INTERNATIONAL NORTH PACIFIC FISHERIES COMMISSION

BULLETIN NUMBER 33

OCEANOGRAPHY OF THE SUBARCTIC PACIFIC REGION, 1960–71

by F. Favorite, A. J. Dodimead and K. Nasu

VANCOUVER, CANADA, 1976

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INTERNATIONAL NORTH PACIFIC FISHERIES COMMISSION

Established by Convention between Canada, Japan and the United States for the Conservation of the Fisheries Resources of the North Pacific Ocean

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PREFACE

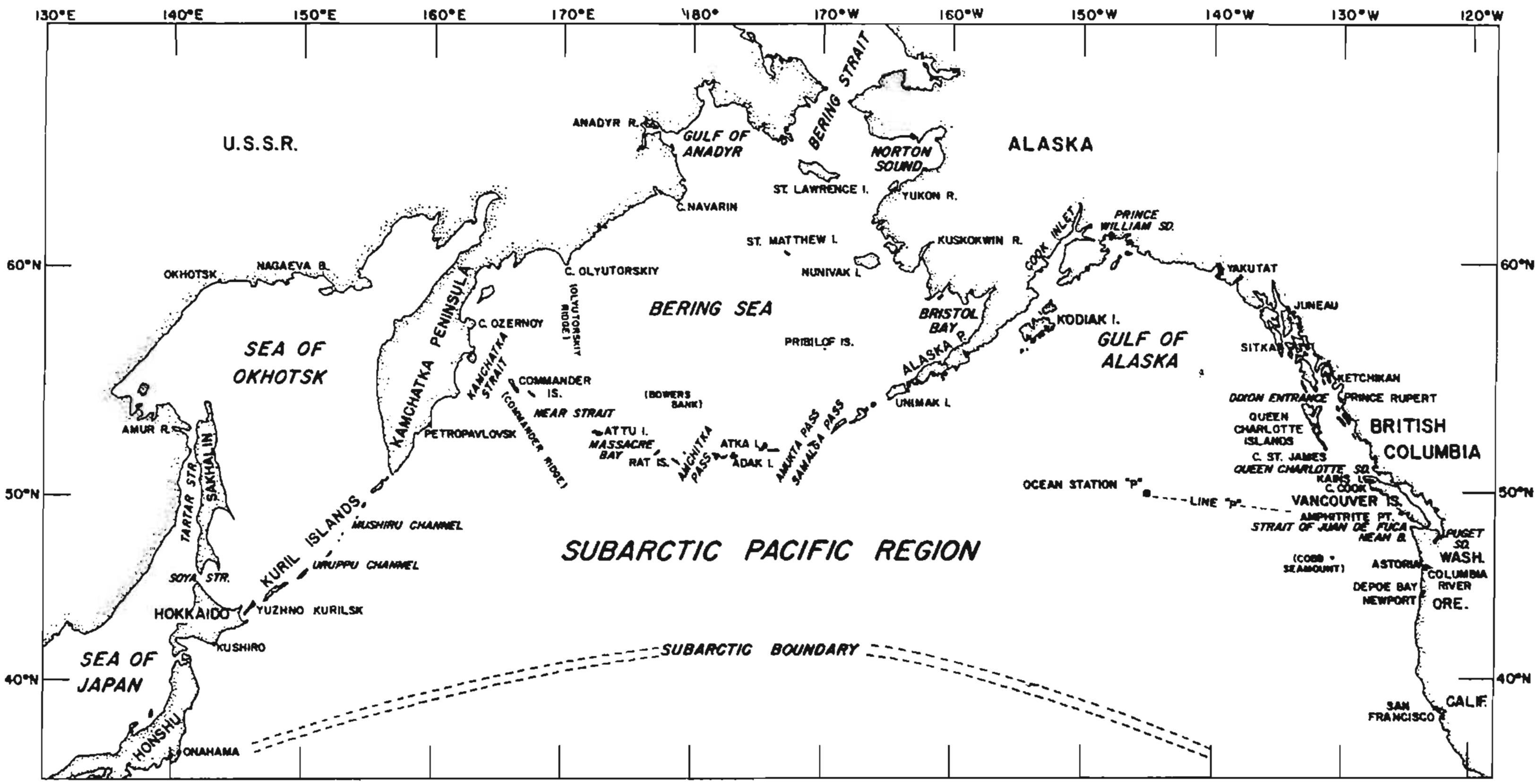
In 1970, the Commission decided to prepare new joint comprehensive reports containing broad syntheses of available information on the distribution and origin of the six species of salmon (genus *Oncorhynchus*) on the high seas of the North Pacific Ocean, and on the oceanographic conditions which are closely related to these salmon. The Commission has published previously similar joint comprehensive reports which provided information available approximately through 1961 (Bulletin No. 13—oceanography, No. 16—coho, chinook, and masu salmon in offshore waters, No. 20—sockeye salmon in offshore waters, No. 22—pink salmon in offshore waters, and No. 25—chum salmon in offshore waters). These reports were parts of a comprehensive report entitled " Salmon of the North Pacific Ocean ", which also provided catch statistics and information on the life history, spawning populations, and offshore distribution of salmon.

The present report, which deals with oceanography, is the second of the new series to be completed (the first in this series concerned coho salmon—Bulletin 31).

Research reports submitted to the Commission for publication in the Bulletin must first receive approval for publication by three scientific referees. At the present time, these referees are: Dr. K. S. Ketchen, Pacific Biological Station, Environment Canada, Nanaimo, B. C.; Mr. Koya Mimura, Research and Development Department, Fishery Agency of Japan, Tokyo; and Dr. F. M. Fukuhara, Northwest Fisheries Center, National Marine Fisheries Service, Seattle, Washington. Following approval for publication by the scientific referees, reports must receive approval for publication by the Commission. Approval for publication by the Commission does not necessarily constitute endorsement of the views of the authors.

Bulletins of the Commission are published separately in English and Japanese and accuracy of translation is the responsibility of the Secretariat. The original language of this Bulletin was English.

INPFC SECRETARIAT
March, 1976



FRONTISPIECE. Subarctic Pacific Region (area including Sea of Okhotsk and Bering Sea is approximately 13×10^6 Km²).

OCEANOGRAPHY OF THE SUBARCTIC PACIFIC REGION

1960–71

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FOREWORD

The International North Pacific Fisheries Commission (INPFC), whose member nations are Canada, Japan, and the United States of America, was established under the International Convention for the High Seas Fisheries of the North Pacific Ocean in 1953 for the purpose of promoting and coordinating scientific studies necessary to ascertain the conservation measures required to secure the maximum sustained productivity of fisheries of common interest to the members. Realizing the importance of the environment, the Standing Committee on Biology and Research recommended oceanography as an aid to an understanding of salmon distribution and their movements. The basic oceanographic requirements or problems were to determine the characteristics of the environment in which salmon are known to live; relate the extent of the environment to the pattern of currents and water structure; observe and recognize annual and seasonal variations in this environment; and determine mechanisms that could account for the observed conditions and factors that cause changes.

Results of research conducted from 1953–59 were reported in the first INPFC Joint Report on Oceanography, INPFC Bulletin 13 (Dodimead et al. 1963).

Although the primary purpose of the bulletin was to serve as a background document for INPFC studies, it was favorably received and has been extensively cited by the international oceanography and marine biology community. It represents a concerted attempt by oceanographers representing three nations —Canada, Japan, and the United States of America—to obtain an assessment of environmental conditions and processes and to establish a common terminology to be used in the reporting of research results. The use of the term domain to define ocean areas having consistent properties, structure and behavior of flow was a major step in achieving common terminology, but recent intensive field investigations indicate a more definitive terminology is possible and an attempt has been made here to define more precisely domains, current systems and other oceanographic features. This may meet with some opposition from oceanographers concerned primarily with gross circulation patterns or water balances, but this approach is reasonable and appropriate at this time if one is to ascertain and describe relations between living marine resources and their environment.

The boundaries of the Subarctic Pacific Region[1], presented in INPFC Bulletin 13, are not very rigorously defined, nor in reality can they be. Although ice in winter in the Sea of Okhotsk and Bering Sea results in environments in these areas that are more Arctic in nature than Subarctic (Tully, 1964a, b) and the shallow continental shelves and the northward intrusions of warm water result in temperature conditions in summer not unlike those in areas nearly 2,000 km farther south, we have selected Bering Strait as the northern boundary of the region. The strait, which lies only about 100 km south of the Arctic Circle and separates the Arctic Ocean from the Bering Sea, represents an acceptable geographical choice even though it is recognized that environmental conditions are not uniform across the strait. The southern boundary, defined by the transpacific location, near 42°N, of the near vertical 34‰ isohaline in the surface layer, is more realistic in terms of environmental conditions but its position is only approximate because of variability in dynamic processes at the surface and at depth that maintain this unique structure. These boundaries and delineations of various domains within them have generally withstood the test of time.

It is our intent that this study on the physical oceanography of the region from 1960–71 be considered an extension of INPFC Bulletin 13, so that the two reports constitute, as completely as possible, a summary of all research activities in the region. In preparing this report, we have reviewed several hundred papers and a summarization of the various results not only proved extensive, but also conflicted with new terminology we wish to establish. However, because the summarization provides a concise synthesis of research activities from 1960–71, contains extensive background information used in the compilation of this report, and should be of great value in the formulation of future research plans, it has been presented in the main body of the report. References to papers published prior to 1960 that were unknown or not available at the time of writing the first report, but have since been acquired, are also included in the list of references. Some references have not been cited but are included for information. A review of field activities, data services, and research results is presented and also summarized in a graphical and tabular form for easy reference. Long-term mean distributions of oceanographic parameters at various levels and locations are presented and discussed. Modifications in the domain concept are made and current systems defined. Annual, seasonal, and monthly mean oceanic conditions during 1960–71 are investigated in order to ascertain periodic and aperiodic environmental changes and their causes, and predictive indices for significant phenomena have

[1] The term "region" throughout this report denotes this Subarctic Pacific Region.

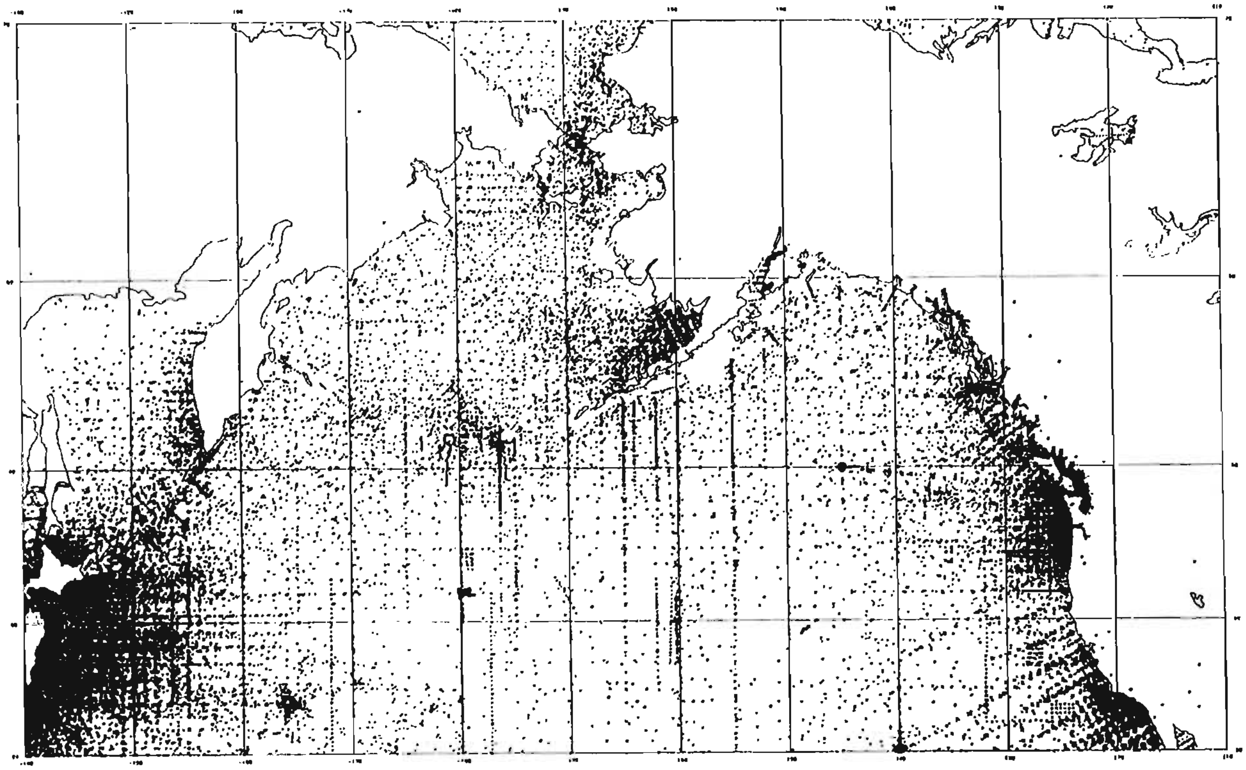


FIGURE 1. Locations of oceanographic stations used to compute long-term mean values in 2×2° quadrangles (based on data available at the U.S. National Oceanographic Data Center's Geofile as of December 1972).

been sought. Finally, recommendations concerning future oceanographic research that will assist in solving problems confronting the INFPC, particularly in regard to the distribution and movements of stocks of pelagic, anadromous, and demersal fishes, are suggested.

It is indeed unfortunate that again in this report, our analyses must be without access to much of the extensive Soviet oceanographic data that appear to be available to Soviet investigators. Efforts by Dr. Favorite, while a member of the U.S.-U.S.S.R. Oceanographic Exchange Delegation in 1965, to obtain Soviet data in the western North Pacific Ocean and Bering Sea proved unrewarding[2] and it was suggested that these data are not fully processed.

I. BACKGROUND

A. Data Sources

The last decade has seen a sharp increase in the use of computers to handle, process, and analyze oceanographic data. New information, nearly impossible to ascertain by previous manual methods, is only now beginning to come to light; such as the coherence in the transpacific movement of anomalously warm and cold surface areas during 1953–60 ascertained after computer analyses of nearly 2 million ship observations compiled in the U.S. National Climatic Center Tape Data Family 11 (Favorite and McLain, 1973). For this report, we have computed long-term means by 2×2° quadrangles from data at over 75,000 stations, and analyses for 1960–71 on over 25,000 stations; these represent all data in our area of interest obtained by Canadian, Japanese, Soviet, and U.S. oceanographic cruises north of 30°N available in the U.S. National Oceanographic Data Center's Geofile as of December 1972. The former stations are shown in a composite map (Fig. 1), and the latter are shown in half-year maps, October-March and April-September (Fig. 2). Because of the large number of vessels and cruises it is not expedient to provide a complete list of various activities, but all cruises associated with major ocean surveys from 1960–71 (particularly those for which the primary mission was to obtain data in relatively unexplored areas or in critical time periods, and for which the data are avail-

[2] Favorite, Felix. 1965. A glimpse of marine research in the Soviet Union. Nat. Mar. Fish. Serv. NW Fish. Center, Seattle, Washington, 55 p+6 appendices (Processed).

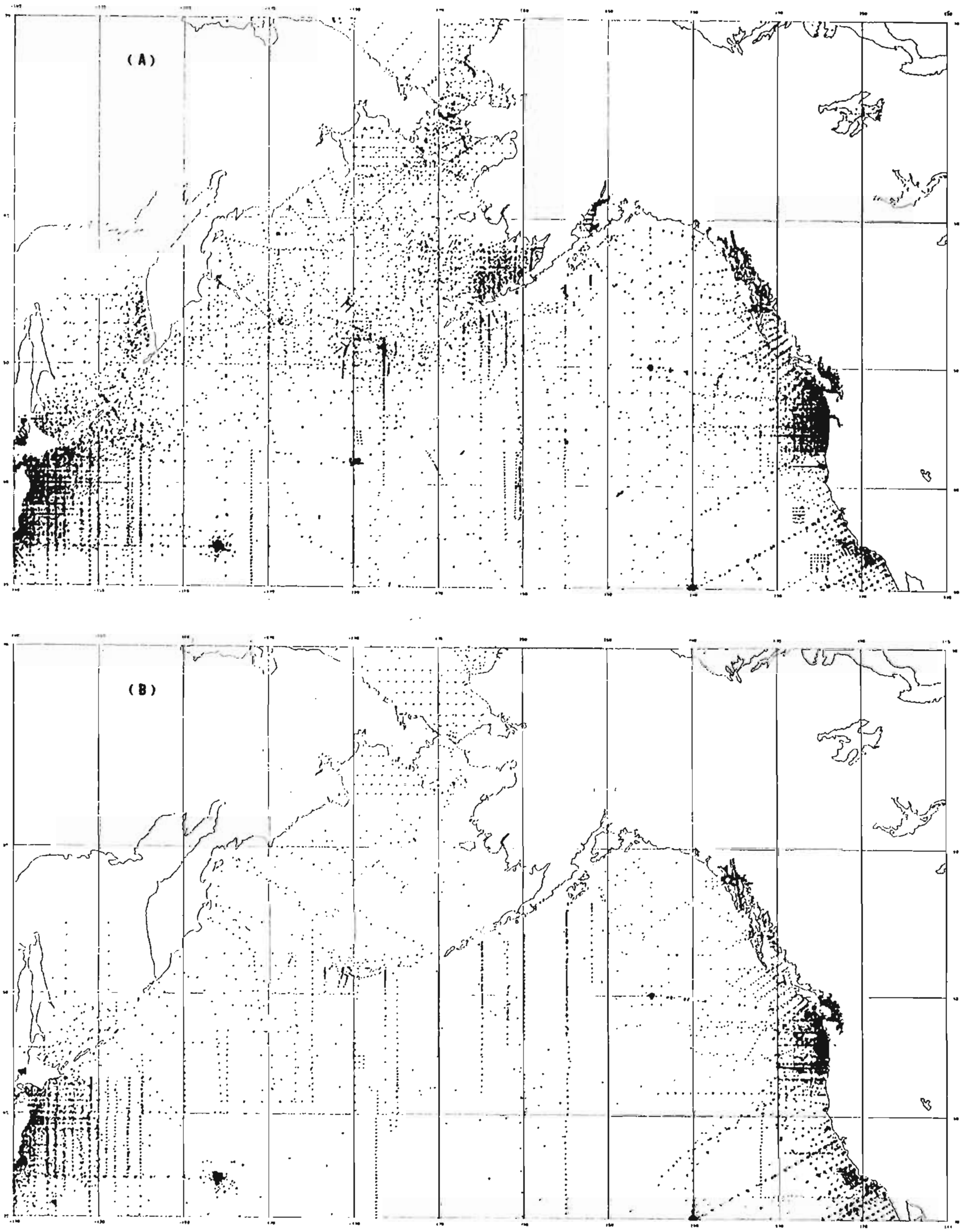


FIGURE 2. Locations of oceanographic stations (A) April-September and (B) October-March (including January-March 1960), 1960–71.

TABLE 1. Periods (months) of major ocean cruises related to INPFC activities.

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971
Argo							I–III					
Beacon Hill	I–II											
Bertha Ann			II–IV									
John N. Cobb		VII	VII	VII	VII							
Endeavour								IX–X	IV, IX			
Miller Freeman									VII–VIII	VI–VIII		
Hakuha										VIII–IX		
Hokusei	VI–VIII	VI–VIII	VI–VIII	VI–VIII	VI–VIII	VI–VIII	VI–VII	VI–VIII	VI–VIII	VI–VII		
Kaiyo								VIII				
George B. Kelez				II–III, VII–IX		X–XII	II–III, VII–IX	I–III, VI–VIII	II–III, IV–VI	I–II, IV–VI, VIII–IX	I–III, IV–VI, VII–IX	V–VI
Kofu				V, VI, VIII, IX, XI	II, V–VI, VIII, IX	II, V, VII–VIII	II–III, VI–VII	II, VII–VIII, XI, XII	II–III, IV–V, VII	II–III, V, VII–VIII	II, IV, XII	
Laymore										IV		
Marine View		V–VIII										
Northwind			VII, IX X	VIII–IX				VIII		VI	VIII	
Oshawa	VIII–IX	II, V–VI	V–VI									
Oshoro	VI–VIII	VI–VII	V–VI	V–VII	VI–VIII	V–VIII	VI–VIII	VI–VIII	VI–VIII	VI–VIII		
Paragon	V–VIII	V–VIII										
Pioneer	V–VIII											
Ryofu	II–III, VIII–IX	II–III, VIII–IX	II–III, VIII, IX	II–III	VIII–IX	I–II, VII–VIII	II–III			V, VII		
St. Anthony		V–VII										
Seifu							VII	VI–II		V	VII	
Soya					II			II				
Takuyo								VII, VIII				
Thomas G. Thompson								II	IV	VII–VIII	VI–VIII	VII–VIII
Whitethroat	VII–VIII		V–VII									
Yushio	II–III, VI, VIII, IX, XI	II–III, V, VI, VIII										

able for analysis) are provided in Table 1.

B. Maps, Atlases, and Monographs

Periodic oceanographic reports covering large areas, transpacific maps (or atlases) of water properties, and monographs that are too general or too extensive to summarize are listed in Tables 2 and 3. Such compilations usually require an extended period of time to complete and, except for near real-time temperature reports, most are based on data collected prior to the time period considered in this report.

Sea surface temperature maps, with additional aperiodic special features or periodic meteorological data for the western Pacific Ocean (at 10-day intervals) prepared by the Japan Meteorological Agency, and those for the eastern Pacific Ocean (at monthly intervals) prepared by the U.S. National Marine Fisheries Service (formerly the Bureau of Commercial Fisheries)—both available prior to 1960 and noted in INPFC Bulletin 13—continue to be distributed. In July 1970, through a cooperative arrangement, the coverage on maps prepared by the latter agency was extended west from 180° to the western side of the region. These maps are based on nearly real-time data and a more complete listing and thorough synthesis of these and other data of this type subsequently available have been used to show monthly mean distributions for the years 1949–62 (Eber et al. 1968). Special monthly anomaly charts for the years 1956–57 have been compiled (Saur and Eber, 1962). Monthly mean, minimum, and maximum surface temperatures based on data from 1854–1961 (LaViolette and Seim, 1969), and monthly mean temperatures at the surface and several subsurface depths based on data from 1941–71 (Robinson and Bauer, 1971) are also available.

Extensive data collected by California Cooperative Oceanic Fisheries Investigations (CALCOFI) off the west coasts of the United States and Mexico have been summarized in a series of atlases: 10 m temperatures and salinities, 1949–59 (CALCOFI, 1963); geostrophic flow, 0/500 and 200/500 db (Wyllie, 1966); 10 m temperatures and salinities, 1960–69 (Wyllie and Lynn, 1971); and drift bottle data (Crowe and Schwartzlose, 1972).

Monthly surveys of sea surface temperatures over the continental shelf off the Washington-Oregon coast, off San Francisco and off Los Angeles using an airborne radiometer began in August 1963 but were discontinued in July 1968 (Squire, 1971).

Twice-weekly maps of temperature conditions in the Gulf of Alaska continue to be produced and distributed by the Canadian Weather Service, Esquimalt, B.C., and an atlas of monthly mean vertical

Table 2. Periodic oceanographic reports, content and sources.

Period	Area	Properties	Depth	Special features	Origin
10-day	10-53°N, 110°E-180°	temp	surface (1°C contours)	aperiodic: decade anomalies, temp at 100 m, surface currents, etc.	Japan Meteorological Agency, Tokyo
weekly	33-61°N, 123-176°W	temp	surface (1°C contours)	magnitude of thermocline (°C), potential layer depth (ft)	Canadian Weather Service, Metoc Centre, Victoria, B.C.
monthly	17°N to Aleutian-Commander Island Arc 113°W-180°, and 40°S-30°N, 70°W-180°	temp, temp anomaly from previous year and from long term mean	surface (2°F contours)	sea surface temp off west coast of U.S. (25-52°N, 112-136°W)	National Marine Fisheries Service Southwest Fisheries Center, La Jolla, Calif.
		Mean barometric pressure and resultant wind	surface		
10-day, weekly, monthly	transocean	temp, currents	surface	various meteorological parameters	Fleet Numerical Weather Central, Monterey, Calif.
annually, aperiodic	E. Bering Sea	ice	surface		Naval Oceanographic Office, Washington, D.C.

TABLE 3. Oceanographic atlases.

Year[1]	Sub-periods[2]	Area	Properties	Depth	Special features	Reference
1960	January-February	Gulf of Alaska 48-59°N, 125-151°W	horiz distr: temp, sal, oxy	10 m, top and bottom of halocline, on 33.8‰, on $\sigma_T=26.6$	vert profiles: temp, sal, oxy along 10 sections	Dodimead (1960)
1956-1957	months	20°N to Aleutian-Commander Island Arc	temp (1°C contours)	surface	monthly temp diff 1956-1957	Saur and Eber (1962)
1949-1959	(monthly)	west coasts U.S. and Mexico 20-49°N, 109-133°W	horiz distr: temp, sal	10 m	monthly temp and anomalies at 22 offshore stations 1950-59; mean monthly 10 m temp 1950-59	California Cooperative Oceanic Fisheries Investigations (1963)
1963	May	Wash-British Columbia coast: 46-50°W, 124-130°W	geopot topog	0/150, 0/1500, 300/1500 db	volume trans 0/1500 db; temp, sal, oxy near bottom	Ingraham (1964b)
			horiz distr: temp, sal	0, 100 m		
			vert distr: temp, sal, sigma-t	0-200 m, 0-2500 m along 8 lines normal to coast		
1956-1963	(monthly)	Station "P"	vert distr: temp, sal, oxy, phos, nit, sil	500 or 1200 m	monthly mean: surf temp, sal, potent layer depth	Robertson, et al. (1965)
selected cruise data	annual	85°S-65°N	horiz distr: temp, sal, accel potent, oxy, phos	surface, 125, 80 cl/ton	vert distr: temp, sal, oxy, phos, thermosteric anomaly around subarctic gyre	Reid (1965)
			vert distr: temp, sal, oxy, thermosteric anomaly along 27°N, 27°S and 160°W	0-6500 m		
mean (1947-63)	12 months	Gulf of Alaska: 35-60°N, 165°W to coast	potent layer depth by 5° quadrangles (top of seasonal thermocline)		mag of seasonal thermocline as indicated by temp diff between surf and 300 ft.	Giovando and Robinson (1965)
1961	summer	transocean: 35-61°N (ex. Sea of Okhotsk)	horiz distr: temp, sal	10 m, bottom of upper zone	depth of upper zone, sal =33.8 and 34.0‰, temp on 33.8 and 34.0‰, schematic of upper and lower zone domains	Dodimead (1965)
			vert distr: temp, sal	146, 150, 165 and 175°E		
			temp, sal, oxy	177, 161, 153 and 145°W; 157°E to coast near 50°N and 132°W to Ore. coast		
1960-1964	(quarterly)	Honshu: 28-46°N, 124-153°E	horiz distr: temp, currents	0, 100, 200 m	surf currents (GEK)	Japan Maritime Safety Agency (n.d.)

TABLE 3. Continued.

Year[1]	Sub-periods[2]	Area	Properties	Depth	Special features	Reference
1949-1965	(monthly)	west coasts U.S. and Mexico: 20-49°N, 109-133°W	geostrophic flow: 0/500, 200/500 db	surface, 200 db	monthly mean values for period 1949-65	Wyllie (1966)
1961-1963	(monthly)	Ore.-Wash.-Vancouver Is. coast: 42-50°N, 124-132°W	horiz distr: sal vert distr: sal	0, 10, 20 m along various sections	seasonal distr: sal, wind vectors, Ekman trans	Duxbury et al. (1966)
1965	summer	CSK area: 0-46°N, 117-160°E	geopot topog horiz distr: temp, sal, oxy vert distr: temp, sal, oxy	0/1000 db 50, 100, 200, 300, 500, 700, 1000 m off Okinawa, Shikoku, Inubosaki, and 133 and 144°E	0/500 db (inland sea)	Japanese Oceanographic Data Center (1967)
mean (1854-1961)	monthly	Sea of Okhotsk	horiz distr: temp, sal sigma-t	0, 50, 100, 300, 600, 1000 m	typical vertical traces of temp, sal, sigma-t for various periods at various places	LaViolette (1967)
1961-1964	July	Wash-Ore coast: 41-49°N, 124-132°W	horiz distr: temp, sal, oxy, sigma-t	10, 100, 500 m	vert profiles of sal, oxy along various lats: depth of mixed layer; geopot topog: 0/500 db; surf sal, salmon catches	Owen (1967)
1963	Oct-Nov.	Wash-British Columbia coast: 46-50°N, 124-131°W	vert distr: temp, sal, oxy, sigma-t	0-300 and 0-3000 m	surf temp and sal: bottom tem, sal, oxy at 55, 183, 914, 1829 m; geopot topog 0/1500, 300/1500 db; vol trans 0/1500 db	Ingraham (1967a)
1956-1966	winter	CSK area: 0-46°N, 118-162°E and 49-59°N, 150°E-176°W	geopot topog horiz distr: temp, sal, oxy vert distr: temp, sal, oxy	0/1000 db 50, 100, 200, 300, 500, 700, 1000 m 135°E, 144-145°E, and 34°N	0/500 db (inland sea)	Japanese Oceanographic Data Center (1968)
1949-1962	monthly	20°S to Aleutian-Commander Island Arc (ex. Japan and Okhotsk Seas)	temp	surface		Eber et al. (1968)
1965 1966	April-June April-Aug	44-59°N 125-160°W	horiz distr: temp, sal vert distr: temp	surface along various sections at 275 m	vert distr: temp at Station "P"	Dodimead (1968a)
1966	winter	175°E, 41-53°N, 165°W, 42-54°N	vert distr: temp, sal sigma-t geostr currents	0-1500 m	T-S curves	Dodimead (1968b)

(1854–1961)	monthly	Bering Sea	temp, sal, sigma-t	0, 50, 100, 300, 600, 1000 m	max, min and mean vertical traces in selected regions	Hamilton and Seim (1968)
mean (all data at NODC to 1964)	quarterly	55°S–65°N, 70°W–100°E	horiz distr: temp, sal, sigma-t	10 m	variability · depth and oxy at Marsden squares 9, 16, 20, 52, 57, 87, 93, 122, 129, 158, 165, 195, 308, 315, 320, 349	Barkley (1968b)
			horiz distr: depth, sal, oxy	sigma-t surfaces		
			horiz distr: depth, sal, sigma-t	sigma-t surfaces 27.0, 27.2, 27.4, 27.6, 27.7		
			vert distr: depth, sal, oxy	sigma-t surfaces along 127, 141, 161, 179°E and 159, 139, 121, 101, 85°W: 47, 35, 25, 11, 5°N: 5, 15, 25°S		
1966	summer	7–45°N, 118–162°E	geopot topog	0/500, 0/1000 db		Japanese Oceanographic Data Center (1969)
			horiz distr: temp, sal, oxy	50, 100, 200, 300, 500, 700, 1000 m		
			vert distr: temp, sal, oxy	along 137°E, 145°E, 20°N, 34°N		
mean (1854–1961)	12 months	20°S–60°N	temp (2°F contours)	surface	distr: min, max	LaViolette and Seim (1969)
1967	Jan–Mar	1°S–45°N, 110–161°E	geopot topog	0/500, 0/1000 db		Japanese Oceanographic Data Center (1970)
			horiz distr: temp, sal, oxy	50, 100, 200, 300, 500, 700, 1000 m		
			vert distr: temp, sal, oxy	137°E, 144–145°E, 20°N, 34°N		
1967–1968	April–June July–Sept. Oct–Nov. Jan–March	CSK area: 5°S–46°N 118–122°E	geopot topog	0/1000 db		Japanese Oceanographic Data Center (1971)
			horiz distr: temp, sal	50, 200, 500 m		
1950–1969	(monthly)	west coasts U.S. and Mexico: 20–49°N, 109–133°W	horiz distr: temp, sal 1960–69	10 m	monthly temp and anomalies at 21 off-shore stations, 1960–69; vert profiles: mean temp, sal, oxy along 4 lines normal to coast	Wyllie and Lynn (1971)
			horiz distr: mean temp, sal, oxy 1950–1968	150 m		

Continued . . .

TABLE 3. Continued.

Year[1]	Sub-periods[2]	Area	Properties	Depth	Special features	Reference
1965–1969	quarterly	Honshu: 28–46°N, 124–153°E	horiz distr: temp, currents	0, 100, 200 m	surf currents (GEK)	[Japan] Maritime Safety Agency (n.d.)
1955–1964	monthly	Honshu: 28–46°N	currents	surface		Japan Maritime Safety Agency (1971)
mean (1854–1961)*	12 months	5°S to Bering Strait	temp	0, 100, 200, 300, 400 ft	thermocline depth	Robinson and Bauer (1971)
mean	quarterly	Wash-Ore coast: 41–49°N, 124–130°W	horiz distr: temp, sal sigma-t, oxy	0, 10, 20, 30, 50, 75, 100, 150, 200, 300, 500, 800, 1000 m		McGary (1971)
1963–1968	(monthly)	west coast U.S.	temp	surface	aircraft obs	Squire (1971)
1955–1971	(monthly)	west coasts U.S. and Mexico	currents, drift bottles	surface		Crowe and Schwartzlose (1972)

[1] ( ) following *mean* denotes years mean values are based on; * not all data for years indicated were used.
[2] ( ) denotes intermittent or approximate period.

temperature structure in this area was compiled by Giovando and Robinson (1965).

In addition to the extensive compilation of maps of near-surface conditions there have been a number of atlases and reports which deal with water properties at depth. Reid (1965) and Barkley (1968b) have presented conditions on selected surfaces, over the entire Pacific Ocean, but data within the Subarctic Pacific Region were relatively sparse. Dodimead (1960, 1965, 1968a, b) has presented atlases of conditions in the region during 1960, 1961, 1965, and 1966; and Robertson *et al.* (1965) have presented an atlas of conditions at Ocean Station "P" for 1956–63. Conditions off the Washington and Oregon coasts during a study of the Columbia River effluent in 1961–63 have been summarized by Duxbury *et al.* (1966) and in a novel computer presentation by McGary (1971); conditions in this area in May 1963, and in October and November 1963, and in January 1964 have been presented by Ingraham (1964b, 1967a, b); and conditions in July 1961–64 have been presented by Owen (1967).

The Japan Maritime Safety Agency (n.d., n.d., 1971) has published a series of temperature and current atlases presenting data from 1955–69 and the Japan Oceanographic Data Center (1967, 1968, 1969, 1970, 1971) has and continues to publish a series of atlases in relation to Cooperative Studies of the Kuroshio (CSK). Recently a series of "Prompt oceanographic reports" on conditions near Japan have been disseminated by the Maizuru and Hakodate Marine Observatories.

The U.S. Naval Oceanographic Office compiled atlases of mean temperature, salinity, and density in the Sea of Okhotsk (LaViolette, 1967), and in the Bering Sea (Hamilton and Seim, 1968).

There are a number of reviews on the oceanography of the entire, or parts of, the Pacific Ocean; these include general, large-scale descriptions of circulation or distributions of physical-chemical properties in parts of the Subarctic Region. Excellent general descriptive summaries of conditions, such as Muromtsev (1958), Reid (1965, 1973), Bruevich (1966), Dobrovol'skii (1968b) and others (Table 4) provide information on gross, steady-state conditions, but most are based on data prior to 1960. Although it is our intent to define steady-state conditions as accurately as possible, we are especially interested at this time in seasonal and annual deviations or anomalies from these conditions. The former define the long-term environments that are acceptable or beneficial to various living marine resources, but it is the latter, the moderate and short-term fluctuations in the environment, that affect migrations of fish and

TABLE 4. Reviews of oceanographic conditions in the Subarctic Pacific Region (subsequent to INPFC Bull. 13)

Reference	General title or description
Muromtsev (1958)*	Principal hydrological features of the Pacific Ocean
Dodimead, Favorite, and Hirano (1963)	Review of oceanography of the Subarctic Pacific Region
Uda (1963)	Oceanography of the Subarctic Pacific Ocean
Ivanenkov (1964)	Hydrochemistry of the Bering Sea
Arsen'ev (1965)	Currents and water masses of the Bering Sea
Reid (1965)	Intermediate waters of the Pacific Ocean
Brucvich (1966)	Chemistry of the Pacific Ocean
Dobrovol'skii (1968b)	Hydrology of the Pacific Ocean
Marr (1970)	The Kuroshio: A symposium on the Japan Current
Stommel and Yoshida (1972)	Kuroshio: its physical aspects
Takenouti et al. (1972)	Biological oceanography of the northern North Pacific Ocean
Pruter and Alverson (1972)	The Columbia River estuary and adjacent ocean waters
Reid (1973)	Northwest Pacific Ocean waters in winter
Hood and Kelley (1974)	Oceanography of the Bering Sea

* Not listed in INPFC Bulletin 13.

result in year-to-year variability in distributions and abundances of these resources.

C. Climatology

Our concern with climatology is largely related to energy exchange and ascertaining knowledge of ocean conditions in the absence of the extensive amount of oceanographic data required to adequately define specific phenomena. For example, without question, ocean currents are largely wind-driven and surface winds can be derived, or certainly estimated, from distributions of pressure at sea level.

Although weather reports from ships at sea have continually increased, the information ascertained from daily satellite pictures of cloud cover since the mid-1960's has increased immeasurably the ability to ascertain pressure distributions at sea level. Far more complex patterns have been evidenced than previously anticipated, but these data are relatively recent. Mean values of meteorological conditions—cloud cover, air pressure at sea level, and energy exchange—have been compiled and are based on shipboard observations for 20-year period 1951–70.

Monthly mean pressures at sea level (Fig. 3) indicate the interactions between three major systems. First, the east Siberian high pressure system, which is present from October to March, reaches a maximum in January; it is replaced by a low pressure system from May to August. Second, the Aleutian low pressure system, which is evident year round (except in July), gradually increases in intensity from August until January—from August to December its center moves southeastward from the northern Bering Sea to the Gulf of Alaska but shifts abruptly to the western Aleutian Islands in January—after which the system progressively weakens and is no longer evident in July. And third, the eastern Pacific high pressure system, which is present year round off the coasts of California and Baja California, reaches maximum intensity during June-August, at which time it encompasses the whole or most of the Gulf of Alaska. It is obvious that a near reversal of transpacific conditions occurs between January and July. In January, the ocean area is dominated by an intense low pressure system having a high pressure system to the west and a moderately high pressure system to the east, whereas in July the ocean area is dominated by an intense high pressure system with a moderate low pressure system to the west and a weak low pressure system to the east. These conditions dictate the presence of intense cyclonic (anti-clockwise) winds during January and moderate anticyclonic (clockwise) winds in July. The effects of these winds on ocean circulation can be translated into a " surface " flow (Ekman transport) computed from surface wind stress, and a total flow computed from the curl of the wind stress. These flows are discussed in a later section.

The ocean also receives energy from incident and reflected radiation, but this is a two-way exchange for without equivalent losses the oceans would continually gain heat and ocean temperatures would continually rise. Maximum heat losses (600 cal/cm^2/day) occur in the Sea of Japan in December, and losses greater than 200 cal/cm^2/day occur in a zonal, nearly transpacific, tongue-like protrusion originating at the western side of the ocean south of 40°N, in the area of the Kuroshio-Oyashio confluence, and extending eastward along the southern edge of the Aleutian low pressure system to the general location of the eastern Pacific high pressure system (Fig. 4). Maximum heat gains occur in July at the western side of the ocean east of the Phillipine Islands, well south

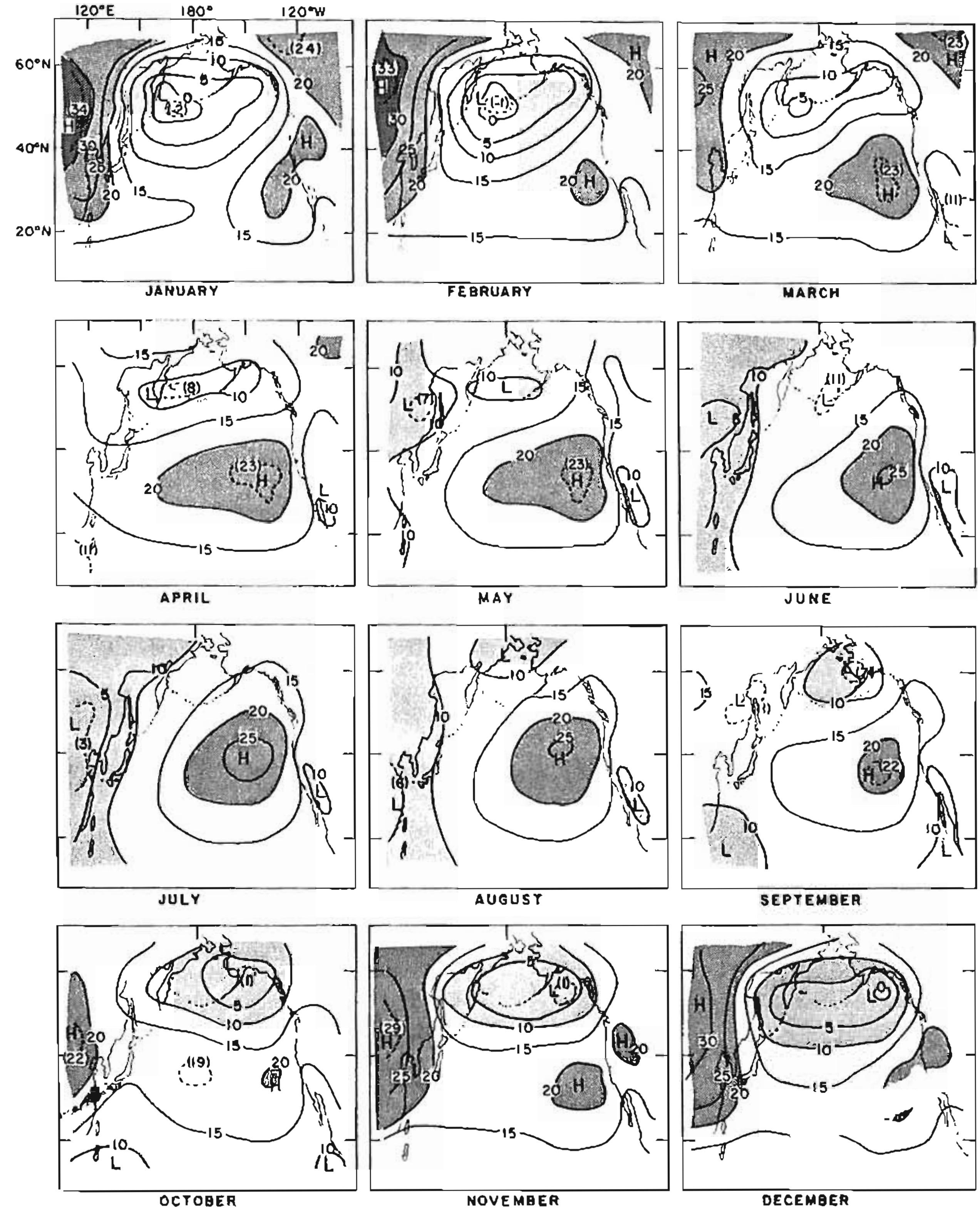


FIGURE 3. Monthly mean air pressure at sea level (value+10,000)/10=mb (based on U.S. National Climatic Center, Tape Data Family—11; 1951–70).

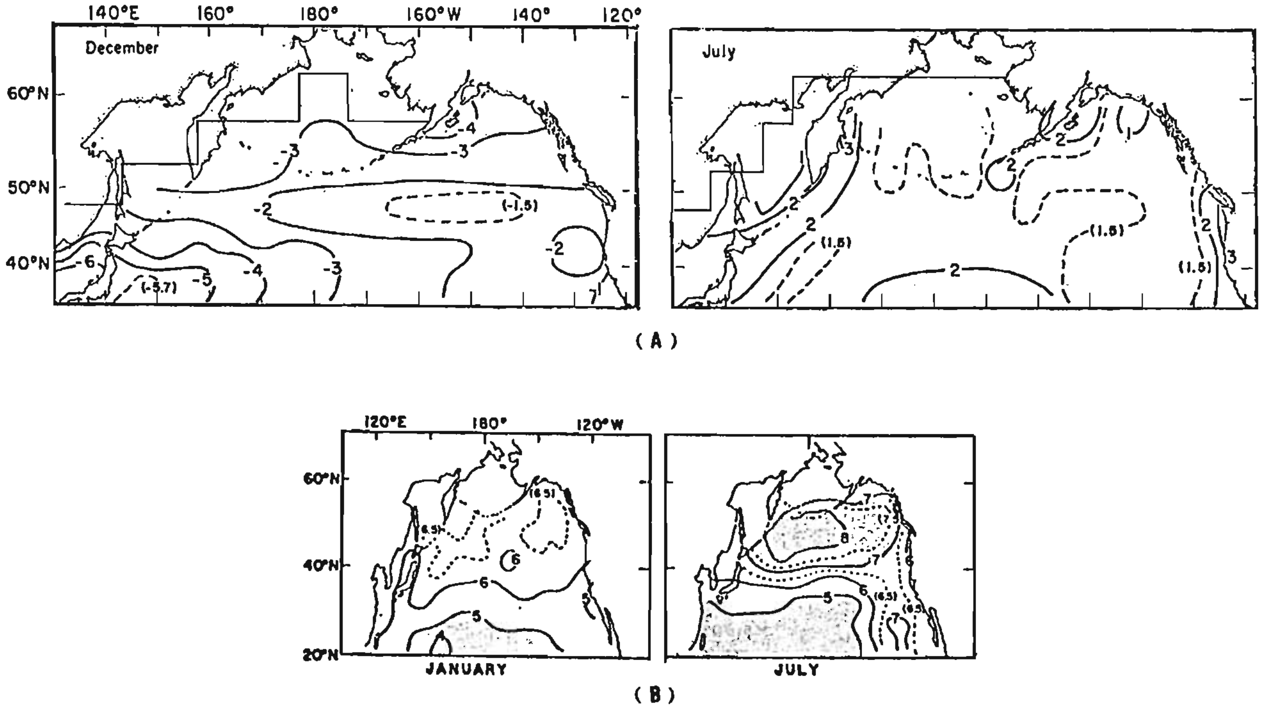


FIGURE 4. Monthly (A) mean energy exchange (×100=cal/cm²/day) December and July, and (B) mean cloud cover (eighths) for January and July (based on U.S. Climatic Center, Tape Data Family—11; 1948–67).

of the Kuroshio-Oyashio confluence.

Although maximum energy exchanges are found in areas where great differences in air and sea temperatures occur, incident radiation is primarily a function of latitude and cloud cover. Monthly mean cloud cover (in eighths) for January and July 1948–67[3] (Fig. 4) indicates a marked zonal boundary near 40°N. South of this latitude mean cloud cover is generally less than 75 percent year round, but northward of this latitude there is a gradual increase in cloud cover, from over 90 percent in January to overcast conditions in July.

II. REVIEW OF PHYSICAL OCEANOGRAPHY STUDIES

The reference list at the end of this report reflects the large amount of research that has been conducted in the region since the publication of INPFC Bulletin 13. However, few authors have attempted to assign specific terminology to areas or features of water structure and circulation. The general surface circulation is for the most part closed, and as reported in INPFC Bulletin 13, it encompasses 5 upper zone domains—Transitional, Western Subarctic, Central Subarctic, Alaskan Stream, and Coastal Domains; three cyclonic gyres were shown in the western part of the region—the Sea of Okhotsk, Western Subarctic and Bering Sea Gyres: and, one in the eastern part, the Alaskan Gyre (Fig. 5A). Four lower zone domains were also identified—Western Subarctic, Central Subarctic, Transitional and California Undercurrent Domains (Fig. 5B). The Coastal Domain encompassed the western, northern and eastern boundaries of these domains, whereas, the Alaskan Stream Domain existed only south of the Alaskan Peninsula and Aleutian Islands. Interactions among these 5 domains and 4 gyres results in a marked variability of flow within the overall general cyclonic circulation pattern. In this section, new information concerning currents, domains and other identifiable features are discussed, using the above terminology, starting at the southwestern part of the region. New terminology is presented in Section IV. For ease in following summaries of current observations (drift bottles, drogues, and current meters), the general locations of major

[3] Ship data for the period 1968–70 were not in an adequate format to permit obtaining 20-year mean values for the period used for pressure at sea level (1951–70) but no significant differences should be evident in mean values derived for these two periods. The geographical extent of energy exchange data is considerably less than that of pressure data at sea level due to paucity of year round oceanographic observations in the Sea of Okhotsk and Bering Sea.

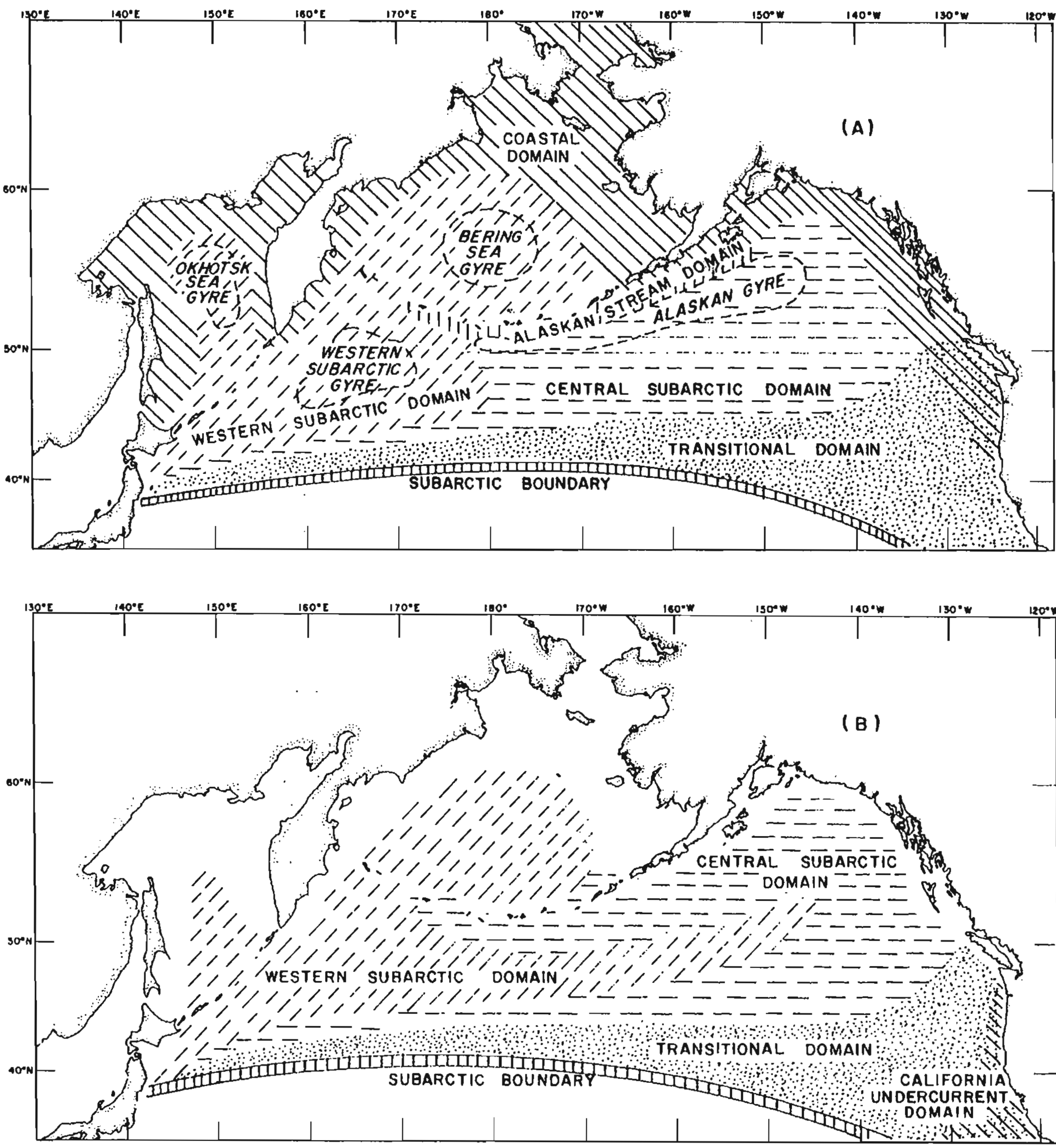


FIGURE 5. Schematic diagrams of (A) upper zone and (B) lower zone domains as defined by Dodimead, Favorite, and Hirano (1963).

experiments during 1960–71 are presented (Fig. 6).

A. SUBARCTIC BOUNDARY, AND TRANSITIONAL AND CALIFORNIA UNDERCURRENT DOMAINS

These features lie southward of the cold (<4°C) temperature-minimum stratum characteristic of the northern part of the region.

1. *Kuroshio-Oyashio Confluence*

Although INPFC oceanography studies continued throughout the 1960's, there is little question that the internationally coordinated Cooperative Study of the Kuroshio (CSK) was the most intensive oceanographic study in the North Pacific Ocean during this period. Initial planning commenced at the Second

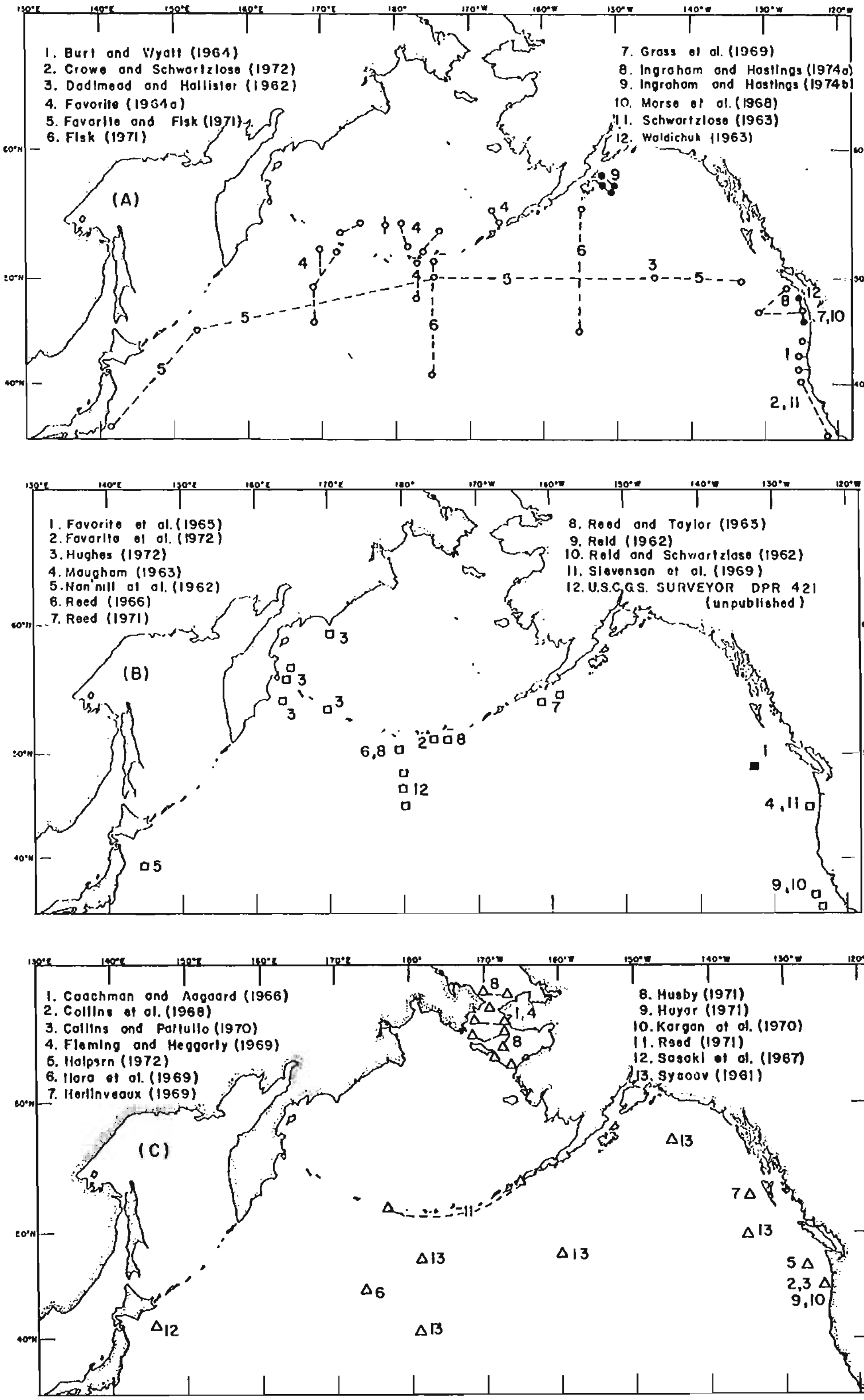


FIGURE 6. Approximate locations of oceanic (A) sea bed drifter –●– and drift bottles releases –○–, (B) parachute drogues –□– and drifting telemetry buoy observations –■–, and (C) current meter measurements –△– (1960–71).

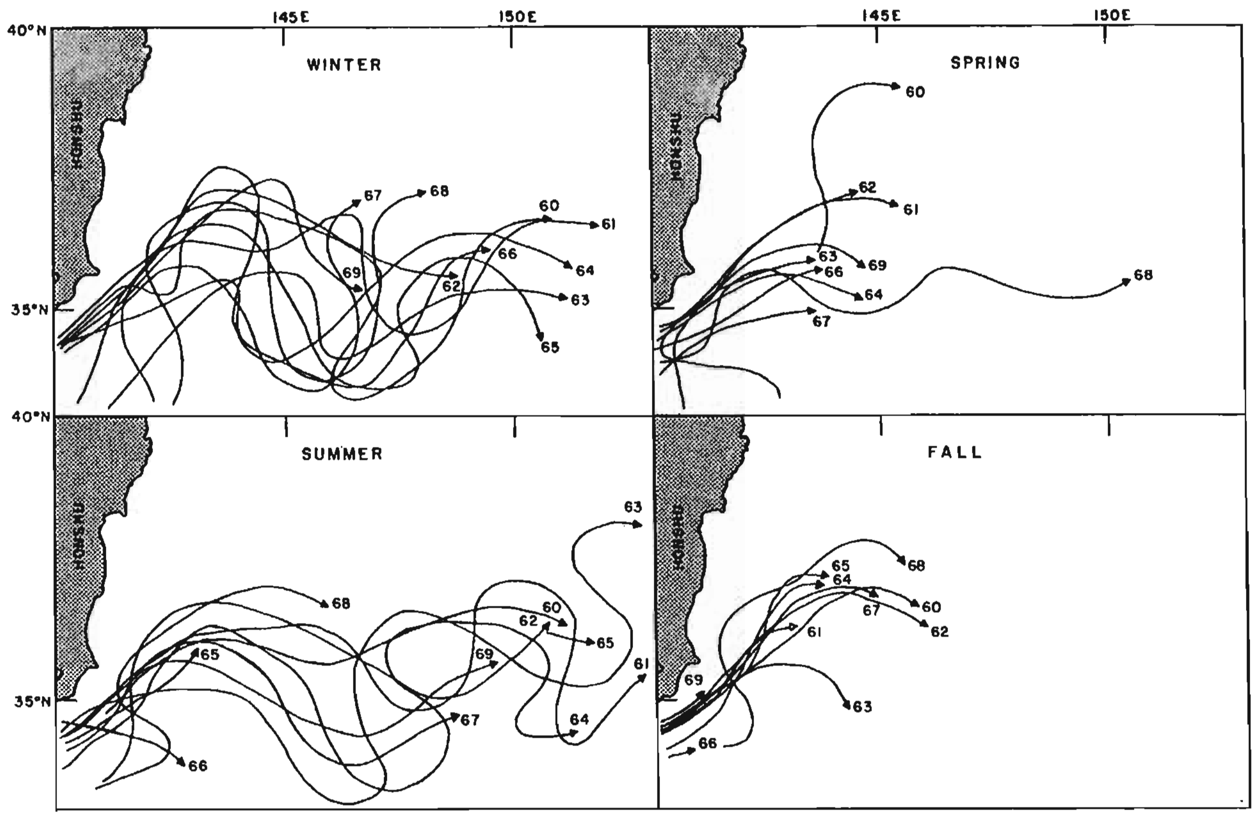


FIGURE 7. Seasonal fluctuations in the axis of the Kuroshio Current, 1960–69 (based on data from the Hydrographic Division, Japan Maritime Safety Agency).

Meeting of Marine Science Experts in East and Southeast Asia held in Manila in February 1962 (Wadati, 1965), and field programs commenced in summer 1965. The northern and eastern limits of this survey program were 43°N and 160°E, respectively, and considerable information in the southwestern part of the Subarctic Pacific Region was obtained. This study not only accelerated analyses of previous data, but provided several CSK atlases (see Table 2) and two special volumes of Kuroshio Studies (see Table 4); vessels participating in this work are too numerous to mention. Unusually intense quasi-synoptic surveys were carried out in the CSK area adjacent to Japan by the Japan Meteorological Agency in winter and summer 1966 (Akamatsu and Sawara, 1967).

The confluence of the Oyashio and Kuroshio Currents has a predominant effect on the location of the Subarctic Boundary in the western part of the region and conditions in this area are extremely variable (Fig. 7). Kawai and Sasaki (1961) in a review of the multiple ship survey off the east coast of Honshu in 1958–60 presented a 10-sequence series of water mass movements, based on temperature distributions at 50 m, for the period April 29–July 23, 1959. This clearly showed the southward movement of Oyashio water along the east coast of Honshu at 37°N in May and the concurrent southward retreat of Kuroshio water. In June, the Oyashio water moved eastward along the northern boundary of the Kuroshio Current and appeared as a cut-off cold water mass near 145°E. Extensive changes in the extent and configuration of cold and warm water areas were evident in this time period. Hata (1969a, b) using summer data obtained over long periods (1933–41, 1954–66) showed that, although the Kuroshio-Oyashio confluence may be confined to a shear zone near 38°N, the main axis of these flows can at times be nearly 500 km apart, 40° and 35°N, respectively. It is interesting that several branches of the Kuroshio Extension evident in earlier Japanese works were not recognized, but 2 branches of the Oyashio Current, one intruding southward along the east coast of Honshu near 142°E and the other intruding southward east of Hokkaido at 148°E were shown. It was also reported that when a warm eddy is detached from the north edge of the Kuroshio Current, this eddy can persist for more than a year and have the following characteristics: a diameter of 240 km, a volume transport of 20–30 Sverdrups (Sv) and a surface speed of 150 cm/sec. Kawai (1972) has presented six previous interpretations of the complicated surface currents in the area east of Honshu, generally referred to as the Kuroshio Extension area. Although these schematic diagrams were generally based on limited data obtained largely from the NORPAC Expedition conducted in 1955, nearly 15 years previously, a highly complicated but interesting flow pattern based on a synthesis of surface streamlines, thermal structures of the upper layer, surface currents measured by a Geomagnetic Electrokinetograph (GEK), and dynamic topography was presented. The main axis of the Kuroshio Current winding eastward along the southeast coasts of Japan was shown to split into several branches but to reform off the east coast of Honshu where it attained its previous intensity because of the impingement of southward flow in the Oyashio Current. The resulting narrow band of high velocity flow underwent several marked meanders, divergences, and convergences, but was clearly identifiable as far east as 160°E where a counter-current appeared at its north edge and extended westward to 154°E. Bubnov (1960) has also used NORPAC data to show the complexity of flow in this area. Masuzawa (1960b) and Nan'niti (1960) found no statistical relations that permitted the prediction of the spatial and temporal positions of the axis of the Kuroshio Current and indicated that random fluctuations were prevalent. The complexity of the meanders is in sharp contrast to the suggestion by Barkley (1968a, 1970b) that the conditions at the Kuroshio-Oyashio confluence are in reasonably good quantitive agreement with a theoretical, highly ordered, compound vortex street phenomenon. Field experiments suggested to test this hypothesis have not been accomplished, but verification of the existence of this phenomenon would provide great insight into processes in this area.

Thus, it is still not possible to characterize flow in this area in a simple, representative manner, other than recognizing that two opposing flows, Oyashio and Kuroshio Currents, merge and interact in a very kinematic manner, and nonlinear, time-dependent forces are major factors. Kawai (1972) has suggested that the term " Perturbed Area " be used to describe the area between the two currents because there is little information on actual mixing processes. Although many fisheries are affected by conditions in this area, salmon are found largely well to the northward.

2. *Transition Area*

Immediately north of the Subarctic Boundary a narrow, zonal, transpacific Transitional Domain was identified in INPFC Bulletin 13 as originating at the Kuroshio-Oyashio confluence; it gradually widened to the eastward, and attained considerably latitudinal extent in the eastern part of the region. It is essentially a transition zone in which mixing and diffusion combine water from the south having a pronounced salinity-minimum stratum near 800–600 m depth, and water from the north having a temperature-minimum stratum (in the range of 2–3°C) at 100–300 m depth, so effectively that neither characteristic is evident. The sharpest boundaries of this domain necessarily occur off the east coast of Honshu.

The domain concept, although quite a general, descriptive tool, provided the much needed description of dominant oceanographic features of the region and avoided the controversies inherent in a joint study in delimiting boundaries of specific, three-dimensional features using fragmentary data. There was some reluctance to accept the southern boundary of the Transitional Domain as a southern boundary of the region, not only because of the high temperatures in this domain, but also because of the absence of the shallow temperature-minimum stratum characteristic of the entire region north of approximately 45°N. Favorite and Hanavan (1963) suggested that the southern limit of the region be defined by temperature structure and that the northern boundary of Pacific Central Water be defined by salinity structure. A transition zone was shown between these two primary water masses. However, the surface, and particularly the subsurface distribution of the 34‰ isohaline provided an easily identifiable boundary, and because its location generally delimited the southern distribution of salmon, the Subarctic Boundary was defined in the INPFC Bulletin 13 in terms of this isohaline; thus, the Transitional Domain automatically became part of the region. Because of the paucity of data, the Subarctic Boundary was shown in INPFC Bulletin 13 in an unvarying, nearly zonal, position (41–42°N) in the central Pacific Ocean.

There are a number of reports concerning variability in the position of the boundary. Acara (1962) compared positions in summer 1955 and 1958 and found that even though it maintained a nearly zonal attitude, its position in the central Pacific Ocean varied; he believed that this suggested the existence of periodic oscillations in the axis of the Kuroshio Extension caused by periodic oscillations of wind stress. However, Nan'niti (1960) analyzed data from 1931-60 at 140° and 160°E, 180° and 160°W, and reported that there was not a good correlation between fluctuations in wind stress and the location of the boundary. Kitano (1967a) selected six areas in the western part of the region where repetitive temperature data were available for a number of years and on the basis of long-term fluctuations in vertical temperature structure reported that the Subarctic Boundary (polar front) exhibited 4–5 year fluctuations. Southward displacements were indicated in 1935–36, 1940–41, 1945–46, 1949–50, 1953–54, 1957–58, and 1962–63 and these coincided with periods of abnormal oceanic conditions found in 1936, 1954, and 1957–58; the paucity of data in 1940–41, 1945–46, and 1949–50 prevented making any comparisons for these periods. On the other hand, Gorbanev (1971) noted that to ascertain long-period fluctuations caused by advection it was necessary to study variations below the superficial surface layer and compared fluctuations of the 15°C isotherm at 100 m with fluctuations in the latitude of west winds. He found a negative correlation in real time, but suggested a correlation existed if a lag time of 3–4 years, half the period of the rotation of water masses around the North Pacific gyre, was considered. Finally, Bulgakov (1971) using data from 1933–67 analyzed the thermohaline structure of the boundary (subarctic front) and presented 5 schematic diagrams for winter and summer conditions in the frontal zone between subarctic and subtropic waters. These were distinct from three additional structures found adjacent to Honshu.

Although oceanographic cruises prior to 1960 presented in INPFC Bulletin 13 provided some indication of conditions near the boundary in summer, winter data were practically nonexistent and were required to ascertain the movement, if any, of this zonal boundary in response to the seasonal north-south oscillation (6–10°N) of the North Equatorial Current (located near 6°N in winter). Data from the winter cruise of the *Bertha Ann* (Favorite *et al.* 1964) along 175°W indicated no appreciable latitudinal shift of the boundary at this longitude, if anything, the boundary shifted northward, contrary to what might have been expected. One interesting aspect of these relatively closely spaced (48 km) station data was an unusual band of dilute surface water (33.6 ‰), less than 100 km in width, imbedded within isohalines of higher salinity and evident in the salinity distribution to depths in excess of 100 m. Station positions occupied by the *Pioneer* along five north-south sections between 160°W and 180° from about 25°N to the Aleutian-Commander Island Arc from 1960-63 (Barbee, 1965) were spaced too widely apart (generally 100 km) to ascertain if this surface condition was present; although there was a suggestion of a salinity minimum at the surface near 41°N in May 1963. A narrow band of minimum surface salinity was evident in the western part of the region in winter 1966 and continuity was implied between the Sea of Okhotsk and the central part of the region (McAlister *et al.* 1970); however, data were very limited. In summer 1966, the *Yaquina* (Oregon State Univ.) was scheduled to make a north-south transect across this domain and it was suggested that closely spaced stations be taken to ascertain if this feature could be detected; although attempted, this venture was not successful and the results were inconclusive. Bruevich (1966) using chemical parameters showed that the southern boundary of the "Subarctic Region" was in the general vicinity of 38–42°N. Roden (1970), in an analysis of station data obtained from the *Thomas G. Thompson* along 178°, 168°, and 158°W in April 1968, accepted the southern boundary of the Subarctic Water Mass as being between 42° and 44°N and defined a "transition zone", between subarctic and subtropic water masses, extending from 32–42°N whose width and sharp boundaries were determined by the wind stress distribution at the sea surface. A southward Ekman transport greater than 2×10^4 gm/sec/cm extended as far north as 30°N, and lesser transports within an approximate 10° latitudinal band in this area were reported. However, the vertical distributions of water properties do not seem to justify such a broad transition zone and, in addition, the transports given are several orders of magnitude less than geostrophic transports in the area. In a subsequent paper Roden (1972) presents data on gradients of properties at the subarctic front (42°N) and notes that the subtropical front (near 30°N) is the much weaker of the two.

Kitano (1972) in a further study of this boundary has supported the existence of a Subarctic Boundary by proposing that a polar frontal zone existed between subarctic and subtropic water. The mid-Pacific southern boundary of the former was reported to extend to 45°N, and the northern boundary of the latter extended to 36°N; both water masses having transition zones extending to 40°N. This division of the polar frontal zone was considered justified because of thermal and salinity fronts at each of these latitudes. Thus, water predominately of subarctic origin extended to near 40°N in this area.

Although a temperature-minimum stratum can be found in the water column between approximately 40–45°N in the central part of the region, these inversions are less than 1C°. They occur within the 10–12C° temperature range, and are found at two depth levels—less than 100 m, and 100–200 m. The former are clearly the results of winter cooling at the sea surface and subsequent turnover of the water column to this depth (Favorite and Morse, 1964). The latter, inversions at 100–200 m, are believed to be interleafing or entrainment associated with the upper boundary of the salinity-minimum stratum, which occurs at these depths, and are not greatly affected by external heating and cooling at the sea surface. Thus, this area, 40–45°N, represents a frontal zone between water north of 45°N where temperatures of 3°C are found within 100 m of the surface, and water south of 40°N, where temperatures of 3°C occur in an entirely different stratum near 1000 m.

3. *California Current*

The eastward flowing West Wind Drift was shown in INPFC Bulletin 13 to separate into two streams about 500 km offshore near 45°N ; one branch veered northward and flowed into the Gulf of Alaska, the other branch flowed southward to form the California Current. The latter was considered to be part of a typical, broad, diffuse eastern boundary current and formed the eastern sector of the major North Pacific Gyre. Its western edge, the Subarctic Boundary, was not well defined but occurred essentially 800–1000 km offshore, and little new information has been obtained at this boundary.

Although the intense oceanographic coverage of this area conducted by CALCOFI in the 1950's was reduced in the 1960's and there were no cooperative studies such as the 1955 NORPAC expedition, a number of individual studies have been reported that provide substantial new knowledge. The establishment of a monitoring program off the Oregon coast by Oregon State University, extensive studies conducted by the University of Washington to determine the distribution of Columbia River water in the northeast Pacific Ocean, several cruises by the U.S. Bureau of Commercial Fisheries (now National Marine Fisheries Service) vessels, an observational program aboard U.S. Coast Guard vessels associated with Ocean Station NOVEMBER (30°N, 140°W), a number of Canadian cruises off the British Columbia-U.S. coast by the Fisheries Research Board of Canada (Nanaimo), as well as incidental vessels transiting the area, constitute the major portion of monitoring and research activities. In addition to these, there have been numerous studies associated with flow and upwelling processes along the coast in this area (for example, Bakun, 1973).

An excellent summary of oceanographic and meteorological features of the southern part of this area, compiled by Reid *et al.* (1958) was based largely on CALCOFI data prior to 1955, and considerably more information is available now that most of the CALCOFI physical-chemical oceanographic data (1949-69) have been assembled in atlas format (CALCOFI, 1963 ; Wyllie, 1966 ; Wyllie and Lynn, 1971). These maps indicate that, although considerable seasonal and year-to-year variations exist and numerous cyclonic and anti-cyclonic eddies occur, the predominant feature is the seasonal onshore and offshore movement of surface waters in the southward flowing California Current. During late summer and fall (August-October) this current is offshore ; but inshore, a northward flowing surface countercurrent (the so-called Davidson Current) is evident and persists until early spring (April-May) at which time the California Current moves inshore. This eliminates northward flow at the surface, although a relatively weak flow persists at depth. This subsurface flow was referred to as the California Undercurrent Domain in INPFC Bulletin 13, and it is clearly a significant feature of the flow in this area. The seasonal surface reversal of flow is evident in several drift bottle studies (Schwartzlose, 1963 ; Crowe and Schwartzlose, 1972 ; and others), and a northward surface flow, at times nearly 180 km in width, with a mean velocity of 14 cm/sec, extends over 1100 km along the west coast of United States.

Direct current measurements have also been instrumental in documenting flow in the southern part of the California Current. Measurements of nearshore surface currents (using parachute drogues) along the coast of central California in October 1958 and January 1959 (Reid and Schwartzlose, 1962) showed that northward flow had commenced in October and was well established in January. It was about 90 km in width and speeds of 10–25 cm/sec were observed in January 1959. Measurements of flow in the countercurrent at 250 m below the surface off the California coast seaward of the 1820 m isobath were made in November-December 1961 using parachute drogues (Reid, 1962). Northward flow, about 75 km in width, with a maximum flow of 22 cm/sec, was observed near the coast. Along the next 110 km of the drogue line (75–185 km seaward of the 1820 m isobath) flow was southeastward at speeds up to 26 cm/sec. However, the measurements farthest offshore (185–230 km from the 1820 m isobath) indicated flow toward the northeast, possibly turning toward the southeast at speeds of 20–25 cm/sec. The latter flow was considered to be part of one of the large eddies frequently observed at the surface and at 200 m depth in the geostrophic flow in this area.

Drogue and drift bottle experiments by Oregon State University have provided considerable new information on the complexity and large variability of flow in the California Current off the Oregon coast. Maughan (1963), reporting on results of drogue measurements made 90 km off the coast of Oregon during six cruises in 1962, noted flow above 250 m was predominately northerly from November-March and southerly from April-October. A significant portion of the flow was onshore, except during July when a definite offshore component was found. Currents from the surface to 50 m were considered geostrophic, while below approximately 100 m and above 250 m the flow was ageostrophic. Drift bottles (6,207) released off Oregon between June 1959 and October 1963 to determine surface currents within 265 km of the coast (Burt and Wyatt, 1964) showed a northward flow from October through March, which at times was at least 265 km in width, much wider than previously reported. The flow extended as far north as 50°N. Minimum velocities for bottles released in January 1961 were about 20 cm/sec and considered typical for this flow. Varying surface currents, both north and south, were present during April, May, and September, marking the transition from winter to summer and from summer to fall conditions. During June, July, and August, the surface flow was predominantly toward the south. Concurrent drift bottle and wind data off Oregon indicated that surface currents were very closely related to the local winds at the sea surface. Additional information on drift bottle results can be found in a summary of drift bottle releases and recoveries for 87 cruises taken between January 1961 and January 1971 compiled by Wyatt *et al.* (1971). Stevenson (1966) reporting on drogue measurements made over a period of four years (1962–65) 85 km off the Oregon coast, in water 800 m deep, observed some northward flow. However, he found that the average flow was to the south at all depths between the surface and 300 m. Collins *et al.* (1968) reporting on simultaneous drogue and current meter measurements in Oregon coastal waters in September 1965 and 1966 showed that both drogue and current meter data yielded similar results with respect to the mean flow, and indicated northward flow at depth below the pycnocline and southward flow in the surface layer. Measurements in September 1966 indicated that the subsurface northward flow persisted for at least one month and was at least 18 km wide. Currents at 70 km off the Oregon coast were also measured by parachute drogues set at selected depths from the surface to 500 m depth in all seasons during 1962–1965 (Stevenson *et al.* 1969). Mean speed at 10 m for all drogues was 10 cm/sec and the maximum velocity, 48 cm/sec to the east, occurred during September 1962. At depths below 50 m, mean speeds were less than 18 cm/sec. At all depths, most of the drogues drifted toward the south. Northward drift was observed only 20 times among 99 trajectories and 14 of these occurred at or near the surface (0 to 150 m), not below the pycnocline. Mean velocities in the pycnocline differed somewhat from those at other levels. The lowest mean speed was at 75–150 m, the upper part of the permanent pycnocline. Total transport in the upper 500 m for the area within 100 km of the coast was 1.9 Sv, somewhat east of south. Mean zonal transport was toward the east in the surface layer, decreased with depth, and became westward below 200 m. The general direction of flow was southward in the summer and northward during the fall and winter ; during spring, and some fall periods, flow tended to be transitional and variable, but the general southerly flow in summer and northerly flow in fall and winter are in agreement with known mean seasonal fluctuations in surface current direction.

In addition to drogue and drift bottle experiments, Oregon State University also initiated a program to study physical processes in the Oregon coastal regime by means of moored arrays containing recording instrumentation, and by use of complementary hydrographic and meteorological data which are available in several data records (Collins *et al.* 1966 ; Wyatt *et al.* 1967 ; Mooers *et al.* 1968 ; Pillsbury *et al.* 1970). Collins (1967) and Collins and Pattullo (1970) reported on current measurements over the Oregon continental shelf during four periods of 25 days each—in July (at 20 and 60 m), September (at 20 and 60 m), October 1965 (at 20 m) and in February 1966 (at 25, 50, and 75 m). During July the flow at 20 m was consistently south-southwestward, parallel to local topography, with a mean speed (regardless of direction) of 21 cm/sec. At 60 m the direction varied over periods of several days from north-eastward to southward and back again. In September mean vector flow was northward at both 20 m and 60 m ; flow at 60 m was slightly stronger than flow at 20 m. During the early part of this observational period when southward flow occurred at both depths, it persisted 5 days longer at 20 m than at 60 m. During October, the flow at 20 m was northward until near the close of the observational period. In September and October, mean current speed at 20 m was 16 cm/sec. In January and February progressive vector diagrams for 25, 50, and 75 m were remarkably similar and currents were both northerly and southerly. Mean speeds of the deeper currents during this period were higher than during any of the other three periods ; about 24 cm/sec at 50 and 75 m. Maxima in the current velocity and temperature appeared to be associated with maxima in wind velocity. Regression techniques, used to estimate residual currents in the absence of wind, indicated that these currents were southward at both depths in February and at 20 m in July, but northward at both depths in September and October and at 60 m in July. They suggested that because the northward flow was strongest at 60 m in September, it was driven from below and was associated with a " California undercurrent " which was confined to the continental shelf. Huyer (1971) analyzed current meter data at 40 m depth taken during August-September 1969 off the coast of Oregon, 7 miles west of Depoe Bay near the 200 m isobath and wind observations made 27 km west of Newport (also at the 200 m isobath), and concluded that at low frequencies, periods longer than 2–5 days, local currents off the coast of Oregon are closely related to the wind. The current was considered to have two components; a response current, which is related directly to the wind, and a residual current which is also variable. The amplitude of the response current depends on the amplitude of the wind and on the density profile of the water and can be interrupted or modified when the wind changes too rapidly. When this occurs the residual current can change unpredictably, suggesting that short current records are not indicative of the mean flow.

Only limited direct measurements of flow near the bottom in relative deep water in this area have been made, but these are interesting. Korgen *et al.* (1970) reported on the results of near-bottom current measurements using a temperature-current probe at distances of 1–3 m above the ocean floor off the Oregon coast (between Newport and Astoria) in August 1968. Mean current speeds for continental slope stations, at depths from 725–1700 m, ranged from 5–20 cm/sec with maxima of 20–24 cm/sec depending on water depth. There was a systematic and significant increase in speed with decreasing depth. However, data on the direction of flow were not obtained.

Information on currents obtained by indirect methods has also been reported for the Washington-Oregon coast. Lee (1967) made a study of geostrophic currents off the Oregon coast in the area from 117–297 km off Newport, using data from a total of 21 cruises during the period February 1962-December 1965. The annual mean geopotential anomaly was 1.31 dynamic meters (dyn m) for the entire section, the spatial variation was less than 1 dyn cm. In summer the geopotential anomalies ranged from 1.37–1.32 dyn m; in spring it varied from 1.29–1.26 dyn m. The seasonal variation was from 1.39–1.25 dyn m, the highest geopotential anomaly usually occurred in September; the lowest usually occurred in April. The seasonal variation in oceanic heat content in the upper 100 m and geopotential topography were closely correlated, suggesting that the specific volume anomaly off the Oregon coast is primarily influenced by the heat content of the upper layer. Surface geostrophic currents ranged from 2–6 cm/sec and a maximum speed of 21 cm/sec occurred between 153 and 189 km from the coast in September. Throughout the year inshore (117–189 km) mean currents, 3–12 cm/sec, were stronger than those offshore, 1–5 cm/sec. Inshore flow was predominately southward from June to November, while offshore flow was northward; from December through May the reverse occurred. These flows were in general agreement with direct measurements using drogues.

Chekotillo (1961a) utilizing data from the cruise of the *Vityaz* in the winter of 1958–59 examined geostrophic currents in the intermediate layer (300 to 2–3000 m) using a reference surface of 2000 decibars (db). The dynamic topography of the 800 and 1000 db surfaces (relative to 2000 db) indicated the existence of a northward flow in the California Current system and was designated the California deep coun tercurrent. The mainstream of this current occurred at approximately 132°W at 50°N and continued as far north as 55°N; this northward flowing current was also indicated by distributions of salinity and phosphorous at 800–1000 m depth. Using data collected by the Fisheries Research Board of Canada in August 1957[4], he also noted that this northward countercurrent was present from 125–135°W between 43° and 55°N. Further evidence of a deep northward flow (between 1000–2000 m) in this area was presented by Pytkowicz and Kester (1966) using apparent oxygen utilization (AOU) and inorganic phosphate concentrations.

Extensive research conducted by the University of Washington for the Atomic Energy Commission off the Columbia River provided descriptions of the river-ocean front in this area (Budinger *et al.* 1964; Duxbury *et al.* 1966; Duxbury and McGary, 1968; Oregon State University, 1971; Pruter and Alverson, 1972; Duxbury, 1972; and Barnes *et al.* 1972) and an atlas of mean seasonal conditions of temperature, salinity, dissolved oxygen, and sigma-t distributions at various depths in 1961–63 (McGary, 1971) indicated the intense summer upwelling along the coast. The most notable feature in this area is the low salinity plume resulting from the discharge of the Columbia River (average discharge of 7300 m^3/sec). Budinger *et al.* (1964) suggested that the 32.5‰ isohaline can be used satisfactorily to define both the horizontal and vertical extent of dilution by the Columbia River as it flows over and into the local coastal and oceanic waters. Data available show that there is a con-

[4] These latter data were also the basis for the reporting of this northward flow as the California Undercurrent Domain in INPFC Bulletin 13.

sistent pattern to the seasonal trend and short-term variability of the distribution and dispersion of the Columbia River water; during summer the plume extends 300–400 km seaward and 500 km or more southwest, and during winter the region of dilution extends seaward about 50–100 km and along the coast from about 100 km south of the river mouth northward to the Strait of Juan de Fuca (Barnes *et al.*, 1972). Park (1966) identified the Columbia River plume by chemical methods and estimated that a value of 0.126 may be used as a reasonable lower limit for the specific alkalinity of the plume; this specific alkalinity corresponded closely to the 32.0‰ isohaline in August 1961.

Oceanographic cruises in this area were also conducted by the National Marine Fisheries Service during the period 1961–65. The various configurations and locations of the coastal upwelling zone and the offshore area of dilute surface water during July, for 4 consecutive years (1961–64) are documented in an atlas prepared largely from station data obtained during exploratory albacore cruises (Owen, 1967, 1968). Three areas were identified: a plume province, off the mouth of the Columbia River bounded by the 32.2‰ isohaline; a nearshore province, lying along the coast in summer as a band of cold, saline water about 90 km wide, dominated by effects of coastal upwelling, which cause horizontal gradients of temperature, salinity, density, and dissolved oxygen concentration from the sea surface to depths exceeding 250 m; and an offshore province, lying seaward of the plume province and having typical oceanic characteristics.

A seabed drifter program provided evidence that a northward flow occurs year round near the bottom over the continental shelf off the Oregon and Washington coasts at depths somewhat greater than 40 m (Gross et al. 1969). Releases from 30 stations on 12 different occasions over the continental shelf from northern Oregon to southern Vancouver Island during June 1966 to February 1968 indicated the following movement of inshore drifters: releases made less than 10 km from the mouth of the Columbia River moved toward the river mouth with typical speeds of 1.4 km/day; releases made less than 70 km from the Strait of Juan de Fuca entrance moved toward the entrance of the strait with speeds ranging from 0.1–2.8 km/day; releases made in waters less than 40 m deep generally moved toward the coast with speeds ranging from 0.7–2.5 km/day, releases in the outer continental shelf waters (>40 m depth) generally moved northward. Northward movements along the continental shelf of up to and over 100 km at speeds of 0.4–3.2 km/day were especially characteristic of seabed drifters released in waters deeper than 40 m.

Oceanographic conditions north of the Columbia River based on station data obtained during a series of cruises off the Washington and Vancouver Island coasts and seaward to Cobb Seamount during 1963–65 are available in atlas form (Ingraham, 1964b and 1967a; Ingraham and Fisk, 1966). A summary of oceanographic conditions and transports for spring and autumn periods 1963 showed that eddies complicate the pattern of flow during spring (Ingraham, 1967b). In eddies off the Washington coast, geostrophic currents at 200 m in spring and summer were significantly greater than those at the surface. An appreciable northward volume transport was reported at the edge of the continental shelf and, although the distribution of properties in the lower zone suggested an increase in northward flow at depth in autumn, this was not reflected in the net volume transport. Near-bottom observations confirmed the absence of any significant change in the salinity, temperature, or dissolved oxygen at a particular depth along the continental slope between the Columbia River and Cape Cook, Vancouver Island; however, significant seasonal variations in water properties occurred to 200 m depth. In spring, near-bottom observations at 55 m indicated uniform salinity values between 31.9 and 32.0‰ north of the Strait of Juan de Fuca, but salinities increased south of the strait reaching a maximum of 33.4‰ near the Columbia River. The range of temperature values at 55 m was about 1°C. At 183 m (near-bottom samples) the range of salinity was 33.67–33.95‰; the temperature range at 183 m was the same as at 55 m, 1°C. Values of salinity, temperature and dissolved oxygen at 55 m were significantly different during spring and fall; temperatures at 55 m increased 3°C off Vancouver Island, and 4–6°C off the Washington coast; however, at 183 m only slight increases, about 0.6°C, occurred.

4. *Vancouver Island Area*

The intrusion of the Transitional Domain and the annual fluctuation of its extent off the west coast of Vancouver Island, resulting in variations in the character of the water in this area, have been well documented. Dodimead (1961b) examined the subhalocline circulation and water masses in this general area for the years 1955–60 and reported that there were annual variations in the position of the Transitional Domain and of the division of West Wind Drift; also, that there was a northward geostrophic flow off the Washington-Oregon coast. Warm water conditions off the west coast of Vancouver Island were shown to be dependent on: a northward shift in the

Transitional Domain, a southward shift in the area of division of the lower zone waters, and an intensification of the northward flow in the sub-halocline waters off the Oregon-Washington coast. The first two features seemed to be mutually dependent in that a northward displacement of the Transitional Domain usually accompanied a southward shift in the location of the division of the West Wind Drift.

During the early 1960's, as part of a coastal monitoring program (Crean, Harling, Tripp, Dobson, Meikle, and Hollister, 1962; Crean, Tripp, and Hollister, 1962), and again in the late 1960's and early 1970's as part of a coastal-oceanic monitoring program, extensive field studies off the west coast of Vancouver Island were conducted by the Fisheries Research Board of Canada. During the latter period, the cruises were more intensive and permitted better definition of the circulation pattern and the seasonal shift of boundaries. Some preliminary results of the latter cruises have been presented in INPFC Annual Reports (1968–70). Surface distributions of temperature and salinity confirmed the seasonal offshore movement (summer) and onshore retention of surface waters (winter). Also, seasonal variations in the current pattern were noted: in summer, the geostrophic currents were relatively weak and there was evidence of numerous eddies and meanders in the overall northward flow; in winter, the currents appeared to be stronger and the meanders and eddies less pronounced. Also, a seasonal reversal of coastal flow north of the Strait of Juan de Fuca occurred, as evident in several reports of drift bottle studies (Waldichuk, 1963; Favorite *et al.* 1965; Fisk, 1971; and Ingraham and Hastings, 1974a). Dodimead and Pickard (1967) considered that major year-to-year changes take place in the temperature distributions of the seasonal (top of halocline) and nonseasonal (on the 33.8‰ surface) waters in the eastern part of the region, for example, a meridional shift in the isotherms offshore in the Transitional Domain, which may be accompanied by meridional and/or zonal shifts of isotherms along the coast, as well as an eastward intrusion of relatively cold water from the central part of the region. The monthly minimum sea surface temperatures at Ocean Station " P " for these years were considered indicative of the year-to-year trends in the extent of warm water in the upper zone. Thompson (1971, 1972) suggested that both the onshore Ekman transport, resulting from a meridional wind stress component, and the relative warmth of the upper oceanic layer in winter were responsible for the variations at the top of the permanent halocline. At the bottom of the halocline, comparison of the meridional wind stress component with the temperature variations suggested that other processes besides the direct effect of Ekman transport are important in determining the variations at that level. Additional information from reports on oceanographic conditions along Line " P " is summarized in a later section.

