a = density of air (gr cm^{-3})
U_a = air velocity (cm sec^{-1})
C_D = drag coefficient (dimensionless)

A value of 2×10^{-3} was chosen for the drag coefficient. (Roll, 1965) and an air density of 1.25×10^{-3} gr cm^{-3} was assumed. The wind stresses were then broken up into their north-south and east-west components.

Results of the computations showed the wind stress was highly variable in direction for both 1969 and 1970 (Tables 3 and 4). A negative (north monthly mean wind stress was found at Cold Bay for each month except August 1969. The negative values would support a net Ekman transport into Bristol Bay along the Alaska Peninsula. Examination of Cold Bay wind stress values indicated that the northward component was an order of magnitude greater during April 1970 than in April 1969, but in May these conditions were reversed. During June the northward component was the same for both years. The conclusion from the wind stress values at Cold Bay must be that the high salinity water found in central Bristol Bay in 1970 cannot be correlated with the

TABLE 3

Monthly mean wind stress and standard deviations for Cold Bay (dynes cm^{-2})

	E-W	S.D.	N-S	S.D.
1969				
April	-1.57×10^{-1}	1.05	-4.15×10^{-2}	1.51
May	3.09×10^{-1}	1.41	-7.78×10^{-1}	1.35
June	2.41×10^{-1}	6.4×10^{-1}	-4.64×10^{-1}	9×10^{-1}
July	-6.24×10^{-2}	4.6×10^{-1}	-2.41×10^{-1}	5.9×10^{-1}
August	-9.69×10^{-1}	1.16	2.39×10^{-1}	8.7×10^{-1}
1970				
April	-6.03×10^{-1}	2.05	-4.20×10^{-1}	2.18
May	3.17×10^{-3}	1.40	-7.47×10^{-2}	1.41
June	1.69×10^{-1}	1.17	4.68×10^{-1}	1.32
July	6.67×10^{-2}	1.28	-9.65×10^{-1}	1.43
August	8.08×10^{-1}	1.54	-5.62×10^{1}	9.4×10^{-1}

TABLE 4

Monthly mean wind stress and standard deviations for St. Paul
(dynes cm^{-2})

	E-W	S.D.	N-S	S-D
1969				
April	2.84×10^{-1}	1.11	5.69×10^{-1}	1.48
May	3.47×10^{-1}	1.18	1.66×10^{-1}	1.44
June	2.72×10^{-1}	6.6×10^{-1}	3.37×10^{-1}	9.8×10^{-1}
July	-2.65×10^{-1}	4.6×10^{1}	4.09×10^{-2}	5.4×10^{-1}
August	4.28×10^{-1}	7.9×10^{-1}	-1.61×10^{-1}	6.9×10^{-1}
1970	**E-W**	**S.D.**	**N-S**	**S.D.**
April	-9.36×10^{-2}	1.95	1.04	2.41
May	1.66×10^{-1}	7.1×10^{-1}	6.01×10^{-1}	1.06
June	1.10×10^{-1}	7.9×10^{-1}	2.87×10^{-1}	9.9×10^{-1}
July	-2.40×10^{-1}	8.7×10^{-1}	-2.26×10^{-1}	6.6×10^{-1}
August	-4.78×10^{-1}	1.06	-8.01×10^{-2}	1.16

northward component of wind, as in Kihara's study.

The monthly mean wind stress vectors at Cold Bay tended to be northward, while at St. Paul, mean vectors generally pointed to the south. This may indicate a generally cyclonic wind system for the area which could drive upwelling. A closer examination of the wind stress between Cold Bay and St. Paul revealed that the wind was much more constant between these two locations than indicated by the monthly mean wind stress vectors. Wind deviations between Cold Bay and St. Paul were computed for each day and the monthly means of these values were generally less than 90° (Table 5). If winds were consistently opposite at Cold Bay and St. Paul, which are located approximately 200 km apart, much larger deviations would have been found between the two areas. The conclusion from the comparison of winds at Cold Bay and St. Paul is that wind stress is generally constant over Bristol Bay and that the possibility of upwelling produced by a mechanism such as Ekman pumping must be minimized.

Wind stresses at Cold Bay were examined to find the possible correlations between winds and the conditions observed around Unimak Pass. Winds from the east would tend to transport water north through Unimak Pass into Bristol Bay and may have been responsible for the lower salinities found north of Unimak Island in 1970. This low salinity (31.6°/₀₀) water north of Unimak Island was present from April to June. During this period, monthly mean east-west wind stress values were both positive and negative and did not tend to favor either the east or west direction consistently. The 1970 east-west mean monthly wind stresses for April and June also indicated less net transport into Bristol Bay

TABLE 5

Monthly mean difference and standard deviation in wind direction at St. Paul and Cold Bay

1969

	Degrees	S.D.
April	50.3	48.5
May	47.4	80.7
June	60.0	56.7
July	46.8	55.0
August	64.3	42.7

1970

	Degrees	S.D.
April	38.3	45.7
May	41.4	45.3
June	60.3	42.7
July	44.7	64.7
August	67.0	49.4

through Unimak Pass in this year as compared to 1969. This is due to a smaller positive (westward) monthly mean wind stress in May and June 1970 and a larger negative (eastward) component in April 1970 when these values are compared with corresponding months of 1969.

Summary

Regions of cold surface water found consistently in central Bristol Bay are believed to be directly attributable to upwelling. These regions would be maintained by a constant vertical transport of cold bottom water to the surface. This vertical transport may be induced by a subsurface convergence of the cyclonic circulation in the bottom Ekman layer. The degree of upwelling would thus be dependent on the magnitude of the cyclonic circulation. During periods of increased flow, upwelling would be more extensive and intensified; when circulation is slow, upwelling may be less extensive. The current meter records of Coachman and Schumacher provide a clue in regards to this concept. Coachman and Schumacher found that during pulses in the mean flow, temperatures recorded by sensors on the current meters dropped suddenly. These sudden temperature drops (2°C) may have been due to the upwelling of cold water, but they may also be caused by vertical mixing or the horizontal migration of a lateral temperature front between cold shelf water and warm coastal water (Coachman and Schumacher, unpublished document).

Temperature and salinity correlations support the hypothesis that the higher salinities and lower temperatures observed in middle central Bristol Bay during March to July 1970, compared to 1969 and August 1970, were due to upwelling from the southwest. Upwelling of deeper water into central Bristol Bay from a region in outer Bristol Bay or the eastern Bering Sea may be driven by a mechanism other than a bottom Ekman convergence. Evidence for this statement is the fact that the energy required for upwelling of deeper water from the southwest of central Bristol Bay cannot be provided by the cyclonic circulation (from what is known of this circulation at this time). The energy provided by the cyclonic circulation is adequate to overcome the stratification between the surface and bottom in central Bristol Bay (which tends to be only thermally stratified), but is insufficient to drive upwelling of more saline water from the southwest.

It is felt that the mechanisms responsible for the observed upwelling conditions from March to July 1970 in central Bristol Bay cannot be adequately described from regional processes and are coupled to larger scale processes occurring in the eastern Bering Sea. A complex, large scale current system running parallel to the Aleutian Chain and along the shelf break, known as the Bering Slope current (Kinder et al., 1975), may have a major effect on conditions observed in Bristol Bay. A longshore current such as the Bering Slope current may induce mid-shelf upwelling in Bristol Bay in the manner described by Hseuh and Ou (1975).

