The Nearshore Physical Oceanographic Environment of the Pacific Northwest Coast

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DEPARTMENT OF OCEANOGRAPHY
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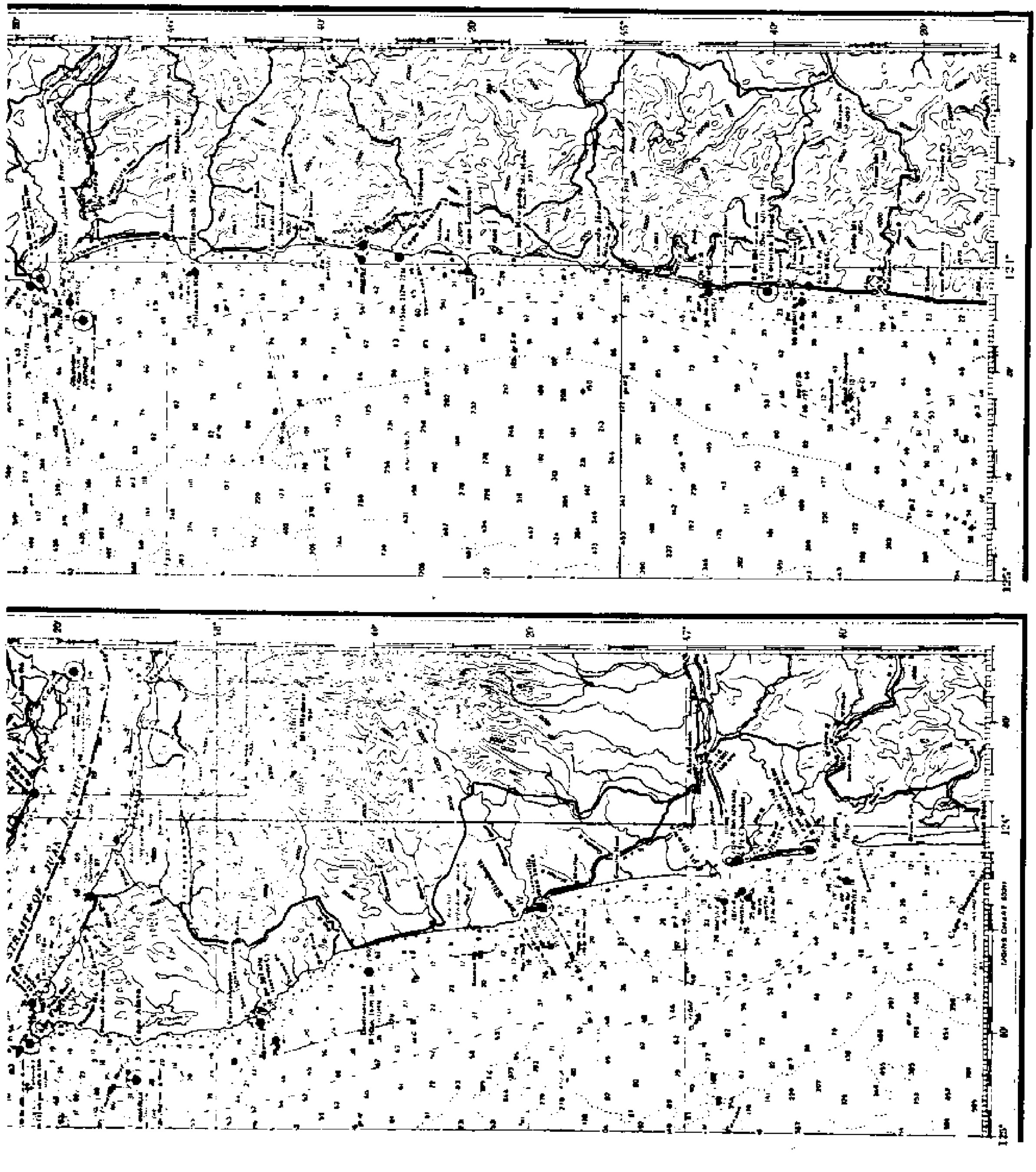

PLATE I

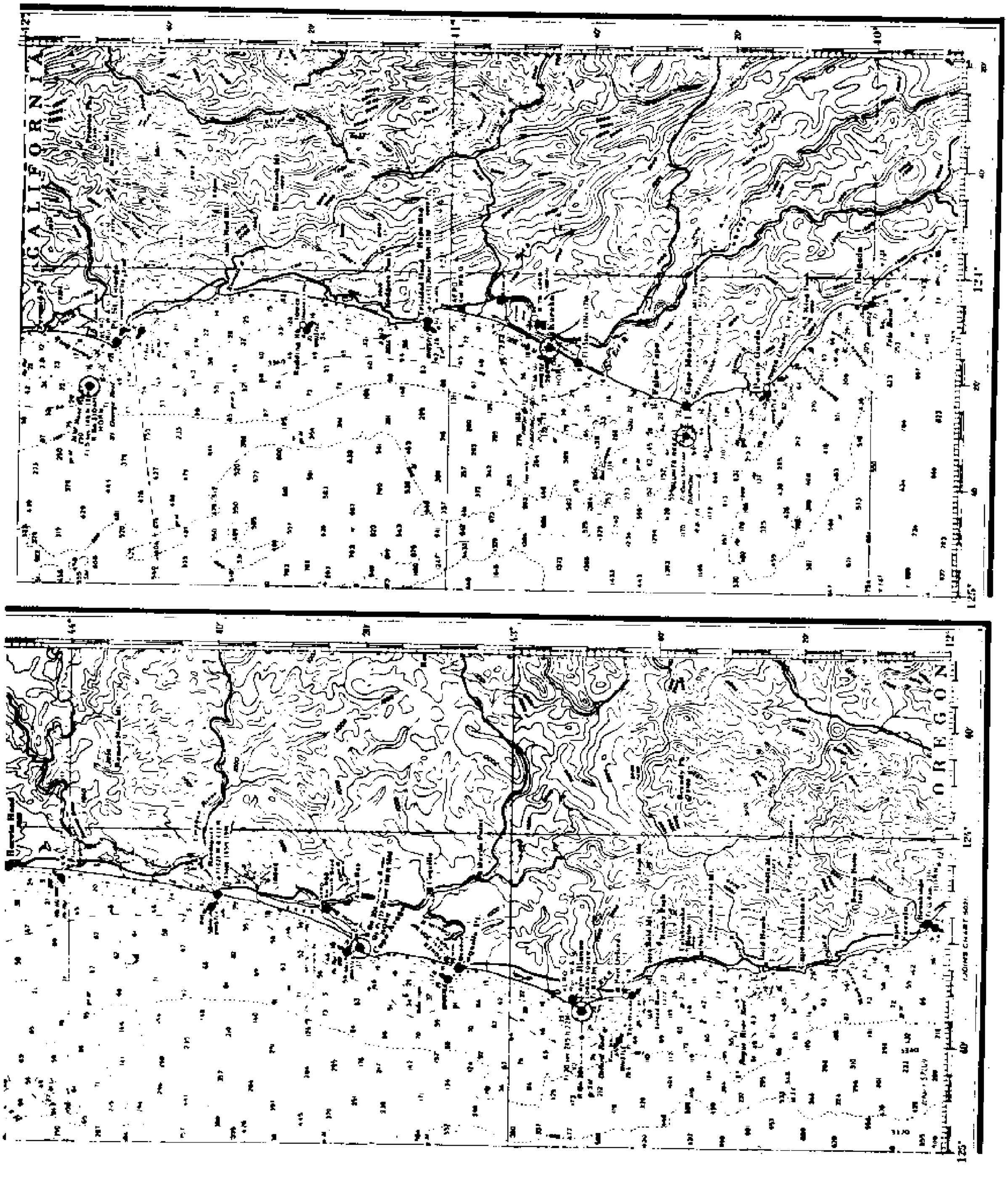

PLATE II

Chapter 1. INTRODUCTION

The oceanographic, meteorologic, and geologic environment of the near-shore region of the Pacific Northwest Coast is described in the report. Specifically, it is a compilation and summary of the available data from the coastline to ten nautical miles offshore extending from Cape Flattery, Washington, to Cape Mendocino, California. The study area consists of broad sandy beaches set between protruding rocky headlands. Plates 1 and 2 show the coastal zone described in this report.

The Coastal Pollution Group formed by the Department of Oceanography at Oregon State University, performed this study. In July 1969, a one year Federal Water Quality Administration grant enabled the group to conduct a literature survey and to assemble and analyze all the available oceanographic data gathered within 10 nautical miles of the Pacific Northwest Coast. This survey included biological and chemical oceanographic investigations as well as physical. After completing the literature survey, the group felt that a compilation of available information concerning the physical oceanographic environment of the coastal region of the Pacific Northwest could be useful to oceanographers, engineers, and state and federal maritime administrators. In addition, the lists of references at the end of the chapters should prove useful as they contain extensive listings of both published and unpublished pertinent papers.

Environmental parameters are reviewed and presented in separate chapters. Chapter 2 lists the available navigational charts applicable to this region; Chapter 3 provides a geological description including bottom profiles of the nearshore area. A summary of the discharge rates for the major coastal rivers is presented in Chapter 4. The seasonal wind pattern determined from stations on shore and at sea is described in Chapter 5. The temperature and salinity variations of the nearshore waters are discussed in Chapter 6. Chapter 7 provides information on the heat budget for this area and Chapters 8 and 9 describe the seasonal variations in the wave regime and current flow, respectively, for the nearshore region.

Acknowledgments

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We acknowledge the support and assistance of Dr. John V. Byrne, Chairman of the Department of Oceanography and Frederick J. Burgess, Head of the Department of Civil Engineering.

Our appreciation is expressed for the partial support of this work provided by Oregon State University National Science Foundation Sea Grant - Institutional Grant GH-45.

Chapter 2. NAUTICAL CHARTS OF THE PACIFIC NORTHWEST COAST

The following Coast and Geodetic Survey Charts pertain to the area covered by this report. They may be purchased from the Director, Coast and Geodetic Survey, Environmental Services Administration, Rockville, Maryland 20852 or Officer in Charge, U. S. Naval Oceanographic Distribution Office, Clearfield, Utah. These charts are listed in two general catalogs: (1) Nautical Chart Catalog No. 2 (1) of the U. S. Coast and Geodetic Survey, and (2) Catalog of Nautical Charts and Publications, No. 1-N Region 0 (2).

AREA	CHART NO.
A. San Francisco to Cape Flattery	C. &G. S. 5052
1. Monterey Bay to Coos Bay	" 5021
a. Pt. Arena to Trinidad Head	" 5602
(1) Cape Mendocino & Vicinity	" 5795
(2) Humboldt Bay	" 5832
(3) Trinidad Harbor	" 5846
b. Trinidad Head to Cape Blanco	" 5702
(1) St. George Reef & Crescent City	" 5895
(2) Pyramid Pt. to Cape Sebastian	" 5896
(3) Cape Sebastian to Humbug Mt.	" 5951
(4) Port Orford to Cape Blanco	" 5952
2. Cape Blanco to Cape Flattery	" 5022
a. Cape Blanco to Yaquina Head	" 5802
(1) Coquille River Entrance	" 5971
(2) Coos Bay	" 5984
(3) Umpqua River to Reedsport	" 6004
(4) Siuslaw River	" 6023
(5) Yaquina Bay & River	" 6055
(6) Approaches to Yaquina Bay	" 6056

AREA		CHART NO.
b. Yaquina Head to Columbia River	C. & G. S.	5902
(1) Tillamook Bay	"	6112
(2) Nehalem River	"	6122
(3) Columbia River to Harrington Pt.	"	6151
c. Columbia River to Destruction Island	"	6002
(1) Willapa Bay	"	6185
(2) Grays Harbor	"	6195
d. Destruction Island to Amphitrite Pt. (Vancouver Is.)	"	6102
(1) Cape Flattery	"	6265

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Chapter 3. GEOLOGY

Geology and Geomorphology

The geology of the nearshore region of the Pacific Northwest has not been studied in much detail. Inference must be drawn from the larger volume of geologic data gathered along coasts and beaches and from the marine surveys which have generally been conducted farther offshore than 2 to 3 miles. The geology of the Pacific Coast is discussed by Palmer (1); the west coast of North America by Menard (2); selected areas of the Pacific Northwest by Byrne (3); and the coastal sand dunes of Oregon and Washington by Cooper (4). A continuing study of the continental margin off Oregon is being conducted by the Department of Oceanography at Oregon State University. A detailed report for the southern Oregon coast has been compiled by Kulm (5) and for the entire Oregon coast by Kulm and Fowler (6). Major bathymetric features off the coasts of Oregon and Washington have been described by McManus (7). Humboldt State College (8) has documented the nearshore geology of the northern California region between Trinidad Head and the Eel River.