B. Central Subarctic, Coastal, and Alaskan Stream Domains

These domains were shown in INPFC Bulletin 13 to occur in the eastern part of the region and the predominant feature in this area is the cyclonic Alaskan Gyre. Eastward flow in the Subarctic Current forms the southern edge of the gyre and the merging of this flow and a northern component of the West Wind Drift (of the Transitional Domain), which sweeps northward into the Gulf of Alaska, forms the eastern edge of the gyre. Constrained by the coast and further modified by conditions in the local Coastal Domain, this flow turns westward at the head of the Gulf as a boundary current, one branch closing the gyre and another branch extending westward along the south side of the Aleutian Islands into the area denoted as the Alaskan Stream Domain. The extensive cruises conducted for the INPFC by the Fisheries Research Board of Canada in the Gulf of Alaska in late 1950's were continued up to 1962 aboard the *Oshawa*, *Whitethroat*, and *St. Anthony* (Dodimead, Abbott-Smith, and Hollister, 1960; Dodimead, Giovando, Herlinveaux, Lane, and Hollister, 1960; Dodimead *et al.* 1961; Dodimead *et al.* 1962). Except for the 1963–66 exploratory fishing cruises, conducted by the Pacific Biological Station, during which only bathythermograph and surface salinity data were gathered and the cruises related exclusively to Ocean Station " P " and Line " P ", the only major oceanographic cruise in the Gulf of Alaska was that of the *Thomas G. Thompson* (University of Washington) in February 1967 (Roden, 1969). The extensive cruises in the central Aleutian area conducted for the INPFC by the National Marine Fisheries Service, Northwest Fisheries Center, were continued up to 1962 aboard the *Paragon*, *Pioneer*, and *Marine View*, and were resumed from 1965 to 1971 aboard the *George B. Kelez*, *Miller Freeman*, and *John R. Manning* (Favorite, 1974).

1. *Gulf of Alaska*

There have been several reports of Soviet research in the Gulf of Alaska. Bodganov (1961c) reported on the water circulation in the Gulf of Alaska and its seasonal variability, utilizing data gathered by Canadian and U.S. agencies during the period July 1957-September 1959. Using a reference level of 1000 db, he noted that circulation in winter appeared to be stronger than in summer ; and that, in winter the main axis of the North Pacific Current was displaced 2–3° northward. However, the evidence was not conclusive enough to suggest a seasonal variation in circulation in the Gulf of Alaska where the flow was reported as cyclonic in winter and summer. Flow along the North American continent north of 45°N was chiefly northward. Surface speeds fluctuated at various points in the region between 1 and 45 cm/sec ; the highest values 30–45 cm/sec, were found near the coast ; below 300 m, speeds decreased gradually to 1–5 cm/sec. Comparison of observations of currents made at anchored buoy stations during the 29th voyage of *Vityaz* in 1958–59 with computed values indicated that speeds of observed currents were almost twice the geostrophic currents and the directions were entirely different. The above data were also used in several Soviet publications which provided information on the physical and hydrochemical features of this area. Kozlyaninov and Ovchinnikov (1961) have shown that current systems and their extent are in good agreement with transparency observations. Shirei (1961) confirmed general features of the temperature and salinity distributions in this area and subdivided the Subarctic Water Mass into several components which he considered related to the main water mass but possessing individual characteristics. Smetanin (1961) discussed features of the oxygen distributions at selected levels to 3000 m and surface phosphate and silicon distributions. Kostikova (1965) has provided a hydrochemical description of the Gulf of Alaska based on data for summer-autumn 1962, and Shuronov (1964) and Chernyi (1967a, b) have also discussed other Soviet investigations which basically confirm results of earlier studies in this area.

The oceanographic program at Ocean Station " P " initiated by the Fisheries Research Board of Canada (Nanaimo) and presently carried out by the Fisheries and Marine Service (Victoria) has provided excellent time-series data for this area. Tabata (1965) has utilized these data to summarize the variability of oceanographic conditions at Ocean Station " P " during 1956–62, and relates variability to fluxes across the air-sea boundary, vertical mixing, and water transport. The annual cycle of temperature in the upper zone is such that the annual maximum occurs progressively later in the year at successive depths—at 50 m in mid- or late autumn, and at 100 m in mid-winter. Appreciable long-term variations occurred in both the halocline and the lower zone ; and, although these were present in the upper zone, they were usually overshadowed by the annual cycle, which has a much larger amplitude. Variations appeared to possess a periodicity of about two years and were most conspicuous in the halocline and to a depth of 300 m in the lower zone, but did occur to depths of at least 700 m. Maximum temperatures occurred in 1958, 1960, and 1962, while minimum temperatures occurred in 1959 and 1961. Variations in salinity were most marked in the upper zone and the halocline, but also occurred at all depths to at least 1000 m and were an order of magnitude less between 500 and 1000 m than in the upper zone. In the upper zone, salinities were lowest during the heating period, reaching a minimum value in the mixed layer (upper 30 m) in late summer or early autumn, and a maximum in late winter or early spring. Minimum salinity values occurred progressively later in the year at successive depths in the upper zone. At depths of 75 and 100 m the annual cycle appears to be in opposite phase to that in the surface layers—a maximum in autumn and a minimum in spring. Non-seasonal changes occurred at all depths with some evidence of a periodicity of two years in the data. The principal feature of the variations in dissolved oxygen is that marked annual changes occurred in the upper zone, especially in the upper 30 m surface layer. The maximum occurred in late winter or early spring and the minimum in late summer or early autumn. During autumn, dissolved oxygen decreased at depths of 75 and 100 m but increased in the 0–75 m layer. Non-seasonal variations of dissolved oxygen in the halocline and in the lower zone were, in general, in phase with those in the halocline. Water mass characteristics at Ocean Station " P " varied during the period 1956–62 ; in 1956 and in the first half of 1957 it possessed characteristics of subarctic water ; whereas, from 1958-60 it had some characteristics of subtropic water. In 1961 and 1962 subarctic characteristics were evident.

Tabata (1965) also computed the net heat and freshwater fluxes, as well as water transport at Ocean Station " P ". The net heat flux had a pronounced annual cycle: maximum heat gain occurring in summer and maximum heat loss occurring in winter (the net heat gain, 24,000 g-cal/cm^2/year, is sufficient to warm the upper 120 m of water by 2.5C°/year). A comparison of observed and computed monthly changes of heat content in the upper 120 m showed good agreement between the observed and computed values, indicating that heat flux was the dominant factor influencing conditions, but other effects, either singularly or combined, were important. Horizontal transport of cold water in the region and upward transport of cold water through the halocline occurred. Both precipitation and evaporation underwent annual variations, reaching a maximum and minimum respectively at the same time. Some correlation was noted between observed and computed salinity changes for the summer months, however, little correlation existed otherwise and an excess precipitation over evaporation of about 23 cm/year was reported. Vertical transports were computed, based essentially on the Sverdrup equation, using monthly mean atmospheric pressure distributions. Vertical upward transport at Ocean Station " P " was found to be in the range of 15–20 m/year.

Fofonoff and Tabata (1966) described the variations in temperature and salinity, and the transport, between Ocean Station " P " and the Canadian coast for the years 1959–1961. They noted that, although the annual cycle of surface temperature was nearly constant along this line, the annual range at the various stations was about 6C° in 1959, 7C° in 1960, and 9C° in 1961. The winter minimum was attained in late March and the summer maximum in late August of each year. Where differences in phase could be detected, the extremes occurred slightly earlier in the eastern half of the line. Also, the temperature gradient along the line remained relatively constant during both winter and summer; the mean difference between the coast and Ocean Station " P " was 2.5C°. The coastwise increase of temperature was not uniform but was usually interrupted by one or more pairs of relative maxima and minima and was believed to be related to the presence of countercurrents or eddies in the general northward flow. The uniformity of the annual variations of temperature along the line was attributed to the fact that the temperature is controlled primarily by the heat exchange across the surface and only secondarily by the winds and currents. Maximum temperatures occurred about 300 km offshore; lower temperatures found near the coast were attributed to upwelling of cold water as a result of seasonal changes in the wind system and other factors such as tidal mixing and increased frequency of fog in summer. Surface salinity decreased coastward along the line, and superimposed on this gradient was an annual cycle of salinity variation along the eastward section of the line that was related to drainage of fresh water from the land and the component of Ekman transport near the coast. The salinity distributions reflected two minima during each year—a weak minimum in spring related to the winter maximum of rainfall in the coastal area, and a more prominent minimum in August related to river runoff from melting snow. The salinity minima occurred about 2 months later than the peaks of coastal and river runoff. Along the western section of the line, the annual range of salinity was relatively small (0.2‰) but in phase with the temperature variations; and the salinity minimum at the various stations coincided with the temperature maximum. Density along Line " P " decreased toward the coast and underwent an appreciable annual cycle.

In the lower zone, temperatures increased shoreward; isothermal surfaces descending about 400 m from Ocean Station " P " to the coast. The slight upward slope of the isohaline surfaces toward the coast was not sufficient to offset the effect of the much larger downward slope of the isothermal surfaces and, as a result, surfaces of constant density sloped downward toward the coast, descending nearly 200 m from Ocean Station " P " to Station 1 (inshore station). Dissolved oxygen decreased from near-saturation values at the surface, 6–7 ml/l, to a minimum of 0.3–0.6 ml/l at depths of 800–1200 m. Below the minimum stratum, the dissolved oxygen content increased gradually with depth reaching at the bottom about one-half the upper zone value; values in the minimum stratum decreased and its depth rose toward the coast. Annual cycles in the variations of temperature and salinity at 200 m were clearly discernible in the eastern half of the line and appeared to be produced chiefly by vertical displacements of the 26.8 sigma-t surface, whose depth decreased in summer and increased in winter. Near the coast, the vertical movements were attributed to the annual cycle of the Ekman transport component normal to the coast.

The mean total transport through the section, as calculated from the curl of the wind stress, was 5.8 Sv and was directed northward. The average baroclinic flow was 1.3 Sv. These transports were consistent if the mean depth of no motion was at 1400 m with southward flow in the bottom portion. Acara (1964) has reported that the magnitude of the meridional transport in the upper zone and halocline along Line " P " varied from 10^4–10^5 cm^3/sec; the vertical velocity varied from 10^{-5}–10^{-4} cm/sec. Favorite (1974) showed that the anomalous increase in corrected sea level data at Yakutat, Alaska, during winter could be accounted for by the increase in northward flow in the Gulf of Alaska indicated by windstress transports and suggested that actual flow in winter could be as much as 50 percent greater than that indicated by geostrophic methods which reflect only steady state conditions.

Circulation in the Gulf of Alaska, north of 50°N and east of 155°W, was investigated in February 1967 (Roden, 1969). Surface distributions of temperature, salinity and density were presented. The features noted were the tongue of relatively warm and low-salinity water along the southern and southeastern coast of Alaska and the elliptical area of cold temperature and high salinities southeast of Kodiak; however, the centres of lowest temperatures and highest salinities did not coincide. Ekman and total transport were calculated for a $1 \times 1°$ quadrangle grid from monthly sea-level atmospheric pressure distributions. Although the data do not justify using such a finite grid, typical values for Ekman transport ranged between 10^4 and 10^5 gm/sec/cm, and a conspicuous divergence of the Ekman transport in the west-central gulf with the water being moved toward the shore of Alaska was reported, which was considered to account for upwelling in the area southeast of Kodiak Island. A band of convergence was noted in the east-central gulf where large horizontal temperature gradients occurred. Mean speed in the Ekman layer (considered to be 100 m in depth) was of the order of 1–10 cm/sec. Typical values for total transport varied between 2×10^5 and 2×10^6 gm/sec/cm and a complicated flow pattern resulted. The geopotential topography of the sea surface relative to the 1500-db level indicated speeds generally less than 10 cm/sec, except in the vicinity of the continental shelf where speeds up to 20 cm/sec occurred. In the halocline, a slight velocity maximum, or a layer of minimum shear, was observed at many stations and provided a mechanism for the formation of warm and cold cores, which were frequently observed. Vertical velocities above the halocline indicated that maximum speeds, slightly above 4×10^{-3} cm/sec, occurred in the west-central gulf where maximum salinities above the halocline occurred.

2. *Aleutian Islands Area*

The Alaskan Stream occurs immediately south of the Alaska Peninsula and Aleutian Islands and is characterized at the surface by a westward tongue of dilute (<32.6‰) water originating from the Gulf of Alaska. As a result of previous reports one could obtain the impression that it represents merely a thin surface layer, but this is not correct. Temperature and salinity (T-S) relations to depths of 1000 m from data obtained in summer 1956 and 1959 that clearly identified a Coastal Water Mass in this area were presented in the INPFC Annual Report for 1960 (Favorite and Hebard, 1961) and evidence of a significant westward flow, a wind-stress transport of 10–20 Sv, denoted as the Alaska Boundary Current, was reported in the INPFC Annual Report for 1961 (Favorite and Morse, 1963). Previous analyses of station data in this area gave no indication of such a large transport because of the widely spaced and inappropriate locations of station data; however, vessel drifts in excess of 50 cm/sec reflected an appreciable westward flow. The results of the 1961 summer cruises reported in the INPFC Annual Report for 1962 (Favorite and Morse, 1964) clearly showed that westward flow extended beyond 165°E. Although perhaps characteristic of the period, much effort was devoted to an extensive exploratory fishing program and the description of ocean conditions in relation to salmon catches, but little effort was made to quantify flow in the Stream because little time was available aboard U.S. research vessels for independent oceanographic studies during this phase of experimental fishing.

A number of reports pertaining to flow in this area were forthcoming in the 1960's. At a meeting of the Eastern Pacific Oceanic Council (EPOC) in 1958, the need for obtaining direct current measurements was discussed, and arrangements were made for the *Explorer* to conduct a direct-current study in the central Aleutian Islands area in summer 1959; as this study was carried out, extensive oceanographic observations were made along north-south cruise tracks along various meridians south of the Aleutian Islands from vessels chartered by the National Marine Fisheries Service and assigned to INPFC research. However, except for the presentation of horizontal and vertical distributions of temperature and salinity based upon data from the latter vessels, which were summarized in INPFC Bulletin 13, little quantification of total flow in the Alaskan Stream along the south side of the Aleutian Islands was accomplished until the continuity of a volume transport of approximately 6 Sv (referred to 1000 db) from 160°W–171°E was presented in the INPFC Annual Report for 1963 (Favorite, 1964b). In an extension of this study, (Favorite, 1967a) it was shown that this flow was the result of wind stress acting on the sea surface in the Gulf of Alaska, and that the subsurface Commander Ridge near 163°E influenced its westward extent. Publication of the direct-current measurements from aboard the *Explorer* in 1959 was accomplished 6 years later (Reed and Taylor, 1965) and results showed that westward velocities at the surface in excess of 50 cm/sec and at times approaching 100 cm/sec occurred within 54 km of the south coast of Atka Island; flow at a depth of 300 m was diminished by only 30 percent, but these data did not provide information on a zero reference level needed to properly evaluate geostrophic flow. Nevertheless, it was clear from the data accumulated by 1961 that the Alaskan Stream was an important current system of the Pacific Ocean. It not only extended much farther west, but had a velocity and volume transport much greater than known heretofore.

Subsequent studies documented the variability of flow in the area. Winter data south of the central Aleutian Islands were obtained for the first time during the cruise of the *Bertha Ann* in 1962 (Favorite *et al.* 1964). These data indicated the Alaskan Stream was not merely a seasonal flow but a permanent year round feature of the region; although the wide station spacing, approximately 50 km, did not permit an accurate estimate of actual flow. However, data from closely spaced surface observations south of Adak Island during the *George B. Kelez* cruise in summer 1963 indicated that southward flow of Bering Sea water through Aleutian Islands passes forced the westward flowing Alaskan Stream offshore in the Adak Island area and that the boundaries of these two flows could be detected by marked temperature and salinity fronts (Favorite, 1964b). Ohtani (1965) analyzed data from a series of cruises in the Aleutian area conducted aboard the *Oshoro Maru* and *Hokusei Maru* from 1956 to 1963 and reported the width of the Alaskan Stream at various longitudes (220–290 km at 172°W, 250–320 km at 180°, and 140–250 km at 172°E) and volume transports of 2.8–6.5 Sv (referred to 600 m). In November 1965, INPFC cruises aboard the *George B. Kelez* in the Aleutian area were resumed. Observations at closely spaced stations (8 km) south of Adak Island revealed westward geostrophic flow in the Alaskan Stream in excess of 40 cm/sec at depths of 100–200 m (Favorite *et al.* 1967), and this flow was shown to extend westward beyond Attu Island (173°E). These observations were repeated in March and September 1966 and considerable variability of flow in the Stream was apparent: the width varied from 115–189 km, the distance offshore from 26–72 km, the maximum velocity from 43–61 cm/sec, the depth of maximum velocity from 20–200 m, and the volume transport from 5.2–9.9 Sv (Ingraham and Favorite, 1968). Further documentation concerning the variability of flow in this area ascertained by subsequent cruises of the *George B. Kelez* during 1966–69 have been reported (McAlister, Ingraham, Day, and Larrance, 1969, 1970).

Various techniques have been used to ascertain the westward extent of the Alaskan Stream. It was obvious that station data from early studies were too widely spaced to permit ascertaining accurate patterns of geostrophic flow, and in some instances data for various years were combined to obtain a general composite picture of flow. These methods were suspect because of the rapid seasonal changes in conditions (although some attempts were made to compensate for the effects of insolation on temperature distributions over certain defined periods) and annual variability. Mesothermal temperatures were used to show that water of undisputable Alaskan Stream origin extended at depth westward beyond 165°E near 50°N in 1959 and 1961 (Favorite and Morse, 1964). This fact was of particular significance because the Japanese high-seas commercial salmon fishing fleets usually commenced operations each spring at this location even though the superficial surface oceanographic observations obtained by the fleet provided little reason for this decision, and little or no advance scouting was performed because of the usually severe winter conditions in this area. An accelerated study of conditions in the area commenced. The usual surface temperature observations obtained by research vessels of the Fishery Agency of Japan were augmented by numerous bathythermograph casts. Fujii *et al.* (1965) reported that good salmon catches occurred in the area 165–175°E, 46–52°N, from late May to late June each year and were associated with the 3°C isotherm in the dichothermal layer, which extended to 164°E at 48°N in 1964. Ohtani (1965) defined the domain of the Alaskan Stream as the vertical 4.0°C, or 3.75°C isotherm at the depth of 150 or 200 m (basically the mesothermal layer), and also showed its westward extent in summer 1959 and 1961. Salmon catches in relation to temperature distributions in the dichothermal layer were discussed generally in the area 45–55°N, 180°–160°E, for the ten-day intervals data were available during the period May-August for the years 1958–1964 (Ohtani, 1966). Kitano (1967b) noted that the terminus of the Alaskan Stream extended to 164–165°E at 50–51°N and reported a complex eddy structure in the area.

The primary purpose of the March 1966 *George B. Kelez* cruise was to ascertain the effect of the Commander Ridge on the terminus of westward flow in the Alaskan Stream in this general area. Observations from the surface to the sea floor obtained on both sides of the ridge along east-west transects indicated that westward flow above 1500 m depth turned northward into the Bering Sea at the eastern side of the ridge, convincing evidence of its influence on flow; and, that unprecedented northwestward geostrophic flow of 25 Sv occurred south of Attu Island (Favorite *et al.* 1967; Ohtani, 1970; McAlister *et al.* 1970). The discovery of this large transport, double previous estimates, led to an investigation of wind-stress transports as a possible cause. Subsequent calculations revealed mean integrated wind-stress transports (for the period 1950–59) of 20 Sv in a westerly direction south of the central Aleutian Islands during winter (January, February, and March), but greatly reduced flow was indicated for other seasons, particularly summer (Favorite *et al.* 1967).

Relative flow in the Alaskan Stream had been generally defined by 1968 and, in spring and summer

1969, efforts were directed to ascertaining the nature of fronts at the boundaries of the stream (Favorite *et al.* 1971 ; Favorite *et al.* 1972). Continuous records of surface temperature and salinity during *George B. Kelez* transects south of the Alaska Peninsula (155 and 165°W) in spring indicated a front associated with the southern boundary of westward flow in the stream about 100 km from the coast where abrupt decreases in temperature and increases in salinity occurred. A meridional shift in the position of this front of over 20 km occurred in a period of 10 days.

Observations were also made south of Adak Island where the westward flow of warm, dilute coastal water is forced offshore by the southward intrusions of cold, saline water from the Bering Sea through Aleutian Islands passes. This results in a front considered to denote the northern boundary of the Alaskan Stream. In summer, an increase of 6C° and a decrease of 0.8‰ occurred at this front, which was located about 15 km offshore. Changes in the meridional location of the front of 30 km occurred within a few days. About 60 km farther offshore, where the southern boundary of the Alaskan Stream meets the northern boundary of the eastward flowing Subarctic Current, such marked changes do not occur but a front can be detected. Direct current measurements at the northern front using drogued buoys indicated that westward flow at the surface continued undiminished on both sides of the front, but in the area of minimum salinity, southward of the front, a northward flow occurred suggesting that, although temperature and salinity distributions may denote different environments, one should be cautious in using these distributions to denote actual flow.

Although oceanographic data were obtained in the area where the Alaskan Stream impinges on the Western Subarctic Gyre, largely as a result of INPFC studies and Japanese mothership operations, little information has been obtained on the interaction of the Alaskan Stream and that branch of the Subarctic Current that turns northward near 180° and forms the eastern edge of the gyre. Kitano (1967b) reported a northward penetration of subtropic water near 170°E in summer 1964 based on sea color and transparency data. Evidence of a northward flow in winter in this area was provided by two drift bottle experiments ; one conducted aboard a ship-of-opportunity, *Java Mail*, in fall 1964 (Favorite, 1967b, and Fisk, 1971), and the other conducted aboard the *George B. Kelez* in March 1966 (Favorite and Fisk, 1971). However, these data may reflect only surface wind drifts.

Favorite (1974) has summarized flow into the Bering Sea through the Aleutian Islands passes, including Near Strait but not Kamchatka Strait. Although questions as to the validity of geostrophic flow and wind-stress transport calculations in this area were noted, the following estimates of mean annual flow were obtained : westward flow in the Alaskan Stream south of the eastern Aleutian Islands—12.5 Sv ; loss through the central Aleutian Islands passes (Amchitka)—4 Sv ; gain from the Subarctic Current across the southern boundary of the Alaskan Stream —3 Sv ; loss through Near Strait (sill depth ~2000 m)—10 Sv ; and loss westward along the southside of the Aleutian-Commander Island Arc below 2000 m—1.5 Sv. This results in a net flow of 14 Sv into the Bering Sea east of the Commander Islands or 15.5 Sv if the flow below 2000 m (1.5 Sv) enters the Bering Sea through Kamchatka Strait (other flow through Kamchatka Strait was not considered in these estimates). This transport was somewhat more than 9.5 Sv proposed by Batalin (1964) and less than the 19.5 Sv reported by Arsen'ev (1967), but only about half the annual mean transport of 30 Sv suggested by Hughes *et al.* (1974) as a result of analyses of station data and direct current observations aboard the *Thomas G. Thompson* in the vicinity of the western Aleutian-Commander Island Arc. Obviously more observations are required because it is difficult to believe that volume transport in this area is equivalent to one-half that of the Kuroshio.

C. Western Subarctic Domain

1. *Bering Sea*

Conditions in the Bering Sea are greatly influenced by near-surface intrusions from the Alaskan Stream and deep flow through Kamchatka Strait, and our knowledge of this area has greatly increased in the last decade primarily because of oceanographic observations obtained in relation to the exploitation of fisheries resources. The oceanic structural history of the Bering Sea has been presented by Ewing *et al.* (1965) and a geographical description of bottom sediments has been compiled by Bezrukov (1959). Dobrovol'skii *et al.* (1959) have presented a history of Bering Sea explorations, particularly Soviet activities prior to 1959, which was not available at the time of writing INPFC Bulletin 13 but few of the oceanographic data used in these studies are available for further analyses. The far-ranging cruises of the *Oshoro Maru* and research vessels of the Japan Fisheries Agency in the 1960's reflect the significant Japanese interest in the environment of marine resources in the Bering Sea. Extensive cruises of U.S. vessels during this period reflect a wide range of interests. Some U.S. oceanographic studies were conducted in the northeastern Bering Sea in relation to the U.S. Atomic Energy Commission's Project CHARIOT, which was designed to obtain background environmental data prior to a proposed experiment to blast a deep-sea harbor out of the rocky Alaska coast using nuclear energy (*Brown Bear* and *John N. Cobb*); associated and independent studies were also conducted aboard U.S. Navy and Coast Guard icebreakers (*Burton Island*, *Staten Island*, and *Northwind*). Fisheries research cruises in relation to INPFC salmon problems were conducted during spring and summer in the Aleutian Islands and Bristol Bay areas in 1960 (*Pioneer* and *Marine View*). Although experimental fishing was conducted for the first time in the central Bering Sea in January and February 1963 aboard *George B. Kelez*, the only oceanographic equipment aboard ship at that time was a portable bathythermograph winch (Favorite, 1964b). Oceanographic observations in relation to king crab studies in the southeastern Bering Sea shelf area were obtained in spring 1968 (*John R. Manning*), spring 1969 (*Miller Freeman* and *Commander*) and spring 1970 (*Miller Freeman* and *Oregon*). The first U.S. oceanographic cruise in the western Bering Sea during winter was conducted aboard the *Argo* in 1966 (Reid, 1966) and other research studies on Bering Sea circulation were conducted aboard the *Thomas G. Thompson* in summer 1969, 1970, and 1971 (Hughes *et al.* 1974). There have been several attempts by the University of Washington (Dr. L. K. Coachman) and the NMFS Northwest Fisheries Center (Dr. F. Favorite) to conduct cooperative oceanographic cruises during winter in the central Bering Sea, but it has not been possible to obtain vessel time. However, in 1970, a change in the operation schedule of the *George B. Kelez* permitted short cruises in the central Bering Sea over Bowers Ridge in spring 1970 (Favorite and Ingraham, 1972), and in the eastern Bering Sea in spring 1971 (Favorite *et al.* 1971).

Although extensive fishing activities were conducted by Japanese whaling, salmon, crab, and groundfish fleets, and by U.S. commercial fishing vessels, the intensive, highly organized Soviet Bering Sea Expedition, which commenced in 1958, provided a significant increase in our knowledge of oceanographic conditions in the Bering Sea. This was accomplished in two ways; first, by extensive analyses of previous oceanographic data; and, second, by extensive oceanographic observations obtained from vessels of fishing fleets. The comprehensive summaries of geological features (Bezrukov, 1959), of hydrochemical features (Davidovich, 1963, and Ivanenkov, 1964), and of physical-chemical conditions (Arsen'ev, 1967), provide excellent compilations of knowledge prior to the 1960's. Many results of geological, chemical, biological, and physical oceanography research conducted aboard various vessels of the fishing fleet (no major oceanographic vessels participated in these studies) are available in an excellent series of individual reports, documenting Soviet fisheries investigations in the northeast Pacific (Moiseev, 1963–72).

There are a number of summaries of oceanographic conditions in the Bering Sea. Although discussion of Bering Sea conditions was largely omitted from a previous Soviet summary of hydrological features of the Pacific Ocean (Muromtsev, 1958), it was noted that vertical movement of water at great depths from the Pacific Ocean greatly affected circulation in the surface layer in this area, and vice versa; thus, the Bering Sea influences and is influenced by the overall circulation of the Pacific Ocean. An atlas of temperature, salinity, and density distributions at various levels for monthly or seasonal periods based on data up to 1961, available at the U.S. Naval Oceanographic Office, has been compiled by Hamilton and Seim (1968) and reflects seasonal heating and cooling, coastal dilution, and general cyclonic geostrophic circulation; however, only gross well known features are evident. Ivanenkov (1964), in an extensive study of dissolved oxygen and nutrient distributions, combined the water mass classifications of Leonov (1947 and 1960a), Smetanin (1961), Dobrovol'skii and Arsen'ev (1961), and others, all largely based on temperature and salinity (T-S) relations from data prior to 1956, and defined 4 water masses in the Bering Sea Basin; (1) surface, homogeneous in winter but stratified in summer, (2) subsurface, (3) North Pacific intermediate and (4) North Pacific deep. Only the boundary between the first two could be satisfactorily determined using this method, and stability indices permitted separation of the first three. The surface and intermediate water masses are the same as the upper and lower domains presented in INPFC Bulletin 13, but Ivanenkov's work is of particular value because it is perhaps the only definitive summary of the inaccessible Soviet data in the western Bering Sea, even though largely limited to discussions of nutrient constituents. Analyses of distributions of dissolved oxygen, pH, and phosphate indicated a year round general cyclonic circulation with 4 cyclonic gyres—in the western basin, and, in the northwestern, southwestern and southeastern parts of the central basin—the positions of these gyres were highly variable; and 4 anticyclonic gyres—around the Commander, Near, Rat, and Andreanof Islands. These gyres, rather than being limited to the surface layer as suggested by Dobrovol'skii and Arsen'ev (1961), extended to the bottom. Arsen'ev

(1967) prepared an extensive, critical work on currents and water masses of the Bering Sea, which deals more exclusively with physical phenomena, and should be considered as a companion work to that of Ivanenkov's (both were limited to data obtained prior to 1960). Arsen'ev resolved conflicting results of previous Soviet researchers concerning flow through the Aleutian-Commander Island Arc and concluded that drift currents in deep water areas in spring and summer were small and flow was accurately denoted by geostrophic currents; flow in winter (although the data are probably not as reliable), indicated increased velocities of 1.2–1.7 times that of summer. Deviations from the typical subarctic water structure were found in three areas: the deep southwestern part, shallow northeastern part, and in the vicinity of the Aleutian Islands. Ohtani (1973) has also reviewed general conditions in the Bering Sea.

Extensive information on conditions over the continental shelf in the eastern Bering Sea is provided by studies in relation to salmon, groundfish, and king crab fisheries in this area. Koto and Maeda (1965) presented temperature and salinity distributions at the edge of the shelf during April-June 1960. Maeda *et al.* (1967, 1968) compared conditions in 1963 with those of 1960, and presented a summary of conditions for years 1955, 1956, and 1958–67. Data from the eastern Bering Sea cruises of the *Oshoro Maru* from 1963–66 have been analyzed by several authors. Kihara and Uda (1969) defined 3 bottom water types in relation to demersal fishing grounds south of 60°N: Alaskan coastal water (7.5°C, 30.2‰); boreal cold water (−1.8°C, 31.2‰), found over the continental shelf seaward of the above; and Alaskan Stream extension water (4°C, 33.6‰) protruding inshore over the shelf north of the Alaska Peninsula. Ohtani (1969) defined 8 " regions " in terms of the vertical distributions of temperature and salinity during winter and summer, and noted that north of 60°N the halocline prevented winter convection from reaching the bottom and this containment of dilute river runoff near the surface accelerated the ice forming process in this area. Kitano (1970a, b) using data from 1964–66 defined 4 environmental regimes: 2 warm water intrusions, through Amukta and Amchitka Passes: and " extremely dilute (30.3‰) core water " south of St. Lawrence Island, and, an " extremely " cold water mass (−1.0 to −1.7°C) in the Gulf of Anadyr which extended southeastward to St. Matthew Island. Favorite and Ingraham (1973) reported an anomalous surface tongue of dilute water extending over 200 km southward of the Pribilof Islands in spring 1971 that challenges the concept of northward surface flow at the shelf edge in this area.

Recent distributions of temperature and salinity in Bristol Bay area are available from king crab studies conducted by the National Marine Fisheries Service, Auke Bay Fisheries Laboratory during May and June 1968 (Hoopes and Greenough, 1970), September and October 1968 and spring and summer 1969 (Hoopes *et al.* 1971), and April and May 1970 (Hoopes *et al.* 1972). Monthly mean oceanographic conditions from May-September and during winter in this area by 1 × 1° quadrangles have been prepared by Ingraham (1973). Studies of turbulent upwelling and water mass identification in the vicinity of Samalga Pass have been reported by Kelley, Hood, Goering, Barsdate, Nebert, Longerich, Groves, and Patton (1973) and by Kelley, Hood, Groves, and Longerich (1973).

Although flow out of northern Bering Sea through the narrow, shallow Bering Strait supplies 22% of the inflow into the Arctic Basin (Gudovich, 1961), this is less than 5% of the total inflow into the Bering Sea and is not considered an important factor in the water balance. However, this flow does permit the exit of a considerable amount of the freshwater runoff along the coast of the eastern Bering Sea, as well as some of the dilute water found off the coast after the sea ice over the continental shelf melts in late spring. There have been a number of estimates of flow through the strait. Coachman and Barnes (1961) reported a northward flow of 1.4 Sv in summer and an annual mean flow of 1.0 Sv. Fedorova and Yankina (1963) summarized estimates of 9 Soviet authors, ranging from 20,000–45,000 km^3/yr and proposed an estimate of 29,997 km^3/yr (0.9 Sv). Extensive direct measurements from 1953–1958 by Bloom (1964) indicated 1.46±0.74 Sv for the period August through November; and Coachman and Aagaard (1966) observed a flow of 1.4 Sv in August 1964. Northward flow in summer is reported to be 3–4 times greater than in winter (Gudkovich, 1961; Fedorova and Yankina, 1963). However, Coachman and Aagaard (1966), in an extensive review of research in Bering Strait, reported that seasonal fluctuations are insufficiently documented and, although southerly flow was on occasion evident along both coasts, there was no substantial evidence for a net southerly flow occurring in any season. There are two dominant hypotheses for causes of the northward flow. Shtokman (1957) proposed that a downward slope to the north was the primary mechanism and a slope of 2.6×10^{-6} was calculated by Coachman and Aagaard (1966). Fedorova and Yankina (1963) found no relation with respect to local wind-stress, but presented evidence that flow may be in response to southward flow out of the Arctic Ocean into the Atlantic Ocean. Flow of Bering Sea water through the strait has a pronounced effect on conditions in the Arctic Ocean. The heat content is sufficient to remove almost half the surface ice in the Chukchi Sea and it requires over 3 years for this flow to lose its identity in the Arctic Ocean by mixing enroute with water from strata above and below it (Gushchenkov, 1968). Further effects of this flow on water properties in the Arctic Ocean have been discussed by Coachman and Barnes (1961), Kinney *et al.* (1970) and others. Monthly mean temperatures at the sea floor near the east shore can be expected to fall below 0°C in November, reach minimum values of −1.8 to −2.0°C by February, rise above 0°C in June, and reach values of 5–9°C in August (Bloom, 1964), but temperatures as high as 20°C can occur in Norton Sound. Oceanographic conditions in this general area obtained as an adjunct to a general overall mission of U.S. Coast Guard vessels are reported by Gladfelter (1964), Gladfelter and Codispoti (1965), Husby (1969a, 1971), Husby and Hufford (1971) and Hufford and Husby (1972). Sporadic ice reports obtained during the years 1960–68 (U.S. Naval Oceanographic Office, 1962–69) have been replaced by near real-time (weekly) maps of ice conditions obtained by satellite. The latter are discussed in a later section.

There has never been a concerted or large coordinated effort to ascertain circulation in the Bering Sea. Although an International Symposium for Bering Sea Study was recently held at Hakodate (January 31-February 4, 1972) under the auspices of the University of Alaska and Hokkaido University, it will probably be several years before cooperative planning will result in significant field activities. Most field studies have been limited to those conducted aboard single vessels and there have been several attempts to piece these fragmentary studies together into a coordinated whole. Although Hughes *et al.* (1974) presented schematic diagrams of the various circulation patterns proposed by various authors no nomenclature for these currents was included. There are about 20 currents, which have been assigned names by various authors (Table 5) but there is general agreement in the definitions of only two—the northward flow into Bering Sea is generally referred to as the Pacific Current, and flow out along the western side of the Bering Sea is considered to be the East Kamchatka Current; however, there is considerable disagreement as to amount and direction of surface and subsurface flow in these two current systems.

TABLE 5. Bering Sea currents

A. WESTERN BERING SEA
1. Kamchatka—Dobrovol'skii and Arsen'ev (1959, 1961)[1], Leonov (1960b), Burkov (1962), Reid (1966).
2. East Kamchatka—Dodimead, Favorite, and Hirano (1963), Favorite (1966a), McAlister, Favorite, and Ingraham (1970).
3. Oyashio (Kamchatka)—Boisvert (1970).
4. Oyashio—U.S. Navy Hydrographic Office (1958a), LaViolette (1967).

B. SOUTHERN BERING SEA
1. Bering—Dobrovol'skii and Arsen'ev (1959, 1961)[2].
2. Copper— " " " "
3. Attu— " " " "
4. Tanaga— " " " "
5. Komandorsky—Burkov (1962).
6. Amchitka Branch, Alaskan Stream—Favorite and Ingraham (1972).
7. Aleutian—Moiseev (1963-70).

C. CENTRAL BERING SEA
1. Bering (Gyral)—Uda (1960).
2. Cyclonic Gyre— " "
3. Bering Sea Gyre—Dodimead, Favorite, and Hirano (1963).

D. EASTERN BERING SEA
1. Transverse—Dobrovol'skii and Arsen'ev (1959, 1961)[1], Arsen'ev (1967).
2. Pacific—Leonov (1960b).
3. Bering—Boisvert (1970).
4. Alaskan Coastal—Saur, Tully, and LaFond (1954).

E. NORTHERN BERING SEA
1. Kamchatka—Dall (1882).
2. Bering— " "
3. St. Lawrence—Dobrovol'skii and Arsen'ev (1959, 1961).
4. Polar—Shtokman (1957), Gudkovich (1961), Favorite (1966a).
5. Pacific—Leonov (1960b), Maksimov (1944)[2], Meilakh (1958)[2], Gushchenkov (1968).
6. Arctic—Leonov (1960b).
7. Anadyr—Dobrovol'skii and Arsen'ev (1959), Leonov (1960b), Boisvert (1970).

[1] As shown by Arsen'ev (1967).
[2] As shown by Gudkovich (1961).

2. *Kuril Islands Area*

Southwesterly flow along the southeast coast of the Kamchatka Peninsula and the northern Kuril Islands is still poorly defined. Burkov (1958), using data from the May-June 1955 cruise of the *Vitiaz*, shows that this flow is greatly influenced by cold, dilute coastal water in this area. Kawai (1972) reviewed the names given to this flow by various authors, such as Kamchatka Current, Kuril-Kamchatka Current, Kuril Current, etc., and suggested that the term East Kamchatka Current used in INPFC Bulletin 13 be accepted as the proper terminology.

Transport in this current during summer was usually considered to be 8 Sv, and Reid (1966), during an unprecedented winter cruise aboard the *Argo* in this area, found a flow of 23 Sv (referred to 1500 db), which was assumed to be due to a seasonal change in the wind in this area. He also reported a strong extension of the Alaskan Stream (Alaska Current) westward to the Commander Islands that supposedly contributed to this flow during winter, but analyses by Japanese Oceanographic Data Centre (1968), McAlister *et al.* (1970), and Ohtani (1970), based largely on data also obtained from a 1966 winter cruise aboard the *George B. Kelez* over the Commander Ridge, show that the Alaskan Stream turned northward through Near Strait. However, the southwest transport in the East Kamchatka Current compared favorably with estimates of mean integrated wind-stress transports in this area of 29 Sv in winter and 6 Sv in summer (Favorite *et al.*, 1967).

In INPFC Bulletin 13, the East Kamchatka Current was shown flowing southward along the southeast coast of the Kamchatka Peninsula and diverging off the northern Kuril Islands, one branch continuing southward and the other turning westward into the Sea of Okhotsk. Kawai (1972) noted that the former branch, the southward flow along the east side of the Kuril Islands that does not enter the Sea of Okhotsk, should also be called the Oyashio Current. On the other hand, LaViolette (1967) and Boisvert (1970) considered the Oyashio Current to extend northward to the east coast of the Kamchatka Peninsula. Because the low temperatures usually associated with the Oyashio Current originate largely from the Sea of Okhotsk, the interpretation of the origin of the Oyashio Current—the central Kuril Islands—presented in INPFC Bulletin 13 is considered correct.

3. *Sea of Okhotsk*

Isolated from the main North Pacific basin by a sill depth along the Kuril Islands of about 2300 m, the Sea of Okhotsk has a maximum depth of about 3400 m. The narrow, shallow Soya (maximum depth 50 m) and Tartar (maximum depth 10 m) Straits, south and north of Sakhalin Island, respectively, provide connections to the Sea of Japan. During the 1960's, knowledge of oceanographic conditions in the Sea of Okhotsk increased substantially. Leonov (1960c) has presented a general regional summary of geological history, climate, weather, water masses, currents, zoogeography, and chemistry. He defined four water masses: (1) coastal-influenced by river runoff, salinity <30‰; (2) surface Okhotsk-influenced seasonally, −1.5 to 15°C, 32.8–33.8‰, extending to 100–200 m; (3) intermediate Okhotsk, modified by mixing, −1.7 to 2.3°C, 33.2–34.5‰, extending from 200–400 m to 1000–1300 m; and (4) deep Pacific—relatively unmodified, 1.8–2.3°C, 34.4–34.7‰, extending below 1000–1300 m. Kitani (1972) has shown that the distribution of the temperature-minimum stratum (dichothermal water) in summer generally corresponds to that of sea ice in winter, and at the center of the cyclonic gyre, where advective effects are reduced, multi-layering of strata occurs. Batalin and Vasyukova (1960) report that the amount of ice formed is nearly equivalent to that in the Bering Sea.

LaViolette (1967) has compiled an atlas of mean temperature, salinity, and density values for various time periods (e.g., monthly, quarterly, or annually) and depths, but these maps appear to lack the detail presented in the analysis of 11,000 deepwater stations presented by Moroshkin (1966), who also discusses papers by Dobrovol'skii (1961) and other Soviet oceanographers. Five water masses are identified: a Surface, and a Cold Intermediate Layer (both influenced seasonally); a Cold Transitional Layer (150–750 m); a Deep Warm Layer (800–1250 m); and a "Southern Trough" Layer (below the sill depth of the Kuril Island Arc). However, Yasuoka (1967) reporting results of the Hecateus Expedition in the southern Sea of Okhotsk in 1966 and 1967 found a similar water structure and used similar terminology, but defined different strata. Soya Warm Water, identified by high salinity and extending to 150 m, was distinguished from Okhotsk Surface Water in the southern part of the sea; but eventual mixing of the former with the latter in the northern area resulted in a uniform surface layer extending to 50 m. Okhotsk Intermediate Water, found under the above, encompassed the extreme temperature-minimum stratum and extended to nearly 300 m. However, water in the stratum in which the temperature rose from a minimum to a maximum, 300–1200 m, was denoted as Transient Layer Water; and the water below the temperature-maximum stratum, usually denoted Okhotsk Proper Water (e.g., Iida, 1962), was divided into two water masses: Okhotsk Deep Water, which extended to the second temperature-minimum stratum (1°C) near 2400 m, and the Okhotsk Bottom Water, which occurred below. However, an analysis of these data in terms of stability in the water column (Yasuoka, 1968) showed maximum stability at the surface, a minimum near 150–250 m, and a secondary maximum near 600–900 m, suggesting that there is a substantial physical basis for the analysis presented by Leonov (1960c). Kitani (1973) has defined four strata: surface water (0–100 m), transitional water (150–600 m), warm

TABLE 6. Widths and sill depths of Kuril Islands passes, and percent sectional areas of four major openings.

	Width between channels (km)	Sill depth (m)	Sectional area (%)
PACIFIC OCEAN			
Nemuro channel	16	10	
Kunashiri channel	23	205	
Etorofu channel	40	630	8.1
Minami Uruppu channel	31		
Kita Uruppu channel	67	2,318	43.3
Shimushiru channel	22	300-400	
Ketoi channel	27	>300	
Shurishu channel	23	80	
Rashowa channel	29	>200	
Mushiru channel	85	1,920	24.4
Shashikotan channel	29	70	
Harumukotan channel	16	50	
Onnekotan channel	52	500-600	9.2
Horomushiru channel	4	20	
Shumushu channel	13	200	
JAPAN SEA			
Mamiya channel	7	5	
Soya channel	41	55	

deep water (700–1800 m), and deep water.

There is considerable disagreement as to characteristics of specific currents in the Sea of Okhotsk. Five surface circulation patterns are shown by Moroshkin (1966): 2 cyclonic, over the central part of the deep basin, and off the northeast tip of Sakhalin Island; and 3 anticyclonic at the southwest tip of the Kamchatka Peninsula, off the central west coast of the Kamchatka Peninsula, and off the southeast coast of Sakhalin Island. A narrow band of strong coastal currents is shown to encircle the sea commencing with the northward flowing (West) Kamchatka Current along the west coast of the peninsula, a generally westward flow around the northern extremity of the sea, a pronounced southward flowing East Sakhalin Current along the east coast of Sakhalin Island (which turns eastward near 49°N), and an eastward flowing Soya Current along the northwest coast of Hokkaido. There are only 2 openings through the Kuril Islands with sill depths greater than 1000 m (Table 6), one near 48°20′N (Mushiru Channel) and the other near 46°45′N (Kita Uruppu Channel). Yasuoka (1968) reported 3 deep cyclonic circulations associated with these openings. Westward flow at depth (>1000 m) through the former follows the bathymetry of the basin. One branch, following the 1000 m isobath, turns northwestward following this contour around the basin; the other, restricted by the 1500 m isobath, continues westward and eventually southward. Westward flow through the latter opening results in a cyclonic circulation having a smaller radius than the flow around the 1500 m isobath. These circulations are referred to as the Okhotsk Deep Cyclonic Circulation, the Kuril and the Inside Kuril Basin Deep Cyclonic Circulation, respectively. Eastward flow through the island arc at a depth of 1000 m, implied by the distribution of dissolved oxygen, was evident only at the southern opening. According to Watanabe (1962a, b, and 1963a, b) the East Sakhalin Current turns eastward near 49°N and flows into the Pacific Ocean through the southern Kuril Islands passes during summer (as indicated in INPFC Bulletin 13). New information presented on the Soya Current, which flows eastward between Sakhalin and Hokkaido and southeastward along the northern coast of Hokkaido, indicated the presence of another cyclonic gyre in the southern corner of the sea south of the anti-cyclonic gyre reported by Moroshkin (1966) in this area. In winter, the East Sakhalin Current extends southward beyond 49°N to the northeast coast of Hokkaido and at times carried ice westward through Soya Strait, but usually veers southeastward along the Hokkaido coast and into the Pacific Ocean through the southern Kuril Islands passes. Other studies of the Soya Current (Iida, 1962; Maeda, 1968; Aota, 1968; and Moriyasu, 1972b) show that the warm, saline water in this current is easily differentiated from the cold, dilute water in the Sea of Okhotsk during spring, summer, and fall, and that a similar flow may even extend under the ice during winter.

As in the Bering Sea, there is little uniformity in

TABLE 7. Sea of Okhotsk currents.

A. EASTERN OKHOTSK SEA
1. Pacific—Leonov (1960c).
2. South Okhotsk—Leonov (1960c).
3. South Okhotsk, East Branch—Leonov (1960c).
4. South Okhotsk, Kuril(e) Branch—Leonov (1960c).
5. South Okhotsk, West Branch—Leonov (1960c).
6. Kamchatka—Moroshkin (1966).
7. West Kamchatka—Yasuoka (1968).
8. Penzhinsk—Leonov (1960c).

B. WESTERN OKHOTSK SEA
1. Udsk—Leonov (1960c).
2. Amur—Leonov (1960c).
3. Tugursk—Leonov (1960c).
4. Ul'bansk—Leonov (1960c).
5. North Okhotsk—Leonov (1960c).
6. East Sakhalin—Watanabe (1962a, b; 1963a, b), Moroshkin (1966), LaViolette (1967), Yasuoka (1968).

C. SOUTHERN OKHOTSK SEA
1. South Japan—Leonov (1960c).
2. Soya—Iida (1962), Moroshkin (1966), Maeda (1968), Moriyasu (1972b).
3. Soya Warm—Watanabe (1963b), Aota (1968).

D. SUBSURFACE
1. Okhotsk Deep Cyclonic Circulation—Yasuoka (1968).
2. Kuril(e) Basin Deep Cyclonic Circulation—Yasuoka (1968).
3. Inside Kuril(e) Basin Deep Cyclonic Circulation—Yasuoka (1968).

terms denoting specific current systems. Of the currents denoted by name, only the East Sakhalin Current appears to have general recent acceptance (Table 7).

4. *Western Subarctic Gyre*

The discharge from the Sea of Okhotsk flows into the Pacific Ocean. Although this water can only be identified by water properties at depth, it is apparent that, rather than rejoining the East Kamchatka Current, this flow forms two branches; one continues eastward forcing the East Kamchatka Current to turn eastward also, resulting in the formation of the southwestern edge of the Western Subarctic Gyre. This merging of the eastern branch of the Sea of Okhotsk discharge and the southern branch of the East Kamchatka Current is the true origin of the Subarctic Current, and the only way that the large winter transport of the East Kamchatka Current (shown by McAlister, Favorite, and Ingraham, 1970) can be accounted for. This flow is also apparent in the CSK atlas prepared by the Japanese Oceanographic Data Center (1968).

The southern branch of discharge from the Sea of Okhotsk provides the dominant characteristics of water properties associated with the Oyashio Current. Sugiura (1960, 1961) has summarized conditions in this area, and Shimazaki (1967) showed the variability in temperature conditions during June 1961–64. A poorly defined turbulent flow of Sea of Okhotsk origin passes the Tsugaru Current (Iida, 1960; Yasui and Hata, 1960), which flows eastward between Hokkaido and Honshu; these flows merge and neither a clear flow pattern, nor an appreciable transport results. Hata (1965) summarized data from 1949–64 and reported volume transports of 1–4 Sv and great variability in flow. Thus, the surface confluence of the Oyashio and Kuroshio Currents is largely the result of a warm boundary current, the Kuroshio Current, forced eastward in a jet-like flow by the configuration of the south coast of Honshu.

5. *Subarctic Current*

Water in the Subarctic Current, which on a given sigma-t surface is colder and more dilute than those to the north or south (McAlister, Favorite, and Ingraham 1970), extends eastward into the central Subarctic Region. The main axis of this flow is evident as a narrow (100–200 km) tongue having slight downstream gradients of properties suggesting diffusion as the primary dissipative mechanism (Alvarez-Borrego and Park, 1971). Favorite *et al.* (1972) have shown that the eastward extent of this tongue is dependent upon interactions between the westward flow to the north, in the Alaskan Stream, along the south side of the Alaskan Peninsula and Aleutian Islands, and eastward flow to the south.

In an attempt to define eastward flow in this area, drift bottles were released from *George B. Kelez* along 175°W from the Aleutian Islands to 41°N at each degree of latitude (Favorite, 1964a). Those released south of the Alaskan Stream Domain and north of the Subarctic Boundary moved eastward, nearly zonally, to the North American coast; those released in the Central Subarctic Domain (between 47–49°N) were recovered on the North American coast south of 50°N. The rate of drift of the early recoveries was approximately 8 km/day. None of the releases south of the Subarctic Boundary was recovered.

Synthesizing data from a series of cruises in the central part of the region, Favorite (1969) defined 3 areas in the general eastward flow southward of the Alaskan Stream that could be readily identified: (1) Recirculation Area, where segments of the westward flow in the Alaskan Stream penetrated the dynamic ridge structure at its southern boundary and joined the eastward flowing Subarctic Current; (2) Western Subarctic Intrusion Area, composed of water from the Sea of Okhotsk discussed above; the (3) Subarctic

Current Area, near the boundary of the Central Subarctic and the Transitional Domains, where water structure resulted in maximum geostrophic eastward velocities.

III. MEAN CONDITIONS

In INPFC Bulletin 13, conditions in the region were described in relation to three strata in the water column ; an upper zone, subject to seasonal effects of heating, cooling, precipitation, evaporation, river runoff, and wind stress ; a halocline, which imparted considerable stability to the water column at the base of the upper zone ; and, a lower zone, below the halocline, where water properties changed monotonically with depth, and conditions at similar depth levels were generally homogeneous over large areas. In this section, an attempt is made to show continuity of oceanographic features irrespective of zones. As pointed out in numerous INPFC discussions and documents, the paucity of data in time and space, the transitory nature of temperature regimes, the relative uniformity of salinity at the sea surface, the winter turnover of the surface layer, the highly variable Ekman transports, all hinder ascertaining by descriptive techniques continuity of discrete surface flows that influence movements and, ultimately, distributions of marine organisms. At this point, the dominant, quasi-permanent features are identified, not the transitory ones. In this section, mean surface and subsurface conditions are presented and features evident in the distributions of temperature, salinity, density, and dissolved oxygen, mean geostrophic flow, mean energy exchange, and mean sea level are discussed.

A. Distributions of Water Properties

Some mention should be made at the outset concerning station data and data processing techniques. In INPFC Bulletin 13, presentations of distributions of properties and circulation patterns were limited to station data from individual cruises conducted at

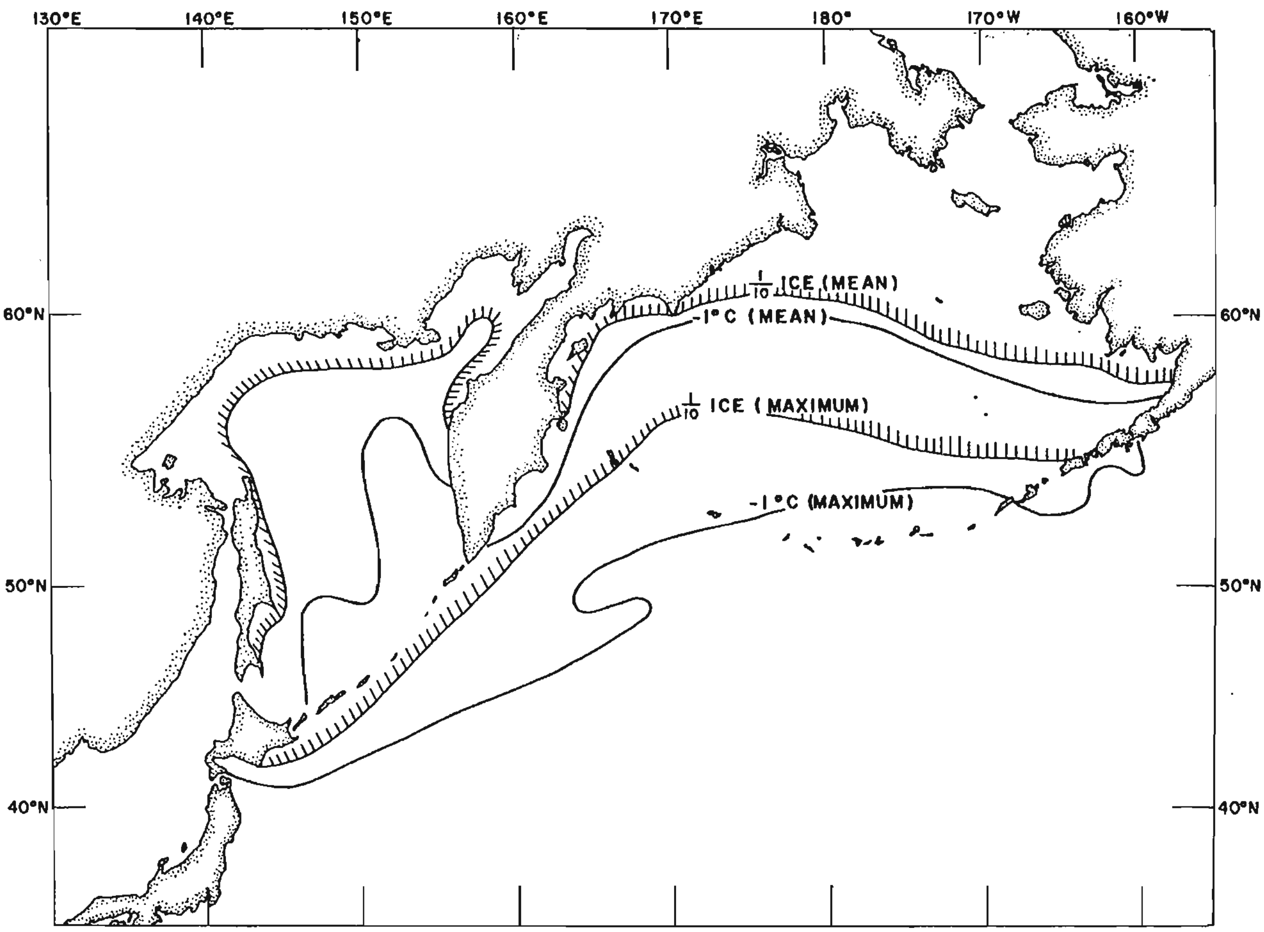


FIGURE 8. Mean and maximum southern extent of sea ice of 1/10 or greater concentration, and of the −1.0°C isotherm, during March (based on data from U.S. Navy Hydrographic Office).

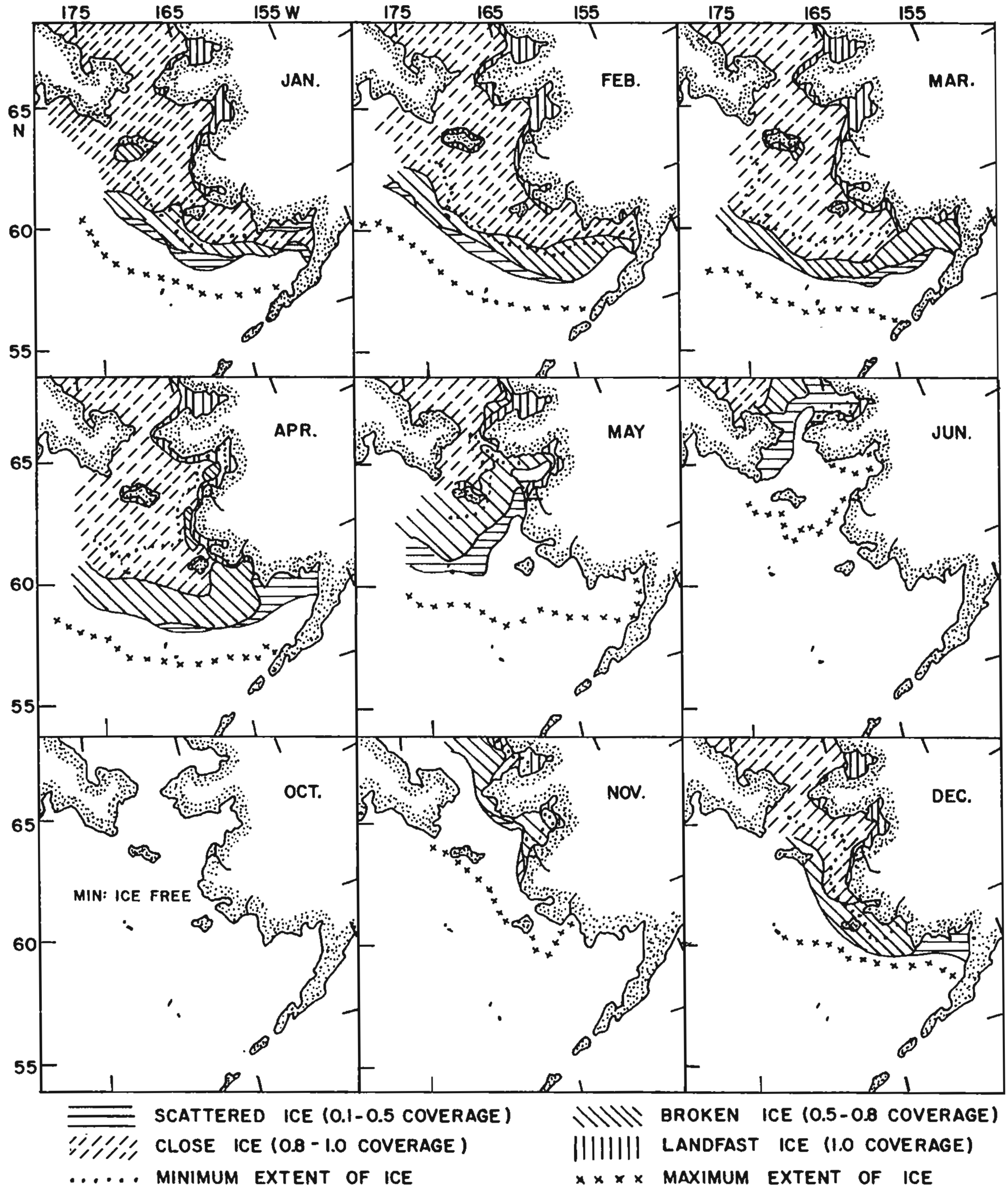


FIGURE 9. Mean and extreme ice conditions, eastern Bering Sea (based on data from U.S. Naval Oceanographic Office).

various time periods from 1955–59. Because of variability in time and in location of oceanographic stations, as well as the paucity of stations, isopleths of distributions of properties and flow were unavoidably biased and it was difficult to assess actual changes from one year to another. Easier access to computers at this time has permitted an extensive compilation of historical and recent observations. This allows an excellent assessment of mean, transregion conditions and provides greater insight into oceanographic features.

Station data from all locations shown in Fig. 1 north of 34°N have been compiled in the form of vertical array summaries listing maximum, mean, and minimum values at standard depths by 2 × 2° quadrangles for various time periods. Unfortunately the data are too sparse to permit extracting meaningful maxima and minima values. Further, although such a grid system is adequate for desired presentations in oceanic areas, it is too coarse to show adequate continuity of properties along the coastlines and, in particular, along the Aleutian-Commander and Kuril Island Arcs. This dilemma is not totally resolved even by accepting a 1 × 1° grid system, and computation and plotting effects would have increased fourfold. In addition, the amount of data rarely justify using a 1 × 1° grid system, except perhaps well off the east coast of Japan, and the west coasts of California, Oregon, Washington, and British Columbia. Data from 30–34°N are exclusively subtropic in character, even at the western side of the ocean, and have been eliminated.

Although numerous computer-constructed maps were made for various depths and time periods, it has been necessary to be rather parsimonious in the selection of those to be presented. The limitations in the use of unrestricted compilations of mean data as being representative of actual conditions are recognized and care has been exercised in this regard, but the opportunity to view the region as a whole instead of in fragmentary time and area segments has considerable advantages that are quite obvious.

1. *Surface Regimes*

As indicated in Table 3 there is already an overabundance of atlases of surface temperature and little improvement can be made on the monthly mean maps of surface isotherms presented in INPFC Bulletin 13. However, those maps excluded conditions in the Sea of Okhotsk and Bering Sea areas where the presence of ice during winter has a dominant effect on surface conditions. Seasonal variations in surface salinity in the region are also poorly documented, and analysis of these data provide insight into surface conditions and flow.

The maximum extent of sea ice of 1/10 or greater concentration occurs in March and encompasses the entire Sea of Okhotsk and Kuril Islands area, as well as about 3/4 of the Bering Sea (Fig. 8). Depending on the density of ice cover and surface salinity, sea

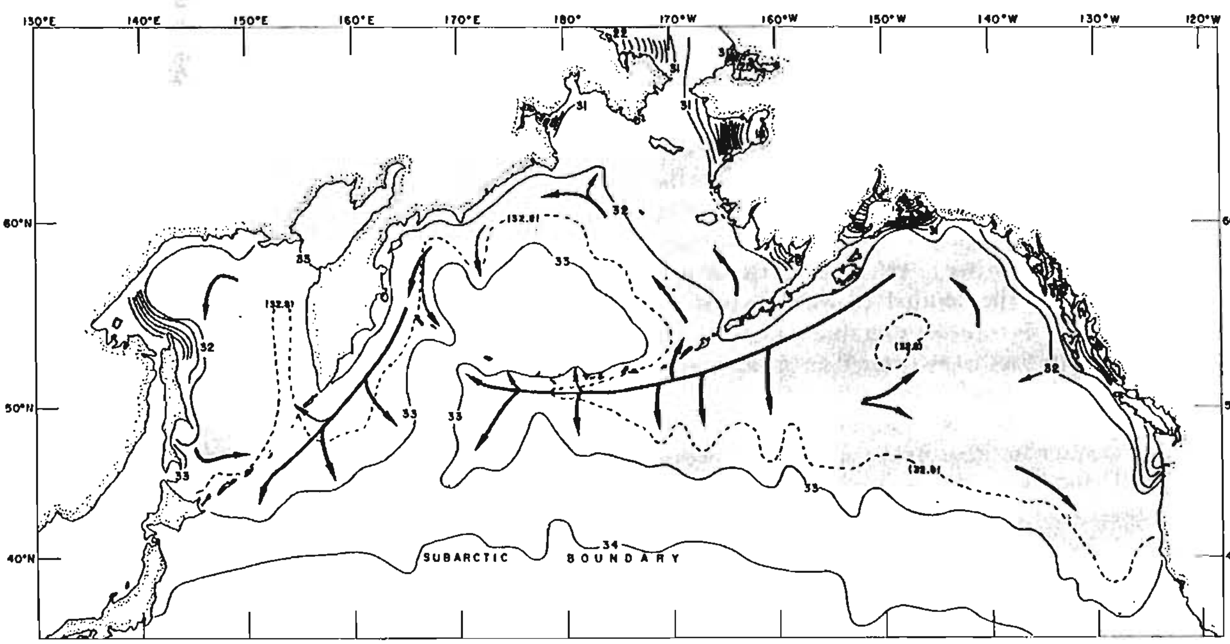


FIGURE 10. Long-term mean distribution of surface salinity (‰) indicating seaward extent of 33‰ isohaline, arrows suggest surface flow (2 × 2° quadrangles).

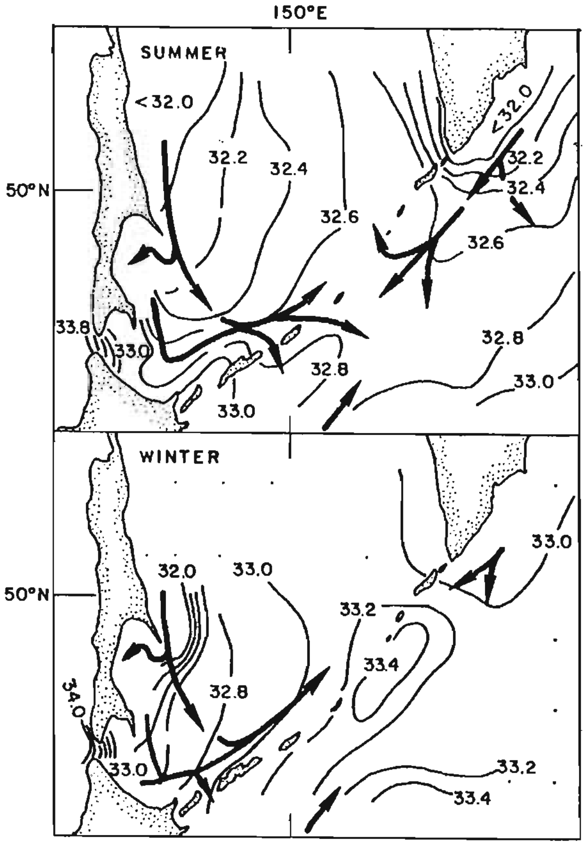


FIGURE 11. Long-term mean summer (July-Aug-Sept) and winter (Jan-Feb-Mar) distributions of surface salinity (‰) in the Kuril Islands area, arrows suggest surface flow (2×2° quadrangles—dots indicate no data).

surface temperatures of −1.5 to −1.8°C occur in this area, and mixing and stirring processes can result in negative temperatures to depths of 100 m or more. Because at these temperatures ice is present at the sea surface, the mean seaward extent of the −1.0°C isotherm in March sufficiently delineates the southern boundary of an ice regime. Of course, there are large fluctuations in the annual seaward extent of ice, and this results in considerable differences in the configuration of the isotherms based on mean data, and those based on extreme values for March. For example, the latter indicates a pronounced eastward tongue of cold water in the western part of the region south of the Bering Sea.

Recent observations of sea ice obtained by satellite have resulted in new information concerning ice cover. Near real-time reports by the U.S. Navy Fleet Weather Facility, Suitland, and the National Oceanic and the Atmospheric Agency National Environmental Satellite Service, Washington, D.C., are beginning to provide data that, except for limited reports by ice patrol vessels, have largely been missing since the late 19th century when U.S. whaling activities were sharply curtailed in this area. Ice is largely limited to the shallow continental shelf areas, which have considerable width in the northern Sea of Okhotsk and eastern Bering Sea. However, at times, ice does extend seaward over parts of the central Sea of Okhotsk and northern and western Bering Sea, depending on the severity of winter conditions. Maximum ice coverage in the eastern Bering Sea occurs by late February or early March and drift ice may extend to the Alaska Peninsula (Fig. 9). This condition can persist into May; on the other hand, in warm years, the entire area may be ice free by late May. Ice free areas occur first along the southeastern coast, but there is evidence of openings between the Nunivak and Pribilof Islands that extend from the coast to the shelf edge. Subsequently, ice south of St. Matthew Island, and in Norton Sound and Anadyr Bay, melts leaving a wide strip of sea ice extending southwestward from Bering Strait around St. Lawrence Island and north of St. Matthew Island to the shelf edge. Although some ice may be found along the north coast of St. Lawrence Island in early June, the Bering Sea is generally ice free by mid-June.

Another distinguishing characteristic of the region, discussed in INPFC Bulletin 13, is the subsurface temperature-minimum stratum, which is caused by winter turnover, present year round, and reflects winter surface temperatures. Lowest temperatures occur in areas where ice is or has been present, but a well-defined stratum is primarily evident in areas where advective flow is at a minimum, such as central areas of the Western Subarctic, Alaskan and Bering Gyres. Although vertical divergence also occurs in the latter areas, it is very slow, approximately lm/mo. Discharge of cold water out of the Sea of Okhotsk also contributes to the formation of a temperature-minimum stratum, which, because of the general continuity of ice in winter along the east shore of Kamchatka Peninsula and northern Kuril Islands, is difficult to separate from the stratum associated with the Western Subarctic Gyre. However, the extreme winter temperatures in this general area result in a stratum having a greater density and thus existing at a greater depth than the stratum associated with winter turnover in the Alaskan Gyre; this permits identifying the horizontal extent of water associated with these two general areas. The temperature-minimum stratum in the Bering Sea is largely isolated seaward of the continental slope by the overall cyclonic flow around the periphery of the Bering Sea basin.

It has long been recognized that the region is also characterized by a dilute surface layer. If the 33‰

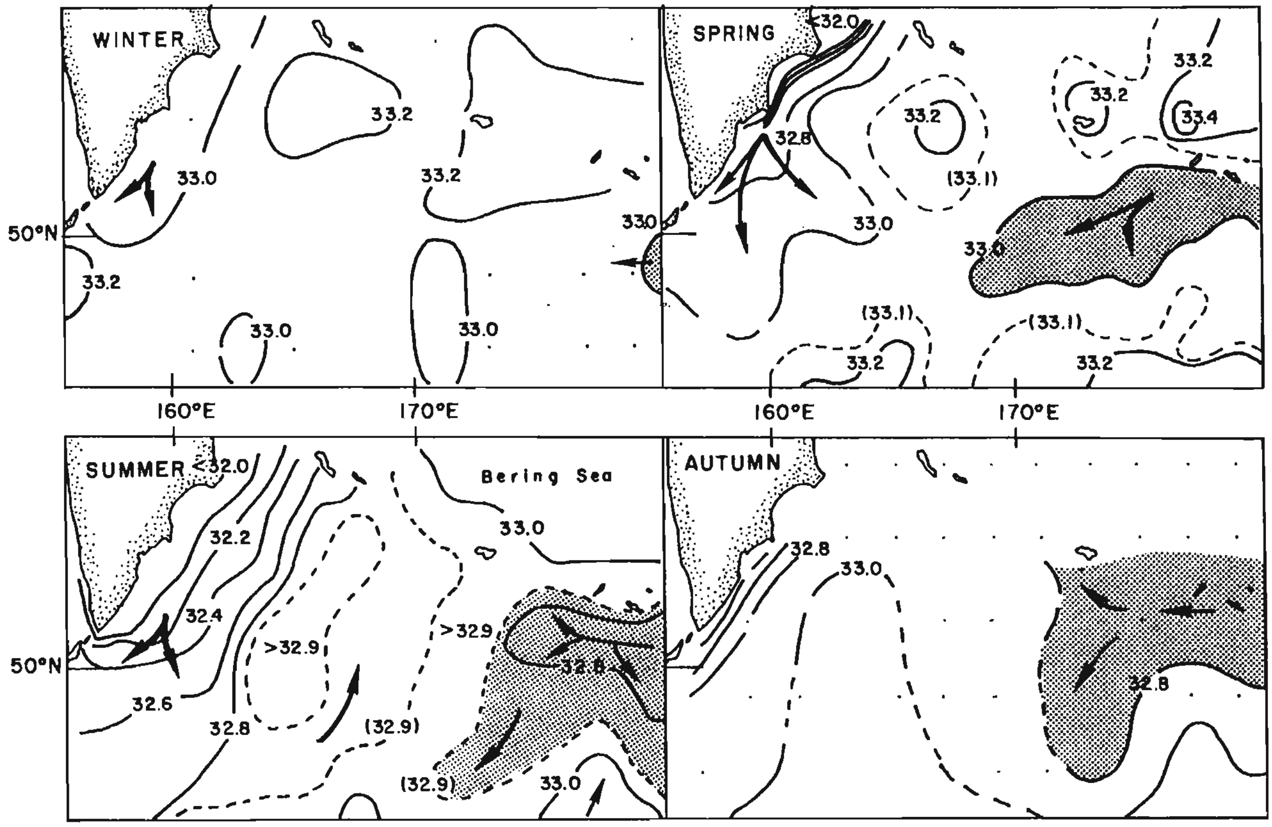


FIGURE 12. Long-term seasonal mean (Jan-Feb-Mar, April-May-June, July-Aug-Sept, Oct-Nov-Dec) distributions of surface salinity (‰) in the western part of the region, arrows suggest surface flow (2 x 2° quadrangles—dots indicate no data).

isohaline at the sea surface is accepted as indicative of the seaward spread of coastal dilution, the resulting area (based on long-term mean values) covers more than half of the region (Fig. 10). The obvious extreme dilution (<31‰) in coastal inlets and sounds, Sea of Okhotsk and eastern Bering Sea, is well known. Also apparent is the lack of westward continuity of this isohaline south of the Commander Islands at 170°E, and south of Attu Island near 170°W, suggesting isolation of east and west flows near the recognized westward terminus of the Alaskan Stream. There is a marked southward penetration of dilute water on the eastern side of the separation south of Attu Island. Maximum values (>32.8‰) in the area of the Alaskan Gyre provide evidence of vertical divergence, but there is no indication of a similar feature in the area of the Western Subarctic Gyre. Quarterly mean surface salinity distributions reveal considerably more details (App. Fig. 1). In the Kuril Islands passes, minimum salinities occur in summer, and maximum salinities occur in winter (Fig. 11). Although salinities of less than 32‰ occur in the Sea of Okhotsk, mixing in the southern part of the sea and in the Kuril Islands passes results in mean salinities greater than 32.6‰ seaward of the Kuril Islands. The most dilute water seaward of the island arc originates from the east coast of Kamchatka Peninsula where salinities of less than 32‰ occur, and the southward, tongue-like intrusion of this water along the east side of the Kuril Islands is apparent. Maps of monthly mean surface salinity (not included in this report) indicate that the progressive dilution of water along the east coast of Kamchatka Peninsula from local runoff and ice melt occurs from May to August, and penetrates only as far south as 46°N. However, monthly mean data indicate that water of 32.4–32.6‰ originating from extreme dilution in the western Sea of Okhotsk reaches and penetrates through the southern Kuril Islands passes in September and contributes to local dilution south of 46°N; there is no evidence of this phenomenon in October. Although salinities less than 32‰ may still be present in the western Sea of Okhotsk in winter, vigorous mixing in the Kuril Islands passes results in a band of maximum salinity, greater than 33.4‰; whereas, water of less than 33‰ occurs off the east coast of Kamchatka Peninsula. Thus, it is apparent that there is not a significant seaward penetration of low salinity surface water (<32.6‰) from the Sea of Okhotsk and when such a penetration occurs, it should be limited in north/south extent, exist as a narrow plume, and be evident in late summer. This is in marked contrast to the broad area of dilution which occurs off the southeast coast of Kamchatka Peninsula primarily in late spring.

The separation of the 33‰ isohaline in the vicinity of 170°E shown by the long-term mean surface salinity distribution is more relevant to INPFC research, and maps of seasonal salinity distributions in this area are presented (Fig. 12) even though autumn and winter data are limited. This isolation of dilute water of undisputable eastern origin south of the Aleutian Islands, from that of western origin off the coast of Kamchatka Peninsula, is obvious in spring and summer, and apparent in winter and autumn in spite of limited data in the latter two quarters. This is the first time such clear evidence of the probable mean westward extent of water from the eastern part of the region has been presented. Surface temperature data do not show such westward penetration because of nearly uniform latitudinal heating and cooling. Although the extent of this penetration has been implied through distributions of properties on various surfaces, such as dichothermal and mesothermal layers, these generally occur at depths of 100–300 m. This penetration has also been reflected

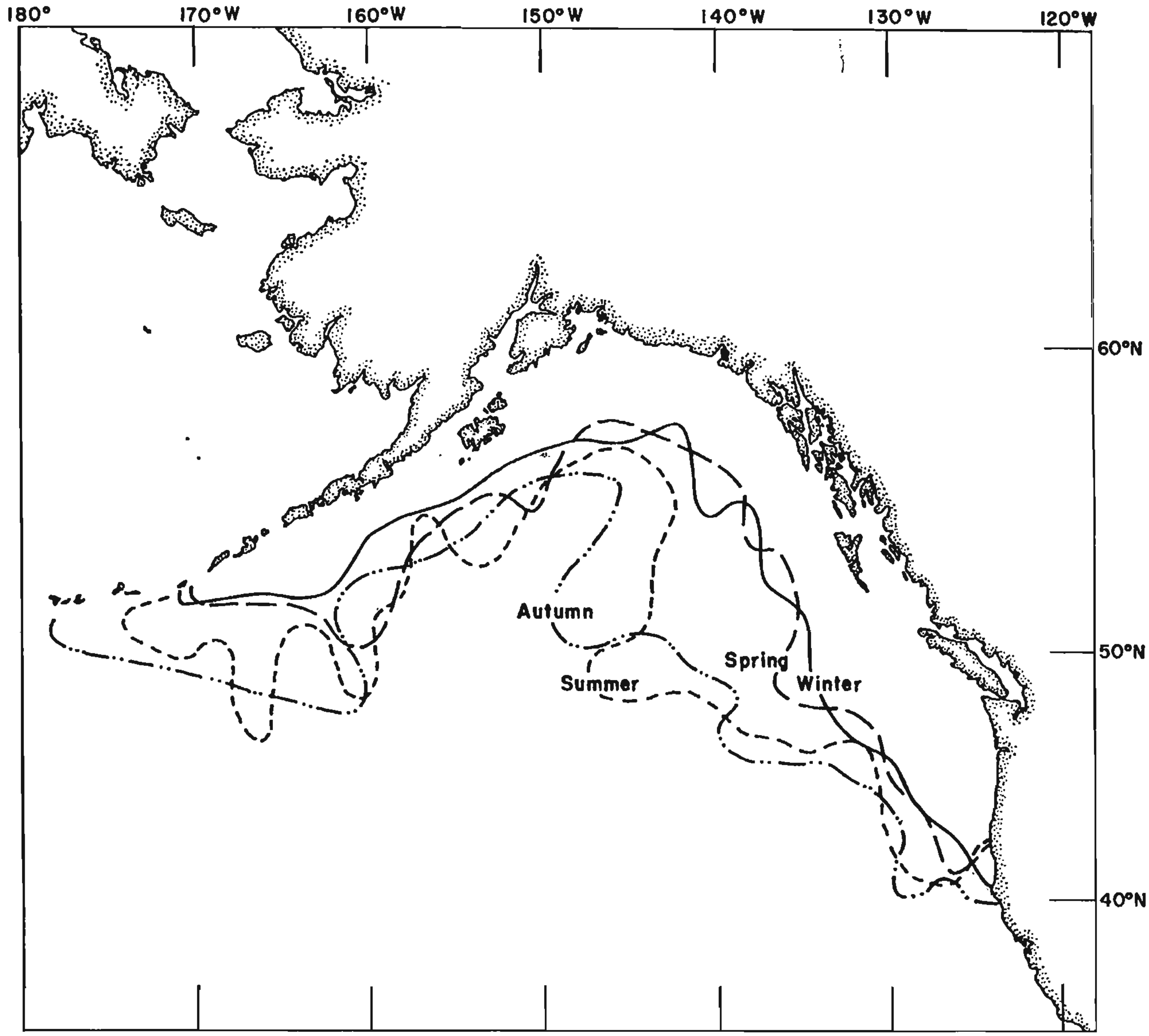


FIGURE 13. Seasonal configuration of the 32.6‰ isohaline in the Gulf of Alaska based on long-term mean data (2×2° quadrangles).

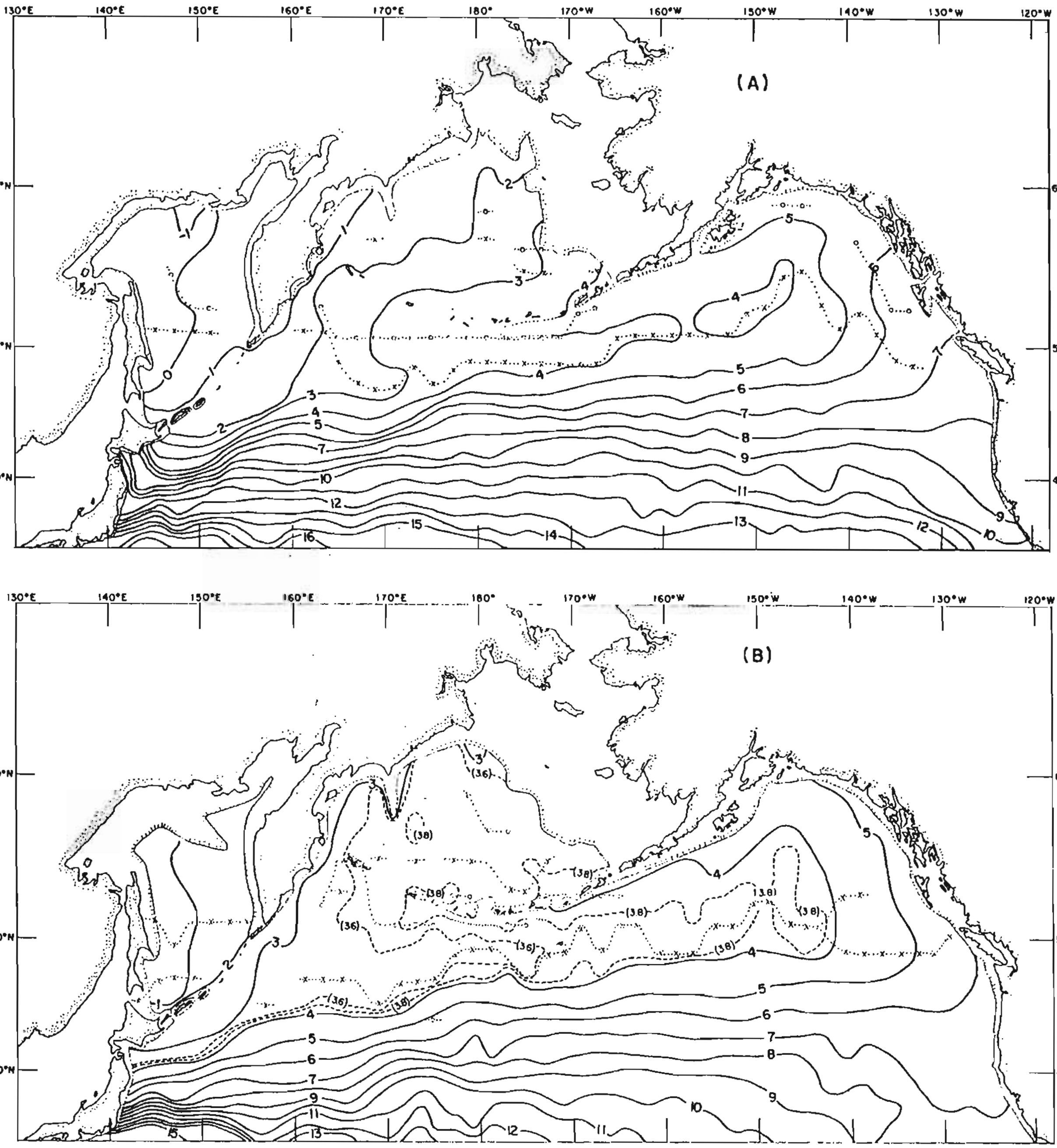


FIGURE 14. Long-term mean temperature (°C) distributions at (A) 125 and (B) 300 m (2×2° quadrangles) (–×– indicates minima; –O– maxima).

in maps of geostrophic currents, but these do not necessarily indicate the continuity or extent of discrete water properties that may be significant to salmon. Also apparent in the general area of the Western Subarctic Gyre is the lack of a consistent location of a salinity maximum at the surface that would indicate vertical divergence within the gyre associated with cyclonic flow.

However, maximum surface salinities in the Gulf of Alaska, associated with the Alaskan Gyre, are always present, the physical constraint of the Alaskan coast obviously is a factor here and makes the latter gyre a more dominant feature. The seasonal maps of surface salinity also permit showing for the first time seasonal changes in the seaward penetration of dilute surface water in the Gulf of Alaska (Fig.

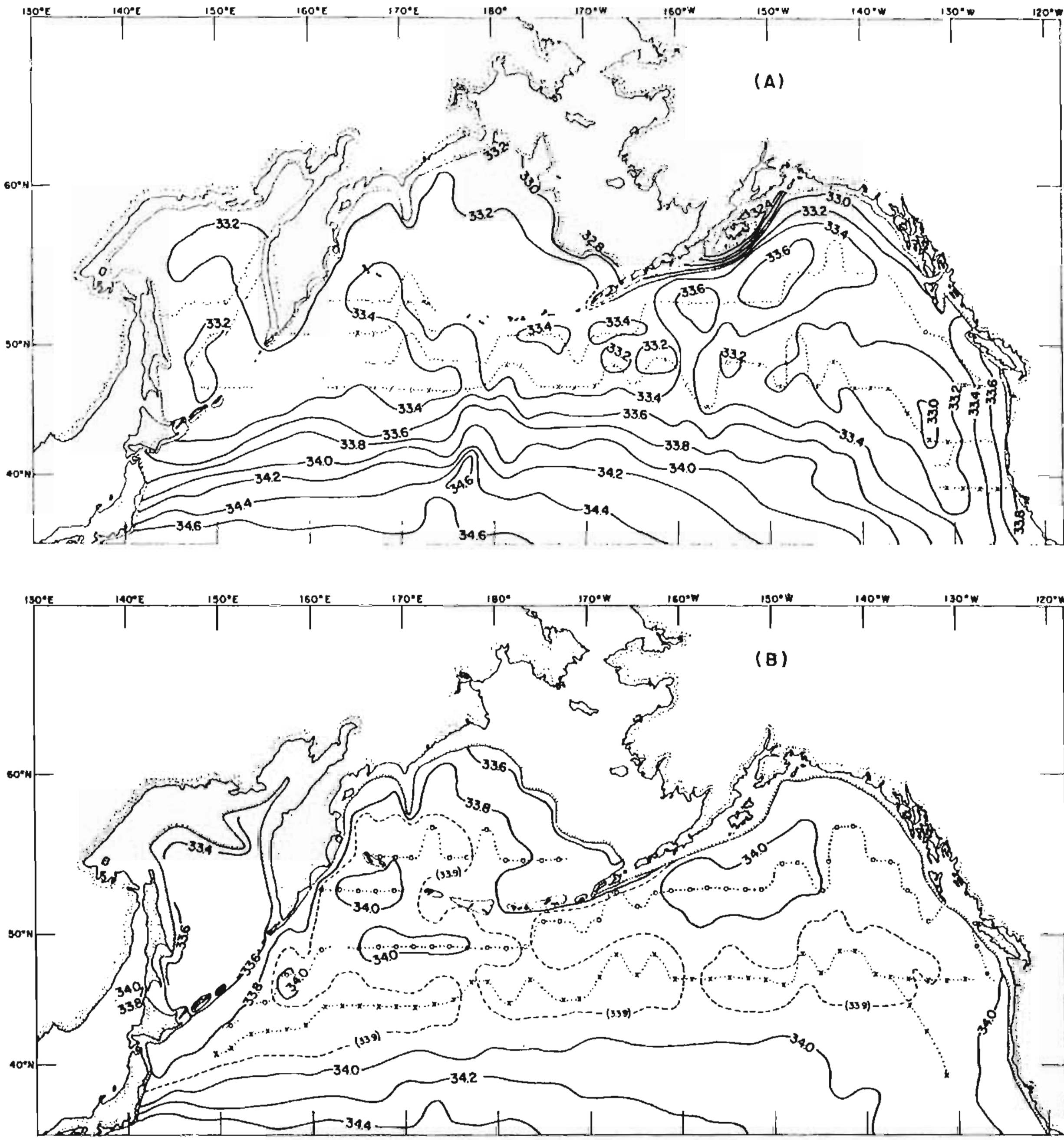


FIGURE 15. Long-term mean salinity (‰) distributions at (A) 125 and (B) 300 m (2×2° quadrangles) (–×– indicates minima; –O– maxima).