CHAPTER FOUR

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The analysis of temperature and salinity data gathered during the springs and summers of 1969 and 1970 for Bristol Bay was carried out. Wind data from Cold Bay and St. Paul during this same time period were also examined. The analysis of data revealed the following:

1. Distributions of bottom temperature and salinity paralleled isobaths, reinforcing the hypothesized cyclonic circulation proposed in earlier works.

2. The existence of cold surface regions, which are found consistently in surface temperature distributions and can be explained by the constant upwelling of cold bottom water.

3. High salinities and cold temperatures found in middle central Bristol Bay from March to June 1970 indicated that upwelling of deeper water from a source located to the southwest of central Bristol Bay may be occurring during this time.

4. Energy calculations indicated that the energy needed to drive small scale upwelling and maintain the cold surface regions can be provided by the cyclonic circulation but that large scale upwelling of water from the southwest of central Bristol Bay required more energy than provided by the cyclonic circulation.

5. Fresher water, found intermittently in the southwest corner of the bay north of Unimak Island, may indicate the intrusion of water from the south through Unimak Pass.

6. The wind stress was highly variable during the study period and examination of wind data was inconclusive in interpreting the different conditions observed in 1969 and 1970.

Recommendations

Oceanographic work in Bristol Bay will be intensive during the next several years, and the following points should be beneficial to further studies.

One area in which further work is necessary is circulation. The cyclonic circulation has been vaguely confirmed, and now the spatial distribution and periodicity of the flow must be determined. The possible correlation between winds and circulation needs to be investigated. The current meter records of Coachman and Schumacher provided data for initial investigations into these aspects of circulation and additional current meter studies will provide additional valuable information. Hydrographic data gathered in conjunction with current meter data will aid in a better understanding of observed conditions and processes which govern them.

Several areas of Bristol Bay seem to command more interest than others, and these areas warrant further study. Such areas include the Unimak Pass region, central Bristol Bay and the region located approximately along the 50 m isobath. The connection and interaction between Bristol Bay and the eastern Bering Sea needs to be determined as much as possible. This is required because large scale processes occurring in the eastern Bering Sea ultimately affect conditions found in Bristol Bay.

The simultaneous measurement of several nutrients such as oxygen, phosphate and nitrate may provide useful tracers such as "NO" and "PO" (Broecker, 1974) in a biologically active area such as Bristol Bay. Chemical tracers such as radon 222 may also provide the key to locating source water in upwelled regions.

Winter data should be collected in order to describe seasonal changes and to substantiate or disprove winter processes which, to this point, have merely been speculations. Conventional methods of obtaining oceanographic data for Bristol Bay are impractical in the winter due to the extensive ice cover. The ice conditions during winter may play a major role in affecting observed conditions found in spring and summer. Consequently, the relation between observed conditions and the ice cover should be pursued. Satellite information and remote sensing techniques should be utilized to the fullest extent to obtain information for winter months. Satellite photographs have already been used by several investigators (Muench and Ahlnas, 1976; McClain and Favorite, unpublished document; Konishi and Saito, 1974) to examine ice conditions in the Bering Sea.

One of the most vital aspects concerning the study of Bristol Bay is international cooperation. The mutual exchange of ideas and information between scientists from the United States, U.S.S.R. and Japan is necessary in order to understand as much as possible about Bristol Bay.

APPENDIX ONE

LOCATION OF STATIONS

USED IN THIS WORK

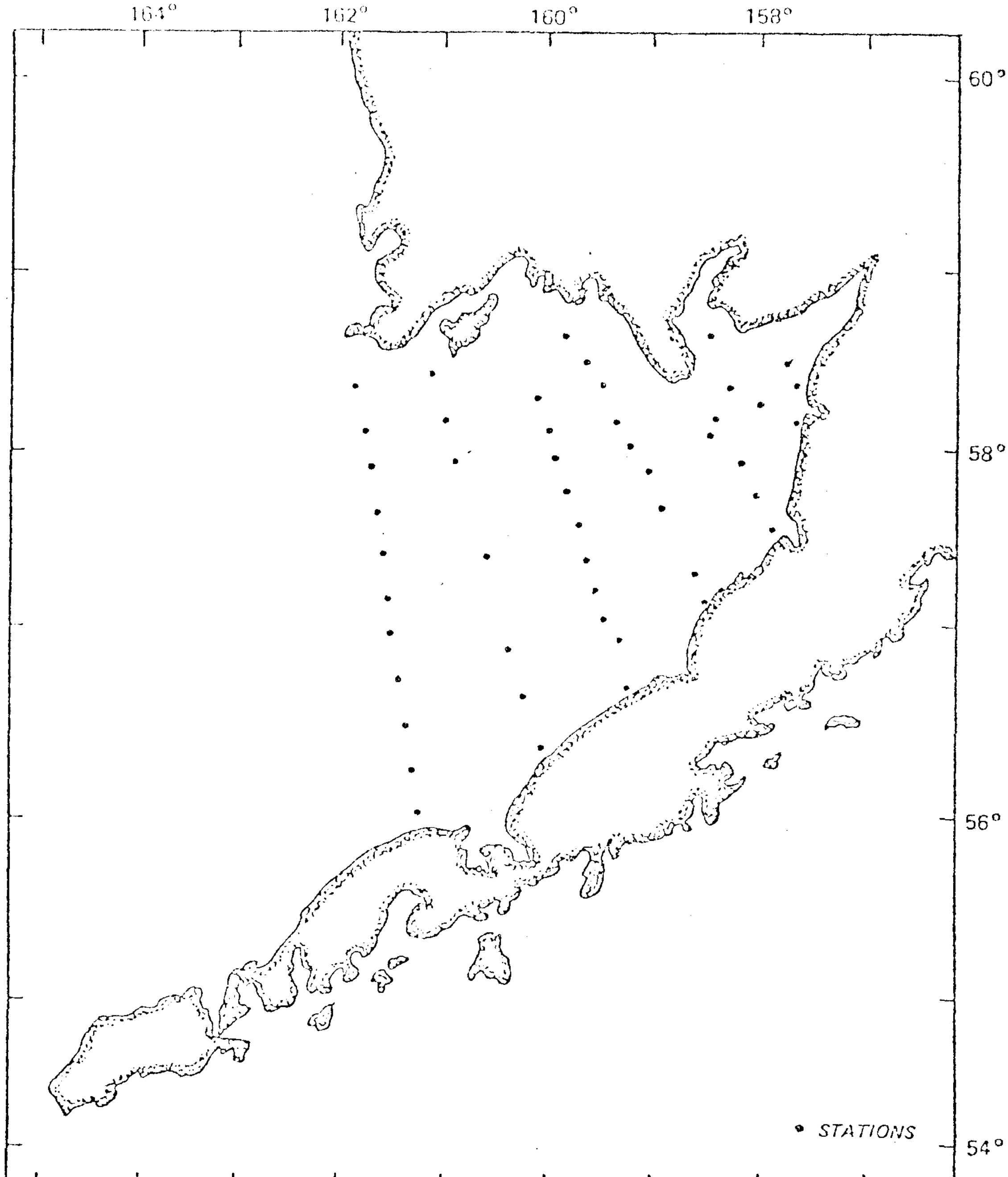


Fig. 25 Stations occupied in Bristol Bay June 17 - July 3 1968.