The coastal region of the Pacific Northwest may be described as erosional tectonic with uplifted submarine banks and coastal terraces. Numerous steep and often unstable cliffs are interspersed between sandy beaches. Rock outcrops are frequent in the vicinity of headlands and some river mouths (Figures 3-1 and 3-2). In southern Oregon typical areas of rock exposure are Cape Blanco, Cape Arago, and off the mouths of the Umpqua, Coquille and Rogue Rivers. Off the Washington coast, extensive gravel deposits have been found off Grays Harbor, the Quinault River, Ozette Lake, and Cape Flattery (Venkatarathnam, 9). Site investigations for structures located on headlands or other cliff-like areas should consider possible slumping or slope failures (North and Byrne, 10). General geologic features are shown and described on geological maps for Washington, Oregon, and California. Examples of these are:

(a) Geologic map of Oregon west of the 121st meridian (Peck, 11)
(b) Geologic map of Washington (Huntting, et al., 12) and
(c) Geology of Northern California (Bailey, 13).

Sediments

Surface sediments of the nearshore zone are primarily sands consisting of detrital quartz and feldspar. This sand zone extends from the shoreline out to a water depth of approximately 50 fathoms (300 feet) off the northern

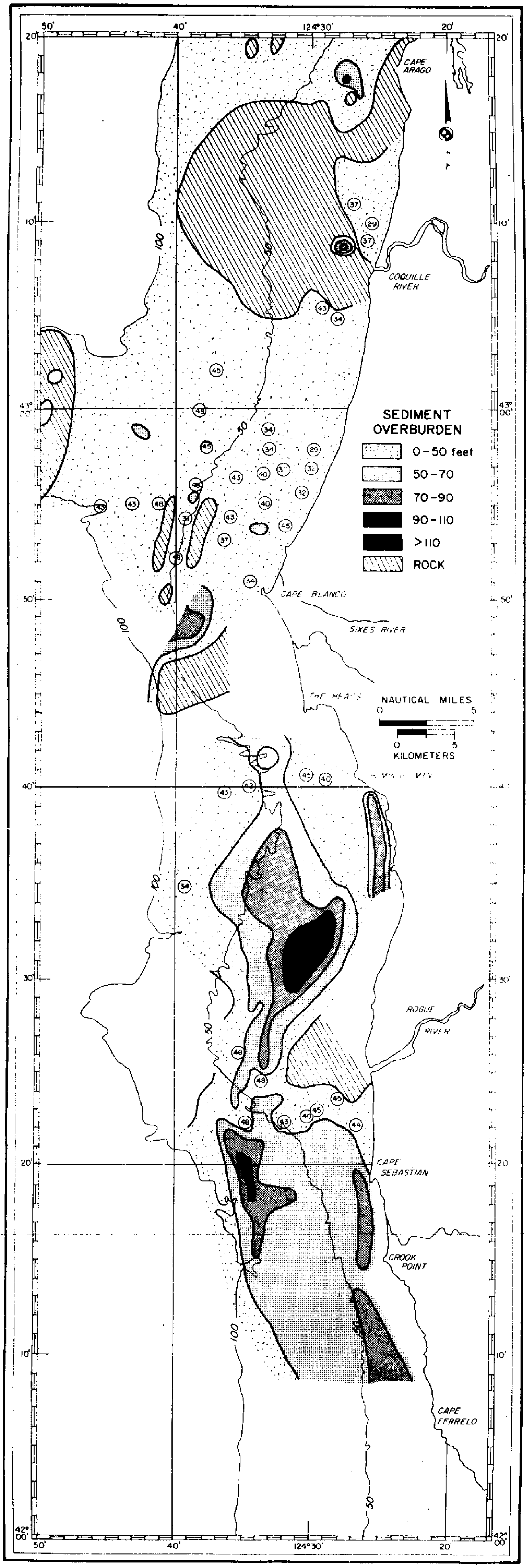

Figure 3-2. Sediment overburden. Numbers in circles indicate exact sediment thickness when measurable for the 0-50 foot interval. Contours in fathoms. (from Kulm, 5)

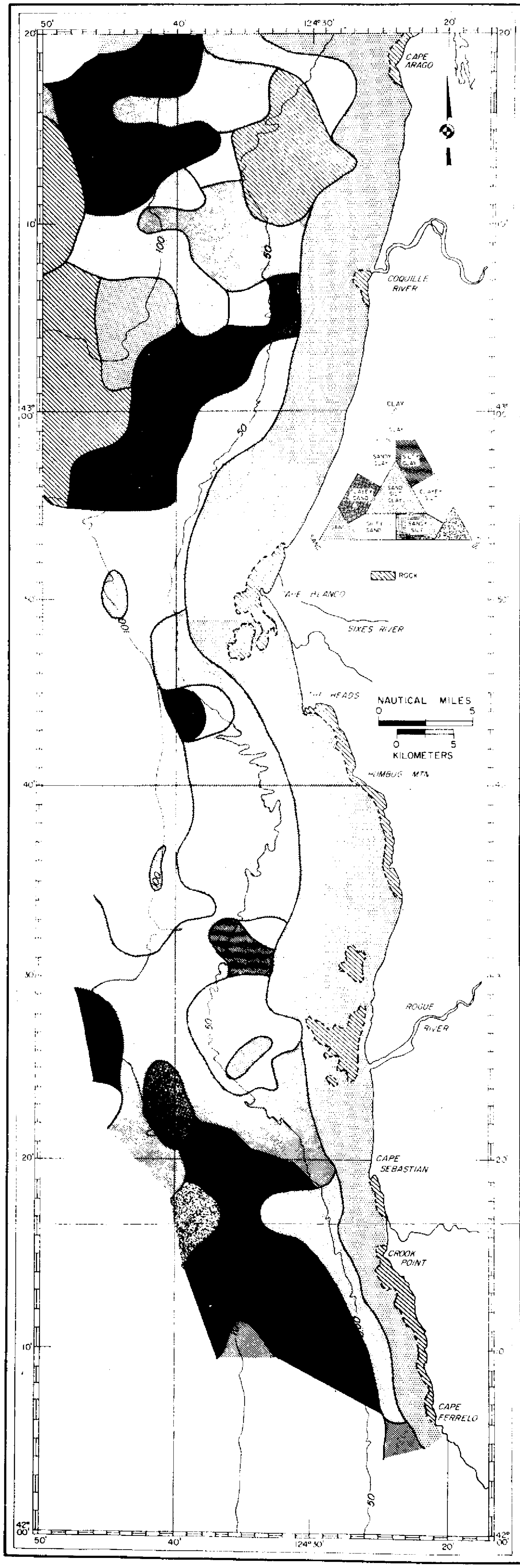

Figure 3-1. Surface distribution of sediment types. Sediment classification according to Shepard (1954). Contours in fathoms. (from Kulm, 5)

and central Oregon coast (Figure 3-3). South of the Umpqua River the sand forms a narrow belt along the coast in generally shallower water (30 fathoms or less)(Figure 3-1). Off the Washington coast the sand zone extends at least to a depth of 30 fathoms (Figure 3-4). Off southern Oregon sediment thickness varies between zero and 90 feet (MacKay, 14) (Figure 3-2). The onshore-offshore transport rate of sand is greatest during winter where, in areas subject to high wave attack, beaches may lose from 5 to 15 feet of sediment thickness. The longshore seasonal transport is generally to the north in winter and to the south in summer. Net longshore transport is believed to be north, but may vary with location (Kulm, et al., 15). Ripples in the bottom sediment have been found at water depths of 80 meters in winter and 30 meters in summer (Neudeck, 16). The transport and distribution of sediments from the Columbia River has been investigated by Ballard (17) and Gross and Nelson (18).

Sediment Motion

When a progressive wave advances into shoaling water, a depth is reached where the oscillatory fluid motion on the bottom is of sufficient magnitude to initiate sediment motion. This sediment motion may be significant to construction in the nearshore region.

Observations indicate that offshore gravity forces dominate over onshore hydrodynamic forces during the winter. Therefore, in the winter, beach sand is generally transported offshore. Under summer wave conditions the net onshore hydrodynamic force is greater than the offshore gravity force and the sand moves onshore.

Few observations have been made in the oceans to determine at what depth significant sand motion is initiated (see Inman, 19) although considerable work has been done in laboratory wave tanks (Ippen, 20). At present, the correlation between laboratory work and ocean observations is uncertain.

Inman (19) indicates that the alignment of characteristic sediments parallel to the shoreline is caused by onshore/offshore sand movement, not littoral drift. Ippen and Eagleson (20) have shown that the depth of established equilibrium motion (the deepest depth a characteristic sand particle remains in motion through a complete wave cycle) can be calculated for a characteristic beach slope, sand size, and wave. Figure 3-5 depicts depths of equilibrium motion for a beach with a slope of 0.015 and a sand diameter of 0.24 mm (D_{50}) for varying wave conditions.

A second approach to determine the depth at which sand movement is initiated for given wave conditions is to use small amplitude wave theory and Hjulstrom's curve (Figure 2.2 in 21) for threshold velocities for different

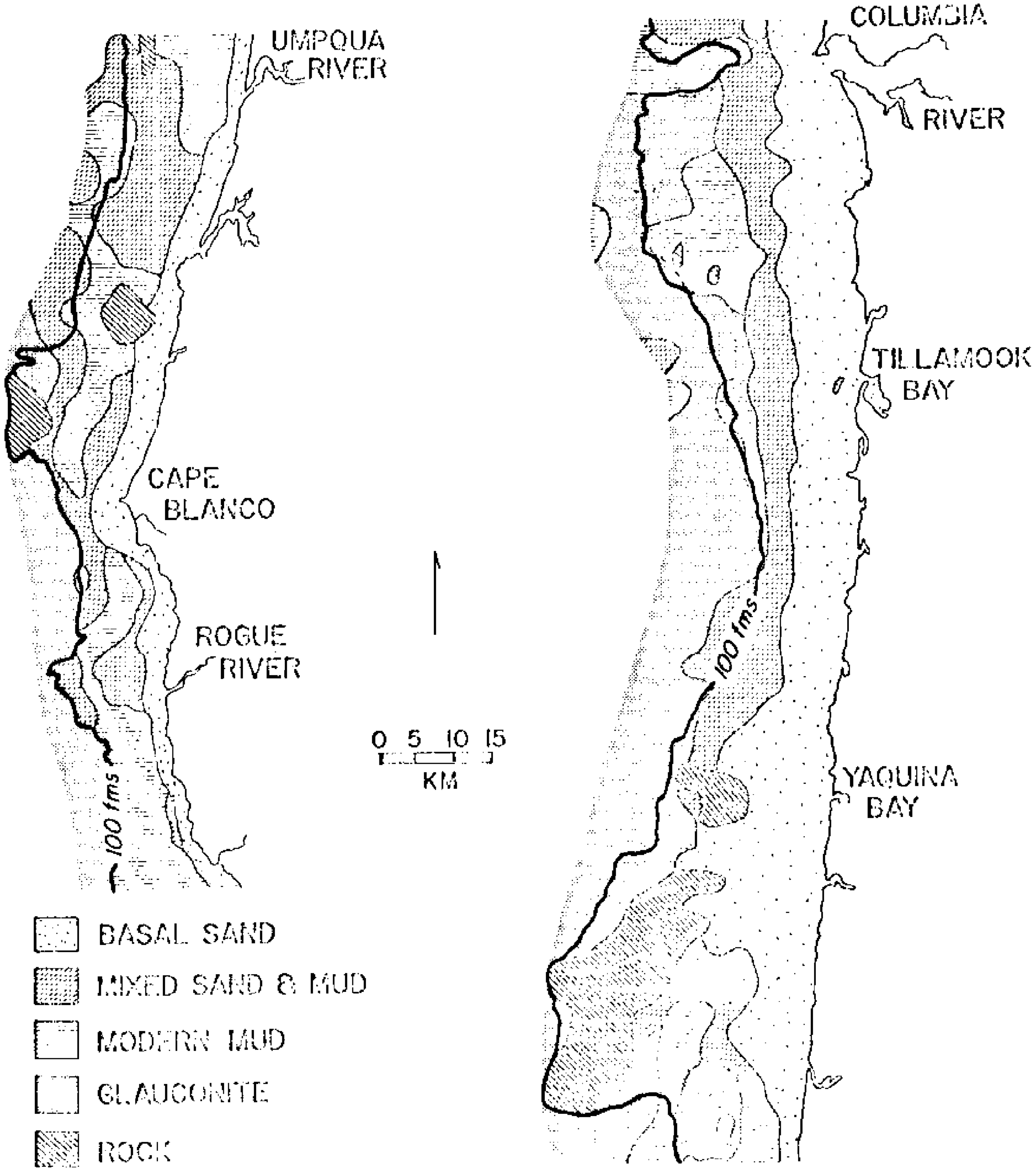

Figure 3-3. Sedimentary facies of the Oregon continental shelf. (from Kulm and Fowler, 6)