13). The 32.6‰ isohaline is used to indicate coastal intrusions into oceanic water, and the configuration of this isohaline in winter closely follows the trend of the coastline. The southwestward plume of the Columbia River is evident in spring, and seaward intrusions also extend westward off Queen Charlotte Sound, and southward from Kodiak Island and the Alaska Peninsula. The seaward extents of these intrusions increase greatly in summer and persist in autumn. There are indications from synoptic data that the westward intrusions from the west coast of southeastern Alaska and southward in trusions south of the Alaskan Peninsula merge and achieve continuity south of the Alaskan Gyre; however, the seaward extent of the former raises serious questions concerning the nature of the generally

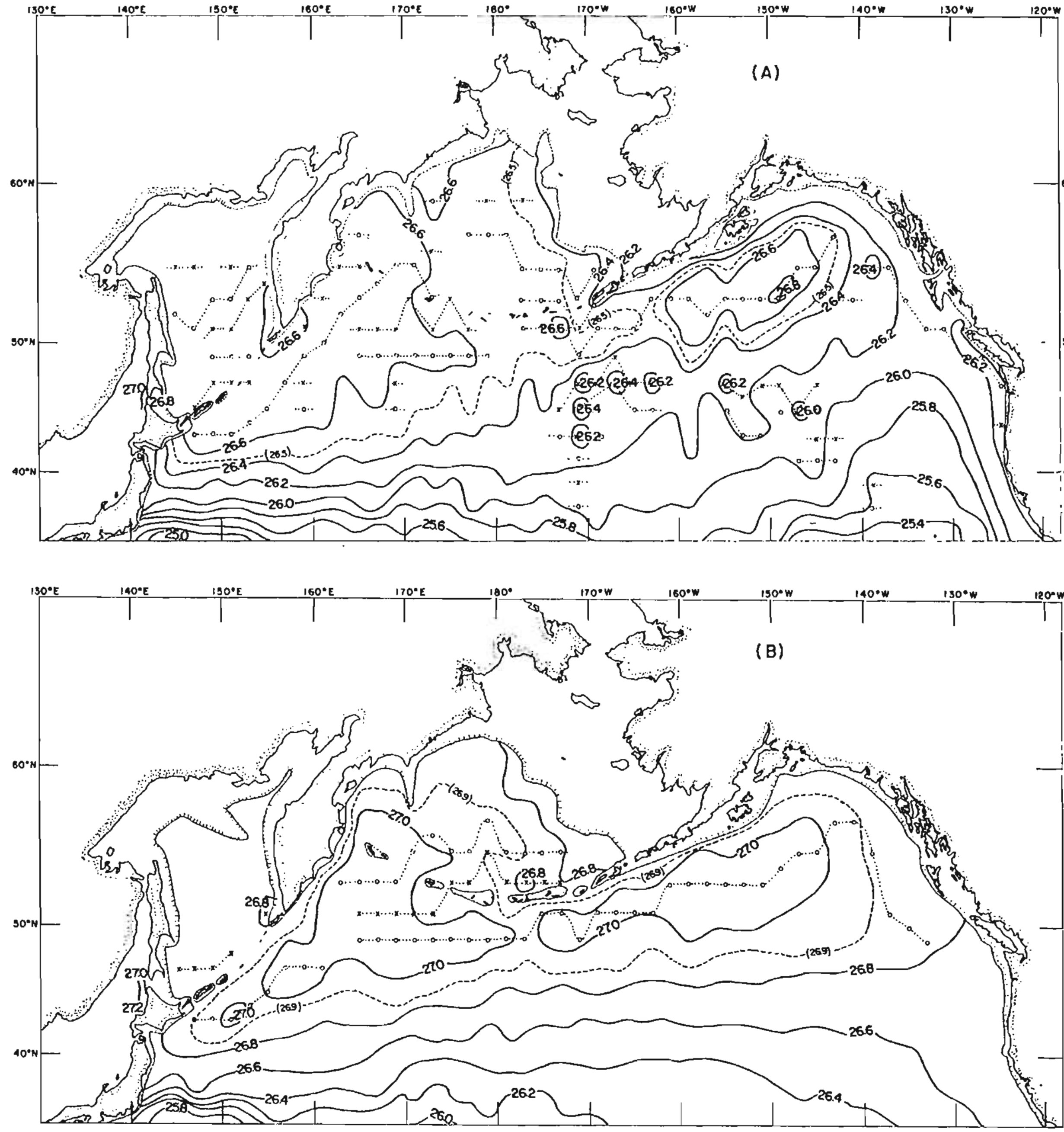


FIGURE 16. Long-term mean sigma-t distributions at (A) 125 and (B) 300 m. (2×2° quadrangles) (-×- indicates minima; -O- maxima).

accepted eastward and northward flow in this area.

2. *Subsurface Regimes*

Before discussing the general circulation and wind-stress transports in the region, it is instructive to provide a general description of the mean water structure and mean distributions of water properties. This is best accomplished by a combination of trans-region distributions of properties at uniform depth levels and distributions of properties in vertical sections. Additional information, particularly of flow, is also afforded by distributions of properties on constant sigma-t (σ_t) surfaces, the assumption being that mixing occurs along such surfaces because of reduced energy requirements. In the Subarctic Pacific Region, winter turnover extends to approximately 125

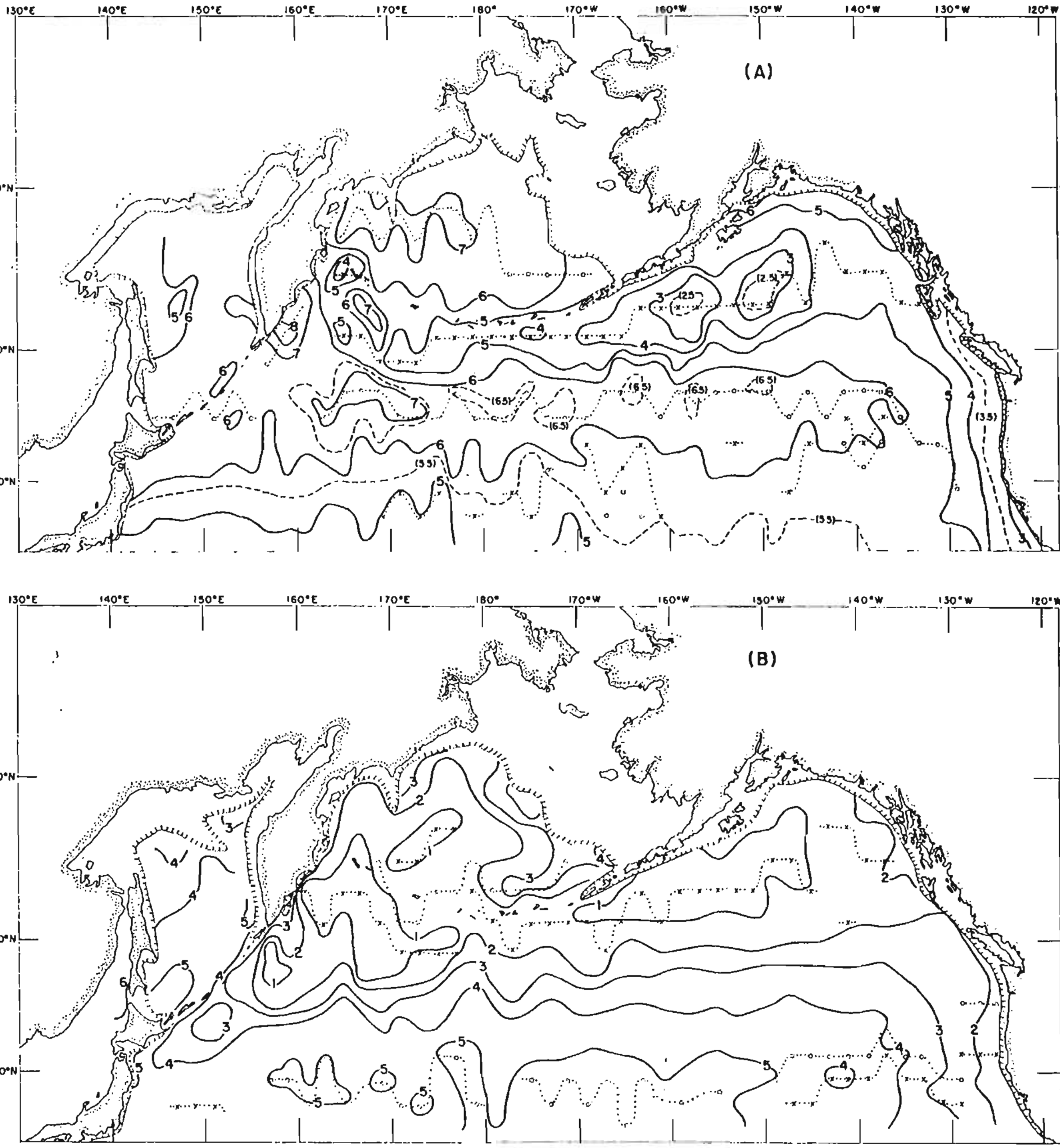


Figure 17. Long-term mean dissolved oxygen (ml/l) distributions at (A) 125 and (B) 300 m (2 × 2° quadrangles) (-×- indicates minima; -○- maxima).

m and, because spring and summer warming stabilizes the water column near the surface, conditions at and below this depth are largely subject to only diffusion processes for extended periods. Discussions are limited mainly to general features evident at 125 and 300 m, however, distributions of properties at 200, 500, 1000, 2000, and 3000 m are also presented (App. Figs. 2–6). Areas of maxima and minima are not shown on distributions below 500 m, except for temperature at 1000 and 2000 m. Because the main features are self evident in the figures, only brief descriptions are necessary.

Cold conditions are apparent at 125 m (Fig. 14) at the western side of the region from Cape Olyutorski to Hokkaido and sub-zero temperatures occur in the western Sea of Okhotsk. North of about 45°N there is a transregion west-east tongue in which the temperature increases eastward, 2 to 4°C, and the near zonal area of temperature-minimum (denoted by crosses) dips southeastward at the eastern side of the region. The west-east and southeast continuity of the features has not been identified previously. South of 45°N sharp gradients occur at the Kuroshio-Oyashio confluence and the central area is characterized by gradients of about 1°C per degree of latitude. At 300 m similar features are noted; the general area north of 45°N is again characterized by a west-east tongue of relatively low uniform temperatures (3–4°C), except in the Sea of Okhotsk where temperatures less than 1°C occur.

The salinity distribution at 125 m (Fig. 15) shows near-zonal bands not only of salinity maximum generally north of 50°N, but a salinity minimum south of 50°N; at the eastern side of the region these also dip southeastward. Minimum values of 32.4‰ occur near the coast in the northern Gulf of Alaska, but values generally range from 33.0 to 34.0‰ at the Subarctic Boundary. Values of 33.6‰ in the Alaskan Gyre and off the Washington-Oregon coast are considered to signify vertically upward displacements. At 300 m, values greater than 34‰ (except southward of the Subarctic Boundary) are found off the U.S. coast, in the Gulf of Alaska, and also in the Western Subarctic Gyre and denote the three main areas of vertically upward displacements.

Sigma-t distributions (Fig. 16) reflect the upward displacements discussed above. Maximum density at 125 m occurs in the Alaskan Gyre. Sharp meridional gradients occur in the Kuroshio-Oyashio confluence area and off the west coast of United States, and a markedly weak one occurs in the area 145°W–180°. However, at 300 m, the isopleths between 35° and 50°N are nearly zonal, except for a divergence at the eastern side of the region, and nearly uniform transregion meridional gradients occur. The general locations of the Western Subarctic and Alaskan Gyres are denoted by the outlines of the 27.0 σ_t isoline.

Distributions of dissolved oxygen at 125 m (Fig. 17) indicate lowest values (<2.5 ml/l) occur in the vicinity of the Alaskan Gyre and denote upward displacement of water. Values less than 4 ml/l are also evident near the Commander Islands and off the west coast of the United States. Although values of 7 ml/l occur in the northern Bering Sea these high values are primarily due to deeper winter convection, as well as the increased solubility of oxygen at lower temperatures which occur in that area. Particularly dominant is the broad zonal band of maximum values between 40–50°N related to the downward displacement of surface waters. At 300 m extremely low values (<0.5 ml/l) occur in the areas of the Western Subarctic and Alaskan Gyres again denoting upward displacement. Trans-Pacific meridional gradients occur between 40–50°N, except east of 140°W where near-zonal gradients occur. Low values (<1.0 ml/l) in the central Bering Sea suggest a broad upward displacement of water in this area. Of particular interest, but beyond the scope of this report, are the dissolved oxygen distributions at 1000–3000 m (App. Figs. 4–6). At 1000 m, minimum values (<0.4 ml/l) occur off the Washington coast; at 2000 m, minimum values (<1.25 ml/l) occur well offshore in the eastern part of the region; and, at 3000 m, minimum values (<2.5 ml/l) occur again off the Washington coast.

Several north-south and east-west sections have been constructed from vertical array summaries, thus the values represent grand means. Maximum and minimum values at each standard depth were also obtained but, because data are rarely available in each of the 12 months, these extremes are biased and have not been presented. For the same reason, data in the upper 100 m cannot be considered to represent accurate long-term means, but data below 100 m, where seasonal effects are minimal, are considered the most complete and most accurate assessment of subsurface conditions heretofore presented.

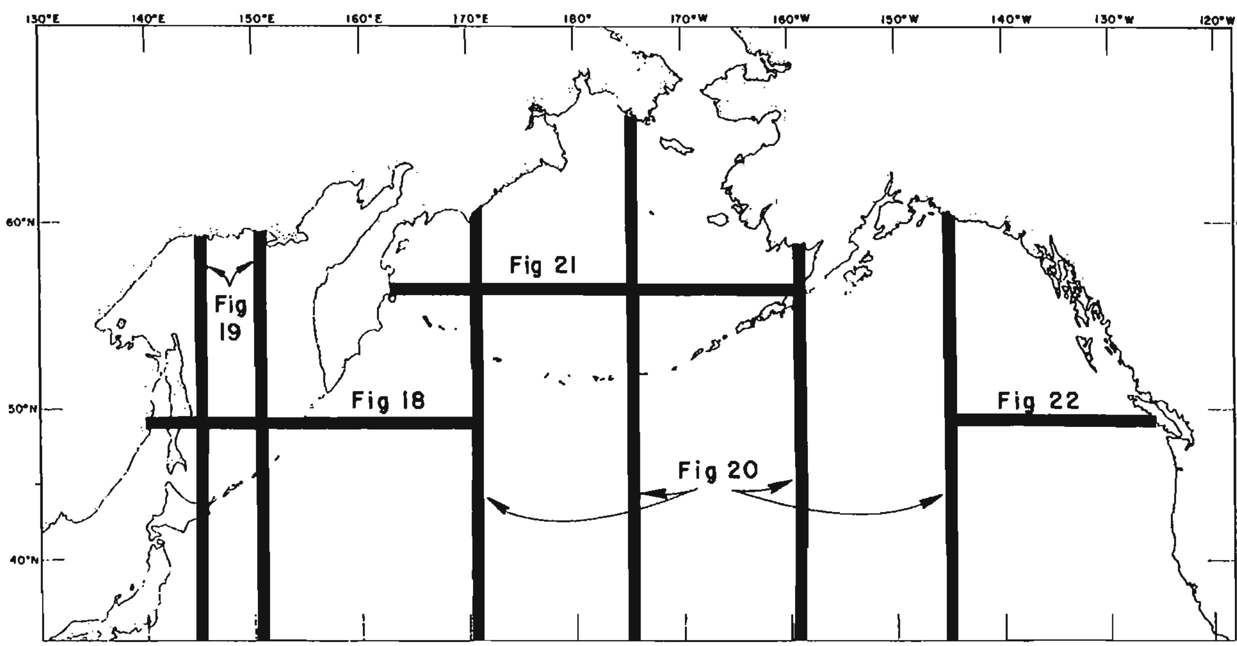
The vertical sections of water properties at the western side of the region along 49°N indicate the marked differences in water properties in the northern Sea of Japan, Sea of Okhotsk, and western Subarctic Pacific Region (Fig. 18). First, below 50 m there is a marked seaward gradient of minimum temperatures that extends from the western side of the Sea of Okhotsk eastward through the Kuril Islands passes; however, in the Sea of Japan temperatures at this depth are about 2C° higher than those in the western Sea of Okhotsk. The temperature-minimum stratum in the Sea of Okhotsk extends to about 800 m and a temperature-maximum stratum (~2.3°C) lies between 800 and 1800 m; whereas, seaward of the Kuril Islands, the temperature-minimum stratum extends from 50–200 m and the temperature-maximum stratum occurs between 200 and 800 m. At 1500 m, temperatures are quite similar in both areas. High salinity water (33.0‰) occurs at the surface in the Sea of Japan, but in the western Sea of Okhotsk surface values are low (31–32‰); values of 34‰ occur at 150 m in the Sea of Japan, however, equivalent values occur at 700 m in the Sea of Okhotsk and at 250–500 m seaward of the Kuril Islands. The lowest dissolved oxygen values (~0.5 ml/l) occur in an oxygen-minimum stratum at 400–1300 m seaward of the Kuril Islands, whereas, in the Sea of Okhotsk the oxygen-minimum stratum (~1.3 ml/l) occurs near 1000 m. Although the gradient is smaller, the oxycline in the Sea of Okhotsk occurs at a deeper level (300–800 m) than seaward of the Kuril Islands (150–250 m).

Vertical sections along 145° and 151°E (Fig. 19) show the marked difference in the north-south distribution of properties in the Sea of Okhotsk and in the area east of Japan. A pronounced temperature-minimum stratum at 100 m depth is present in the Sea of Okhotsk, with temperatures of about −1.8°C occurring along the north coast. Sharp gradients of temperature, salinity, and sigma-t occur in the upper 1000 m immediately southward of the Kuril Islands. The location of the Subarctic Boundary lies south of 40°N in these sections. The differences in the values and in the depth of the dissolved oxygen-minimum stratum inside and outside of the Sea of Okhotsk are not as great as at 49°N.

North-south vertical sections of water properties along 171°E, 175°W, 159°W, and 145°W (Fig. 20) all show the basic water structure south of the land barrier or boundary imposed by the Aleutian-Commander Island Arc and its extension—the ridging of the isolines immediately south of the island arc, with westward flow in the Alaskan Stream to the north and eastward flow in the Subarctic Current System to the south of the ridge (see Section IV-B-2 for discussion of current systems). The southward extent of the temperature ridge is greater than that of the salinity ridge. In fact, coincident with the southern portion of the temperature ridge, salinities are a minimum. These low temperature salinity waters are associated with the Subarctic Current System. The vertical trending 34‰ isohaline in the upper 300 m of the water column denotes the southern boundary of the Subarctic Pacific Region. The southward protruding tongue of salinities less than 34‰ below 500 m, the salinity-minimum stratum, signifies the presence of the Pacific Intermediate Water Mass formed as a result of sinking of surface water in the region.

The northern part of the vertical sections along 171°E, 175°W, and 160°W, and the east-west section along 57°N (Fig. 21) indicate conditions in the Bering Sea. A trans-Bering Sea temperature-minimum stratum occurs between 50 and 200 m and a west-east and north-south gradient of temperature is apparent, minimum temperatures occurring at the western and northern coasts. Marked surface dilution characterizes the continental shelf area in the eastern part of the Bering Sea.

Conditions off the west coast of Vancouver Island along 49°N (Fig. 22) reflect, in general, gradual changes in water properties with depth. Isotherms and to a lesser extent sigma-t surfaces slope downward toward the coast. The surface isohalines reflect the seaward penetration of river runoff, and the upward slope of the isoxyls toward the coast reflect the effects of upwelling in the upper 300 m. The oxygenminimum stratum is present at 700–1200 m.



Location of vertical sections in Figs 18–22.

The depth and distributions of temperature and salinity on sigma-t surfaces reflect the general features, flow patterns and intrusions below the surface layer in the region. The isopycnal $\sigma_t = 26.6$ fluctuates between the middle and bottom of the halocline except near the subarctic boundary where the halocline is absent or poorly defined. Sharp gradients of properties occur at the Kuroshio-Oyashio confluence (Fig. 23). The depths of this surface in the western part of the region and offshore south of the Alaskan Peninsula are relatively uniform (~125 m). The separation of cyclonic flow in the Alaskan and Western Subarctic Gyres as indicated by the 150 m isolines occurs at 172°W, and there is a suggestion of cyclonic flow in the central Bering Sea near 180°. Although the transpacific tongue of cold, dilute water from the Sea of Okhotsk to the Gulf of Alaska is evident, the salinity distribution indicates the presence of cells or eddies near 180°. Also, the cold water on the western side of the region extends from the Kuril Islands

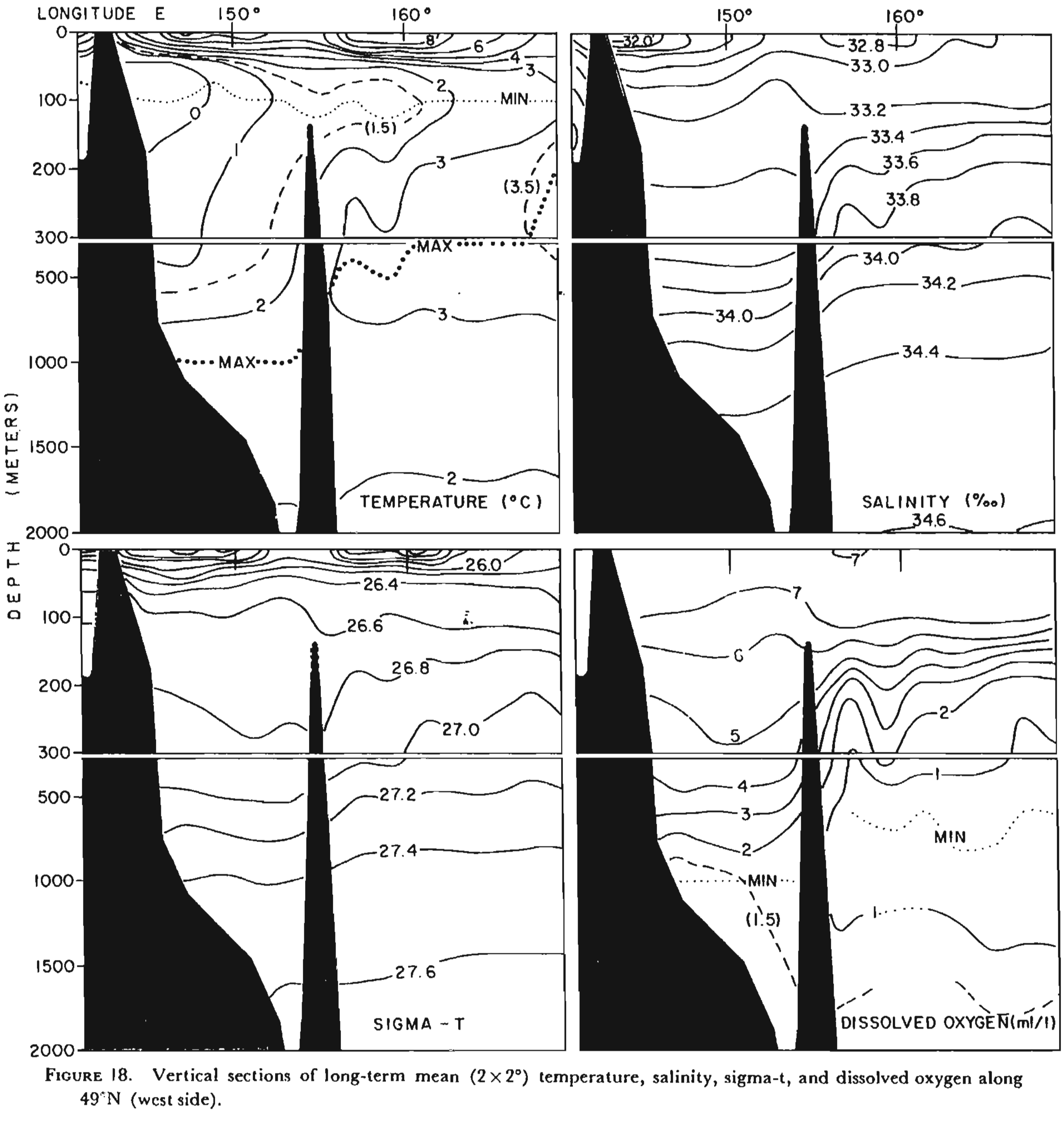


FIGURE 18. Vertical sections of long-term mean (2×2°) temperature, salinity, sigma-t, and dissolved oxygen along 49°N (west side).

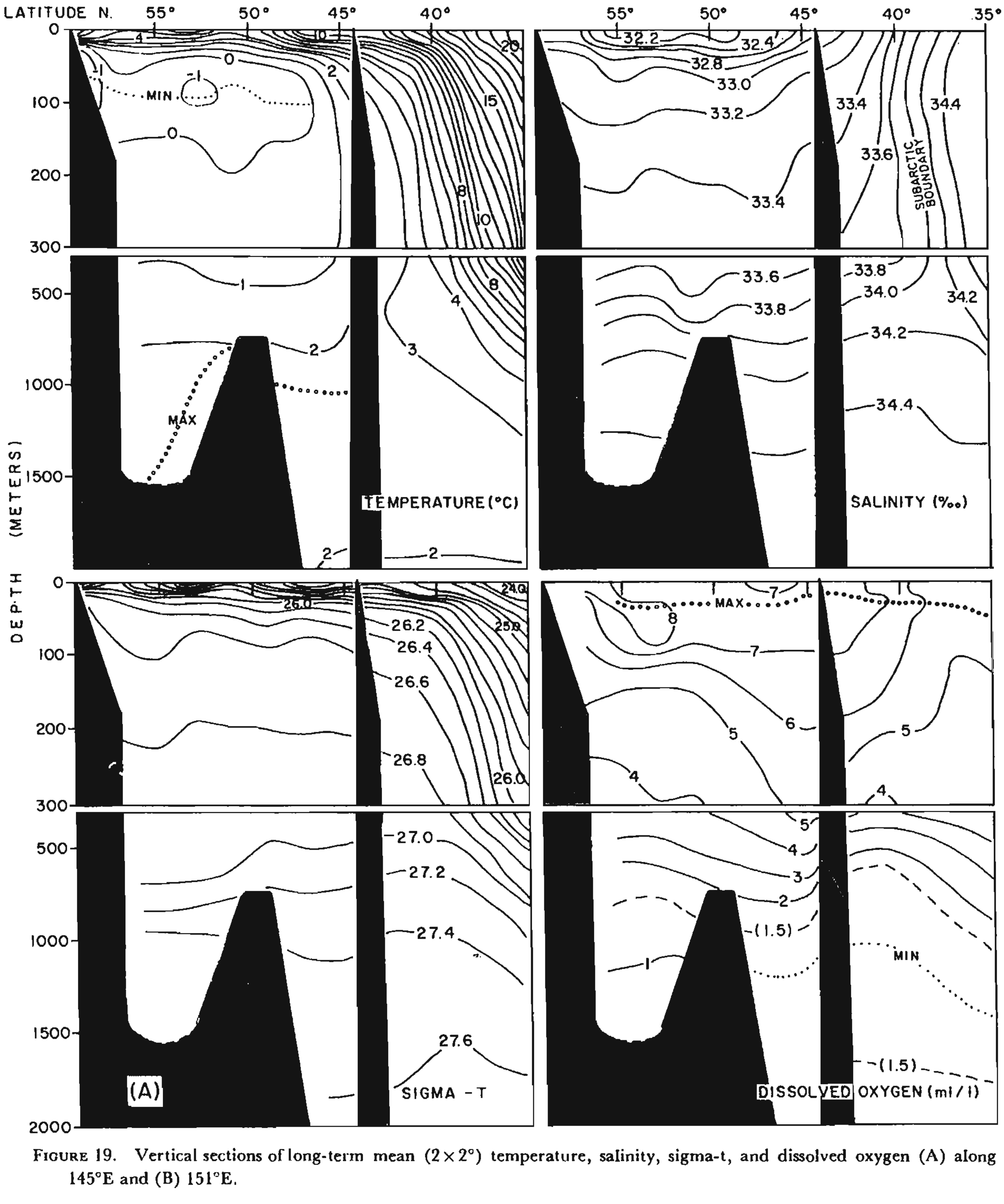
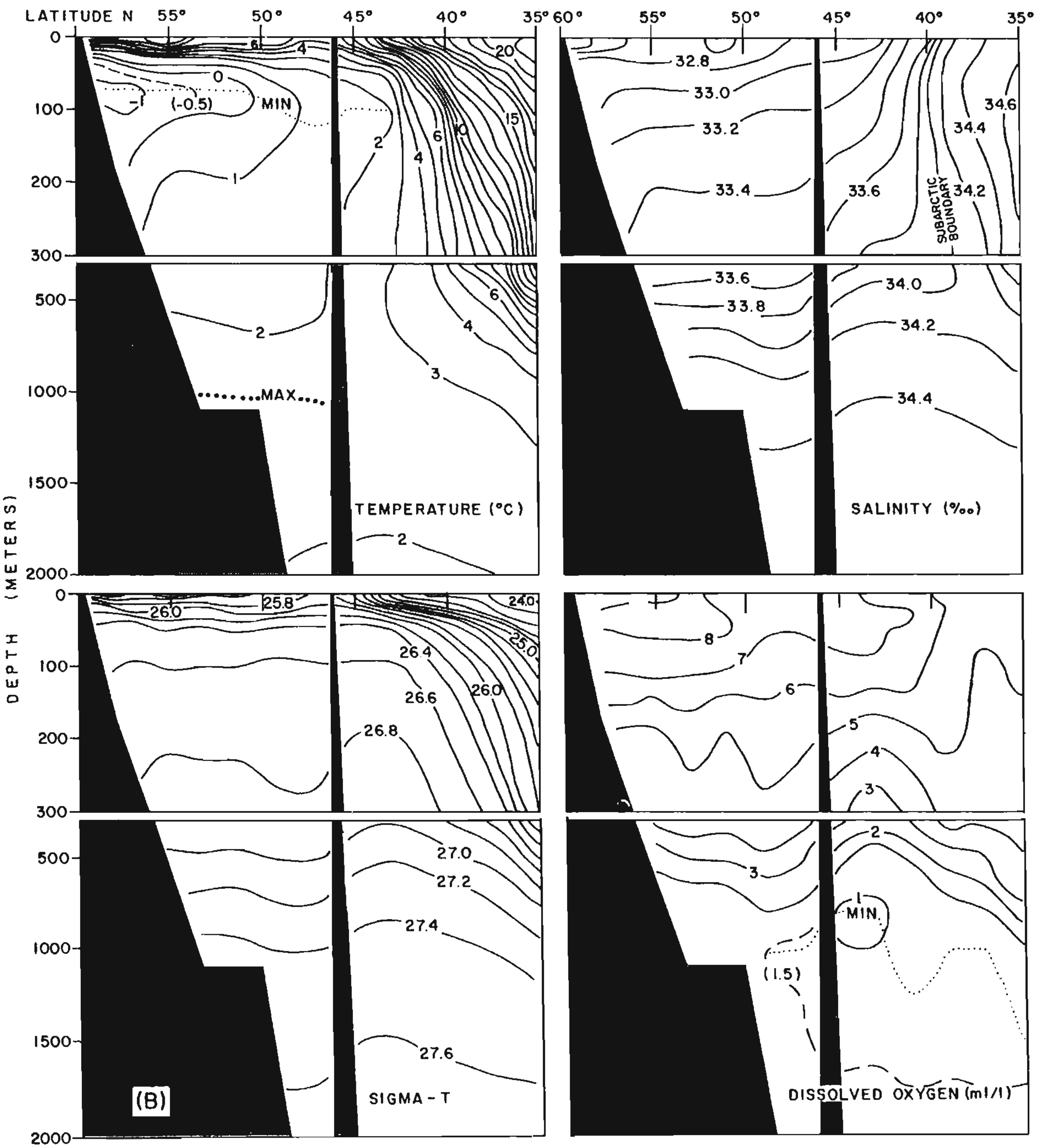


FIGURE 19. Vertical sections of long-term mean (2×2°) temperature, salinity, sigma-t, and dissolved oxygen (A) along 145°E and (B) 151°E.


LATITUDE N
DEPTH (METERS)
TEMPERATURE (°C)
MIN
MAX
SALINITY (‰)
SUBARCTIC BOUNDARY
SIGMA - T
DISSOLVED OXYGEN (ml/l)
MIN.
(B)

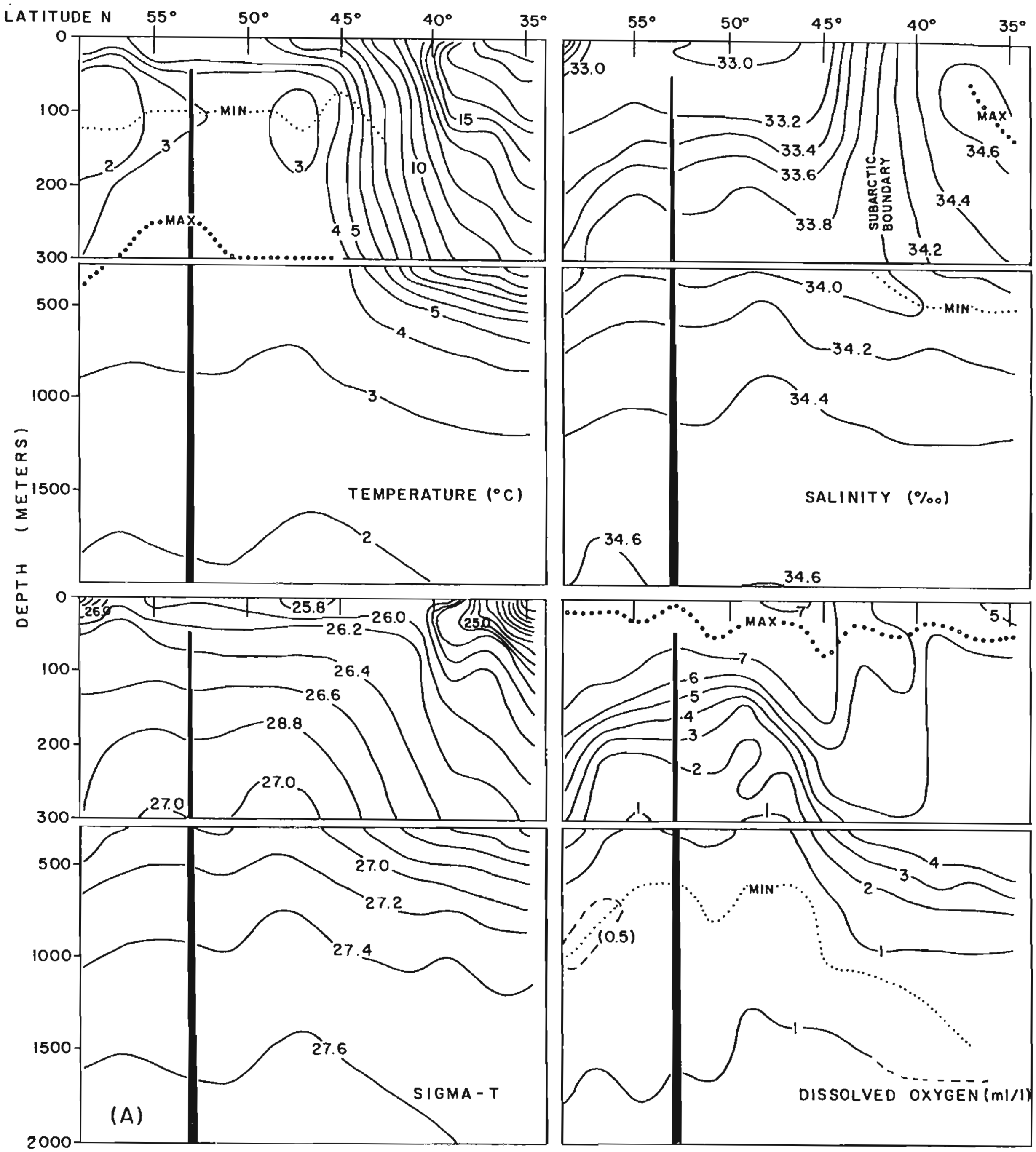
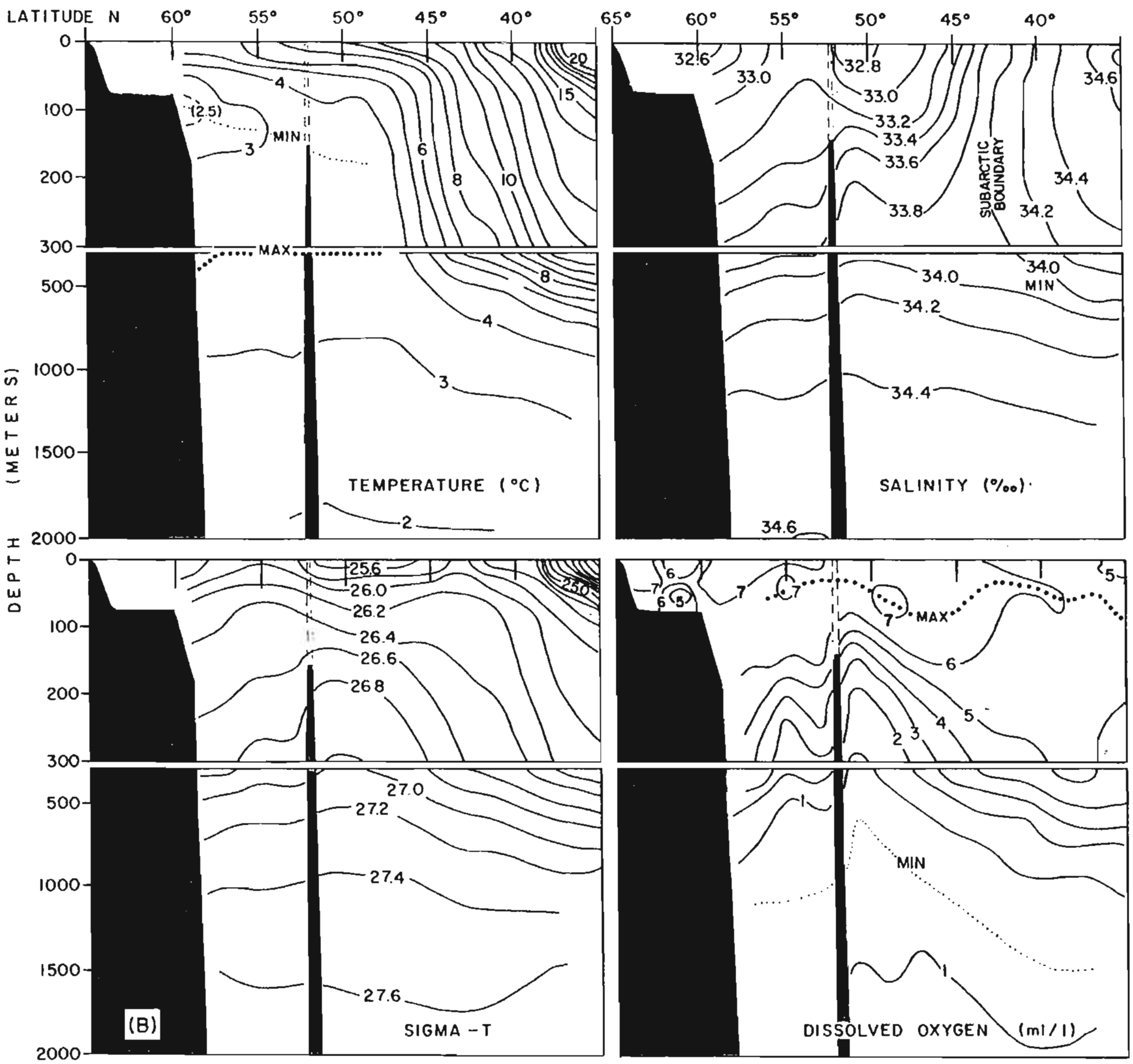


FIGURE 20. Vertical sections of long-term mean (2×2°) temperature, salinity, sigma-t, and dissolved oxygen (A) along 171°E, (B) 175°W, (C) 159°W, and (D) 145°W.

northward to the northern Bering Sea. In the Gulf of Alaska, the continuity of the cold water (<4°C) is interrupted by intrusions, supposedly from the north and south, of warmer water (>4°C). Off the California coast relatively uniform salinity values (33.95 ‰) are found extending over 2000 km seaward.

The isopycnal, $\sigma_t=27.0$, occurs well below the halocline and represents the distribution of properties in the lower zone. Features evident on this surface usually have continuity to at least 1000 m and may be evident at depths of 2000–3000 m. The depth of this surface varies from approximately 200 m in the Alaskan and Western Subarctic Gyres to 700 m south of the Subarctic Boundary (Fig. 24). These two gyres are clearly outlined by the 300 m depth contour and are separated near 178°W, farther to the west than at the 26.6 σ_t surface. Sharp gradients still occur at the Kuroshio-Oyashio confluence and also in the vicinity of the Kuril Islands, and along the east coast of Kamchatka Peninsula. Except for the small area of vertical movement northeast of Attu Island (175°E) there is still little evidence of a centrally located Bering Sea Gyre, rather, it would appear that the center of cyclonic flow is located northeast



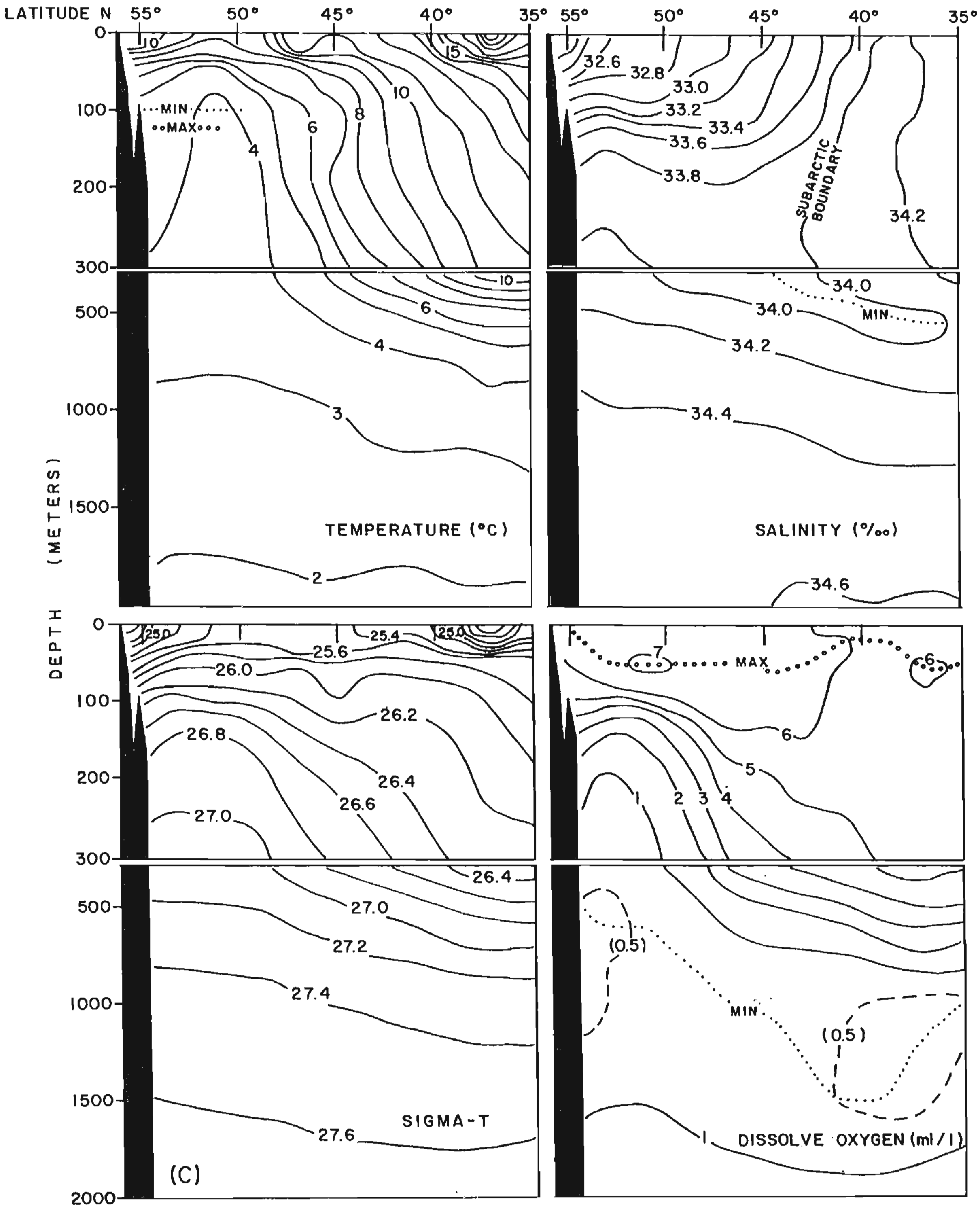
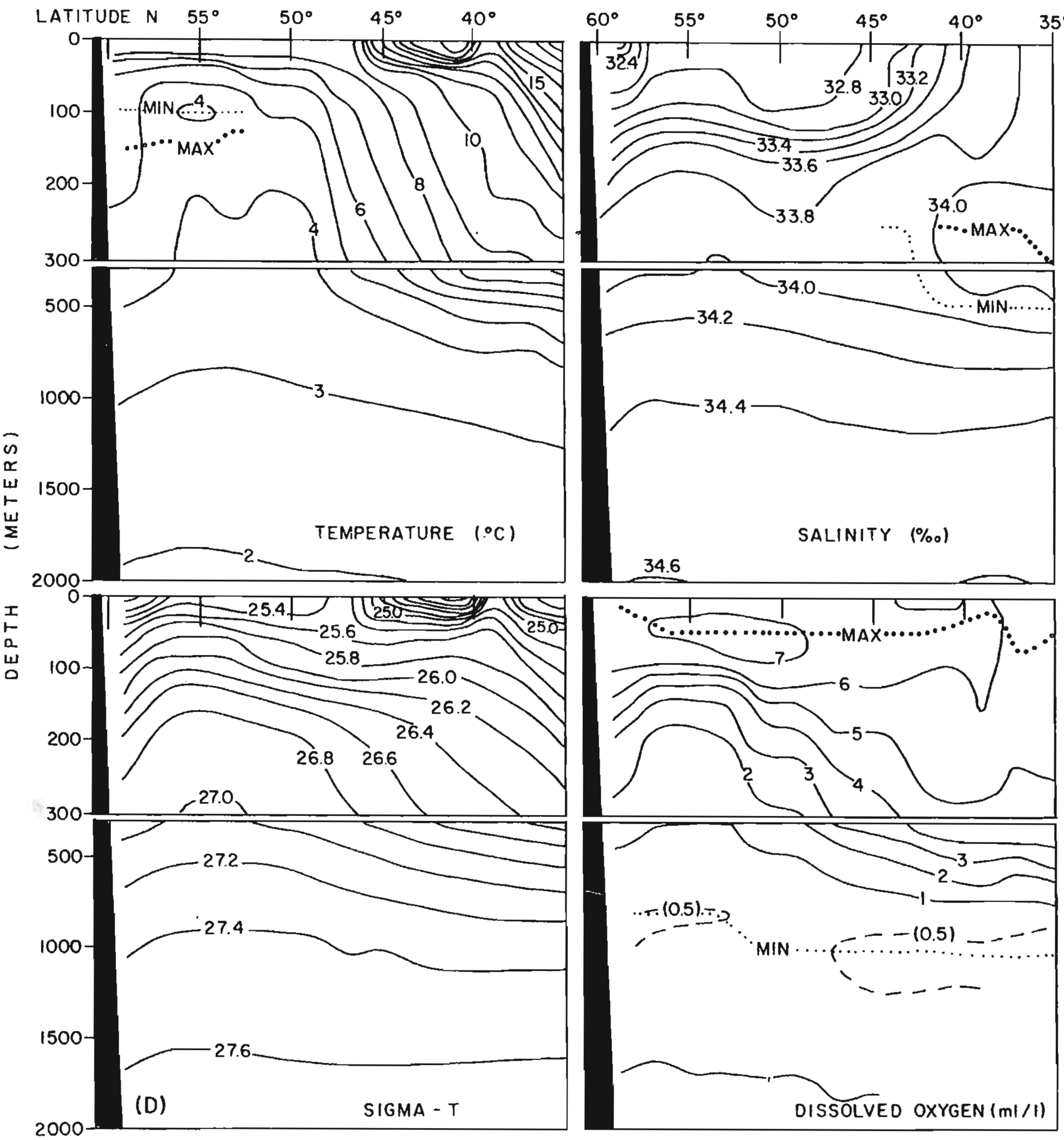


FIGURE 20. Continued.


LATITUDE N
55°
50°
45°
40°
60°
35°
DEPTH (METERS)
MIN
MAX
TEMPERATURE (°C)
SALINITY (‰)
(D)
SIGMA - T
DISSOLVED OXYGEN (ml/l)

of the Commander Islands. Along the continental margin of North America the divergence of eastward flow is evident by the reversal of shoreward slope of this surface, downward from the center of the Alaskan Gyre to the southeastern Alaska coast and downward from the California coast seaward; in the northern Gulf of Alaska, the narrow westward flowing Alaskan Stream is evident. The distributions of temperature and salinity show the continuity of the transpacific intrusion of cold (1–4°C), dilute (33.6–34.0‰) water extending from the Sea of Okhotsk to the Gulf of Alaska. A northward intrusion of warm (5–5.5°C), saline water (34.1–34.2‰) along the California coast, and extending well offshore is also evident.

B. Circulation

In the absence of direct current measurements in offshore areas, there is still only fragmentary information concerning oceanic circulation. Calculations of geostrophic currents are based on distributions of temperature and salinity and thus largely reflect flows evident in distributions of these properties in spite of dissimilar diffusion coefficients. Wind stress transports suggest a far greater variability in flow than evident in these currents, but the coupling between wind and water is not precisely known and the truth must be somewhere between.

1. *Geostrophic Currents*

Discussions of circulation are usually based on geostrophic calculations, which are at best an approximation, invalid near boundaries, and do not take into account the barotropic mode. Essentially, they represent flow based on a long-term adjustment of mass in the water column to long-term effects of variable wind-stress at the sea surface, thermohaline circulation, bottom stress, internal friction, and other factors; also, the zero reference level from which calculations are made is somewhat illusory and always subject to question. Such approximations may be reasonably valid in the central, sub-tropical ocean where these factors are not predominant; for

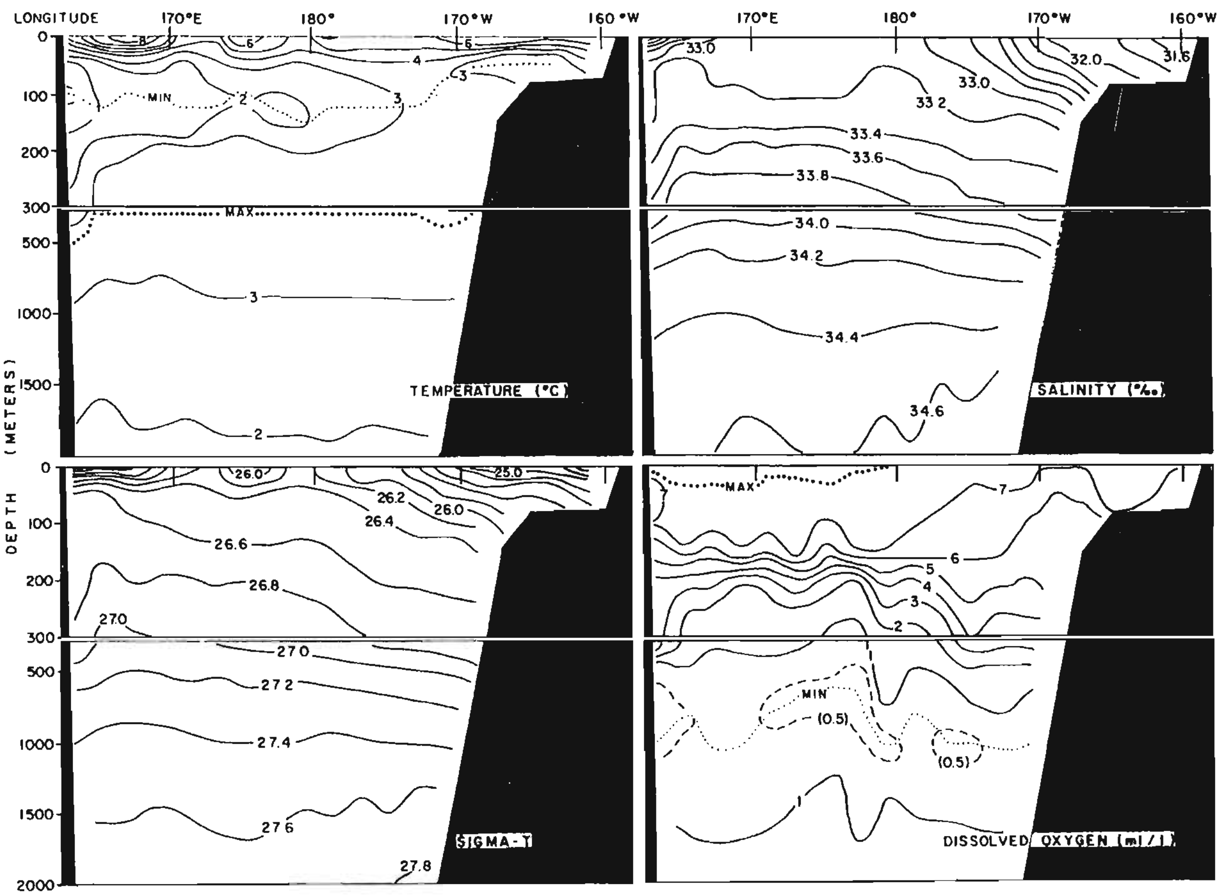


FIGURE 21. Vertical sections of long-term mean (2×2°) temperature, salinity, sigma-t, and dissolved oxygen along 57°N (Bering Sea).

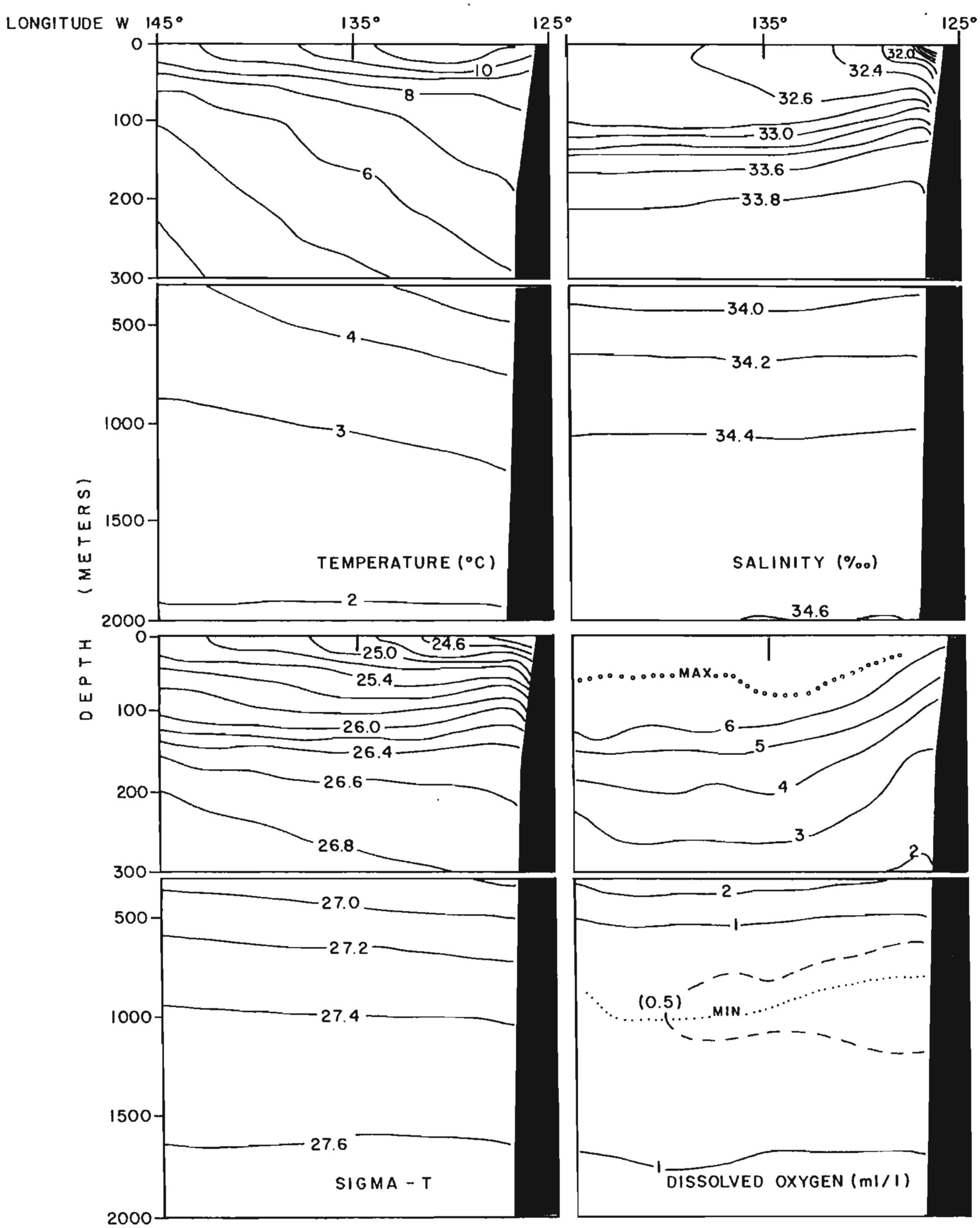


FIGURE 22. Vertical sections of long-term mean (2×2°) temperature, salinity, sigma-t, and dissolved oxygen along 49°N (east side).

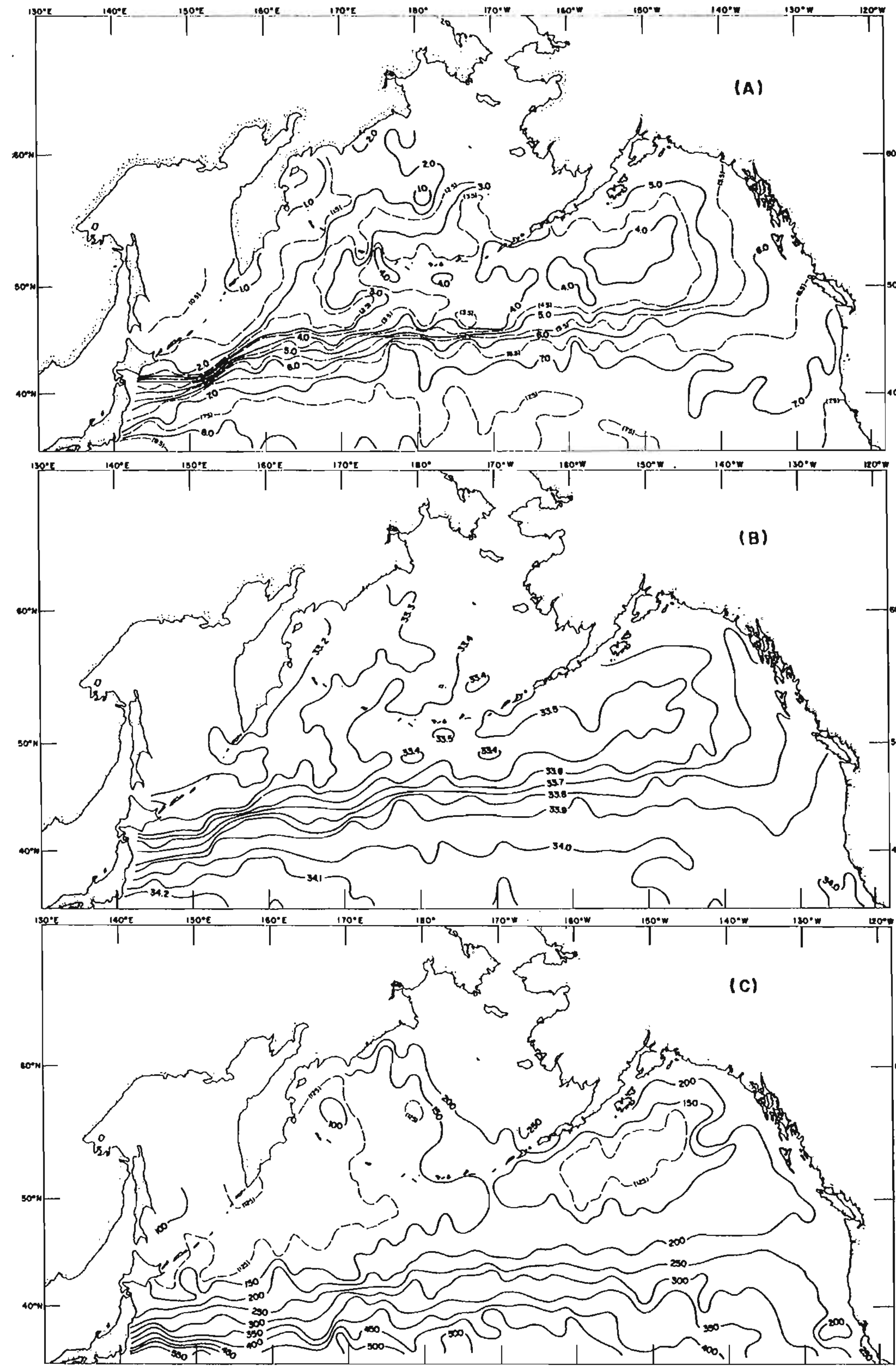


FIGURE 23. Long-term mean (A) temperature and (B) salinity distributions on sigma-t surface=26.6, and (C) depth of surface (2×2° quadrangles).

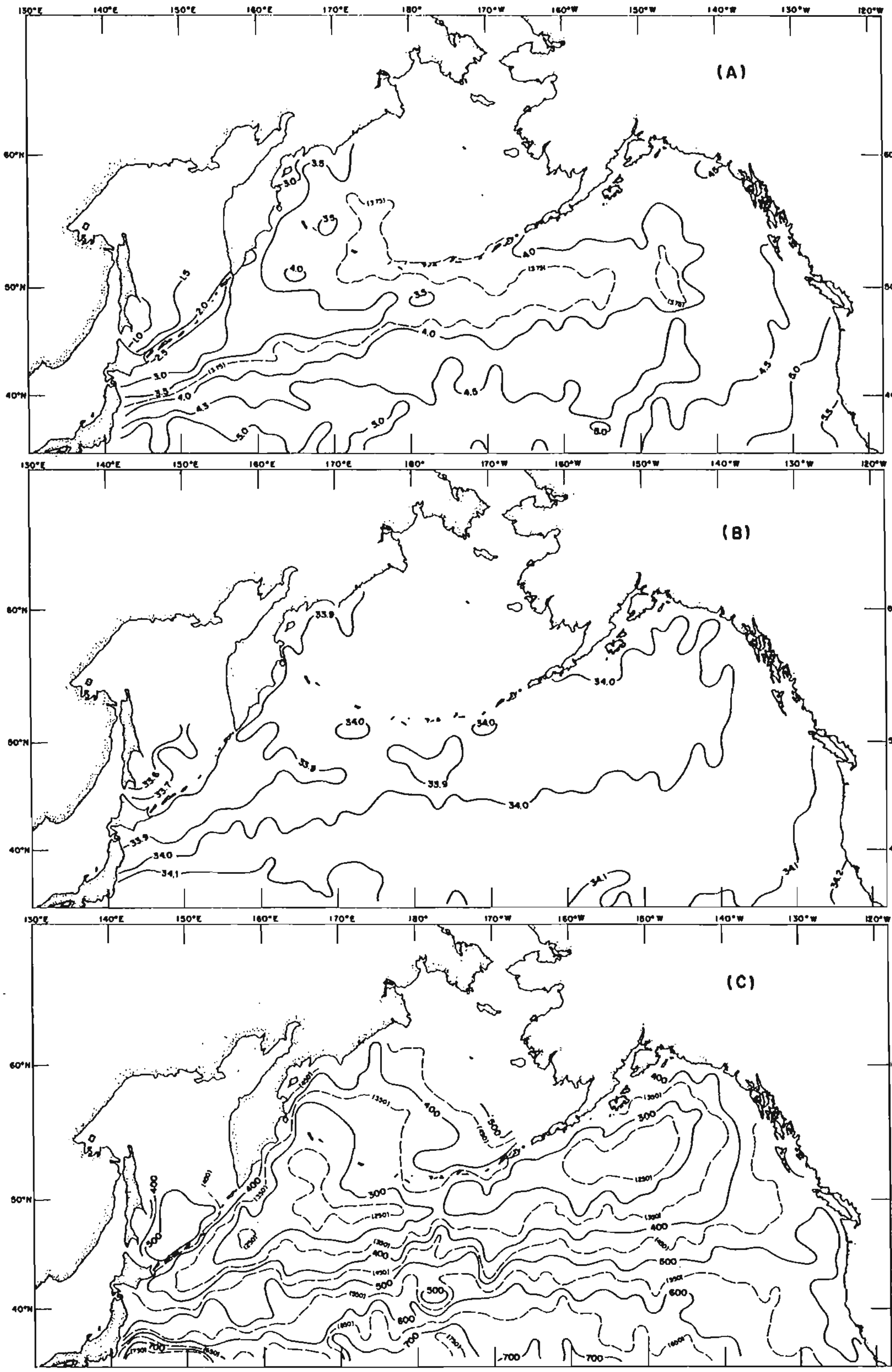


FIGURE 24. Long-term mean (A) temperature and (B) salinity distributions on sigma-t surface=27.0, and (C) depth of surface (2×2° quadrangles).

example, land boundaries are distant, the winds are relatively constant in direction and magnitude, and water temperatures and evaporation processes are also fairly constant. However, the Subarctic Pacific Region is divided by two extensive island arc systems and coastal flow is an important aspect of circulation ; winds in winter are in many cases from an opposite direction and of a much greater magnitude than those that occur in summer ; seasonal temperature changes are extreme ; and, evaporative processes change markedly. The point to be made is that an adjustment has been made in the distribution of mass throughout the water column over decades, perhaps centuries, and short-term changes do not alter it significantly. Seasonal changes in density, as a result of heating or cooling and dilution, occur only in the upper 100–300 m of the water column, and do not appreciably affect circulation patterns based upon the distribution of mass to depths of one or several kilometers used as a basis for calculations of geostrophic flow. Nor are the changes of sufficient duration to permit adjustment of the distribution of mass in the water column. In a similar way, winter intensification of winds associated with the Aleutian low pressure system results in changes in the slope of the sea surface and causes modifications to actual flow. These changes are not reflected in geostrophic calculations because the distribution of mass does not completely adjust to the new flow regime before the direction and magnitude of the wind stress is altered by summer wind conditions. Thus, although geostrophic currents must be viewed with caution when one is seeking actual flow, which is the case in most fisheries investigations, they are presented here as gross mean indices of flow.

In INPFC Bulletin 13, presentations of geostrophic currents were limited to actual observations made in summer or winter in individual years from 1955–59. Few observations extended below 1000 m and it was necessary to accept this depth as a reference level even though it was obvious that considerable variations in the distributions of temperature and salinity (implying flow) occurred at this level. Further, because of the variability in station locations the configurations of geopotential topography for individual years were unavoidably biased and continuity of flow over large areas was not apparent.

In order to show transregion continuity of flow, geopotential anomalies have been obtained from data at standard depths in the vertical array summaries for 2 × 2° quandrangles. Mean anomalies for the 0/500 m stratum were compiled for three time periods —monthly, quarterly, and annually, but no appreciable differences were evident. Data below 1000 m are still scarce and, although a reference level of 3000 or 4000 m would be more appropriate in much of the region, a reference level of 2000 m was selected. The 500/2000 m field (Fig. 25) was constructed and missing values linearly interpolated from existing data. In order to obtain the 0/2000 m geopotential topography for various time periods the 0/500 m values were added to the mean 500/2000 m values for corre-

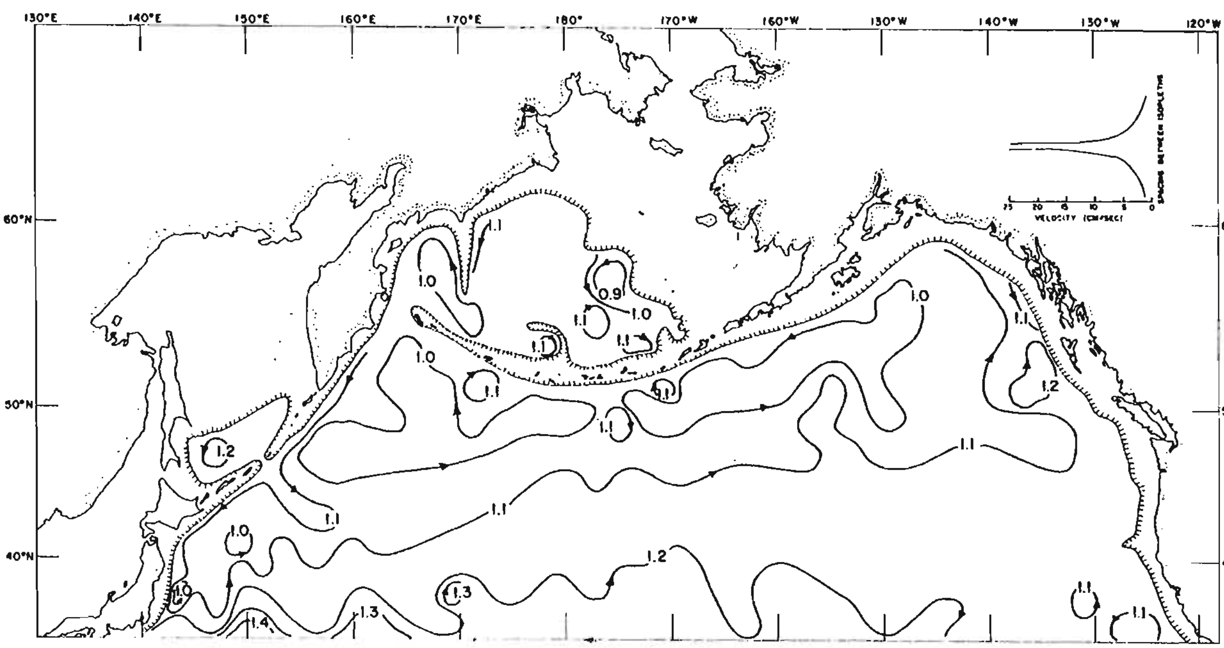


FIGURE 25. Long-term mean dynamic topography 500/2000 db, velocity scale computed for 50°N (2 × 2° quadrangles—see text).

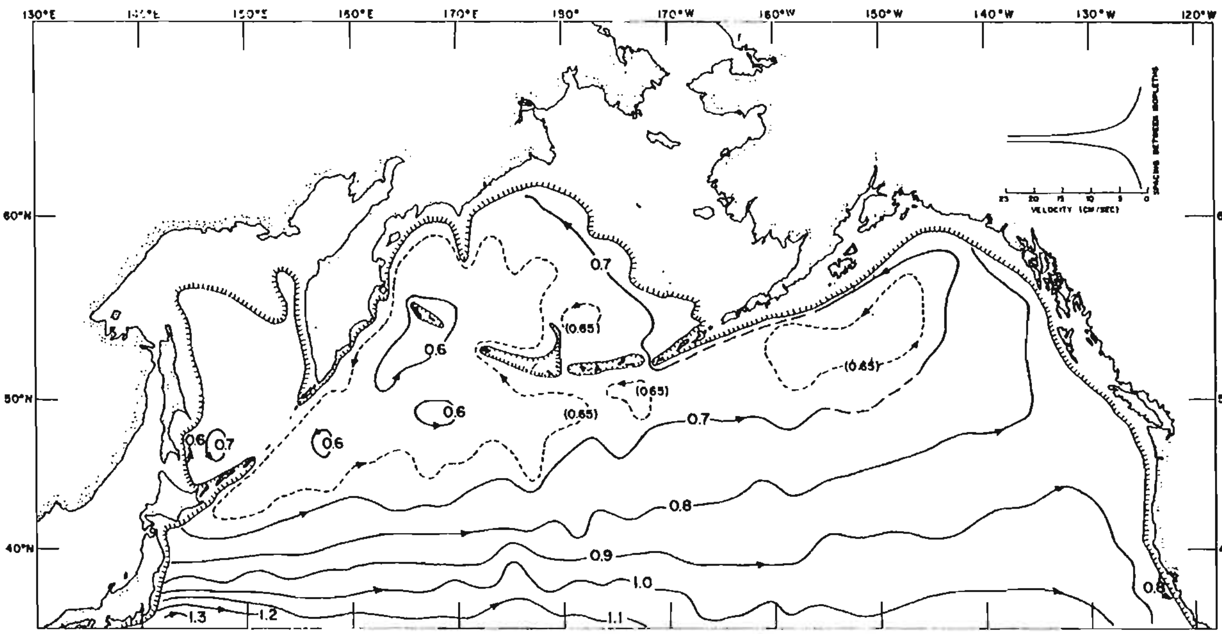


FIGURE 26. Long-term mean dynamic topography 0/500 db, velocity scale computed for 50°N (2 × 2° quadrangles).

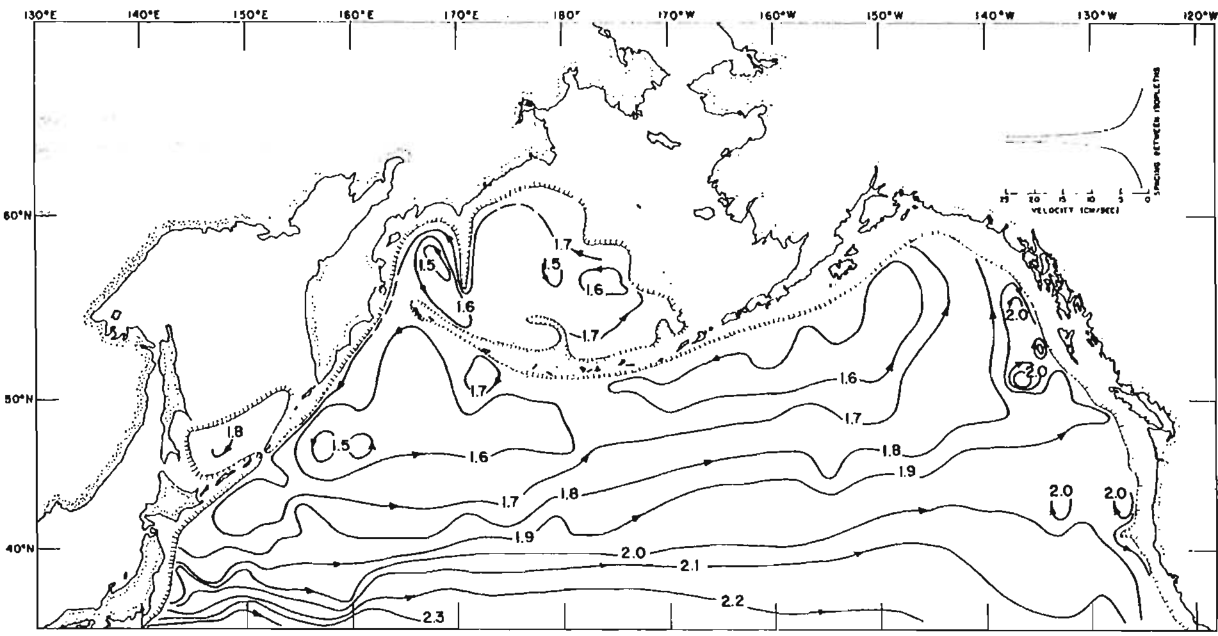


FIGURE 27. Long-term mean July dynamic topography 0/2000 db, velocity scale computed for 50°N (2 × 2° quadrangles—see text).

sponding quadrangles.

As pointed out earlier, the 2 × 2 grid does not permit obtaining precise continuity of flow near land boundaries, particularly in the vicinity of the Aleutian-Commander and Kuril Island Arcs, where even a 1 × 1 grid can extend over both sides of the arc; but gross circulation patterns are evident. The long-term mean composite of 0/500 m topography (Fig. 26) indicates the broad eastward flow between 34° and 45°N that diverges off the Washington coast. The cyclonic circulation in the Gulf of Alaska is evident and a gross cyclonic circulation occurs in the western part of the region, extending from Hokkaido to northern Bering Sea, with northward flow west of

Attu Island.

Similar features are evident in the mean geopotential topography 0/2000 m for July (Fig. 27). The Western Subarctic Gyre is well defined south of the Commander Islands and the cyclonic circulation in the western Bering Sea is well developed. There is a pronounced seaward flow west of Queen Charlotte Sound and the western extent of cyclonic flow in the Alaskan Gyre extends to 175°W. It is assumed that if a 1×1 grid was used that the 1.6 dyn m isoline would encompass both the Western Subarctic and Alaskan Gyres. Northwest flow into the Bering Sea is evident through the Aleutian Islands passes westward to Attu Island. The cyclonic circulation west of the Pribilof Islands, also present in the 0/500 m map, suggests this is a significant feature of the eastern Bering Sea. These general flows will be translated into specific current systems in a subsequent section.

2. *Wind-Stress Transports*

The direction and magnitude of major ocean currents are generally recognized as being directly related to wind stress over the sea surface. Although direct estimates of surface stress by winds are not available these can be obtained by computing geostrophic winds from the sea-level atmospheric pressure distributions. The method used to estimate surface stresses is similar to that used by Fofonoff (1960). Integrated total transports, meridional and zonal components of Ekman transports for the 10-year period 1960–69 and anomalies for the period 1960–72 have been calculated for a regular set of grid points (alternate points of a 5° rectangular grid in lat. and long.). It should be noted that transports computed by this method largely reflect tendencies of ocean circulation.

The Ekman transport is induced directly by the action of the surface wind stress. In the steady state, it is directed at right angles to the direction of the wind stress and is equal in magnitude to the stress divided by the Coriolis parameter. The Ekman transport is confined to the upper layers of the ocean and hence is an indication of the movement of " surface " waters. The significant features are the presence of an area of divergence in the Aleutian area during winter and an area of convergence in the southern part of the region in summer (Fig. 28). Monthly mean values (App. Fig. 7) indicate high transports in December, January, and February; the position of the divergence zone generally occurs between 50° and 55°N. In March, in the Gulf of Alaska, the area of divergence shifts northward, and, by May, a northward shift over the remainder of the area has occurred so that its position lies between 55° and 60°N across the region. In June, the extent of the area of divergence is limited to the Aleutian Islands area and its intensity is relatively insignificant. Absent in July and August, the area of divergence is again established in September, lying between 55° and 60°N, and remains in this position until December, when a southward shift to 50–55°N occurs. The fact that this feature exists for most of the year suggests that vertical transport should be considered as an important mechanism in this area. Fairly extensive convergent areas, opposing Ekman transports, are also noted, but these are confined to the southeastern parts of the region in July-September and to the southwestern part of the region in September-October. The seasonal variability in Ekman transport along the North American coast is well documented. Along the coast of California, offshore transport occurs through the year; it is a minimum from November to February, and reaches a maximum in June. Over the remainder of the area, there is a seasonal reversal of Ekman transport. Large onshore transports occur in December, January, and February with maximum transports in the Gulf of Alaska. In March, the onshore transport decreases, and is followed by a reversal in direction which first occurs off the Washington-Oregon coast. By June, the transport is offshore all along the coast, and its magnitude decreases northward. In September, onshore transport commences in the Gulf of Alaska and by October, it extends along the coast to California. Off the east coasts of Kamchatka Peninsula and Japan, a similar seasonal trend is observed. However, the onshore components are relatively small, except in December and January off the coast of Japan, and in December, January, and February off the coast of the Kamchatka Peninsula. These offshore components are also small compared to those found off the U.S. coast.

Integrated total transports provide an opportunity to look at flow throughout the entire region and possible sequences of events throughout a year. Of course, there are limitations in such data: the calculations are only valid in central parts of the ocean, the coupling of wind-stress and water transport is not precisely known, and conditions derived for specific time periods imply that equilibrium between stress and flow has been established. These shortcomings notwithstanding, ocean currents are largely wind driven and wind-stress transports provide indices of flow presently unattainable by any other method. The intensification and cyclonic nature of winds in the region during winter, associated with the atmospheric Aleutian low pressure system, are well known and result in an increase in water transport. Unfortunately, the effect of this wind intensification on ocean circulation is not known. Oceanographic sta-

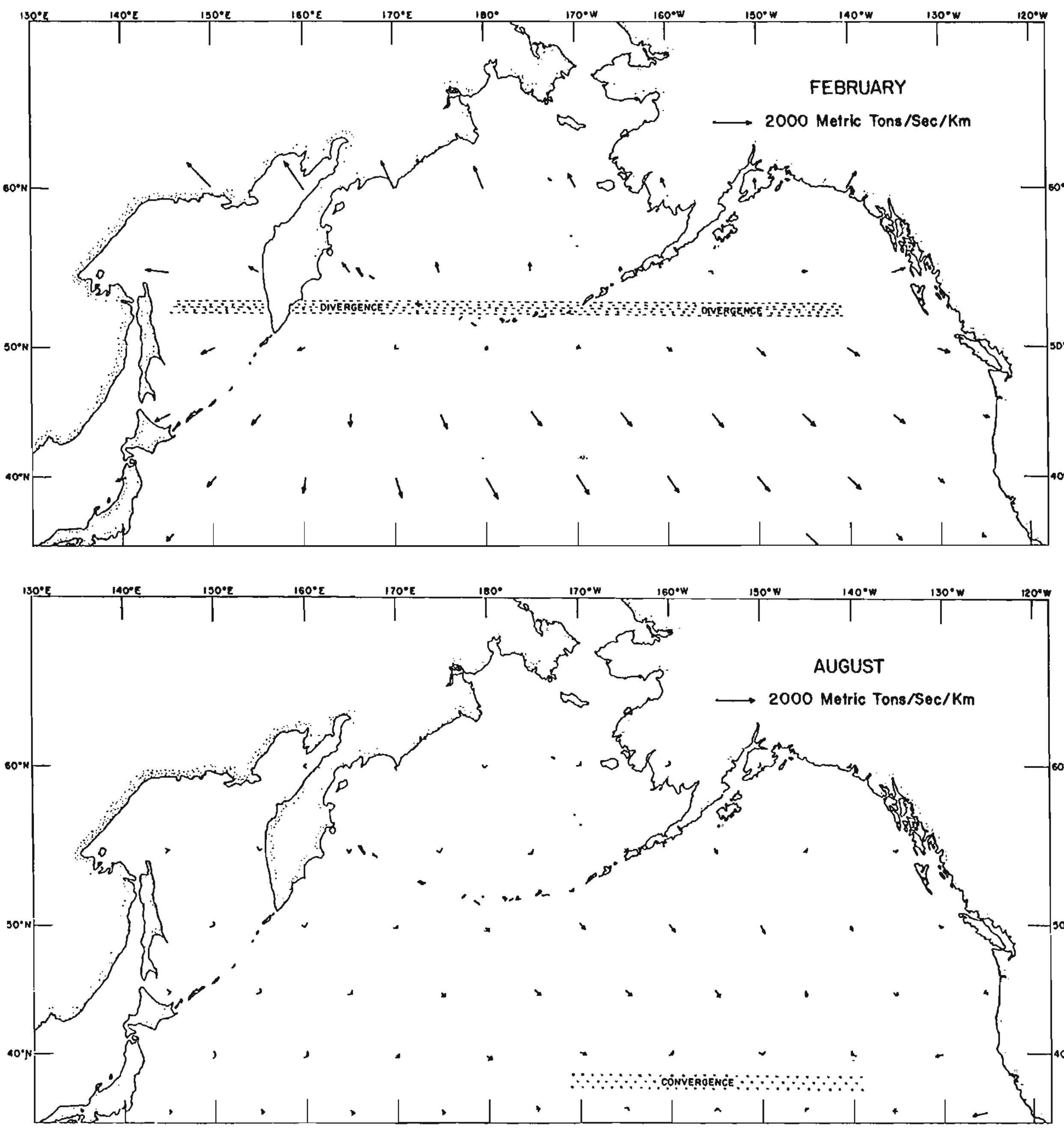


FIGURE 28. Long-term mean Ekman Transport during February and August.

tion data during the period intensification occurs, November to February, are not adequate to verify if comensurate increases in actual water transport occur. Even if the data existed the problem would not be resolved because, although the four-month period provides sufficient time to alter basic surface flow, it is not enough time to permit readjustments in the distribution of mass throughout the water column. Direct current measurements are required. Nevertheless, the method permits ascertaining meridional transport at grid points along a parallel of latitude and, commencing at the eastern boundary, continuity is satisfied across the ocean to the western boundary. The following conditions have been imposed: (1) northward transport in the Gulf of Alaska (north of 55°N) is constrained by the coast to flow westward along the Alaska Peninsula; (2) this flow is used to satisfy continuity requirements for transports east of 155°W between 50–55°N, and the remainder is confined south of the Aleutian Islands to 175°E where requirements for northward transport into the Bering Sea are also satisfied; (3) residual flow at 175°E is permitted to continue westward; (4) transport over the shallow eastern Bering Sea shelf and in the Sea of Okhotsk is ignored; and (5) northward transport in the Bering Sea is constrained by the coast to flow westward along the east coast of Kamchatka Peninsula. These are fairly realistic boundary conditions. Perhaps the three most obvious deviations from general conditions are that: no northward flow is permitted through the central Aleutian passes (mainly Amchitka Pass); no attempt has been made to terminate westward flow south of the Aleutian-Commander Island Arc at 170°E by requiring residual flow in this area to turn southward and contribute to eastward continuity requirements south of 50°N, and flows through Bering and Soya Straits (1 Sv) are ignored.

The data (App. Fig. 8) reflect several interesting conditions: winter intensification of flow, zonal divergence in winter at the Subarctic boundary, zonal divergence in summer north of the Transition Domain, marked northward displacement of maximum zonal flow in the western part of the region from winter to summer, and variations in intensity in flow in the Gulf of Alaska and in the Alaskan Stream. The latitudinal zone of horizontal divergence, where eastward flow is diminished by both northward and southward components of integrated total transports changes significantly. From December to March, this zone occurs at 35–40°N at the western side of the ocean; near 180°, it trends northeastward, reaching 45–50°N at the eastern side and remains at this latitude (except during some summer months when reduced flows cause some variations in this pattern) until November. This indicates a great reduction of the area having northward components of flow during summer in the western and central parts of the region. The confined, shallow nature of the Sea of Okhotsk invalidates concepts involved in the computations of wind-stress transports, but transport data might be informative if it were not for variable ice conditions. The wind field between the east Asian high and the Aleutian low pressure systems reflects an appreciable northward transport, 15–20 Sv, that would result in a strong, southerly flowing, boundary current along the east coast of Sakhalin Island. However, assuming that any contribution to flow in this area from river runoff on the Soya Current is small in comparison to total southerly flow seaward of the Kuril Islands, flow into the Sea of Okhotsk is equivalent to flow out and does not appreciably alter the net north-south flow seaward of the Kuril Islands. Previous discussions of fragmentary data on geostrophic currents and distributions of water properties have indicated the Subarctic Current is composed of three components, a southward flow along the east coast of the Kamchatka Peninsula and northern Kuril Islands, an eastward flow out of the Sea of Okhotsk, and an offshore northward flow east of Honshu and Hokkaido. Wind-stress transports provide some indices of the intensities of various flows in this area. Maximum southward flow along the east side of the Kuril Islands, 30–40 Sv, occurs in December, January, and February. Although continuity requirements of eastward flow in the 5° latitudinal bands 45–50°N and 40–45°N diminishes this flow, it extends southward to Honshu where a maximum eastward transport of approximately 25 Sv occurs. The residual southward flow is not sufficient to satisfy this eastward transport and a northward flow of approximately 10 Sv is required; thus, a strong convergence of southward and northward flows occurs off Honshu. It is during this period that temperatures in the surface layer of the southward flow are at a minimum, actually only a few degrees above the ice point, and density differences in the water columns of the converging flows result in vigorous mixing in this area. The southward flow diminishes in March to about 20 Sv and, although the dominant eastward transport still occurs at 30–40°N, this must be satisfied entirely by northward flow along Honshu and the convergence zone of north-south flow shifts northward to 40–45°N. From April to November, southward flow diminished to a minimum (6 Sv) in August and progressively increases to maximum winter values; but, throughout this period, the convergence zone and maximum eastward transport occur at 45–50°N, adjacent to the central Kuril Islands.

This annual cycle suggests the following seasonal conditions: in winter, (1) ice cover in the Sea of Okhotsk reduces wind-driven circulation in that area and therefore discharge of Okhotsk water through Kuril Islands passes, (2) a maximum southward transport along the east side of the Kuril Islands establishes the Oyashio Current off the east coast of Hokkaido and Honshu, (3) increased southward flow impinges on the Kuroshio Current System resulting in a turbulent regime that is the genesis of the Transition Domain, and (4) maximum eastward transport occurs in the area of the Transition Domain. In spring: (1) flow along the Kuril Islands is greatly diminished, (2) the convergence zone shifts northward, and (3) increased northward wind-stress transport in the Sea of Okhotsk derived from the East

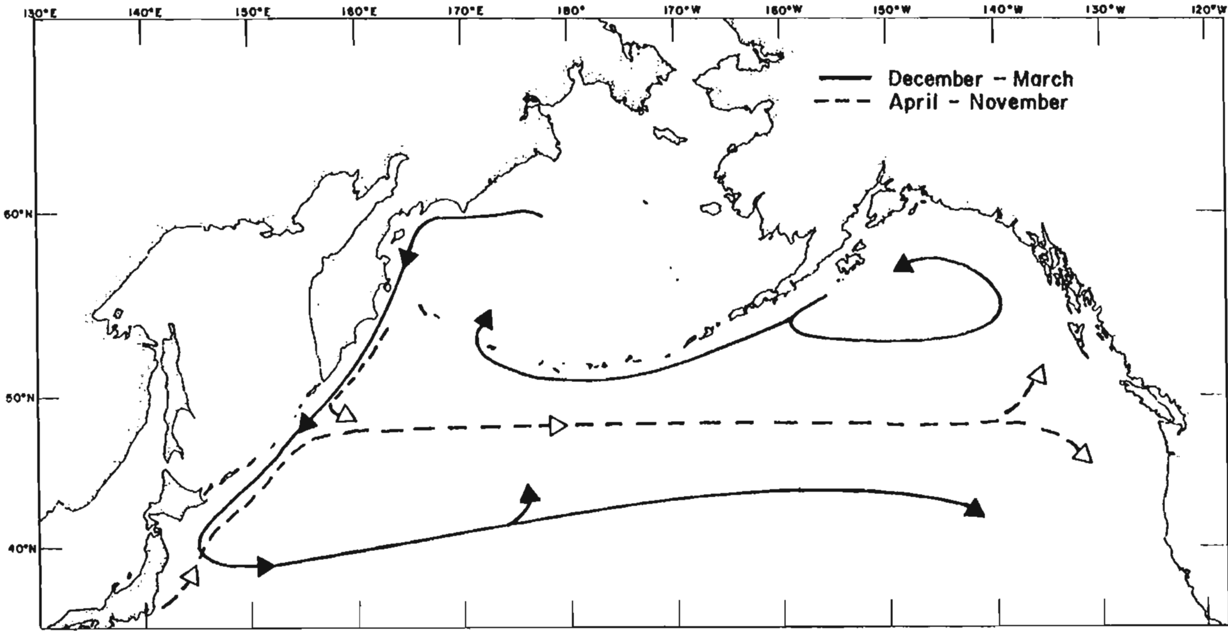


FIGURE 29. Schematic diagram of integrated total wind-stress transport during winter and summer.

Kamchatka Current, results in a reduction of southward flow in the boundary current along the central Kuril Islands and increases the discharge of the Okhotsk-Kuril Current System eastward through the southern Kuril Islands passes. All of the above facilitate an eastward penetration of Okhotsk water into the central North Pacific Ocean. This implies an intensification in the Subarctic Current System that is out of phase, of longer duration, and lacks the strength of the high eastward transport evident at 35–40°N during winter in the Transition Domain.

Although northward transport in the Gulf of Alaska originates south of 50°N in all months, the dominant flow is across 55°N and this requirement is satisfied by recirculating part of the westward flow along the Alaska Peninsula at 155°W. Maximum westward flow along the Alaska Peninsula, 24 Sv, occurs during December and January. Residual westward flow moves westward along the Aleutian Islands and is reinforced by northward components across 50°N, resulting in maximum transports of 15–30 Sv from September to February and minimum transports of 5 Sv in July and August at 175°E.