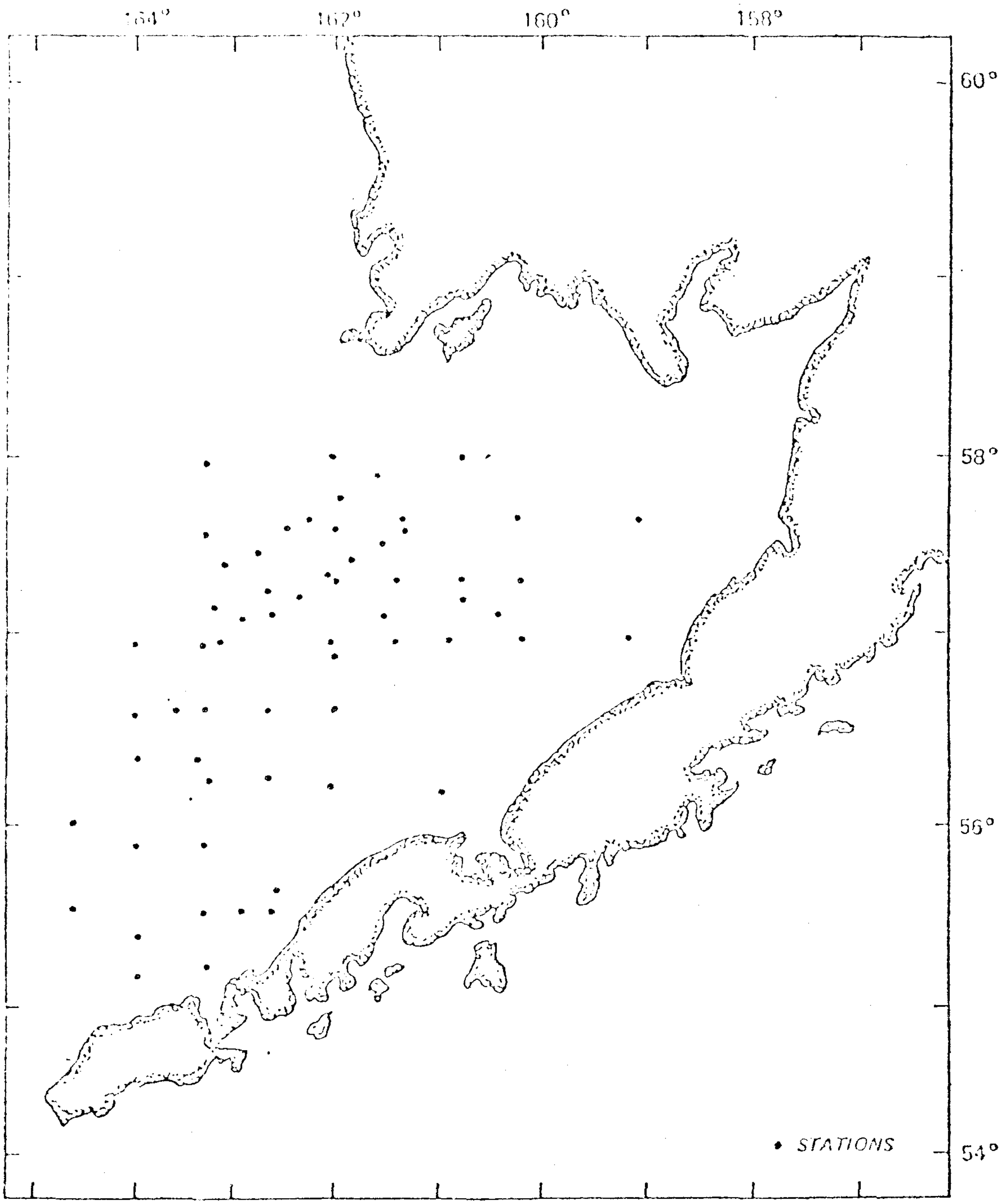


Fig. 26 Stations occupied in Bristol Bay April 11-30 1969.

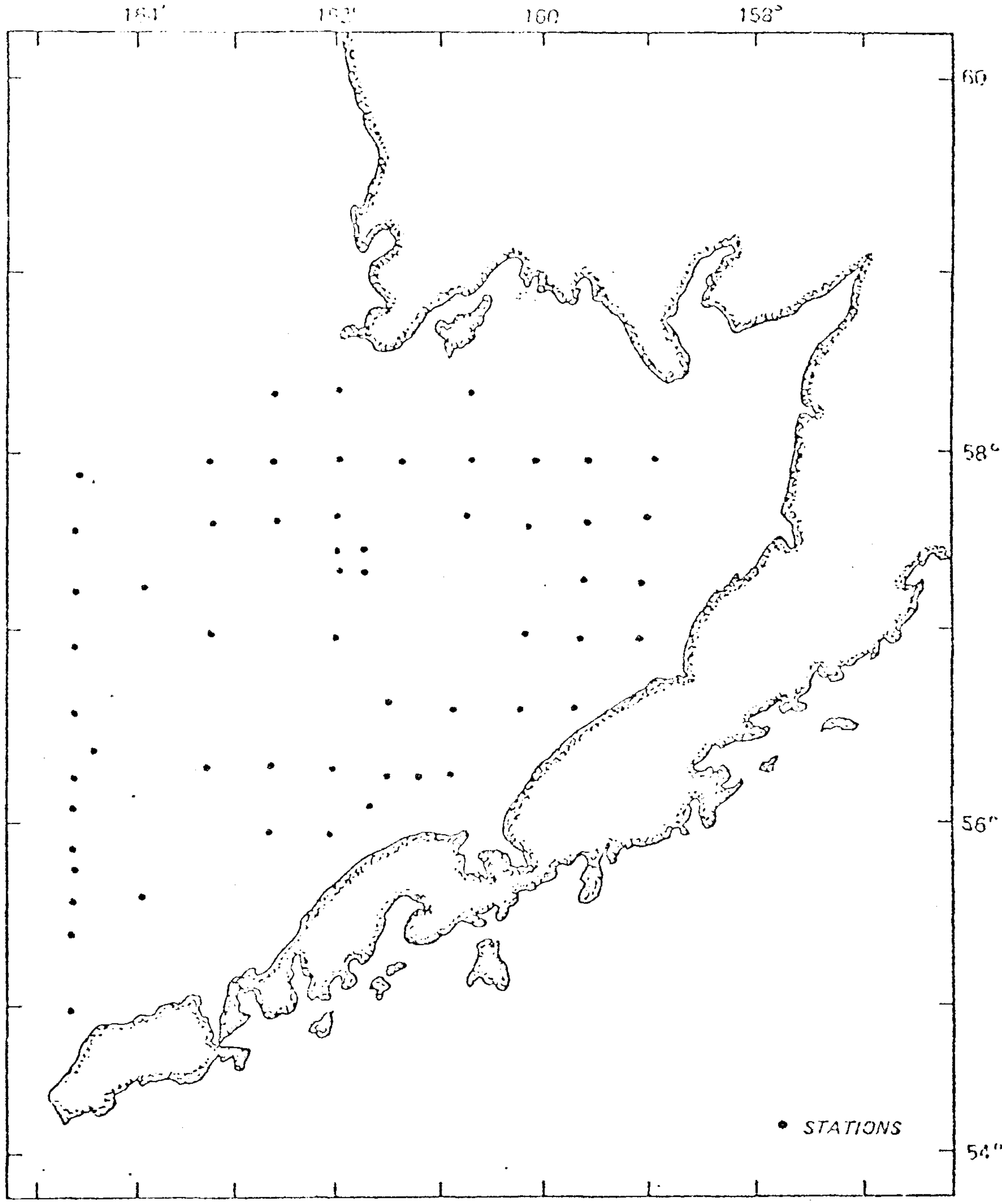


Fig. 27 Stations occupied in Bristol Bay May 1 - June 6 1969.