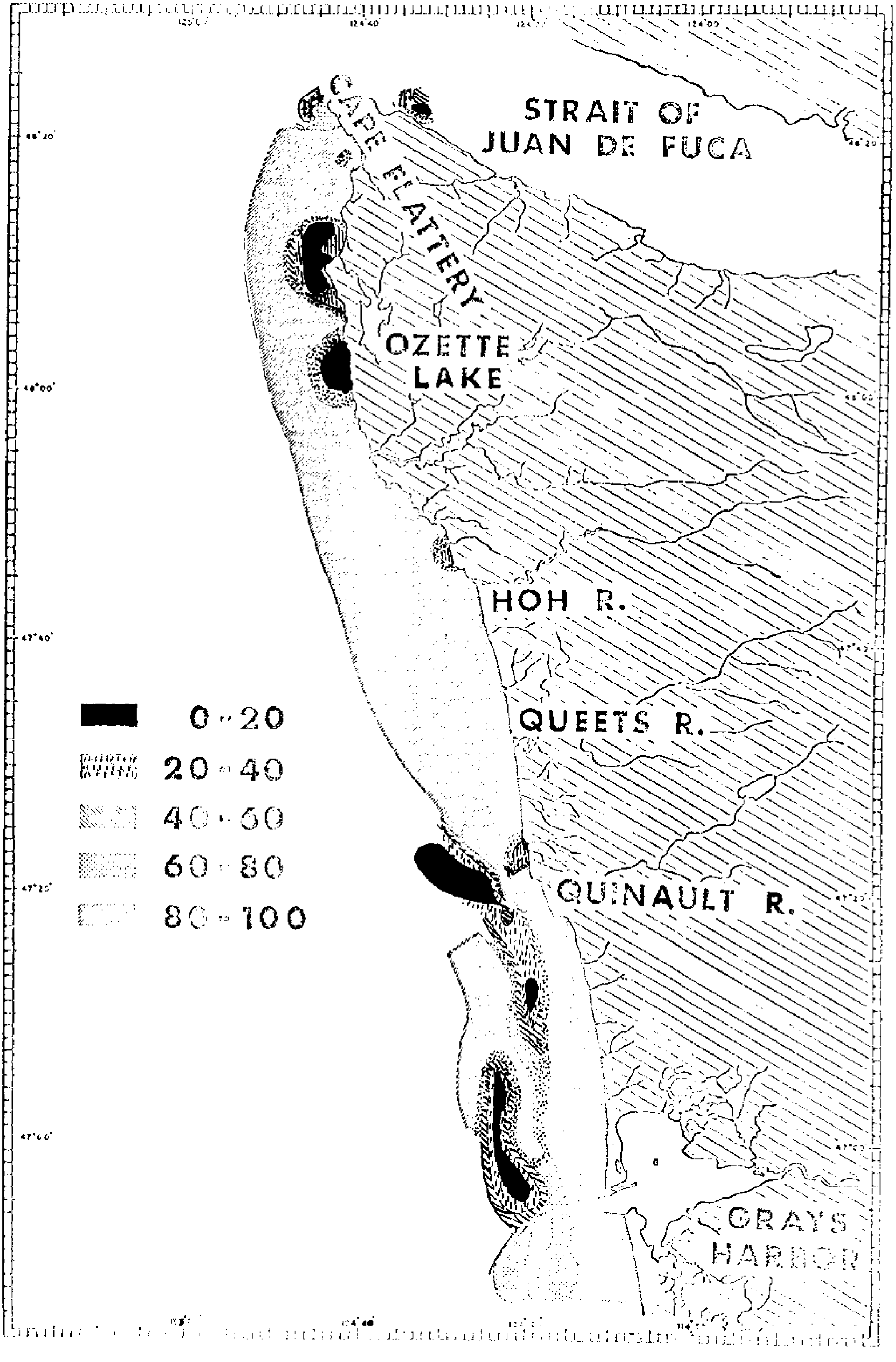

Figure 3-4. Distribution of sand off Washington (from Venkatarathnam, 9)

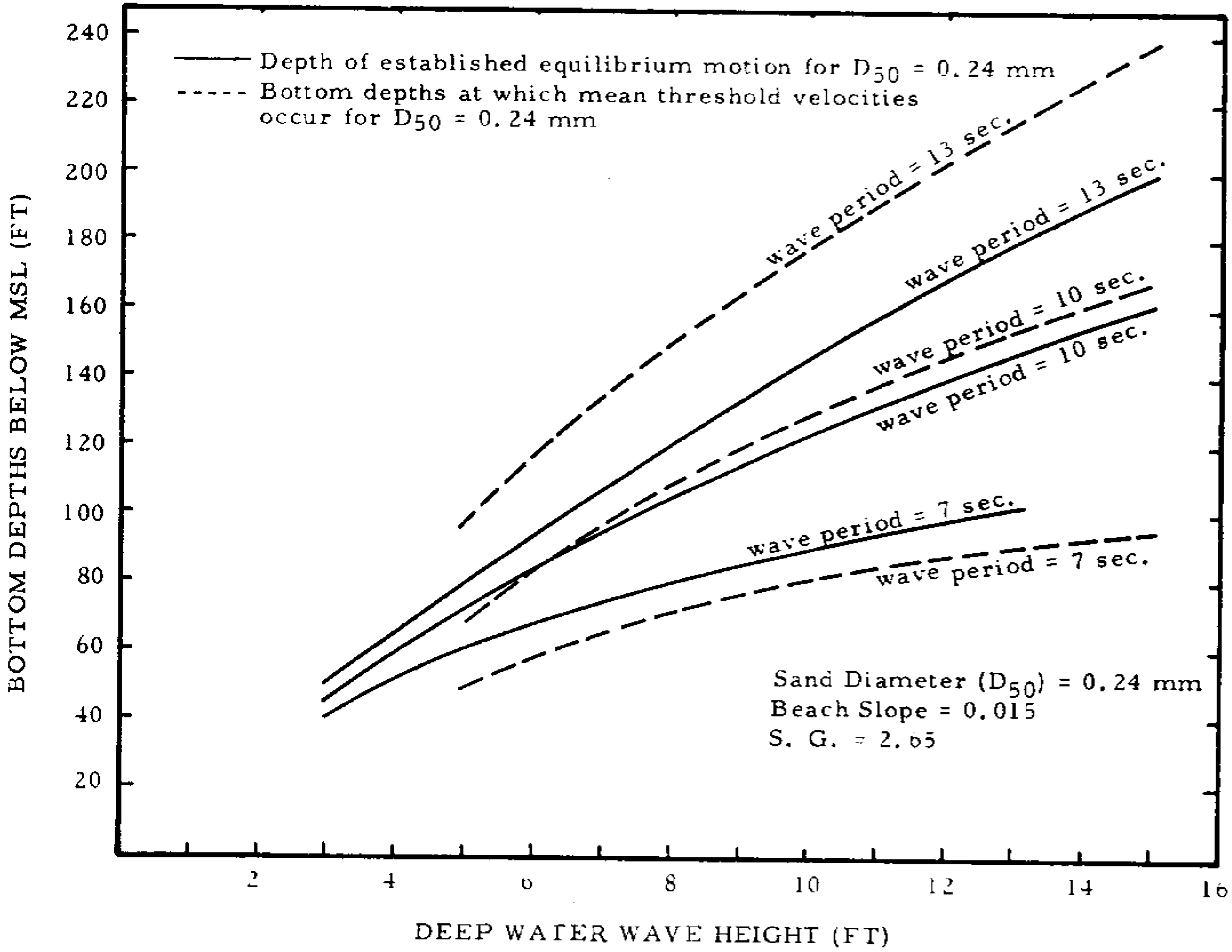

Figure 3-5. Movement of bottom sand due to waves.

sand sizes. Figure 3-5 also shows solutions to the equation for threshold particle velocity on the bottom due to various wave conditions for a sand size of 0.24 mm (Glenne, 22). The 0.24 mm sand size and 0.015 beach slope are representative of the Oregon coast.

Sorting of sediment sizes on the foreshore slope of a beach (landward of the breaker) is shown in Figure 3-6 from C.E.R.C. TR-4 (21). The larger sized grains are associated with steeper beaches (a result of the higher orbital velocity of the water particles), but this relationship is also influenced by water level variability, wave exposure, and ground water level. Median grain size has been shown to be a satisfactory parameter for generally evaluating the transportability of littoral material.

Seismology

The coastal area of the Pacific Northwest is relatively aseismic compared to the remainder of the Pacific Coast. Hence, it may be considered a preferential siting area. The lack of major seismic activity is seen in the plot of tectonic flux (Figure 3-7)--an integration of earthquake intensity and number of quakes. Shear zones have been postulated through Cape Blanco and at Coquille Point, but these have not been active since post-Miocene (Dott, 23).

Byerly (24) and Menard (2) have discussed earthquakes and faulting, respectively, along the Pacific Coast. Ryall, et al. (25) have studied the seismicity, tectonism, and surface faulting of the Western United States. A discussion of Oregon earthquakes may be found in Berg and Baker (26). Faults and shear zones of the continental shelf off Washington have been investigated by Grim and Bennett (27).

Sources of Information

The following list of departments and bureaus are the major repositories of geologic data and information. These sources should be investigated for pertinent available data before commencing geologic surveys.

a. State

   1. Department of Geology and Mineral Industries, State of Oregon
   2. Washington Department of Conservation, Division of Water Resources