The large grid size and paucity of data in the Bering Sea indicate that, except for the obvious indication of winter intensification of flow, transports in this area are not considered necessarily representative; however, total wind-stress transport into (and thus out of) the area substantially agrees with observed geostrophic transport. This description of flow indices (summarized in Fig. 29) suggests that our previous interpretations of ocean currents, based on fragmentary station data, may not be as representative of actual conditions as one might have believed. Nevertheless, the year to year changes in water properties from place to place ascertained by field investigations, are real and provide much of the basis for this study, as well as permitting formulations of hypotheses concerning relations between the ocean environment and salmon distributions. However, it is only through considerably more knowledge of actual flow conditions that accurate relations will be ascertained. Further, it should be noted that the above transports are based on mean data and considerable variations occur in individual years.

3. *Numerical Models*

The near impossibility of obtaining adequate synoptic data at sea and the complexity of short- and long-term changes in the distributions of water properties have prompted a number of attempts by various investigators to model ocean conditions (for example, Bryan, 1962, 1969a, b; Bryan and Cox, 1968a, b; O'Brien, 1971; Larson and Laevastu, 1972, and numerous others). There are various types of models and various methods are associated with each scheme. Of particular interest is the barotropic numerical model devised by Galt (1973) for use in the Arctic Ocean. This model, conditionally stable and having second order accuracy in space

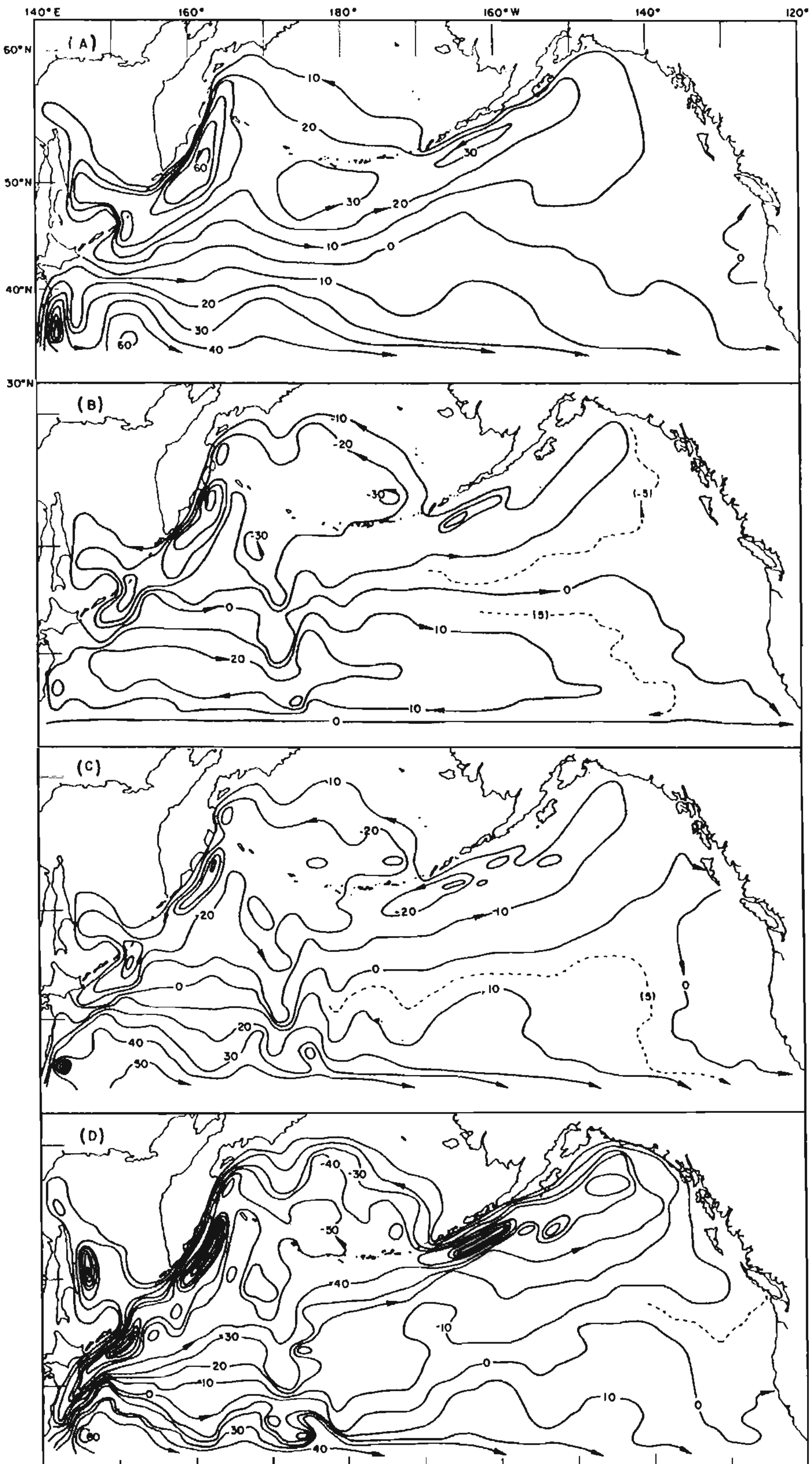


FIGURE 30. Transport (Sv) obtained by numerical model; (A) mean wind stress, Kuroshio 50 Sv., (B) mean wind stress, depth factor 0.1; (C) mean wind stress, Kuroshio 50 Sv, depth factor 0.1; and (D) January wind stress, Kuroshio 50 Sv, depth factor 0.1 (see text).

and time, is formulated to include irregular basin shape, variable bathymetry, lateral and bottom friction, and nonlinear terms; in addition, source-sink distributions can be applied around the perimeter of the basin. The bathymetry is represented as a mean depth and a percentage deviation from the mean, which provides qualitative effects of weak stratification and depth variability. This model is being applied to the region and initial efforts employ a 2° lat. grid (222.4 km), but depending on computer size and budgetary considerations any grid size can be used; these studies have only recently been instigated at the Northwest Fisheries Center and the purpose of introducing the model is to indicate the future potential of numerical models in aiding studies of the region. Different combinations of source-sink wind-stress and depth factors are used in the four maps presented (Fig. 30), which reflect conditions after a 30 day spin-up.

In the first case, mean annual wind stress is applied at the sea surface and a source of 50 Sv is input at the southwestern corner and removed linearly as a sink along the southern boundary between 160°E and the North American coast. The resulting transport isolines reflect the generally accepted basic large-scale cyclonic flow pattern around the region. East of Honshu an intense eddy develops and seaward of this eddy a pronounced northward intrusion of flow occurs. East of 160°E isolines trend zonally eastward to 180° where the flow diverges and circulation around the Alaskan Gyre is evident. Obviously with such a coarse grid, features in the Aleutian area cannot be expected to show any detail, but eddies develop at critical locations, south of the eastern and western Aleutian Islands. An intense cyclonic eddy develops east of Kamchatka Peninsula that extends southwestward along the Kuril Islands and into the Sea of Okhotsk.

When no source-sink is applied (no transport across the southern boundary) and mean wind stress is applied to a case using an irregular bathymetry determined by depth of factor of 0.1, similar patterns, particularly the locations of eddies, are evident. Because of the limited spin-up time, reduced transports occur. The most striking feature is the deviation in zonal flow caused by the southward deflection near 170°E of isolines which reflect the influence of the Emperor Seamount chain, whose peaks reach to within 1000 m of the surface. This, and the bathymetric effects of the Kuril trench, give rise to a pronounced northward component of flow along 165°E that is not evident in the mean distributions of water properties. When the 50 Sv transport is again added to the above conditions major changes occur only along the southern boundary and in the divergence off the coast of North America.

Maximum monthly mean wind stress occurs during winter, and when the mean wind stress for January is substituted for the annual mean wind stress under the above conditions, it is obvious that the gross features remain. However, transport in the eddies is greatly intensified, and there is an interesting southeastward expansion of flow in the area of the Alaskan Gyre.

Obviously, such a numerical model when expanded and tuned can provide not only numerous new advances in our knowledge of conditions and processes in the region, but a rational basis for future field studies.

C. Heat Budget

Although incident energy is primarily a function of latitude and cloud cover, ocean circulation has a dominant effect on energy exchange at the air-sea interface. The transfer of energy at the air-sea interface in the form of heat exchange influences not only the temperature but also the salinity of the water. Neglecting advection, and employing a simple heat budget equation, energy exchange (Q_T) is obtained by assessing net heat gains and losses. Incoming radiation is corrected for cloud cover to obtain incident energy from the sun and sky (Q_I) and, through knowledge of air and sea temperatures, dew point, and winds, the effects of back radiation (Q_B), evaporation (Q_E) and conduction (Q_H) are obtained. Thus, a brief expression of the net energy exchange is:

$$Q_T = Q_I - Q_B - Q_E + Q_H$$

Numerous calculations of the various heat budget components have been compiled by various authors (Hanzawa, 1962; Laevastu, 1963a, b, c, 1964, 1965; Wyrtki, 1965a, 1966; Wyrtki and Haberland, 1968; Hishida and Nishiyama, 1969; Bathen, 1970a, b; and others).

1. *Cloud Cover*

Monthly mean cloud cover in eighths for the period 1948–67 (Fig. 31) indicates a zonal trend to the isopleths (no data were available for the Sea of Okhotsk and Bering Sea). North of the Subarctic Boundary, cloud cover is in excess of 75% (6/8) year round. A general annual pattern is evident, with cloud cover increasing in spring, reaching a maximum in July, and decreasing throughout summer and fall. Of particular interest is the marked deviation from the general zonal trend of isolines off the west coast of California. Cloud cover of less than 5/8 occurs along the coast in all months, except for July and

FIGURE 31. Monthly mean cloud cover (in eighths) 1948–67 (5×5° quadrangles).

August, and a nearly meridional band from 120–140°W of maximum cloud cover occurs between the coast and the Hawaiian Islands. The cloud cover in this band follows the same seasonal pattern, reaching a maximum in July.

2. *Energy Exchange*

Energy exchange at the sea surface has been computed (using ship of opportunity data for 1948–67) following the technique used by Johnson *et al.* (1965). The effects of back radiation and conduction are relatively minor compared to that of evaporation, which varies seasonally and reached a maximum in winter as cold, dry, air blowing off the Asian continent encounters the warm oceanic flow sweeping northward along the Asian coast. As a result marked energy exchanges occur in the vicinity of the Kuroshio-Oyashio confluence. Monthly mean values of energy exchange (cal/cm²/day) by 5 × 5° quadrangles (App. Fig. 9) permit an easy assessment of transregion conditions. Maximum energy losses (>600 cal/cm²/day) occur to the west of Honshu in December and to the east of Honshu, but well offshore, in January. An eastward gradient of about 100 cal/cm²/day/10° of longitude extends to near 170°W during the months of December, January, and February. Although local exchange values vary from near 0–200 cal/cm²/day from April to September the eastward gradient is not present. Nevertheless as indicated earlier (see Fig. 4) during most of this period maximum heat gains occur at this time north of the Philippine Islands.

Of particular interest is the dominant, nearly transpacific, zonal (45–50°N) band of not only minimum heat losses in winter but maximum heat gains in spring. This anomalous condition is primarily due to a marked reduction in evaporation (Q_E) and, not only are heat losses markedly reduced because of smaller differences in temperatures of water and air, but the reduced loss of fresh water from the surface helps to maintain the lower salinity values in this area already indicated in Fig. 10.

In regard to other specific local areas, maximum heat loss occurs in the eastern Bering Sea in February (>400 cal/cm²/day) and maximum heat gain in June (>200 cal/cm²/day). Along the east coast of the Kamchatka Peninsula and the Kuril Islands, maximum heat losses (>300 cal/cm²/day) occur in January and maximum heat gains (>200 cal/cm²/day) occur in a band approximately 500 km wide from Hokkaido to the Commander Islands during May-July. Values in the Gulf of Alaska follow a seasonal progression of maximum losses in January (>300 cal/cm²/day) to maximum gains (~200 cal/cm²/day) in June and July; whereas, off the California coast maximum losses (>200 cal/cm²/day) occur in June.

IV. NEW DOMAIN AND CURRENT SYSTEM TERMINOLOGY

In INPFC Bulletin 13 upper and lower zones were divided into areas having common characteristics and denoted as domains. The term domain is used in the same sense but, in addition, current systems will be identified where continuity of water properties and flow are apparent. This does not imply that the concept of water masses being associated with distinct vertical strata is not valid; a distinct surface layer exists and is a dominant characteristic of the region, but in most instances horizontal flow is continuous throughout these strata. In this section previous definitions of domains are revised, and major current systems and related water masses are identified using temperature-salinity (T-S) relations.

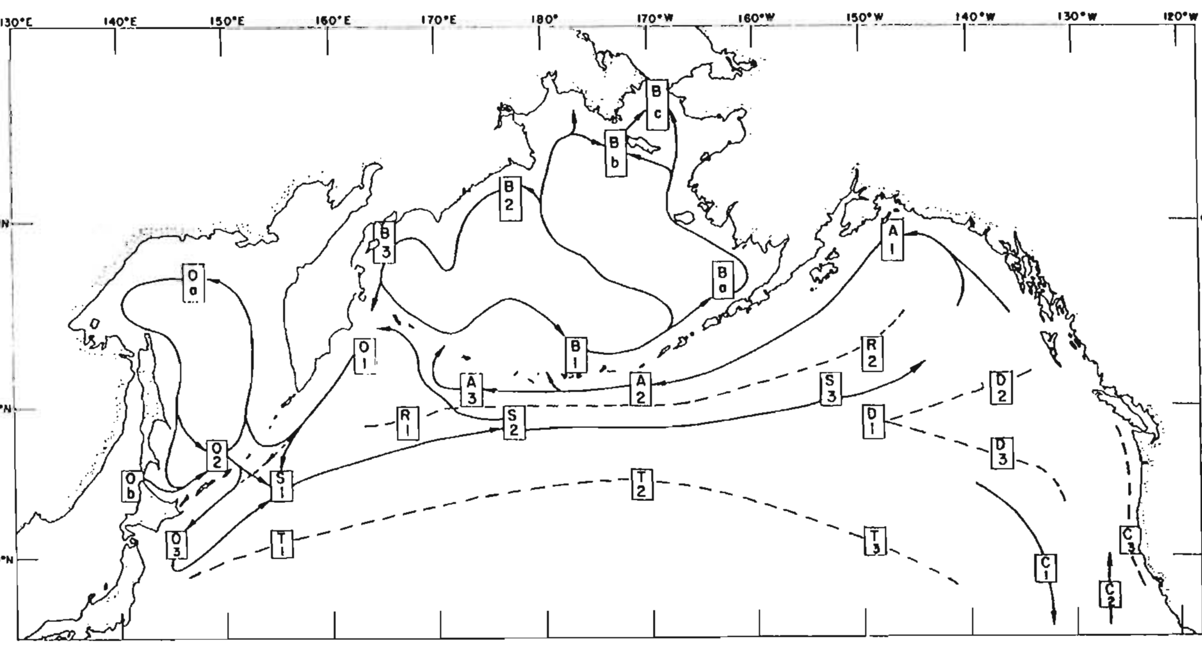


FIGURE 32. Locations of 2 × 2° quadrangles selected to show the range of temperature and salinity (T-S) relations in various domains and current systems.

Data from the vertical array summaries have been used to compile T-S curves indicative of periods of maximum cooling and heating at selected locations in domains and along axes of major current systems (Fig. 32). In general, these conditions occur in February and September but, in some cases, such as in northern Bering Sea where maximum surface temperatures occur earlier in summer, data for other months have been selected. There are a few instances where data for the above months are not available in a desired location. In this case, either a less desirable quadrangle or alternative month has been selected. Further, it should be pointed out that in coastal areas, maximum dilution usually occurs in late spring and data for this time period are not presented. Finally, two types of T-S presentations are provided: text figures show mean winter and summer relations at standard depths, and ranges of temperature and salinity values from which the mean data were derived are presented in the Appendix (App. Fig. 11).

Water masses by definition have distinguishing temperature, salinity, depth relationships unique to a specific source area, and the extent of an individual water mass is determined by the distance an identifiable integrity can be maintained. This technique is useful in distinguishing basic characteristics of large segments of the oceans. The general characteristics of the Subarctic Pacific Water Mass, although long recognized, have at times been misinterpreted. Low temperatures (3–5°C) and low salinities (32–33‰) in the upper 300 m of the water column are the natural result of local subarctic conditions, but water properties below this depth (except off the Sea of Okhotsk), associated with salinities greater than approximately 34.2‰, are largely the result of conditions and processes in southern latitudes. However, the vertical movement of this water is so slow that local changes in temperature and salinity are still dominant in the upper 300 m.

Because the region has a relatively closed circulation, various current systems essentially merge at numerous locations and identifying features are not always associated with large changes in water properties. Further, because winter turnover results in complete mixing to depths of 100 m or more, distinguishing features are less apparent near the surface, except perhaps in local areas where river runoff is significant. Sea surface temperature is the most variable characteristic of the region and in addition to general seasonal cycles marked differences occur between areas subject to ice cover during winter (the northern and western parts) and in areas where warm intrusions occur (the southern and eastern parts); however, salinity, particularly in the upper layer, is perhaps the most distinguishing characteristic.

A. Domains

Earlier discussions of surface regimes and geostrophic current clearly indicate the distinct differences in conditions in the western and eastern parts of the region that in conjunction with circulation patterns and subsurface conditions formed the basis for

Table 8. Volume discharge of eastern Subarctic Pacific river systems.

River	Station site	No. years data[1]	Approximate time period	Average discharge (m^3/s)
1. Yukon	Kaltag	8	1957-64	6,210
2. Columbia	Dalles	86	1879-64	5,520
3. Fraser	Hope	52	1913-64	2,710
4. Kuskokwim	Crooked Creek	13	1952 64	1,280
5. Copper	Chitina	9	1956-64	1,040
6. Skeena	Usk	16	(1929-55)	920
7. Nass	Aiyansh	11	(1930-64)	830
8. Bristol Bay	[2]	9	(1953-71)	820
9. Puget Sound	[3]	33	1939-72	710
10. Sacramento	Sacramento	16	1949-64	650
11. Anadyr	Navy Eropol	12	1958-69	510
12. Klamath	Klamath	30	(1911-64)	490
13. Stikine	Telegraph Creek	2	1966 67	390
14. Umpqua	Elkton	59	1906-64	210
15. Eel	Scotia	54	1911-64	200

[1] All data based on available UNESCO and U.S. Geological Survey tabulations.

[2] Kvichak River, Igivgig; Nushagak River, Dillingham (Nuyakuk River); Wood River, Aleknagik.

[3] Deschutes River, Rainier; Duckabush River, Brinnon; Green River, Tukwila; Nisqually River, McKenna; Puyallup River, Puyallup; Skagit River, Marblemount; Skokomish River, Hoodsport and Union; Snohomish River, Monroe.

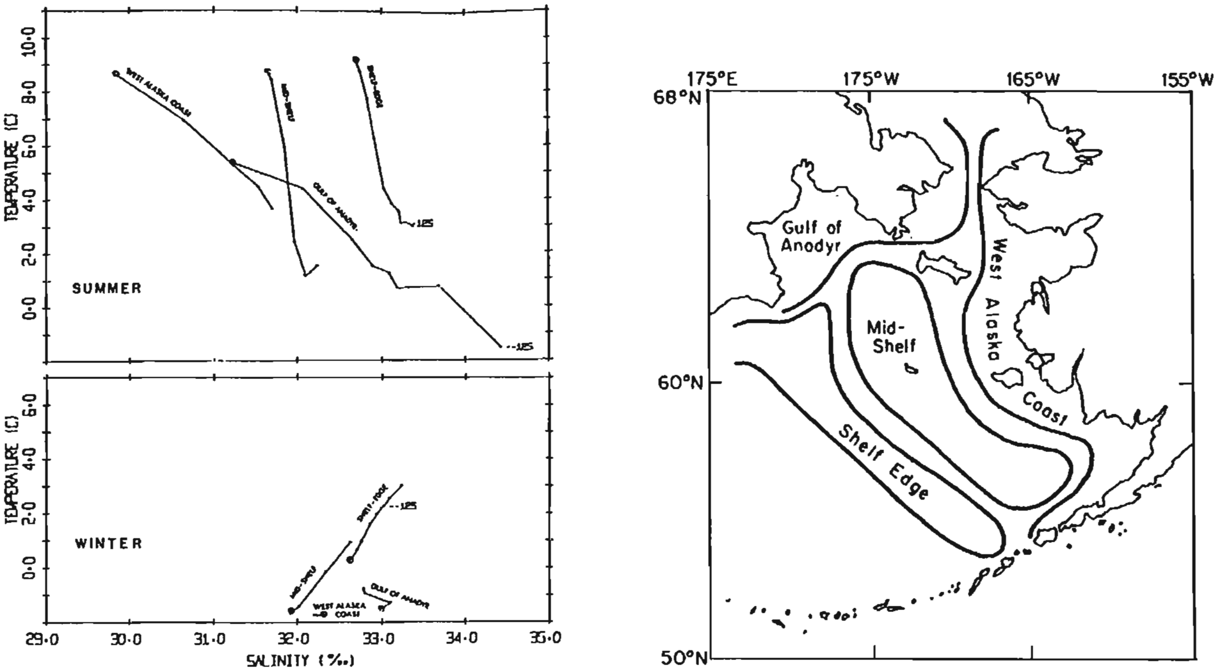


FIGURE 33. Eastern Bering Sea environments and associated T-S relations in the Coastal Domain (1 × 1° quadrangles).

defining the Western and Central Subarctic Domains. However, the terminology of these and other domains presented in INPFC Bulletin 13 have been modified as follows: The Coastal, Transition (previously referred to as Transitional) and California Undercurrent Domains have been retained and, except for the Coastal Domain, more clearly defined. The Western Subarctic, Central Subarctic, and Alaskan Stream Domains have been divided into the Okhotsk-Kuril, Bering Sea, Subarctic, and Alaska Current Systems. Three new domains have been added: the Dilute Domain off the west coast of North America; the Ridge Domain, which separates the Subarctic and Alaska Current Systems and is associated with both the Western Subarctic and Alaskan Gyres; and the Upwelling Domain, which occurs immediately off the west coast of North America from California to Vancouver Island.

1. *Coastal Domain*

Delineation of a Coastal Domain in areas having little river runoff, minor coastline irregularities, and a narrow continental shelf poses few problems, but such conditions are rare in the region. River discharge is high (Table 8) and seasonal. Mean discharge in June of the Yukon River is 20 times that in March and mean discharge in June of the Columbia River is 5 times that in January. During periods of high discharge, river plumes extend far out into oceanic regimes. Coastal embayments such as Puget Sound, Queen Charlotte Sound, Prince William Sound, Cook Inlet, and others, perhaps even the entire broad eastern Bering Sea shelf, possibly should be denoted as sub-coastal domains, (Fig. 33) but such considerations are beyond the scope of this report. Nevertheless, the concept of a Coastal Domain, where oceanographic conditions and features vary markedly from one area to another because of local variations in runoff, heat exchange, winds, tides, etc., remains unchanged. It was impossible to present complete descriptions of various Coastal Domains in INPFC Bulletin 13, but descriptions of local areas of interest, the west coast of Vancouver Island and Bristol Bay, were included in the Appendix. In the intervening years no extensive investigations of coastal areas have been conducted except off the mouth of the Columbia River, off Vancouver Island, in Bristol Bay, and along the east coasts of Honshu and Hokkaido. These investigations have been summarized in a previous section and additional information has been incorporated in the section on Current Systems. Conditions in the Coastal Domain are of great significance to living marine resources and existing knowledge should be summarized and future research proposed. However, the purpose of this report is to summarize research in the oceanic environment where INPFC research has been concentrated, and discussions will be limited largely to offshore areas.

2. *Transition Domain*

This domain, which lies just northward of the Subarctic Boundary, is retained, but the term West Wind Drift has been dropped. Transpacific zonal flow, which expands in meridional extent from west to east and veers southward off the North American coast, is characterized by marked meridional gradients of temperature and salinity and, at times, by interleafings of cold, dilute water at the northern edge, and warm, saline water at the southern edge. However, its northern boundary in the western and central part of the region is clearly delineated by cold water (<4°C) below 100 m depth characteristic of the Subarctic Current; in the eastern part of the region, the northern boundary of this domain is limited by the Dilute Domain, discussed later. The entire southern boundary of the Transition Domain is denoted by the vertical 34‰ isohaline which constitutes the Subarctic Boundary. Maps of quarterly mean surface salinity (see App. Fig. 1) show that the location of the 34‰ isohaline is remarkably constant (Fig. 34). The general configuration of this isohaline at the surface corresponds closely with the location of the long-term mean 34‰ isohaline at 100 m. This gives considerable credibility to this mid-ocean environmental boundary as a recognizable, quasi-permanent feature.

Although the meridional extent of this domain is easily delineated below 100 m depth, its extent above 100 m can only be ascertained at the southern boundary; the point being that this particular salinity is not necessarily a specific, critical environment threshold but, because of the nature of flow conditions in this area, the surface isohalines have a vertical trend and a meridional gradient at the surface that permits easy identification of this boundary. At the northern edge, where the surface isohaline of 33.0‰ is generally located, isohalines have a horizontal trend and the meridional extent of a specific surface isohaline may change by 200 km merely as a result of mixing and stirring processes at the sea surface. Thus, at the surface, the boundary between water in this domain and the Subarctic Current System to the north is difficult to ascertain by distributions of temperature or salinity but, in the future, other parameters such as CO_2 may permit distinguishing this boundary. The inference is that water in the Subarctic Current System has recently swept along the shores of the western part of the region, attaining specific chemical characteristics (e.g. odors, micro-constituents), and is advected seaward largely unmodified; thus, it could furnish indicators of specific coastal environments in midocean areas, whereas water in the Transition Domain is greatly modified by admixture of water in the Kuroshio Current which is entirely of subtropical origin and has different, although perhaps subtle, chemical characteristics.

Mean T-S relations at 3 selective locations (T1, T2, and T3—see Fig. 32) during February and July/August (Fig. 35) indicate rather uniform conditions at the surface in both western and eastern parts of the domain in summer (19–21°C, 33.6–33.7‰) but colder and more saline conditions on the western side during winter (7.5 vs. 10°C and 34.0 vs. 33.5‰). Conditions in the central part of the region are colder and more dilute than either of these two areas in both summer and winter (13.5°C, 33.1‰ and 4.5°C, 33.3‰, respectively). This domain is considered to extend down to about 300 m, and conditions below 500 m are typical of a large part of the region (see App. Fig. 11 for ranges of temperature and salinity at standard depth levels for this and all subsequent domains).

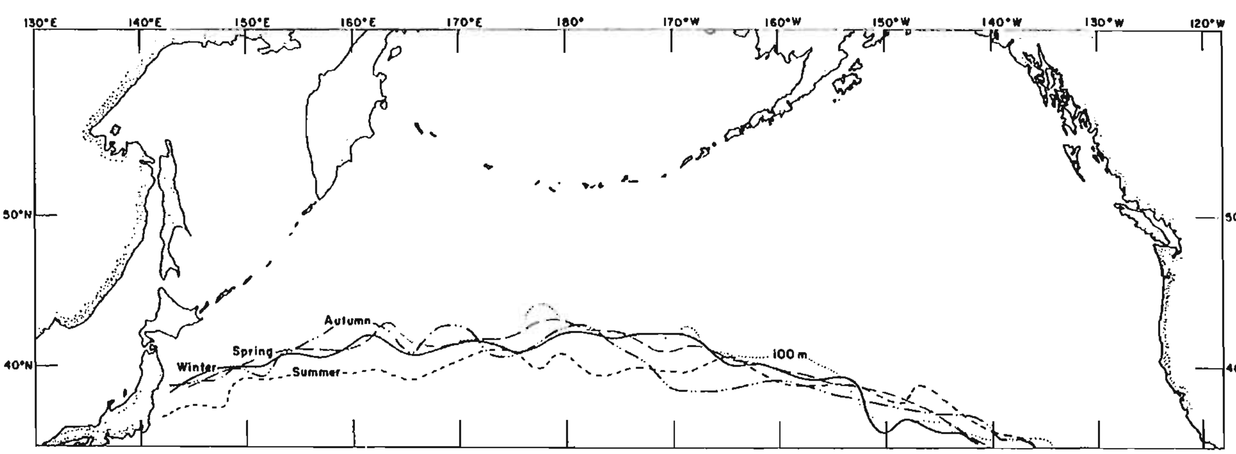


FIGURE 34. Locations of the long-term mean isohaline=34‰ at the surface by season and at 100 m depth (2×2° quadrangles).

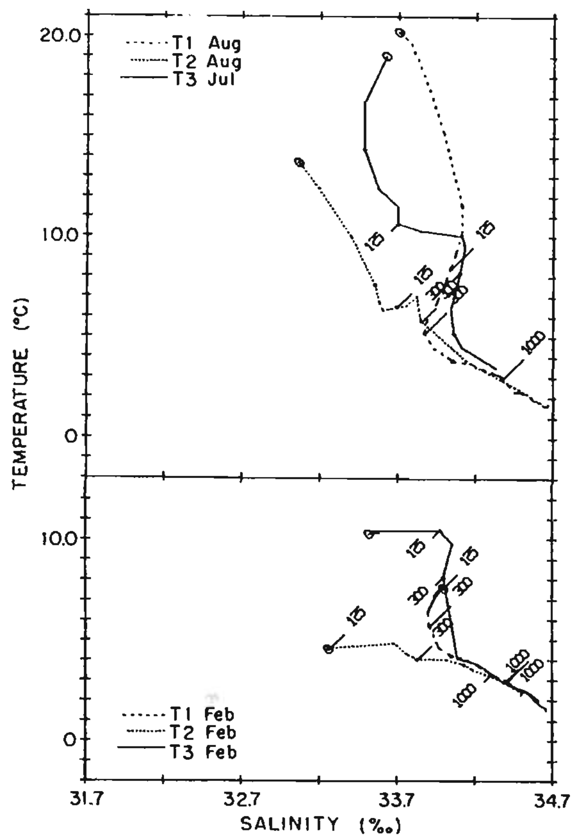


FIGURE 35. Long-term mean T-S relations in the Transition Domain (see Fig. 32).

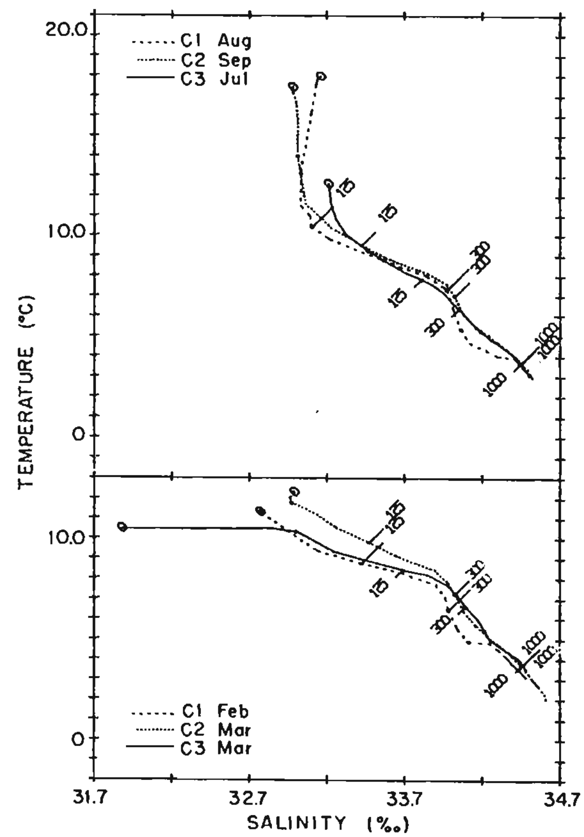


FIGURE 36. Long-term mean T-S relations in the Upwelling Domain (see Fig. 32).

3. *Upwelling Domain*

The presence of upwelling off the California, Oregon, Washington, and British Columbia coasts during late spring, summer, and early fall, is well documented by surface temperature maps and is presently the subject of an intensive cooperative effort, Coastal Upwelling Ecosystems Analysis (CUEA). Although upwelling in this area was discussed in INPFC Bulletin 13, it was not identified as a specific domain. Separate and distinct from the much deeper California Undercurrent Domain, but inextricably linked to the seasonal reversal of flow along the coast (sometimes referred to as the Davidson Current), the seasonal discharge of the Columbia River Plume, and the southward flowing California Current, this area is considered a domain until more information is forthcoming. T-S relations (Fig. 36) in 3 quadrangles (C1, C2 and C3—see Fig. 32) permit comparison of conditions in this domain (C3) with those in the oceanic regime farther offshore (C1 and C2). Mean surface temperatures in summer are more than 5C° lower, and mean salinities are 0.1–0.3‰ higher, in the Upwelling Domain than in the offshore area; these conditions reflect an active upwelling process. The marked dilution during winter probably reflects an increase in the amount of data from inshore areas over that of offshore areas during this stormy period rather than extensive coastal dilution due to runoff, which reaches a maximum during late spring. Particularly significant are the differences in T-S relations below 300 m in the domain compared to those in the Transition Domain, which are representative of the region (see Fig. 35). Temperatures in all three quadrangles (C1, C2 and C3) are considerably higher at corresponding salinities and reflect a northward intrusion of the California Undercurrent discussed in a later section.

4. *Dilute Domain*

The divergence of the eastward flowing Subarctic Current off the west coast of North America is generally recognized, and the westward extrusion of dilute plumes from the Columbia River, Strait of Juan de Fuca, Queen Charlotte Sound and Dixon Entrance have been documented by individual investigations; but the combined effect of these two phenomena

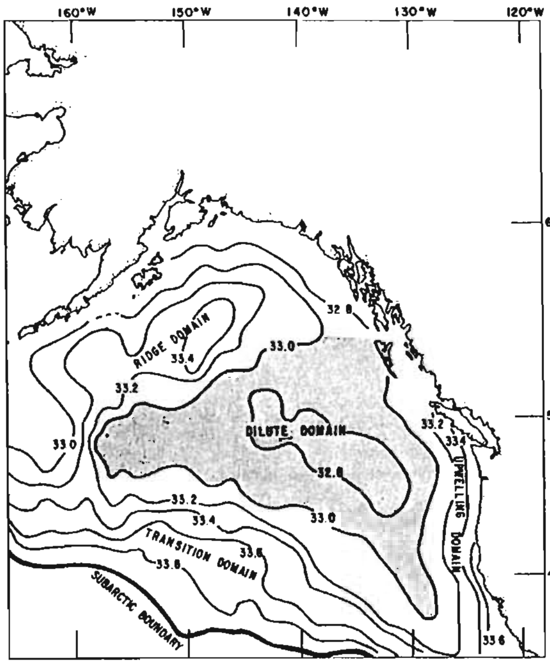


FIGURE 37. Location and extent of the Dilute Domain as indicated by the salinity distribution at 100 m.

results in a distinct area of considerable dilution that has not been recognized previously. Until direct current measurements can be made and the mechanics of flow ascertained, this area, which extends seaward to 160°W, is denoted as the Dilute Domain. Below 50 m, vertical divergence in the Upwelling and Ridge Domains (discussed in the following section) and the normal high salinity values in the Transition Domain, isolate the dilute water from the coast ; this isolation is particularly evident at 100 m (Fig. 37). The domain is no longer identifiable at 300 m where transpacific continuity of a salinity-minimum stratum between the Transition and Ridge Domains exists. The marked dilution from the surface to 125 m in summer is evident in the three selected T-S relations (D1, D2 and D3—see Fig. 32) for this domain (Fig. 38). Temperatures in the 4–6°C range occur at 125–300 m in summer, and from 0–300 m in winter, except at D3. T-S relations below 300 m are similar, except at D1 where water of a more subarctic character is evident in winter, but below 500 m relations are similar to those below the Transition Domain and typical of the region. One interesting feature of the salinity distribution in this domain is that, although above 200 m salinities at geometric depth levels are lower in the eastern than in the western part of the region, the reverse is true from 300 m to 1000 m (see Fig. 15 and App. Fig. 3). The lower salinity water at depth originates from the Sea of Okhotsk, in spite of the adjoining high salinity water of the Kuroshio Current System to the south.

5. *Ridge Domain*

This domain also was not defined in INPFC Bulletin 13, but its presence was suggested by the Western Subarctic, Alaskan, and Bering Sea Gyres. Bounded by various current systems, it is one of the most significant features of the region. Although difficult to define in the surface layer because of seasonal warming and cooling, as well as periodic and aperiodic intrusions, the domain is easily recognizable at depths below 100 m, except in the Bering Sea, where it exists below 200 m.

Although northward flow in the Pacific Ocean at depth from the Antarctic Region is poorly documented, there is little question of its existence and, on impingement at the barrier imposed by the Aleutian-Commander Island Arc, this flow is deflected upwards resulting in a vertical, tongue-like protrusion of cold, saline, nutrient-rich but oxygen-poor, deep water into the dilute surface layer of the region. Thus, below the surface layer, much of the water of the region is

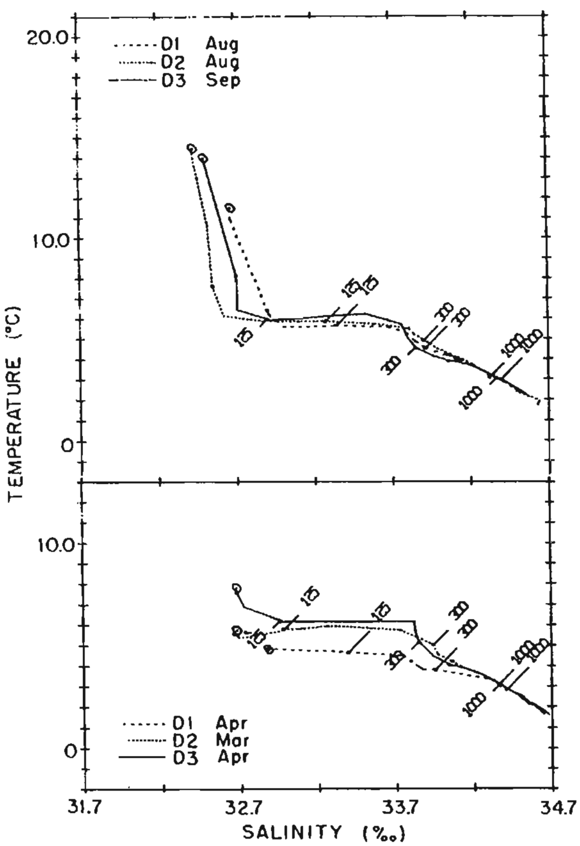


FIGURE 38. Long-term mean T-S relations in the Dilute Domain (see Fig. 32).

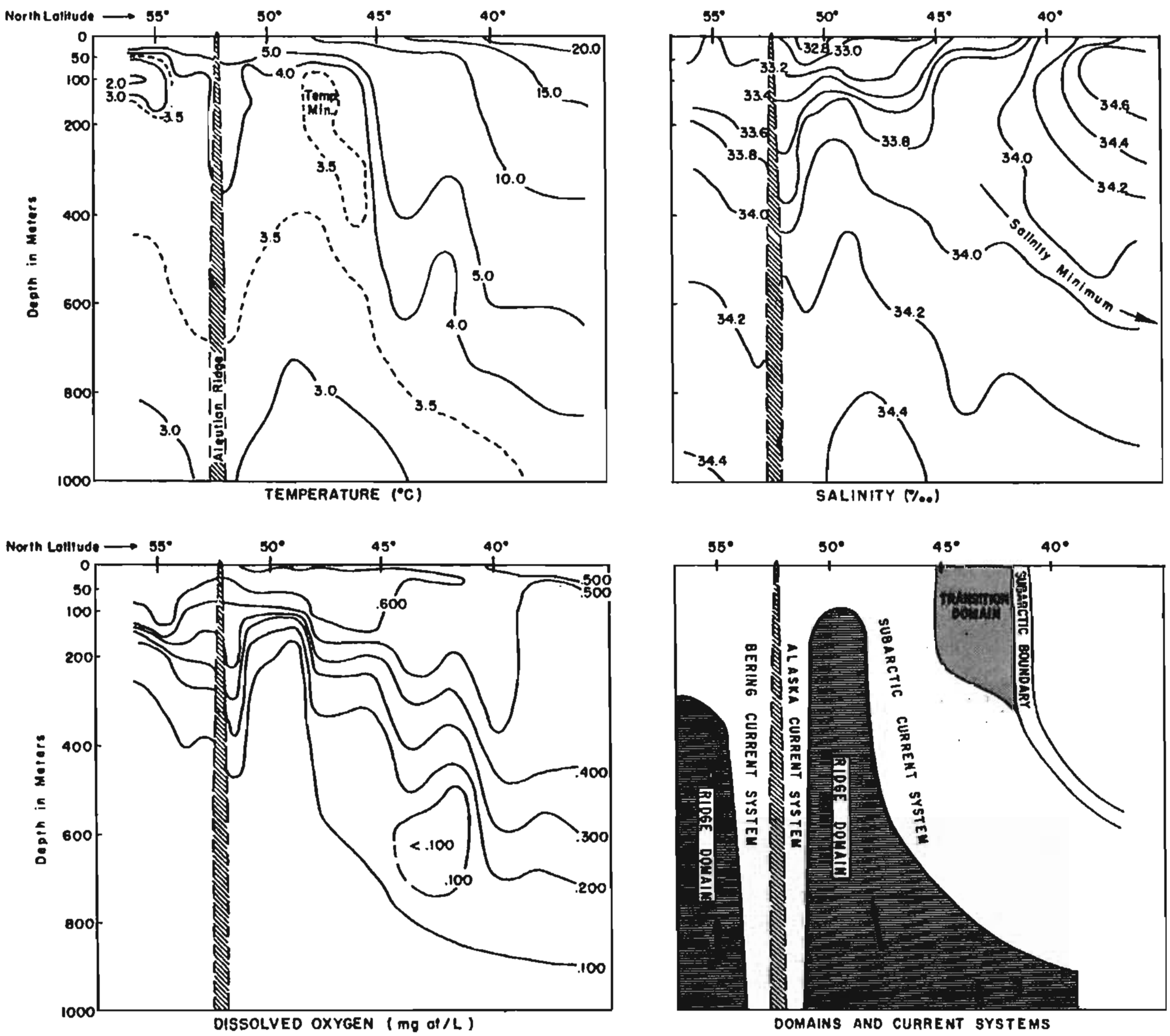


FIGURE 39. Representative vertical sections of temperature, salinity, dissolved oxygen, and current systems and domains in the central part of the region.

largely of southern origin. It is this upward flow indicated by ridging of the isolines that makes this part of the region so highly productive and even may provide surplus amounts of many vital nutrients, particularly in the Gulf of Alaska. It should be pointed out that the ridging of isolines, specifically sigma-t, is also in some respects a normal adjustment of mass to cyclonic flow around the domain.

Numerous meridional vertical sections of water properties were presented in INPFC Bulletin 13 and mean distributions are discussed in an earlier section. It would be instructive at this time to show a representative section based on actual quasi-synoptic data in the central part of the region (Fig. 39) that permits viewing the Ridge Domain south of the Aleutian Islands with both the Transition Domain and flow along its northern and southern boundaries. The pronounced vertical displacement of isolines of salinity and dissolved oxygen near 50°N outline the domain at depth. The southern boundary of the Ridge Domain near 48°N does not necessarily coincide with the location of the 4°C isotherm in this area because a southward displacement of this isotherm can occur as a result of an intrusion of cold water from the west in the upper 300 m. The vertical intrusion of extremely low dissolved oxygen values (and associated high nutrient values) nearly into the surface layer attest to the deep origin of water in the domain.

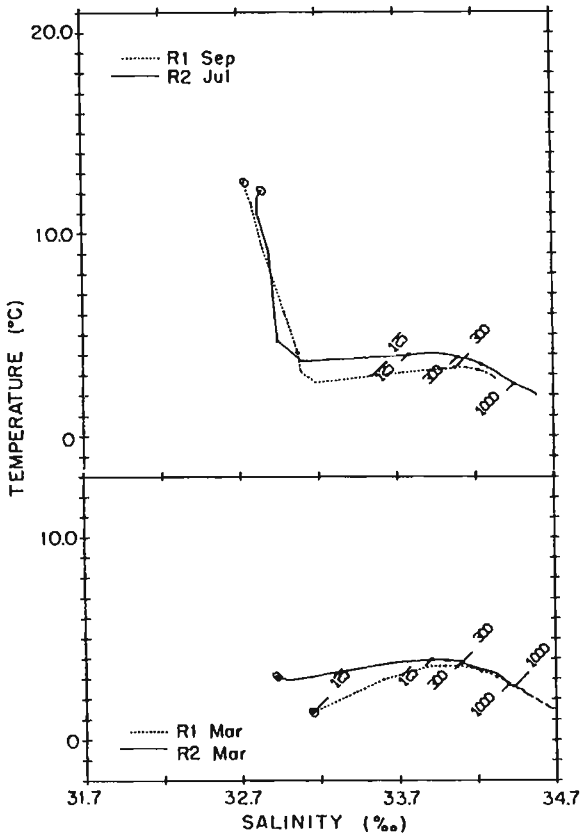


FIGURE 40. Long-term mean T-S relations in the Ridge Domain (see Fig. 32).

Vertical gradients of properties in the surface layer reflect the stability of the halocline and associated features presented in INPFC Bulletin 13. The domain has transpacific continuity between the Western Subarctic and Alaskan Gyres. Zonal flow in this band of vertical divergence is a minimum and, although northward and southward intrusions across the domain occur south of the island arc in the upper 300 m, the fragmentary observations in this area (usually along north-south lines) suggest that, except for closure around the gyres indicated by geostrophic currents, meridional flows are intermittent and confined to the upper part of the water column. The aperiodic nature of these intrusions is indicated also by continuity of the zonal bands of minimum temperatures and maximum salinities as shown in the long-term mean horizontal distributions of water properties (see Figs. 14 and 15). However, in the eastern part of the region, northward and southward intrusions of the 4°C isotherms near 100–200 m at the southern and northern boundaries of the domain suggest that the vertically upward flow influences horizontal circulation in the vicinity of the halocline. T-S relations (Fig. 40) show conditions at the western side to be colder throughout the water column to a depth of about 1000 m. Isothermal conditions in winter extend to 75 m in the eastern side and 125 m at the western side, and surface temperatures in summer are 10–12C° higher than those in winter.

The significance of assigning a specific name to this area, in which essentially relatively uniform horizontal

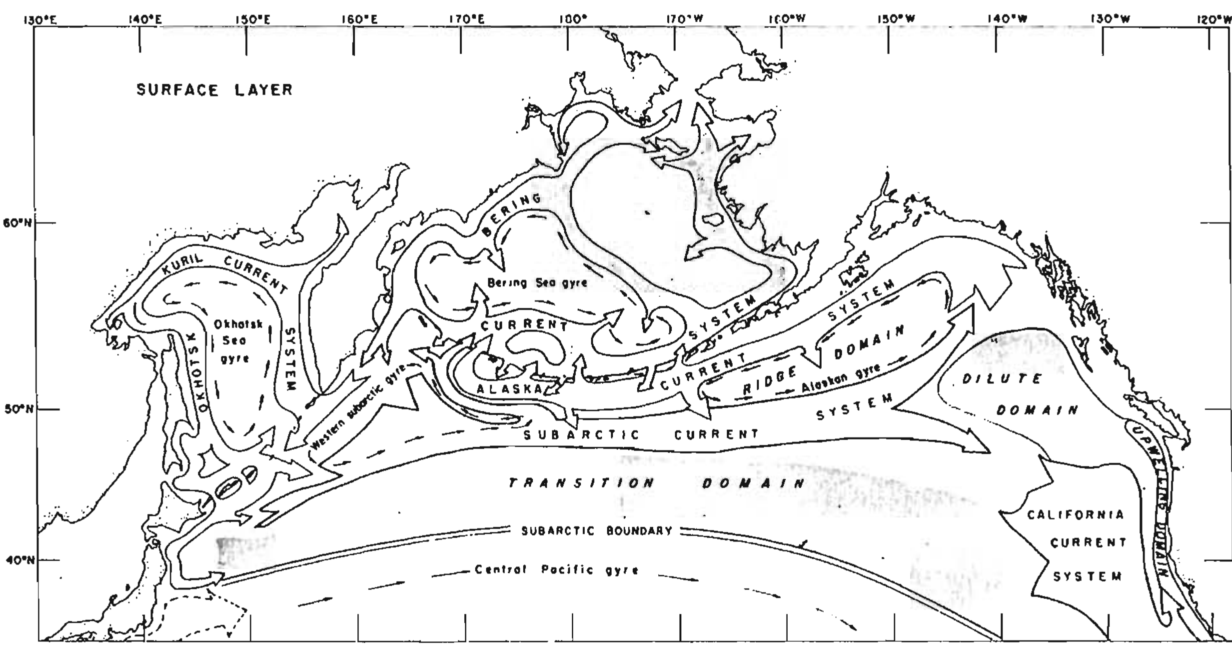
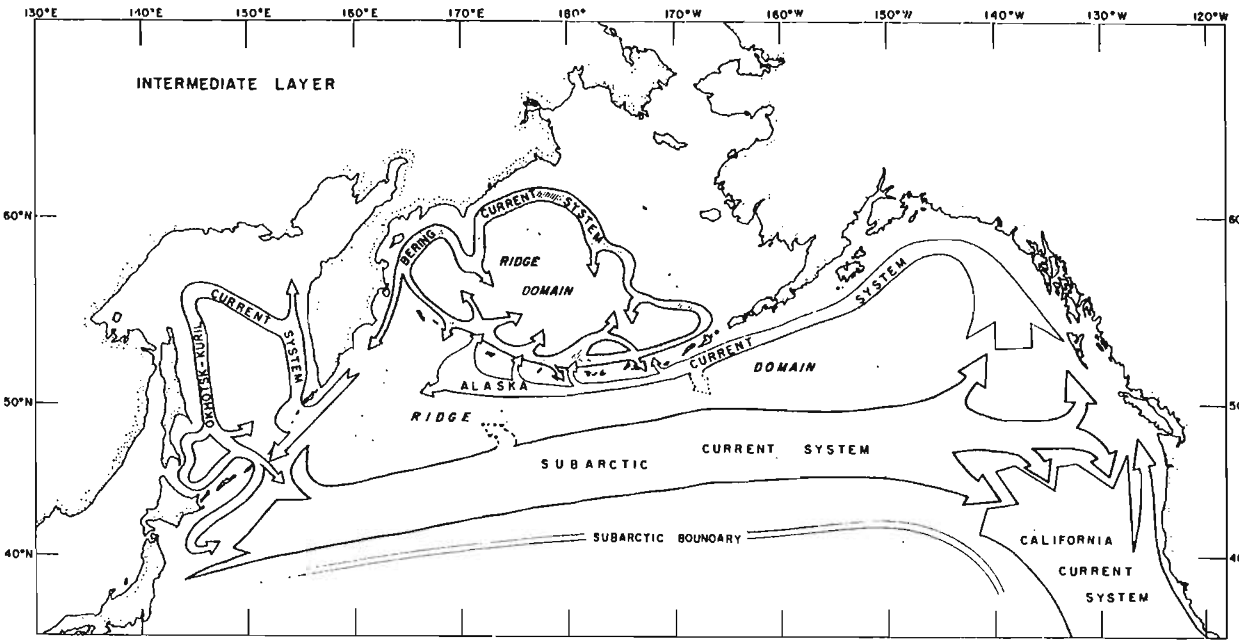
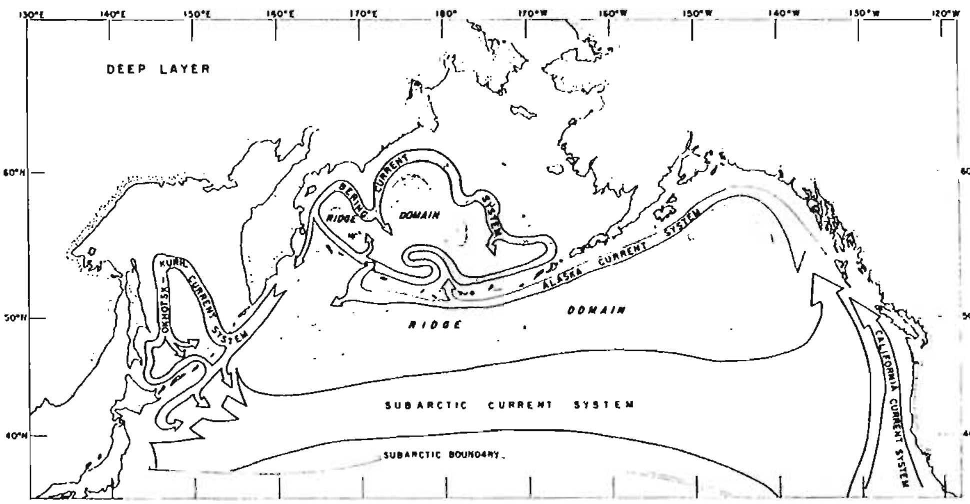


FIGURE 41. Schematic diagrams indicating extent of domains and current systems in the Subarctic Pacific Region.





fields of properties are displaced upward, may not be entirely obvious to those only interested in surface phenomenon. However, particularly south of the island arc, the intermittent north-south flows notwithstanding, the vertical divergence and minimum zonal flow characteristic of this domain could have a marked influence on biological phenomena, and knowledge of its presence provides an opportunity to investigate specific relations between organisms and their environment. The distinct separation of the Transition and Ridge Domains, and the isolation of the Ridge Domain from the Aleutian land mass are associated with the Subarctic, Alaska, and Bering Current Systems, respectively. These and other current systems are defined in the following section, and the geographic extents of these systems and the domains described above are shown at levels of 125, 300, and 500 m (Fig. 41).

B. Current Systems

Recent INPFC oceanographic data when combined with the historical data base permit description of flow in the Subarctic Pacific Region in terms of five systems. The Kuroshio System and its extension, the North Pacific Current, essentially serve as the southern boundary of the region, but are not considered part of the region. The five systems are: the Okhotsk-Kuril Current System, in the Sea of Okhotsk; the Subarctic Current System, originating east of the Sea of Okhotsk and extending eastward across the Pacific Ocean to the Gulf of Alaska Gyre; the California Current System, occurring off the west coast of the United States; the Alaska Current System, commencing in the Gulf of Alaska and extending westward along the Aleutian-Commander Island Arc and northward into the Bering Sea; and the Bering Current System flowing cyclonically in the Bering Sea. Although the Kuroshio and Subarctic systems are composed largely of eastward flow, marked differences between the subtropic conditions of the former and the subarctic conditions of the latter permit not only isolating these two systems, but also identifying the Transition Domain (in the upper 300 m) which separates the two systems. The California Current System provides an exit for the dilute subarctic surface water. The Subarctic and Alaska Current systems are both subarctic in character and minor differences in water properties are significant; however, these opposing zonal flows separated by the Ridge Domain can be readily distinguished by water structure. The Bering Current System is considered as an entity largely because of geographical constraints, such as the Aleutian-Commander Island Arc, which interrupts or at least makes continuity with the above two systems difficult to ascertain, and Bering Strait, which restricts exchanges with the Arctic Ocean. The extensive and relatively isolated continental shelf area in the eastern Bering Sea and the relation of flow in this area to that of the deep basin precludes defining this area entirely as a domain or a distinct current system, thus extensions of components of the Bering Current System are identified.

The origin and general continuity of these current systems are presented (Fig. 42) because of the value of associating exploratory fishing operations with specific oceanographic features. Further, a concerted attempt has been made not only to show recognized flows, but to assign, where considered justified, appropriate names. In addition to increasing knowledge through inevitable controversy, it is hoped that

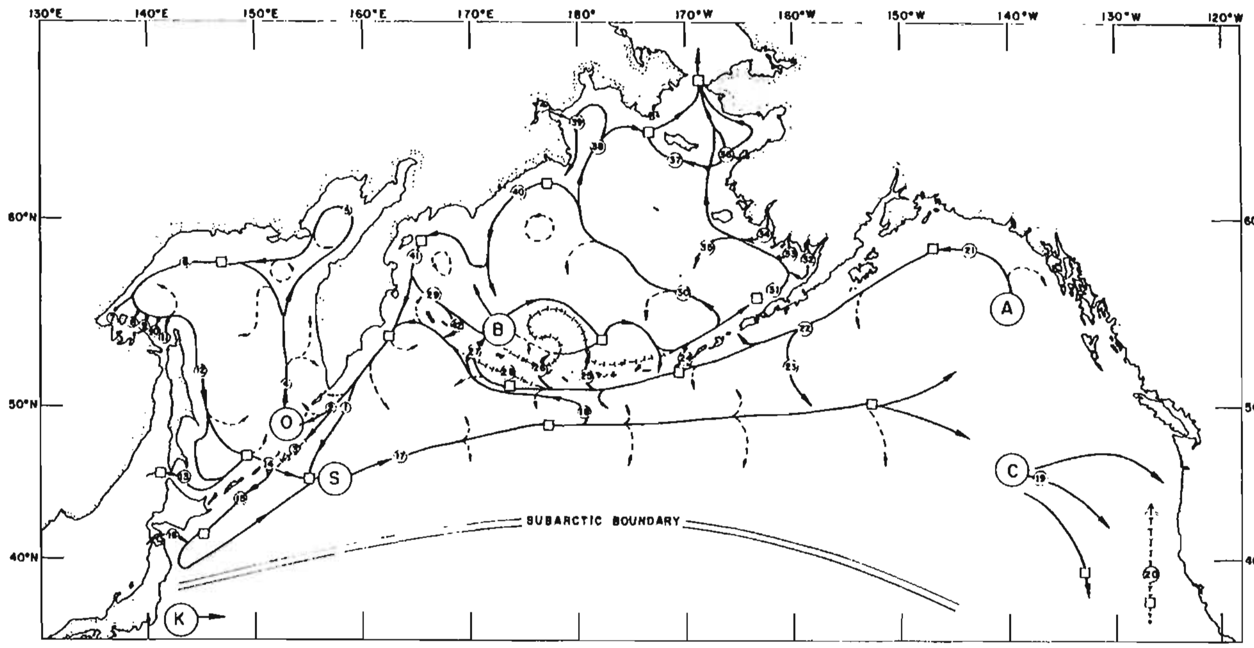


FIGURE 42. Location of recognized currents in the Subarctic Pacific Region (1—Southeast Kamchatka; 2—Southwest Kamchatka; 3—East Kamchatka Deep; 4—West Kamchatka; 5—Penzhinsk; 6—North Okhotsk; 7—Udsk; 8—Tugurk; 9—Ul'Bansk; 10—Amur; 11—West Sakhalin; 12—East Sakhalin; 13—Soya; 14—Kuril; 15—Oyashio; 16—Tsugaru: 17—Subarctic; 18—Western Subarctic; 19—California; 20—California Undercurrent; 21—Alaska; 22—Alaskan Stream; 23—Aleutian; 24—Amukta; 25—Amchitka; 26—Buildir; 27—Near; 28—Alaskan Stream Undercurrent; 29—Commander; 30—Transverse; 31—West Alaska; 32—Kvichak; 33—Nushagak; 34—Kuskokwim; 35—Pribilof; 36—Yukon; 37—St. Lawrence; 38—Navarin; 39—Anadyr; 40—Olyutorskiy; 41—East Kamchatka; 42—Copper).

this initial attempt to provide environmental nomenclature will result in investigations to delineate the extent of particular environments rather than to merely carry out general surveys.

1. *Okhotsk-Kuril Current System*

The dominant characteristics of this system are generated locally, but its origin stems from southerly flow out of the Bering Current System along the southeast coast of Kamchatka Peninsula, the East Kamchatka Current which extends to a depth of several kilometers. Near Cape Shipunskiy a branch turns eastward forming a cyclonic gyre south of the Commander Islands, and near the north Kuril Islands another divergence occurs. One branch, the Southeast Kamchatka Current (1)[5] is forced southeastward near the central Kuril Islands by discharge out of the Sea of Okhotsk and becomes part of the Subarctic Current System. The other branch, the Southwest Kamchatka Current (2) turns westward into the Sea of Okhotsk through various openings in the Kuril Island Arc; however, this flow is restricted to 2000 m, the maximum sill depth of the passes. At depth, below 2000 m, southerly flow, the East Kamchatka Deep Current (3), continues along the seaward side of the Kuril Island Arc and eventually becomes part of the Oyashio Current.

Surface flow into the Sea of Okhotsk turns northward along the west coast of the Kamchatka Peninsula as the West Kamchatka Current (4), one branch turning northeastward and sweeping around Shelikof Bay, the Penzhinsk Current (5); the other turning westward along the north coast as the North Okhotsk Current (6). The Udsk (7), Tugurk (8), Ul'Bansk (9), Amur (10), and West Sakhalin (11) Currents have local influences on the flow in the northwest part of the sea and the resulting flow turns southward along Sakhalin Island as the East Sakhalin Current (12). At the south end of the island, the eastward flowing Soya Current (13) merges with this flow which discharges eastward into the Pacific Ocean through various openings in south Kuril Islands as the Kuril Current (14). Seaward of the island arc this flow diverges; the Kuril Current continues eastward to form part of the Subarctic Current System and the other branch sweeps southwestward along the east coast of Hokkaido as the Oyashio Current (15). Overriding the East Kamchatka Current and joined by the Tsugaru Current (16), which flows eastward between Hokkaido and Honshu, the Oyashio Current impinges on the Kuroshio Current and veers northeastward. At the southern edge of the Oyashio Current, interleafings of various strata with the Kuroshio Current result in the formation of the Transition Domain; however, water at the northern edge of the Oyashio Current retains its subarctic identity and becomes part of the Subarctic Current System.

Extremely low air temperatures and extensive ice cover during winter, and ice melt and river runoff during late spring, as well as exchanges with the Sea of Japan and the Pacific Ocean, give the Okhotsk-Kuril Current System broad ranges of temperature and salinity. During winter, temperature increases with depth from −1.6°C at the surface to about 2.2°C at about 1300 m, and then decreases to 1.8°C near the bottom, approximately 3400 m; during spring and summer, the surface layer (0–25 m) warms to 15°C or above, but negative temperatures are still encountered at 100 m. The presence of the temperature-minimum stratum near 125 m is attributed to winter turnover, but the deep extent (150–900 m) of water having temperatures less than 2°C is attributed to cold saline bottom water from the northwestern shelf area and to the winter influx of cold, saline water in the Soya Current whose density at 600 m is equi-

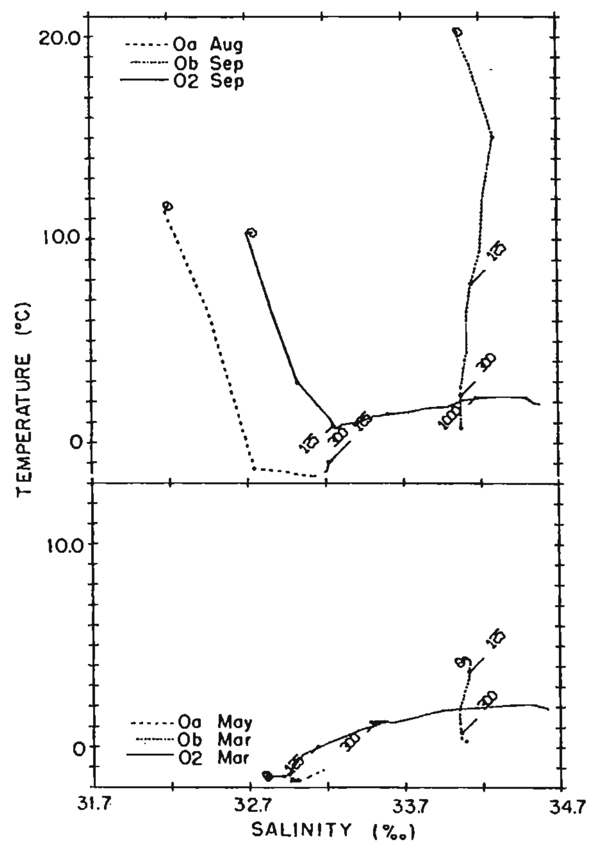


FIGURE 43. Long-term mean T-S relations in the Okhotsk-Kuril Current System (see Fig. 32).

[5] Numbers refer to symbols shown in Fig. 42.

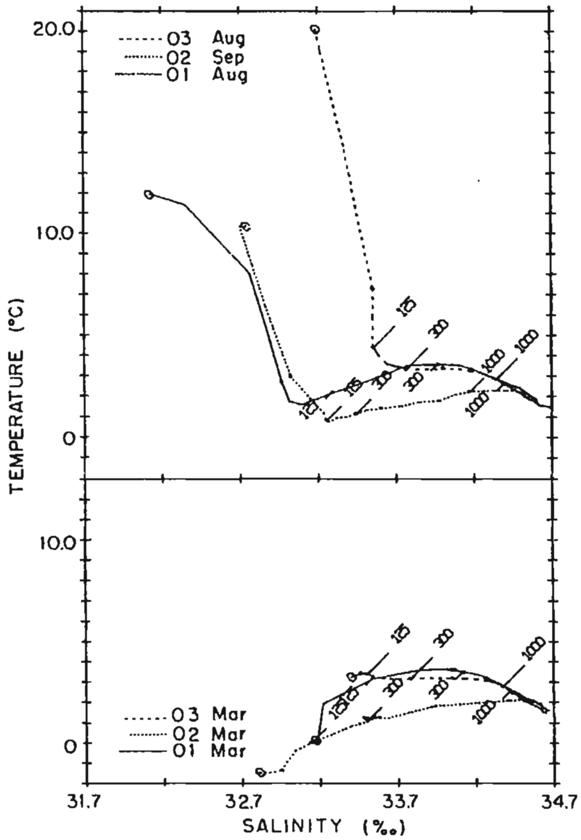


FIGURE 44. Long-term mean T-S relations from areas forming the Subarctic Current System (see Fig. 32).

valent to that of water at 1000 m in the Sea of Okhotsk. Water in the temperature-maximum stratum, having temperatures of 2–2.3°C at 1500–2000 m, probably originates from the East Kamchatka Current where water (below the surface layer) in this temperature range is associated with higher salinities, and the resulting increase in density permits it to descend to greater depths in the Okhotsk basin.

T-S relations at 3 locations (Oa, Ob, and O2—see Fig. 32) in the Sea of Okhotsk have considerably different characteristics (Fig. 43). The extreme warming of nearly 13C° (from −1.5 to 11.5°C) from May to August in the northern part of the sea (Oa), and 16C° (from 4–20°C) near Soya Strait (Ob), as well as the large difference in surface salinity in these two areas in summer, 32.2 and 34‰, respectively, are proportionately reflected in the T-S relations near the Kuril Islands area (O2). Ranges of temperature and salinity at standard depth levels for this and all subsequent current systems are shown in the Appendix (App. Fig. 12).

2. *Subarctic Current System*

The confluence of the Southeast Kamchatka Current, the eastern branch of the Kuril Current, and the northeast flow of the Oyashio Current merge near 45°N, 155°E and form the Subarctic Current System, which flows eastward across the Pacific Ocean to depths of 2–3 kilometers to the Gulf of Alaska. T-S relations representative of flows from these areas (O1, O2 and O3—see Fig. 32) indicate the various conditions that form the origin of this system (Fig. 44). At approximately 180° the Subarctic Current (17) diverges; a northern branch, the Western Subarctic Current (18), turns westward at the southern edge of the Alaskan Stream and northwestward near 170°E at the westward terminus of surface flow south of the Aleutian Islands. North of 50°N, this current diverges, one branch turning northeastward into Bering Sea, and the other continuing northwestward south of the Commander Islands until merging with the East Kamchatka Current, essentially closing the surface circulation in the Western Subarctic Gyre.

The main flow in the Subarctic Current continues eastward at 180° along the south edge of the Ridge Domain to 150°W where a divergence occurs in the surface layer (upper 250 m), one branch turning northeast into the Gulf of Alaska and merging into the

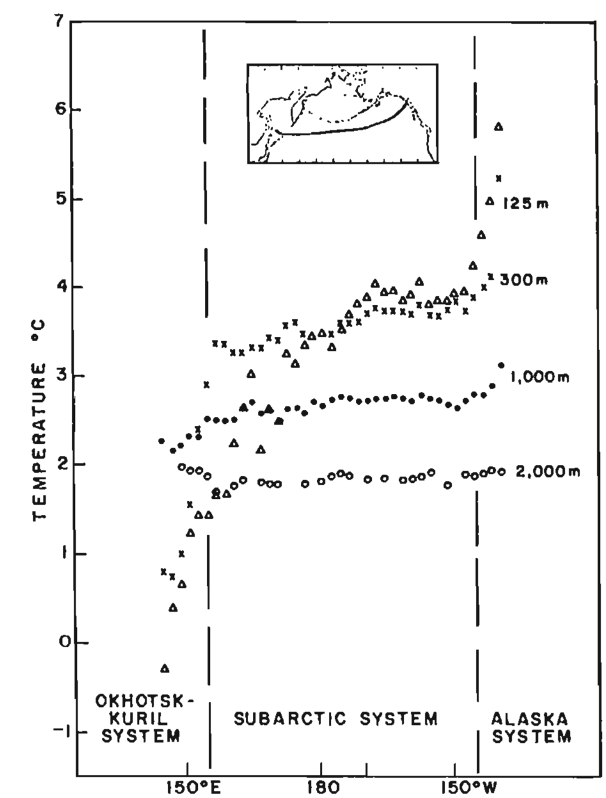


FIGURE 45. Long-term mean temperatures at 125, 300 1000, and 2000 m along a transpacific line, see insert (2×2° quadrangles).

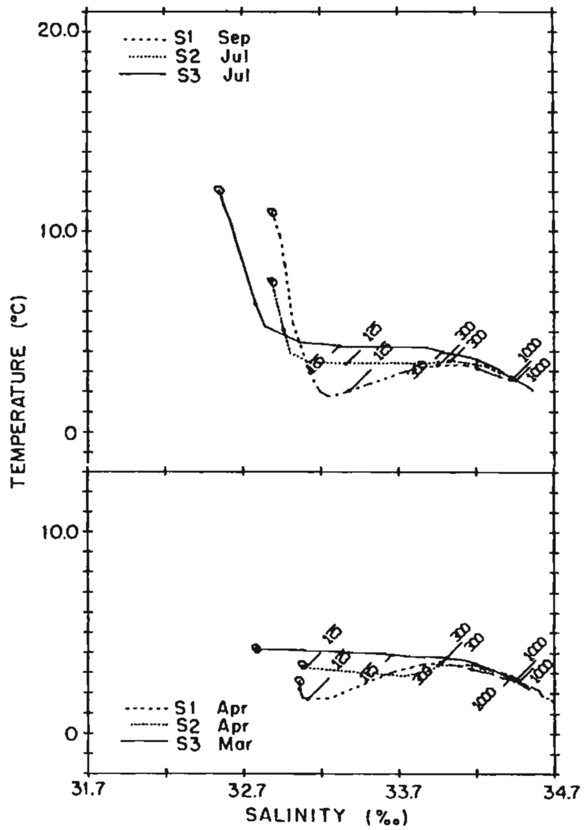


FIGURE 46. Long-term mean T-S relations in the Subarctic Current System (see Fig. 32).

Alaska Current System, and the other turning southeast and merging into the California Current System. Below 300 m, this divergence occurs closer to the coast and farther southward. This is, of course, an overly simplified description of flow in one of the most important currents in the region. However, very little is known about this very complex system other than what can be inferred from the distributions of properties and wind-stress transport.

Mean temperatures at 125, 300, 1000 and 2000 m obtained from 2 × 2° quadrangles along a line from the southern Sea of Okhotsk to the northern Gulf of Alaska define the extent of and conditions in the Subarctic system (Fig. 45). The system lies between the sharp temperature gradients at 155°E (which denote the eastern edge of the Okhotsk-Kuril system) and at 145°W (which denote the western edge of the Alaska system). Between 155° and 170°E, temperatures at 125 m reflect the variable extent of ice cover; between 170° and 155°W, temperatures near 4°C occur because the 2 × 2 quadrangles are too wide to isolate the eastward, tonguelike intrusion of cold water, which in this area is generally less than 100 km in north-south extent. Slight temperature gradients occur at 300 and 1000 m depth, and at 2000 m (below the sill depth of the Kuril Island Arc) temperatures are quite uniform.

T-S relations at the western origin (S1), central portion (S2), and eastern terminus (S3) of the Subarctic Current System are generally uniform near the surface but this is not indicated by the data available (Fig. 46). However, specific identification of this system can be made at levels below the surface layer where progressive warming eastward is evident. Between 170°E and 160°W the Ridge Domain is less than 100 km wide, and northward intrusions of cold water from this current system are easily detectable below the surface layer as they, like southward intrusions of warm water from the Alaska Current System to the north, breakdown the water structure in the Ridge Domain. Present chemical data are not adequate to ascertain whether any unique properties acquired during residence time in the western part of the region are detectable at the surface thoughout the eastward extent of this current system. This is unfortunate because it is difficult to obtain meaningful relations between near-surface salmon catches and the relatively homogeneous surface environmental conditions in this area. East of 150°W, water properties in this current system change abruptly and one must assume that there is little possibility of any unique water characteristics from the western part of the region extending eastward of this location; and there is little evidence of Asian salmon east of this longitude. It is at this point that water properties characteristic of coastal environments along the eastern side of the region enter the overall Subarctic circulation.

3. *California Current System*

This system is more complex than the Subarctic Current System and is as poorly understood. The system is recognized as being a general onshore flow composed of water from the southern branch of the offshore divergence of the Subarctic Current and from the general area of the Transition Domain. Two distinct flows occur; the general southeasterly, near-surface flow, the California Current (19), and the northerly flow, the California Undercurrent (20), extending from the coast to 500 km offshore at depths below 200 m. At times this flow may appear at the surface, particularly during winter when upwelling has subsided, and has been referred to as the Davidson Current; considering the seaward extent of the flow, it would appear that California Undercurrent is a more appropriate name. The former is vaguely defined in the literature by drift bottle observations but the existence of the latter was recognized in INPFC Bulletin 13 and denoted as the California Undercurrent Domain. A northward intrusion of warm water (shown by temperatures greater than 6°C on the surface of salinity=34‰) was clearly evident and substantiated by geopotential topography (200/1000 db) in summer 1957, and its presence and continuity have been gradually documented. Mean data from vertical array summaries permit showing the general extent of the water mass associated with this current (Fig. 47) and T-S relations (C1, C2 and C3) have been discussed in relation to the Upwelling Domain (See Fig. 36).

4. *Alaska Current System*

The broad, diffuse, eastern boundary current formed when eastward flow in the northern branch of the Subarctic Current at about 50°N impinges on northward flow along the west coast of North America is considered as the origin of the Alaska Current System. Converging toward the head of the Gulf of Alaska and constrained by the coast, the flow turns southwestward along the Alaska Peninsula as a boundary current known as the Alaskan Stream. Although distribution of water properties around the head of the Gulf of Alaska indicate some lack of continuity in the surface layer (an apparent partial blockage of westward flow suggested by meanderings of the isolines of water properties in the northeast corner), there is little indication of this condition below 500 m. Normally, flow in the Alaskan Stream would result in an elevation of the sea surface shoreward and a tendency, not only for the water to hug the coastline, but to veer to the right (northward) through any openings in the island arc; however, this is not the case. Equilibrium conditions between Coriolis and pressure forces break down and a pronounced component of flow in the surface layer veers southward, closing circulation in the surface layer of the Gulf of Alaska Gyre. The significance of this flow is its ability to penetrate across the Ridge Domain, which lies between the westward flowing Alaskan Stream and the eastward flowing Subarctic Current to the south. This penetration usually occurs above 500 m and is attributed to a vorticity adjustment. It may be found anywhere between 155° and 175°W and several branches may exist. Although observations are usually inadequate to define the number and structure of these jet-like protuberances, there is no question that they are a significant part of the Alaska Current System. At times inshore countercurrents with speeds in excess of 10 cm/sec occur along the continental slope but the continuity of such flows is poorly documented and these eastward flows may be

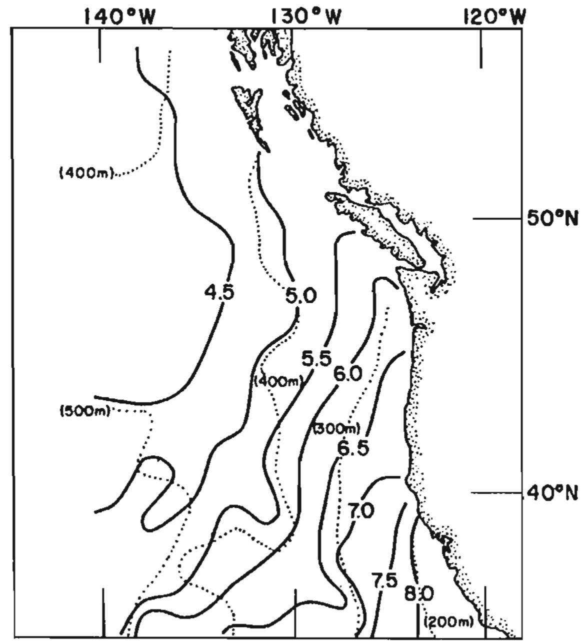


FIGURE 47. Long-term mean temperature on, and depth of salinity surface=34‰ in the California Undercurrent Domain (2×2° quadrangles).

associated with large eddies moving westward in the Stream.

Exchanges with the Bering Sea occur at the northern edge of the Alaskan Stream at various openings in the Aleutian-Commander Island Arc from 165°W–170°E. These exchanges occur to various levels depending on sill depths of the passes, which generally increase in depth to the westward. Of the approximately 40 passes, the following six general areas are the only ones of major significance to flow: Unimak, 165–177°W, 60 m depth (although shallow, this is the first major opening into the Bering Sea); Amukta, 170–172°W, 450 m; Amchitka, 178–179°E, 1150 m; Buldir, 176–174°E, 650 m; Near, 172–169°E, 2000 m; and Kamchatka, 163–155°E, 4400 m. Westward surface flow turns northward into the Bering Sea through Near Strait, east of the Commander Ridge. This flow impinges on the Near Current in the vicinity of 170°E and turns northward into the Bering Sea; but westward flow, below the sill depth of Near Strait (2000 m), continues along the south side of the Aleutian-Commander Island Arc to 166°E, merging with but underriding westward flow in the West Subarctic Current, and turns northward into the Bering Sea through Kamchatka Strait.

Northward intrusions from the Subarctic Current System turn westward at the southern boundary of the Alaskan Stream. These are primarily aspirational effects and aperiodic flows as a result of the action of local wind stress and are limited to the surface layer because there is little indication of any extensive breakdown in the ridge structure at depth between the two opposing current systems. There is also little evidence that these northward intrusions penetrate across the Alaskan Stream; rather, being swept westward along the southern boundary, they serve to increase the westward transport of the system but defy identification by conventional methods of T-S analysis.

Thus, the Alaska Current System consists of the Alaska Current (21) which has a major branch, the Alaskan Stream (22), consisting of seven minor branches; a southward flow into the Gulf of Alaska, the Aleutian Current (23); five northward surface flows into Bering Sea, Amukta (24), Amchitka (25), Buildir (26) and Near (27) Currents, and a subsurface flow existing below 2000 m and discharging into Bering Sea at the west side of the Commander Islands, the Alaskan Stream Undercurrent (28).

The westward extent of this Alaska Current System south of the Aleutian-Commander Island Arc has been the subject of numerous INPFC discussions. The dominant T-S characteristic of this system is the presence of temperatures greater than 4°C associated with salinities greater than 33.3‰. Attempts to show the extent of the Alaskan Stream at a given period by plotting the distribution of the 4°C isotherm at a geometric depth level, such as 100 m, has been considered inaccurate because this stratum undulates. The presence of temperatures greater than 4°C below approximately 100 m signifies the presence of water associated with the Alaskan Stream or a remnant thereof, but the Stream is not limited to this depth; in fact, it may extend to 3000 m along the island arc. Nor does it imply that the Stream is limited to the horizontal extent depicted by the 4°C isotherm, but that it is known to exist to at least that extent. The general wide spatial distribution of temperatures in the mesothermal layer in the range 3.7–3.9°C prevent accurately tracing the westward extremity of the Stream beyond that indicated by the 4°C isotherm, which usually can be traced as far west as 50°N, 165°E. T-S relations at three locations (A1, A2, and A3—see Fig. 31) are shown in Fig. 48.

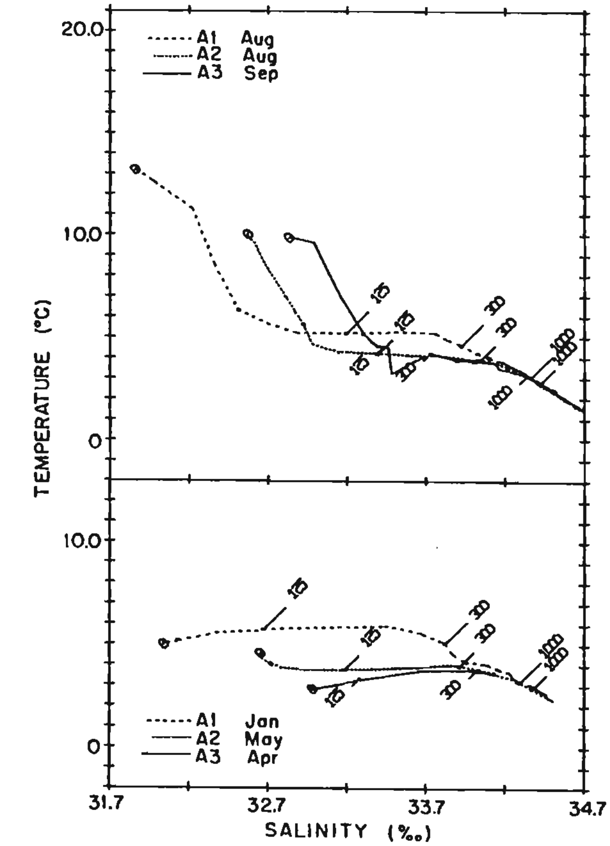


FIGURE 48. Long-term mean T-S relations in the Alaska Current System (see Fig. 32).

5. *Bering Current System*

Although the surface layer in the Bering Sea is composed primarily of water from either the Subarctic or Alaska Current Systems, the relative confinement of the Bering Sea justifies separate consideration of flow in this area. Unfortunately little is yet known about quasi-permanent currents in this area, or the wind systems that could easily alter conditions in the enclosed basin, especially over the broad shelf area in the eastern part where in late spring and summer extensive river runoff occurs. Further, northward discharges through Aleutian Islands passes override the general subsurface cyclonic flow along the continental slope which follows the contours of the Aleutian-Commander Island Arc, including Bowers Ridge, and also the Olyutorskiy Ridge.

The bottom of the surface layer is not as sharply defined by salinity structure as in other systems but the temperature-minimum stratum characteristic of much of the Subarctic Region is clearly present. Flow, as in the Okhotsk Sea, Western Subarctic, and Gulf of Alaska Gyres, is cyclonic, and it is assumed that three gyres are present in the surface layer over, the eastern shelf, the central basin, and the western basin. Dominant flow in the Aleutian passes is tidal, with the flood northward and ebb southward. Although there is evidence of cyclonic eddies encompassing major island groups which require north and south flows through various passes, the main surface flow into the Bering Sea occurs primarily through Near Strait as the Near Current (27). North of Near Strait this flow merges with eastward flow along the north side of the island arc, the Commander Current (29), and subsequently diverges sending one branch northward along the west side of the Olyutorskiy Ridge and the other eastward around Bowers Ridge into the southeastern part of the central basin where the Amchitka and Amukta branches of the Alaskan Stream join this flow.

The frontal zone at the western edge of the continental shelf in the eastern Bering Sea suggests that the main flow in this system turns northward following the continental slope, the Transverse Current (30), and conditions over the shelf area are not greatly influenced by an extensive eastward oceanic flow. In Bristol Bay, tidal currents constitute the dominant flow which oscillates in a southwest to northeast direction. Coastal eastward flow along the north side of the Alaska Peninsula moves northward around Bristol Bay and is denoted as the West Alaska Current (31). This current is influenced by currents originating from local rivers, the Kvichak (32), Nushagak (33), and Kuskokwim (34) Currents. There is evidence of a westward flow south of Nunivak Island, the Pribilof Current (35), but the main flow continues northward past the Yukon River and is joined by the Yukon Current (36) and eventually discharges into the Arctic Ocean through the eastern side of Bering Strait. In spring, there is evidence of a westward flow south of St. Lawrence Island, the St. Lawrence Current (37).

Continuity of the main Bering Current System in the eastern Bering Sea is found in the northward flow along the edge of the shelf to Cape Navarin where a branch extends northeastward to Bering Strait, the Navarin Current (38).[6] The main flow is joined inshore by the Anadyr Current (39) and flows southwestward along the Siberian coast, the Olyutorskiy Current (40). At Cape Olyutorskiy a southward branch forms an eddy in the northern Bering Sea but the main flow continues southwestward along the coast, the East Kamchatka Current (41), to Cape Ozernoy, where the Commander Current (29) branches off to the southeastward and completes the overall cyclonic circulation in the Bering Sea. The East Kamchatka Current continues southwestward along the coast completing the circulation around the region. At the west side of Near Strait this flow diverges, sending one branch southward, the Copper Current (42), which merges with the westward flow south of the Commander Islands; the other branch continues eastward along the north side of the Aleutian-Commander Island Arc and completes the circulation of the Bering Current System.

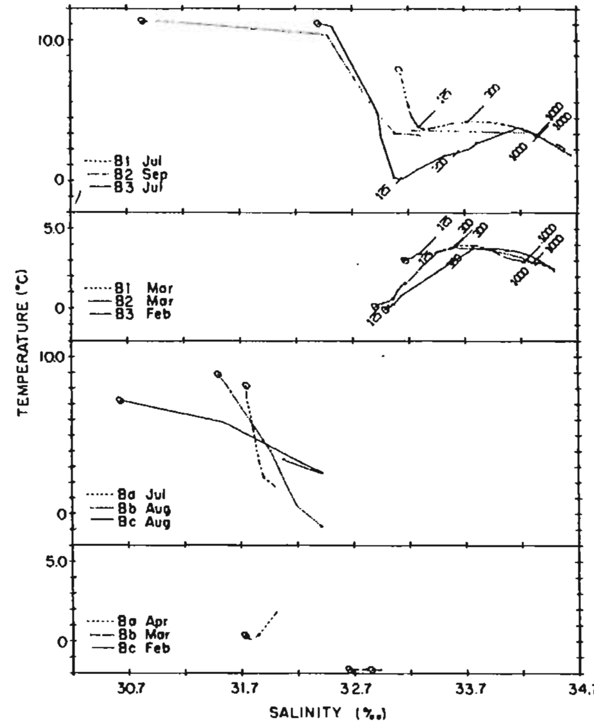


FIGURE 49. Long-term mean T-S relations in the Bering Current System (see Fig. 32).

The formation in winter, and melting in spring, of ice over the continental shelf in the eastern and northern parts of the Bering Sea is a major factor in the marked changes in T-S relations (Fig. 49) from winter to summer. Dilution throughout the water column, particularly in inshore areas, high surface temperatures in embayments in summer, and year-round negative bottom temperatures at midshelf locations, characterize this area. Relatively warm water intrusions through passes in the Aleutian-Commander Island Arc in the southeastern part of the sea, and severe winter cooling by drifting ice in the northern and western parts dominate offshore conditions in these areas.

In summary, each of the Subarctic current systems interacts with one or more of the others, but individually constitutes a unique circulation system; for example, the Okhotsk Gyre in the Okhotsk-Kuril Current System, the Western Subarctic Gyre in the Subarctic Current System, the Alaskan Gyre in the Alaska Current System, and the Bering Sea Gyre in the Bering Current System. Thus, the various paths afforded a water parcel, and associated planktonic organism, or drifting nekton, in moving throughout

[6] The combined flow of the Navarin and West Alaska Currents into the Chukchi Sea is usually referred to as the Pacific Current.

the Subarctic Pacific Region are many. The location and extent of the various current systems change considerably with depth and during certain seasons some systems, or components of systems, may have greater or lesser velocities and/or transports.

V. ENVIRONMENTAL CONDITIONS, 1960–71

It is inevitable that descriptive oceanography terminology eventually will reach the degree of sophistication and definitiveness of that currently employed in descriptive meteorology wherein three dimensional flow is not only evident in types, vertical stratification, and movements of clouds, but documented by radiosonde, and satellite information ; further, the continuity and intensity of low pressure troughs and high pressure ridges that guide air streams are readily apparent in daily data obtained from world-wide networks. Unfortunately, we are perhaps several decades away from similar descriptions of ocean conditions. In this section the fragmentary reports made to the INPFC on local conditions in areas of individual, national cruises are summarized ; deviations of conditions (from long-term means in $2 \times 2°$ quadrangles) are discussed. In addition, cause and effect relations of major changes in the ocean climate are investigated.

A. INPFC Studies

Because the Protocol to the INPFC Convention was centered around an equitable division of salmon, much of the INPFC research was devoted to racial identification, and the distribution of races and stocks of salmon. Initially, broad environmental regimes were considered in relation to distributional patterns of salmon. For example, it was known that surface temperatures in the western part of the region in winter were several degrees lower than those in the eastern part, and the possibility of a general eastward migration during winter was considered, as was an accompanying southward migration out of Bering Sea. Although this hypothesis has yet to be proven because gillnet fishing in the western part of the region during winter has been considered too hazardous for the Japanese fishing vessels, sockeye salmon (although in greatly reduced numbers compared to spring catches) have been caught in the central part of the region in February and early March by U.S. vessels (*Bertha Ann* and *George B. Kelez*) as far west (175°E) and north (57°N) as cruises were conducted. Of considerably more initial interest than the possibility of such a general response to gross surface conditions was the possibility of ascertaining north-south and east-west limits of salmon distributions that were associated with environmental boundaries.

Annual meetings of the INPFC Subcommittee on Oceanography provided a forum for the assessment of annual environmental conditions in the region, and national interests resulted in field observations having general geographical boundaries—Canadian studies were conducted in the area east of 160°W, United States studies largely between 160°W and 175°E, and Japanese studies primarily west of 175°W. Except at Ocean Station " P ", and along Line " P " where a historical data base had been compiled there was little, if any, monitoring of environmental conditions in time or space from year to year that provided baseline data at specific locations for comparative purposes. Cruise tracks of oceanographic and fisheries research vessels were generally of an exploratory and therefore varied nature ; however, ambitious oceanographic programs were carried out and, with few exceptions, all oceanic environmental studies in the Gulf of Alaska and Aleutian Islands areas were primarily associated with INPFC investigations.

Details of the following abbreviated summaries of conditions by years can be found in INPFC Documents, Annual Reports, Proceedings of Annual Meetings, and Bulletins. The southern limit of salmon distribution in the central part of the region was shown to coincide with the presently defined Subarctic Boundary, and the southern limit of the distribution of sockeye salmon, was shown to coincide with the temperature front denoting the northern boundary of the presently defined Transition Domain and the southern edge of the Subarctic Current System. These relations provided the motivation for the investigation of specific environmental features that might provide clues concerning east-west environmental boundaries. Previous discussions in this report define the opposing flows of the Alaska and Subarctic Current Systems that are separated by the Ridge Domain and there are numerous suggestions that these three features influence the distributions and movements of various salmon stocks. But these are countered by reports of distributional studies implying heterogeneous distributions unrelated to environmental boundaries. This controversy can be resolved only by well designed experiments.