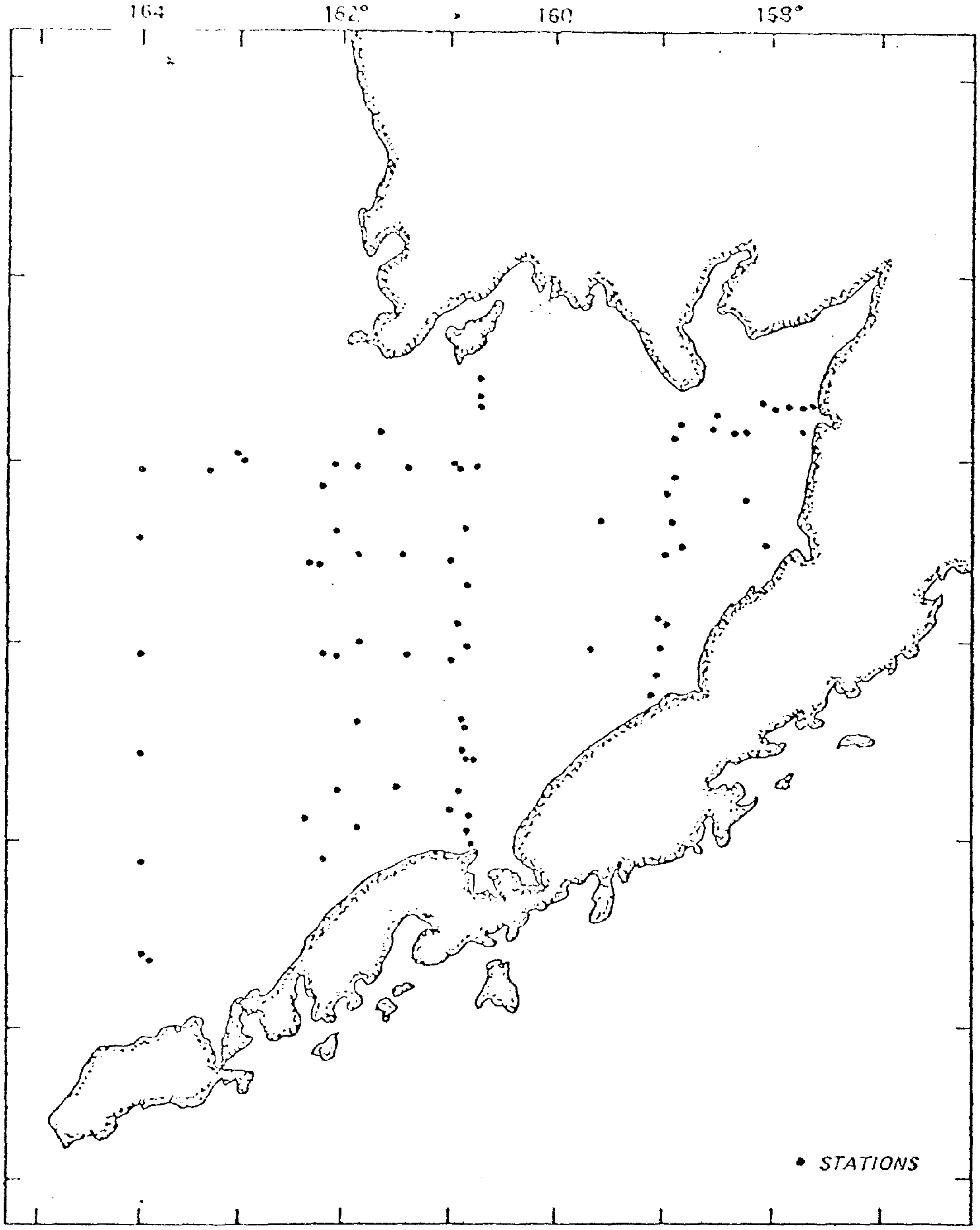


Fig. 28 Stations occupied in Bristol Bay June 15 - July 5 1969.