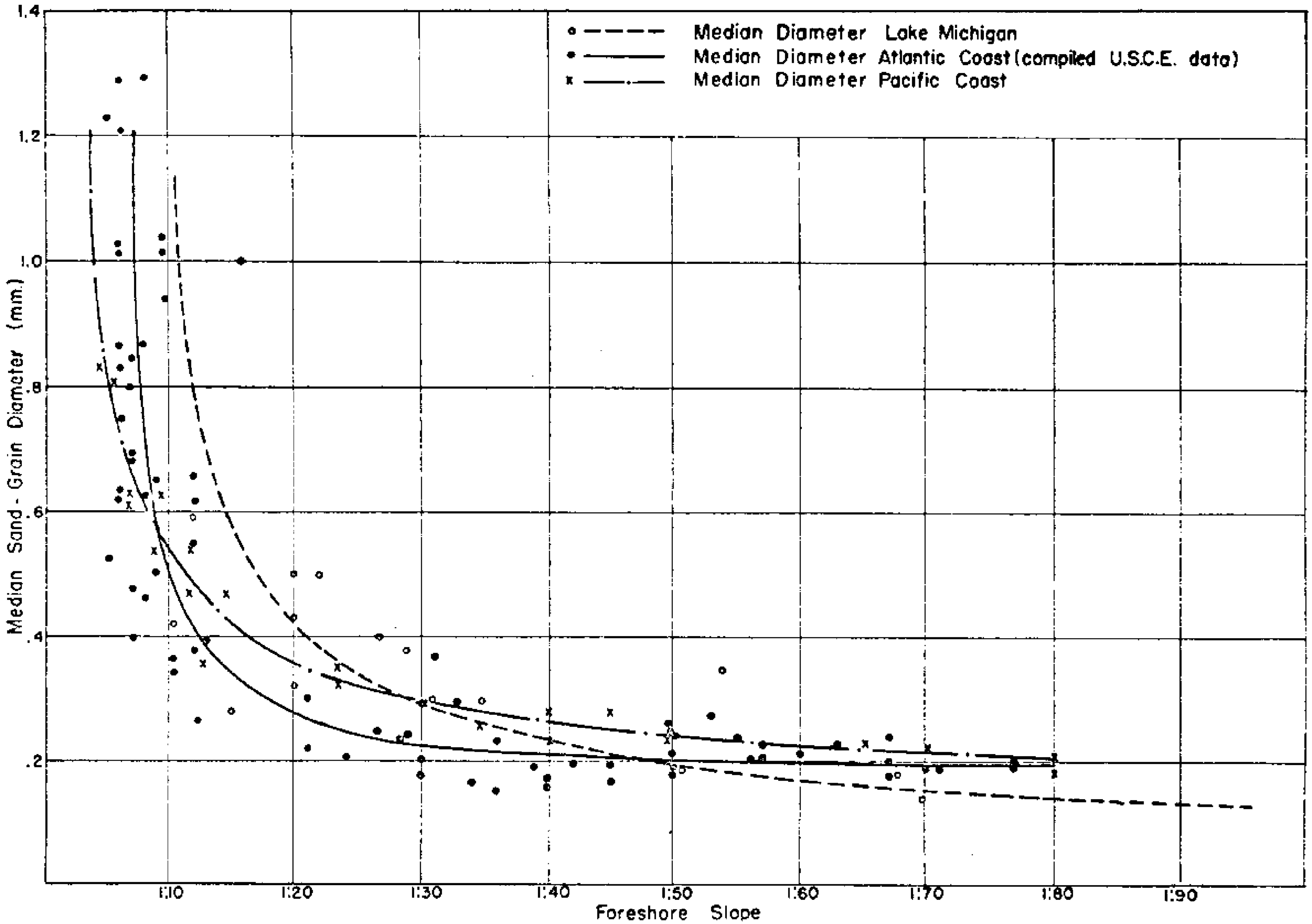

Figure 3-6. Relationship between grain size and foreshore slope (from C. E. R. C., TR-4, 16).

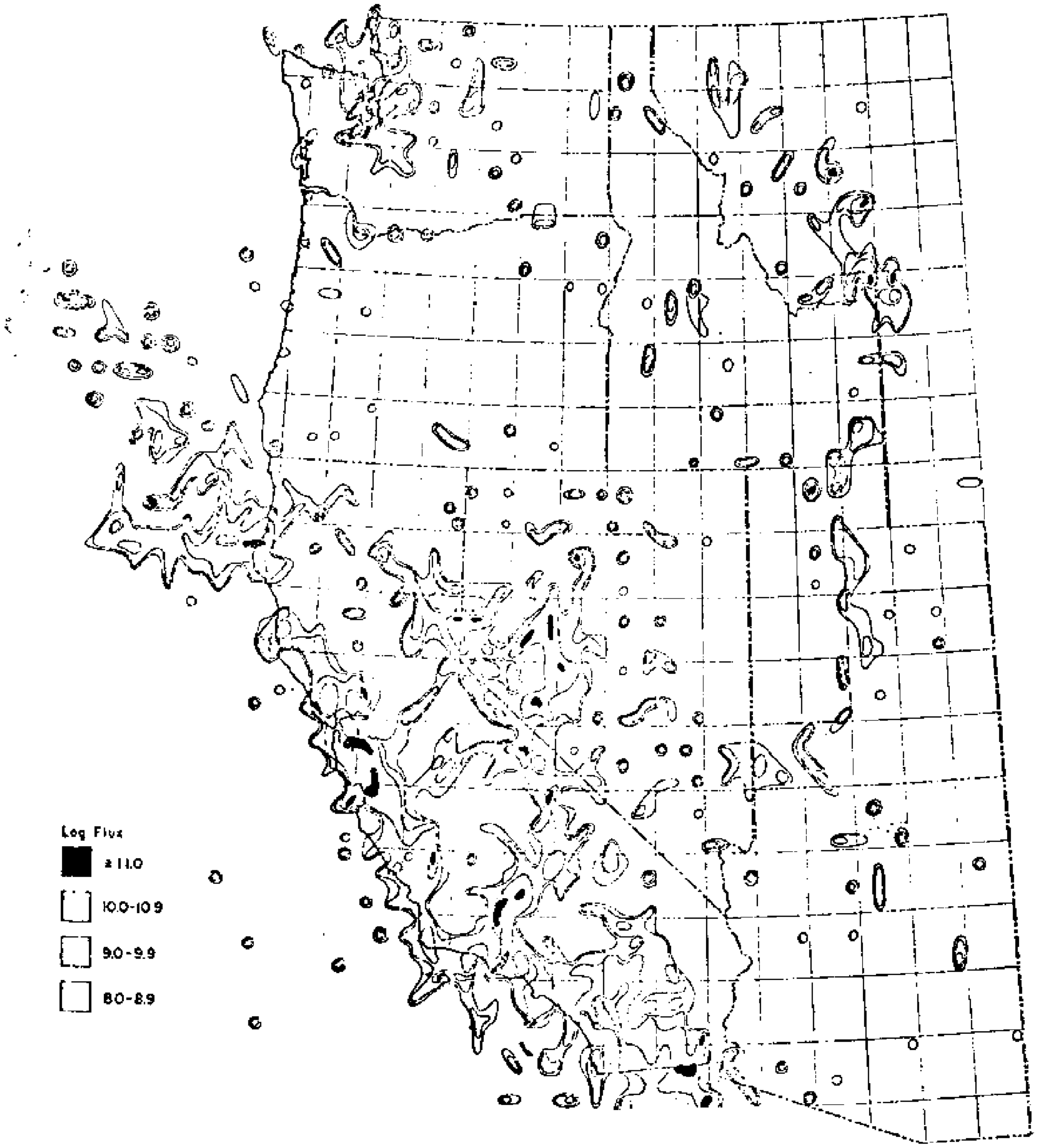

Figure 3-7. Map of tectonic flux for the Western United States (from Ryall, _et al._, 25). . Log flux indicies represent combined intensity and frequency of quakes.

3. Washington Department of Conservation, Division of Mines and Geology
4. California Division of Mines and Geology

b.

1. U. S. Geological Survey
2. U. S. Bureau of Mines
3. U. S. Bureau of Reclamation
4. U. S. Coast and Geodetic Survey
5. U. S. Army Corps of Engineers

Nearshore Topography

The nearshore topography of the study area can be illustrated by profiles of the bottom contour constructed at selected intervals along the coast from the shoreline out to a distance of three miles. Profiles or transects were drawn parallel to latitude lines and were located with reference to significant estuaries, population centers, broad flat beaches, headlands, and other coastal features.

The profiles shown in Figures 3-8 and 3-9 are of transects three nautical miles in length and are subdivided into three increments--shoreline to 0.5 mile, 0.5 to 1.5 miles, and 1.5 to 3.0 miles. The average bottom slope for each increment and the depth of water at 0.5, 1.5, and 3 miles offshore are shown.

The bottom slope of the first half mile increment is significantly greater than the slope farther offshore. From Cape Mendocino northward to Tillamook Head the slope is relatively steep ranging from 1:35 to 1:100 (1.75° to 0.5°); farther northward the slope is less, ranging from 1:100 to 1:200. At distances greater than one-half mile the slope is generally less, varying between 1:100 to 1:600 with the steeper slopes occurring south of Tillamook Head.

At a distance of one-half mile offshore the depth of water varies between 15 feet and 40 feet with a mean depth slightly greater than 30 feet. Three miles offshore in the northern portion the water depth rarely exceeds 100 feet. From Tillamook Head to the southern boundary the depth of water varies from 100 feet to 300 feet.

Several exceptions to the above mean conditions exist, notably around headlands. Here, offshore reefs and haystack rocks abound and bottom

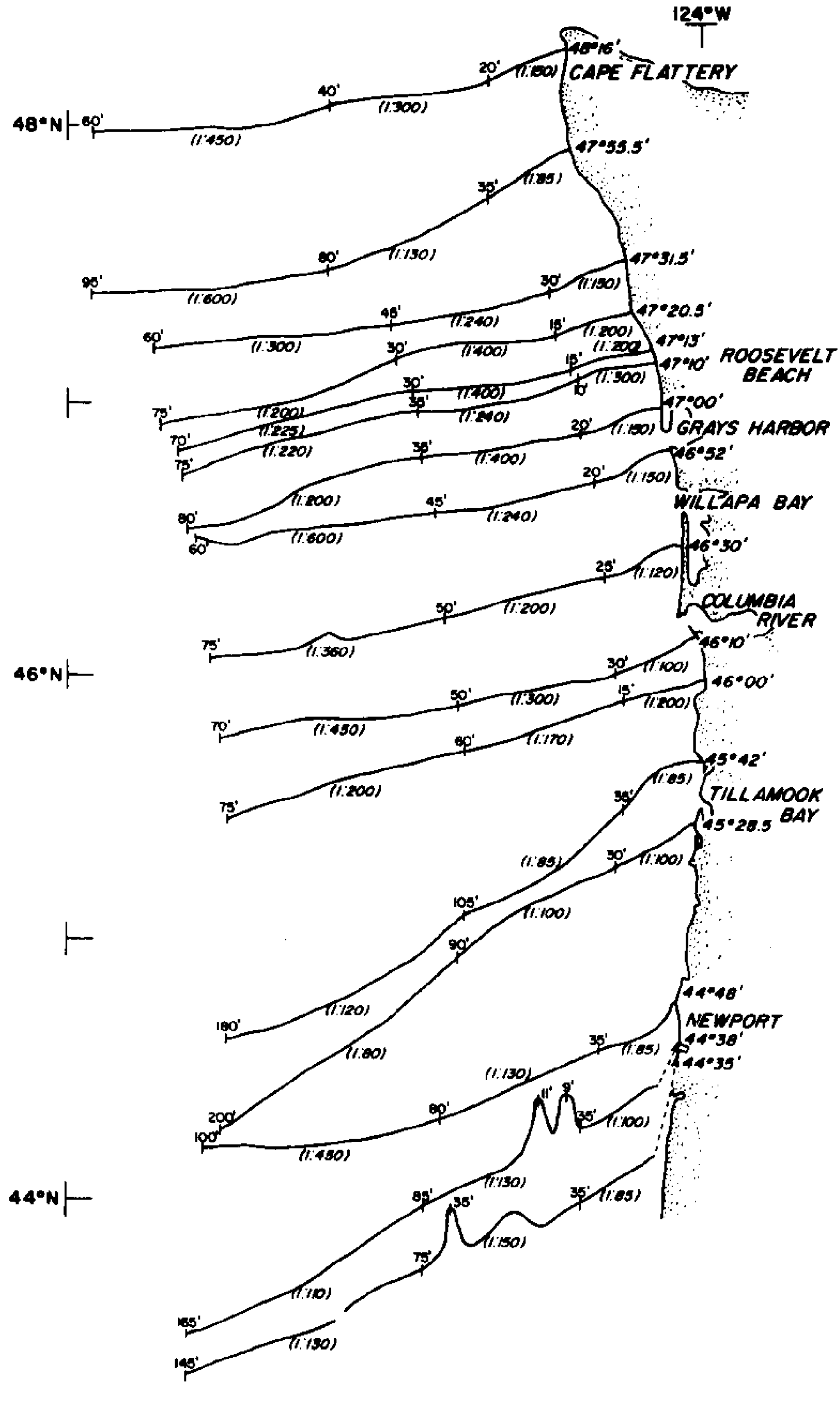

Figure 3-8. Bottom profiles and beach slopes for various locations in Washington and northern Oregon. Water depth is indicated at 1/2, 1 1/2, and 3 miles offshore.