The east-west extent of the Subarctic and Alaska Current Systems and north-south interactions of these two generally zonal flows have been discussed. These flows are considered to exist to depths of a few thousand meters, but we are concerned primarily with describing the salmon environment, which is generally considered to be confined to the surface layer (in many instances much of the data are limited to the upper 100–300 m). It proved impractical to combine fragmentary data in the surface layer into composite mosaics of individual environmental parameters that would be particularly useful in evaluating specific conditions, comparing conditions from one period to another, or aiding the fisheries biologist to ascertain the precise environmental conditions that existed at every research fishing location; one still must study individual observations to investigate specific relations. Nevertheless, even recognizing that time and space variations in data impair the accuracy of configurations of isolines, a great deal of information can be ascertained from a synthesis of annual reports to the INPFC. These clearly show the complexity and variability in environmental conditions in the central part of the region and place restrictions on the manner in which fish catch data from various sets or vessels can be combined or averaged if relations with the environment are sought.

1. *Western Area*

The principle sources of environmental data in the western part of the region reported to the INPFC are the Japanese high seas mothership fleet and fisheries research vessels of the Japan Fisheries Agency. The former data are proprietory and not readily accessible, and the latter data consist primarily of bathythermograph observations. Data from both sources are obtained primarily in areas well seaward of the Asian coast.

It has been pointed out earlier that because of relatively uniform surface conditions it is necessary to search for continuity of specific water masses below the surface layer where conditions are relatively constant and distinct identifications can be made even though small differences in properties exist. For example, south of the Aleutian Islands water temperatures greater than 4.0°C are associated with the Alaskan Stream; whereas, water temperatures less than 3.6°C usually denote components of the Subarctic Current System. Although the bathythermograph is an excellent instrument for obtaining layer depths, problems are encountered in obtaining absolute values. In the absence of Nansen bottle or

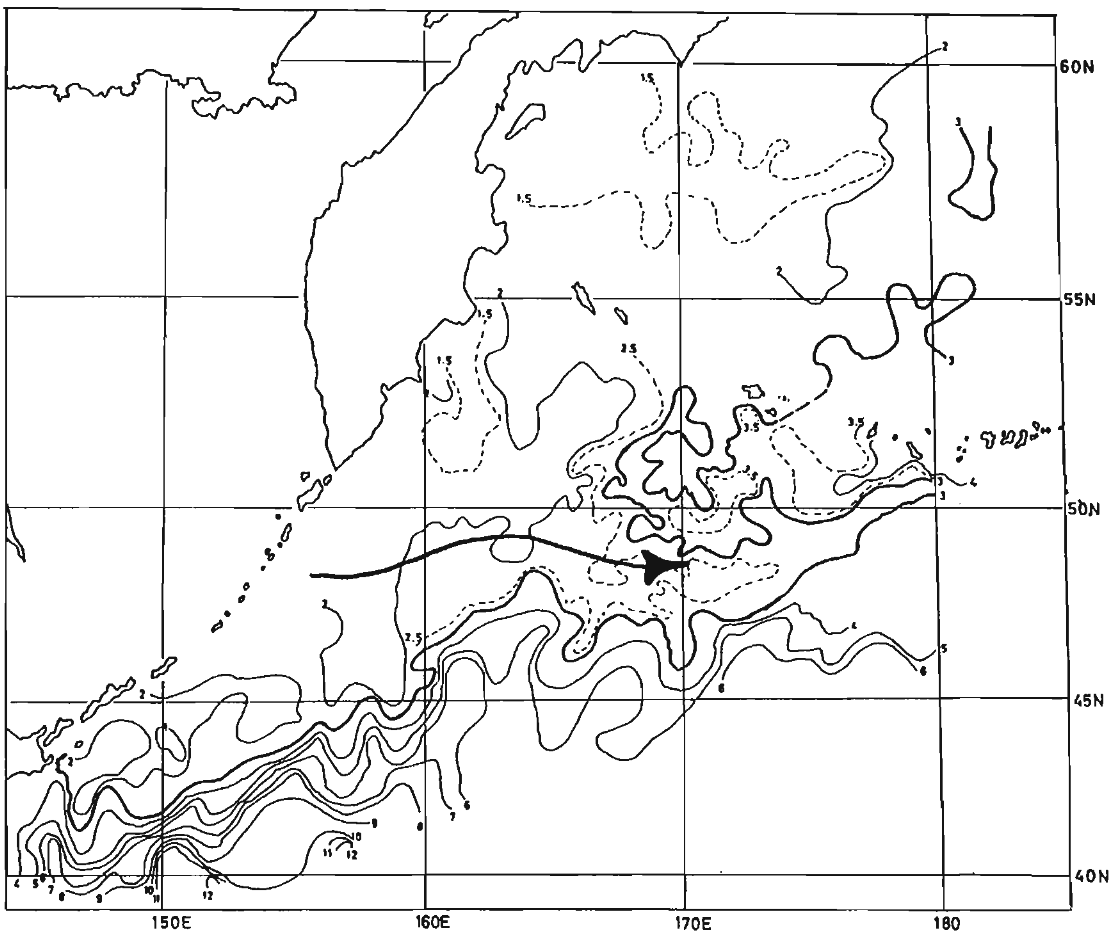


FIGURE 50. Temperature (°C) at 100 m in June 1968 showing complex distribution near 50°N, 170°E (from INPFC Annu. Rept. 1968, p. 53).

STD casts, which provide precise data at depth where temperature changes are small and gradual, the bathythermograph trace must be aligned with an observed surface temperature value before other values can be read off a superimposed grid ; unless extreme care is exercised, errors of 1C° or more can occur. Thus, in many cases, these data indicate not only a somewhat complicated, but confused picture of conditions. Although one should be quick to point out that the interactions between these two flows are indeed dynamic (as evident in surface and subsurface data), nevertheless, spurious data usually prevent ascertaining the continuities that exist at depth in spite of mixing and stirring processes.

The process of winter turnover, which extends to various depths, sometimes penetrating to the σ_t surface=27.0, which is well below 150 m, poses another problem. Although local conditions may stir up the water column, whatever distinct chemical characteristics exist are still present until interaction with another water mass. Below this mixed, surface stratum, conditions within a specific water mass remain relatively unchanged on equivalent density surfaces from season to season. Thus, subsurface continuities,

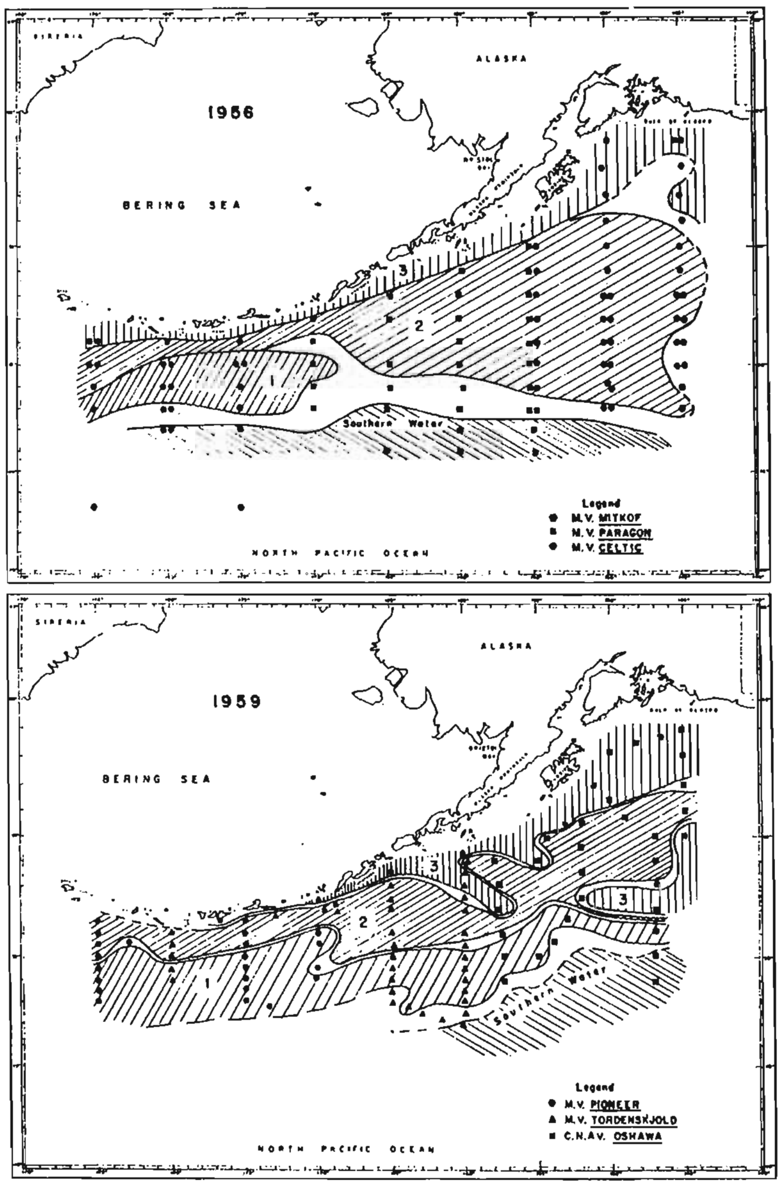


FIGURE 51. Variation in the geographical extent of Water Masses identified by T-S relations showing the greatly extended eastern intrusion of water (1) associated with the Subarctic Current System (from INPFC Annu. Rept. 1960, p. 85).

or pathways, exist and remarkable integrities are maintained even when interleafings of strata of different water masses occur. However, these continuities are not necessarily to be found on level geometric surfaces such as 100 m. Further, bathythermograph data reported at standard levels permit ascertaining only gross features and should not be used for comparative purposes such as, changing conditions over 10-day or monthly intervals, or even equivalent time periods in different years. However, gross features of considerable interest are afforded by these data. For example, temperatures at 100 m in June 1968 (Fig. 50) reflect the eastward penetration of cold water in the Subarctic Current System and a pronounced northward displacement of water having temperatures less than 3°C near 180° is evident. Sandwiched between this tongue and the central Aleutian Islands, a westward protruding tongue of 4°C water is evident, and flow in this area, the Alaskan Stream, is considered the source of water represented by the highly convoluted 3°C isotherm extending westward and northward of 50°N, 170°E. Obviously, the mean distributions of properties in this area (see Fig. 14) are gross simplifications of actual conditions.

The eastward flowing Subarctic Current contributes to the confinement of the westward flow in the Alaskan Stream to a narrow band along the Aleutian-Commander Island Arc only as far west as about 175°E, near which point effects of the westward flow are apparent in a greatly expanded area which extends to 165°E along 50°N. Perhaps the most significant factor is that, although fluctuations in annual conditions occur, these basic features are evident in all years data are available.

Data since 1960 are too sparse to denote specific changes in the eastward extent of the tongue of cold water associated with the Subarctic Current System but an indication of variability was detected by the intense INPFC field programs of 1956 and 1959 (Fig. 51).

2. *Eastern Area*

Major environmental surface and sub-surface features and variability as determined from individual oceanographic cruises (1960–62, and 1967–71), from bathythermograph and surface salinity observations taken during exploratory fishing operations (1965–

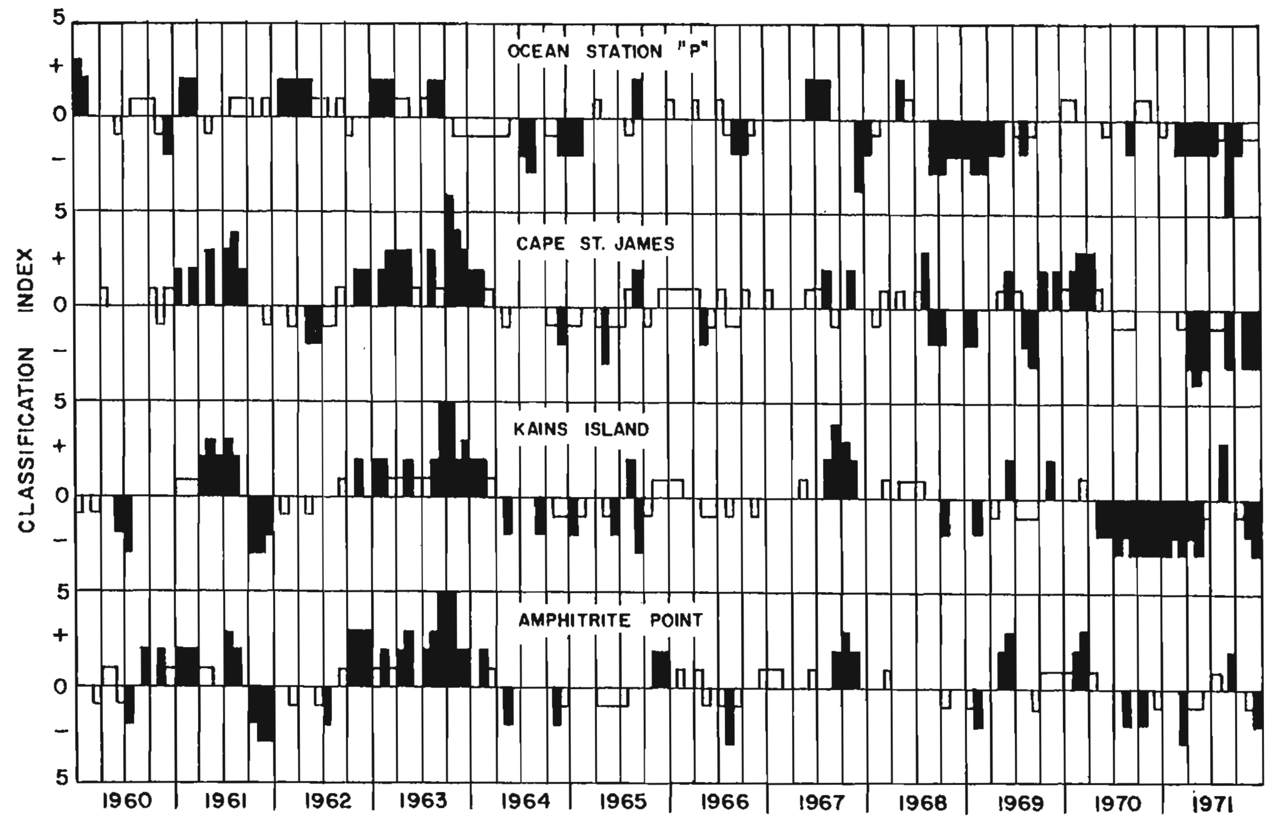


FIGURE 52. Surface temperature anomalies at Ocean Station "P", Cape St. James, Kains Island, and Amphitrite Point, 1960–71 (classification index computed as twice the difference between the monthly and long-term mean divided by the long-term standard deviation).

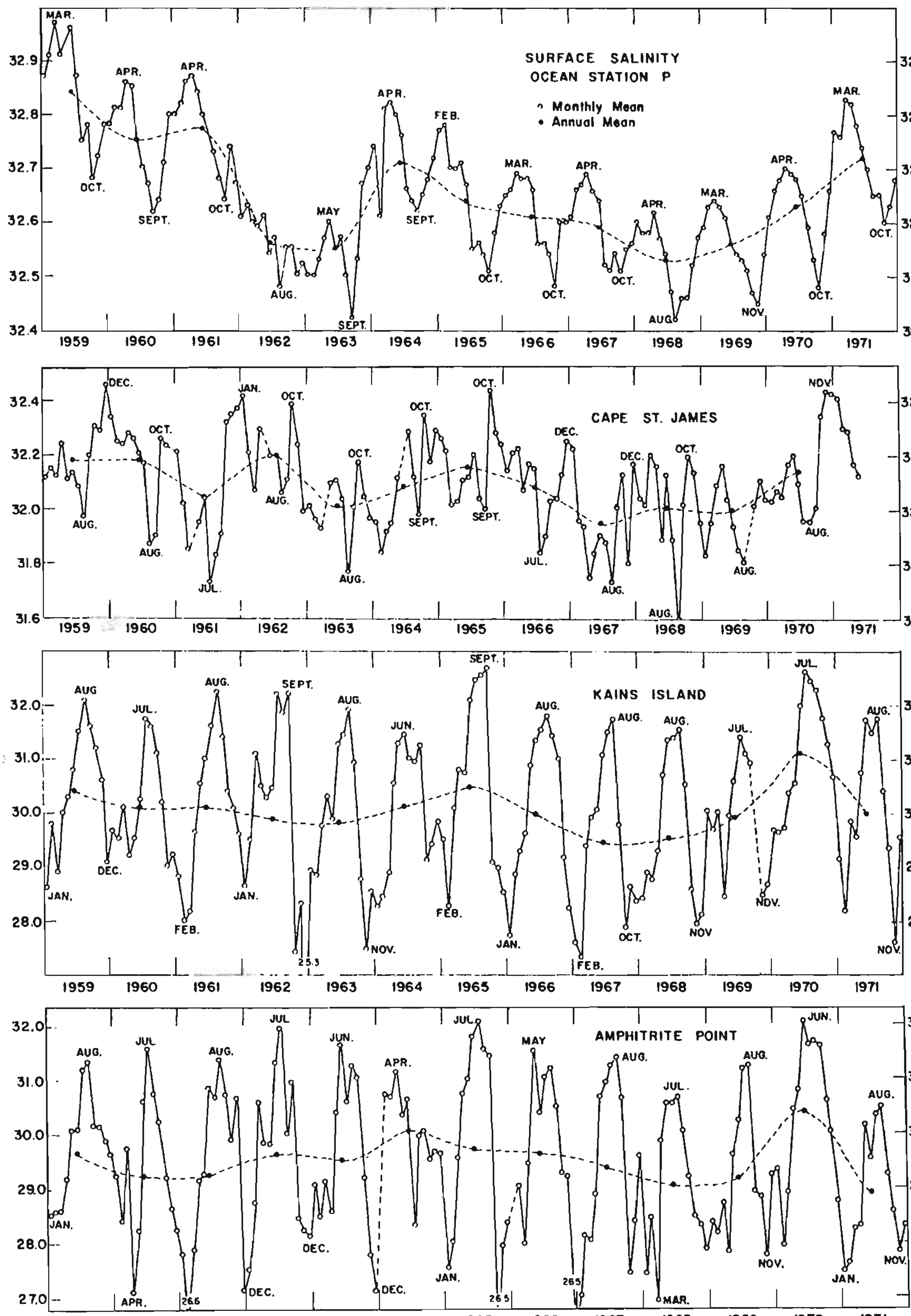


FIGURE 53. Monthly and annual mean surface salinity at Ocean Station P, Cape St. James, Kains Island, and Amphitrite Point, 1959–71.

66), and from time series data of surface salinity and temperature anomalies at Ocean Station " P ", Cape St. James (situated on the southern tip of the Queen Charlotte Islands), Kains Island and Amphitrite Pt. (on Vancouver Island) (Figs. 52 and 53) are summarized.

—Temperature (surface)

In winter 1960, surface temperature conditions over most of this area were generally similar to those observed in winter 1959. Anomalies were generally less than 0.4C°, except in the Gulf of Alaska where temperatures were 0.5°C higher in 1960 than in 1959; along the British Columbia coast, temperatures were slightly lower (0.4C°) in 1960 than in 1959. In summer 1960, surface temperatures over the area were similar to those in 1959, with slightly colder water present westward of Queen Charlotte Sound in 1960. Temperature anomalies at Ocean Station " P " and the coastal lightstations in 1960 show no persistent pattern, both positive and negative anomalies occurred.

During 1961, surface temperature conditions were generally above normal at Ocean Station " P ", particularly during the early part of the year and to a lesser degree during the latter part of the year. At the coastal stations above normal conditions prevailed until late summer, at which time a reversal to below normal conditions occurred.

Surface temperatures remained above average at Ocean Station " P " during most of 1962. On the other hand, at the coastal stations, surface temperatures were near or below normal, except during the latter part of the year when above normal conditions prevailed.

Winter (Jan-Mar) temperatures at Ocean Station " P " in 1963 were above normal and similar to those observed in winter 1958, 1960, and 1962 but reversed to slightly below normal in the latter part of the year. The largest positive anomalies at the coastal stations for the period 1960–71 occurred in 1963, and these conditions prevailed into early 1964.

The slightly below average conditions that occurred at Ocean Station " P " during the latter part of 1963 prevailed throughout 1964 and early 1965, with large negative anomalies in April, May, and December 1964 and in January-February 1965. Negative anomalies also occurred at the coastal stations in 1964 and persisted to about June 1965.

During 1966, both negative and positive anomalies occurred at Ocean Station " P " and at the coastal stations, but there was no persistent pattern. However, at Ocean Station " P " there were significant differences in the timing of commencement of seasonal heating and cooling compared to 1965. The period of minimum temperatures occurred about 6 weeks earlier in 1965 than in 1966. The time difference for maximum temperatures was approximately eight weeks, maximum temperatures occurred later and were 1.5C° higher in 1965 than in 1966. Similar heating and cooling trends occurred during 1966 along Line " P " as at Ocean Station " P ", except near the coast in early August when surface temperatures were 2–3C° lower than the adjacent waters. The cooling trend in the coastal waters was reflected in the daily temperatures from the coastal lightstations as early as mid-July, and at Ocean Station " P " in August.

During the period 1967–71, oceanographic surveys of the coastal and adjacent oceanic waters seaward of Vancouver Island were undertaken in March-April and in September-October. The following discussions are based primarily on these data. Unusual oceanographic conditions existed between Ocean Station " P " and the coast during late summer and early autumn 1967. Sea surface temperatures were about 2–3C° above normal and a well defined mixed layer was generally absent, the thermocline being essentially at the surface. Even as far west as Ocean Station " P ", layer depths in late August were occasionally as shallow as 6 m, compared to layer depths of 15–30 m usually encountered at this time of year. Temperature conditions for this period were similar to those observed in summer 1958, the isotherms trended nearly north and south between Ocean Station " P " and the coast, and the waters along the west coast of Vancouver Island were considerably colder than the adjacent oceanic waters. There was no obvious anomalous pattern in the horizontal distribution of isotherms, suggesting that there was no major change in the circulation, and the warm surface waters resulted from a combination of above normal insolation, light winds, and warm air advection. The geostrophic circulation pattern was dominated by numerous tongues and eddies, but the surface currents were low, of the order of 5 cm/sec. Near the edge and over the continental shelf, surface current speeds were approximately 15–20 cm/sec. It is fairly well established that the circulation in the summer months is dominated by tongues and eddies and their number, position, and intensity vary annually; however, they appear to be most prevalent and best developed during those periods in which sea surface temperatures are anomalously high.

Sea surface temperatures were normal in the coastal and adjacent oceanic waters off the British Columbia and northern coast of Washington, westward to about 133°W in April 1968. Normal conditions also occurred at Ocean Station " P ", suggesting these con-

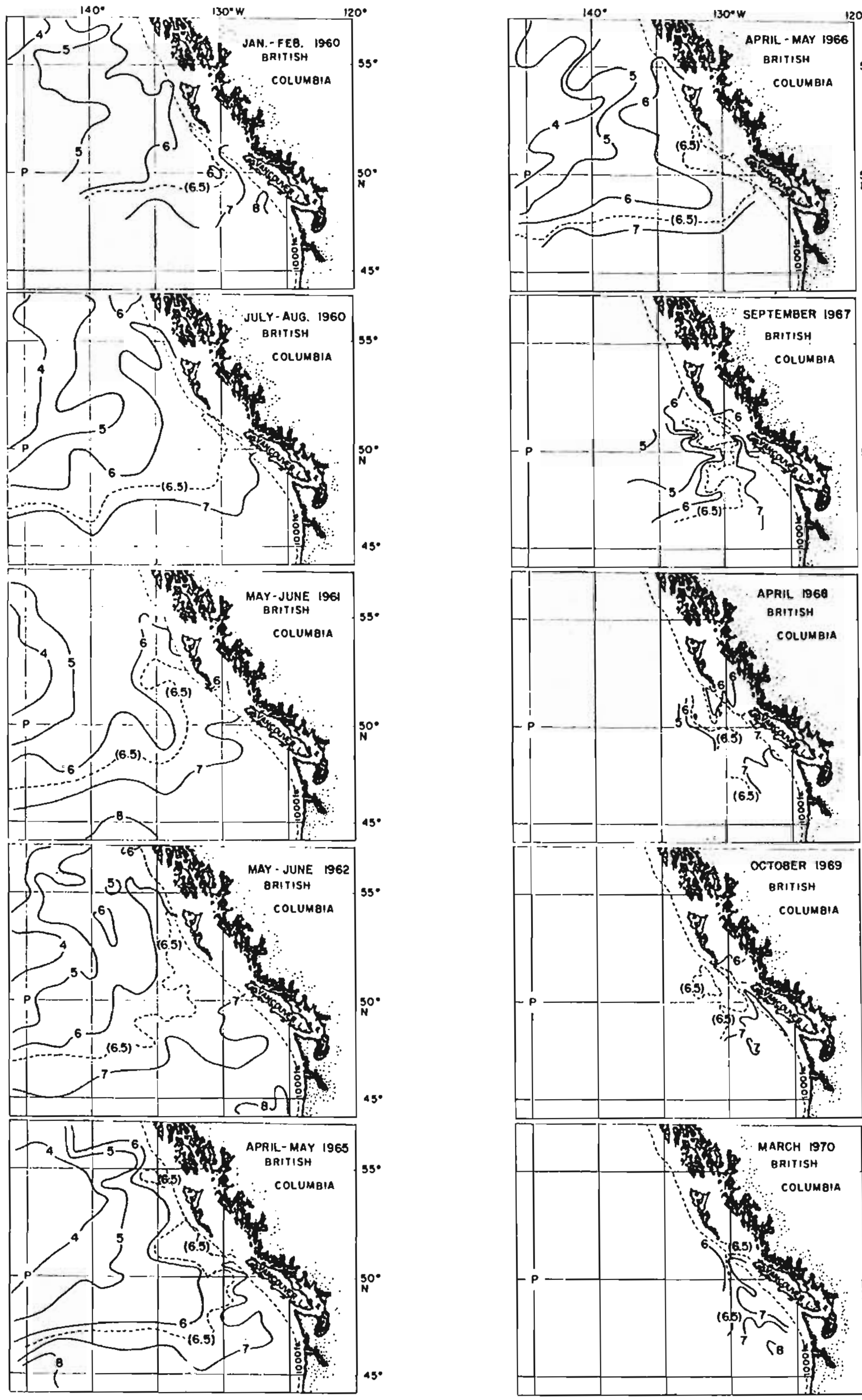


FIGURE 54. Temperature (°C) on the surface of salinity=33.8‰, 1960–62 and 1967–70 and temperature (°C) at 175 m depth (approximate depth of 33.88‰ isohaline) 1965–66.

ditions prevailed throughout the area. During the latter part of the year, sea surface temperatures at Ocean Station " P " were below normal and somewhat similar conditions were encountered at the coastal stations.

The below normal conditions persisted at Ocean Station " P " during 1969. However, at the coast stations conditions alternated between below average to above average.

In March 1970, sea surface temperatures were higher (~1C°) than in March 1969 and greater (~1C°) than normal for the coastal and adjacent oceanic waters off the British Columbia coast. However, during the latter half of the year conditions reversed to below average in the coastal waters, particularly off Vancouver Island. At Ocean Station " P ", conditions were near normal throughout most of the year.

In 1971, below normal conditions prevailed at Ocean Station " P " throughout the year. Below normal conditions also prevailed at the coastal stations except for a brief midsummer period at the Vancouver Island coastal stations when above average conditions prevailed. Sea surface temperatures off the British Columbia coast were significantly lower (1.5–2C°) in March 1971 than in March 1970 and conditions were anomalously cold, about 1C° lower than normal. In the Gulf of Alaska, lower than normal sea surface temperatures occurred during the months of May, June, and July. Temperatures in May were approximately 1C° below normal, and, in June and July, about 2C° below normal.

—Salinity (surface)

The seasonal and annual variations in surface salinity at Ocean Station " P " and at the coastal stations are readily apparent in Fig. 53. At Ocean Station " P ", maximum surface salinities occur in February-April when the depth of the mixed layer is greatest (~100 m) and minimum values in August-October when the depth of the mixed layer is least (~30 m). The seasonal range is about 0.2‰. Superimposed on the seasonal variability was an annual variability; surface salinities were lowest during 1962, 1963, and 1968, and highest during 1960, 1961, 1964, and 1971. At the coastal stations a seasonal variability also occurs, but the periods of minimum and maximum salinities not only are different than those at Ocean Sation " P ", but also differ between the coastal stations. At Cape St. James, salinities are a maximum in October-December and a minimum in July-September, whereas, along the Vancouver Island coast, maximum salinities generally occur in July-August, and minimum values are found in November-February. During June 1966 the tongue of low salinity water, extending westward from Queen Charlotte Sound was clearly delineated. This feature continued to develop through July and persisted into August.

—Temperature (subsurface)

The annual variability in the northward intrusion of warm, nonseasonal waters off the British Columbia coast is well documented for the period 1955–66. The intrusion has been shown in horizontal distributions of temperature on several surfaces, in particular on a salinity surface of 33.8‰ and a sigma-t surface of 26.6. These surfaces lie in the upper part of the lower zone, approximately 175–200 m. Further, it has been shown that temperature distributions on each of these surfaces are very similar for any one period. A summary of temperature conditions on the salinity surface of 33.8‰ for 1960–62 and 1967–70, and at 175 m depth for 1965–66 is presented (Fig. 54). A significant and frequently occurring feature in these distributions is the westward intrusion of warm water at about 54°N. It is apparent that in winter and summer 1960, the intrusion off the British Columbia coast of water >6.5°C was slight and markedly similar. The northward extent of warm water increased in 1961 and 1962, but not quite to that observed in 1958, an anomalously warm year. There are no data for 1963 and 1964, but bathythermograph data for 1965 and 1966 (e.g. the distribution of temperature at 175 m, approximately the depth of salinity of surface 33.8‰) indicate that the intrusion had retreated and it appears to have remained relatively static until October 1970. Because of the similarity in temperature distributions at depth in late winter and summer a steady state condition may exist during this period, and conditions in this nonseasonal layer off the British Columbia coast are normally established during the autumn and early winter period. It is reasonable to assume that the northward flow in the California Undercurrent is a maximum during the autumn and winter period coincident with the seasonal reversal of surface flow along the coast, and that there are annual variations in the strength of the winter flow, resulting in annual variations in the extent of warm water at depth off the British Columbia coast.

3. *Aleutian Area*

The Alaskan Stream is one of the most significant features of the region. It has the characteristics of a western boundary current and because it represents a return flow of water carried into the Gulf of Alaska area, its extent, position and transport are considered to be cumulative effects related to the wind-driven circulation in the northeastern part of the region and therefore depend more on average conditions than

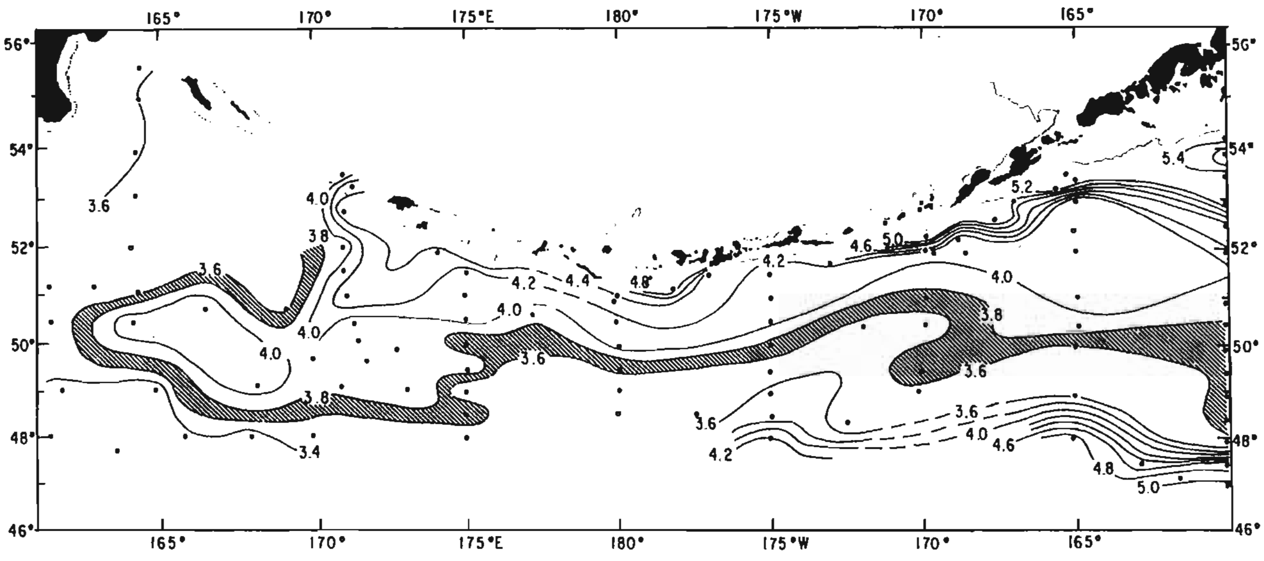


FIGURE 55. Temperature (°C) on sigma-t surface=26.90, summer 1959. Shaded area shows the approximate southern boundary of water influenced by the Alaskan Stream.

on local climatic conditions. Further, any recirculation of these waters in the Gulf of Alaska gyre or penetration through the Aleutian passes will have a pronounced effect on the temperature and salinity regimes of the waters associated with the Subarctic Current in the Gulf of Alaska area and of the waters of the southern Bering Sea, respectively. For these reasons its spatial distribution and its annual, seasonal, and short-term variations in westward extent, width, and transport are of prime significance.

Prior to 1959, available oceanographic data were inadequate to map the spatial continuity of the Alaskan Stream from its origin in the Gulf of Alaska to its western extremity in the western subarctic. In summer 1959, data were gathered that permitted showing the principle features of the Stream. Horizontal distributions of temperature on sigma-t surfaces (Fig. 55) and distributions of temperature-maximum stratum (mesothermal) and temperature-minimum stratum (dichothermal) waters showed that the Alaskan Stream originated in the Gulf of Alaska at approximately 150°W and extended westward in a relatively narrow band south of the Aleutian Islands, eventually separating into two tongues at about 51°N, one extending to 170°E immediately south of the Aleutian Islands and the other extending to 165°E at approximately 50°N. Calculated volume transports (relative to 1000 m) showed a flow of 10 Sv westward along the Alaska Peninsula ; 5.8 Sv or about one-half the transport flowed westward at 160°W, the other 4.2 Sv recirculated in the Gulf of Alaska gyre. This recirculation near 160°W was also evident in the surface salinity distributions. A relatively constant transport of 4–6 Sv extended as far west as 170°E, where the Stream diverged at approximately 51°N, and about two-thirds of the transport moved northward into the Bering Sea and one-third southwestward into the western Pacific. The main features of the flow were confirmed in data gathered in summer 1961. The existence of the Stream in winter was shown in data gathered in winter 1962. Although it was shown to extend as far west as 175°W, where geostrophic flow was in excess of 10 cm/sec, its westward extent was not determined. Also, at 155°W for the same period, it was shown that the Stream shifted 185 km offshore and a well-developed eastward-flowing countercurrent formed inshore of the Alaskan Stream (Fig. 56). Since 1962, data were gathered in order to define more precisely the seasonal and annual variability in transport ; to confirm the existence of recirculation in the Gulf of Alaska ; to identify temperature and salinity fronts associated with the boundaries of the Stream and their movements ; and to show seasonal and annual variations in the position of its axis and in its width.

Intensive investigations in this vicinity during late winter 1966 showed no westward flow south of the Aleutian Islands west of Attu Island (173°E), but an intense northward flow into the Bering Sea near 170°E that was confirmed by drift bottle experiments. The consistency of these cumulative data established the fact that the Alaskan Stream is a permanent year-around feature of the region.

Direct current measurements and the drift of vessels in this domain have indicated surface velocities in excess of 100 cm/sec at distances of 18 to 55 km offshore and that there is appreciable flow, 18–28 cm/sec, at 1000 m depth. Drogue measurements at 0, 300, 600, and 1000 m showed a velocity maximum at 300 m depth. This velocity maximum was confirmed in geostrophic calculations, but its depth occurred at about 200 m. Studies of flow across the Stream at specific longitudes show that there are relatively marked seasonal and annual variations in the flow in the Alaskan Stream. A summary of maximum velocities and volume transport at various longitudes are tabulated in Table 9. South of Adak Island maximum velocities, 48–85 cm/sec, appear to occur during the summer months at a time when the axis of the Stream is relatively close to shore. The seasonal variability in flow is also significant. For example, in spring 1970 a transport (relative to 1500

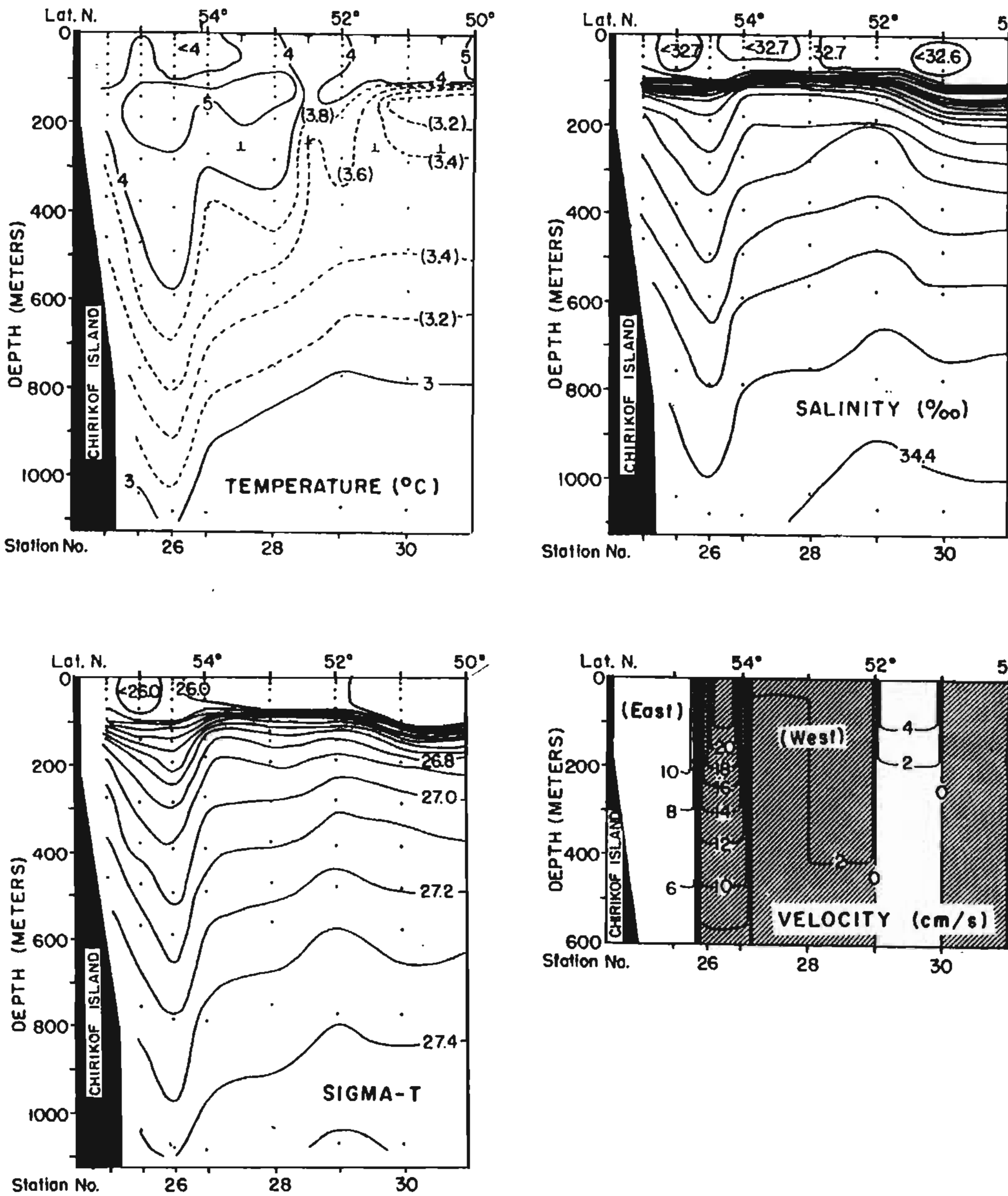


FIGURE 56. Vertical sections of temperature, salinity, sigma-t, and geostrophic currents along 155°W in spring 1962. Geostrophic currents indicate an eastward countercurrent along the continental slope inshore of the high velocity Alaskan Stream.

TABLE 9. Summary of velocity and volume transport in the Alaskan Stream.

Data	Location	Maximum Vel (cm/sec) (0/1500 m)	Maximum transport (Sv) (0/1500 m)
Nov. 1965	175-177°W	53	9
March 1966	"	55	13.9
Sept. 1966	"	67	9.7
June 1967	"	85	9.5
Aug. 1967	"	46	8.4
Feb. 1968	"	43	8.2
April 1968	"	39	8.4
July 1968	"	61	5.1
April & May 1968	162°W	62	7.7
April & May 1968	164°W	50	6.9
April & May 1968	176°W	39	8.4
April & May 1968	179°E	41	8.7
Winter 1969	155°W	—	8
Winter 1969	165°W	—	12
Spring 1969	155°W	—	8
Spring 1969	165°W	—	8
Spring 1969	176°20′W	—	11
Summer 1969	176°20′W	—	6
Winter 1970	165°W	—	11
Spring 1970	167°W	—	9
Spring 1970	176°25′W	—	12
Spring 1970	179°E	—	14
Summer 1970	175°W	—	6
Summer 1970	178°E	—	7

m) of 9 Sv at 167°W was less than the winter transport of 11 Sv near the same location (165°W). Downstream the transport was larger, 12 Sv at 176°25′W and 14 Sv at 179°E. A rapid change in flow conditions was indicated by transport values measured after June 1970; these later values (6 Sv at 175°W and 7 Sv at 178°E) were only half those in May at adjacent locations.

Temperature and salinity conditions in the Alaskan Stream have also varied. Generally the mesothermal water associated with the Alaskan Stream has a temperature of 5.5°C at 155°W. Its temperature decreases through mixing to 4.5°C south of Adak Island at 177°W and to near 4.0°C west of Amchitka Island (174°E). These warm waters usually extend to approximately 200 m depth. In winter 1963, temperature conditions were quite similar to those encountered during winter 1962 along 180°. However, in March-June 1966, south of Adak Island conditions were anomalous; warm water, >4.0°C, normally present up to 185 km from shore at depths to 200 m was not observed. However, by early August, water warmer than 4°C was encountered at depths to 200 m, but was confined to the inshore area. In 1967 and 1969 normal temperature conditions prevailed. Anomalous conditions were again encountered in February 1970. Along 160°W the vertical extent to 450 m of water >4.0°C was greater than normal and the presence of surface temperatures in excess of 5°C was also unusual for this time of year. A most interesting feature observed in spring 1970 was the width and extent of unusually dilute surface water in the Alaskan Stream which terminated in a sharp front near 175°W. Surface salinities less than 32.1‰ which are rarely found offshore west of 170°W were encountered near 175°W. At the same time, the 33.0‰ isohaline, normally located at 48°N south of the Alaskan Stream shifted to 50°N. These conditions suggest a below normal recirculation of coastal waters in the Gulf of Alaska gyre and a partial blocking or restricted westward flow near 175°W as a result of a greater than normal northern component of oceanic flow in this area. This may also explain the approximately one-half reduction in transports noted in the Alaskan Stream from spring to summer 1970. A comparison of subsurface temperatures in May 1971 with those observed in May 1969 (considered normal conditions) south of Unimak Pass indicates temperatures were over 2.5C° lower in 1971 and that the lower temperatures were present along the southern side of the Aleutian Islands to a depth in excess of 500 m. A series of vertical sections of temperature south of Adak Island from 1960–70 is presented in the Appendix (App. Fig. 11).

Recirculation in the Gulf of Alaska has been well documented in a number of reports. However, data are not available that will allow a complete description of the seasonal and annual variability of this feature. Nevertheless it appears that it is a continuous event, varying in intensity from year to year. It may occur anywhere between 155°W and 170°E and appears to be more evident in winter and spring data than in summer data. Recirculation in spring 1966 between 160° and 175°W was evident in surface salinity data and in the distribution of mesothermal water. Extensive recirculation between 165° and 170°W prevailed in April 1968 resulting in unusually warm mesothermal conditions in the ridge and Subarctic Current waters, and effectively blocked the eastward movement of cold water (<3.6°C) beyond 178°W. Recirculation was in evidence in winter 1969 between 155° and 160°W and the eastward shift allowed the penetration of cold subsurface waters of the Subarctic Current to extend eastward to 170°E. Although recirculation was indicated in winter 1970 between 156° and 159°W, it appears to have been relatively weak as the cold subsurface water of the Subarctic Current was clearly defined as far east as 157°W.

An offshore shift in the position of the Alaskan Stream has been observed to occur in the winter months, and may be a seasonal event. This phenomenon was first observed during winter 1962 at 155°W when it was noted that the Stream shifted 185 km offshore and a well-developed eastward flowing countercurrent formed inshore. It was again observed in February and March 1967 at 162° and 155°W; the axis of the Stream shifted to a position 280 km from shore, and a countercurrent developed with an eastward transport near shore similar to that observed in 1962. The fact that such a shift can occur as far west as Adak Island was observed in February 1968; the axis of flow shifted to 100 km offshore south of Adak Island and bands of alternating eastward and westward flow 8–16 km wide shifted onshore. Marked salinity and temperature gradients have also been identified with the boundaries of the Stream and these gradients have also been shown to shift, and over relatively short periods of time. Salinity and temperature fronts were noted south of Adak Island in August 1969. At the front salinity decreased sharply by 0.7‰ in a distance less than 1.6 km and the temperature rose 6C° in about 10 km. A strong westward velocity of about 50 cm/sec occurred in and north of the front. South of the front, however, in the high-temperature, low-salinity water an appreciable northward component existed, and the westward component of drift was only about 5 cm/sec. Repeated temperature and salinity observations along the same longitude revealed that the front shifted position nearly 50 km within a two-week period. These data confirm the fact that high salinity water of Bering Sea origin may intrude southward through one or more of the Aleutian Islands passes and move westward. Similarly a northward intrusion of the Alaskan Stream into the Bering Sea through one or more of the Aleutian Islands passes also occurs.

An important aspect of the Alaskan Stream is its westward extent and configuration. The seasonal and annual variability in its westward extent have been documented using bathythermograph data. Horizontal distributions of temperature at 100 m depth give some evidence of its variability but only broad conclusions can be drawn which are based upon the distribution of water >4.0°C (Alaskan Stream water). In May and June 1963 the westward extent of water >4.0°C was greater than normal, and this water was found west of 170°E. However, in May to mid-June 1964, water warmer than 4.0°C was noted only as far west as 180°; this water gradually moved westward, to the vicinity of 175°E by the latter part of June and to 170°E by late July. In 1965, water >4.0°C was present in the form of an isolated cell as far west as 173°E in late May and this cell moved westward to 170°E by mid-June. Again in 1966, as in early 1964, water >4. °C extended westward only to 180° from late May to late June, and was present to as far west as 170°E at 50°N in July. In summer 1967, water >4.0°C was absent south of the Aleutian Islands between 170°W and 170°E and is considered to be a result of lower than normal subsurface temperatures and not the absence of Alaskan Stream water in this area. Conditions in autumn 1968 showed that the warm water associated with Alaskan Stream extended westward to 170°E and was still present as far west as 172°E in June 1969. A marked anomaly was

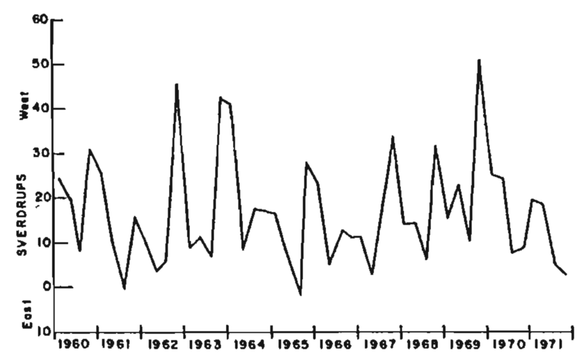


FIGURE 57. Mean seasonal zonal integrated total wind-stress transports (Sv) between Adak Island and 50°N (west flow positive values).

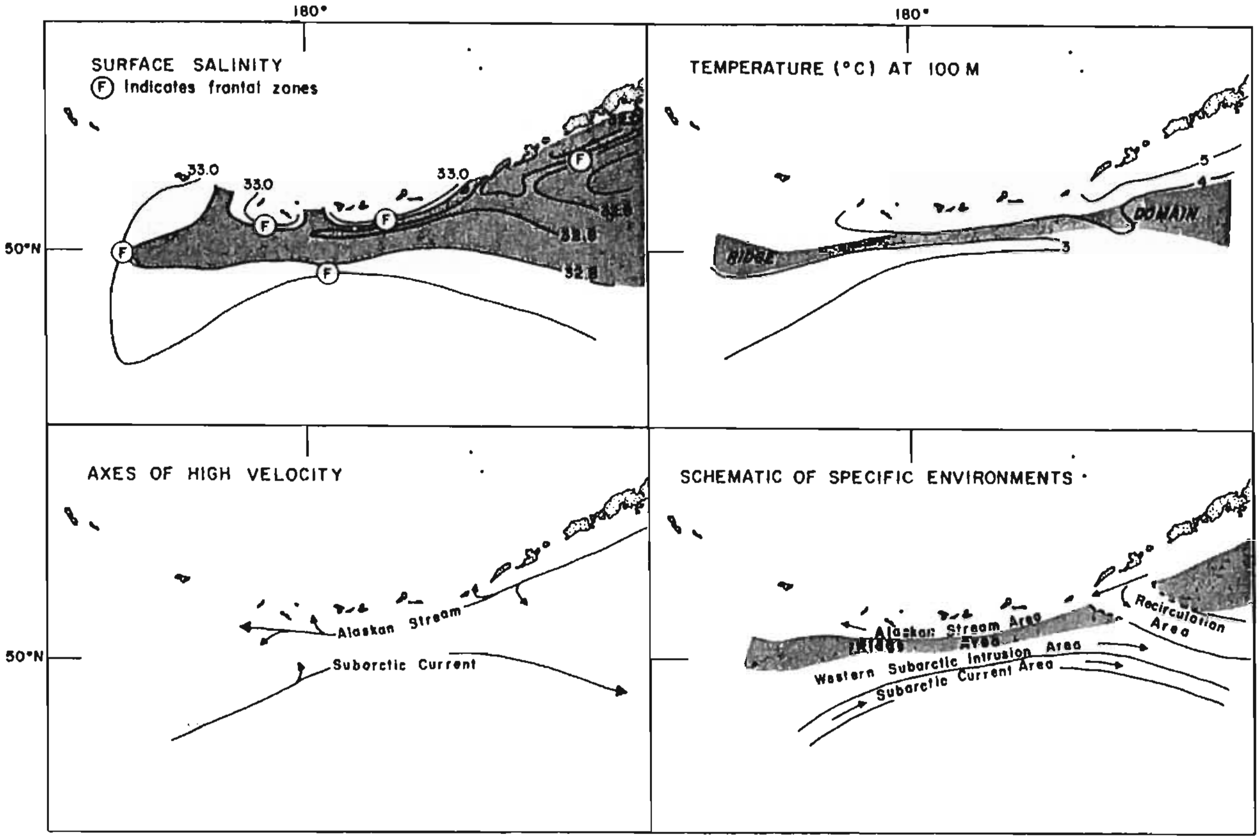


FIGURE 58. Dominant oceanographic features in the Aleutian area.

noted in June 1970; water warmer than 4.0°C was limited to the area east of 170°W. In summer 1971, warm water extended westward to near 170°E and its configuration was similar to that observed in 1968. From these data it is reasonable to conclude that the westward extent of the Alaskan Stream was limited and/or its subsurface temperatures were lower than normal in 1964, 1966 and 1970. However, in 1963 the Alaskan Stream appeared to extend farther west than normal. Possible variability in zonal flow in the Stream from 1960–71 as suggested by seasonal wind-stress transport (integrated total transport) between Adak Island and 50°N is presented (Fig. 57).

A summary of dominant surface and subsurface oceanographic features in the Aleutian area that could influence movements of salmon is presented in the form of schematic diagrams (Fig. 58).

B. Coastal Surface Conditions

Annual reports to the INPFC on oceanographic conditions were usually based on results of individual cruises that consumed all the resources of the small staffs involved. Only in a few instances were data from other sources used to expand or complete the knowledge obtained; in many cases, such data were not available in a proper time frame, and delays of up to a year in dissemination of tabulated results were not uncommon.

Station data from all sources (see Fig. 1) in the area 34–68°N have been sorted into 2×2° quadrangles and mean conditions for various parameters were obtained for various time periods: long-term, annual, quarterly, and monthly to provide an integrated picture of gross conditions. Deviations from these means were obtained by annual, quarterly, and monthly intervals for 1960–71. Because of the relative paucity of data available, the inherent biasing, and the limitations of mean data in reflecting actual conditions, analyses of such data in time and in space should be prudent; however, in view of the immensity and uniqueness of our task, the comparisons made and associations revealed are presented without apology. These are considered to provide a greater insight into actual conditions, the impetus or rational for future oceanographic investigations, a basis for investigating cause and effect relations between salmon distributions and the environment, and background information for environmental and fisheries forecasting models.

The analysis of such a huge amount of data proved to be a difficult task and necessitated a judicious selection of figures to show annual, seasonal and monthly conditions. Maps of monthly mean surface temperature alone would total 144 without including those showing anomalies from a long-term mean or from a previous or subsequent month, or from similar months in other years. It was decided that the information presented should have particular relevance to high seas salmon fishing, and June, a particularly critical month for these operations, was selected as the only individual month for which data are presented. However, it should be noted that in spring rapid warming and concurrent increased river runoff quickly alter conditions in the surface layer; thus, daily or even weekly conditions that may result in good or poor fishing can become not only masked, but completely obliterated when averaged over monthly time periods. Further, there are also two critical environmental periods that must be considered: winter cooling, during which heat is lost from the water, and summer warming, during which heat is stored. Long term climatic conditions require a balance, but local variations occur as a result of meteorological fluctuations, as well as variability in ocean currents. Anomalous losses of heat from the water column during a severe winter can retard normal spring warming and mild winters can have an opposite effect. Thus summaries of winter (Jan-Feb-Mar) and summer (July-Aug-Sept) conditions are also presented. It is usually only through station data obtained largely by research vessels that salinity and other chemical constituents are obtained. However, at the sea surface these data are considerably fewer than those of temperature and permit establishing mean conditions only in areas where intense repetitive surveys have been conducted, specifically off the coast of Japan, and off the southwest coast of British Columbia southward to California, where local oceanographic institutions have ready access to the ocean environment. Nevertheless, conditions in these areas influence shoreward migrations of salmon. Although numerous oceanographic data have been collected by INPFC groups in ocean areas where salmon spend most of the marine phase of their life cycle, the number of cruises and accompanying data in no way match the number and periodicity of observations obtained by local investigations in these two coastal areas (see Fig. 2). This is indeed unfortunate because the Aleutian Islands area is a critical part of the environment of not only salmon, but other living marine resources. In addition, except for its remoteness, this area would be an excellent site for the typical multidisciplinary oceanographic studies presently carried out aboard modern research vessels. Although the data are sparse, conditions in this area are also briefly summarized.

Even though most of the data have been combined into winter and summer periods, they are still fragmentary and assessment is difficult. Surface temperature observations from ships-of-opportunity would increase the amount of data available in $2 \times 2°$ quadrangles, but it was pointed out earlier that even $1 \times 1°$ quadrangles are still too large to adequately assess the extent or intensity of interactions at the Kuroshio-Oyashio confluence, upwelling off the west coast of North America, or the boundary flow along the coast and in the Aleutian and Kuril Islands areas —all of which have critical space scales of less than 50 km. One advantage of presenting station data independently is that temperature and salinity data from these sources are generally commensurate. Marked annual variabilities are evident and should provide the rationale for more intense and better organized field activities aboard research vessels.

1. *Western Area*

Maps of surface temperature and salinity, and anomalies, on which the following discussions are based are presented in the Appendix (App. Fig. 12).

—Temperature

During winter much of the Sea of Okhotsk is covered with ice and observations are scarce, but sea surface temperatures of approximately 0 to −2°C prevail over most of the area. Mean temperatures off the east coast of Honshu were generally 1–2C° below normal in winter 1960, 1961, and 1962, but positive anomalies occurred offshore (east of 145°E) and these increased each year reaching a maximum of 4°C in 1962. Although below normal conditions along the south coast of Honshu in 1963 have been well documented, all quadrangles north of 40°N indicated positive anomalies of 0.2–2.0C°. Variable conditions occurred from 1963 to 1968, but negative anomalies were predominant in 1966, particularly in the Kuril Islands area. Extreme positive anomalies (>4C°) occurred in 1969.

Increasing insolation in June and the onset of vertical stratification in the water column results in variable conditions. Temperatures in 1960–61 were generally below normal in the Kuril Islands area, but above normal east of Honshu. Generally, above normal temperatures occurred in the area east of the Kuril Islands and Hokkaido in 1962–63 and 1967–68, below normal conditions in 1965–66 and 1969–70.

Data for the summer seasons are more extensive and considerable variability in conditions is evident;

however, coherence usually extends over a number of quadrangles. In summer 1960, above normal temperatures occurred in the southern Sea of Okhotsk while below normal conditions extended south of 44°N. Positive anomalies in the Sea of Okhotsk increased in summer 1961 and above normal temperatures (>2C°) extended southward at least to 40°N and eastward to 162°E. In summer 1962, above normal temperatures occurred in the central Sea of Okhotsk, and south of Hokkaido. Except for positive anomalies near the southern tip of the Kamchatka Peninsula and an area centered around 44–46°N, 160–164°E, generally below normal conditions prevailed. And, except for isolated positive anomalies in 1967, extensive negative anomalies extended throughout the western area of the region from 1965 to 1969.

Even in this area of extensive mixing as a result of the Kuroshio-Oyashio confluence long-term warming and cooling cycles were generally evident, except perhaps during the summer period in the Sea of Okhotsk where opposing conditions were evident at times. Particularly evident was an extended period (1965–69) of below normal temperatures that occurred during summer even though in two years (1967–68) large positive anomalies occurred in June.

—Salinity

Seasonal and annual variations in surface salinity in this area are related primarily to the variability in the strength of flow in the Oyashio and Kuroshio Currents which results in variations in the position of the confluence of these two currents and in the subsequent eastward flow. The marked differences in the surface salinity of these currents results in large differences in anomalies in adjacent quadrangles.

Mean winter, June, and summer salinities off the coast of Japan were generally above normal (0.25–1.0‰) in 1960. Salinity anomalies were variable in winter 1961 but, by June, negative anomalies prevailed over most of the area and these lower than normal salinities persisted through the summer months. In winter 1962, the anomalies were somewhat variable but, by June, negative anomalies again prevailed over the region except in one quadrangle, and salinities remained below normal during the summer period, except off the coast of Japan where above normal conditions prevailed. By winter 1963, above normal salinities prevailed over the area. A marked reversal of conditions occurred by June 1963 and the area was dominated by large negative anomalies (0.25–1.0‰) in summer. Variable conditions occured in winter 1964 but, in general, the area was again dominated by negative anomalies. In June 1965, a reversal of conditions occurred in the northeastern part of the area but, by winter 1966, salinities were again below normal, except immediately off the coast of Japan where greater than normal salinities occurred. Salinities were generally above normal in June 1966 and remained above normal in the southern part of the area during summer; however, below normal salinities occurred in the northern part of the area in the latter period. In all three periods (winter, June, and summer) in 1967, salinities were generally above normal and remained above normal off Honshu and in the eastern part of the area. In winter 1968, salinities were above normal, except immediately off the coast of Honshu; but, in June, salinities were below normal over a large part of the area. During summer 1968, positive anomalies were evident. Subsequent to winter, 1969, positive anomalies persisted over most of the area until at least winter 1970.

2. *Eastern Area*

Maps of surface temperature and salinity, and anomalies on which the following discussions are based are presented in the Appendix (App. Fig. 13).

—Temperature

Winter data are somewhat fragmentary but large anomalies were rare. Near normal conditions prevailed in 1960–61; and small negative anomalies occurred along the coast in 1962. Extensive positive anomalies occurred in 1963 and, except for a large offshore area of slight negative anomalies in 1964, near normal conditions prevailed until 1969 when negative anomalies of 2C° occurred.

During June 1960, interspersed positive and negative anomalies occurred along the coast and, in 1961, a large area of positive anomalies occurred inshore of an area of generally below normal temperatures. Negative anomalies dominated the entire coastline in 1962, and these conditions reversed in 1963 when extensive positive anomalies were present. Subsequent June data are fragmentary, but generally below normal temperatures occurred in 1964–65 and above normal temperatures in 1968–69; inshore temperatures were below normal in 1970.

Summer data in this area are fairly extensive and reflect the general 5-year trends of cold and warm periods discussed subsequently. Of particular interest is the reversal of conditions along the coast—from below normal in 1962, above normal in 1963, and below normal in 1964. Below normal conditions prevailed off the coast in 1965–66. Marked warming occurred throughout a large area north of 44° in 1967 and along the Washington and British Columbia coasts in 1968; whereas below normal temperatures occurred south of 44°N in 1968–70.

—Salinity

This area is subject to the seasonal variation in land drainage and seasonal reversal of onshore-offshore flow and annual variability in these factors is reflected in the salinity anomalies. Although both positive and negative anomalies occurred in the coastal area, conditions were generally above normal in 1960 and these conditions persisted through winter 1961, except off the coast of California where salinities were lower than normal. By summer 1961 negative anomalies were dominant. However, in June 1962, conditions had reversed to positive anomalies and these conditions prevailed during the summer except in the northwest part of the area where negative anomalies occurred. A change from positive to negative anomalies occurred during the first half of 1963 and by summer the area was characterized by marked negative anomalies; the anomalously low salinity of the offshore water during 1962 and 1963 was readily apparent in data at Ocean Station "P" (see Fig. 53). During 1964, although conditions were somewhat variable, negative anomalies generally prevailed and these conditions remained during the first half of 1965. However, in summer, the salinity of the near-shore waters was relatively high. These conditions, negative anomalies offshore and positive anomalies inshore, prevailed through 1966. An abrupt change occurred in 1967; by summer, the area was dominated by marked negative anomalies, except in the southern part of the region. Although data for the first half of 1968 are too sparse to establish any trend, salinities during summer were in general below normal north of 46°N and above normal south of this latitude. Salinities remained below normal during the winter 1969, but by summer positive anomalies were dominant in the eastern part of the area and these conditions appeared to prevail through 1970, except in the offshore waters. Again, data at Ocean Station "P" reflect the presence of low salinity water during 1967–69, with salinities increasing during 1970.

3. *Aleutian Area*

—Temperature

Only in 1961, 1962 and 1966 are station data available during winter but these are not sufficient to ascertain valid monthly means. Data during June are more complete but still widely scattered and result in patchy distributions of anomalies. No particular patterns are obvious except for 1963 when, in contrast to general warming throughout the region, negative anomalies occur in all quadrangles from which data were available. However, positive anomalies are widespread and dominate conditions in the other general warming period, 1967.

—Salinity

Although the data in this area are too sparse to establish any seasonal variations, some annual trends can be recognized. Salinities were lower than normal (.05–.25‰) over most of the area in summer 1961 and these conditions prevailed through summer 1963. Relative high salinity water was present immediately south of the Aleutian Islands in the Alaskan Stream in June 1964, but was replaced by low salinity water in the summer, and these conditions persisted through till at least June 1965. In subsequent years, the only obvious trend was the presence of relatively high salinity water in the eastern part of this area in 1968. A feature of the salinity anomalies is the fact that they were generally small in this area, 0.05–0.25‰.

TABLE 10. Subjective comparison of winter (Jan-Feb-Mar), June, and summer (July-Aug-Sept) surface conditions in the western and eastern parts of region, based on inspection of oceanographic station data and anomalies from long-term means by 2×2° quadrangles, 1960-70 (see App. Fig. 13).

	Western Area			Eastern Area		
	Winter	June	Summer	Winter	June	Summer
1960		Cold				Cold
1961	Cold		Warm			
1962					Cold	
1963	Warm	Warm		Warm	Warm	Warm
1964					Cold	Cold
1965	Cold	Cold		Cold	Cold	
1966	Cold	Cold	Cold			
1967		Warm	Cold			Warm
1968		Warm	Cold		Warm	
1969	Warm	Cold	Cold	Cold	Warm	Cold
1970	*	*	*			Cold

* Indicates few data.

This is not unexpected as large salinity gradients occur only south of the islands and these are masked by the large (2 × 2°) grid size.

Conditions in the three areas during 1960–70 are summarized (Table 10) with respect to temperature trends. Although all three areas have indications of warming or cooling suggested previously, in only two instances were such trends dominant in all three periods—above normal conditions prevailed in the eastern area during 1963 and below normal conditions prevailed in the western area in 1966. Of course patchiness is to be expected and perhaps more coherence could be established if smaller areas were selected, however, such analyses are beyond the scope of this report. Nevertheless the long-term trends of warming and cooling are more readily apparent when the data are more complete.

C. Transregion Surface Temperature Anomalies

Because of the paucity of station data in the central part of the region, it was necessary to resort to ship-of-opportunity data to ascertain environmental conditions in this area. There are one or two orders of magnitude more of these data than of station data and over two million observations of sea surface temperature were programmed by 5 × 5° quadrangles to obtain annual and monthly departures from long-term means (1948–67) for years 1960–71. It is indeed unfortunate that, although numerous meteorological data are obtained, oceanographic observations from ships-of-opportunity are limited to this one observation. Perhaps as accurate surface temperature data become available from satellite observations, observations from ships-of-opportunity can be expanded to include data on temperature structure in the water column and on chemical constituents. Some preliminary experiments and equipment tests have already been made aboard merchant ships.

Surface temperature in the region is a capricious water property because, although generally limited to a 10C° range from winter to summer, external and internal influences cause significant fluctuations. Increased insolation in spring results in a stable surface layer several meters thick that warms quickly under calm conditions but can as quickly be destroyed by wind mixing, resulting in abrupt changes of 1–3C°; turbulent mixing as a result of convergences and divergences can also markedly alter surface temperatures as much as 5C° or more, particularly in the vicinity of the Aleutian Islands. And, at the confluence of the Oyashio and Kuroshio currents, meridional changes of 5C° occur within a distance of 50 km. However, considerable insight into fluctuations in transpacific surface conditions is afforded by these temperature data and there is a periodicity to these phenomena.

1. *Annual Trends*

Annual mean data represent an integrated picture of monthly mean conditions which is unavoidably biased because the partial effects of two isolated cooling periods (Jan-Feb-March and Oct-Nov-Dec) are combined with a continuous warming period, April to September. For example, an unusually warm spring and summer period could significantly moderate subsequent fall and winter (Jan-Feb-March of the following year) conditions and a 12-month period of anomalously warm conditions would occur. However, by following strictly calendar months, if in the subject year anomalously cold conditions occurred in Jan-Feb-March that were sufficient to negate the effect of the subsequent warming period, annual mean conditions would reflect normal conditions, thereby effectively masking significant sequential events. Although it is not necessary to resolve this dilemma because monthly anomalies are presented (App. Fig. 14), this condition should be borne in mind when inspecting the annual mean data for 1960–71 (Fig. 59). Negative anomalies were predominant in 1960 and warming trends increased until 1963 when positive anomalies existed through the region. Cooling trends are evident in 1964 to 1966 and in 1967 transpacific positive anomalies occurred. From 1968 to 1971 positive anomalies remained dominant in the western part of the region, whereas negative anomalies were dominant in the eastern part.

One might expect significant trends to be evident in the southwestern part of the region where large energy exchanges occur at the sea surface (see Fig. 4) and less correlation in the eastern part of the region where divergences and other circulatory phenomenon occur. The sequential appearance of positive and negative anomalies off Honshu suggests a relation to oceanic flow. Positive anomalies occurred in 1961, negative anomalies were present in 1964, and positive anomalies reoccurred in 1966, suggesting the 5–6 year periodicity also evident in the previous decade (Favorite and McLain, 1973). Although marked negative anomalies did not occur off Honshu in 1969, they were predominant in the eastern part of the region, where unusually cold conditions, particularly in the Bering Sea, persisted until 1972. Thus, the 5–6 temperature cycles are not as readily apparent in the late 1960's and early 1970's, but monthly conditions discussed in the next section indicate some trends are still evident.

2. *Monthly Fluctuations*

The apparent 5–6 year cycles of extreme warming

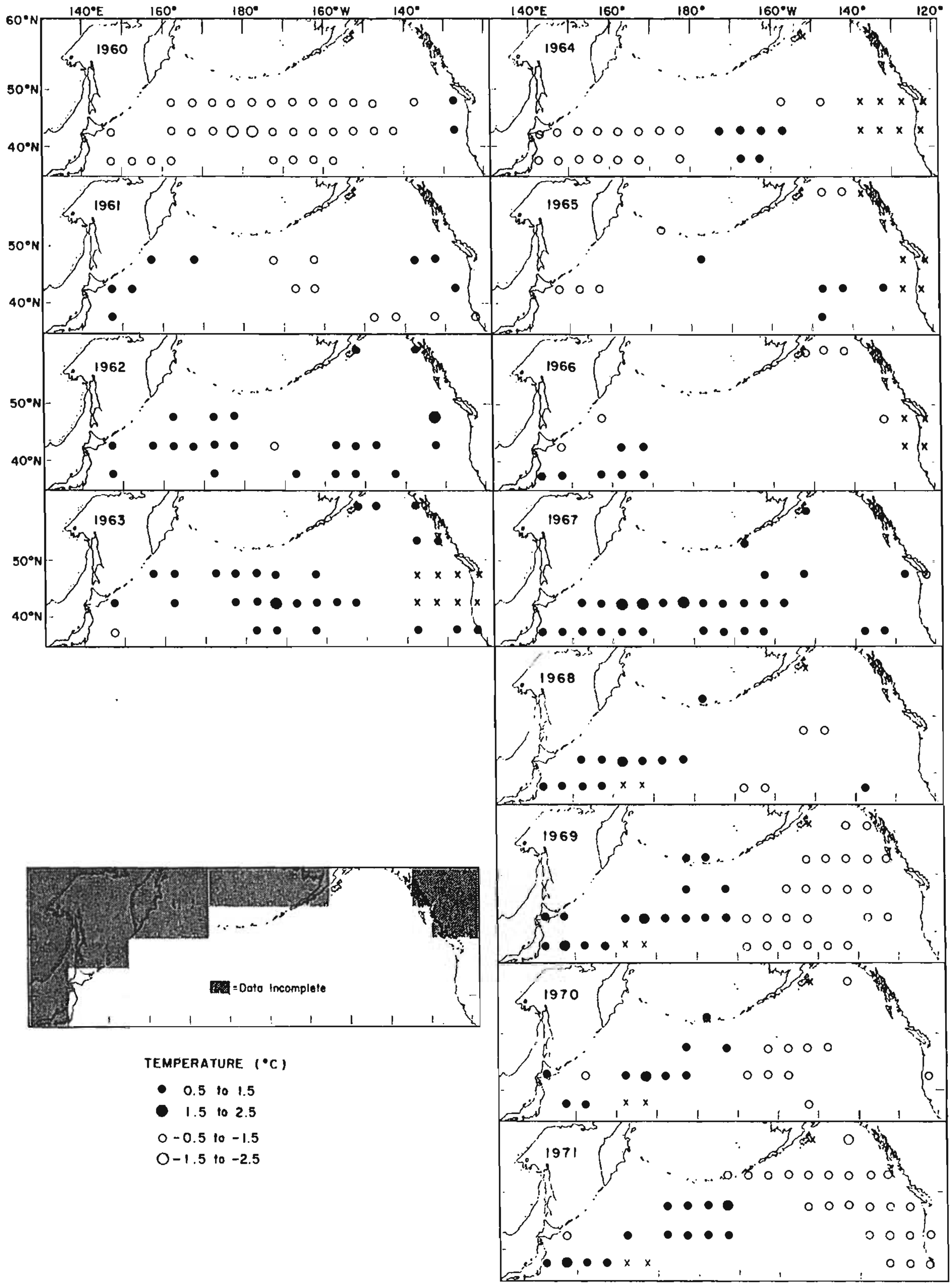


FIGURE 59. Annual mean surface temperature anomalies (5×5°) for 1960 to 1971 (closed circles indicate positive anomalies 0.5 to 1.5°C, and 1.5 to 2.5°C; open circles indicate negative anomalies −0.5 to −1.5°C, and −1.5 to −2.5°C) (× denotes no data—also data for the Sea of Okhotsk, the area just east of Kamchatka and the Bering Sea were incomplete and not shown).

and cooling are more apparent in deviations from mean temperatures in $5 \times 5°$ quadrangles for individual months from 1960–71 (App. Fig. 14). Data in the Sea of Okhotsk and in the northern Bering Sea were too sparse to be included in this analysis, and data from 40–50°N, 120–130°W (four quadrangles) for the years 1964–66 are missing; the latter severely limits discussions of conditions off the British Columbia, Washington, Oregon, and northern California coasts.

Generally transpacific negative anomalies (cold conditions) occurred throughout 1960. Temperatures greater than 2.5C° below normal occurred in the south-central part of the region in January, May, and August and in the vicinity of the Alaska peninsula in April and May. Temperatures were 0.5–1.5C° above normal along the west coast of North America from January to April, near normal conditions existed in late spring and summer, and warm conditions existed from October to December. Temperatures at the western side of the region were near or below normal except in the vicinity of Hokkaido where isolated positive anomalies of 1.5–2.5C° occurred in April, November, and December.

During 1961, marked changes in conditions occurred. Transpacific negative anomalies persisted until April. Normal conditions occurred in the western part of the region in May, but by July marked warming resulted in large positive anomalies throughout the western part of the region. The transpacific advance of areas of positive anomalies and the accompanying retreat of negative anomalies continued through December at which time only 7 quadrangles indicated cold conditions and 5 of these were located at the eastern side of the region along the Washington, Oregon, and California coasts. In marked contrast to the general advent of warm conditions, temperatures in the eastern Bering Sea were generally above normal until April but, by July, temperatures were 2.5C° below normal and below normal conditions generally prevailed until December.

Although transpacific positive anomalies occurred generally throughout the region in 1962, except in the eastern Bering Sea where negative anomalies persisted, this year is characterized as one of, not only warm, but fluctuating conditions, particularly in the western and central part of the region. Negative anomalies occurred in April and May, but marked positive anomalies existed in June and July. Negative anomalies also occurred in August, but positive anomalies persisted in September and October. Also in October, slight negative anomalies occurred in the northeastern part of the region and these persisted through December, even though positive anomalies occurred along the Canadian-U.S. coast.

The general, transpacific, positive anomalies that commenced in June 1961, and continued in 1962, persisted in 1963 through August with marked positive anomalies occurring in the central area in July and August. Off Japan, negative anomalies generally prevailed in several quadrangles until June, but slight positive anomalies occurred in June, July, and August. Marked cooling occurred in the western part of the region in September and, although positive anomalies in this area occurred in November, the warm cycle had generally terminated.

Residual positive anomalies occurred in the Gulf of Alaska early in 1964, but the western part of the region was dominated by negative anomalies that increased in intensity in July, August, and September, and persisted through December. During this period, the eastern part of the region was characterized by slight negative anomalies. In contrast, positive anomalies persisted in the central part of the area from April to December, and were most marked in July and August.

Generally variable conditions prevailed in 1965. In winter and spring, the positive anomalies in the central part of the region gave the appearance of shifting eastward and negative anomalies were predominant in July. A marked warming occured in, and southward of, the western Gulf of Alaska and in the Bering Sea in September and, subsequently, positive anomalies occurred south of the Aleutian Islands in November and December. Generally, negative anomalies prevailed in the western part of the region.

From January to November 1966, the eastern part of the region was generally dominated by negative anomalies. Conditions at the western side of the region were variable until May when general warming was indicated; marked cooling occurred in the central part of the region in July and August. Positive anomalies again occurred in September, and by November nearly transpacific positive anomalies existed except for the Gulf of Alaska area.

Although variable conditions were indicated early in 1967, the warming trend continued. Transpacific, large positive anomalies dominated the region from May until September when some cooling was evident in the eastern part of the region. However, positive anomalies were predominant throughout the year and this condition extended into the first 6 months of 1968.

Positive anomalies continued to dominate the western part of the region until July 1969, but similar conditions did not subsequently occur in the eastern part of the region where widespread negative anomalies occurred throughout this period. With only several exceptions in each month, transpacific negative anomalies occurred during October 1969 to January 1970 when positive anomalies reappeared in the western part of the region and along the west coast of North America. Positive anomalies in the western part of the region intensified and generally expanded eastward throughout the remainder of 1970 and all of 1971, whereas, negative anomalies dominated the eastern part of the region from June 1970 through December 1971.

In summary, in spite of the various seasonal processes in the surface layer such as, winter turnover and summer stratification and numerous areas of convergence and divergence, definite long- and short-term patterns of anomalous sea surface temperatures are evident: a cold period commencing prior to winter 1960 and extending to summer 1961; a warm period extending from autumn 1961 to autumn 1963; a cold period from winter 1964 to summer 1966; a warm period commencing in autumn 1966 that extended through summer 1968; a cold period, except for sporadic warming in the western part of the region, extending from autumn 1968 to spring 1970; and a warm period from summer 1970 to the end of 1971 except for the eastern part of the region. Subsequent data (not shown) indicate that this period extended into 1972.

It is interesting that maximum negative anomalies did not occur in winter, but primarily in early spring or summer; whereas, maximum positive anomalies invariably occurred in summer. It is particularly significant that against the background of long-term trends of heating and cooling short-term trends (monthly) of heating and cooling can be identified. Several of these have been selected for analysis: May-June 1962, warming, central area; July-August 1962, cooling, western area; June-July 1963, warming, central area; August-September 1963, cooling, central area; June-July 1964, cooling, central area; August-September 1964, cooling, central area; August-September 1965, warming, Gulf of Alaska; June-July 1966, cooling, central area; June-August 1967, warming, eastern area; and November-December 1967, cooling, California coast. Possible causes and effects of these anomalous events are discussed in the following section.

D. Anomalous Events

1. *Sea Level Pressure*

Distributions of pressure at sea level, especially when ship reports are augmented by satellite data, provide a basis for estimating wind fields which in turn are used to estimate water transport. Velocity vectors of monthly mean geostrophic winds are rotated 15° to the left and reduced 70% to obtain stress vectors considered to be proportional to the square of the wind speed. Various components of water transport, discussed in a subsequent section, are derived from this knowledge of wind stress on the sea surface.

Monthly mean values of pressure at sea level (based on data from 1960–69) were obtained for transpacific grid points, alternate 5° intervals of longitude and latitude from 35 to 65°N, for the period 1960–71. In order to obtain the locations of major pressure anomalies, the data were screened for monthly anom-

TABLE 11. Frequency of monthly sea level pressure anomalies of 10–15 mb, and greater than 15 mb, 1960–71.

Year	J	A	S	O	N	D	J	F	M	A	M	J
1960												
1960-61						x	X					
1961-62						*0*	*0*	o		o		
1962-63					x	x	X	x	o			
1963-64						x	x	*0*			o	
1964-65						o			o			
1965-66			o		x	o		*0*				
1966-67					*0*				o	o		
1967-68			x				*0*	X				
1968-69					x	o	*0*			x		
1969-70						X	o	x	x			
1970-71					o	o	*0*	*0*				
1971						*0*						

X Negative anomaly >15 mb
0 Positive „ „ „
x Negative anomaly 10–15 mb
o Positive „ „ „

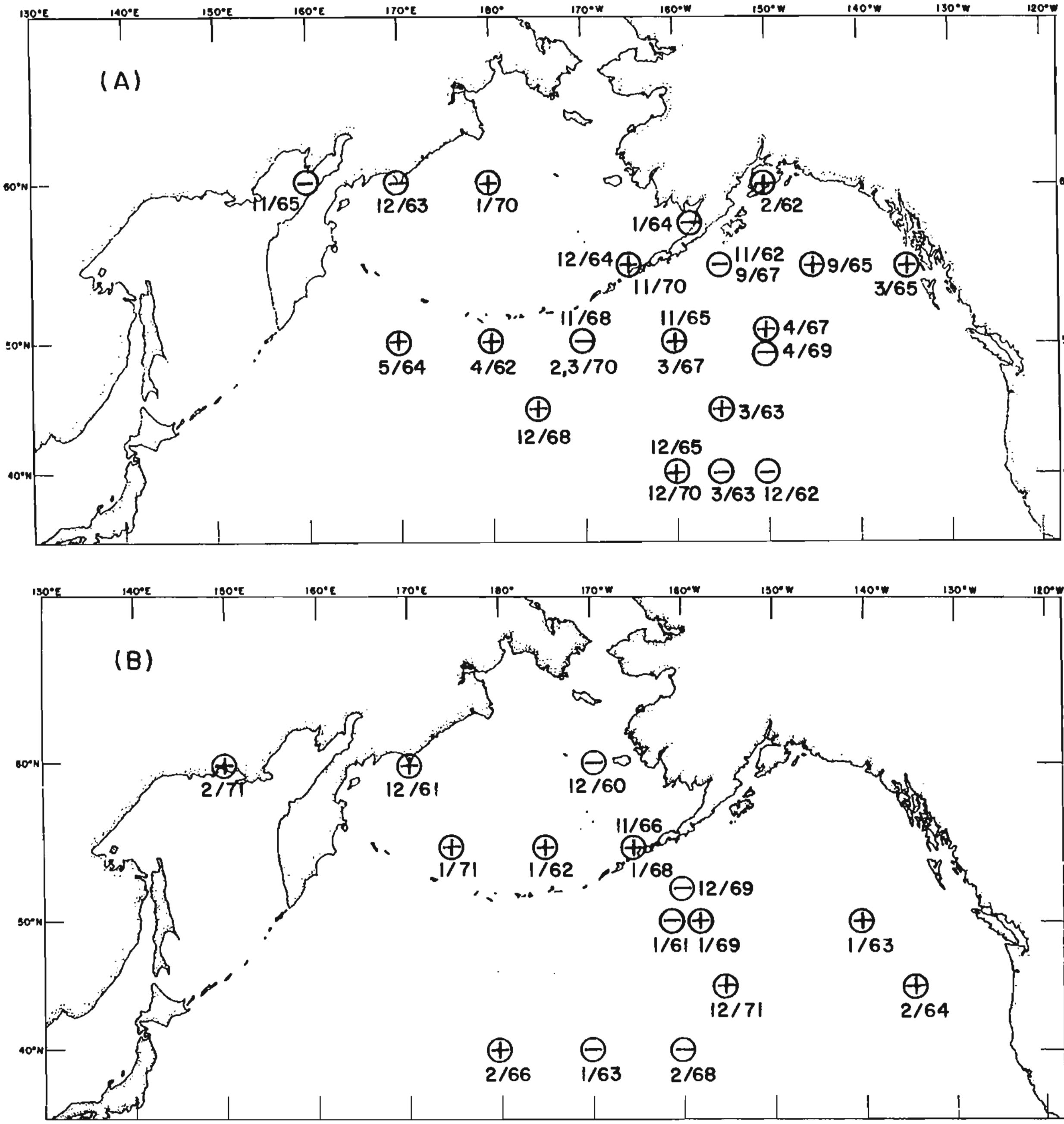


FIGURE 60. Locations and dates of centers of monthly mean sea level pressure anomalies of (A) 10–15 mb, and (B) greater than 15 mb.

alies of 10–15 mb and greater than 15 mb (Table 11), and the maximum value of such anomalous pressure pattern was used to identify the central location of these phenomena (Fig. 60).

During 1960–71 there were only 42 areas where monthly anomalies of these magnitudes occurred and no particular distributional pattern is evident, except that none occurred in the area of the Kuroshio-Oyashio confluence where intense air-sea energy exchanges occur. Only three occurred in the area off the west coast of the United States east of 145°W. Most were located between 150°W to 180° and both positive and negative anomalies occurred suggesting interaction between the Aleutian low and eastern

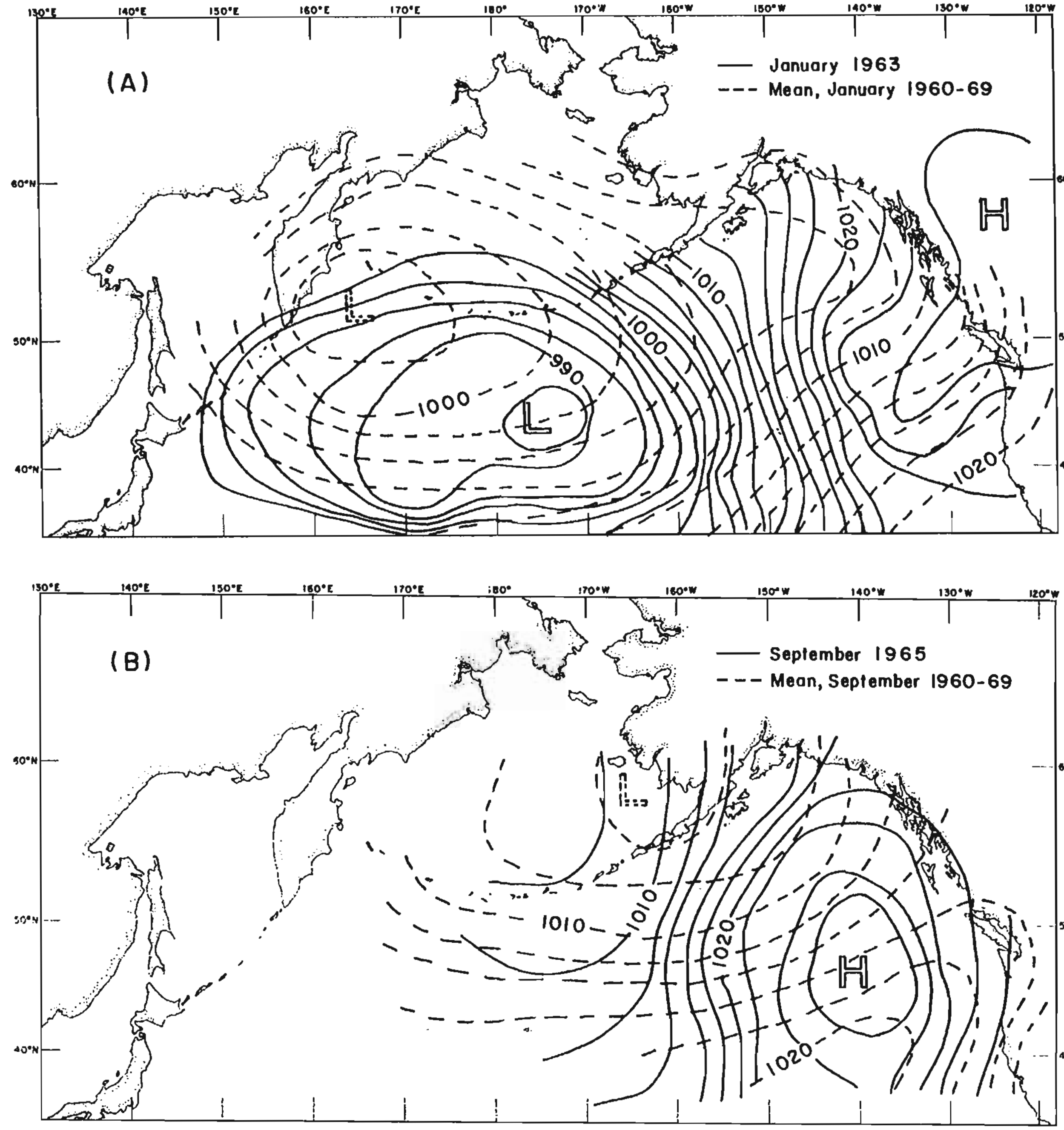


FIGURE 61. Comparison of monthly mean distributions of sea level pressure and mean distributions for 2 months during which pressure anomalies greater than 10 mb occurred; (A) January 1963, and (B) September 1965.

Pacific high pressure systems. Of the 16 occurrences of anomalies greater than 15 mb, only 4 were negative (lower pressure); and, only 16 of the 42 occurrences were negative. Most, 36 of the 42, occurred in the period November to March, suggesting marked variability in the actual location of the center of the Aleutian low pressure system during winter.