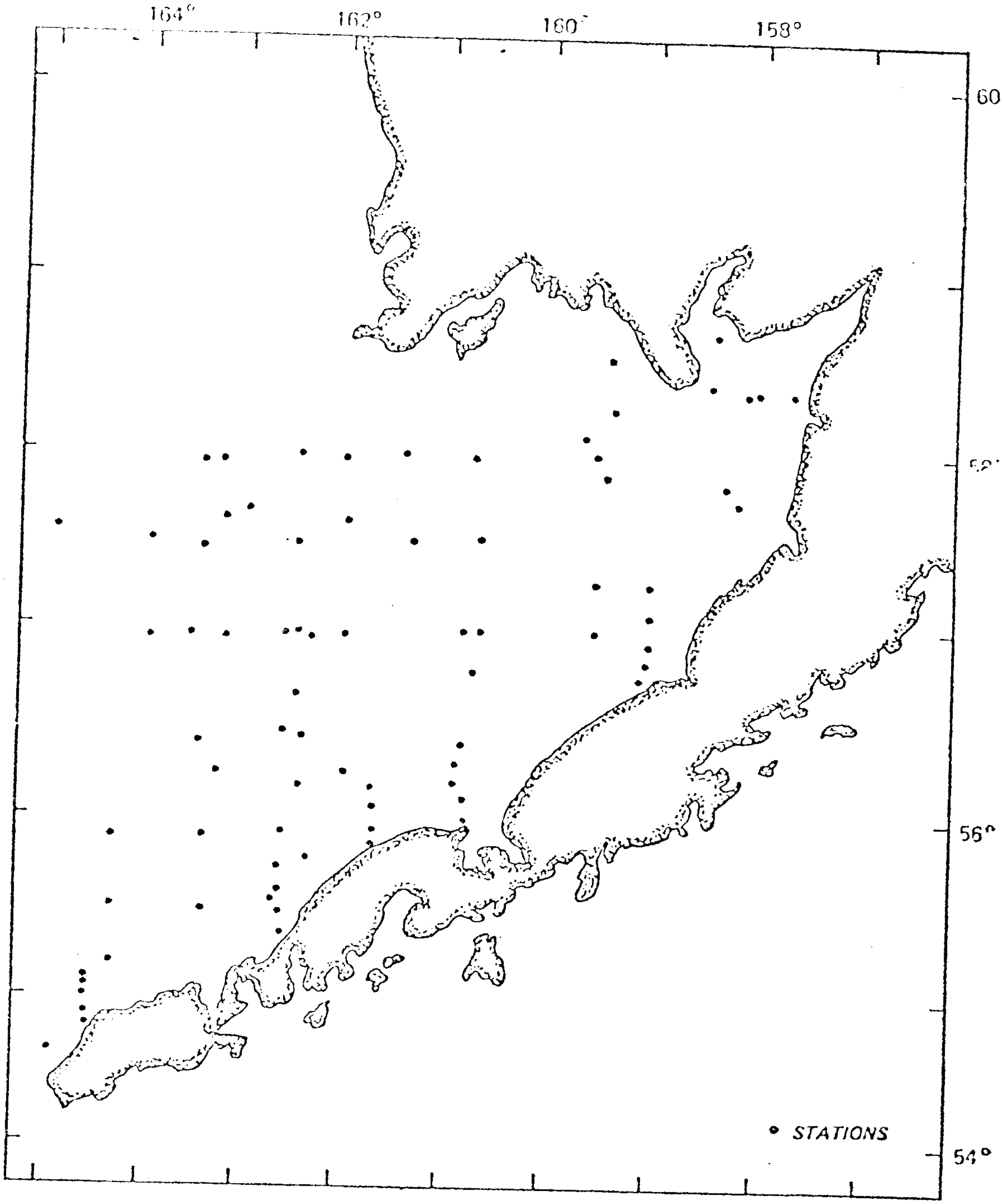


Fig. 29 Stations occupied in Bristol Bay July 5-31 1969.

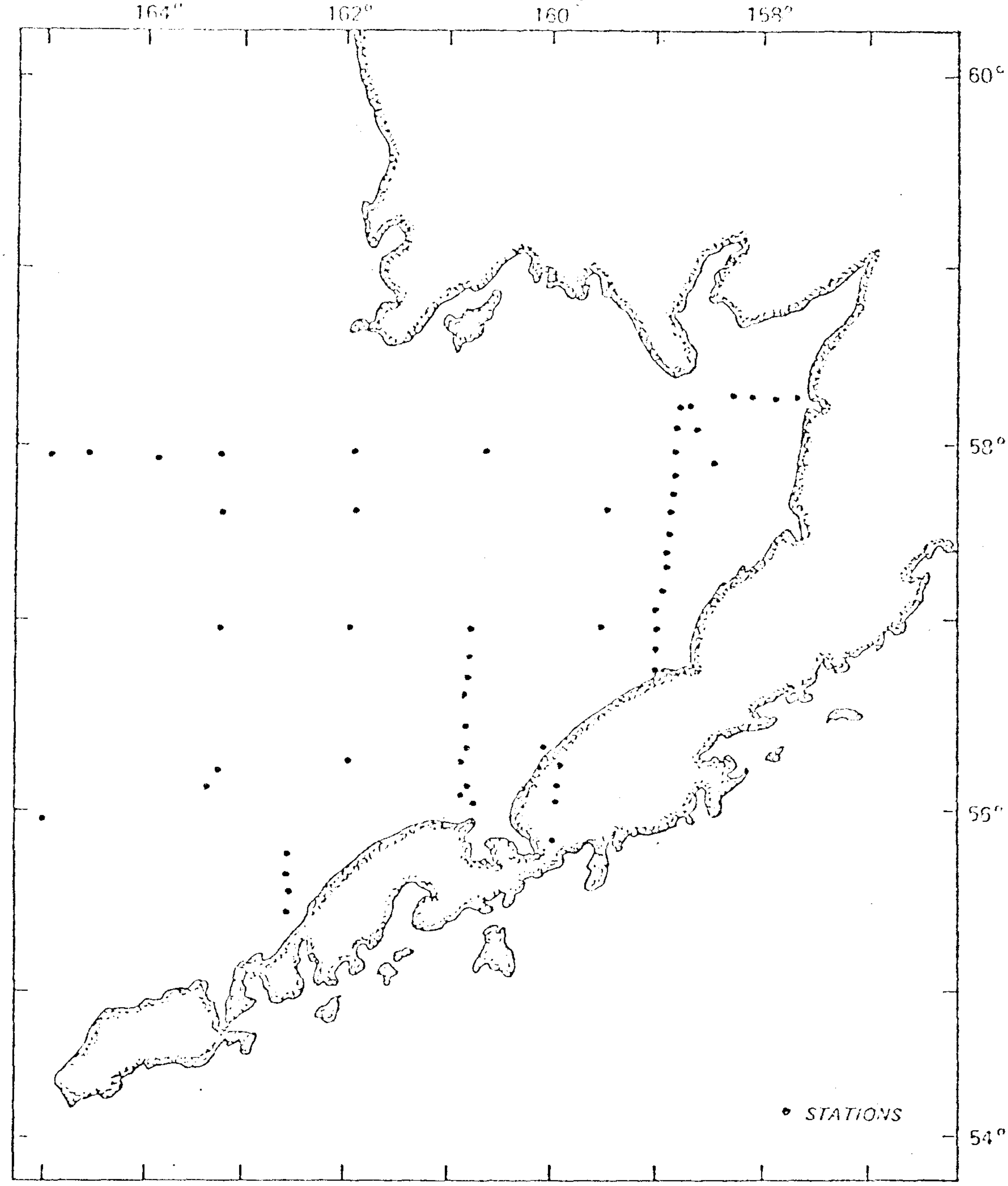


Fig. 30 Stations occupied in Bristol Bay August 1-27 1969.