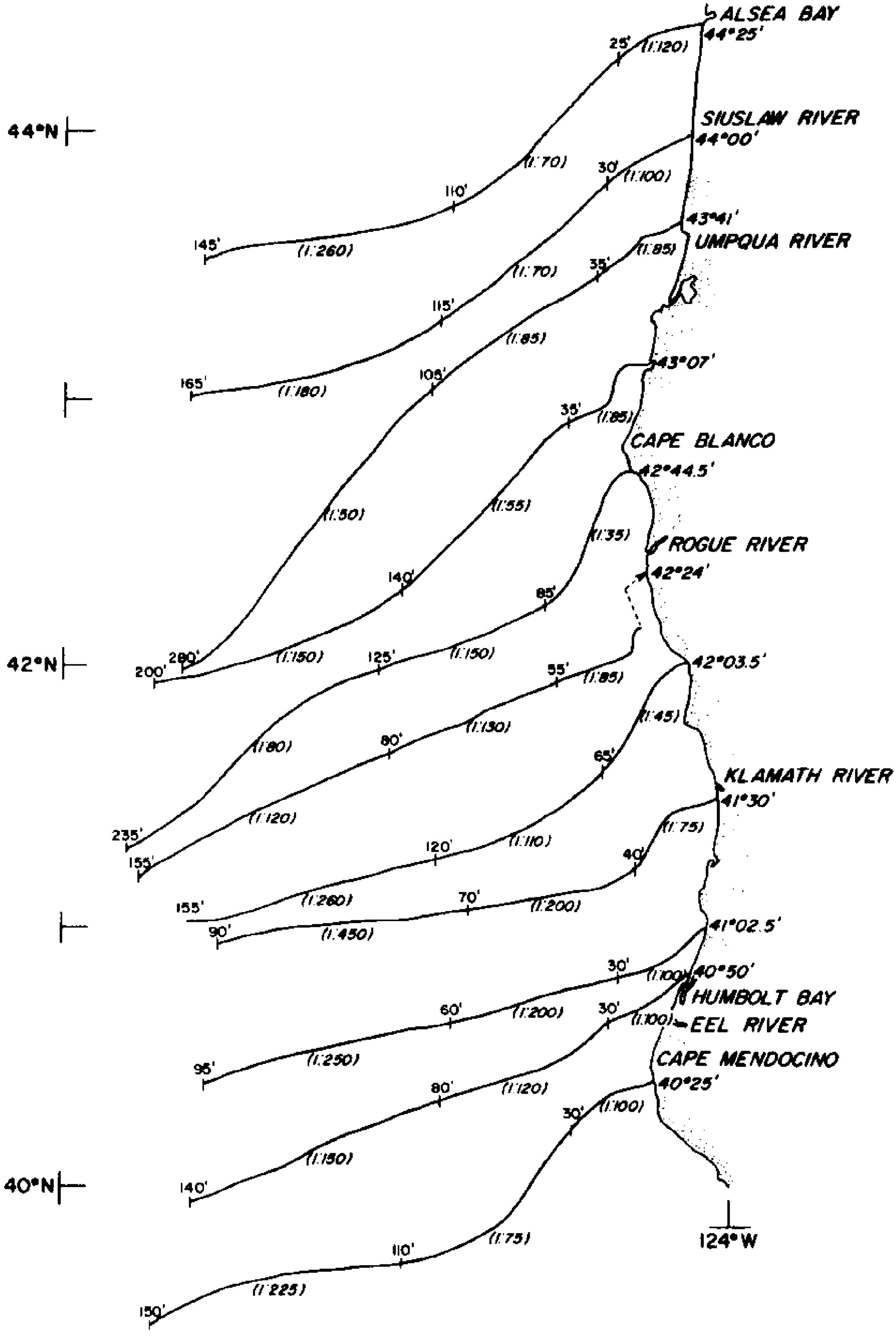

Figure 3-9. Bottom profiles and beach slopes for various locations in southern Oregon and northern California. Water depth is indicated at 1/2, 1 1/2, and 3 miles offshore.

contours become quite irregular. In many of these cases high cliffs terminate abruptly at the water's edge eliminating the formation of any beach.

At Newport, Oregon, from Yaquina Head to approximately a mile south of the entrance jetties a submerged reef runs parallel to the coastline about a mile offshore. This reef alters the nearshore surface circulation pattern creating eddies of variable strength and direction. Similar situations will also exist in the proximity of other offshore rocky areas.

There are no known canyons or troughs that extend to within three miles of the coast. The heads of the Astoria and Eel River canyons terminate farther offshore, 15 miles and five miles, respectively.

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Chapter 4. HYDROLOGY

Streamflow data for the nine major rivers discharging between Cape Flattery and Cape Mendocino are shown in Table 4-1. The data were taken from the records of the lowest gaging station on each river with the exception of the Siuslaw River which was estimated from precipitation records (1) since no gaging stations were installed until 1967. Streamflow data for the Columbia, Rogue, Coos, and Coquille rivers have been extrapolated to the mouths of the rivers.

Streamflow data are available from the annual "Water Resources Data," published for each state by the U.S. Geological Survey (2, 3, 4). The Northwest Water Resources Data Center (5) publishes weekly and monthly streamflow summaries for selected stations in the Pacific Northwest. The Oregon State Water Resources Board has published river basin studies for the coastal basins of which the Rogue River (6), North Coast (7), Mid-Coast (1) and South Coast (8) basin studies were used.

The Columbia and Klamath Rivers show an annual bimodal flow discharge. This is a result of heavy autumn and winter precipitation west of the Cascade Range and spring snowmelt waters. Figure 4-1 shows the average monthly flow for the Columbia River showing the winter rainfall peak and the spring snowmelt peak.

The streamflow for the other rivers shows single peaks in winter due to heavy precipitation on the Coast Range during this season. Figure 4-2 depicts the streamflow for the Chehalis River which is representative of the flow pattern of these coastal rivers. A log-log plot of average coastal river streamflows versus river basin drainage area (Figure 4-3) permits estimation of streamflow for similar type rivers based upon a knowledge of the river drainage area.

To summarize, the discharge patterns of the coastal rivers emptying into the Pacific Ocean from Northern California, Oregon and Washington show broad peaks during the winter and spring months. During summer and fall the discharge rates of these streams are much below their annual average (80 to 96 percent less).

Table 4-1. River discharge data for the Pacific Northwest.

River		Columbia	Chehalis	Umpqua	Rogue	Klamath	Eel	Coos	Coquille	Siuslaw
Drainage area for total basin - (mi^2)		259,000	2,012	4,560	5,160	15,800	3,630	415	1,058	773
Drainage area - (mi^2)		*	1,172	3,683	*	12,100	3,113	*	*	*
Percent of total basin gaged		*	88	80	*	78	86	*	*	*
Observation period		1953-67	1960-68	1953-67	1933-55	1958-67	1958-67	1930-61	1930-61	1937-63
Avg. monthly flow CFS	OCT	140,000	3,300	2,000	2,600	5,400	1,400	550	850	Estimated from precipitation records, stream not gaged
	NOV	192,000	11,200	7,300	6,600	11,100	5,000	2,400	3,550	
	DEC	246,000	15,900	16,600	11,900	24,500	17,000	4,500	6,600	
	JAN	263,000	19,800	18,300	16,200	25,900	18,000	5,300	8,050	
	FEB	266,000	13,000	16,100	15,600	30,600	19,500	5,500	8,250	
	MAR	239,000	10,700	13,200	12,300	24,600	12,700	4,000	6,050	
	APR	279,000	6,700	9,700	10,600	26,100	10,300	2,100	3,150	
	MAY	390,000	3,300	7,300	8,000	19,700	3,900	1,200	1,800	
	JUN	538,000	1,800	4,000	5,000	10,600	1,100	530	750	
	JUL	338,000	1,100	1,700	2,000	4,000	300	180	300	
	AUG	178,000	800	1,300	1,300	2,900	200	90	140	
	SEP	131,000	700	1,200	1,200	3,000	100	90	130	
Mean streamflow (cfs)		266,000	7,600	8,200	7,800	17,200	7,100	2,200	3,300	3,150
Avg. min. daily flow (cfs)		---	500	900	---	2,400	100	---	---	---
Avg. max. daily flow (cfs)		---	65,000	125,000	---	165,000	164,000	---	---	---

*Data extrapolated to river mouth.

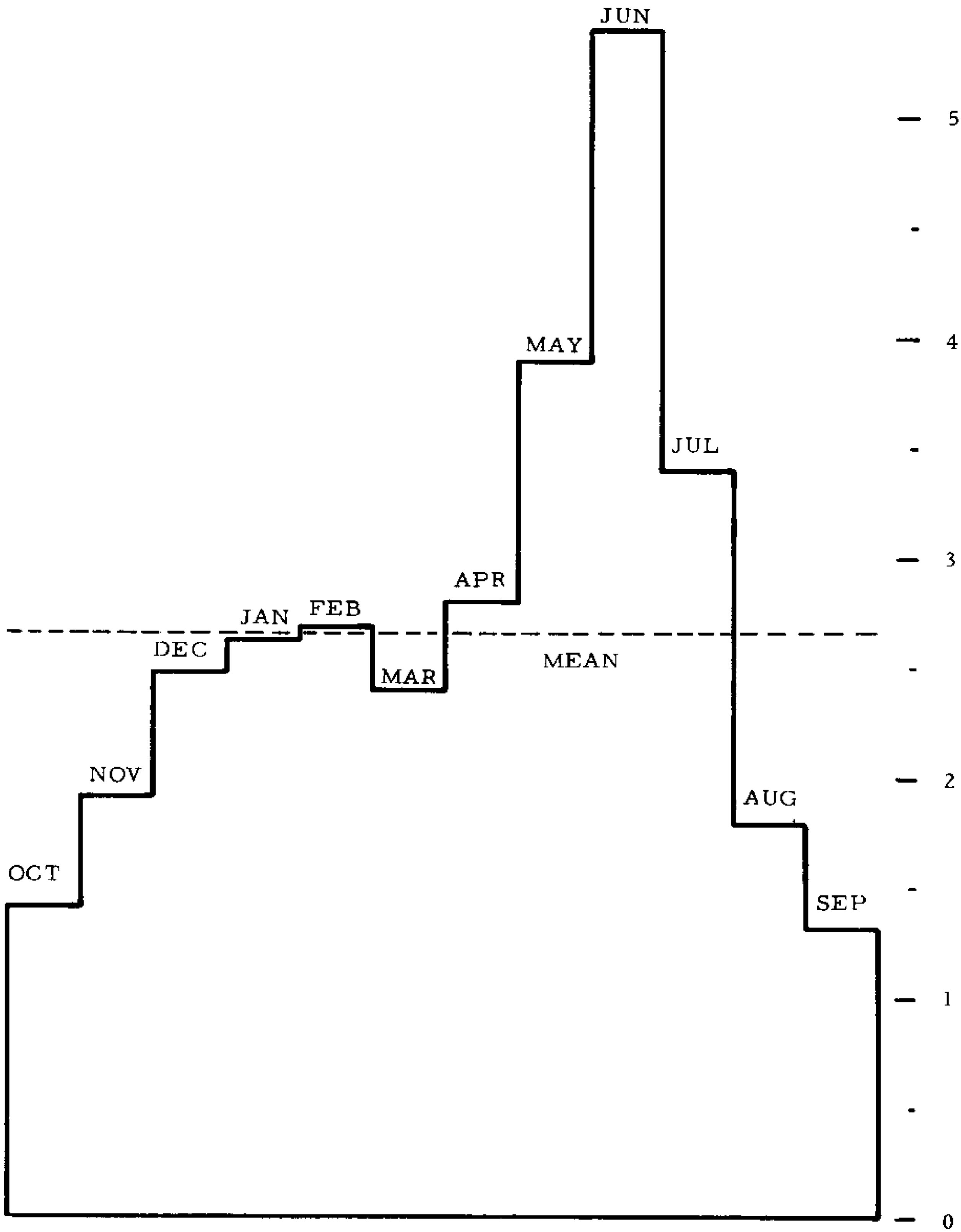

Figure 4-1. Mean monthly flow of the Columbia River extrapolated to the river mouth for 1953-1967. (CFS x 10^5)