Two examples of pronounced monthly mean anomalies in pressure at sea level are presented (Fig. 61). The first is the result of two departures from monthly means of over 15 mb: positive anomalies centered around 50°N, 140°W and negative anomalies centered around 40°N, 170°W during January 1963. These anomalies are reflected in a southeastward displace-

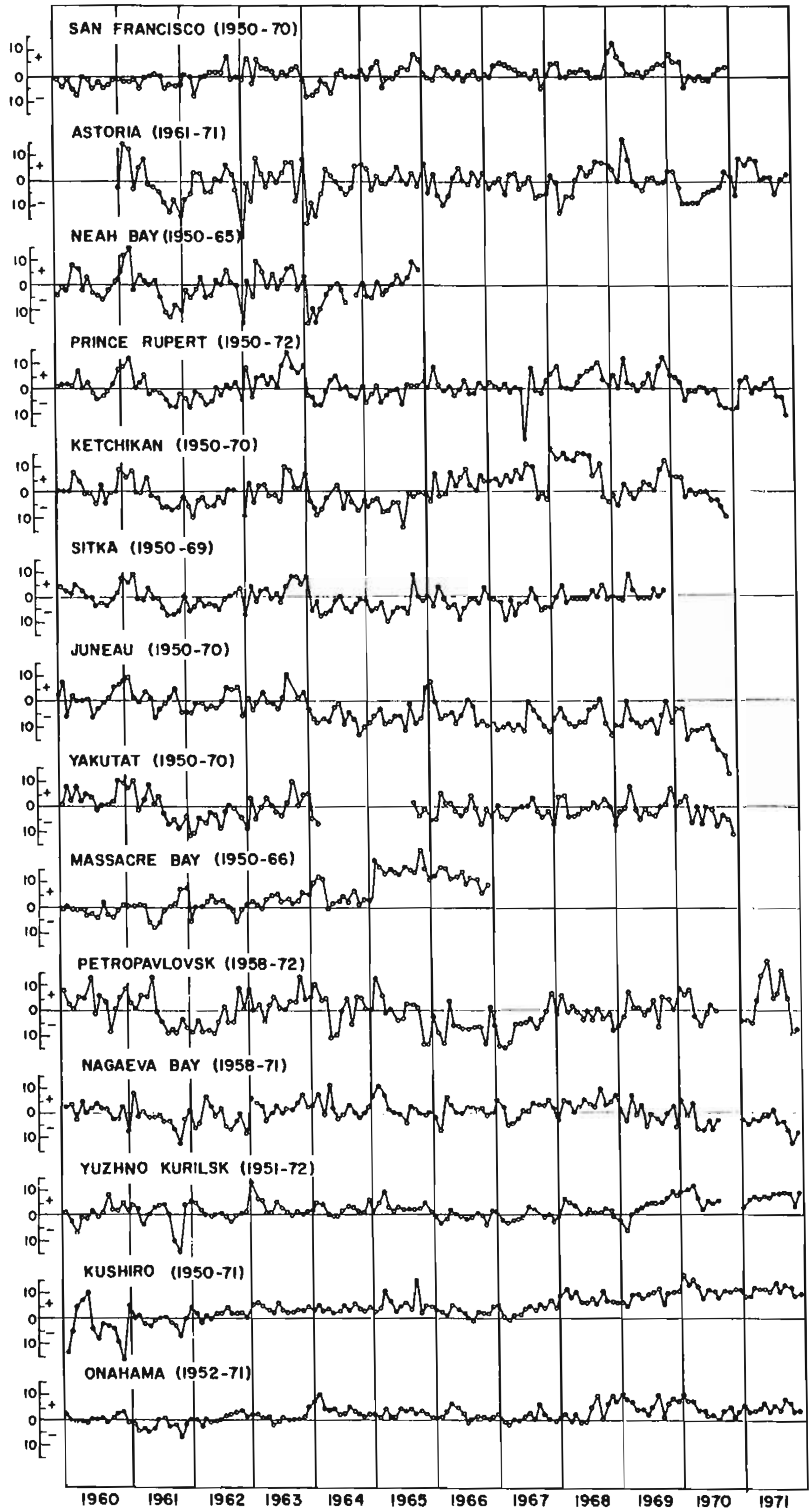


FIGURE 62. Departures from mean sea level at various locations around the rim of the region, 1960–71. (Dates in parentheses indicate the period of the mean).

ment of the Aleutian low pressure center and a northward displacement of the central Pacific high pressure center. Rather than the somewhat normal zonal isobaric pattern, a meridional one occurred with a markedly increased gradient. This signalled intense geostrophic winds of a southern origin and an increase in northerly wind-stress transport between 145–165°W as well as a large (>20 Sv) anomalous southward wind-stress transport in the eastern Gulf of Alaska. However, it will be shown in a later section that anomalous pressure distributions during winter, and the accompanying winds, result in only minor changes of sea surface temperature. Departures from normal or existing pressure patterns, even though of a lesser magnitude, during summer do reflect changes in ocean conditions. The second example is the result of a maximum departure from monthly mean pressure at sea level of 13.6 mb centered in the Gulf of Alaska around 55°N, 145°W in September 1965. This northward displacement of the central Pacific high pressure center again resulted in a shift in the normal near zonal isobaric pattern, to one of a meridional pattern between 145–165°W resulting in anomalous southerly winds and, as will be shown in a subsequent section, an anomalous warming trend in sea surface conditions occurred in this area.

These results provide much encouragement that when adequate data are available and appropriate studies undertaken not only can contributing causes of anomalous ocean conditions be identified, but that predictions of the effect of these conditions can be made. It is beyond the scope of this report to present an analysis of potential effects of all the anomalous distributions of pressure at sea level, but pressure, as well as other factors, are considered qualitatively with respect to known significant departures from monthly mean sea surface temperatures at the end of this section.

2. *Sea Level*

Although sea level is affected by variations in atmospheric pressure, this hydrostatic effect can be eliminated to obtain a corrected sea level. Most of the INPFC oceanographic studies were conducted in oceanic areas with very little attention given to sea level data; however, Favorite (1974) showed that departures from annual mean sea level at Yakutat, Alaska, were well correlated with departures from annual mean northward wind stress transport in the Gulf of Alaska during the period 1950–59, and recent studies of coastal upwelling (CUEA) off the Oregon coast indicate that sea level is a sensitive indicator of reversals in alongshore winds that cause a change in water transport. Thus, sea level data were obtained for a number of stations along the rim of the North Pacific Ocean to ascertain if any correlations existed with other environmental data. Departures from monthly mean sea level (corrected for annual mean pressure) are presented for 1960–71 at the following stations: Onahama and Kushiro, Japan; Yuzhno Kurilsk, Petropavlovsk and Nagaeva Bay, USSR; Massacre Bay, Yakutat, Juneau, Sitka, Neah Bay, Astoria, and San Francisco, U.S.A.; and, Prince Rupert, Canada (Fig. 62).

Although there is little correlation between monthly data at Onahama and Kushiro, both stations indicate a progressive rise in sea level of 10–15 cm that is unexplained. This trend is also evident in data at Massacre Bay up to 1965 and, in all three cases, this trend extends back at least to 1950. On the other hand, data at Yakutat and Juneau suggest progressive decreases in sea level of the same order. Fairly stable long-term conditions, but marked monthly fluctuations, are indicated at Prince Rupert, Neah Bay, Astoria, and San Francisco.

Surprisingly, there is little indication of steric increases or decreases during periods that positive or negative anomalies of sea surface temperature were evident in the oceanic areas. Evidently these effects are masked by local fluctuations, however, there are indications of responses to other environmental factors. For example, both Astoria and Neah Bay data for January 1963 reflect decreases of 10–15 cm, which could be attributed to the anomalous southward transport during this period suggested by wind stress transport calculations (see discussion of Fig. 61). This lowering is not evident in data at Prince Rupert, but conditions in the relatively shallow Queen Charlotte Sound greatly influence sea level at this station. An equivalent lowering of mean sea level occurred at Prince Rupert in September 1967 that was also evident at Ketchikan, but there is no evidence of lowering at any of the other coastal stations. Here again, to investigate each and every anomalous departure from mean sea level is beyond the scope of this report, but extensive studies of sea level data could reveal excellent indications of not only coastal, but oceanic circulation patterns and provide substantive clues to onshore and offshore migrations of salmon.

3. *Ekman Transports*

As indicated in an earlier section, although Ekman transports represent response of the surface layer to existing winds, the integrated response to fluctuating winds over an extended time period (in this case one month) is a derived condition not an observed one. However, conditions are discussed under the assumption that the derived conditions actually occurred. Monthly mean transports at grid points along each 5° of latitude and alternate 10° of longitude for the decade 1960–69 are considered to represent normal conditions.

An examination of monthly Ekman transport charts for the period 1960–71 showed that various large positive and negative anomalies persisted for several months. The larger anomalies (generally greater than 1000 mt/sec/km) that occurred at several adjacent grid points are presented as background information and for subsequent discussions pertaining to cause and effect of sea surface temperature anomalies presented earlier, particularly those anomalies in the southern part of the region, where longitudinal temperature gradients are relatively large and any anomalous north-south transports could result in relatively marked changes in the sea surface temperature distribution. Increased southward transport should reflect anomalously cold conditions, whereas a relaxation in the normal southward transport, or a reversal to northward transport should result in warm conditions. However, the effects of advection may be partially or totally masked by local effects such as changes in cloud cover, evaporation, mixing or heat exchange. A summary of the larger and more persistent anomalies are presented in App Fig. 15, and the following discussions assume that the calculated transports are valid.

Generally normal conditions prevailed in 1960. In April and May, southward transports were somewhat greater than normal in the southeastern part of the region. Again, in August and September, anomalies occurred which were slightly greater than those in the earlier period and extended over a larger area. Northward transports in the Gulf of Alaska and northern Bering Sea, and southward transports in the southern part of the area, except east of Japan, were considerably greater than normal in January 1961. Onshore transports along the North American coast were also large. In February and March, anomalously high transports prevailed in the southeastern part of the region, and to a less extent along the North American coast. Anomalously high transports occurred in the south central part of the region in May; and, in August and September, anomalously high southward transports occurred along 50°N westward to about 160°W. In November, transports in the southeastern part of the region were much below normal. Although near normal conditions prevailed in this area in December, anomalously high northerly transport occurred in the southern Bering Sea and south of the Aleutian Islands. Anomalous conditions occurred in January 1962 in the southern central area, where transports although low, were northward, opposite in direction to the 10-year mean. In February, these anomalous conditions were limited to a relatively small area in the southeastern part of the region. For the remainder of the period, transports at most grid points were near normal. There were significant departures from normal conditions in January 1963; northward transport in Bering Sea was much greater, while in the eastern part of the region, high northward transports occurred, opposite to that of the 10-year mean. However, along the coast onshore transports were less than normal in February. Near normal conditions prevailed until August 1963, when greater than normal southward transports occurred in the eastern half of the region, and onshore transports were also high for this period; these conditions persisted through November. High southward transports also occurred in the eastern part of the region in January and February 1964; and, in August and September, higher than normal southward transports occurred south of the Aleutian Islands. In December, southward transports were either relatively low or northward (opposite to a 10-year mean) in the south-central part of the region. Anomalous conditions occurred in the south and north western parts of the region in February 1965 but, with few exceptions, transports during the remainder of the year were generally near normal. Increased southerly transports occurred south of 40°N and increased northerly transports occurred in the northern Gulf of Alaska in January 1966. Conditions reversed in February; increased transports occurred immediately south of the western Aleutian Islands, whereas reduced transports occurred south of this area. In October and November, transports in the central part of the region were less than normal. Transports for 1967 were near normal, except at 2–3 grid points in March, August, and September. In January 1968, and particularly in February, anomalous conditions occurred, transports were low and northerly in the south-central part of the region. By February, anomalous conditions prevailed over most of the region, and onshore transports were high along the British Columbia and Alaska coasts. Near-normal conditions occurred in March and continued through July. During August and September, high southward transports occurred south of the Aleutian Islands and off the Vancouver Island coast. In December, low transports were evident in the south central area, and these conditions prevailed during January 1969. In February, April, and August 1969, anomalously high southward transports occurred in the south-central part of the region; otherwise conditions were normal, except in August when increased southerly transports occurred south of the western Aleutian Islands, and in November when reduced transports were relatively low in the southeastern part of the area. Near normal conditions occurred in December. In February, March, and April 1970, anomalously high southward transports occurred in the south-central part of the region. Subsequently, normal conditions prevailed, except in August, when increased southerly transports occurred south of the Aleutian Islands, and in November, when reduced transports occurred in the south-central part of the region. The most significant anomalies in 1971 were low transports in the south-central part of the region in January, November, and December. Also, in December, an anomalously high southward transport was evident along 50°N.

4. *Cloud Cover*

The most serious limitation in the calculation of energy exchange at the sea surface is the absence of direct measurements of incoming radiation. Until the mid-1960's, when satellite observations became available, the only source of cloud data was visual observations from ships at sea. Such observations are not only highly subjective, but do not necessarily accurately reflect actual conditions (i.e. distinguish between overcast conditions caused by a thin, low, cloud layer versus several thick cloud decks). Although satellite data provide a more comprehensive picture of cloud distribution (Miller and Feddes, 1971), these have limitations also: thin cirrus and small cumulus clouds are not properly resolved, camera calibration and response are not constant, and cloud composition and layering are still not determined.

Mean cloud data for individual months (1960–68) obtained from ship reports were compiled in 5 × 5° quadrangles to permit determining variability in energy exchange. In order to compare these data with satellite observations, a contract was awarded to F. A. Godshall of the National Oceanic and Atmospheric Administration, Environmental Data Service's Laboratory for Environmental Data Research to furnish monthly mean cloud cover over the region for a one-year period. The year 1968 was chosen because data were fairly complete (except for August) and, because of the better resolution afforded by this technique, a 2 × 2° grid was chosen. The gross annual patterns discussed previously (see Fig. 32) were evident, however, considerable differences in percent coverage and in small scale features were obvious in comparisons of cloud cover during January obtained by both methods (Fig. 63). The paucity of ship observations in the northern parts of the region suggests that some discrepancies can be attributed to disparities in the amount of data. Nevertheless, satellite cloud data are available only in recent years and the cost of extensive data acquisition and analysis of monthly data was prohibitively expensive ($500/month); thus, analyses of energy exchange in the following section have been based entirely on cloud cover data from ship reports. Obviously, the results would appear to lack not only the qualitative, but also quantitative results that will be forthcoming in the future when more precise techniques are developed. Nevertheless, the data permit a useful preliminary look at energy exchange processes.

5. *Energy Exchange*

In order to ascertain anomalous warming and cooling events, surface temperature data in 5 × 5° quadrangles have been used (see App. Fig. 14). The normal seasonal effects of increasing temperatures in spring and decreasing temperatures in fall are eliminated by considering only departures from a monthly mean temperature derived for each 5 × 5° quadrangle. Thus, although actual temperature in a given quadrangle may increase 1–3C° in June over temperatures that existed in May as a result of increasing insolation, this is not considered a warming event unless the temperature anomaly in June is greater than the anomaly that occurred in May. The purpose of this section is to determine whether the marked monthly changes in the anomalies, some of which were greater than 5C°, can be explained and predictive indices ascertained. Generally the most obvious events occur when anomalies shift from positive to negative during warming periods, and vice versa, but examples of increasing positive or negative anomalies are also discussed. Because of the nature of the data and time and space factors operating within each 5 × 5° quadrangle (such as all observations being obtained early in a month during which temperatures are changing rapidly, or all observations in a given month being obtained in the northern part of a quadrangle in which a north-south temperature gradient occurs), some variability in individual quadrangles is to be expected. However, we have selected events that primarily extend over a number of quadrangles in which changes in anomalies of the order of 1–2C° occur. Generally three contiguous quadrangles have been selected for analysis (these are indicated in App. Fig. 14).

It has been shown that nearly all anomalies of pressure at sea level occurred during October to March, and most of the following events occurred during late spring to late summer (in only one event—

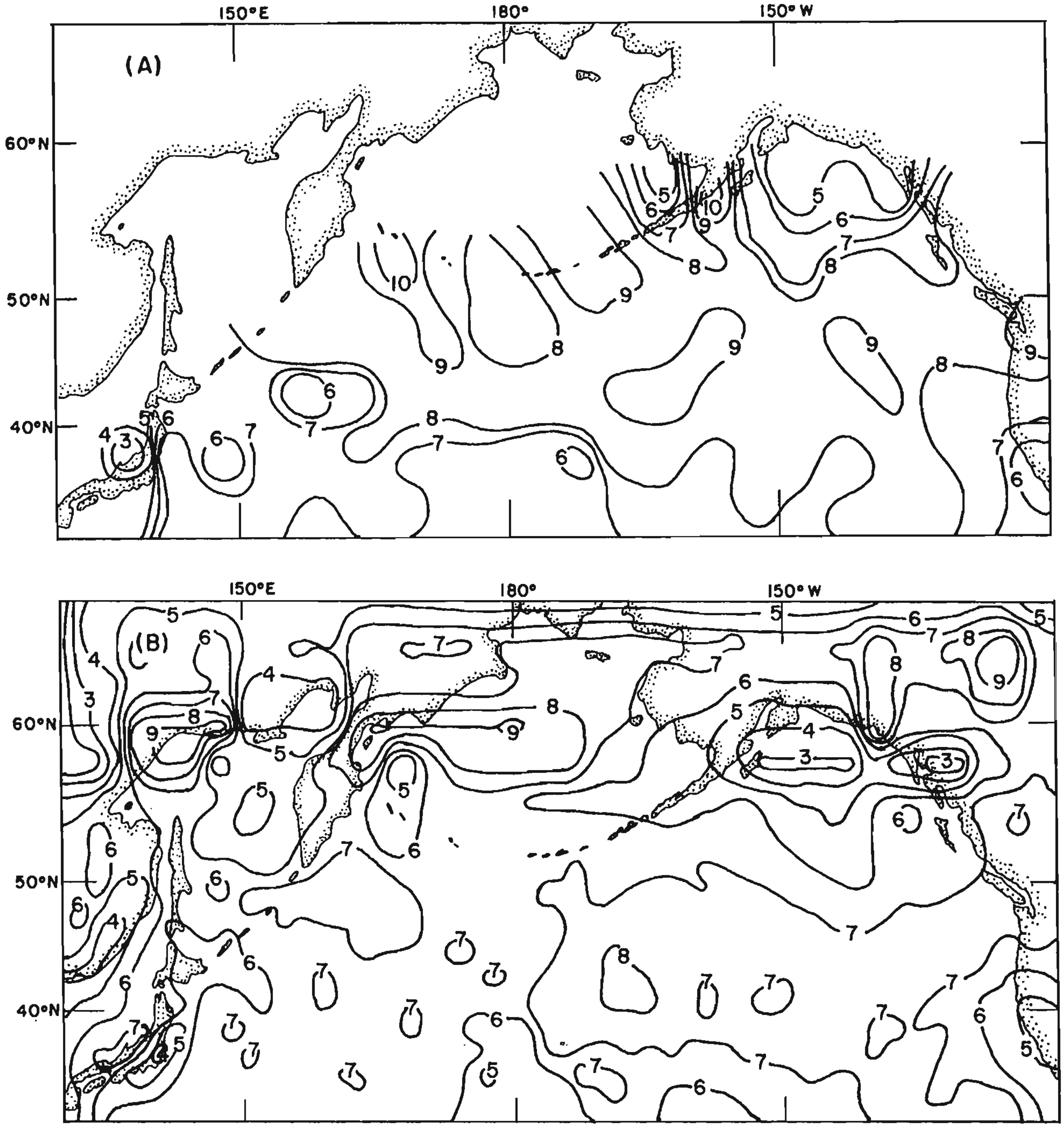


FIGURE 63. Comparison of cloud cover (tenths) for January 1968 obtained by (A) shipboard observations (5×5°) and (B) satellite data (2×2°).

warming, Gulf of Alaska, Aug to Sept, 1965—were anomalies in excess of 5 mb). Thus, the physical process of winter turnover evidently masks to some extent the advective effects of warm and cold air induced by changes in patterns of pressure at sea level. This does not imply significant changes in oceanic flow do not occur under these conditions, only that relatively homogeneous temperature conditions during this period, as well as the great extent of vertical convection in the water column prevent marked sea surface temperature anomalies from occurring. Nevertheless, we can use various components of the heat budget equation to assess cause and effect relations.

The following factors have been considered in evaluating events:

1. An increase (cooling) or decrease (warming) from mean wind speed resulting in an increase or decrease in evaporation and/or lessening or increasing the stability of the near surface layer.
2. An increase (cooling) or decrease (warming) from mean cloud cover.
3. A positive difference (Δt) between air and sea surface temperatures (warming) or negative Δt (cooling).
4. An increase (cooling) or decrease (warming) from mean Q_t (total) energy exchange.

Two levels of significance have been arbitrarily established and are used in Table 12 as follows:

FACTOR	MINOR	MAJOR
Wind speed	0-1 m/s	>1 m/s
Cloud cover	0-.025 eighths	>.025 eighths
Air temperature	0-1°C	>1°C
Δt	0-1°C	>1°C
Q_e	0-25 cal/cm²/day	>25 cal/cm²/day
Q_t	0-50 ,,	>50 ,,

The X's indicate corroborating trends, capital X indicates major level and lower case x indicates minor level. The O's are used in the same manner and indicate non-corroborating trends. The locations of all events are indicated on appropriate annual figures (App. Fig. 14) and presented in Table 12.

TABLE 12. Enviromental trends during major warming and cooling events in various parts of the region, 1960-67.

Event date	Warming-Western 5/62-6/62			Cooling-Western 7/62-8/62			Warming-Central 6/63-7/63		
Marsden Square	163-1	163 2	164-2	164-1	164-2	163-1	161-2	162-1	162-2
Wind Speed	x	x	x	X	x	x	o	x	X
Cloud Cover	—	o	o	x	X	o	X	X	X
Air Temp.	X	X	X	X	x	x	X	X	X
Air minus SST[1]	o	x	o	x	o	x	—	—	x
Q_e	X	X	X	X	X	X	0	0	o
Q_t	x	x	X	X	X	X	o	o	x

Event date	Cooling-Central 8/63-9/63			Warming-Central 6/64-7/64			Cooling-Central 8/64-9/64		
Marsden Square	161-2	162-1	162-2	126-3	126-4	127-4	161-2	162-1	162-2
Wind Speed	x	X	x	0	0	0	o	o	x
Cloud Cover	X	X	X	X	X	X	x	0	0
Air Temp.	x	o	o	X	X	X	o	o	x
Air minus SST	X	x	x	x	x	x	X	x	X
Q_e	X	X	0	0	0	o	x	x	x
Q_t	X	X	o	x	x	x	x	x	o

Event date	Warming-Northeast 8/65-9/65			Cooling-West/Center 6/66-7/66			Warming-Eastern 6/67-7/67		
Marsden Square	159-4	160-3	160-4	163-1	163-2	162-2	157-2	158-1	158-2
Wind Speed	X	o	o	X	x	x	x	x	o
Cloud Cover	o	o	o	o	—	X	X	X	x
Air Temp.	X	X	X	x	X	X	x	X	X
Air minus SST	x	o	o	0	0	x	x	x	x
Q_e	X	x	x	x	x	X	x	x	o
Q_t	x	x	x	x	x	X	X	X	o

Event date	Warming-Eastern 7/67-8/67			Cooling-Eastern 11/67-12/67		
Marsden Square	157-2	158-1	158-2	121-3	121-4	122-3
Wind Speed	x	X	o	X	X	X
Cloud Cover	X	X	X	0	0	o
Air Temp.	X	X	X	X	X	X
Air minus SST	x	o	o	X	X	X
Q_e	x	x	o	X	X	X
Q_t	X	X	x	X	X	X

[1] Sea surface temperature.

The first event to be considered is the shift from negative temperature anomalies to positive anomalies in the western part of the region between May and June 1962. All factors, except cloud cover and air minus sea surface temperature in two quadrangles, indicated warming. Air temperature anomalies in Marsden Square (MS) 163–1 were −2C° in May and +2C° in all 3 quadrangles in June which along with evaporation appear to be the primary causes for this event.

A reversal of the foregoing trend occurred in this general area during August when a marked cooling was indicated. In this case various factors predominated in different quadrangles: wind speed, air temperature, evaporation and total energy exchange in one, and evaporation and total heat exchange in the other two; however, a major increase in heat loss (Q_e and Q_t) occurred in all quadrangles.

Anomalous warming occurred in the same general area in July 1963 and warm air temperatures and cloud cover appear to be major factors even though energy exchange indicates cooling should have occurred. As in 1962, the warming event in this area was followed by a cooling event, however, it occurred in September. In one quadrangle, all 6 factors substantiate the event, 4 indicating major trends. Data from all three quadrangles indicate increasing cloud cover as a probable dominant cause of the cooling event.

Following the foregoing pattern in this area, a warming event occurred in July 1964 and cooling event in September 1964. In the former, data from all three quadrangles indicate that high air temperatures and decreasing cloud cover were major factors. The cooling event in September is indicated primarily by air-sea temperature differences. Although anomalies of air temperature as great as +2C° occurred in August, these decreased 1.5–2C° in two of the three quadrangles, and only in the third quadrangle did a negative air temperature anomaly occur.

During 1965, generally characterized as a cold year, marked cooling or warming events did not occur in the central part of the region, but in September an abrupt warming event was evident in the northeast (Gulf of Alaska) part of the region. Although evaporation and total heat exchange in all three quadrangles reflected this trend, warm air temperatures appear to be the dominant cause of the warming. This is the first instance wherein major sea level pressure anomalies can be shown to have greatly altered surface winds. Anomalous south winds are believed to be the causative effect for this event.

During 1966, a cooling event occurred in July in the central part of the region. This is in contrast to the warming events in this general period in 1962, 1963, and 1964. Data in one quadrangle show substantiating trends in all factors, with major influences from air temperature, major to minor influences from wind speed, evaporation and total energy exchange.

The year 1967 is considered a warm period and significant warming events occurred in the central part of the region in July and August. Air temperature anomalies of less than −1C° in June increased to +1C° in July and +2C° in August, and, with few exceptions, the indicated factors, particularly cloud cover, substantiate the warming trends.

Perhaps the most interesting event in terms of the factors being used was the marked cooling event off the California coast in December 1967. Surprisingly, all factors shows major corroborative trends except for cloud cover. This certainly causes some question as to the possible accuracy of visual observations and/or reporting techniques.

All the above events are summarized in Table 13.

TABLE 13. Dates and times of heating and cooling events in which major and minor factors occurred in all quadrangles considered.

Area	Year	Month	Event[1]	Major[2]	Minor[2]
West-Central	1962	6	W	A, Q_e	W, Q_t
"	1962	8	C	Q_e, Q_t	W, A
Central	1963	7	W	A, C	—
"	1963	9	C	C	W, Δt
"	1964	7	W	A, C	Q_t, Δt
"	1964	9	C	—	Δt, Q_e
East	1965	9	W	A	Q_e, Q_t
Central	1966	7	C	—	W, A, Q_e, Q_t
East	1967	7	W	—	A, Δt, C
"	1967	8	W	A, C	Q_t
"	1967	12	C	W, A, Δt, Q_e	Q_t

[1] W-Warming, C-cooling.

[2] W-wind speed, C-cloud cover, A-air temperature, Δt-air minus sea temperature, Q_e-evaporation, Q_t-total energy exchange.

VI. CONCLUSIONS AND RECOMMENDATIONS

It should be stated at the outset that this has been a much larger and somewhat more frustrating task than initially envisioned. To present a word and picture explanation of conditions and events over such a large area for such a long time period, with such an enormous but still woefully inadequate amount of data has proven an interesting, challenging and rewarding exercise. The Terms of Reference of the INPFC Sub-Committee on Oceanography were always to define the environment, rather than to relate environmental conditions to salmon distribution and abundance. Although numerous inferences to possible relations have been made by all National Sections in numerous INPFC documents, it was exclusively the task of the Salmon Sub-Committee to ascertain distributional patterns and movements of salmon. Thus, in providing a summary of all research activities (Section II), and descriptions of mean conditions (Section III), the first objective of this report, providing background information concerning the salmon environment, has been fulfilled. These sections, as well as the extensive bibliography provided should be of interest and use to all fisheries biologists, ecologists and other marine scientists.

A second objective has been to provide interpretations of this information so that not only relations with salmon catches may become evident or promising avenues of further investigations along these lines are indicated, but also, knowledge of ocean conditions may be increased through acceptance or challenge of these concepts (Section IV). With regard to the former, there is little question that fisheries biologists would prefer a more detailed presentation of conditions in specific areas and at specific times. This would certainly be called for and considered part of our task if the environmental, as well as the fish catch data, were complete. However, the wide spacing in time and space of observations in both data sets do not justify such an exhaustive presentation at this time; thus, we have painted with broad brush and left specific analyses for studies restricted to small time and space scales for another time, or other investigators. Unfortunately, it appears obvious that there are few compatible data sets; the intense quasi-synoptic surveys of oceanographic research vessels provided little or no time for fishing. On the other hand, the extensive exploratory fishing patterns prevented making the closely spaced environmental observations required to denote the presence and extent of fronts and eddies and associated convergence and divergence phenomena that could influence the vertical and horizontal distributions of salmon. However, whenever satisfactory large scale models of distributions and movements of salmon are forthcoming, it is inevitable that small scale studies will ensue.

We have avoided exhaustive analyses of physical processes that are best handled in specific monographs by individual authors rather than several, working hundreds or thousands of miles apart. Because of this there inevitably will be criticism by the physical oceanographic community, to whom eddies at specific fishing locations are just part of the turbulent oceanic regime, micro-scale phenomena in a global, three-dimensional fluid that defies tractable mathematical solutions and precise numerical modeling. However, by pointing out and even providing temporary nomenclature for small scale phenomena, we expand the realm of the descriptive oceanographer, and challenge the theoretician to take into account features present in the real ocean, which he in his own way is trying to describe. There are three major burdens to overcome when one is seeking support for environmental studies. First, there is usually little urgency and there is no disaster motive, except for storms and tsunamis, which are exclusively wave phenomena. However, the spectre of ocean pollution is increasing and will continue to require expanded knowledge of oceanic conditions and processes. The exploration of oil on the continental shelf, particularly around Alaska, and the shipment by vessel of this oil are examples of potential disasters to the marine environment. The INPFC oceanographic investigations provide excellent baseline data for this renewed interest in environmental conditions in the Subarctic Pacific Region. Second, it is usually stated that the vastness and complexity of the oceans defies description and understanding, and that even if we could become aware of conditions and processes in the ocean it would be impossible to influence or control them. Although presumptuous at this time to consider man's control over the immense and diverse forces in the ocean, modern equipment and devices, such as computers and satellites, are gradually making the oceans man-sized. It has been shown (Section V) that at least large-scale phenomena can be detected and basic understandings of processes obtained, even though data are limited and only rudimentary techniques are employed.

It is useful to place the INPFC oceanographic effort in proper focus. Each national section had a different approach to oceanographic research and at no time were cooperative oceanographic studies conducted that were independent of fishing operations. This was primarily because of differences in national organizations and facilities. The Fisheries Research Board of Canada had an established oceanographic capability in existence, the Pacific Oceanographic Group, that was able to respond immediately to requirements for oceanography studies. Initial observations, obtained from naval and auxiliary naval vessels, were almost completely isolated from the fishing effort, and studies were initiated and carried out in the eastern Subarctic Region from 1955–62. From 1962 to 1966, these intensive independent oceanographic studies were curtailed and replaced by casual observations (surface temperature and salinity, and bathythermograph casts) obtained aboard chartered fishing vessels. Subsequent to 1966, oceanographic field programs were limited largely to coastal waters around Vancouver Island. The Japanese oceanographic activities were centered around fishing research vessels chartered by the Japan Fisheries Agency. The movements and activities of these vessels were unencumbered by the abstention principle and they traveled quickly over large areas. Inadequately equipped for extensive oceanographic studies, they made only surface temperature and bathythermograph lowerings at fishing locations, which lacked any particular pattern until the large scale multi-ship studies in the late 1960's. Internal liaisons between the Japan Fishery Agency and the Faculty of Fisheries, Hokkaido University led to some modifications of *Oshoro Maru* cruises, during which extensive oceanographic station data were obtained, but no direct communication or liaison occurred between the University agency and the INPFC Sub-Committee on Oceanography. Limited oceanographic data were obtained aboard Japanese motherships, but because of the proprietary nature of these operations it was difficult to obtain access to these data until some restrictions were removed in the late 1960's. Although never acquiring the modern instrumented techniques, the chartered research vessels have continually increased the acquisition and accuracy of oceanographic observations. The initial U.S. oceanographic program under the aegis of the INPFC embraced desirable aspects of both the Japanese and Canadian programs. Oceanographic research was initially contracted to the University of Washington and involved both intensive, independent studies aboard an oceanographic research vessel, *Brown Bear* and the acquisition of routine serial oceanographic station data at fishing locations from aboard individual exploratory fishing vessels. Budgetary and other considerations eliminated the contractual arrangement in 1957 and this eliminated the services of the research vessel. Although the oceanography program aboard the exploratory fishing vessels was intensified, observations were limited largely to tracklines along which fishing was conducted. These studies continued until 1971. Thus, no consistent level of effort was maintained. The exemplary initial Canadian oceanographic effort was eliminated in the mid-1960's; the intense U.S. studies that commenced in 1955 were somewhat restricted in 1957, though a varying level of effort continued until the early 1970's; and the slow starting but constantly increasing Japanese oceanographic effort, although still not attaining the intensity of the earlier Canadian and U.S. programs, has continued.

The Terms of Reference of the Sub-Committee on Oceanography placed it outside the rather controversial problems concerning the oceanic distribution and intermingling of Asian and North American salmon, and this was a disadvantage because by not being able to discuss what effect the environment might have on the distribution and movement of salmon the sub-committee was essentially relegated to a minor status. Fishery biologists were frequent substitutes for oceanographers at INPFC Annual Meetings primarily because of limitations in the number of scientists each national section was able to send to these meetings, which were held in rotation at Tokyo, Seattle, and Vancouver. Finally, in 1971, the sub-committee was abolished and absorbed by the Salmon Sub-Committee and major Canadian and U.S. oceanographic efforts were largely redirected to other tasks.

In spite of these difficulties, the Sub-Committee on Oceanography was able to complete a number of constructive things. At the outset, standard oceanographic procedures for physical and biological observations were agreed upon and carried out; techniques for rapid data compilation were developed; data were exchanged not only by mail, but also between vessels at rendezvous during mid-points of cruises; atlases of joint data were drawn up; and areas requiring additional study were pointed out. Results of investigations as reported in INPFC documents, bulletins, annual reports, this and a previous joint report (INPFC Bulletin 13), as well as outside journals, have provided not only substantial knowledge of oceanographic conditions and processes, but the impetus and focus for numerous studies by other scientists.

How salmon find their way in the ocean is still one of the most interesting and challenging problems of marine biology. Undoubtedly more than one factor is involved, but there is little question that physical conditions play a dominant role, either directly or indirectly, in the ocean survival, growth, distribution and movements of these fish. INPFC oceanographic research, loosely coordinated because of national requirements and commitments and quite fragmentary in space and time has provided knowledge of the range of annual conditions, an indication of annual fluctuations, and a suggestion of continuity of gross features. However, many questions remain unanswered and more extensive studies than the casual observations now being obtained by fishing vessels are required if we are to advance our knowledge of cause and effect of physical processes, of environmental relations, and for prediction of the environment.

Near transpacific continuity of adjacent although opposing flows in the Alaskan Stream and Subarctic Current has been established from distributions of properties and geostrophic considerations, but direct current measurements are available at only several locations. There is some evidence of narrow bands of high zonal flows at the Subarctic Boundary, the northern edge of the Transition Domain and the southern edge of the Ridge Domain (south of the Aleutian Islands), but this has not been substantiated. The existence and extent of such flows could greatly influence salmon migrations, and the characteristics and continuity of such phenomena would require extensive direct current measurements across these features at various longitudes that could only be accomplished adequately through cooperative dedicated studies.

Results of studies in the Alaskan Stream area show considerable variability in not only environmental conditions but flow, seasonally as well as annually, in this highly turbulent regime. The majority of observations in this area have been made along north/south transects about 400 km apart and involve time periods of weeks to months. Such observations obviously fail to represent any semblance of synopticity and thus do not permit ascertaining the dimensions or frequency of large and small scale eddies that could concentrate or disperse not only forage organisms, but also fish. Obviously cooperative, multiple ship operations are required to document the characteristics of this regime and relations to salmon.

Although numerous observations have been made south of the Aleutian Islands, data north of the islands are woefully inadequate in both space and time to accurately describe the complex distribution of properties and flow in the central Bering Sea. Recent cruises of the *George B. Kelez* (1970) and the *Oshoro Maru* (1973) have indicated some of the complexities in the Bowers Ridge area, but few observations have been made in the northern Bering Sea where salmon have been caught.

The marked variability and complexity in flow of the waters off the Canadian and Alaskan coasts, particularly near and overlying the continental shelf, have been observed, and the presence of sharp gradients, eddies, and extrusions of coastal waters have been documented ; similar conditions prevail along the east Siberian coast. But here again, as in the other areas, data are woefully inadequate to describe the flow regime and environmental features in an extensive area where salmon and other fish occur.

However, one should ask whether a better understanding of oceanographic conditions and processes and their effect on the distribution, growth, and survival of salmon at sea could be accomplished better in the future. Of course the answer is an unqualified yes, primarily because many of the difficulties associated with international cooperative studies have been resolved, vessels of adequate size for year-round studies are available, and present technology is far advanced over that of one and two decades ago. The costs of multiple ship operations necessary to obtain all this information in these general areas, would be prohibitive in the light of present field funds directed to INPFC oceanographic research, but two ways of obtaining much of the data are suggested. The least expensive, most easily implemented, and source of most immediate results would be a drifting telemetry buoy program along the lines proposed by the INPFC Subcommittee on Oceanography at its 1965 meeting. Such buoys are routinely tracked today by satellites. Carefully designed experiments would permit ascertaining the location of zonal flows, convergences, divergences, eddies, etc., and in the light of existing knowledge, would provide not only real-time knowledge of actual flow, but also provide a better rationale for the selection of fishing stations used to estimate the location, abundance, and movement of salmon.

Another approach would be to encourage national and international oceanographic programs to assist in acquiring the environmental data required. There are numerous programs such as GEOSECS, NORPAX, PROBES, CUEA, etc., whose basic concepts are not alien to the needs of INPFC programs for knowledge of baseline data, air-sea interactions, integrated productivity studies, and upwelling phenomena. The reestablishment of the INPFC Subcommittee on Oceanography would provide an effective group with strong, national influences to coordinate and integrate research, and analyze those aspects of studies applicable to problems confronting INPFC as well as to address the problem of predicting environmental parameters affecting marine resources. Such information is required for living marine resources other than salmon. There is little question that extensive oceanographic data will be required to completely understand the distribution, survival and growth of marine species inhabiting the continental slope, continental shelf and coastal areas. Vertical and horizontal flows dictate the dispersal of eggs and larvae of various stocks of flatfish, shrimp, king crab and Tanner crab, not to mention pollock and other pelagic stocks. Studies of multispecies interactions and the inevitable indispensible ecosystems models of the future will also require more complete environmental data. For example, the anomalously cold conditions on the Bering Sea shelf from 1970–74 appear to have significantly influenced the behavior of groundfish and other organisms in that area, but there are no INPFC oceanographic studies being conducted in relation to any fishes other than salmon. This accounts, in part, for the absence of an extensive updating of the oceanography of the shallow eastern Bering Sea that was included in the appendix of INPFC Bulletin 13. Although such a study is warranted, it is considered a separate task.

Perhaps the role of environmental studies can be put in proper focus by realizing that if the oceans became transparent to man's eye and the abundance and movements of individual stocks could be followed through satellite or other observations, all of the present pıoblems of abundance and distribution would be resolved, but we would still require environmental studies, not only to provide an understanding of behavior patterns but also to forecast movements.

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GLOSSARY OF TERMS

AIRBORNE RADIOMETER—infrared sensing device which measures the sea surface temperature from an aircraft.

BAROTROPIC—state when surfaces of equal pressure (isobaric) lie parallel to surfaces of equal density (isopycnal surfaces).

BAROCLINIC—state when surfaces of equal pressure intersect surfaces of equal density.

COMPOUND VORTEX STREET—a pair of von Karman vortex streets (or wakes) arranged side by side, streamlines 180° out of phase.

CORIOLIS PARAMETER (FORCE)—apparent force on moving particles resulting from the earth's rotation. It causes the moving particles to be deflected to the right of motion in the Northern Hemisphere and to the left in the Southern Hemisphere.

CUEA—Coastal Upwelling Experiment Analysis, associated with the International Decade of Ocean Exploration program.

CURL—vector cross-product of a differential operator (∇) and a vector (in subject case, wind-stress) resulting in another vector (of which only the vertical component is considered) representing torque.

DECIBAR—Unit of pressure= 10^5 dynes/cm; roughly numerically equivalent to depths in the ocean measured in meters.

DICHOTHERMAL WATER—a subsurface temperature-minimum stratum located at the bottom of the upper zone formed when, as a result of winter cooling and overturn, water in the upper zone becomes colder than the water in the halocline and subsequent summer heating of the surface layer isolates this stratum.

DOMAIN—Area within the Subarctic Pacific having consistent properties, structure and behaviour (flow, heating, cooling, etc.).

DYNAMIC (GEOPOTENTIAL) TOPOGRAPHY—configuration formed by contouring the dynamic height anomaly between an isobaric and a selected reference surface at a series of oceanographic stations, the resulting chart is used for determining geostrophic currents.

DYNAMIC HEIGHT ANOMALY—excess of the actual geopotential difference between two given isobaric surfaces, over the geopotential difference in a homogeneous water column of salinity 35‰ and temperature 0°C. It is the product of the mean specific volume anomaly and the difference in pressure (in decibars); the latter is assumed to equal the difference in depth in meters.

EKMAN TRANSPORT—wind-induced transport confined to the surface layer directly proportional to the wind stress. Units are metric tons/sec/km or gm/sec/cm.

GEOMAGNETIC ELECTROKINETOGRAPH (GEK)—shipboard current-measuring device dependent upon the principle that an electrolyte moving through the earth's magnetic field will generate an electric current.

GEOSECS—Geochemical Ocean Sections Study, associated with the International Decade of Ocean Exploration program.

GEOPOTENTIAL TOPOGRAPHY—see Dynamic topography.

GEOSTROPHIC CURRENT—current defined by assuming an exact balance exists between horizontal pressure gradient and Coriolis forces.

GEOSTROPHIC TRANSPORT—volume of moving water measured by the geostrophic velocity and the cross-sectional area between two points.

HALOCLINE—salinity gradient representing the transition between the upper and lower zones.

INTEGRATED TOTAL TRANSPORT—wind-induced transport obtained by integrating westward the meridional component of total transport (usually expressed as-metric tons/sec/km).

ISOXYLS—lines of equal dissolved oxygen concentration.

LOWER ZONE—waters underlying the halocline where properties are affected predominantly by internal processes such as advection, diffusion, etc.

MESOTHERMAL WATER—a subsurface temperature-maximum stratum located below the dichothermal water.

MERIDIONAL TOTAL TRANSPORT—wind-induced transport across a unit length of latitude proportional to the curl of the wind stress (units are usually-metric tons/sec/km).

METRIC TON—one metric ton is equivalent to 10^6 gm.

NORPAX—North Pacific Environment, a large scale, long-term physical oceanography and meteorological study of largely the central portion of the eastern North Pacific Ocean, associated with the International Decade of Ocean Exploration program.

OXYCLINE—vertical gradient of dissolved oxygen.

PROBES—Processes and Resources of the Bering Sea Shelf, a proposal for an international research program to ascertain why the Bering Sea is so productive.

PYCNOCLINE—vertical gradient of density.

SIGMA-T (σ_t)—conveniently abbreviated value of density (ρ) of a seawater sample of temperature, t, and salinity, S,: $\sigma_t = (\rho s.t-1) \times 10^3$.

SOURCE—type of flow emanating from a finite origin and spreading out over an infinite area (the reverse constitutes a sink).

SPECIFIC VOLUME ANOMALY—the excess of actual specific volume over that of water of 35‰ and 0 C at the same pressure.

SVERDRUP (Sv)—unit of volume transport equal to 10^6 m^3/sec.

SVERDRUP EQUATION—relation between wind-stress and rate of variation of the Coriolis parameter permitting an estimate of volume transport.

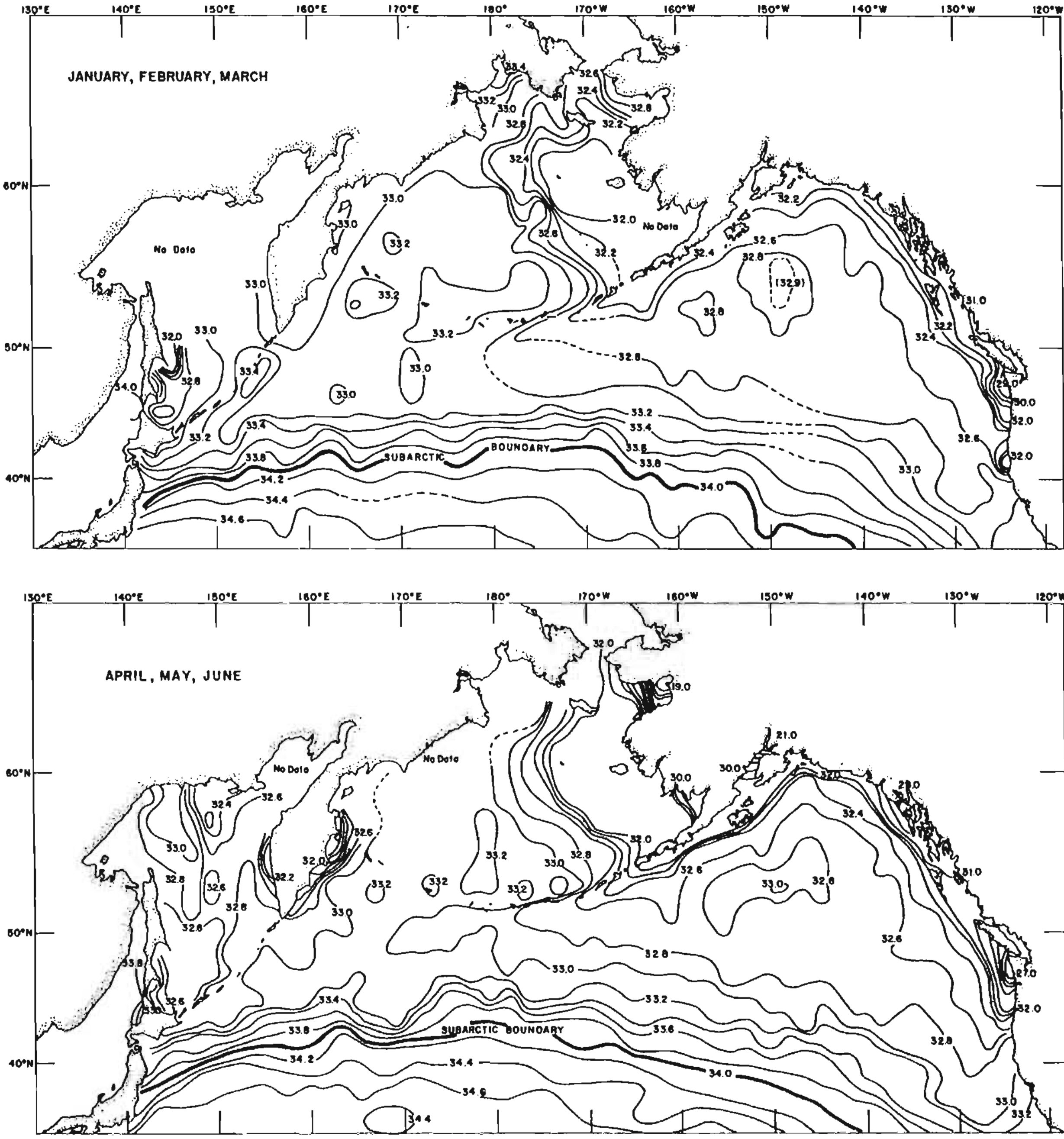
UPPER ZONE—surface layer above the halocline in which the properties of the water are predominantly influenced by such factors as seasonal heating and cooling, precipitation, evaporation, and wind-mixing.

VOLUME TRANSPORT—volume of water moving between two points usually expressed in Sverdrups.

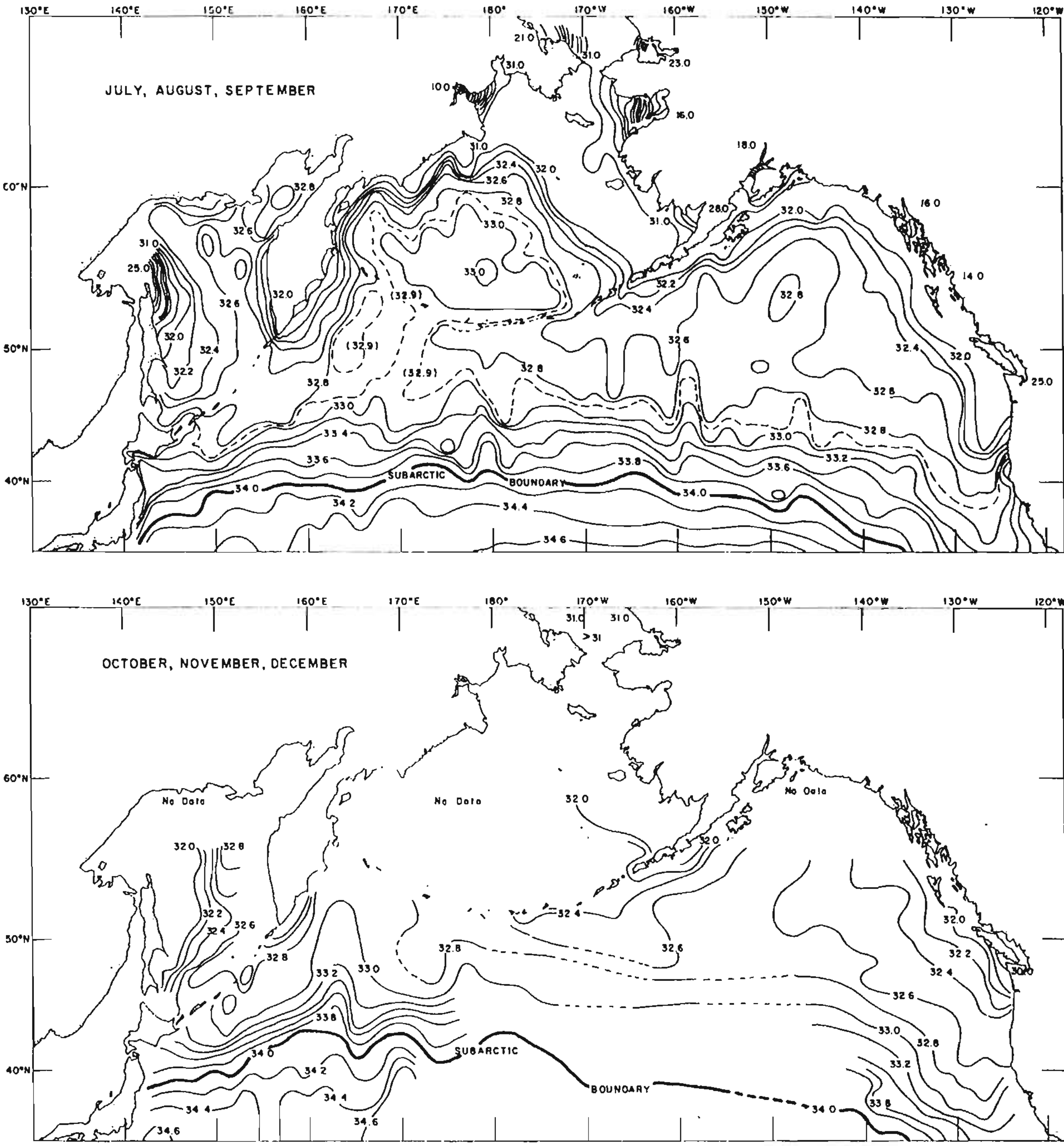
WIND-STRESS—vector assumed to be in the direction of the surface wind and proportional to the square of the wind speed (usually expressed as dynes/cm^2).

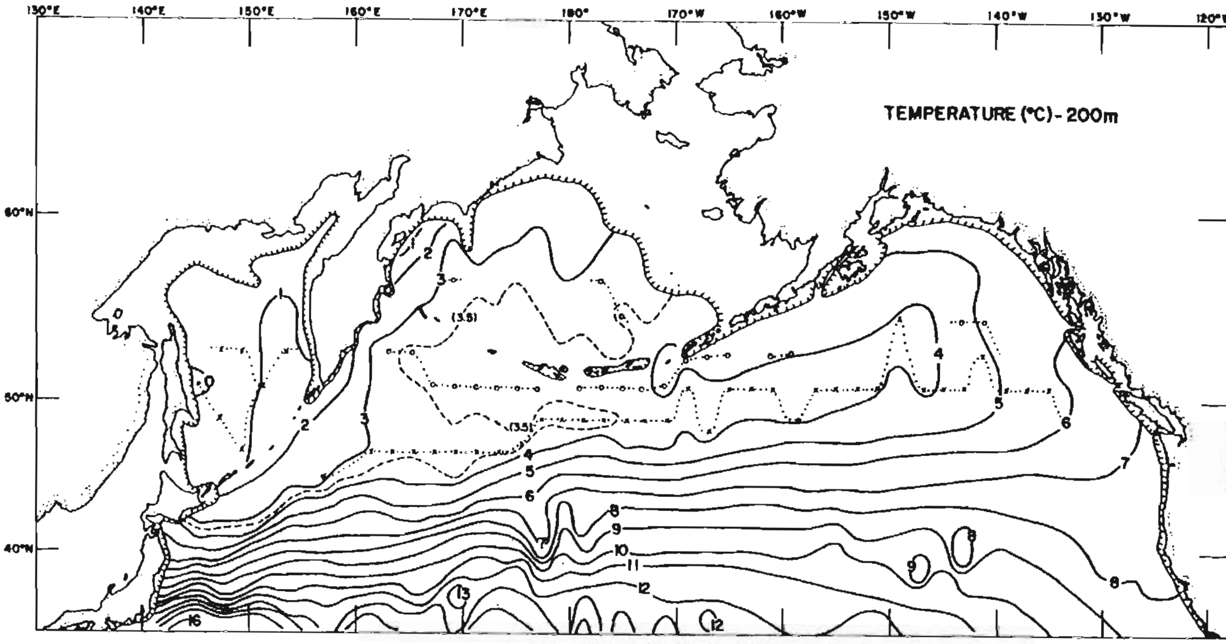
VORTEX STREETS—wakes characterized by a double row of vortices, one row having positive (cyclonic) circulation and the other, negative (anticyclonic circulation); these occur alternately downstream.

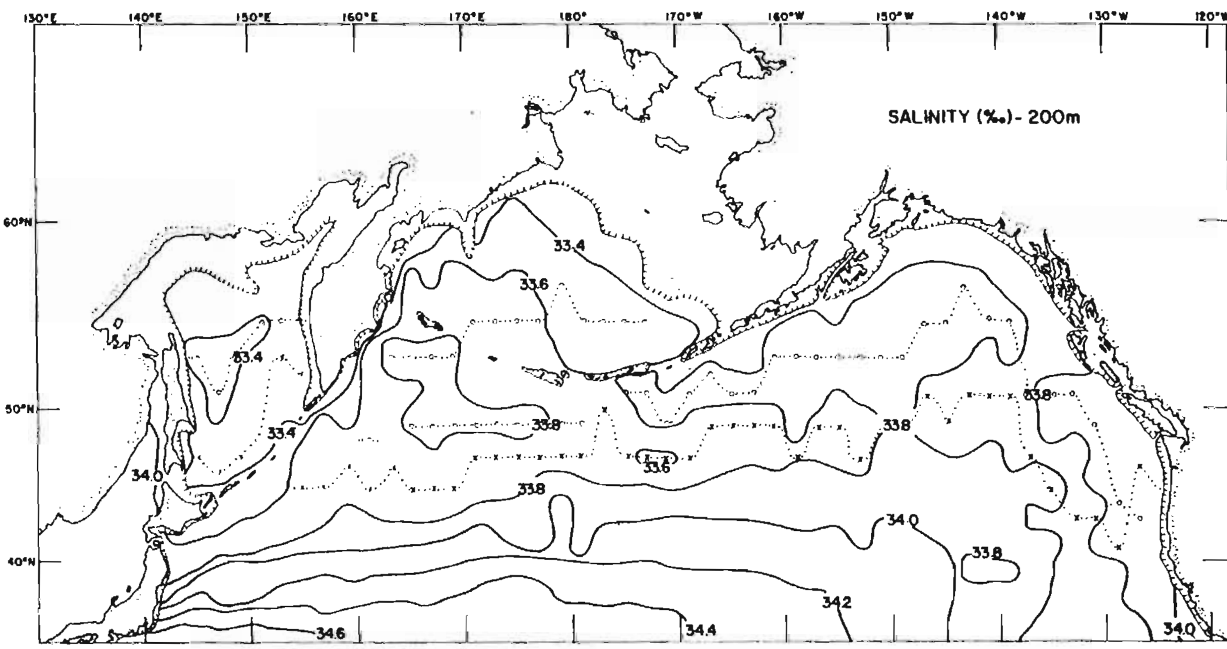
APPENDIX FIGURES—OVERLEAF



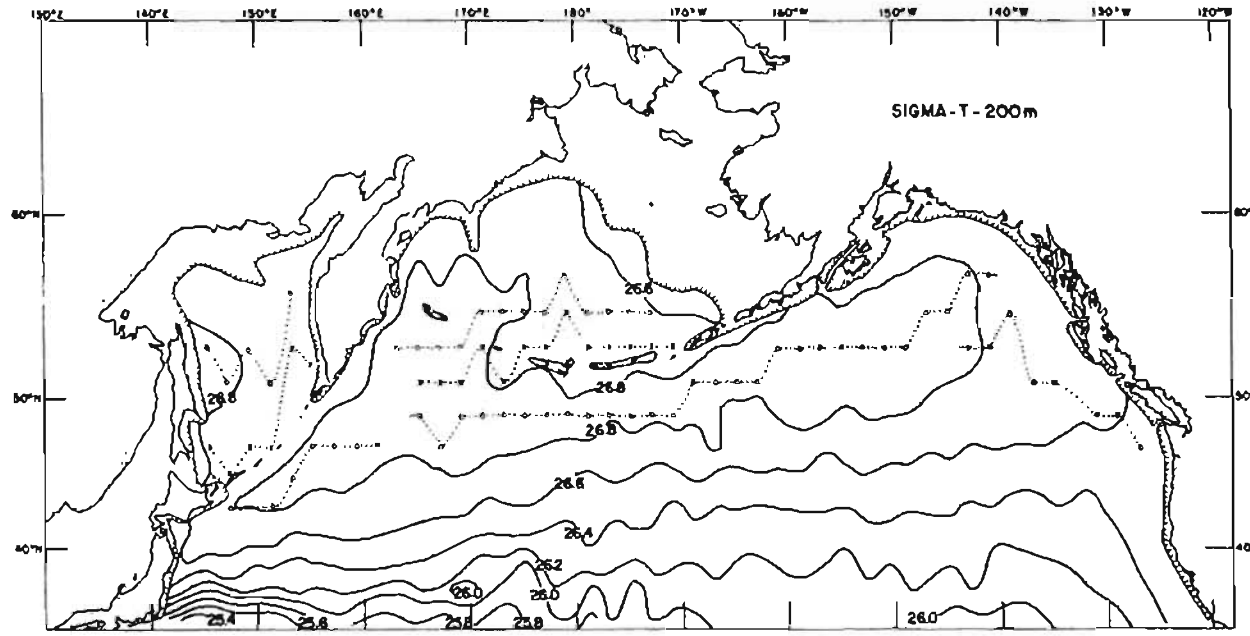
APPENDIX FIGURE 1. Seasonal mean long-term surface salinity distribution.

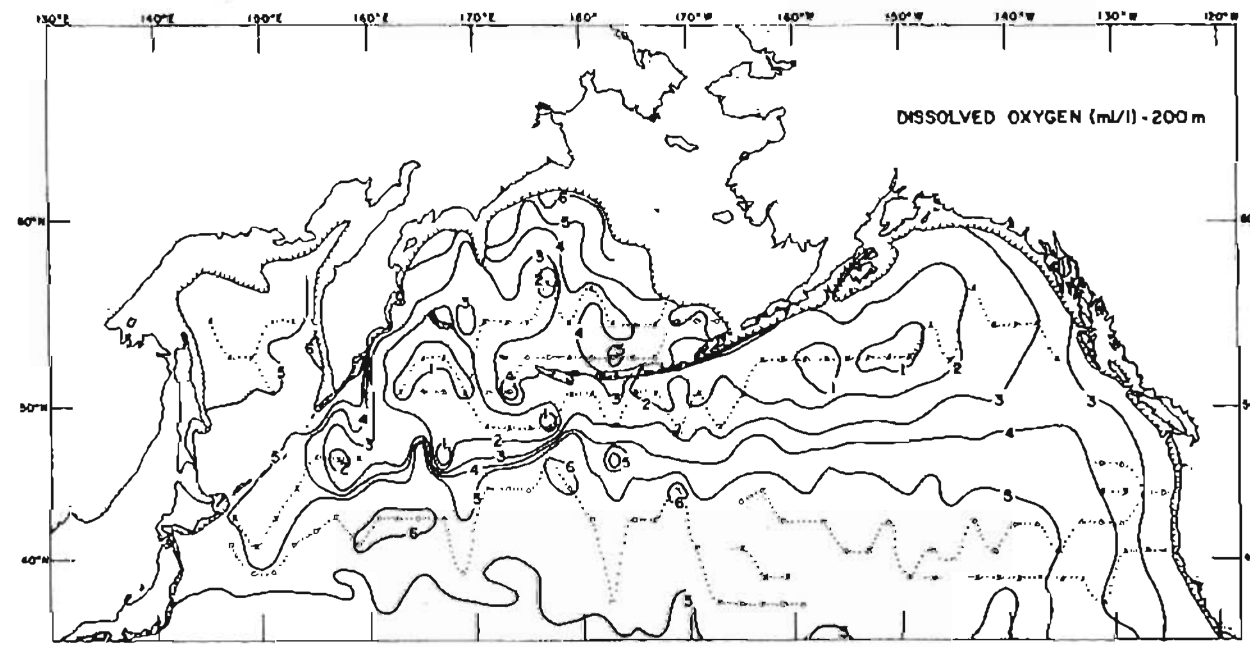

JULY, AUGUST, SEPTEMBER
SUBARCTIC
BOUNDARY
OCTOBER, NOVEMBER, DECEMBER
No Data
No Data
No Data
SUBARCTIC
BOUNDARY

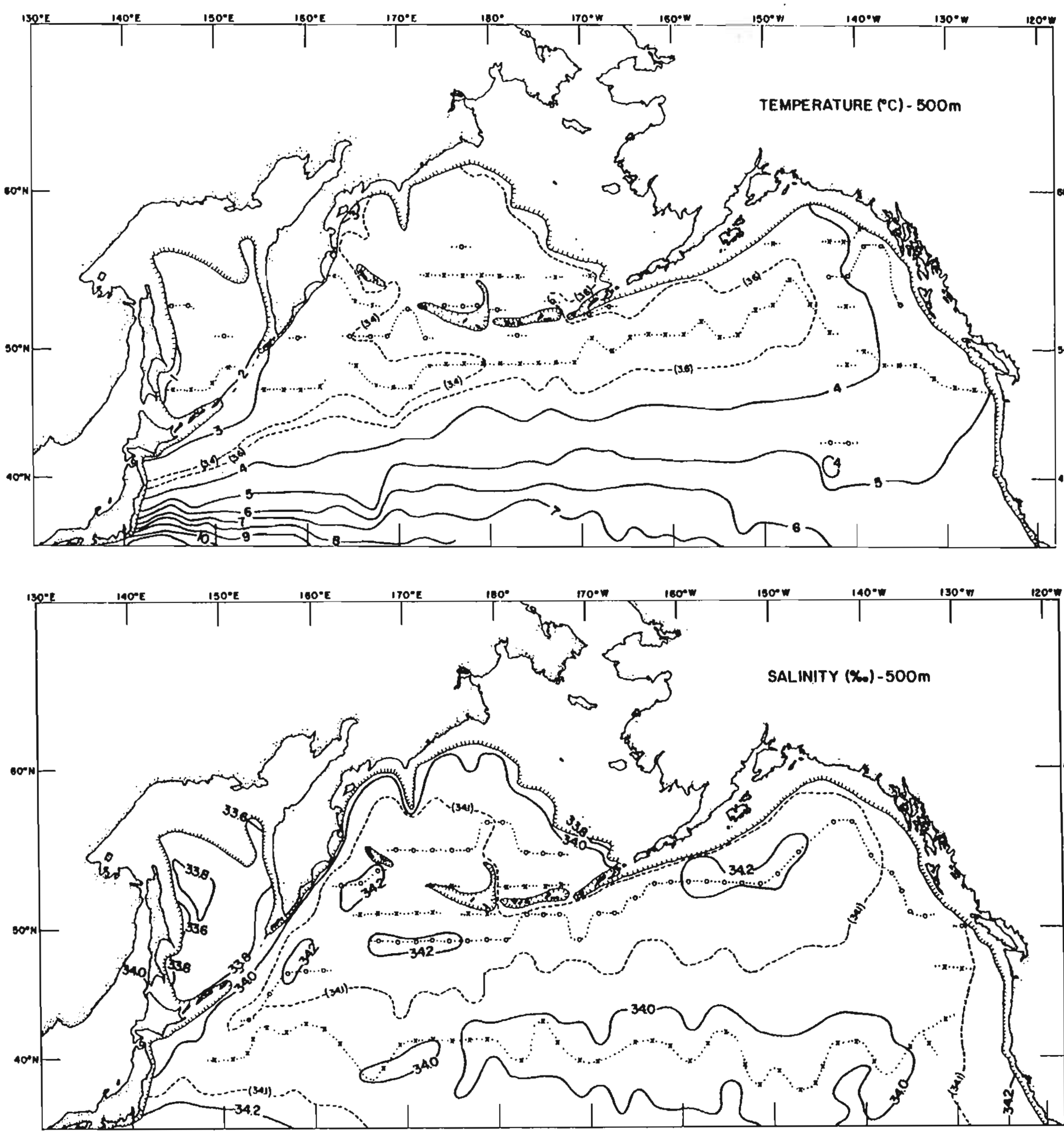




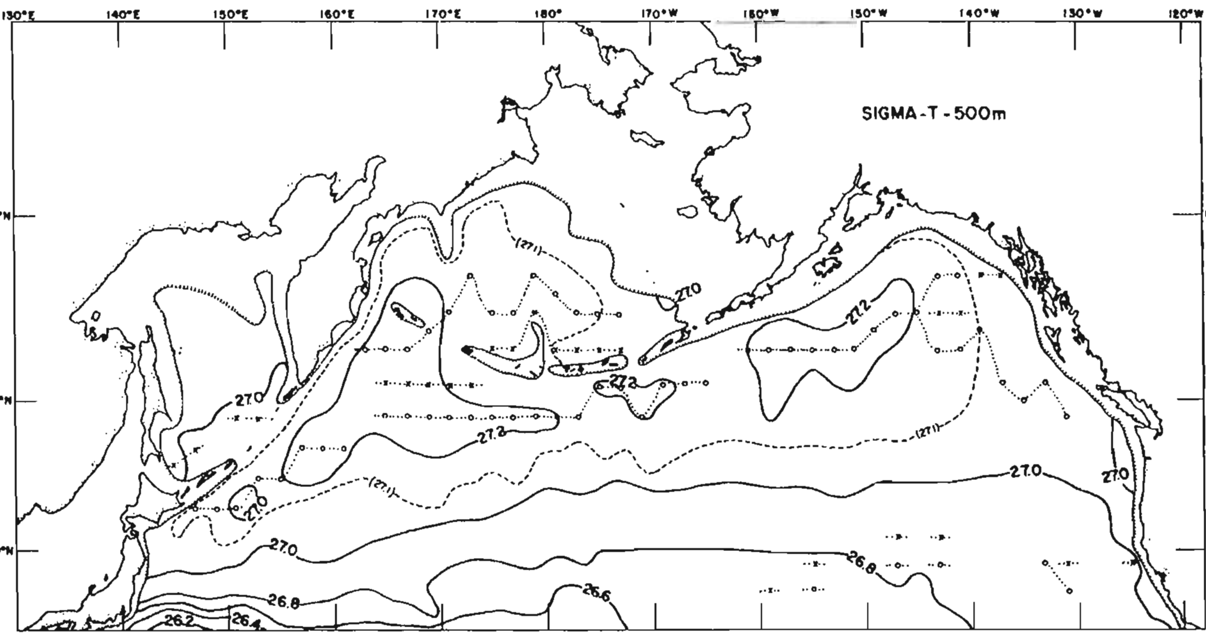
APPENDIX FIGURE 2. Long-term mean temperature, salinity, sigma-t, and dissolved oxygen distributions at 200 m (-×- indicates minima, -O- maxima).

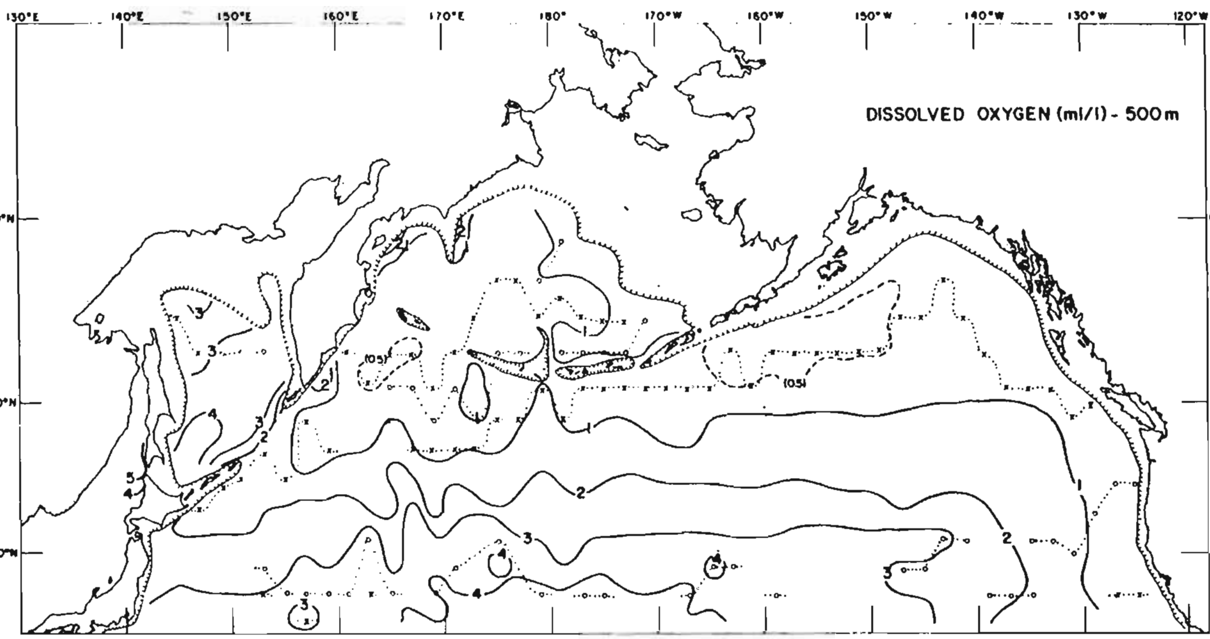

SIGMA-T-200m

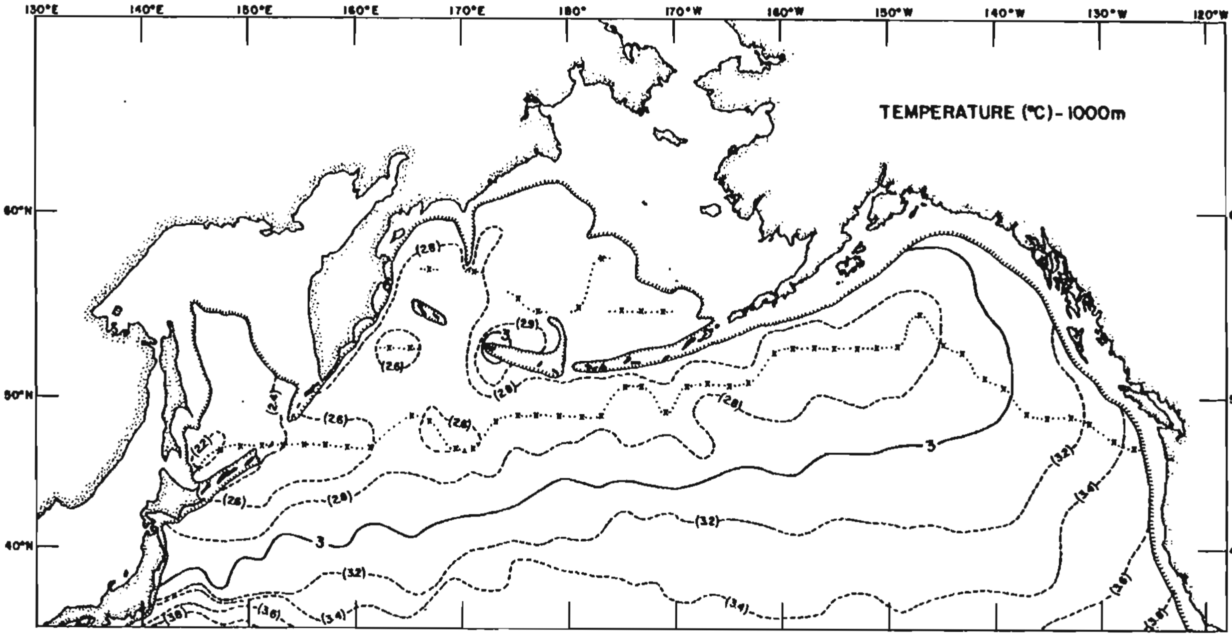

DISSOLVED OXYGEN (ml/l)-200m

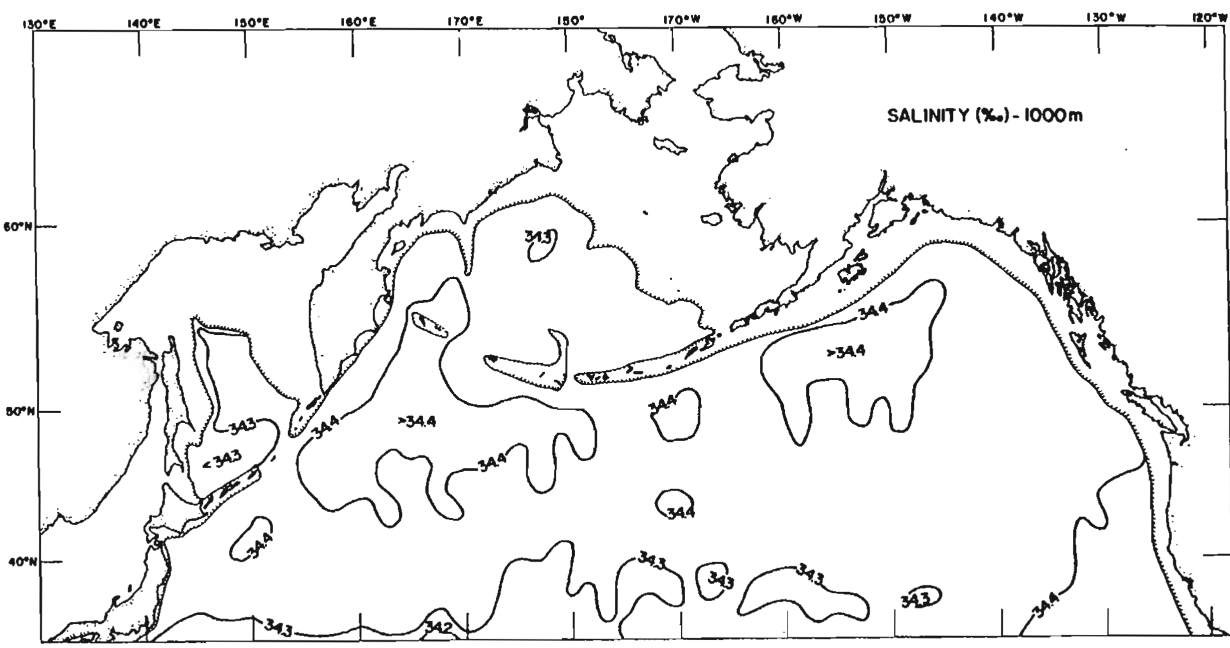


APPENDIX FIGURE 3. Long-term mean temperature, salinity, sigma-t, and dissolved oxygen distributions at 500 m (–×– indicates minima, –O– maxima).

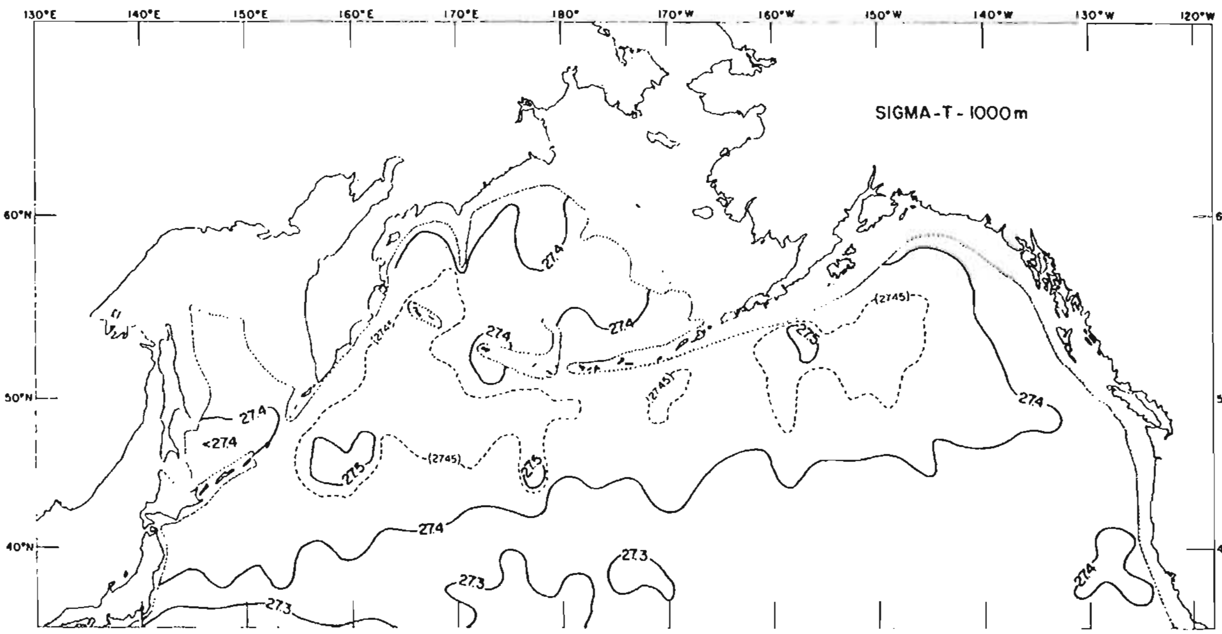

SIGMA-T - 500m
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N
27.0
27.2
27.3
(27.1)
26.8
26.6
26.2
26.4

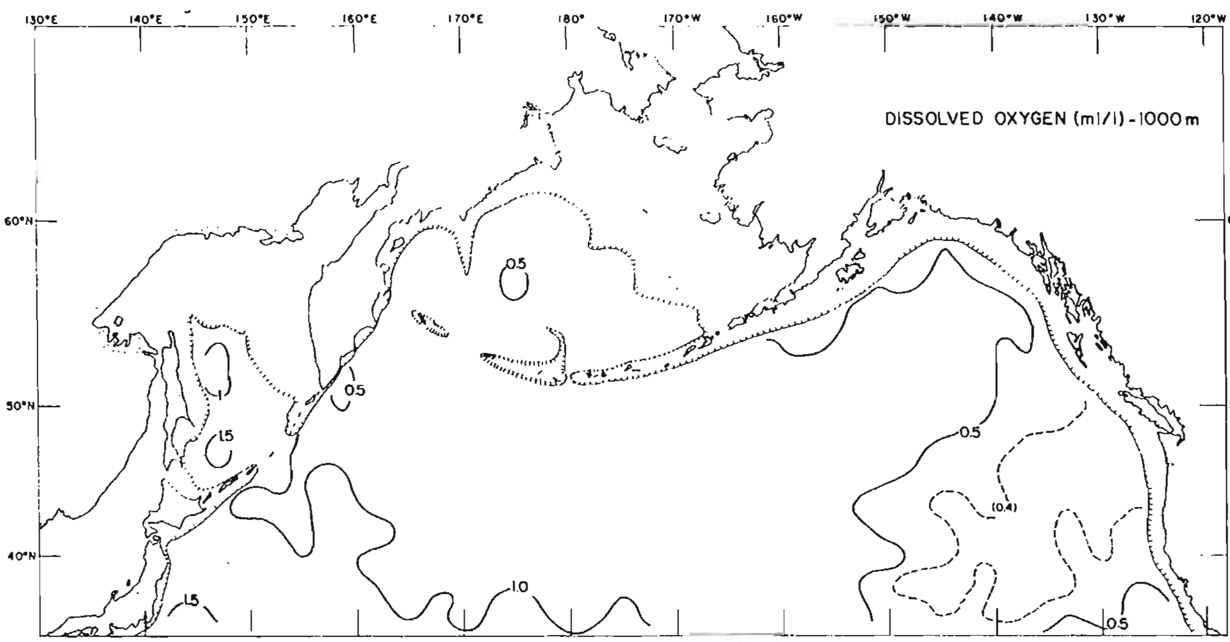

DISSOLVED OXYGEN (ml/l) - 500m
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N
(0.5)
1
2
3
4
5

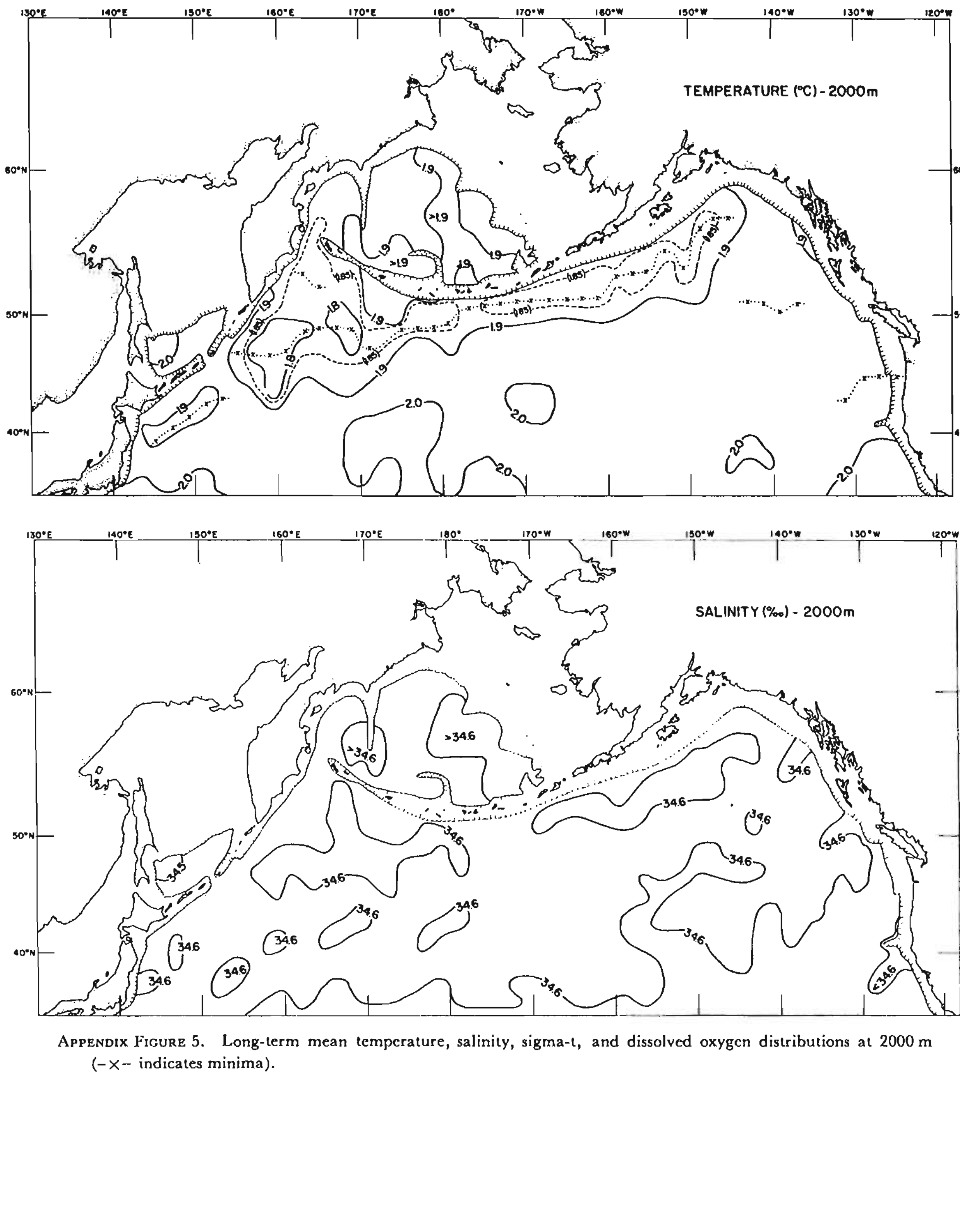




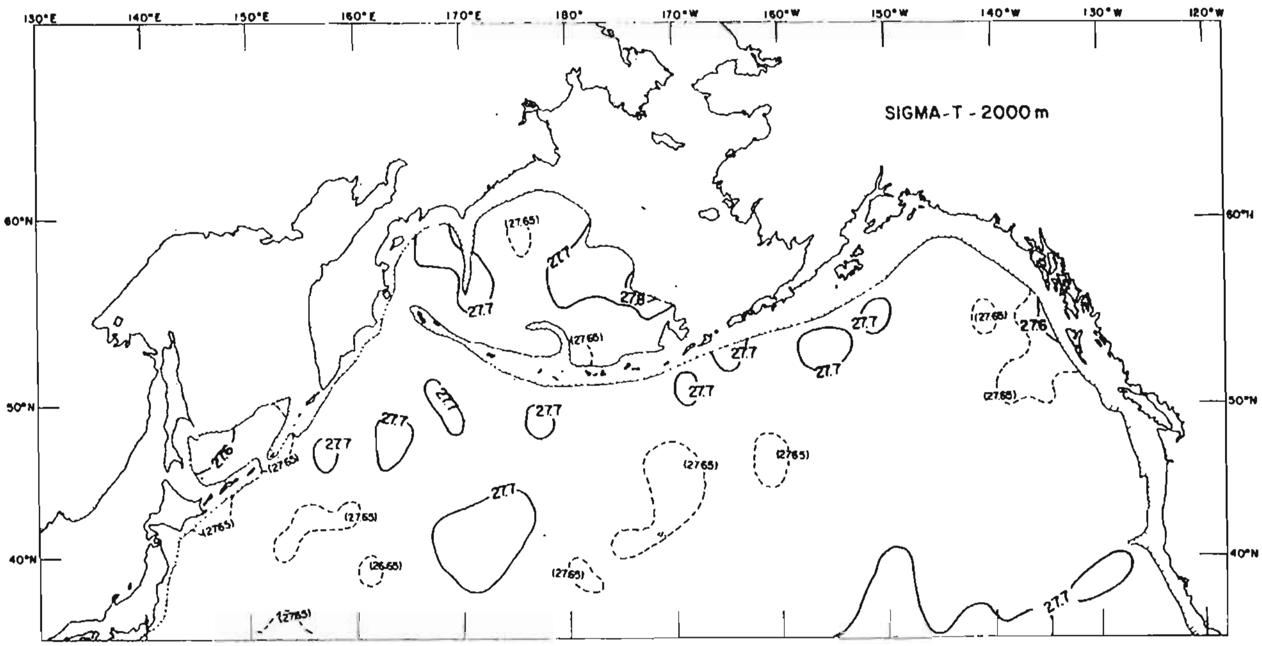
Appendix Figure 4. Long-term mean temperature, salinity, sigma-t, and dissolved oxygen distributions at 1000 m (–x– indicates minima).

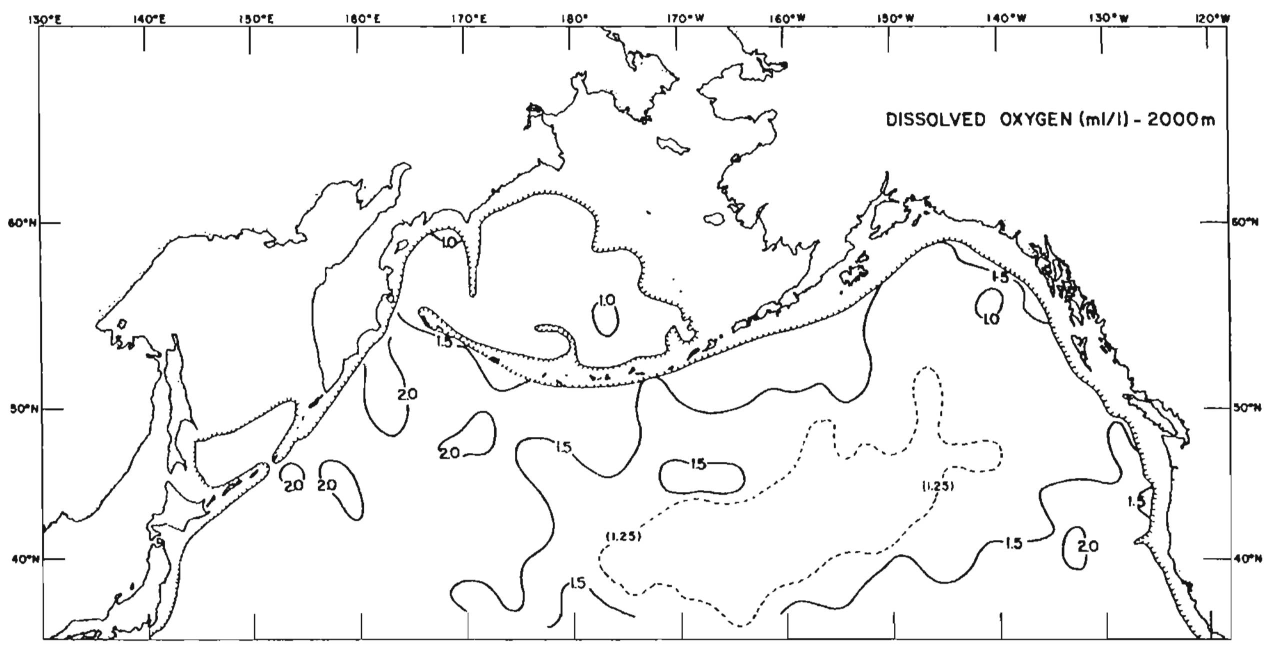

SIGMA-T - 1000 m
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N
27.4
<27.4
27.5
(27.45)
27.3

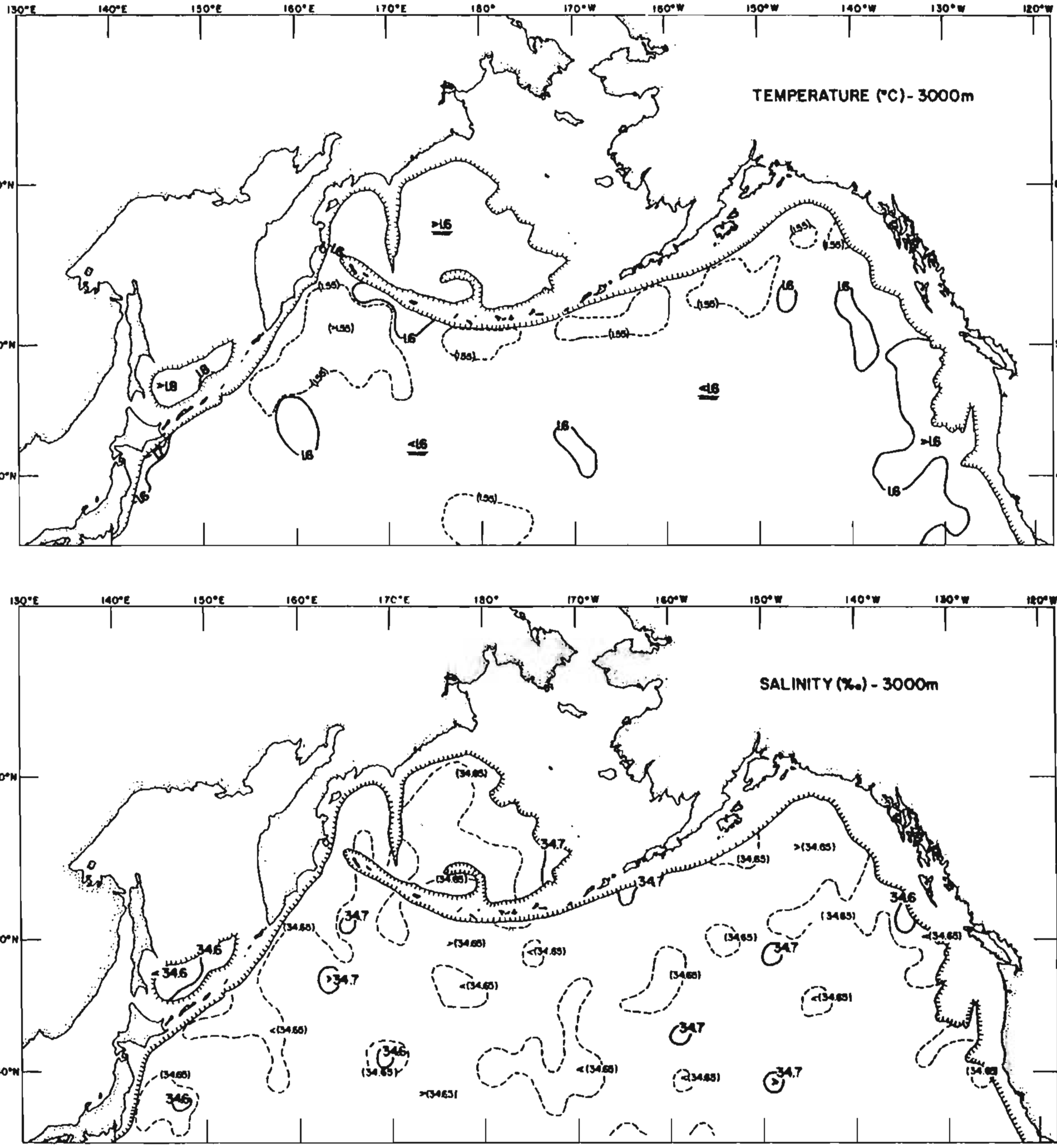

DISSOLVED OXYGEN (ml/l) - 1000 m
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N
0.5
1.5
1.0
(0.4)



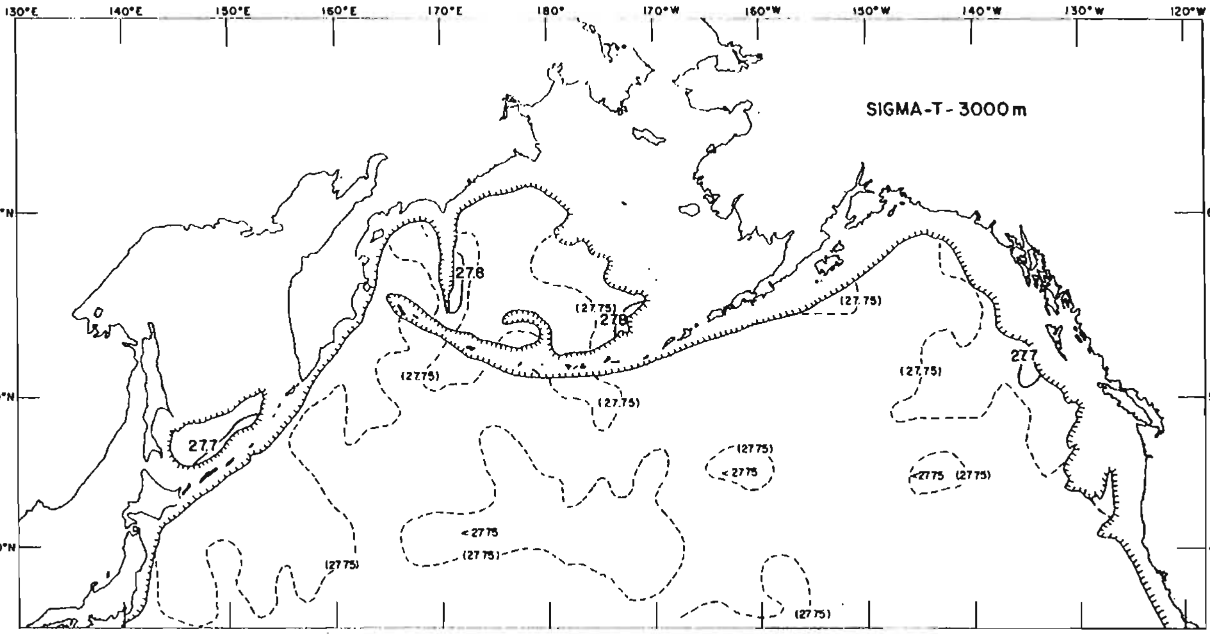
APPENDIX FIGURE 5. Long-term mean temperature, salinity, sigma-t, and dissolved oxygen distributions at 2000 m (–×– indicates minima).