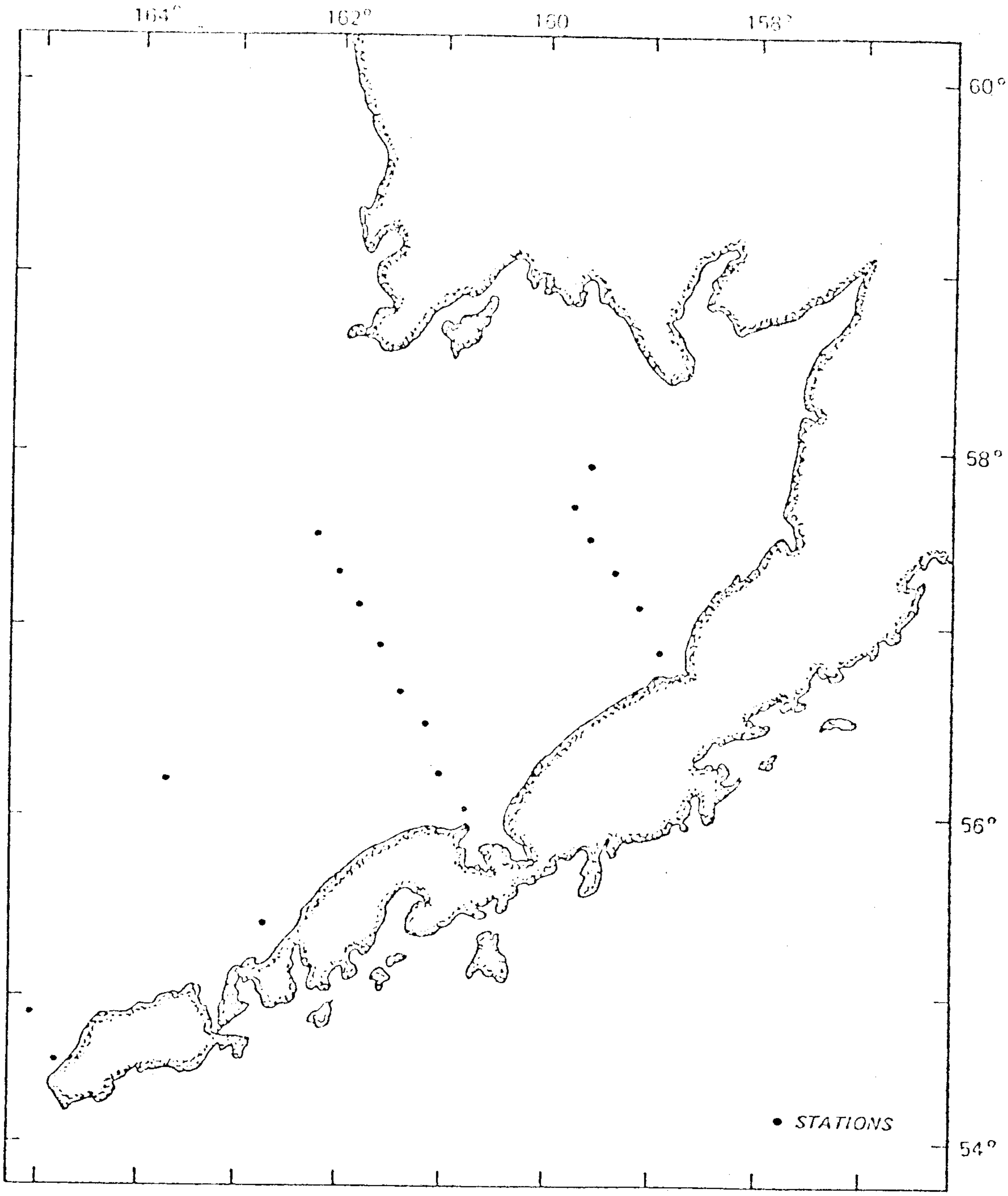


Fig. 31 Stations occupied in Bristol Bay March 29-31 1970.

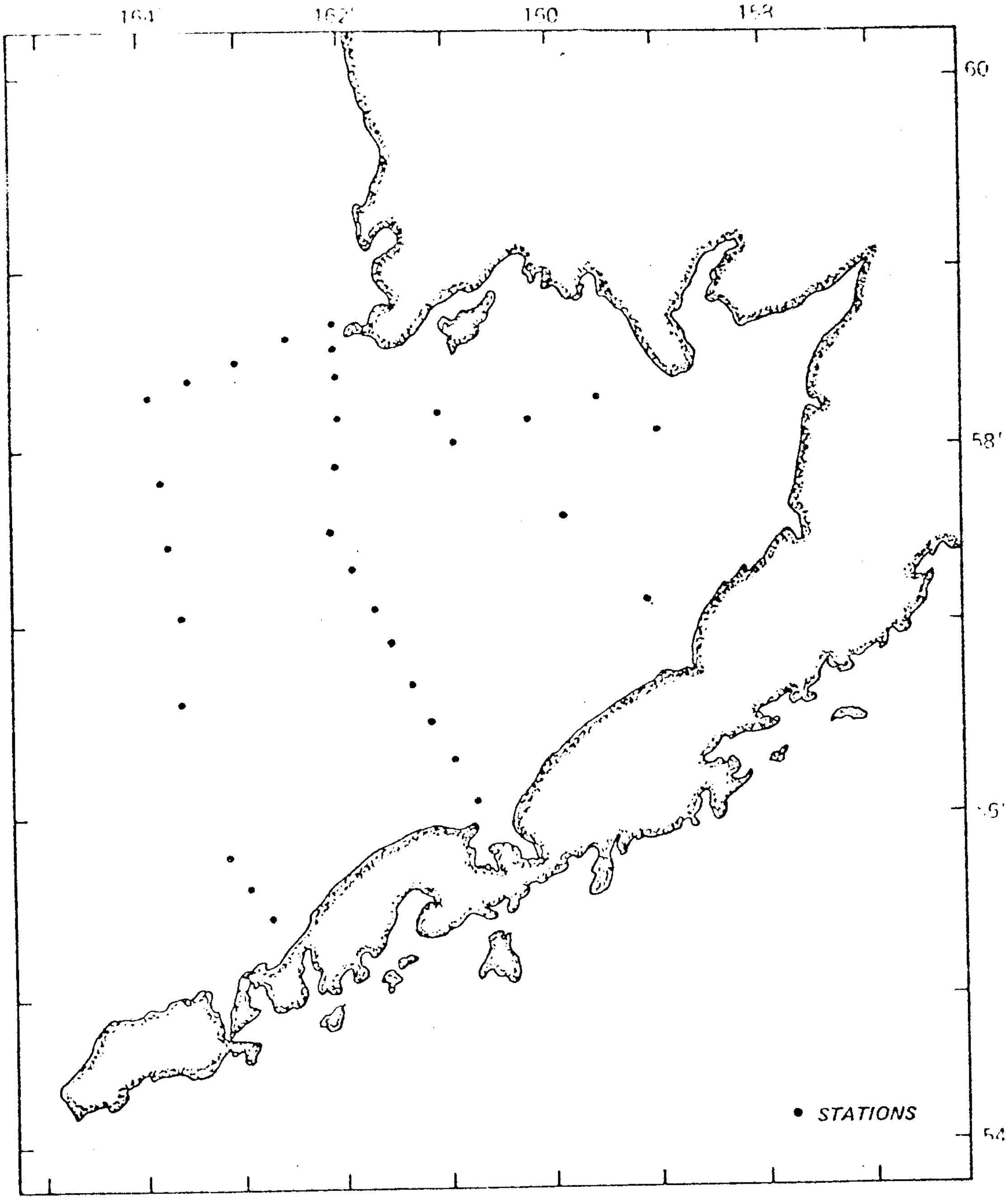


Fig. 32 Stations occupied in Bristol Bay April 1-26 1970.