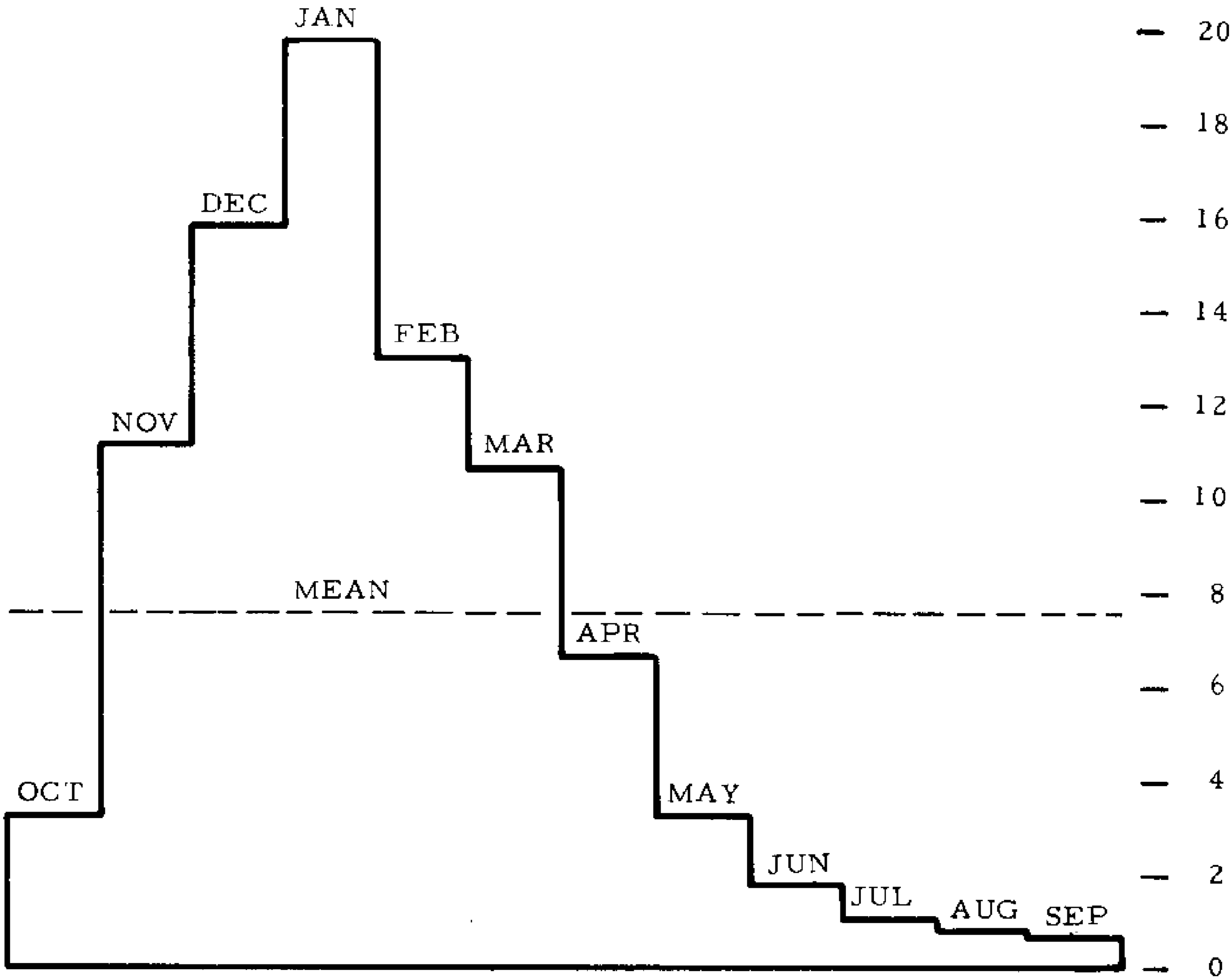

Figure 4-2. Combined mean flow of the Chehalis, Satsop, and Wynoochee Rivers measured at the lowest gaging station on each river for the period 1960-1968. (CFS x 10^3)

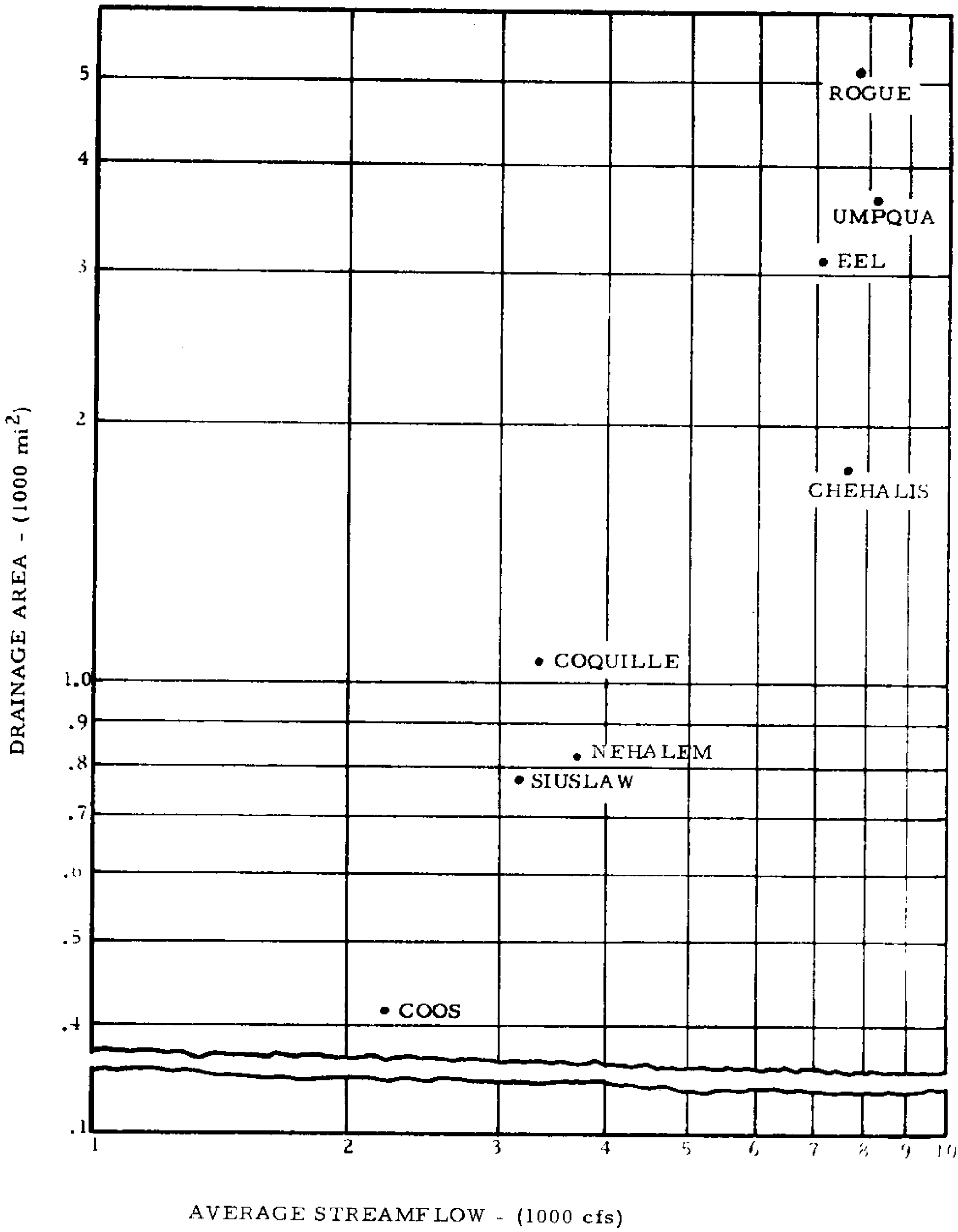

Figure 4-3. Average streamflow of Pacific Northwest coastal rivers versus river basin drainage area.

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Chapter 5. WINDS

General

The Washington, Oregon, and Northern California coasts are located approximately in the center of the zone of prevailing westerlies with local winds varying from northwest to southwest throughout most of the year.

The seasonal cycle of winds on the Pacific Northwest Coast is largely determined by the circulation about the North Pacific high pressure area and the Aleutian low pressure area. During summer the North Pacific high reaches its greatest development (approximately 1025 millibars) and is centered about 30-40° N and 150° W; the Aleutian low is weak during this period (Budinger et al., 1). The interaction of these pressure zones favors the development of summer winds generally from northwest to north over the nearshore and coastal areas of Oregon and Washington.

During winter the North Pacific high weakens and its center shifts about 10° southward while the Aleutian low intensifies (1). The resulting winds, frequently of gale force, approach the Washington-Oregon coast from the southwest.

Extra-tropical cyclones occur most frequently in winter and generally approach the coast from a westerly direction (National Marine Consultants, 2). Depending upon the location of the storm center as it impinges on the coast, the winds may be from northwest to southwest. These winds generate most of the large waves that reach the coast.

The barrier presented by the mountains of the Coast Range influence the general wind pattern, deflecting the winds so that they tend to align with the trend of the coast (Cooper, 3). In regions where the mountains are low the deflecting effect is minimal and normal oceanic wind conditions prevail.

Winds Measured from Shore Stations

Wind speed and direction have long been measured at various locations along the coast (prior to 1900 at some of the larger towns). However, very little of the data has been analyzed or published. For example, weather stations are found in most of the coastal towns, but data from only two locations are published: at Quillayute in northern Washington (U. S. Department of Commerce, 4) and at Astoria, Oregon (U. S. Department of Commerce, 5). For these two stations the resultant wind speed and direction (vector sum of all observations taken each month) and the mean scalar speed for each month have been published since 1967. Prior to 1967 the data listed were the prevailing wind direction, frequency, and the mean scalar speed.

At each of the U. S. Coast Guard Stations the climatalogical data are recorded every four hours. Only the immediate past year's and present year's logs are kept at the stations; the records for previous years are sent to the Coast Guard Archives, Washington, D.C. These records have not been machine punched nor analyzed and have not been used in this report.

In addition to the above two sources of wind data, the U. S. Army Corps of Engineers has completed wind analyses for several harbors and bays in the study area (6-11). Most of these reports are from data taken prior to 1930.

In March 1969 the Weather Facility at the Marine Science Center in Newport, Oregon, installed a recording anemometer on the end of the south jetty of Yaquina Bay. Data from this source should prove quite reliable since the location of the anemometer provides data relatively free of land effects.

Average wind conditions as measured at various coastal sites within the study area are presented in Tables 5-1 and 5-2. Wind roses for winter and summer conditions (January and July, respectively) for Oregon are shown in Figure 5-1.

Winds have been monitored at Quillayute weather station since July 1966. Prior to July 1966 all meteorological observations were made at the weather station on Tatoosh Island. The wind pattern for the northern Washington coast differs from that long the southern Washington, Oregon, and northern California coasts in that at Quillayute summer winds are from the west, whereas, for the latter areas summer winds are generally from the north or northwest.

For the three stations near the Columbia River - Lone Tree, North Head, and Astoria - summer winds are predominantly from the N-NW quadrant paralleling the coast; the highest velocity winds are also from this sector (Table 5-2). During winter the winds are predominantly offshore - from east or southeast. These winds are, however, of moderate speed. The higher velocity winds (16 mph or more, Table 5-2) arrive from the south or southwest, but do not occur as frequently as the moderate easterly winds. High velocity winds from the east also occur in this region during the winter as a result of the concentration of the wind stream in the Columbia River gorge (3). In general, wind speeds are greater in winter than summer with the exception of the high velocity summer winds from the north.

Winds measured at Newport and Coos Bay, Oregon, and at Eureka, California exhibit the similar pattern of north or northwest winds in summer and southeast winds in winter. The winds here tend to follow the general trend of the coastline. Spring and fall are transition seasons during which the wind swings from south to north and vice versa; the weather during these periods is usually clear.

Table 5-1. Monthly averages of wind direction and scalar speed (mph) at selected shore stations.