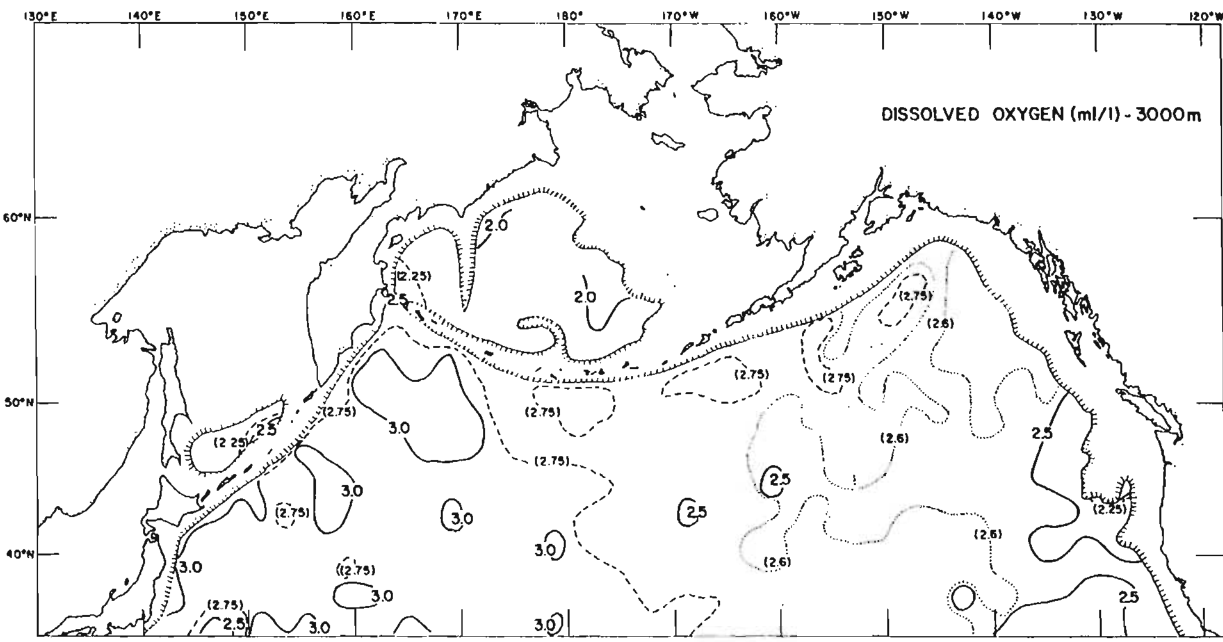

SIGMA-T - 2000 m
27.7
(27.65)
27.8
27.6

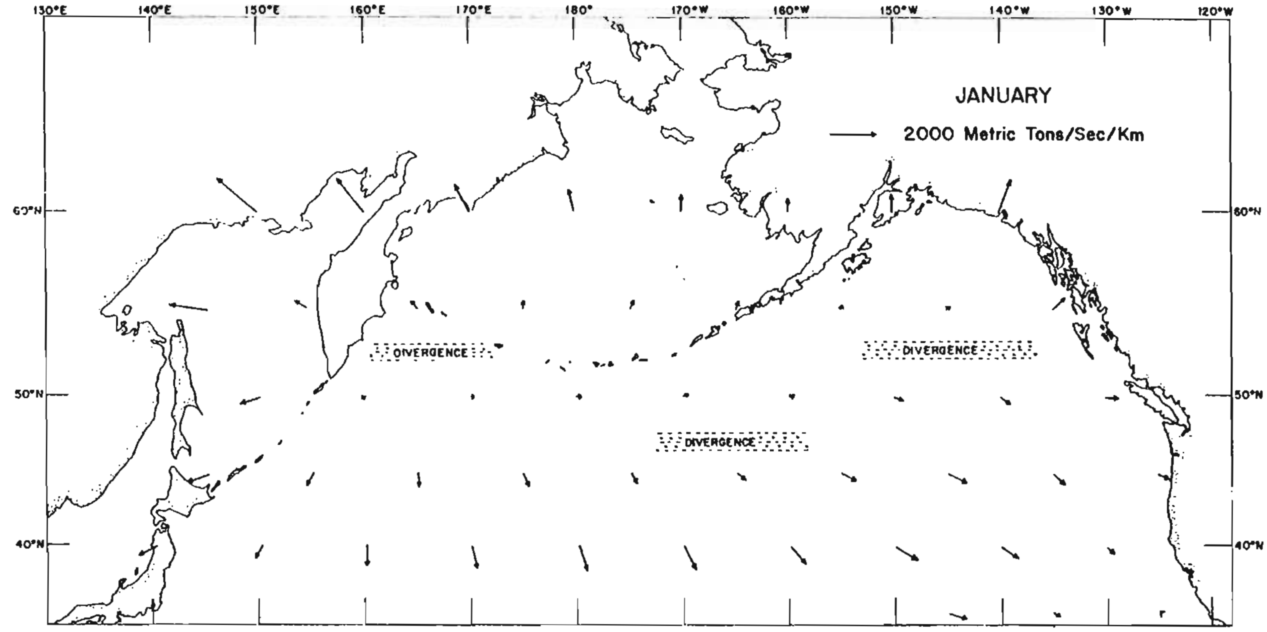

DISSOLVED OXYGEN (ml/l) - 2000 m
1.0
1.5
2.0
(1.25)

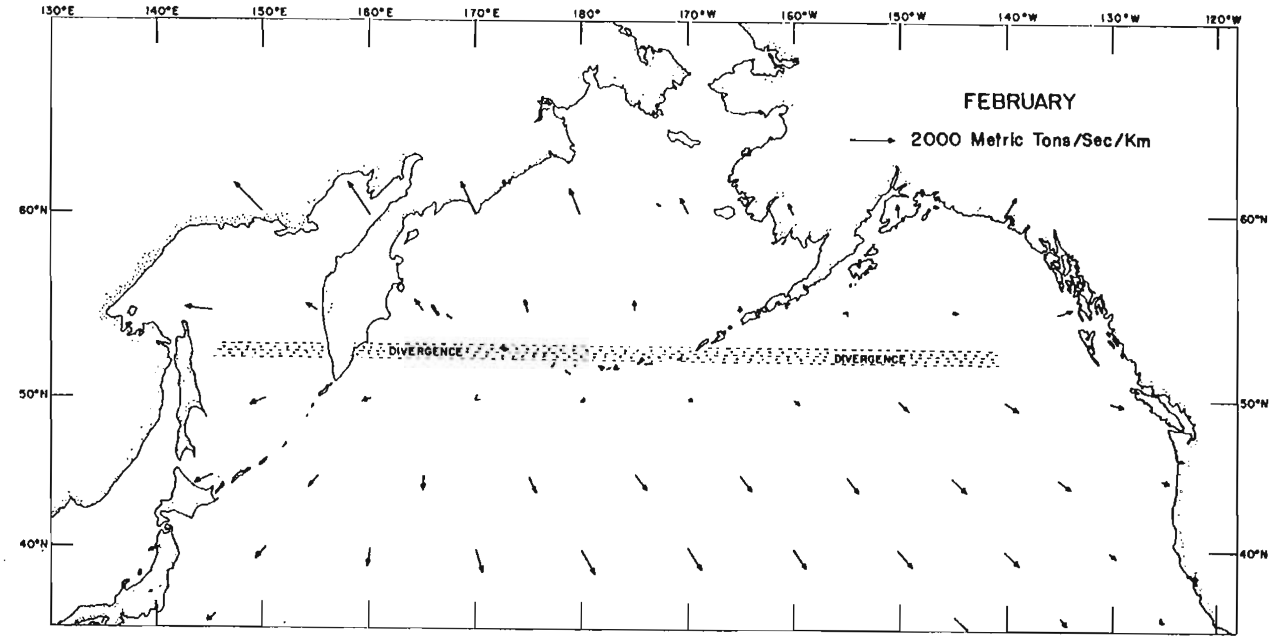


APPENDIX FIGURE 6. Long-term mean temperature, salinity, sigma-t, and dissolved oxygen distributions at 3000 m.

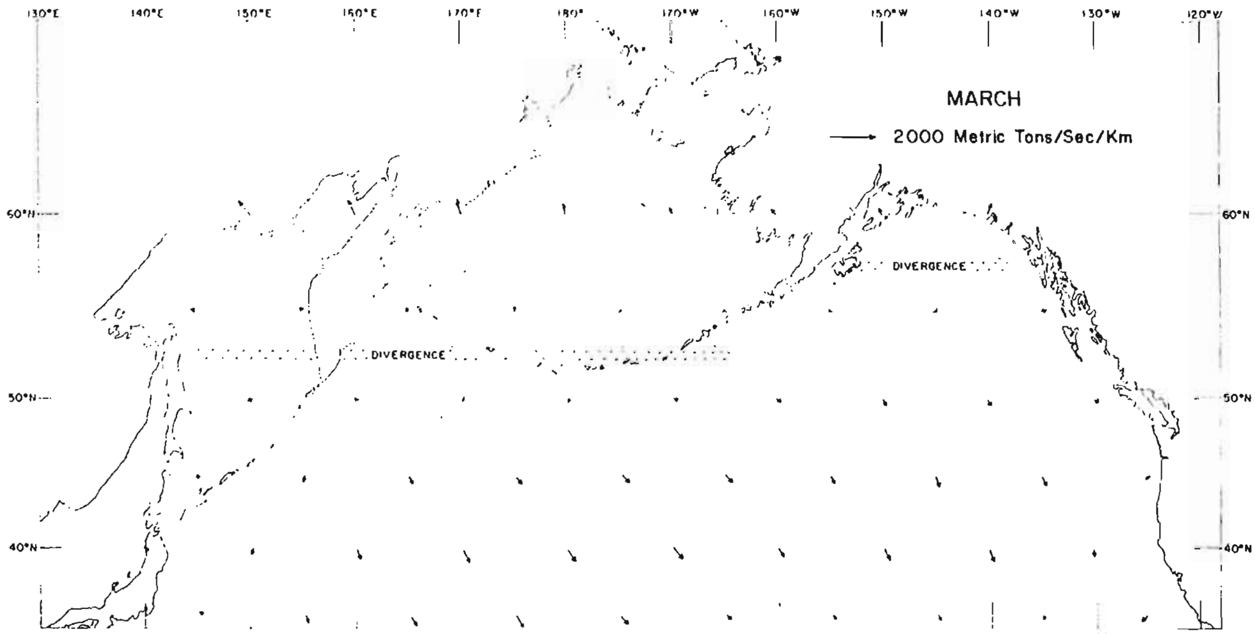

SIGMA-T - 3000 m
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N
27.8
27.7
(27.75)
<27.75

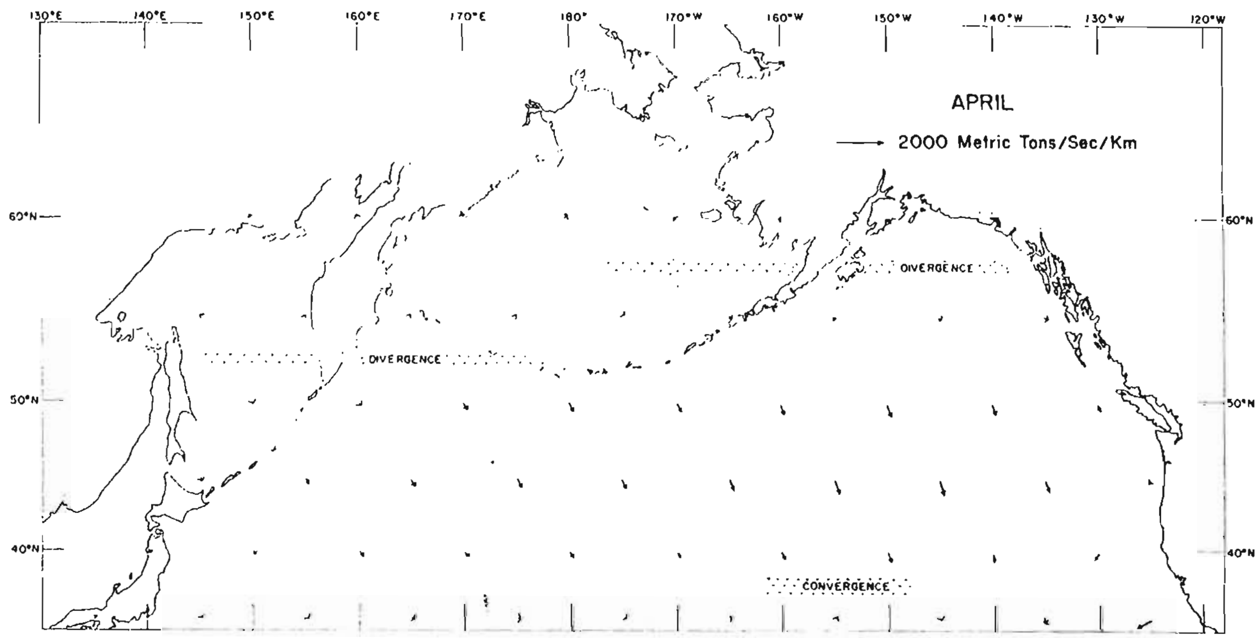

DISSOLVED OXYGEN (ml/l) - 3000 m
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N
2.0
2.5
3.0
(2.25)
(2.75)
(2.6)



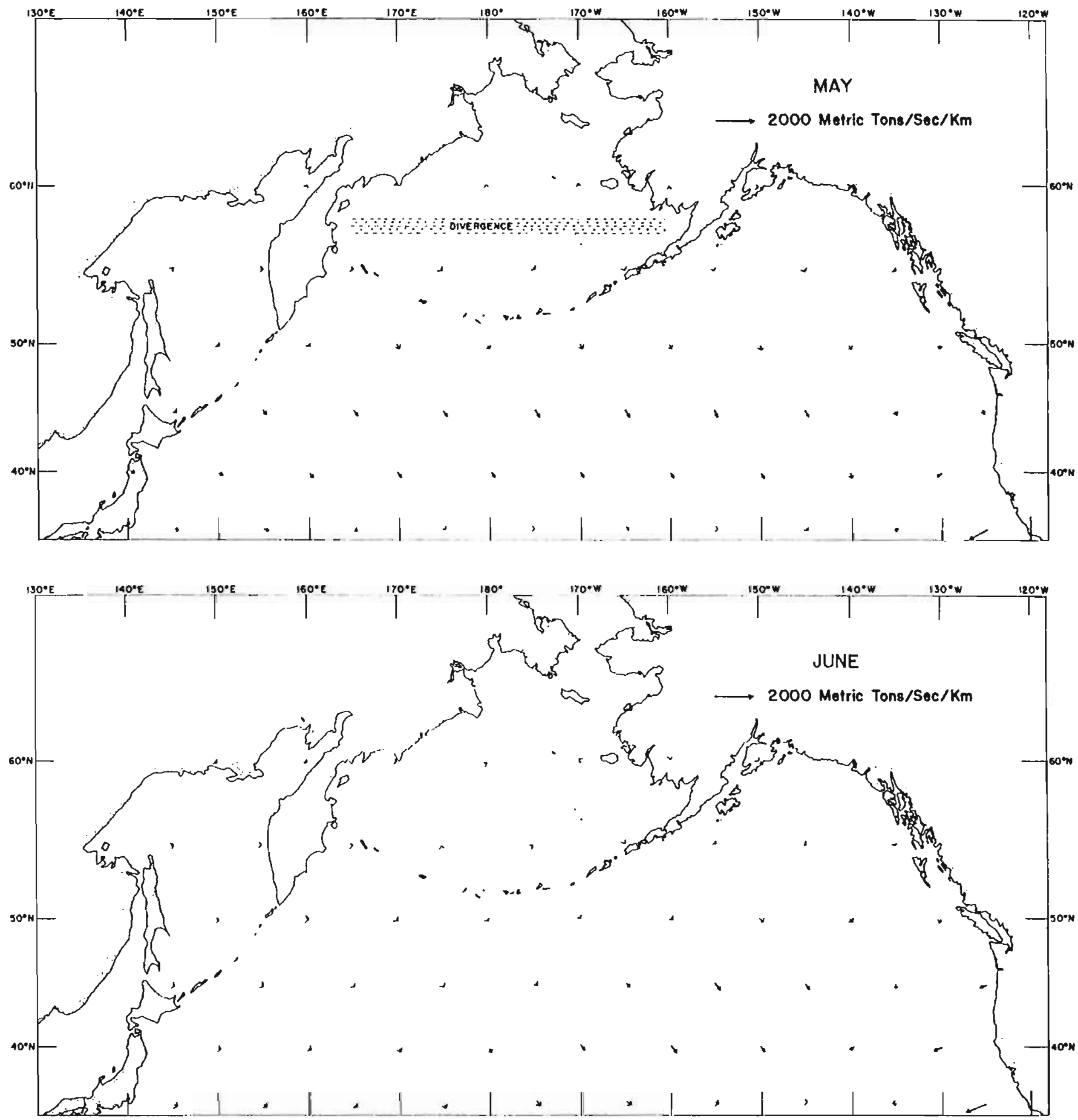


Appendix Figure 7. Monthly mean Ekman transport (metric tons/sec/km), 1960–69.

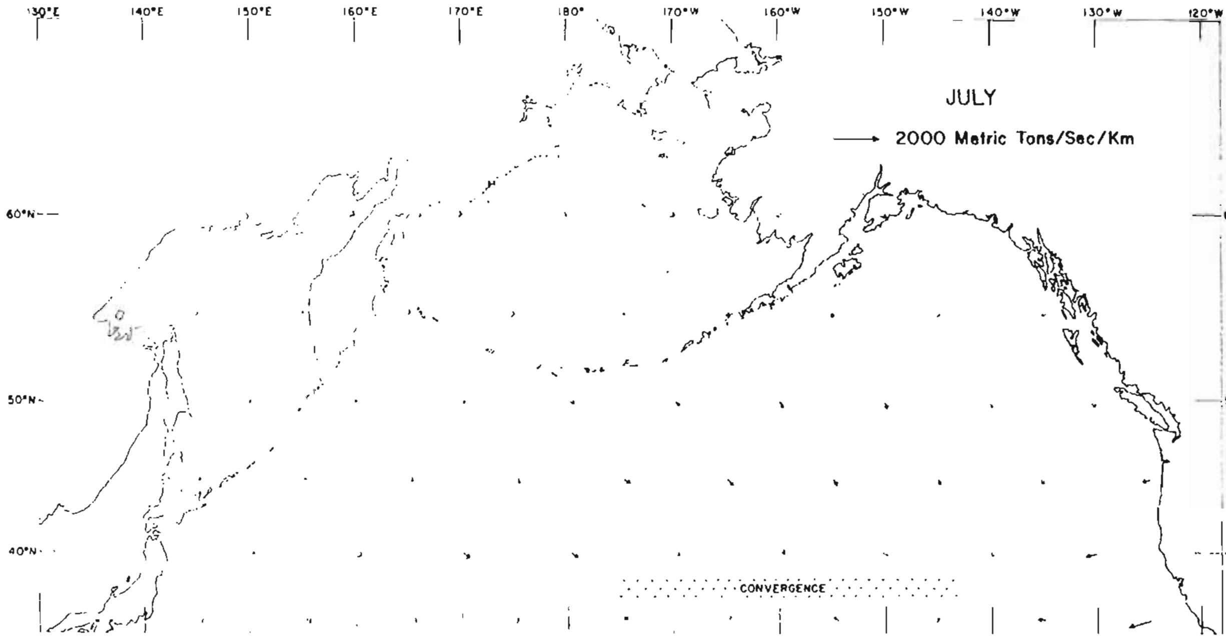

MARCH
2000 Metric Tons/Sec/Km
DIVERGENCE
DIVERGENCE
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N

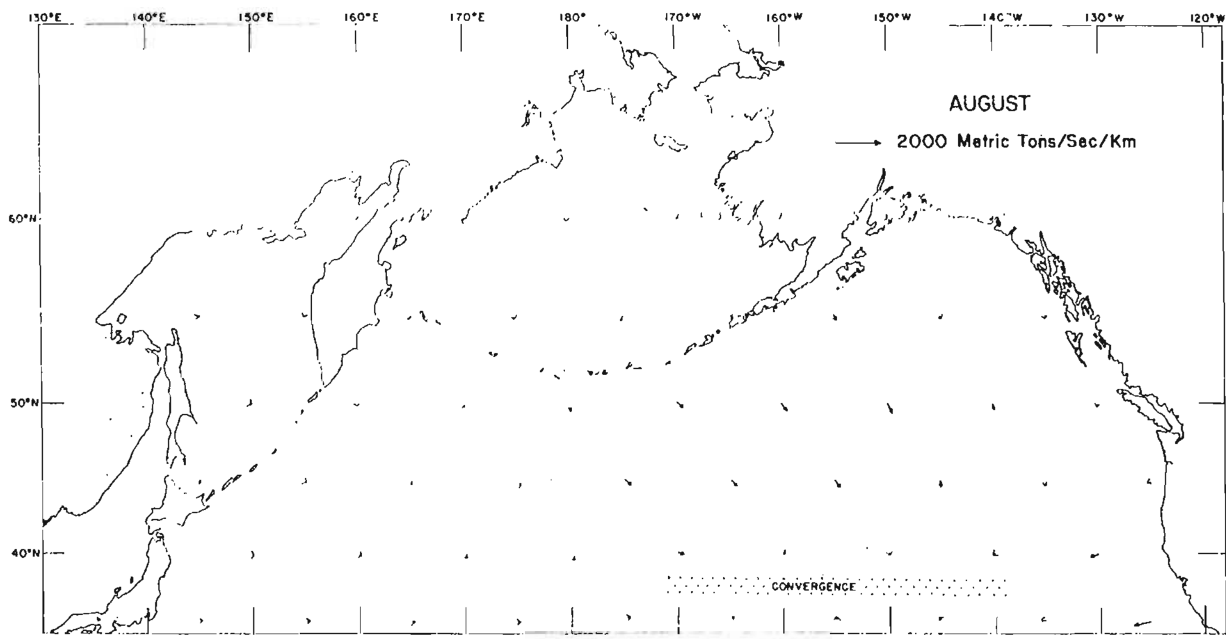

APRIL
2000 Metric Tons/Sec/Km
DIVERGENCE
DIVERGENCE
CONVERGENCE
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N

Continued

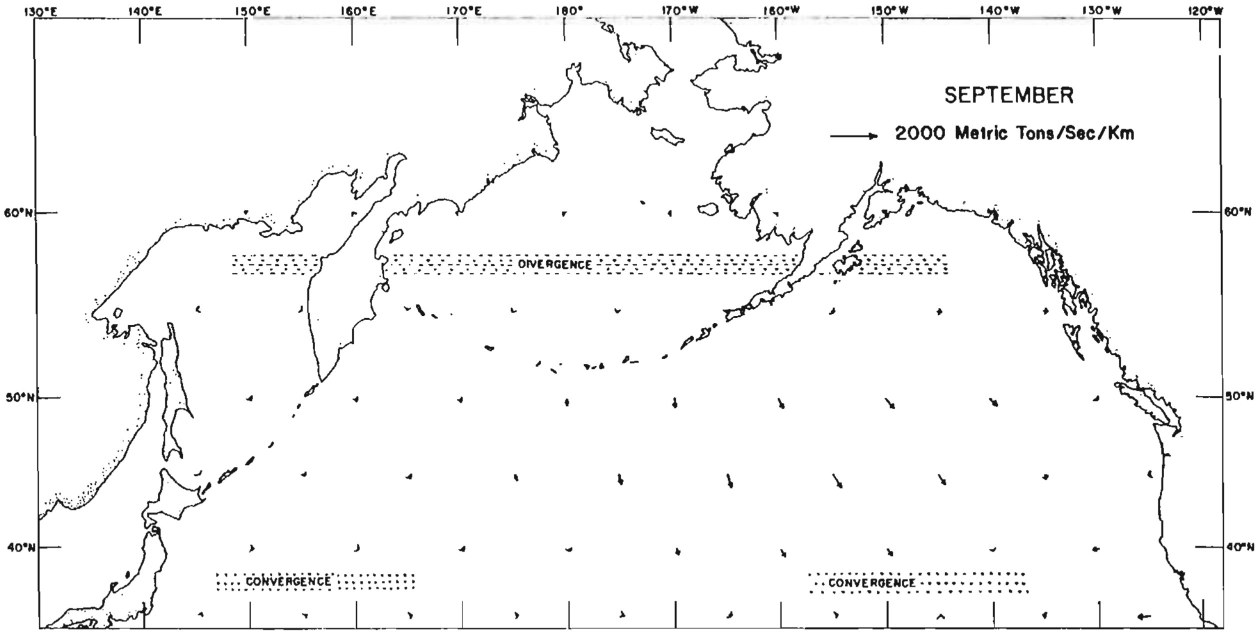


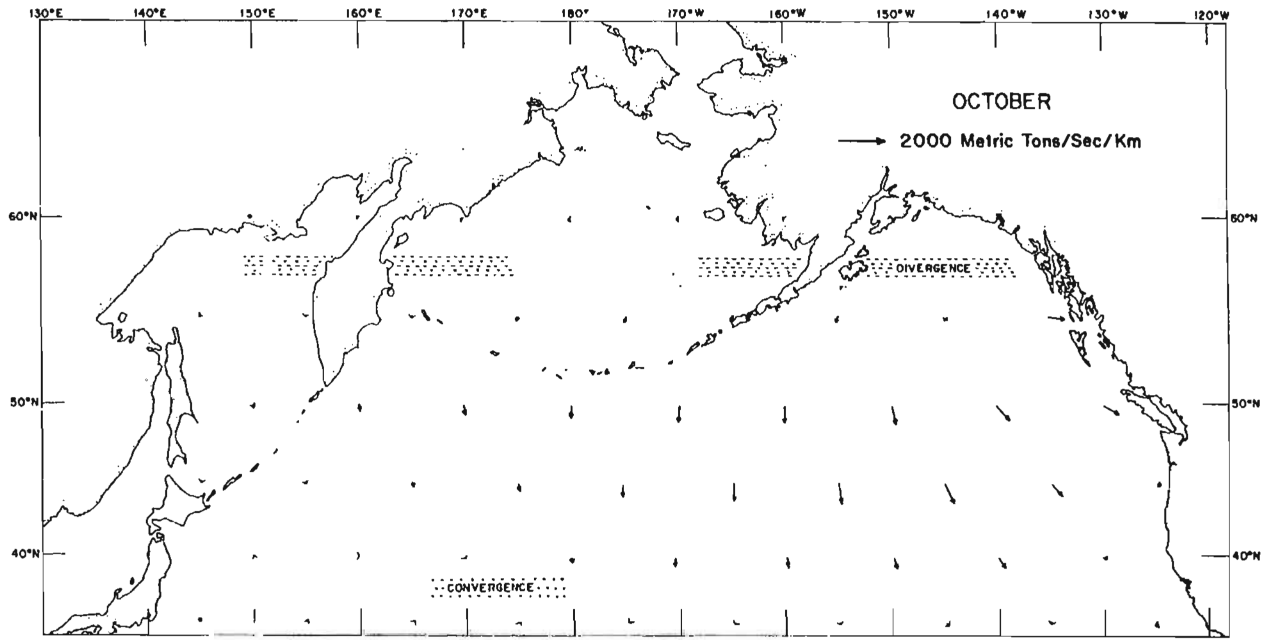
Appendix Figure 7 (Cont.)


JULY
2000 Metric Tons/Sec/Km
CONVERGENCE
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N

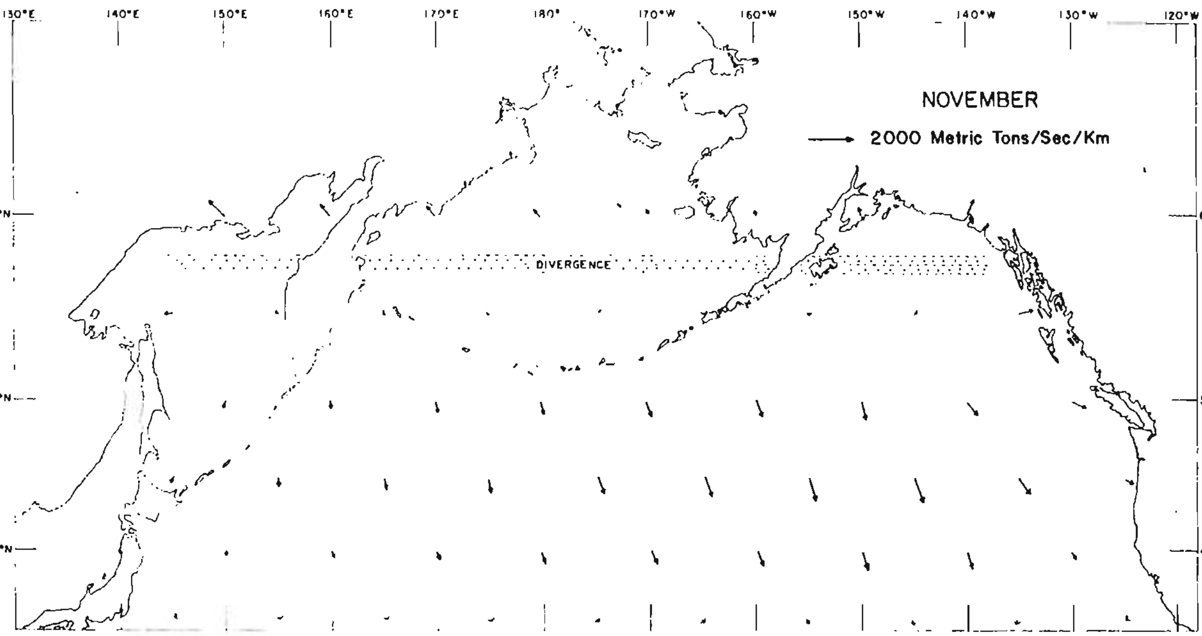

AUGUST
2000 Metric Tons/Sec/Km
CONVERGENCE
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N

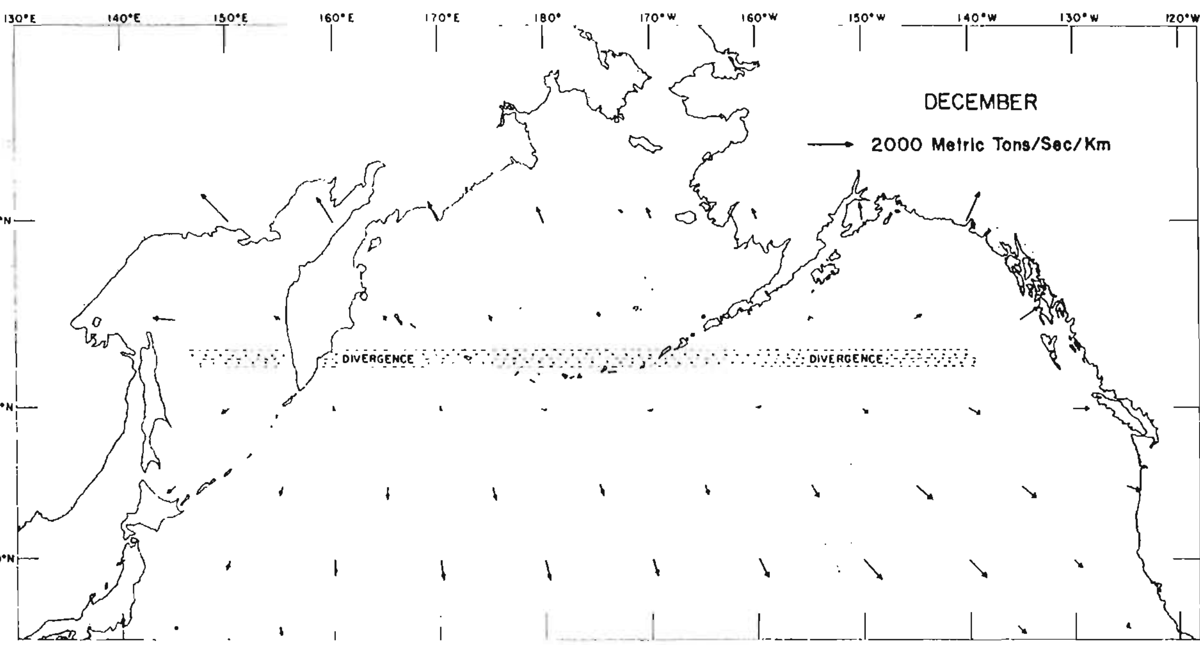
Continued

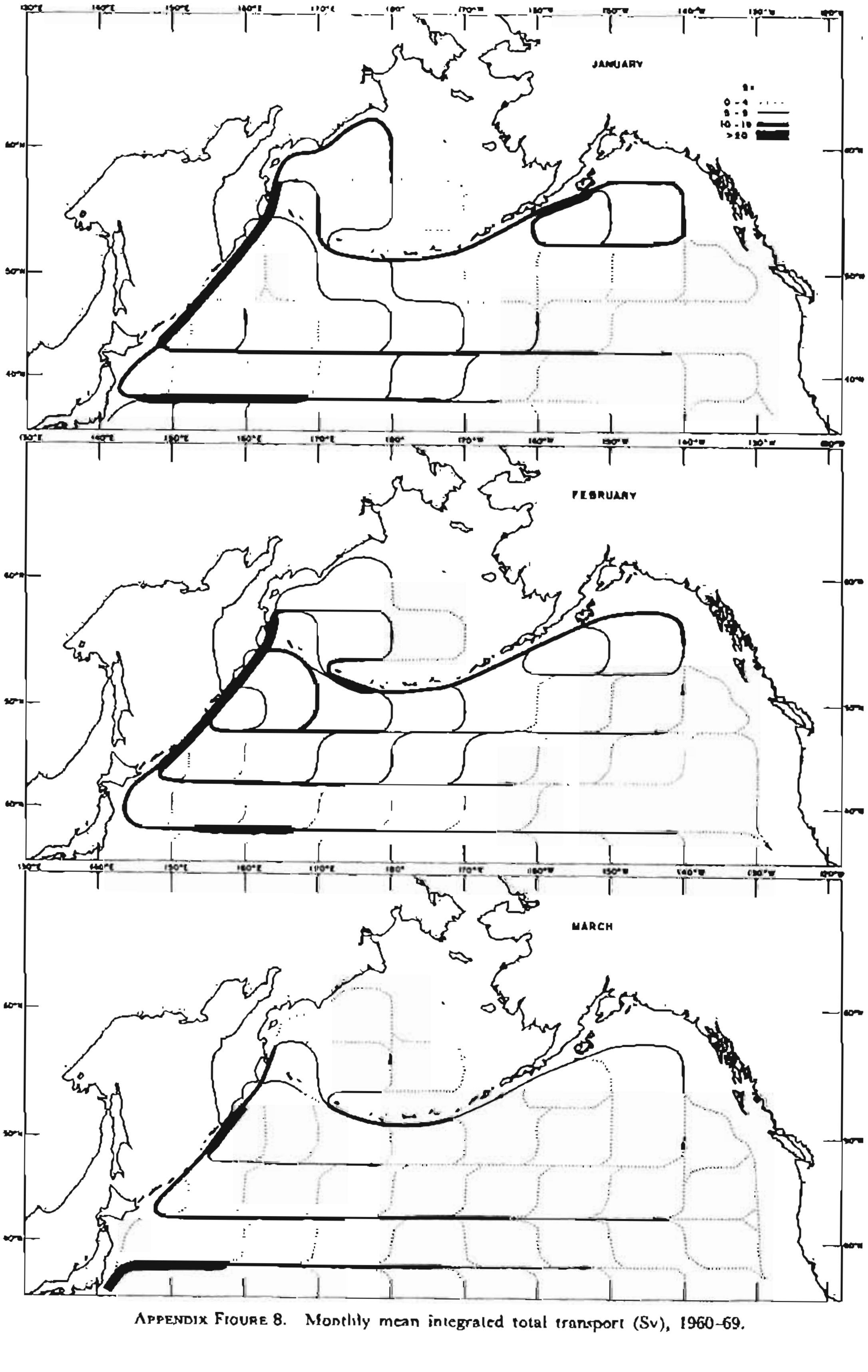




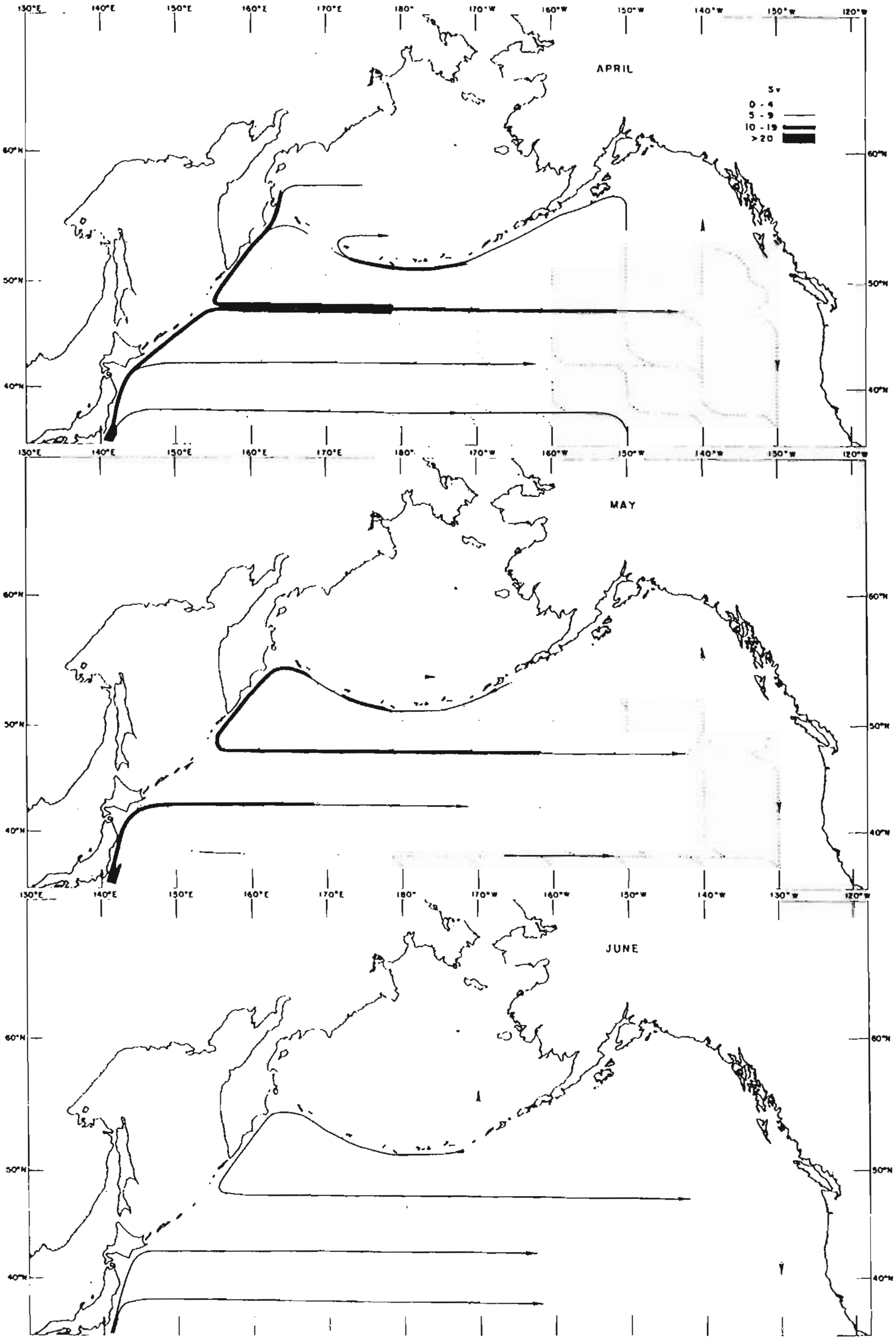
APPENDIX FIGURE 7 (Cont.)


NOVEMBER
2000 Metric Tons/Sec/Km
DIVERGENCE
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N

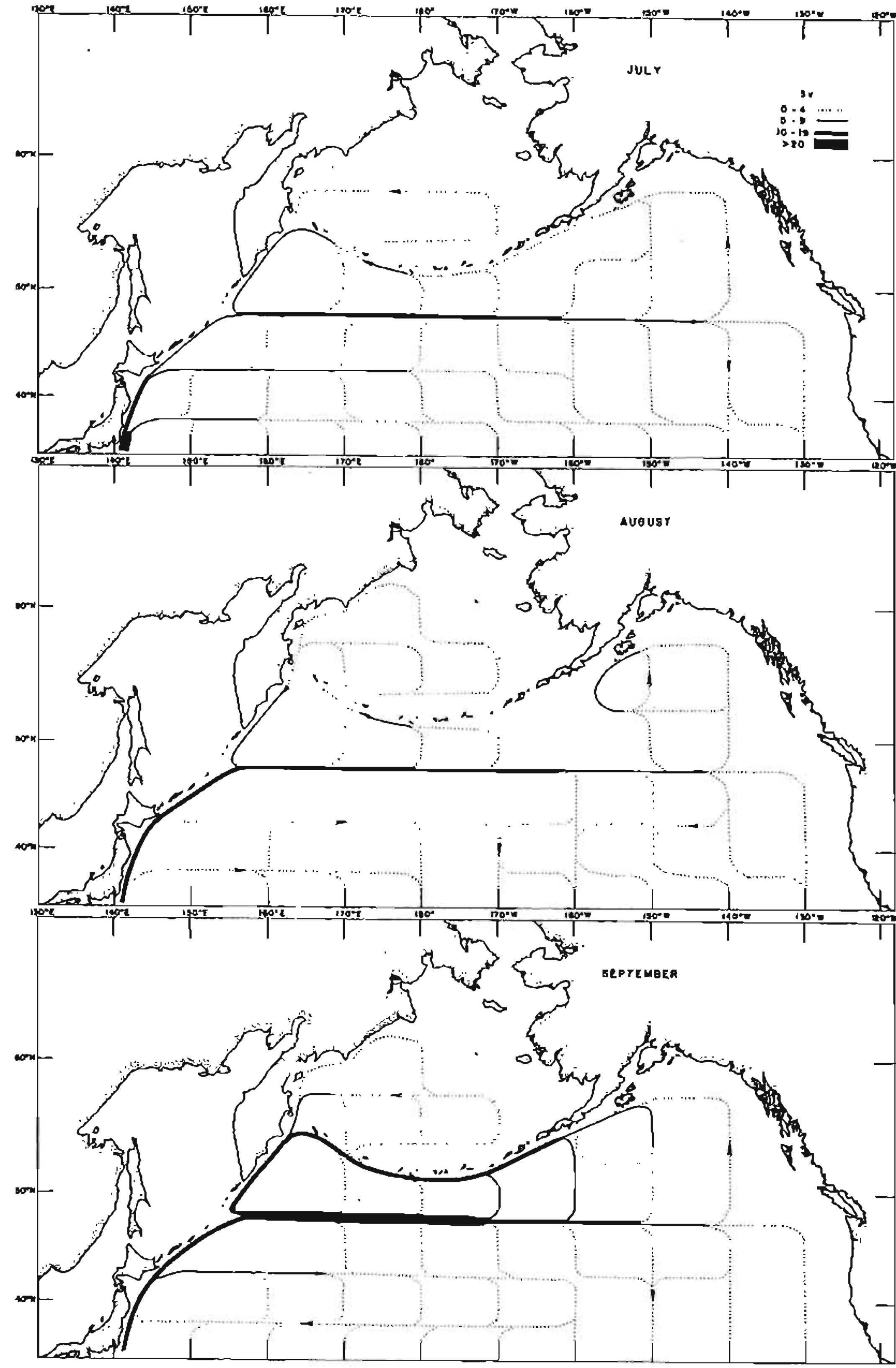

DECEMBER
2000 Metric Tons/Sec/Km
DIVERGENCE
DIVERGENCE
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N



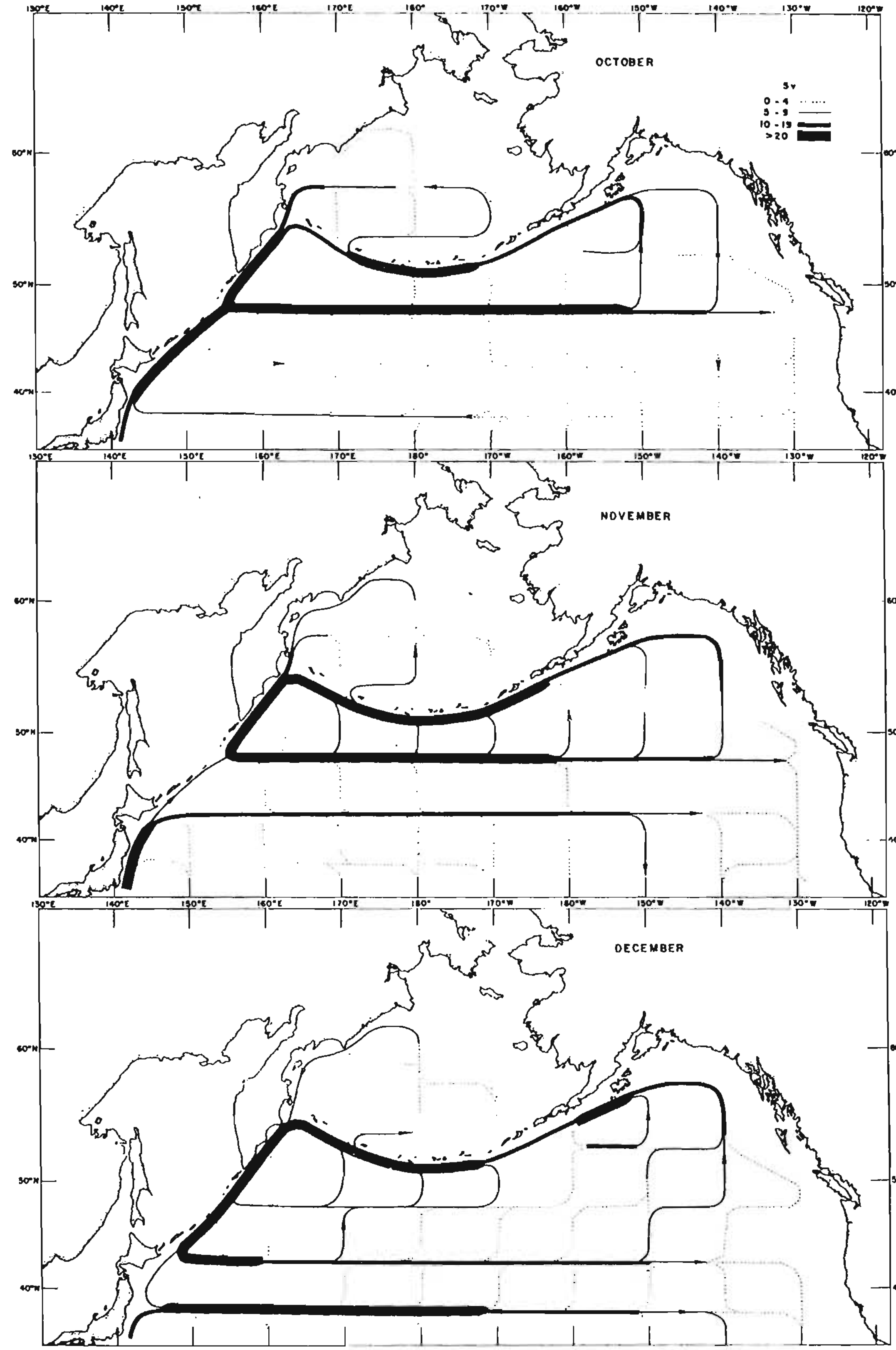
Appendix Figure 8. Monthly mean integrated total transport (Sv), 1960–69.

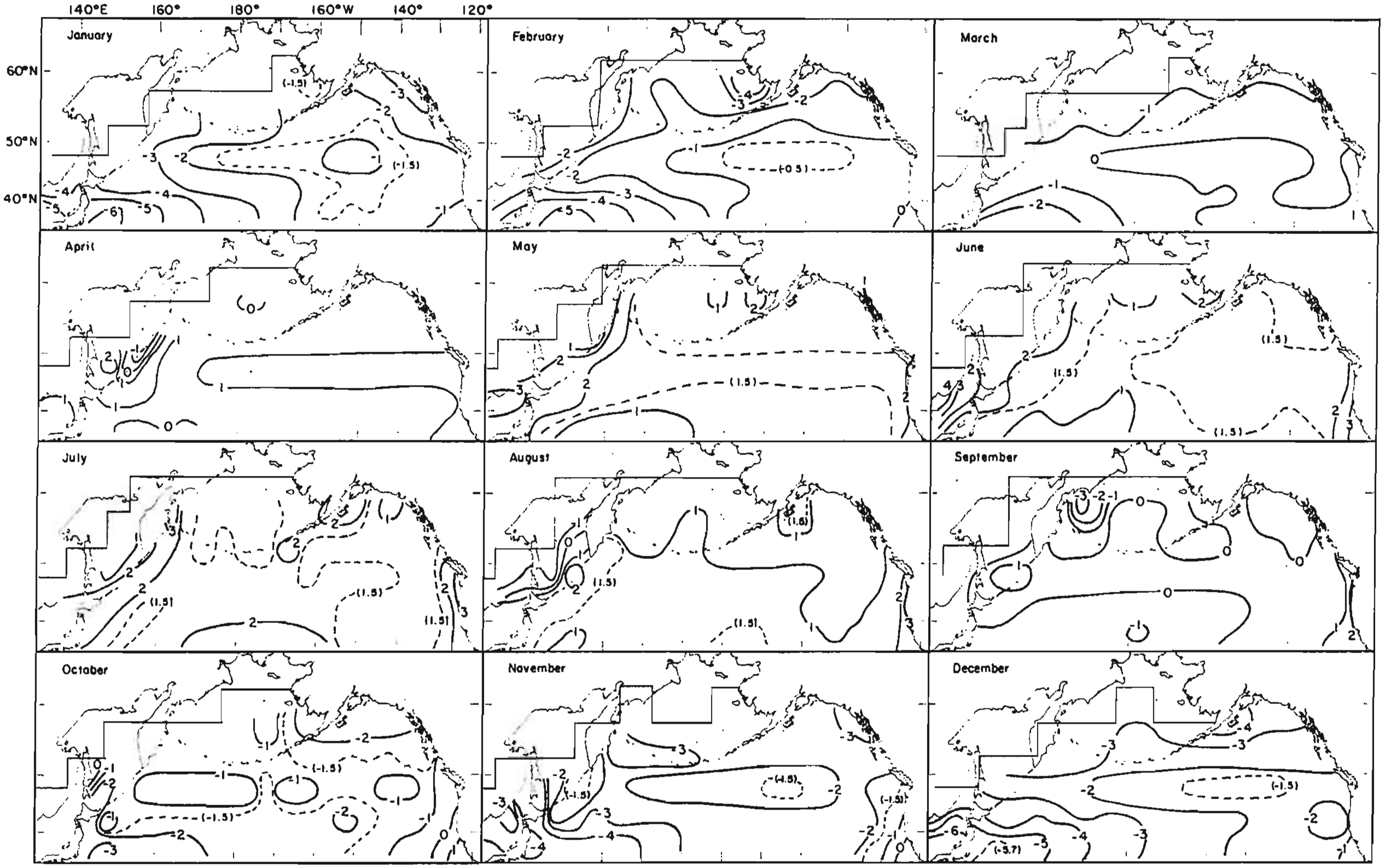

APRIL
Sv
0 - 4
5 - 9
10 - 19
> 20
MAY
JUNE
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N

Continued

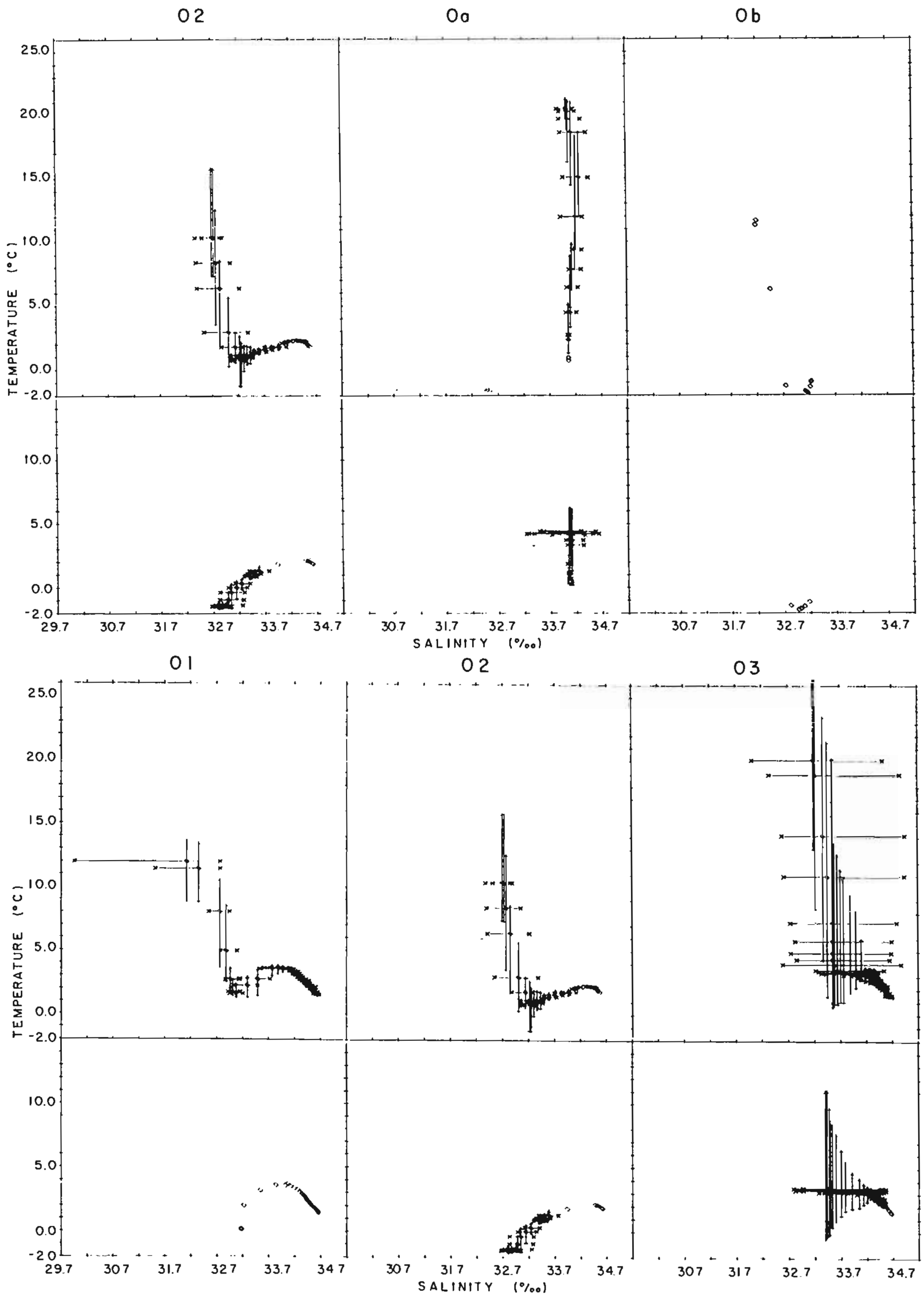


APPENDIX FIGURE 8 (Cont.)

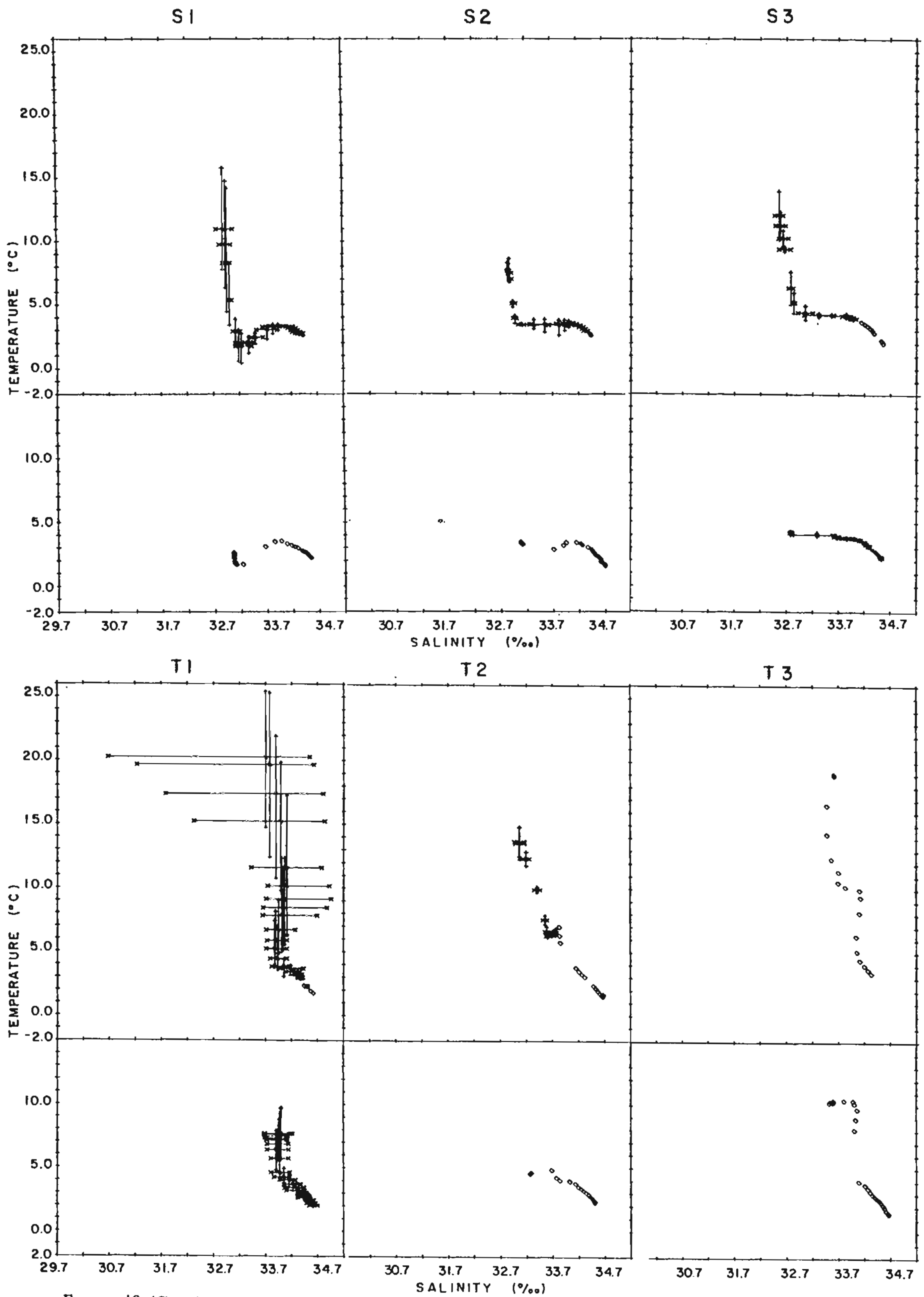

OCTOBER
Sv
0 - 4
5 - 9
10 - 19
>20
NOVEMBER
DECEMBER
130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
60°N
50°N
40°N



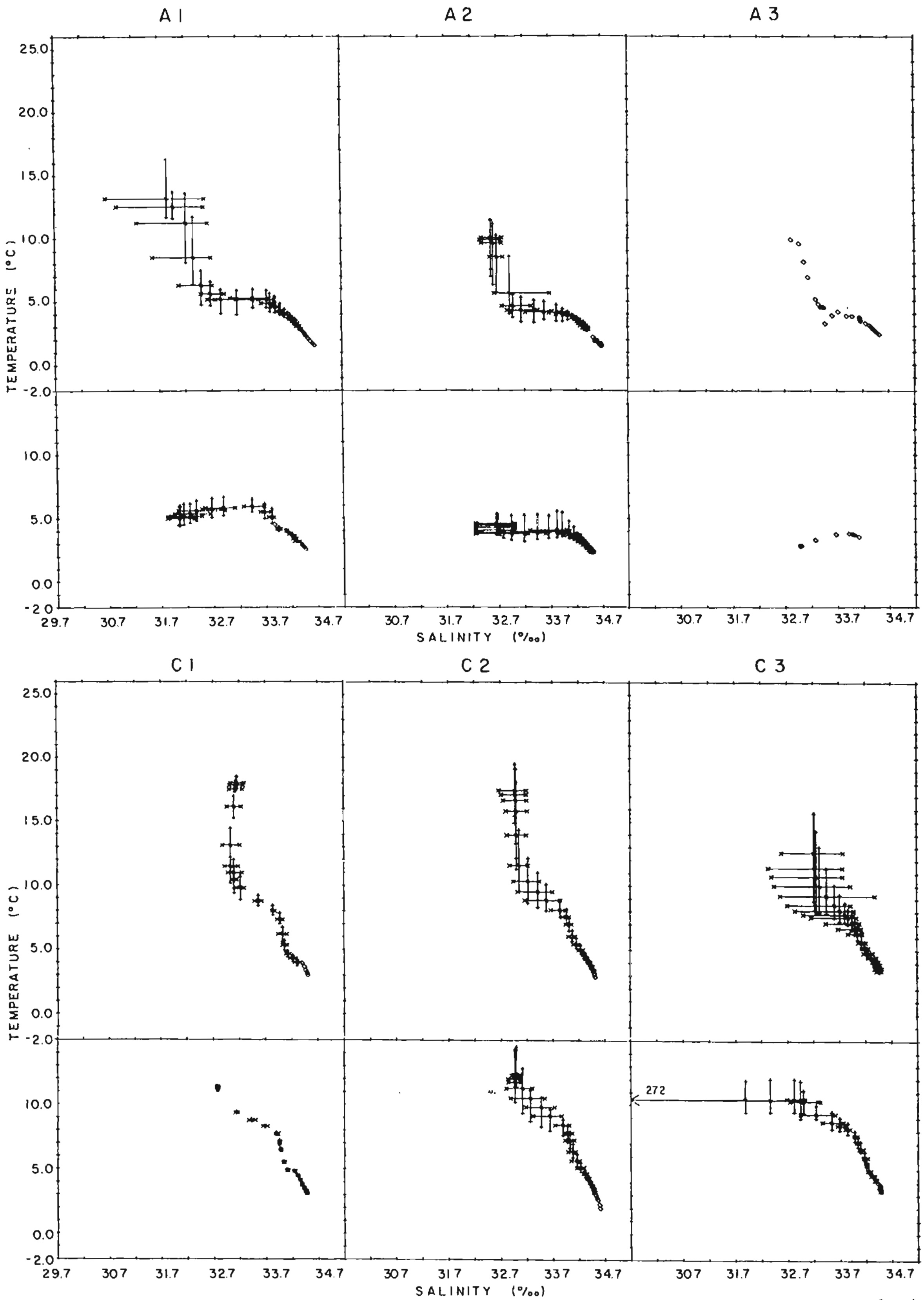
APPENDIX FIGURE 9. Monthly mean energy exchange (cal/cm²/day × 100)—(5 × 5° quadrangles) 1947–68.



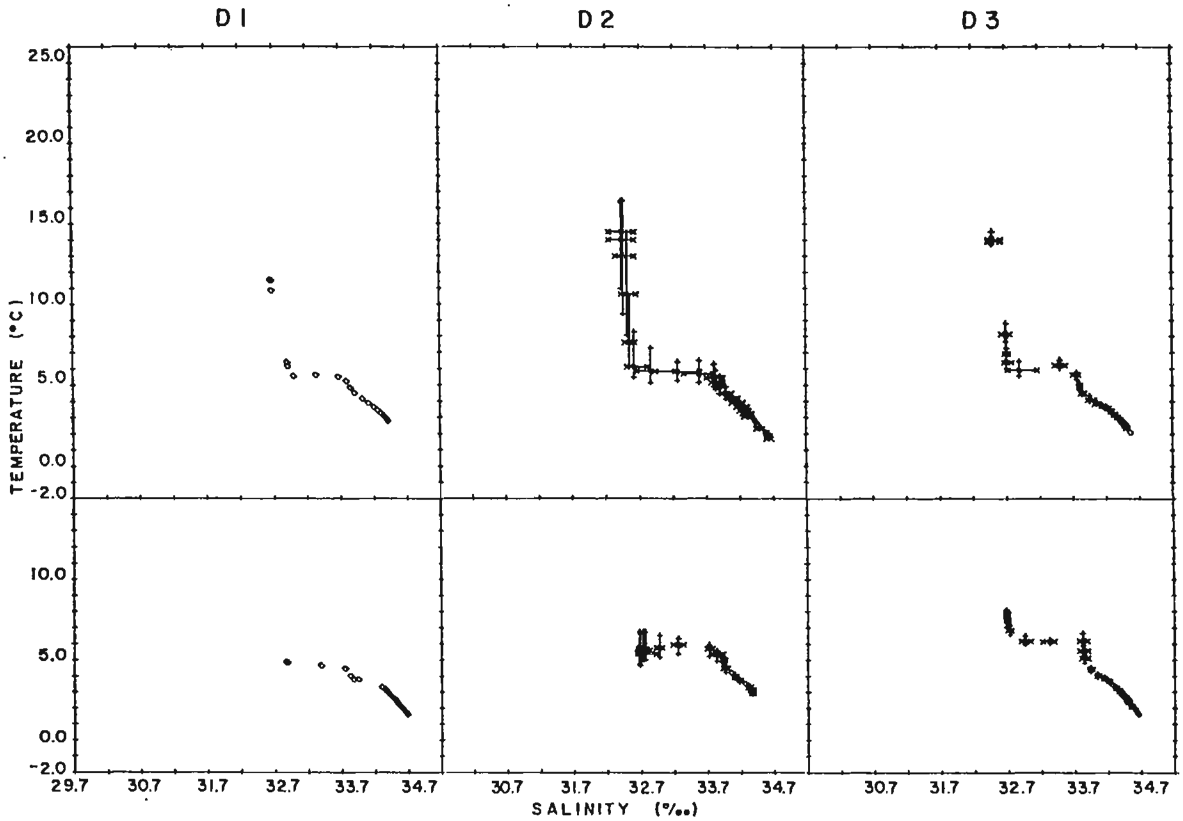
APPENDIX FIGURE 10. Ranges of temperature and salinity at standard depths at locations shown in Fig. 32.

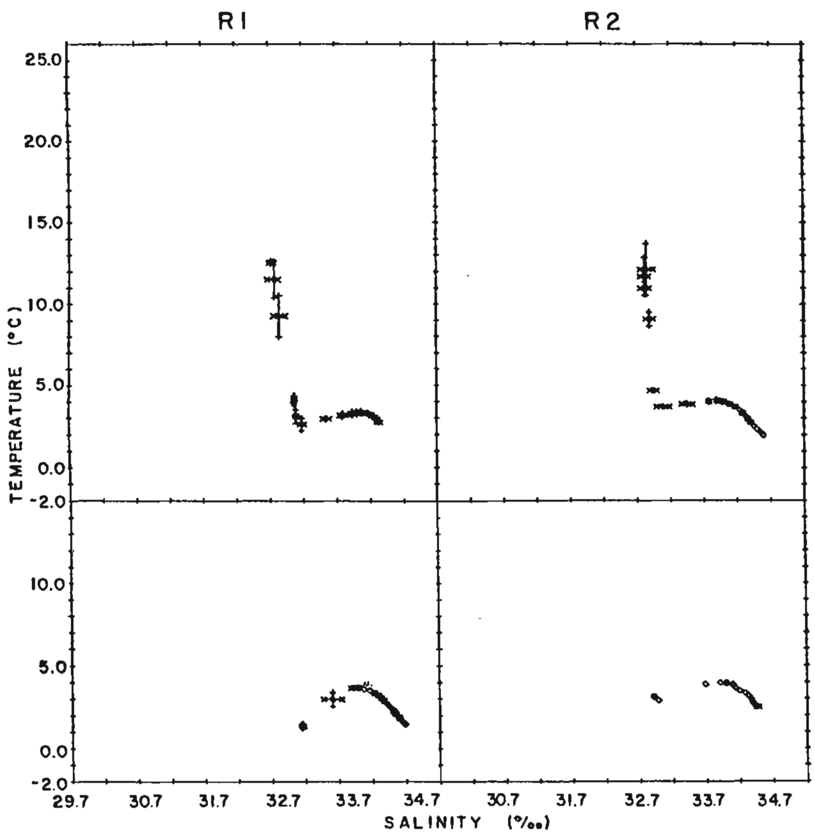


Appendix Figure 10 (Cont.)

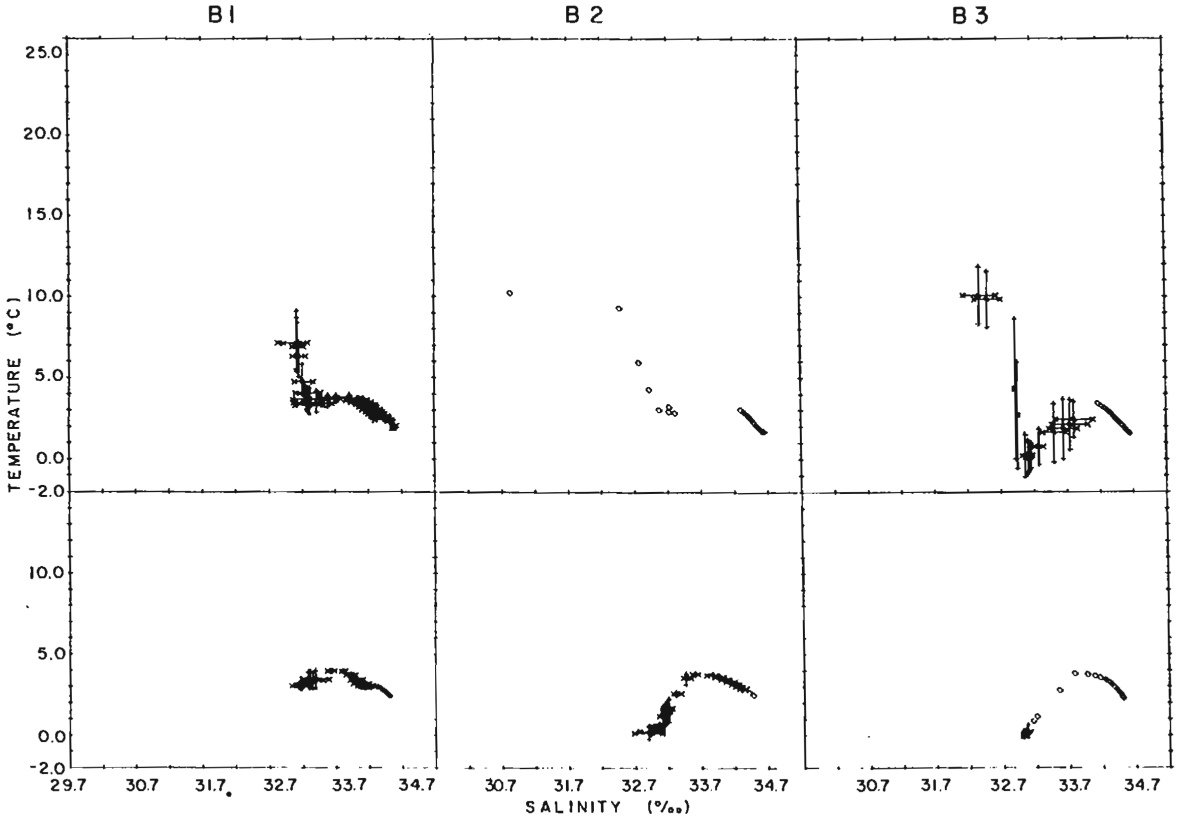

A 1
A 2
A 3
C 1
C 2
C 3
TEMPERATURE (°C)
SALINITY (‰)
25.0
20.0
15.0
10.0
5.0
0.0
-2.0
29.7
30.7
31.7
32.7
33.7
34.7
272

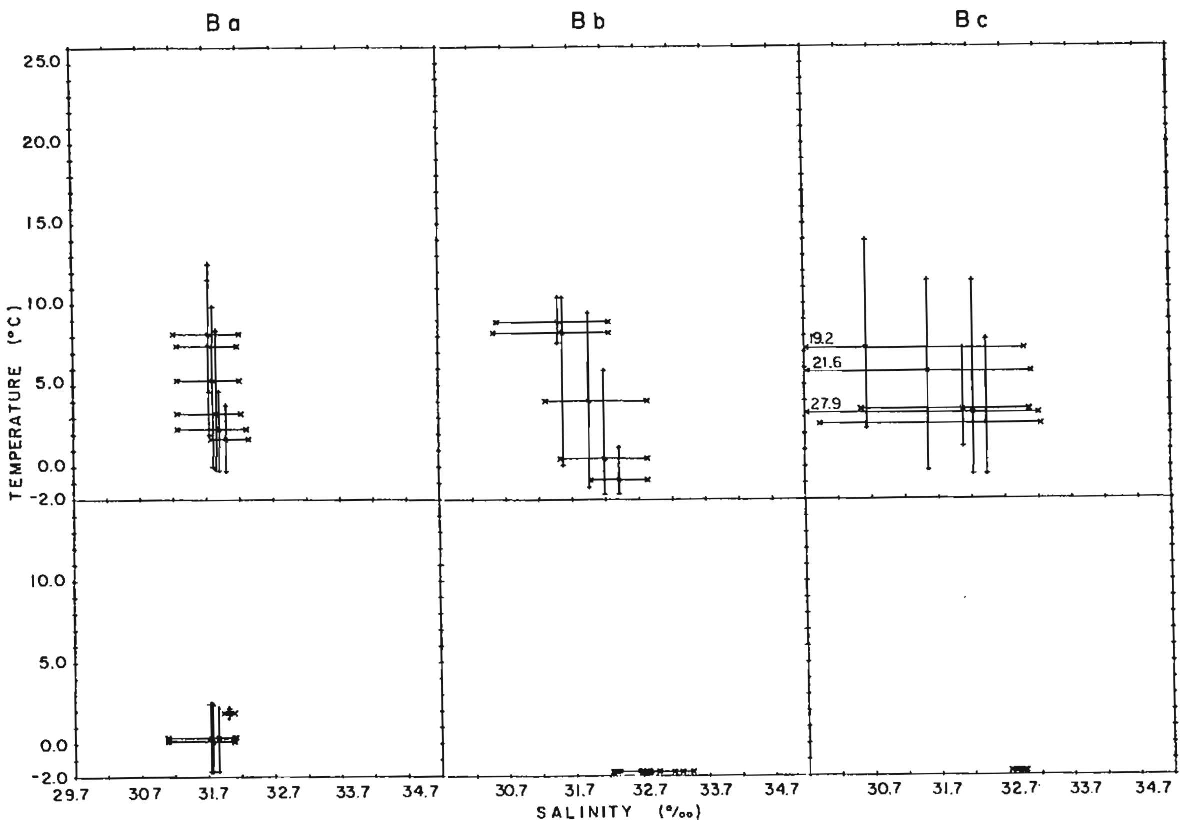
Continued)

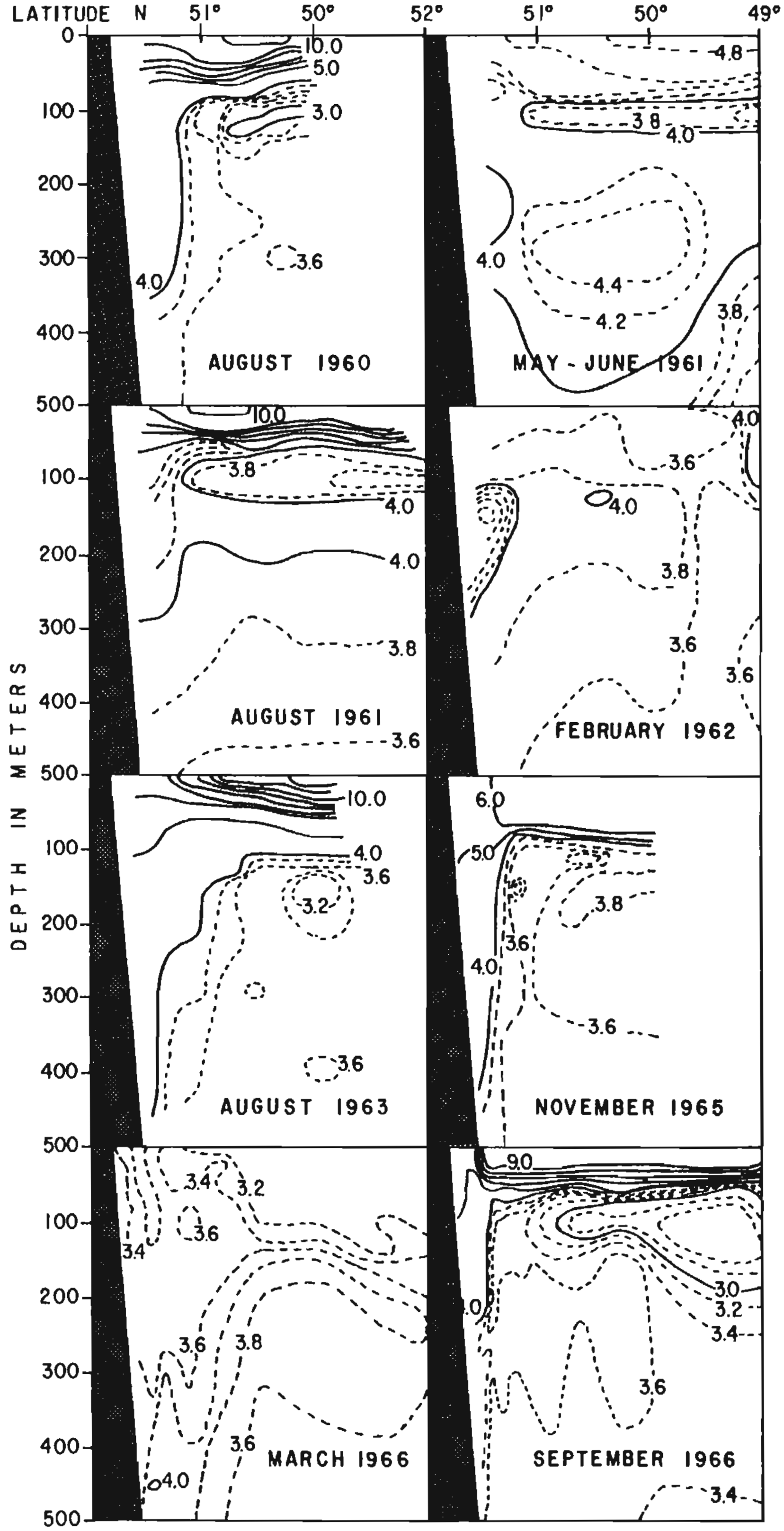




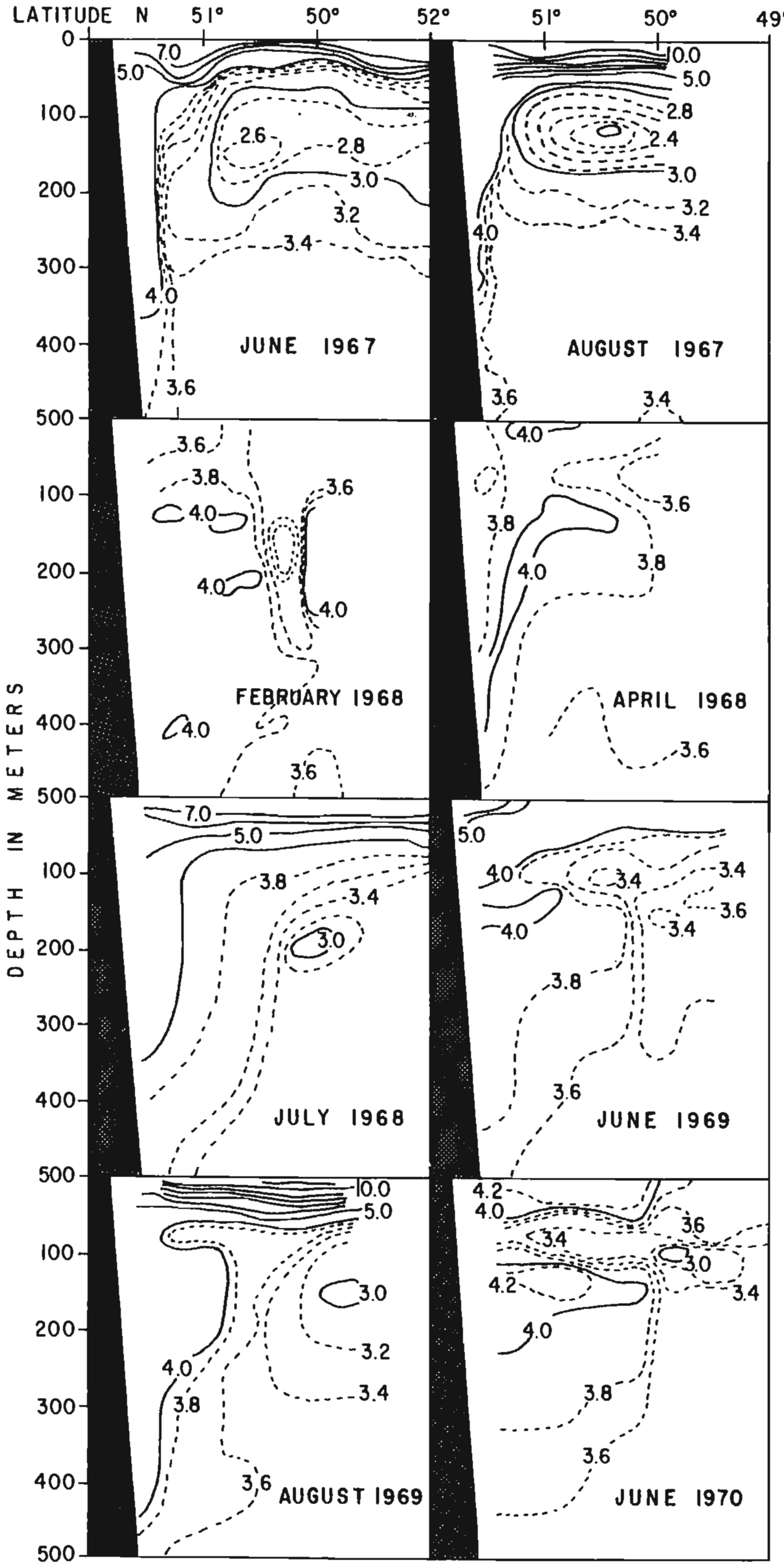
APPENDIX FIGURE 10 (Cont.)

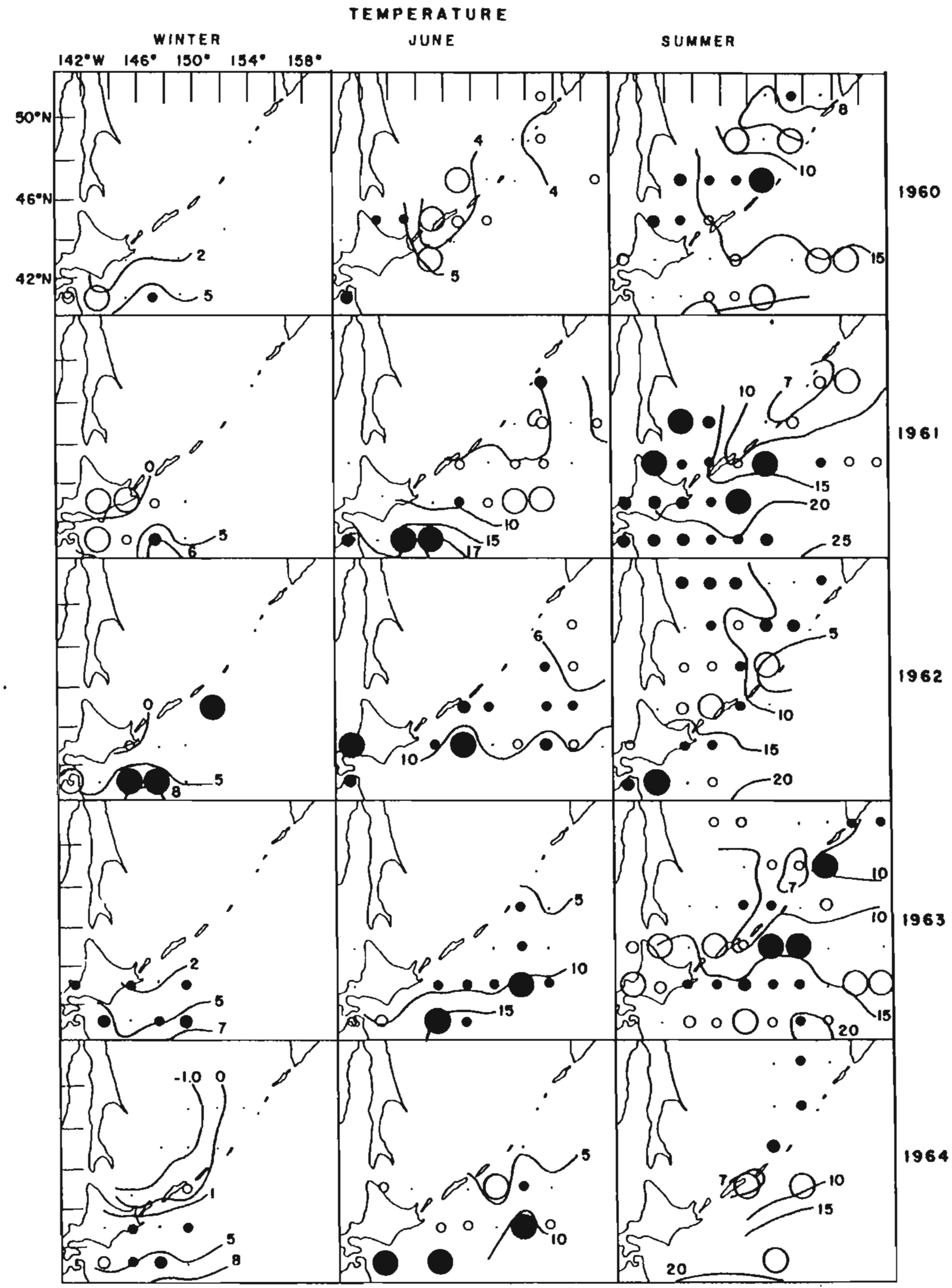

B1
B2
B3
25.0
20.0
15.0
10.0
5.0
0.0
-2.0
TEMPERATURE (°C)
29.7
30.7
31.7
32.7
33.7
34.7
SALINITY (‰)


Ba
Bb
Bc
25.0
20.0
15.0
10.0
5.0
0.0
-2.0
TEMPERATURE (°C)
19.2
21.6
27.9
29.7
30.7
31.7
32.7
33.7
34.7
SALINITY (‰)



Appendix Figure 11. Vertical sections of temperature (°C) south of Adak Island, August 1960 to June 1970.