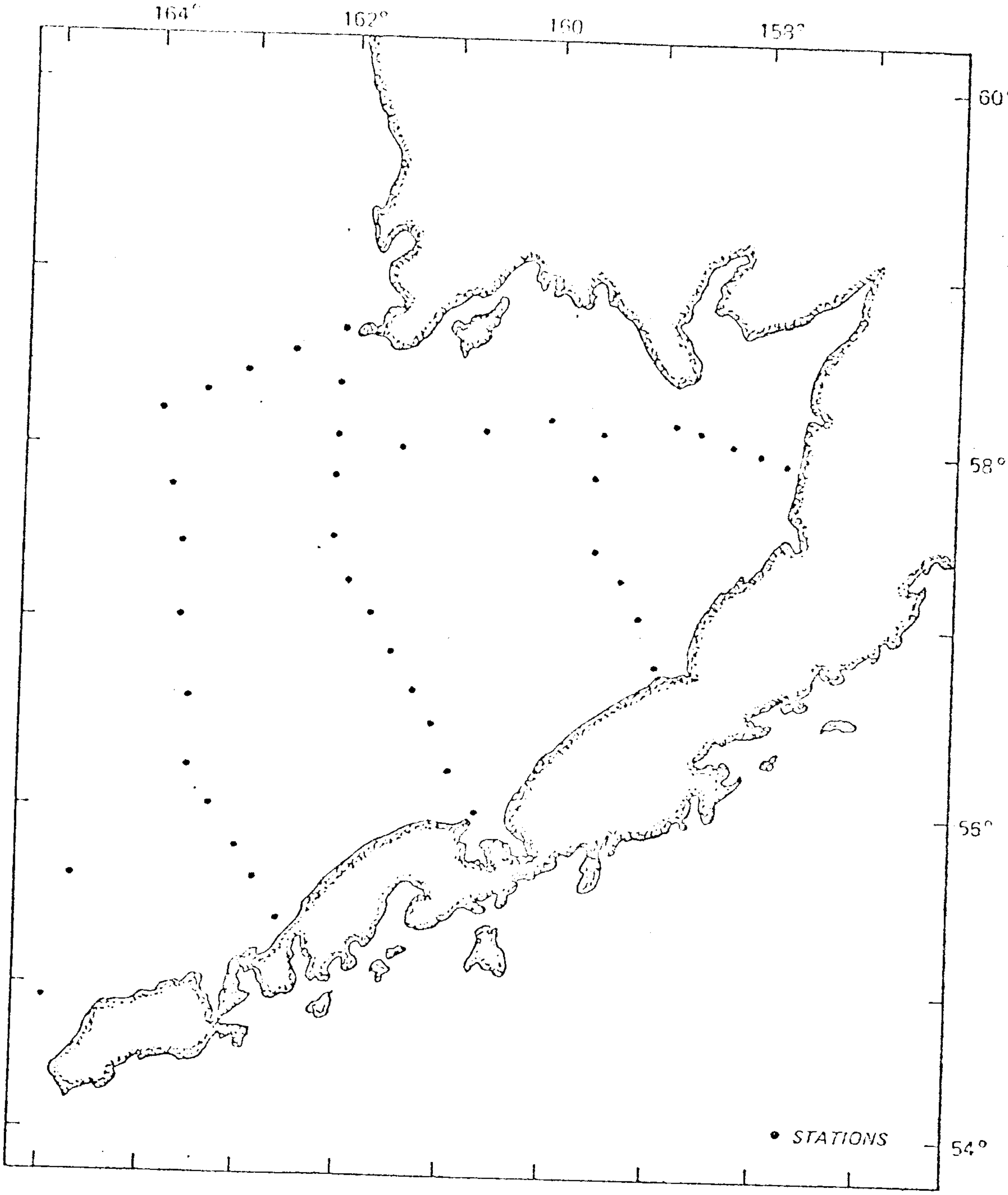


Fig. 33 Stations occupied in Bristol Bay May 22-30 1970.

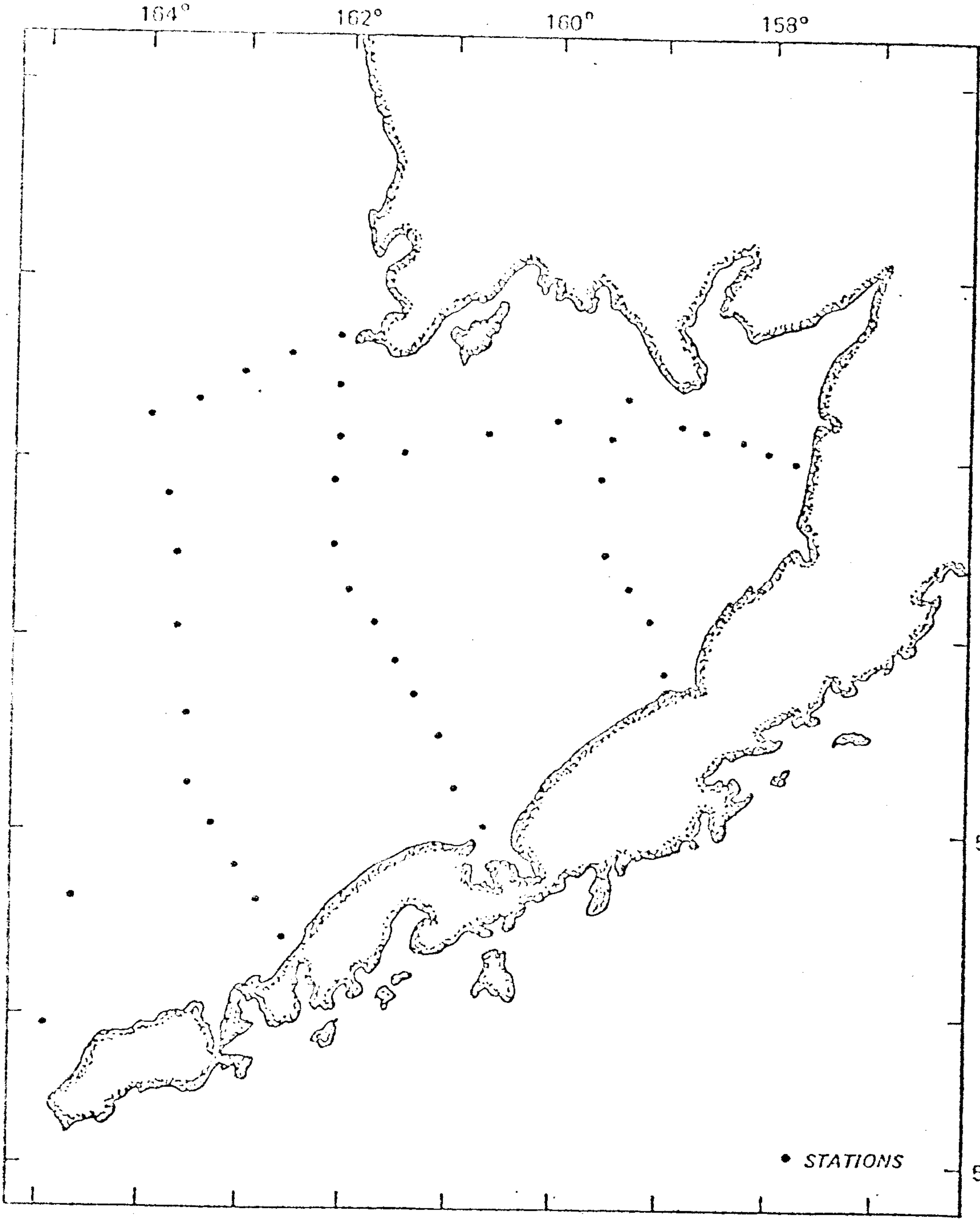


Fig. 34 Stations occupied in Bristol Bay June 7 - July 3 1970.