Station a. Source of Data b. Bibliographic Reference No.	Period of Record		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Quillayute, Washington a. Weather Bureau b. (4)	1966-1969	Average Direction	SE	SE	SSE	S	SW	WSW	W	W	SSW	S	SE	SE
		Avg. Scalar Speed	8.4	7.3	7.7	7.5	6.8	6.3	6.3	6.2	5.6	7.1	7.1	8.4
Moclips, Washington a. Weather Bureau b. (15)	1937-1947	Average Direction	E	E	E	E	NW	NW	NW	NW	NW	E	E	E
Hoquiam, Washington a. Weather Bureau b. (15)	1953-1958	Average Direction	ESE	ESE	ESE	W	W	W	W	W	ESE	ESE	ESE	ESE
		Avg. Scalar Speed	11.4	11.4	11.2	10.3	9.6	9.5	9.1	8.3	8.0	9.4	10.9	11.8
Lone Tree, Pt. Brown, Washington a. Weather Bureau b. (16) and (17)	12 years	Average Direction	SE	E	NW	NW	NW	NW	NW	NW	NW	NW	E	E
North Head, Cape Disappointment, Washington a. Weather Bureau b. (16) and (18)	44 years	Average Direction	E	SE	SE	NW	NW	NW	N	N	N	SE	SE	E
		Avg. Scalar Speed	15.9	14.6	14.1	13.8	13.2	12.8	12.0	11.2	11.7	12.8	15.5	16.2
Astoria, Oregon a. Weather Bureau b. (19)	11 years	Average Direction	E	ESE	SE	WNW	NW	NW	NW	NW	SE	SE	SE	ESE
		Avg. Scalar Speed	8.9	8.7	8.7	8.5	8.2	8.2	8.5	7.7	7.2	7.6	8.5	8.8
Tillamook, Oregon a. Weather Bureau b. (15)	1943-1945	Average Direction	S	SSW	NW	SSW	NW	NW	NW	NW	NW	S	S	S
Newport, Oregon a. Weather Bureau b. (15)	1935-1942	Average Direction	E	E	E	E	NNW	NNW	NNW	NNW	NNW	S	E	E
Cape Arago Light Station, Oregon a. U.S. Army Corps of Engrs. b. (7) and (17)	1915-1925	Average Direction	SE	SW	SW	NW	NW	NW	NW	NW	NW	NW	SE	SE
North Bend, Oregon a. Weather Bureau b. (15)	1950-1959	Average Direction	SE	SE	SE	NNW	NNW	NNW	NNW	NNW	NNW	SE	SE	SE
		Avg. Scalar Speed	9.4	8.4	9.0	9.2	10.0	9.7	11.7	9.8	7.7	6.8	7.2	8.3
Brookings, Oregon a. Weather Bureau b. (15)	1937-1942	Average Direction	NE	NE	NE	NW	NW	NW	S	S	NW	N	NE	NE
Eureka, California a. Weather Bureau b. (20)	-----	Average Direction	SE	SE	N	N	N	N	NW	NW	N	N	SE	SE
		Avg. Scalar Speed	7.0	7.2	7.6	8.0	7.9	7.4	6.8	5.7	5.5	5.6	5.9	6.4

Table 5-2. Frequency and velocity of winds at three stations on the Washington-Oregon coast

July and January

	North Head, Washington Lat. 46°18'			Newport, Oregon Lat. 44°38' 1934-1942			North Bend, Oregon 43°25' 1937-1942		
	Frequency		Av. velocity	Frequency		Av. velocity	Frequency		Av. velocity
	4 m.p.h. and over	16 m.p.h. and over	m.p.h.	4 m.p.h. and over	16 m.p.h. and over	m.p.h.	4 m.p.h. and over	16 m.p.h. and over	m.p.h.
July	1930-1942								
N.	781	410	15.4	389	135	11.9	351	130	12.6
N.-N.E.	15	3	8.4	6	...	4.9	36	2	7.8
N.E.	11	...	5.6	2	...	2.5	37	...	5.2
E.-N.E.	...	...	....	2	...	3.0	2	...	3.3
E.	10	...	5.5	34	...	3.0	6	...	3.1
E.-S.E.	1	...	10.0	11	...	3.8	2	...	3.5
S.E.	44	7	9.2	35	1	3.6	52	...	4.5
S. S.E.	36	10	13.6	9	...	5.4	20	...	5.3
S.	269	114	14.7	60	5	6.4	24	...	4.3
S.-S.W.	39	14	13.4	48	1	7.9	19	...	7.1
S.W.	129	11	10.1	117	...	6.2	39	...	5.7
W.-S.W.	24	1	7.8	34	...	6.7	19	...	7.5
W.	127	9	8.1	55	...	4.7	16	...	4.8
W. N.W.	20	2	9.0	27	...	5.6	12	1	7.6
N.W.	437	155	13.1	160	15	7.9	330	70	10.1
N.-N.W.	323	171	15.9	212	60	12.6	172	45	11.3
January	1931-1942								
N.	84	22	11.8	33	3	7.3	28	...	5.4
N.-N.E.	6	...	7.6	6	...	6.4	4	...	6.2
N.E.	61	2	6.0	17	...	5.7	52	1	6.1
E.-N.E.	6	3	9.1	97	...	7.2	5	...	6.0
E.	501	194	13.0	415	6	7.3	19	...	4.8
E.-S.E.	183	110	16.6	160	2	8.5	12	...	4.4
S.E.	383	152	14.3	235	2	6.7	614	5	7.2
S.-S.E.	36	23	19.2	25	4	10.5	149	2	7.3
S.	313	263	27.8	122	59	14.1	114	15	8.9
S.-S.W.	23	23	27.7	46	23	16.1	28	5	12.1
S.W.	125	87	19.9	75	20	11.2	93	23	11.2
W.-S.W.	6	4	15.1	28	10	13.1	7	1	9.9
W.	127	69	16.0	76	7	8.7	12	1	7.2
W.-N.W.	8	5	16.3	17	1	8.1	3	...	5.8
N.W.	118	68	16.8	32	5	9.5	66	9	8.9
N.-N.W.	13	9	18.8	6	...	9.7	11	...	5.3

(from Cooper, 3)

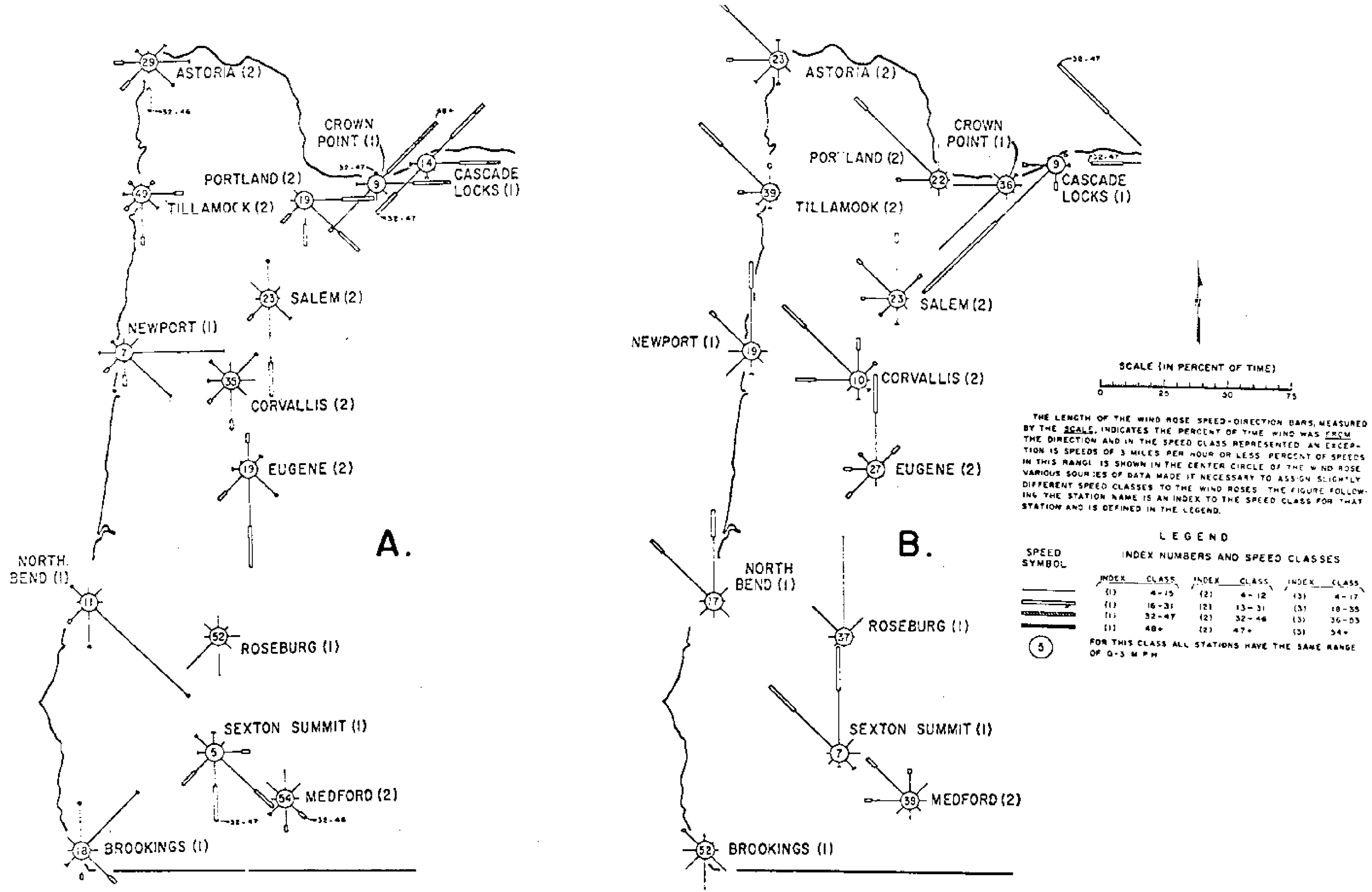

Figure 5-1. Wind roses for winter and summer conditions for western Oregon.
a. Wind roses for January.
b. Wind roses for July.
(from U. S. Dept. of Commerce-Weather Bureau, 21)

Offshore Wind Observations

Winds measured at shore stations, e.g., Weather Bureau and Coast Guard Stations, are generally not representative of wind conditions found one-half to five miles offshore due to the varying topography along the coast. Unfortunately, observations made one to five miles offshore are very few and widely scattered.

Wind speed and direction measured aboard merchant, naval, and research vessels in transit are deposited in the National Oceanographic Data Center (NODC). Analysis of these data to obtain average monthly wind conditions showed that the few observations taken within the study area were too widely distributed in space and time to be of any statistical value.

The geostrophic wind can be computed from twice-daily atmospheric pressure charts prepared by the U. S. Weather Bureau. Corrections can be applied to the geostrophic wind to obtain the approximate surface wind condition for a height of 10 meters above the sea surface. An analysis of offshore wind conditions using this method is described in a technical report of the Department of Oceanography of the University of Washington (Duxbury, et al., 12).

Perhaps the most reliable and representative of actual surface wind conditions recorded are those measured from lightships stationed about five miles offshore. These data are stored at the National Weather Records Center in Asheville, N.C. If specifically requested, the data are machine punched and put on magnetic tape for future analysis.

On a broader scale, the Climatological and Oceanographic Atlas for Mariners, Volume II, North Pacific Ocean (U. S. Dept. of Commerce, 13) shows monthly wind roses for a point located at 41° 00'N, 126° 00'W. Only general seasonal trends can be elicited from this Atlas.

In the future, valuable wind information will be provided by telemetry from buoys such as Oregon State University's Totem. These buoys should provide long and continuous records allowing statistical analysis of short-term fluctuations as well as long-term averages.

Since the early 1950's wind observations have been recorded every six hours from the three lightships located in the project area. These are the Blunts Reef Lightship off Cape Mendocino in northern California, the Columbia River Lightship, and the Umatilla Lightship off Cape Alava in northern Washington (Figure 5-2). The data analysis to obtain average monthly wind conditions were performed for this project by the National Weather Records Center. Table 5-3 lists by month the average resultant wind direction and speed, the average scalar speed and the number of observations during the period of record for each lightship. Appendix 1 of

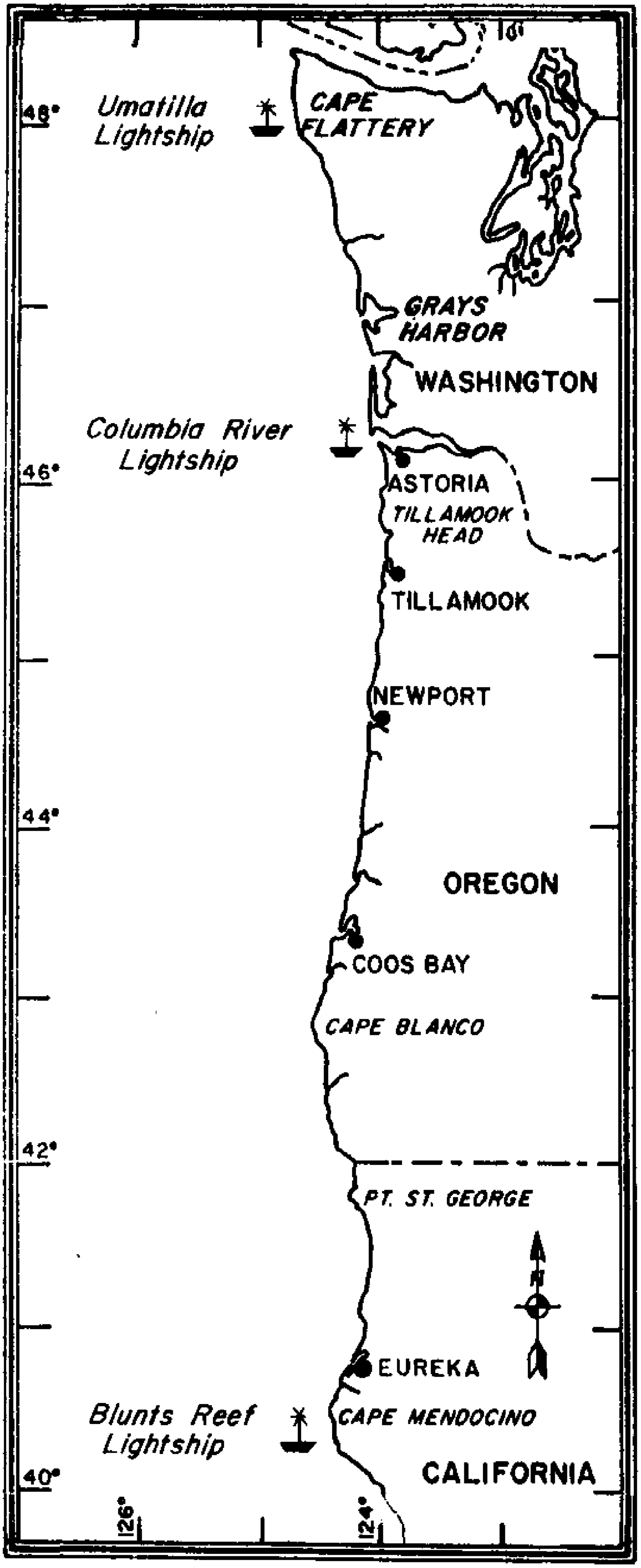

Figure 5-2. Location of lightships off the Pacific Northwest coast.