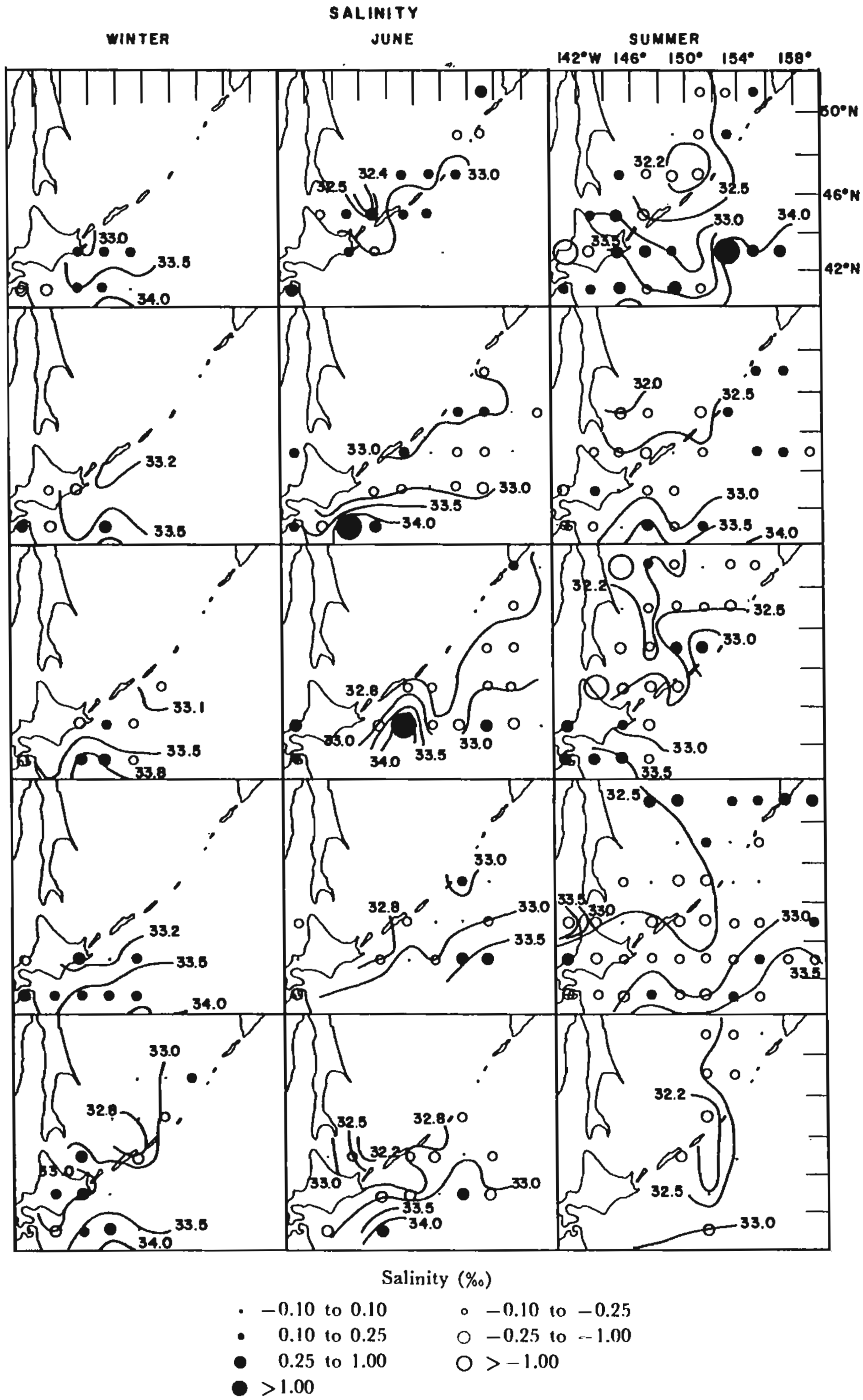

LATITUDE N
51°
50°
52°
51°
50°
49°
DEPTH IN METERS
JUNE 1967
AUGUST 1967
FEBRUARY 1968
APRIL 1968
JULY 1968
JUNE 1969
AUGUST 1969
JUNE 1970

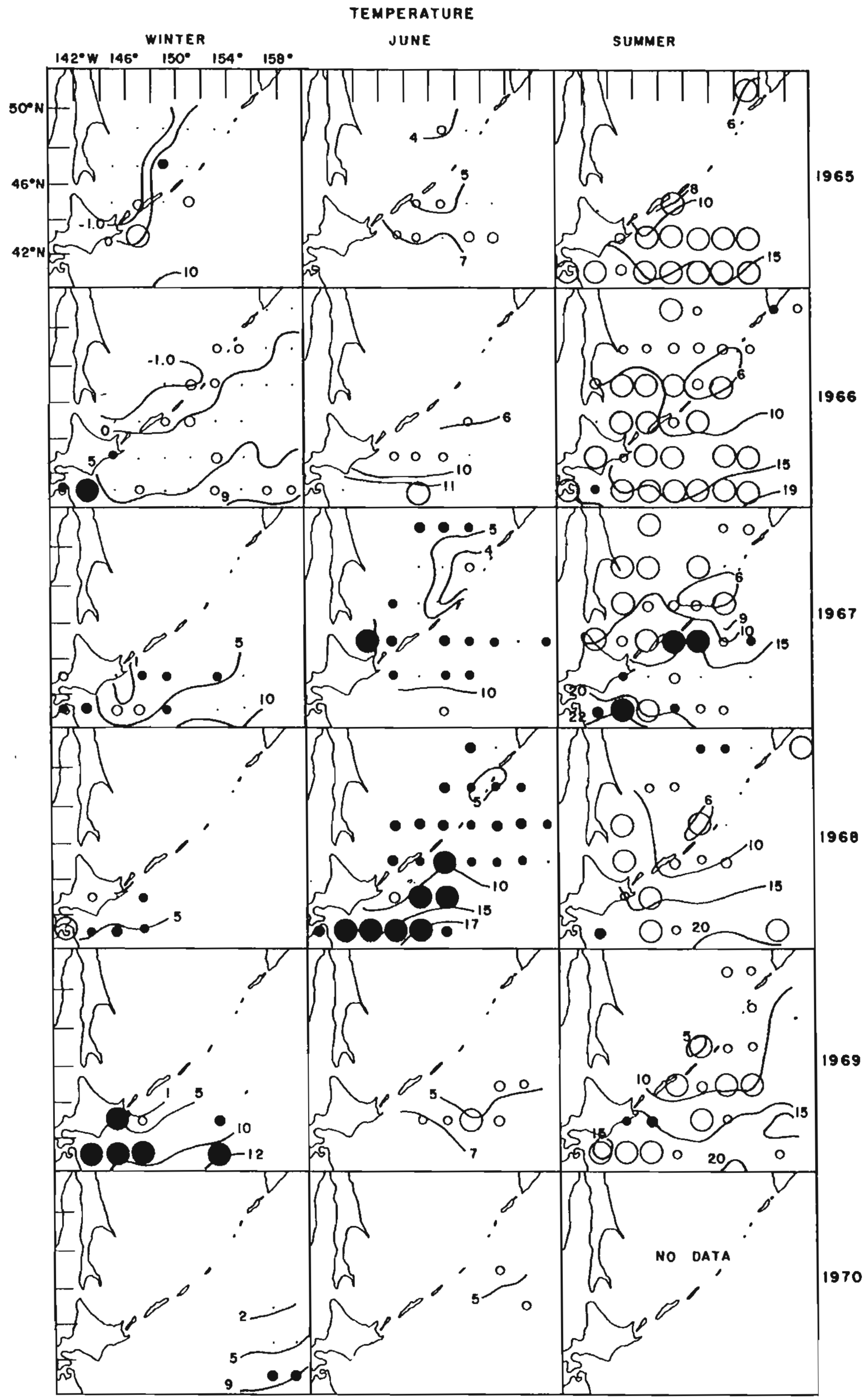


Appendix Figure 12. Mean surface temperature and salinity, and anomalies, winter (Jan-Feb-Mar), June, and summer (July-Aug-Sept) in the western part of the region, based on station data averaged by 2 × 2° quadrangles.

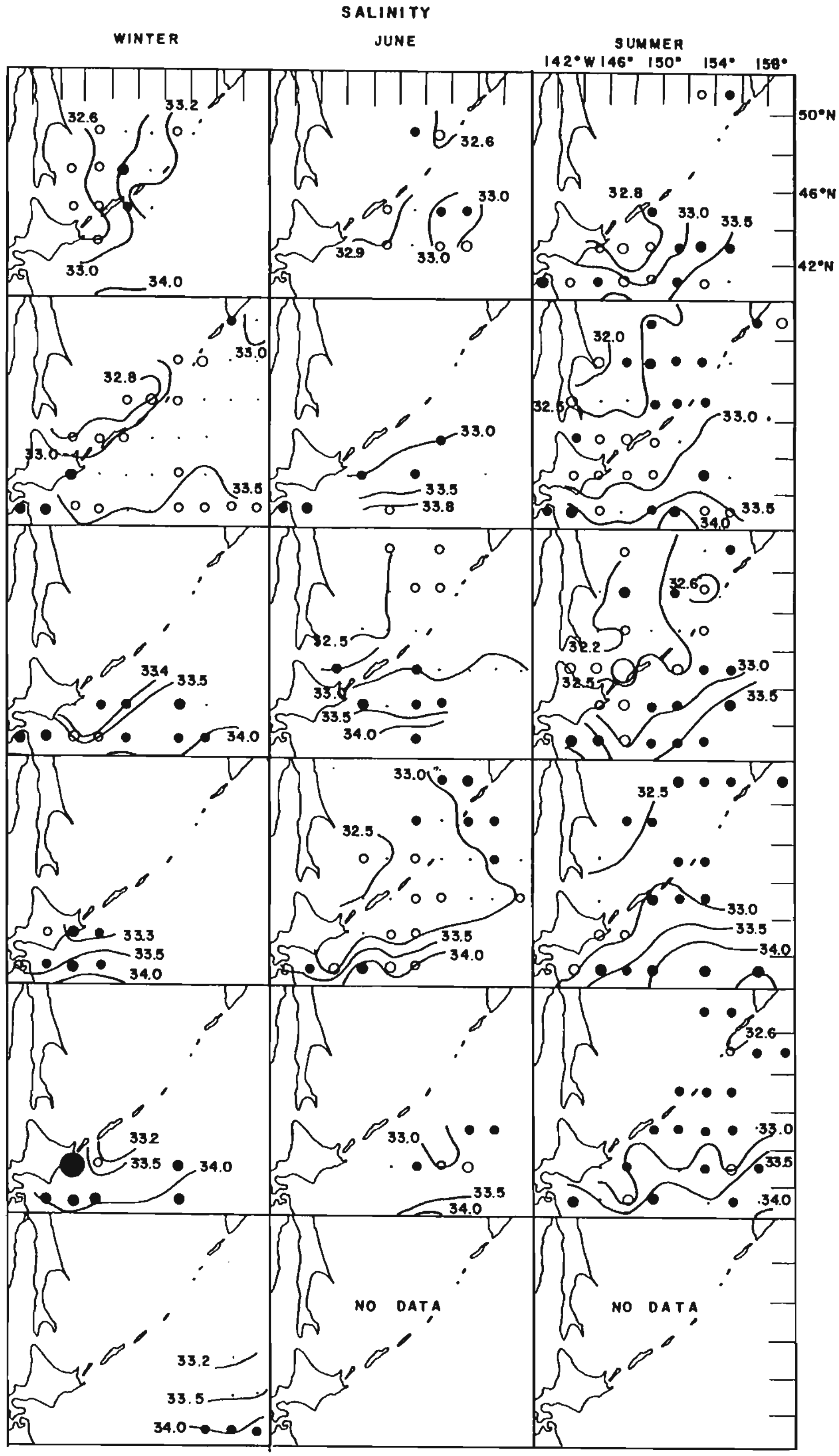
Temperature (°C)

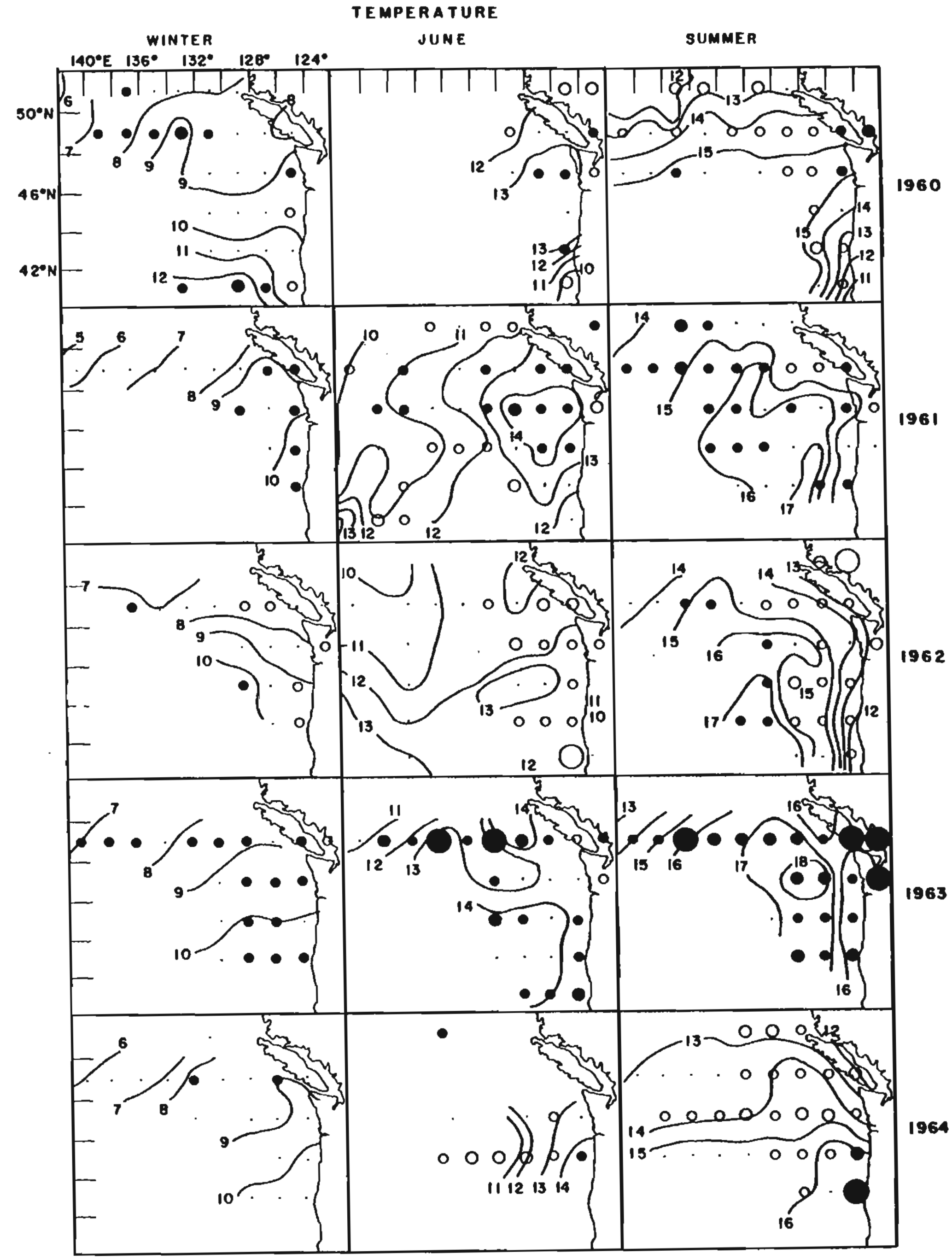
· −0.5 to 0.5	∘ −0.5 to −1.5
• 0.5 to 1.5	○ −1.5 to −2.5
● 1.5 to 2.5	◯ > −2.5
⬤ >2.5	


SALINITY
WINTER
JUNE
SUMMER
142°W 146° 150° 154° 158°
50°N
46°N
42°N
Salinity (‰)
−0.10 to 0.10
0.10 to 0.25
0.25 to 1.00
>1.00
−0.10 to −0.25
−0.25 to −1.00
>−1.00



APPENDIX FIGURE 12 (Cont.)

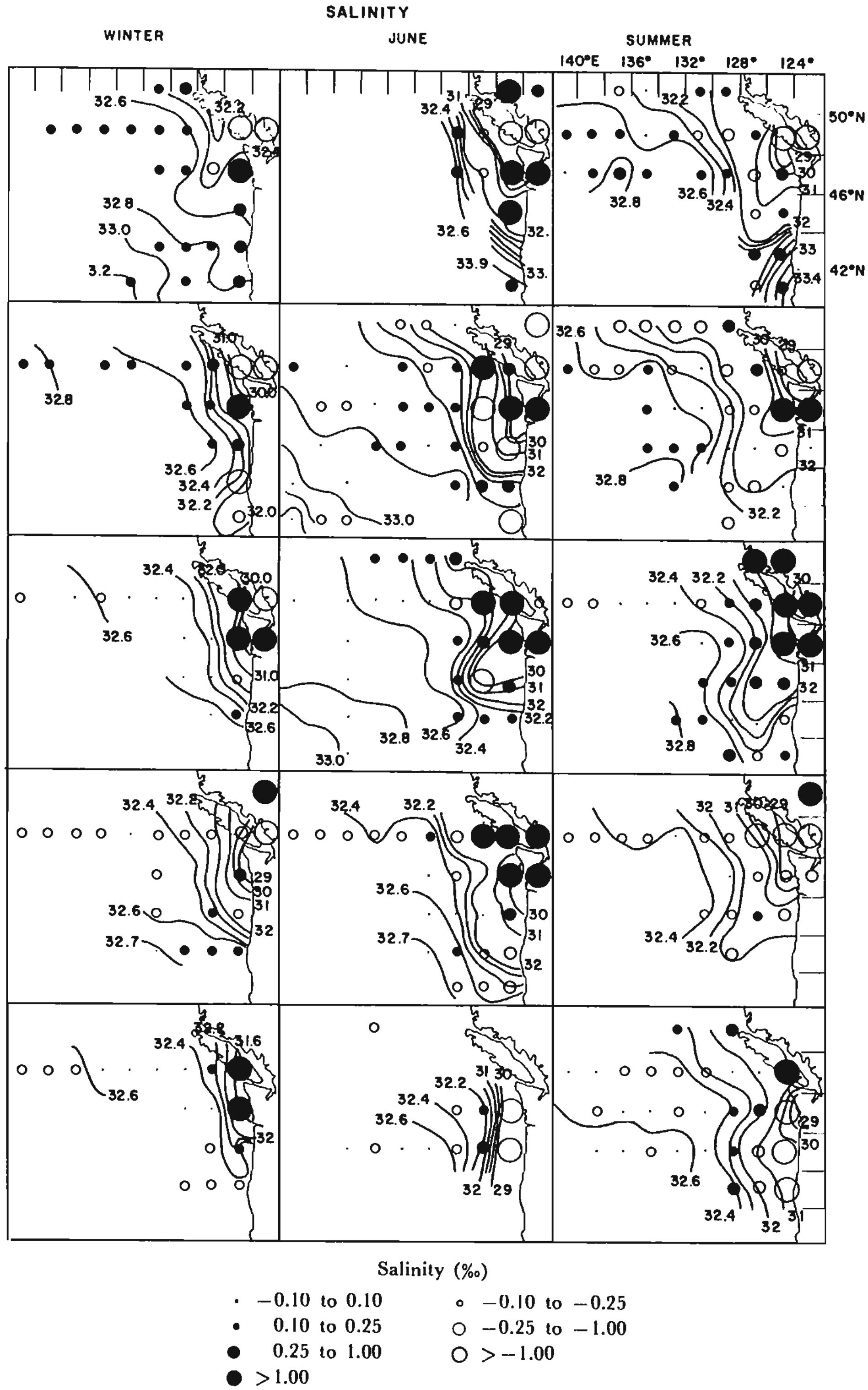

SALINITY
WINTER
JUNE
SUMMER
142°W 146° 150° 154° 158°
50°N
46°N
42°N
NO DATA
NO DATA

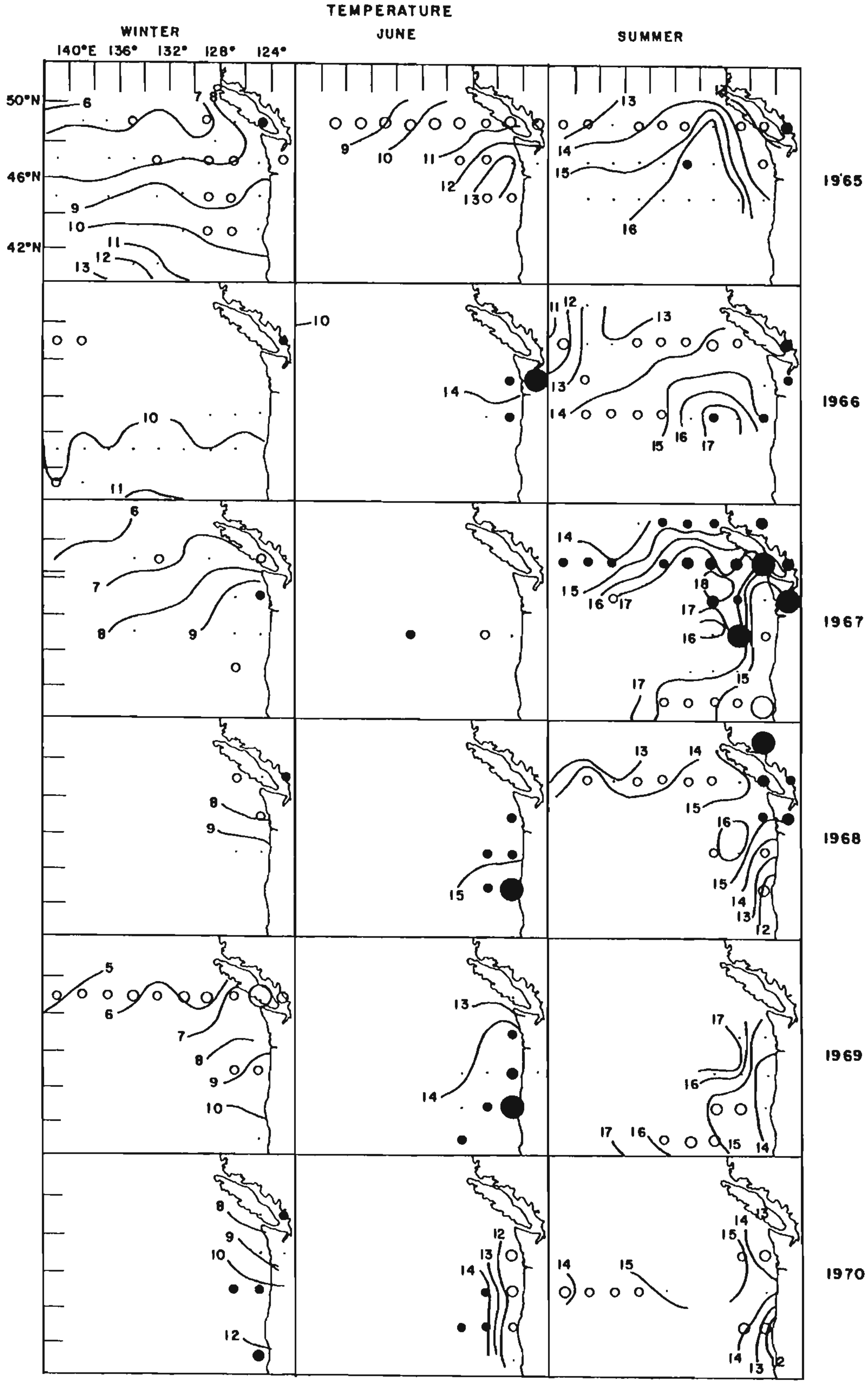


APPENDIX FIGURE 13. Mean surface temperature and salinity, and anomalies, winter (Jan-Feb-Mar), June, and summer (July-Aug-Sept) in the eastern part of the region, 2 × 2° quandrangles. —see legend).

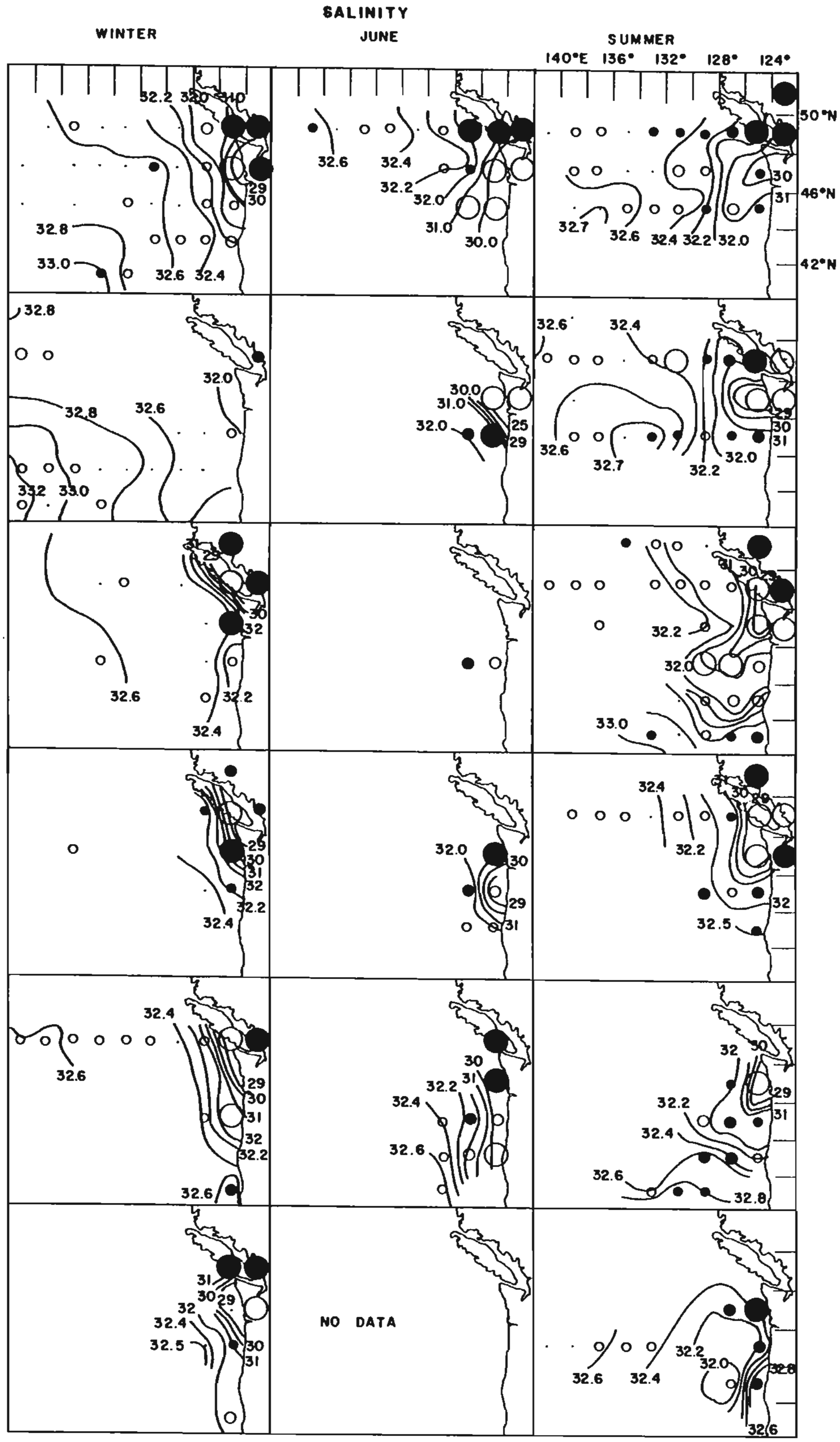
Temperature (°C)

· −0.5 to 0.5	∘ −0.5 to −1.5
• 0.5 to 1.5	○ −1.5 to −2.5
● 1.5 to 2.5	◯ >−2.5
⬤ >2.5	


SALINITY
WINTER
JUNE
SUMMER
140°E 136° 132° 128° 124°
50°N
46°N
42°N
Salinity (‰)
−0.10 to 0.10
0.10 to 0.25
0.25 to 1.00
>1.00
−0.10 to −0.25
−0.25 to −1.00
>−1.00



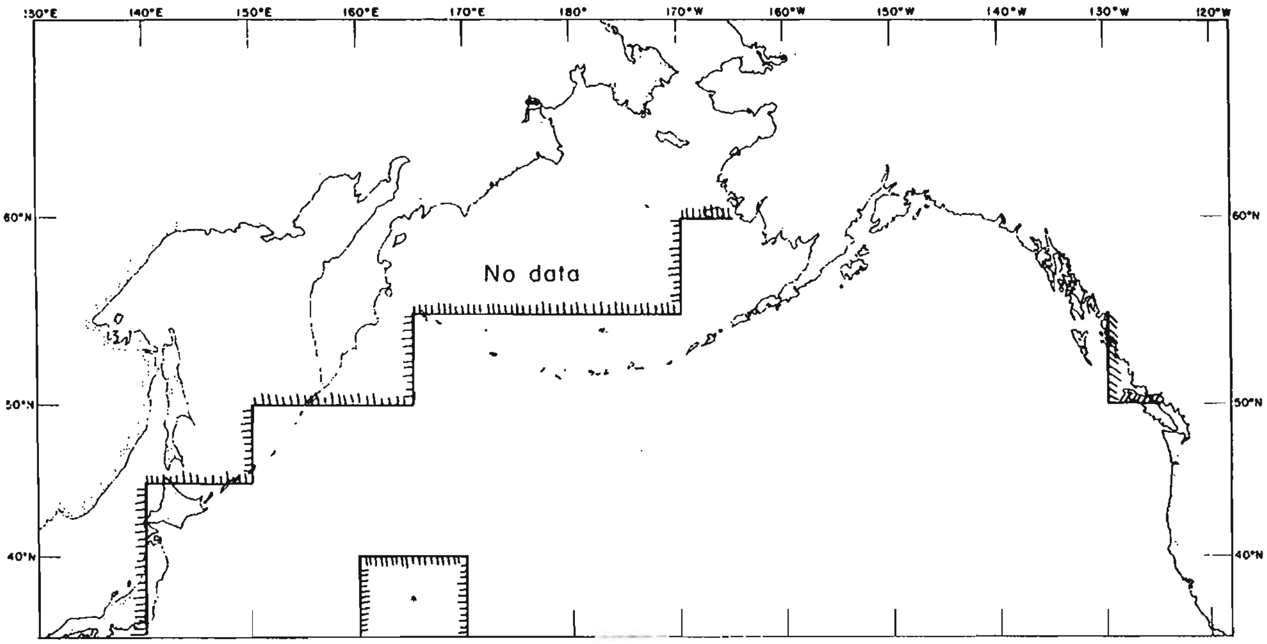
Appendix Figure 13 (Cont.)

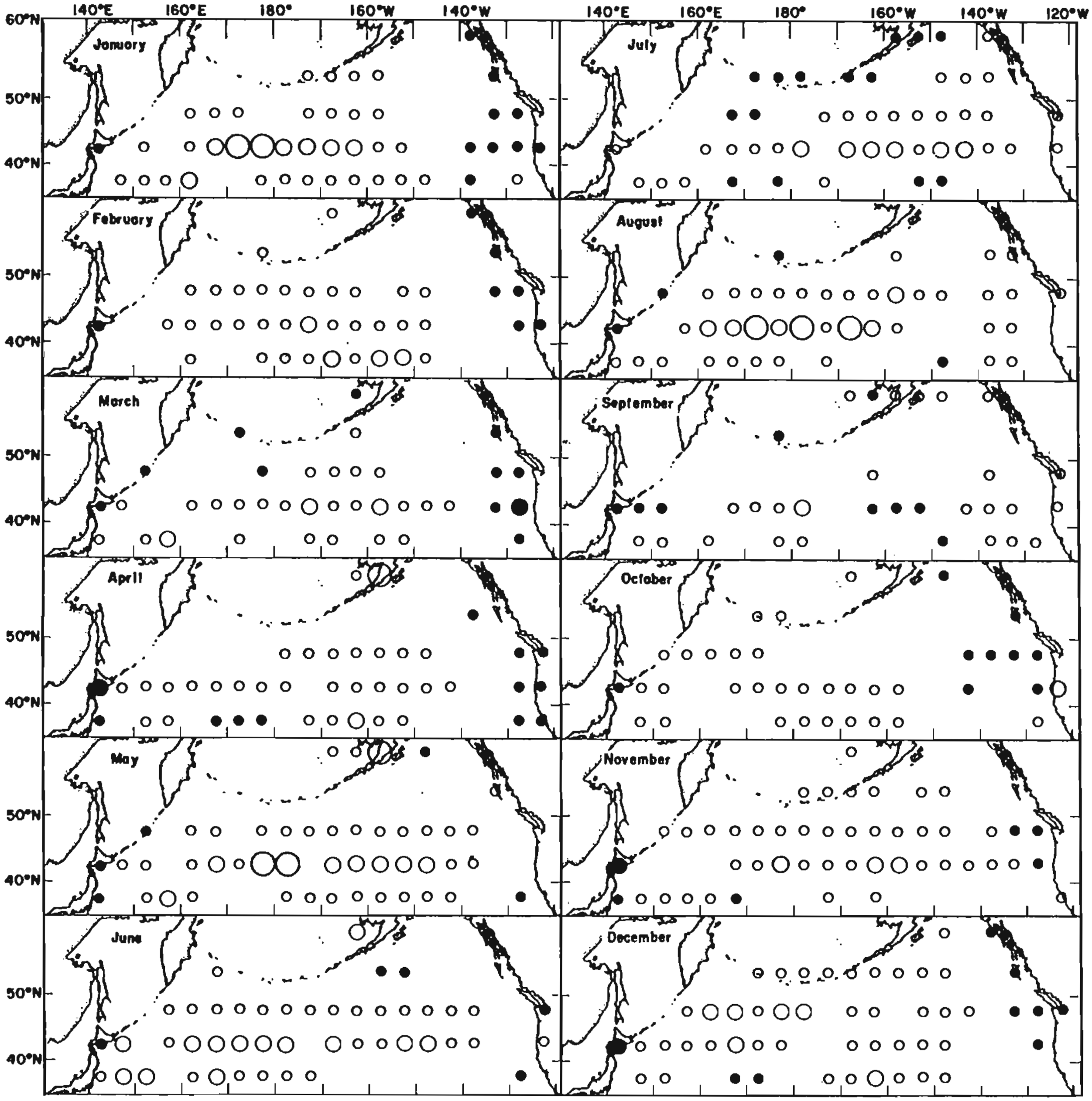

SALINITY
WINTER
JUNE
SUMMER
140°E 136° 132° 128° 124°
50°N
46°N
42°N
NO DATA

APPENDIX FIGURE 14. Monthly anomalies of sea surface temperature, to 1971 ($5 \times 5^\circ$ quadrangles —see legend). *indicates data from July 1968 to December 1971. See Table 12 and text for explanations of rectangles in June and August 1962, July and September 1963, July and September 1964, September 1965, July 1966, July, August and December 1967.

Temperature (°C)

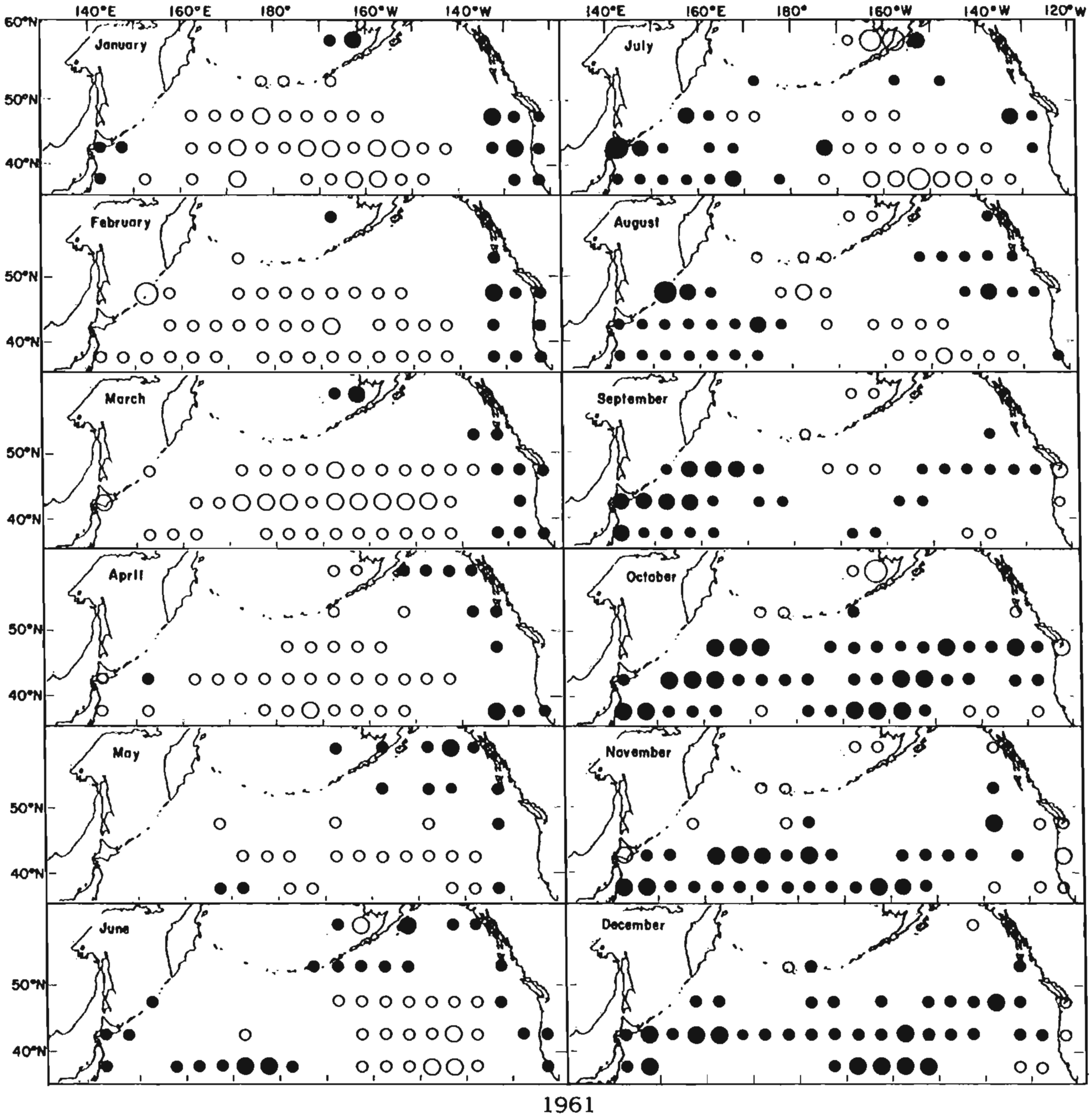
• 0.5 to 1.5	∘ −0.5 to −1.5
● 1.5 to 2.5	○ −1.5 to −2.5
● >2.5	○ > −2.5



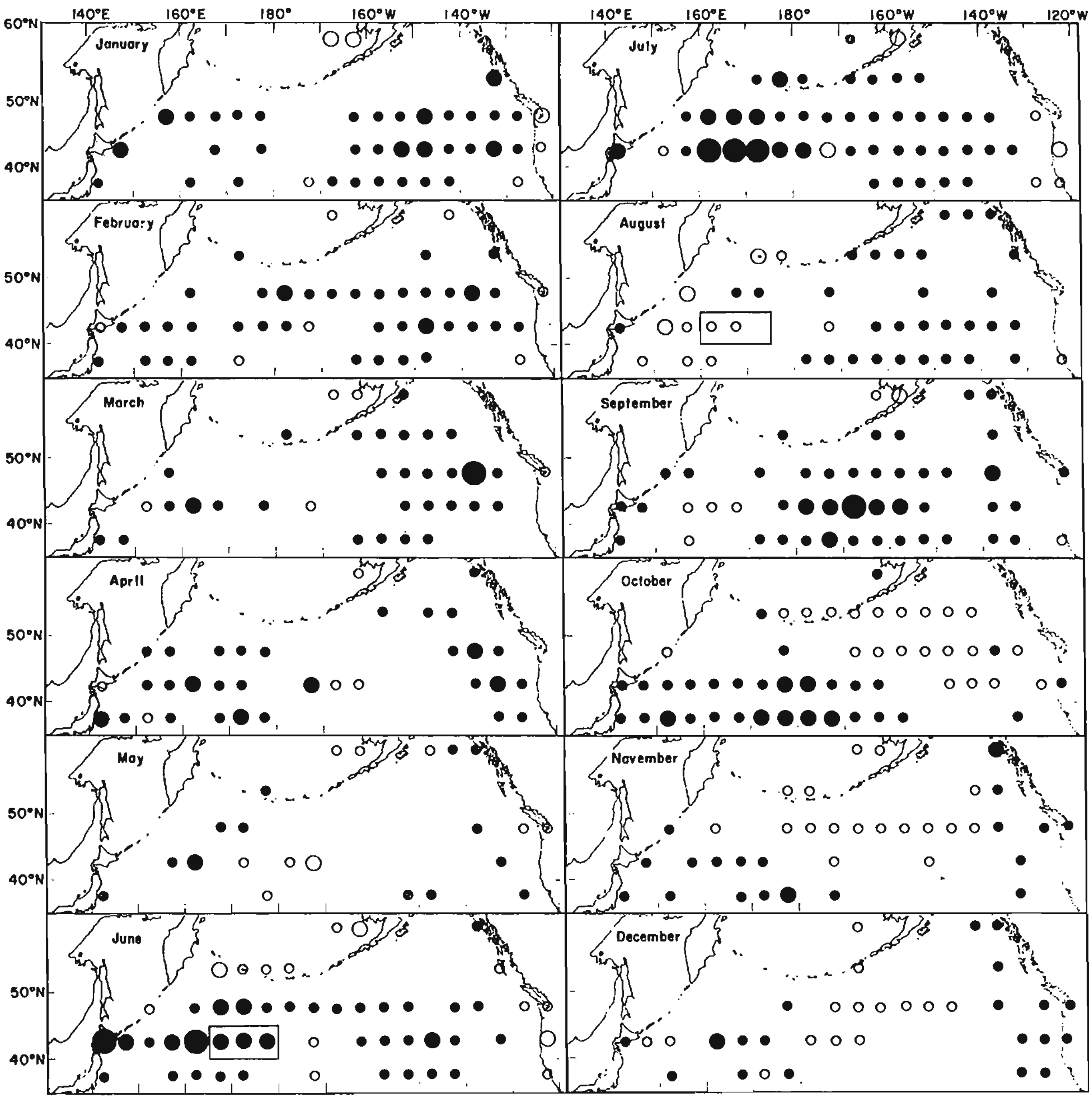


60°N
50°N
40°N
140°E
160°E
180°
160°W
140°W
120°W
January
February
March
April
May
June
July
August
September
October
November
December

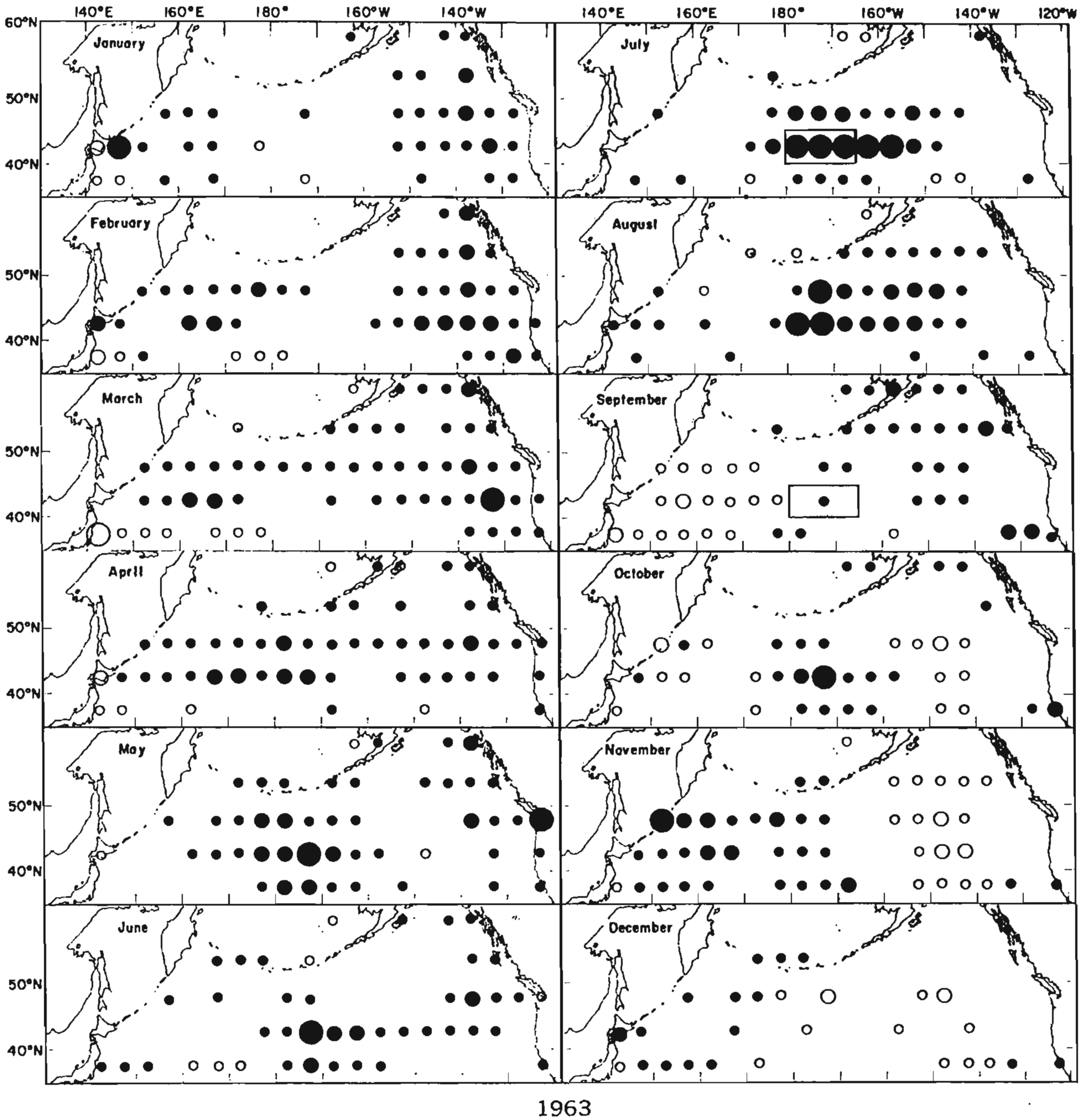
1960



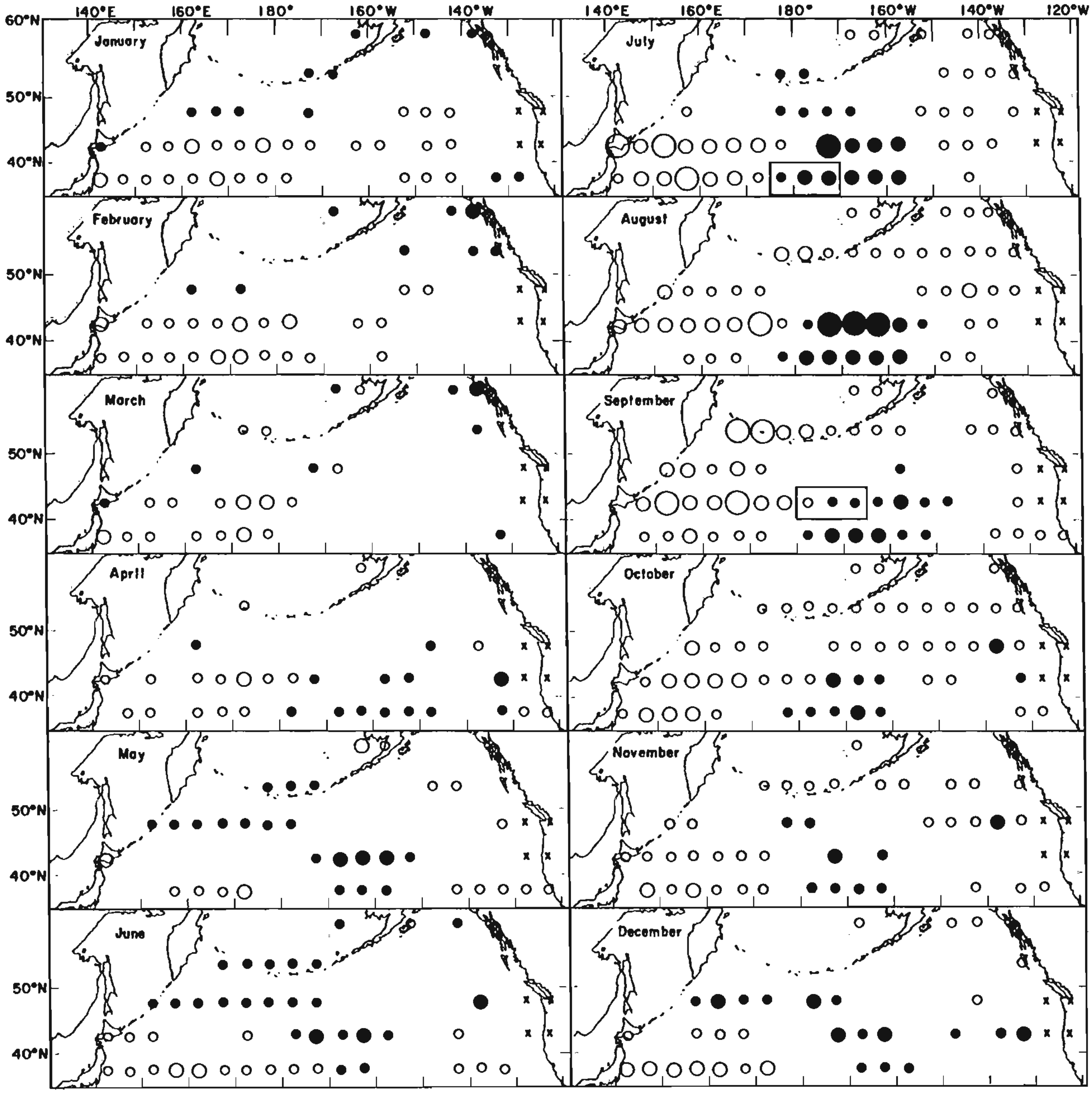
APPENDIX FIGURE 14 (Cont.)


January
February
March
April
May
June
July
August
September
October
November
December
140°E
160°E
180°
160°W
140°W
120°W
60°N
50°N
40°N

1962

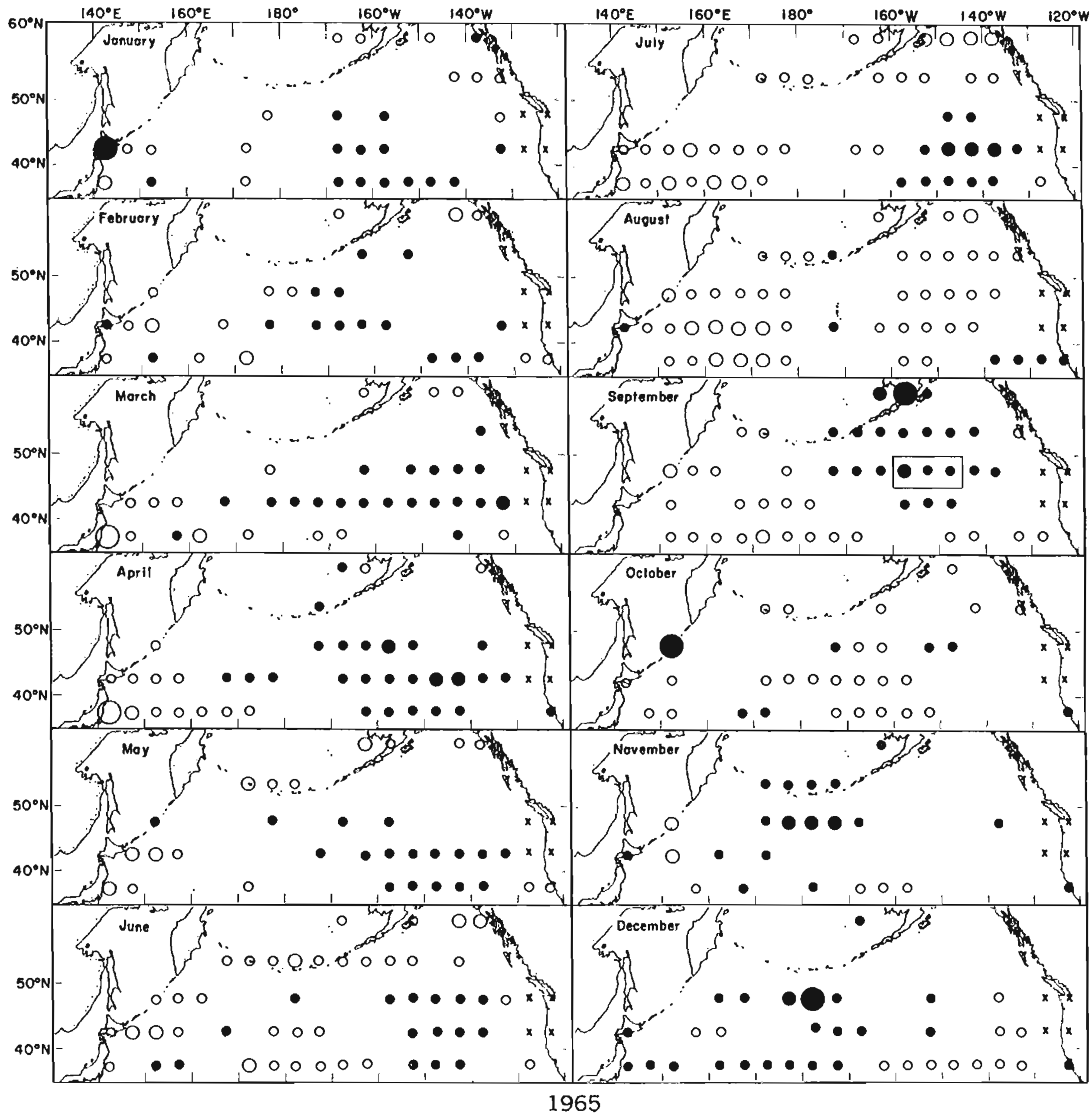


Appendix Figure 14 (Cont.)

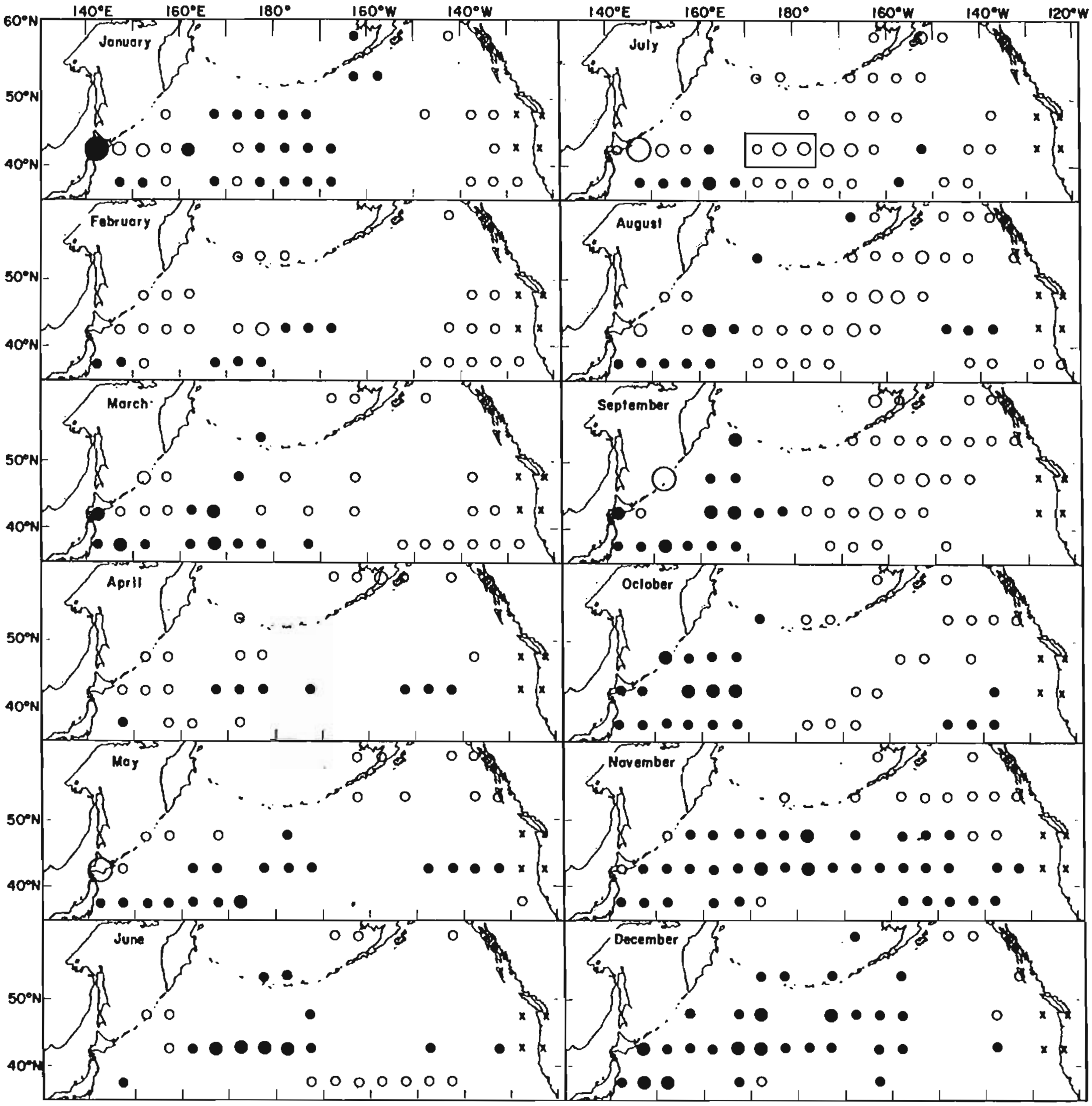


140°E
160°E
180°
160°W
140°W
120°W
60°N
50°N
40°N
January
February
March
April
May
June
July
August
September
October
November
December

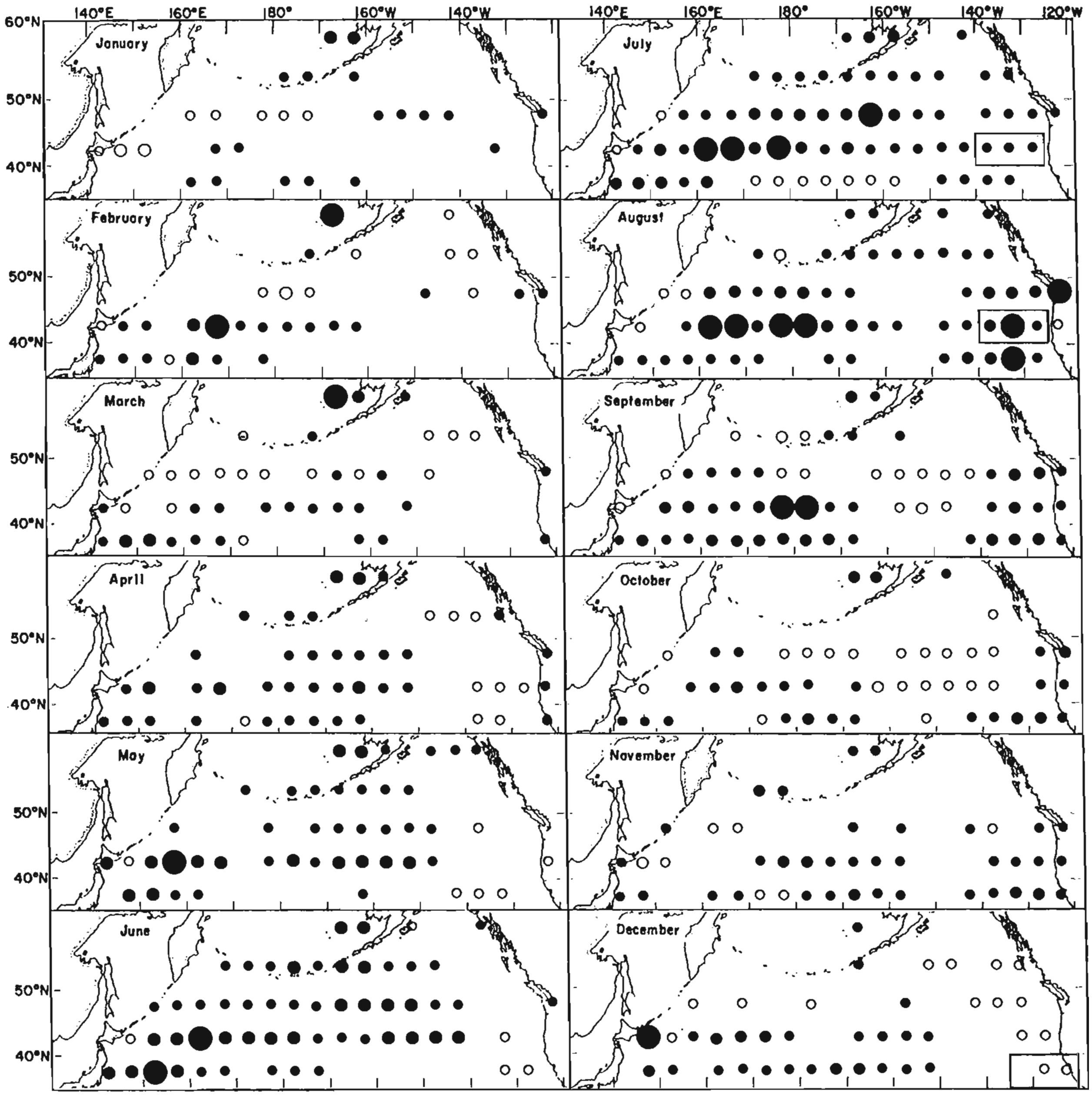
1964



Appendix Figure 14 (Cont.)

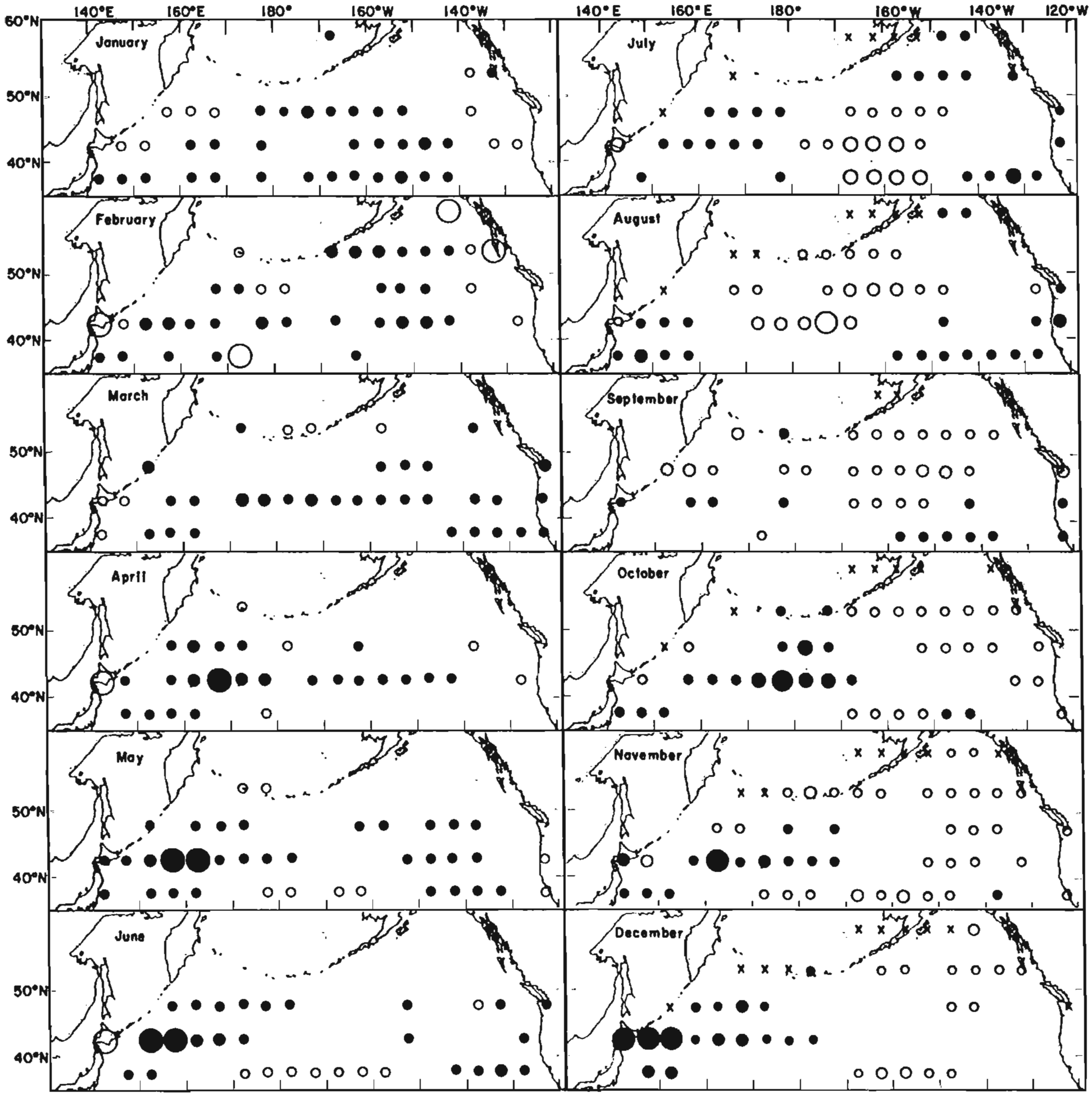

60°N
50°N
40°N
140°E
160°E
180°
160°W
140°W
120°W
January
February
March
April
May
June
July
August
September
October
November
December

1966

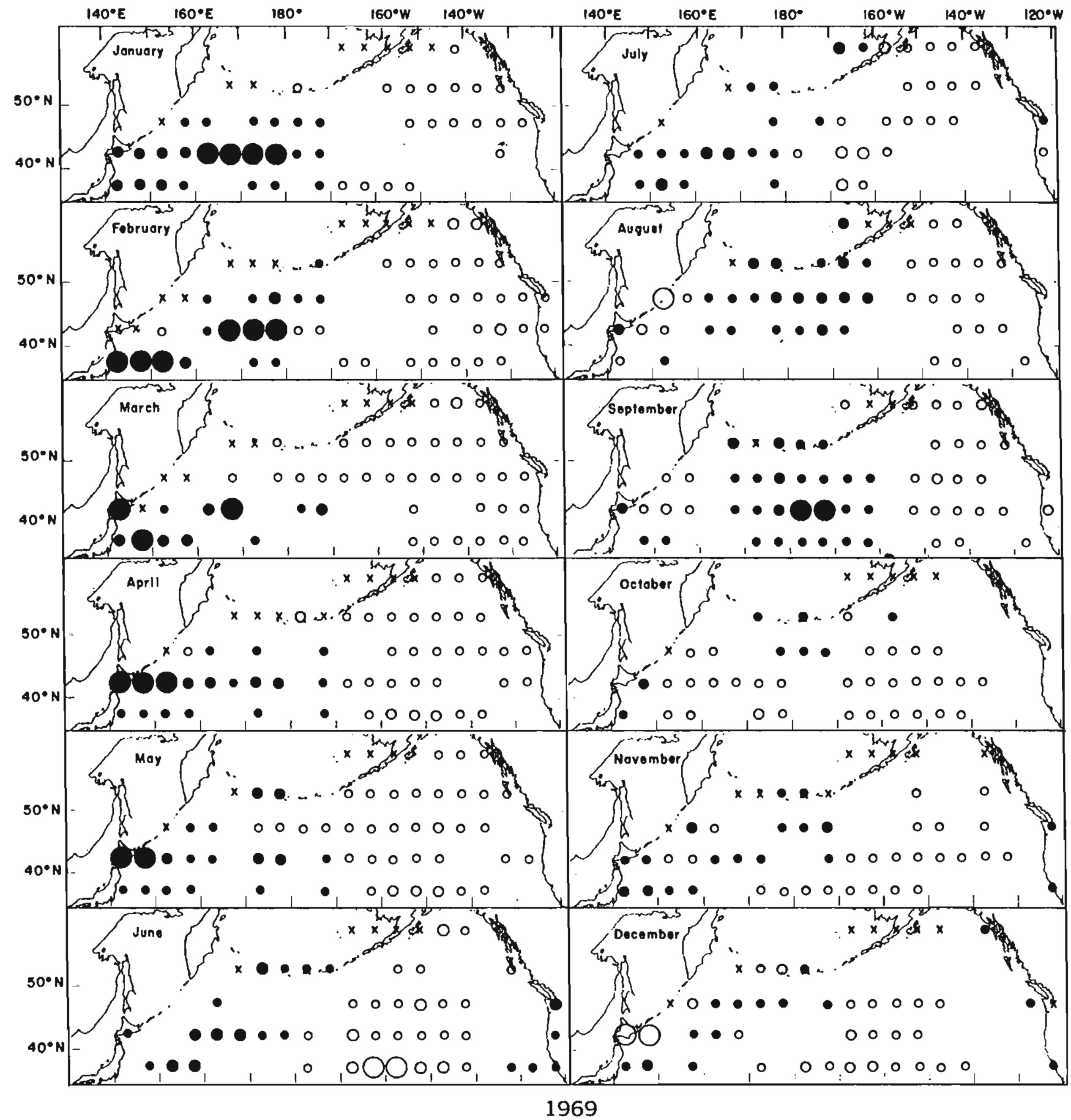


1967

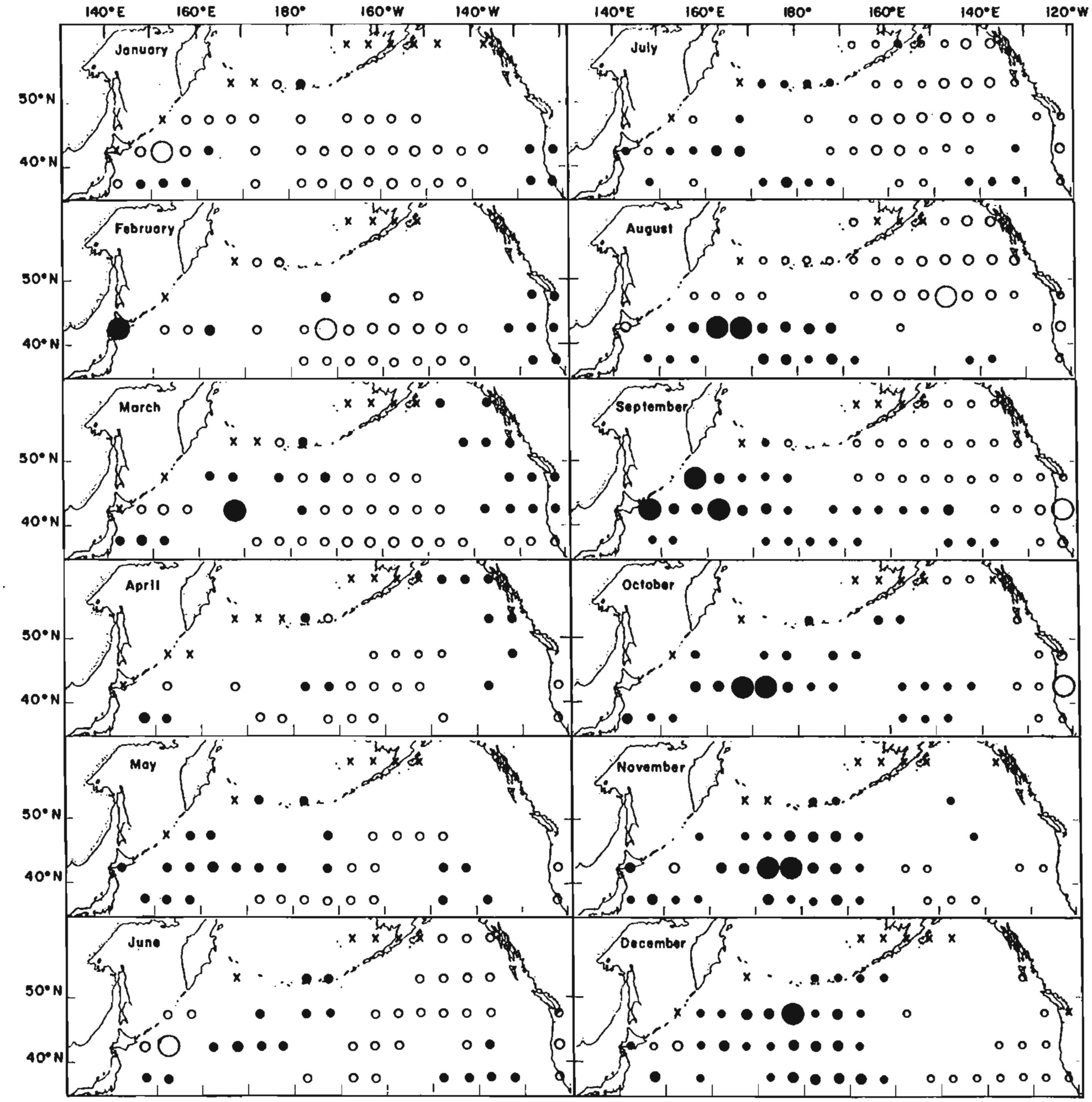
Appendix Figure 14 (Cont.)


140°E
160°E
180°
160°W
140°W
120°W
60°N
50°N
40°N
January
February
March
April
May
June
July
August
September
October
November
December

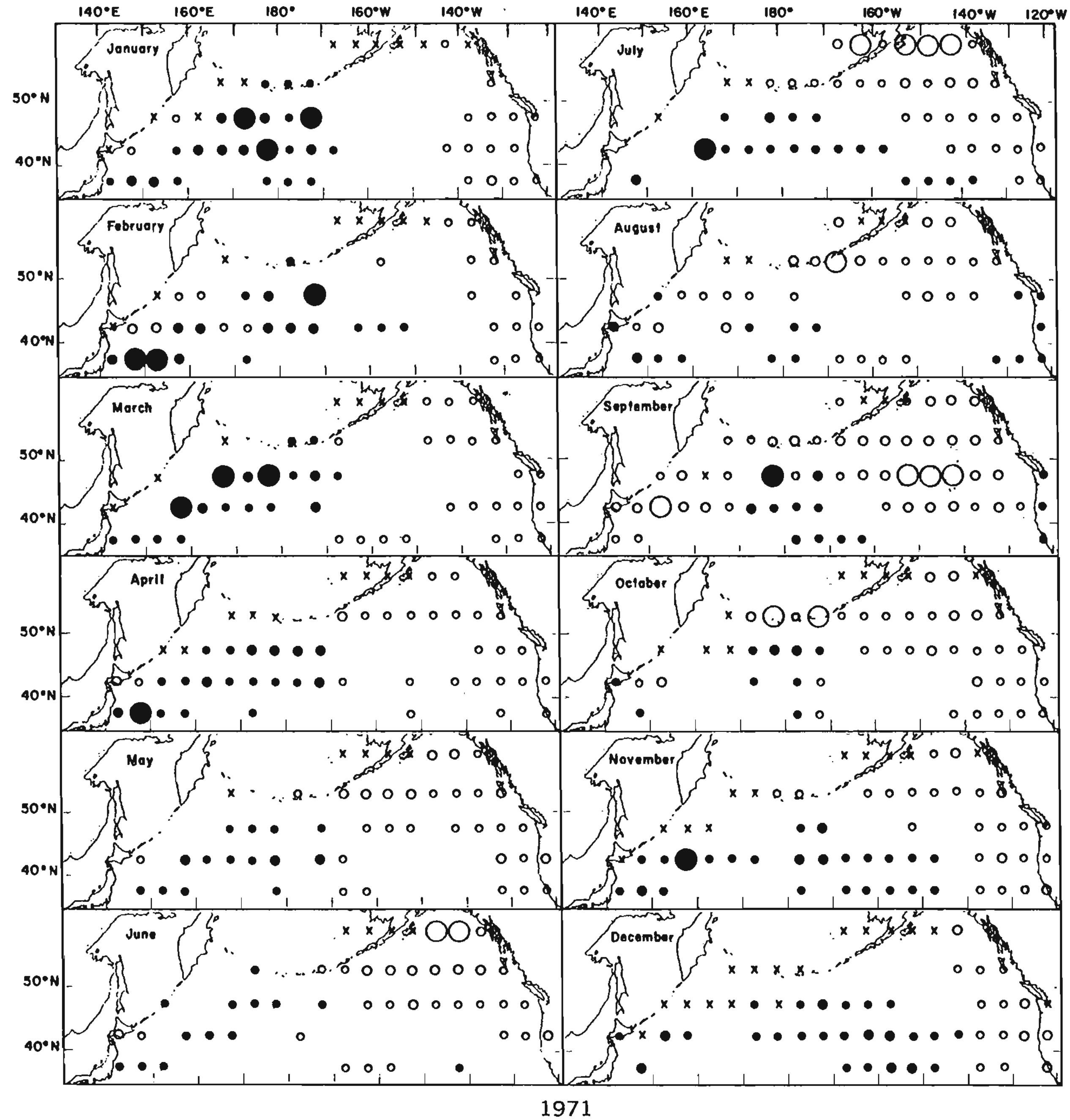
1968



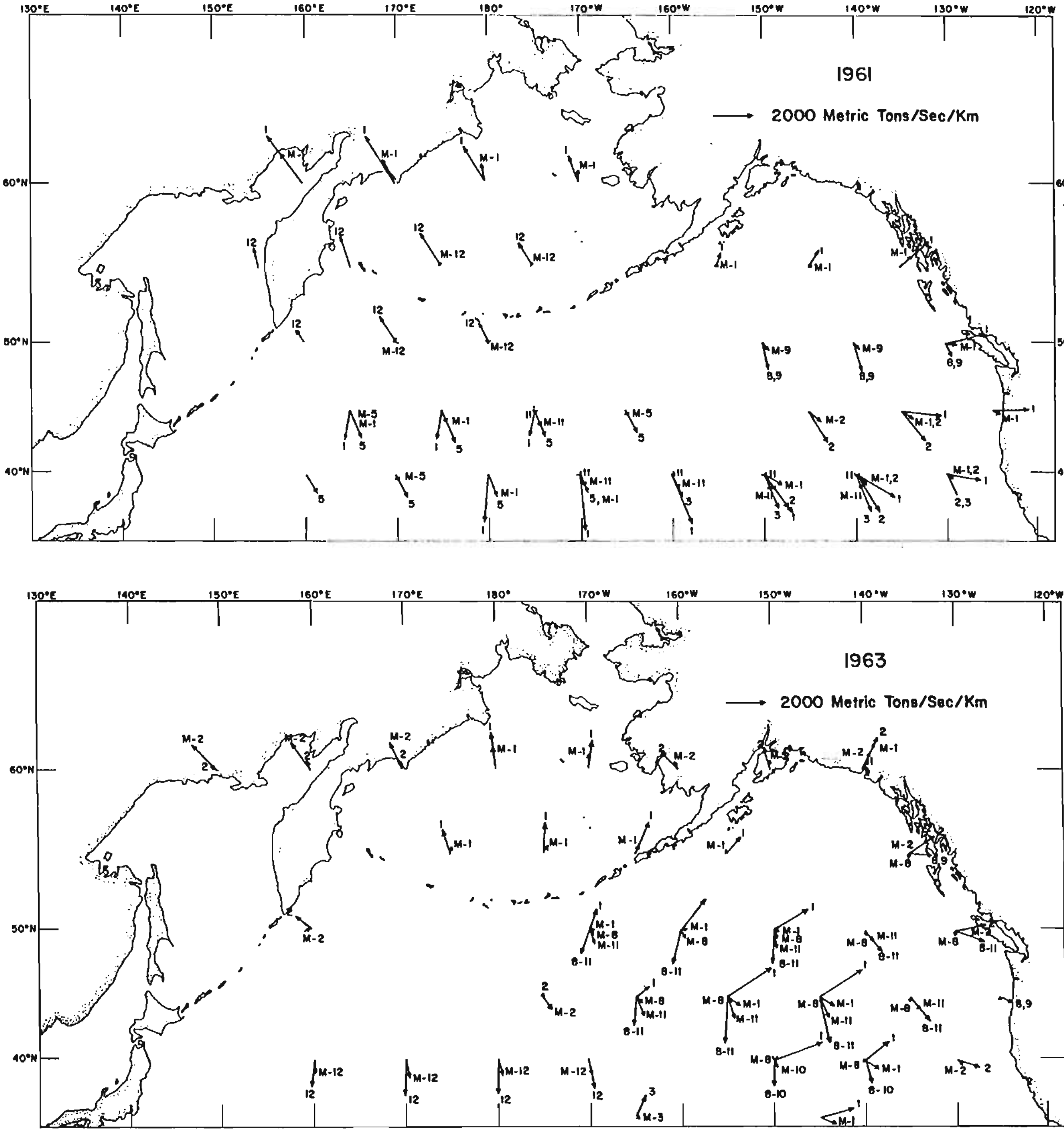
Appendix Figure 14 (Cont.)


140°E
160°E
180°
160°W
140°W
140°E
160°E
180°
160°E
140°E
120°W
50°N
40°N
January
February
March
April
May
June
July
August
September
October
November
December

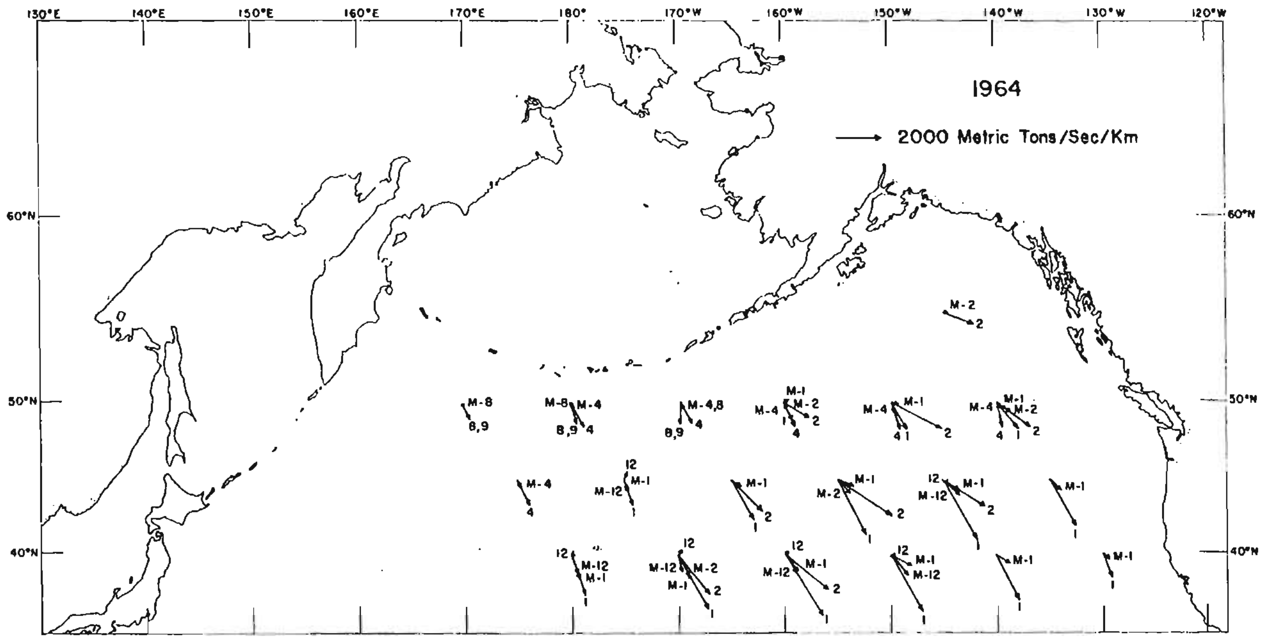
1970

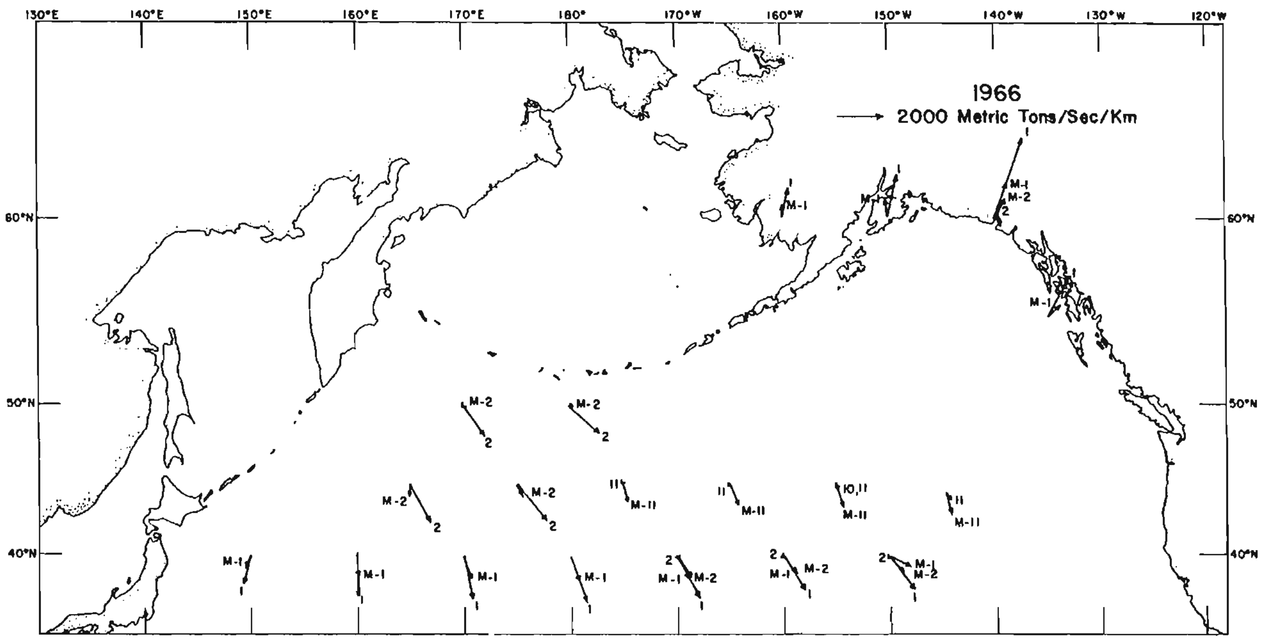


Appendix Figure 14 (Cont.)

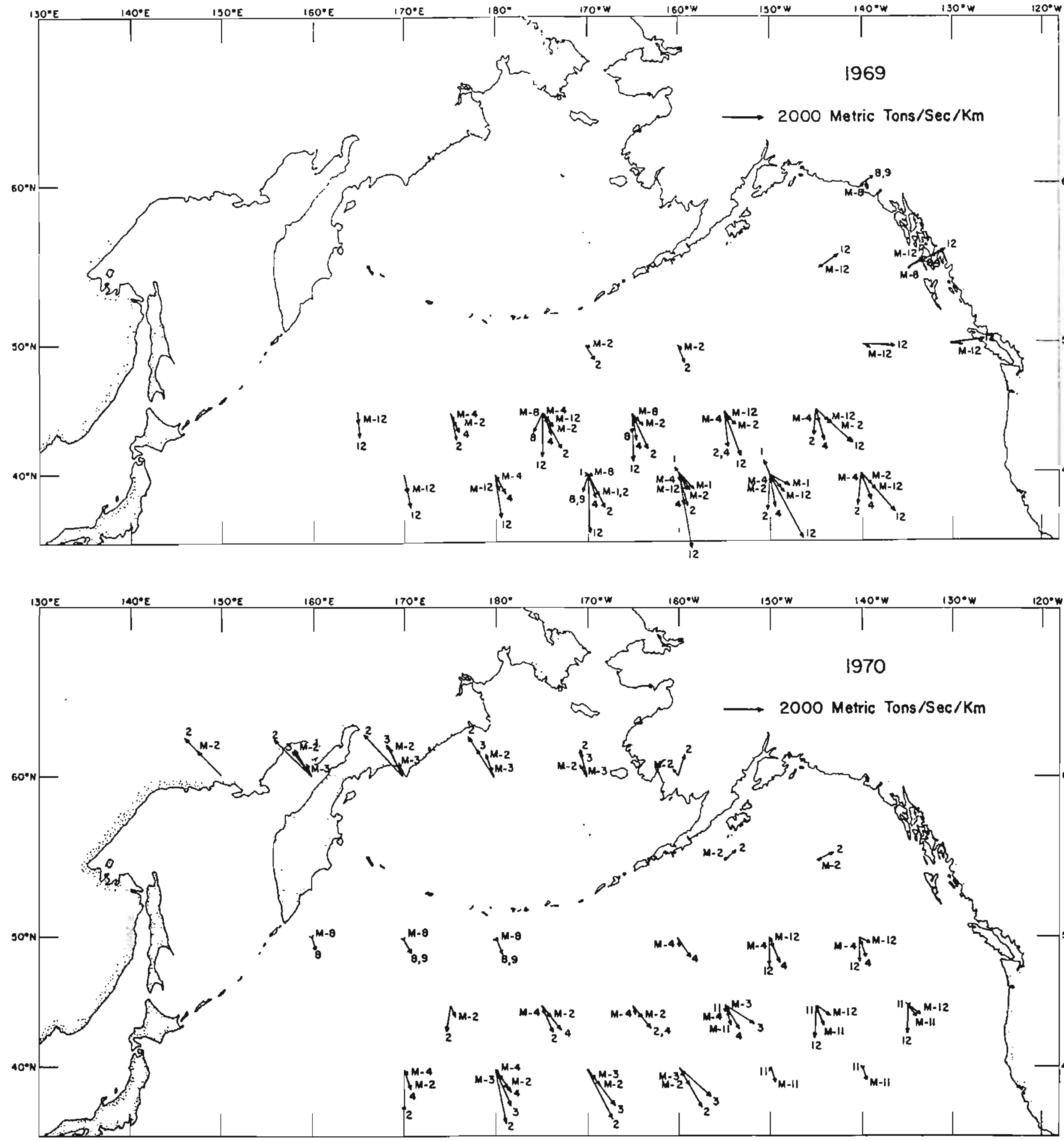


APPENDIX FIGURE 15. Location, month, direction, and magnitude of anomalous Ekman transports, ±1000 m³/sec/km from mean values (indicated by letter M)–1961, 1963, 1964, 1966, 1969, and 1970.





APPENDIX FIGURE 15 Continued.


130°E
140°E
150°E
160°E
170°E
180°
170°W
160°W
150°W
140°W
130°W
120°W
1969
2000 Metric Tons/Sec/Km
60°N
50°N
40°N
1970
2000 Metric Tons/Sec/Km
60°N
50°N
40°N