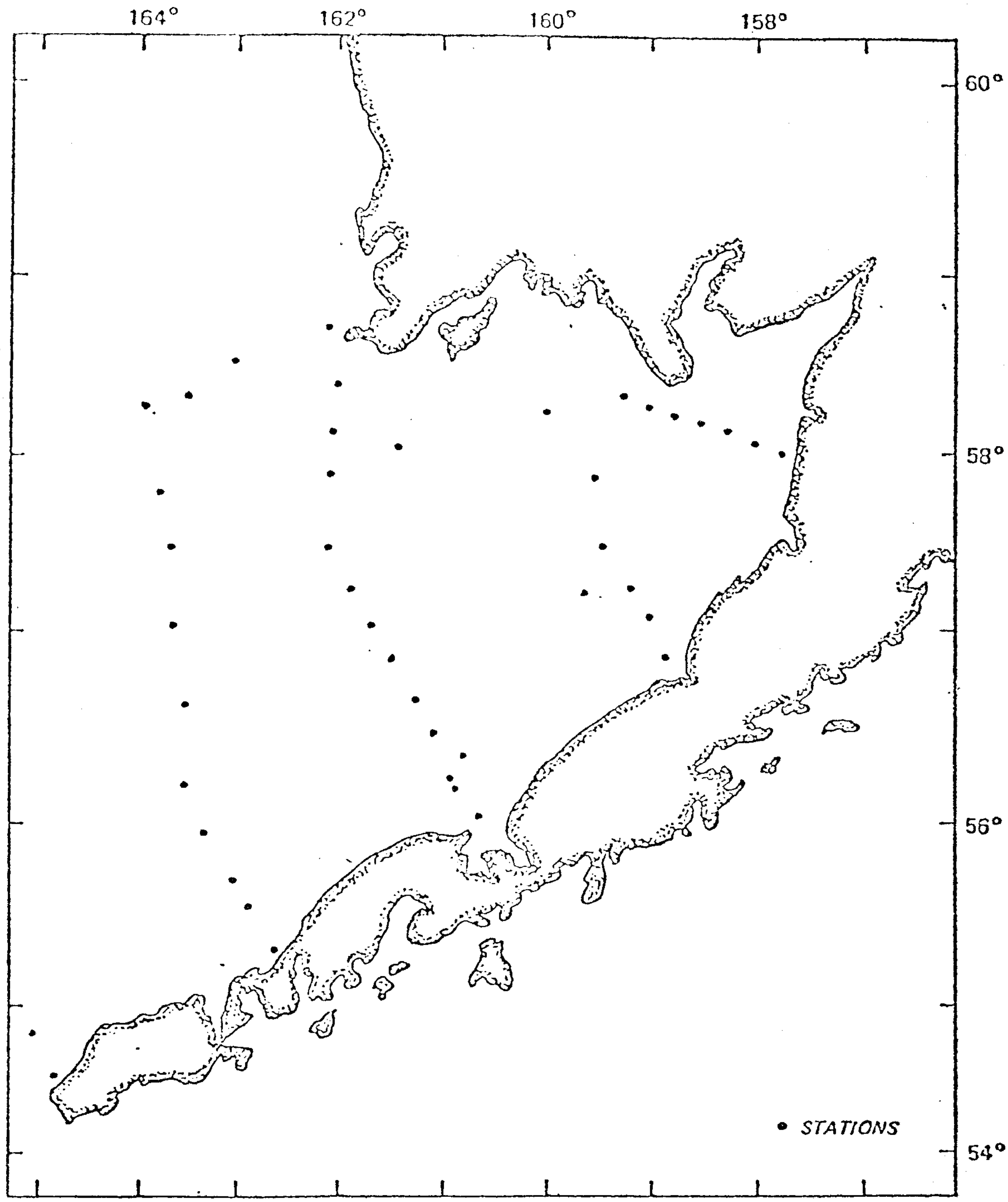


Fig. 35 Stations occupied in Bristol Bay August 10-26 1970.

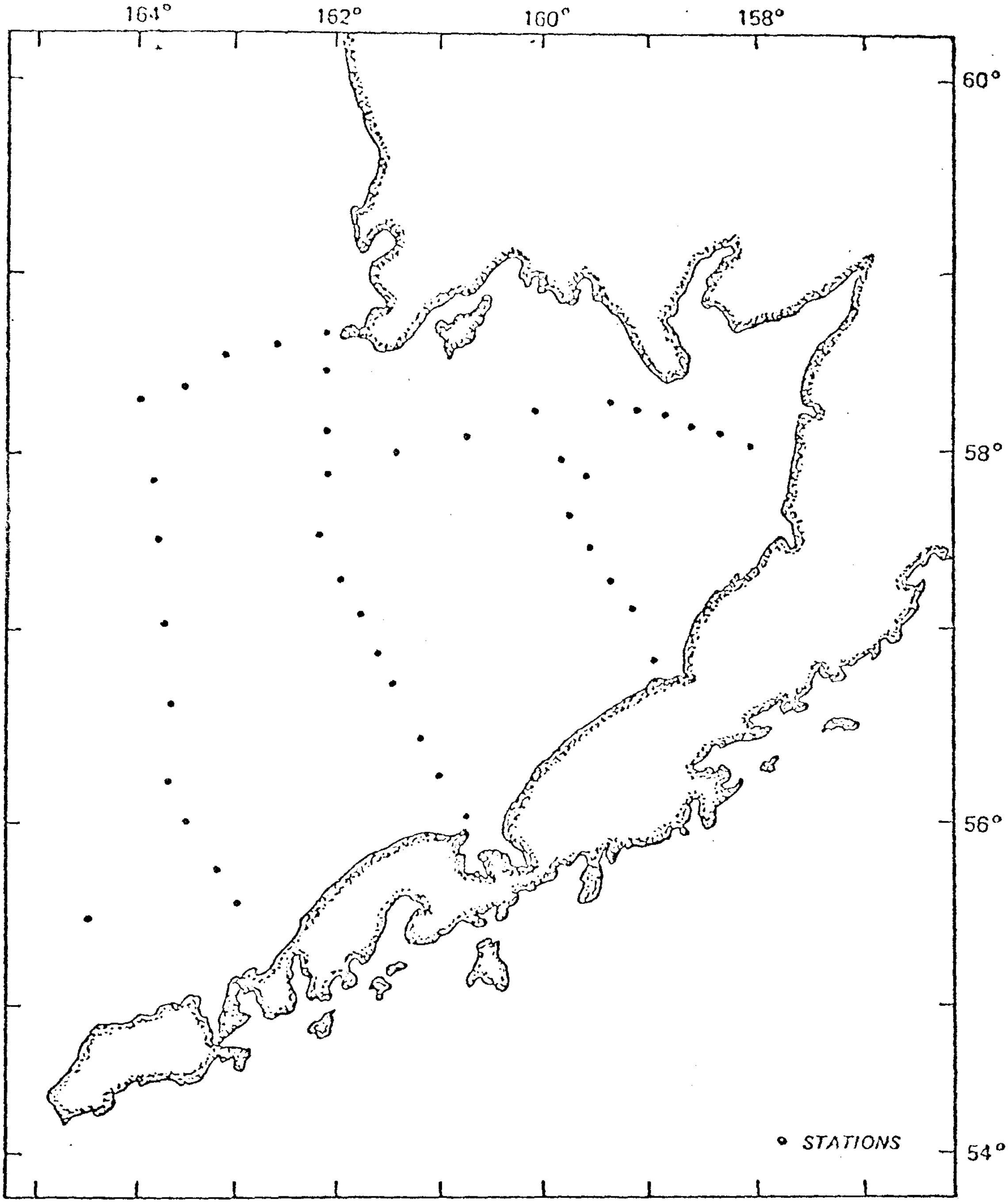


Fig. 36 Stations occupied in Bristol Bay September 16-21 1970.

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