Table 5-3. Resultant wind speed (knots) and direction by month measured from lightships off the Pacific Northwest coast.

Blunts Reef Lightship 1954-1966 (13 yrs)					
	Resultant Direction		Resultant Speed	Scalar Speed	Number Observations
Jan	131	SE	4	18	1609
Feb	091	E	2	19	1465
Mar	023	NNE	2	18	1591
Apr	357	N	8	18	1523
May	355	N	10	18	1481
June	351	N	12	15	1554
July	356	N	14	16	1491
Aug	359	N	13	16	1548
Sept	002	N	9	14	1536
Oct	015	NNE	5	13	1470
Nov	113	ESE	3	16	1554
Dec	134	SE	4	17	1594

Columbia River Lightship 1953-1966 (14 yrs)					
	Resultant Direction		Resultant Speed	Scalar Speed	Number Observations
Jan	155	SSE	9	18	1715
Feb	174	S	6	16	1560
Mar	192	SSW	5	15	1727
Apr	233	SW	4	13	1546
May	279	W	4	12	1627
June	291	WNW	4	10	1680
July	317	NW	6	10	1613
Aug	305	NW	4	10	1732
Sept	298	WNW	1	11	1588
Oct	159	SSE	4	14	1512
Nov	157	SSE	6	17	1507
Dec	163	SSE	8	17	1608

Umatilla Lightship 1961-1965 (5 yrs)					
	Resultant Direction		Resultant Speed	Scalar Speed	Number Observations
Jan	182	S	7	18	557
Feb	167	SSE	4	16	675
Mar	210	SW	3	14	693
Apr	208	SW	5	15	713
May	265	W	5	13	745
June	266	W	5	12	719
July	238	WSW	4	10	860
Aug	206	SW	2	7	925
Sept	179	S	2	8	900
Oct	167	SSE	8	13	923
Nov	161	SSE	9	16	898
Dec	168	SSE	9	17	930

the data report of Renfro, et al. (14) contains a listing of the above information for each year within the period of record.

Offshore winds in the northern section of the area (Umatilla Lightship data) shift from SSE in fall and winter to W in early summer and then reverse the cycle. This same pattern is observed in the central and southern sections except that during summer the winds continue their clockwise swing and arrive from the NW and N, respectively. This annual wind shift is also verified by Figure 5-3 which was derived from geostrophic calculations. These winds, measured five miles off the coast, show that even at this distance offshore the influence of the continental topography is still marked.

Corrected Geostrophic Winds

Duxbury, Morse, and McGary (12) have computed the resultant surface wind from atmospheric pressure charts for eight grid points shown in Figure 5-3. The geostrophic wind velocity aloft was determined and then corrected by rotating the wind vector 15° to the left of its downwind direction and reducing the speed by 30% to obtain a surface wind applicable to a standard height of 10 meters above the sea surface. These winds were then averaged by month for the period 1961-1963 for three offshore grid areas (Figure 5-3). Seasonal trends and latitudinal variations are readily apparent. Winter winds are predominantly from the southwest, while summer winds are northwest in the northern areas and from the north in the southern part. The wind direction changes quite smoothly over a 180° arc between summer and winter and back to summer. Resultant wind speeds during the autumn and spring transition periods are relatively low due to the wide variability in wind direction during these seasons.

Wind roses for each month, centered at the midpoint of the grid from which the wind values were determined, are shown in Figures 5-4 to 5-15. The percentage of each month the wind came from the direction indicated is represented by the length of the bar. The concentric circles indicate both five-knot speed increments and monthly frequency of occurrence in five percent intervals. The small numbers indicate the frequency of occurrence within each five-knot increment; the sum over any particular direction indicates the frequency with which the wind came from the direction shown. The bar graph associated with each rose shows the monthly frequency of wind speed in five-knot increments without regard to direction. The increase in wind strength during winter followed by the decrease in strength in summer is readily observed for the northern and central areas. Winds in the southern area remain relatively strong in both summer and winter. The close agreement of the "corrected geostrophic winds" with those winds observed at the lightships substantiates earlier reports that geostrophic winds may be used in areas where actual wind observations are meager.

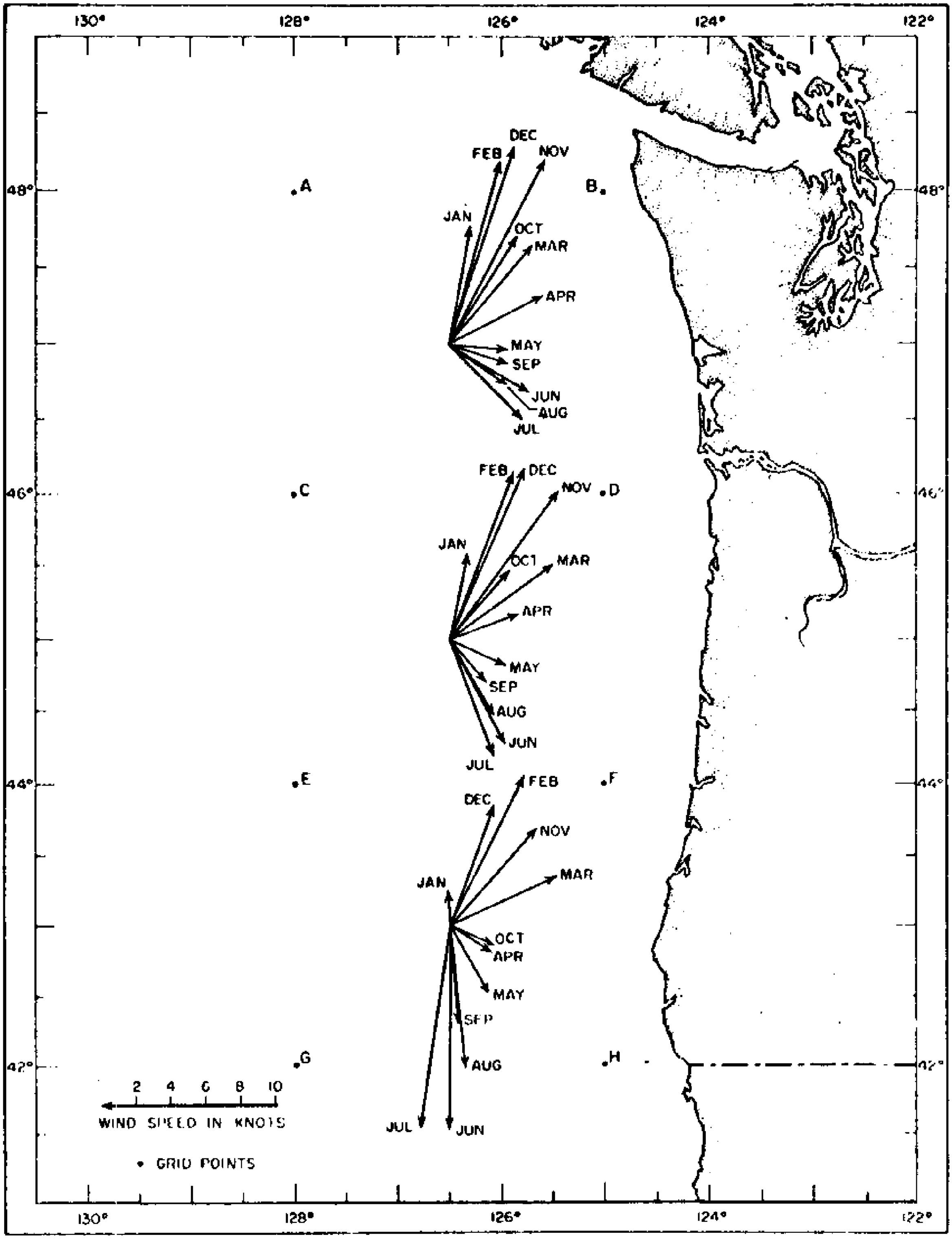

Figure 5-3. Average direction and velocity of monthly winds for 1961-1963. (from Duxbury, et al., 12)

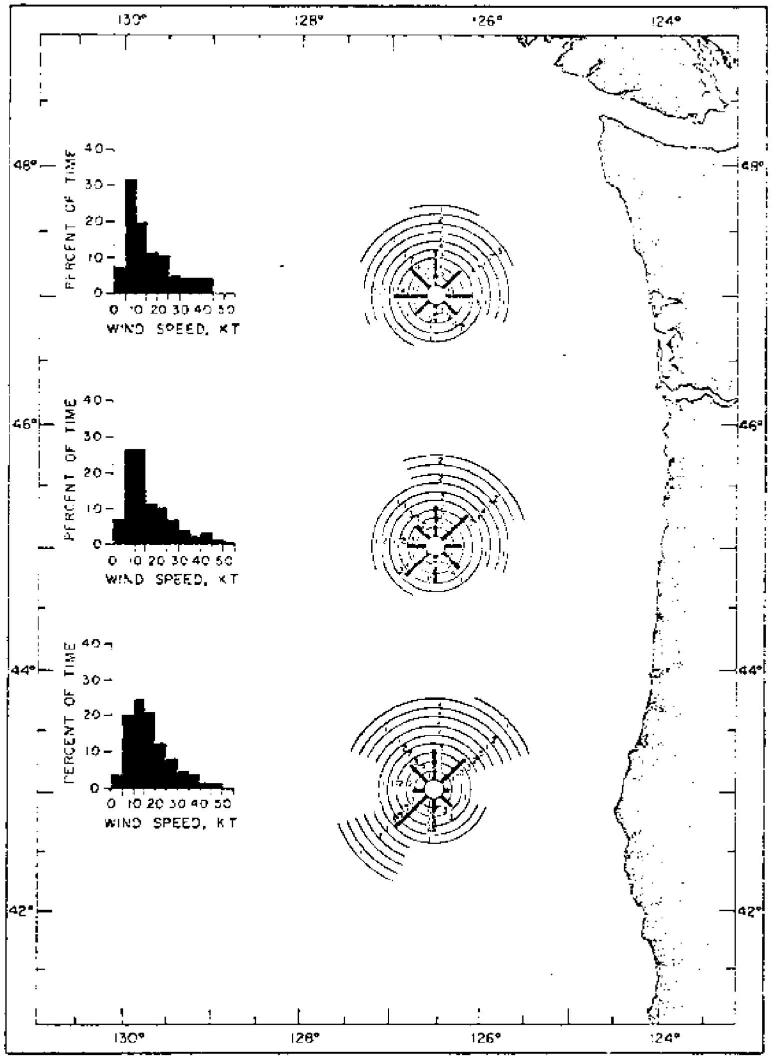

Fig. 5-4. Average direction and velocity of January winds for 1961-1963.

(from Duxbury, et al., 12)

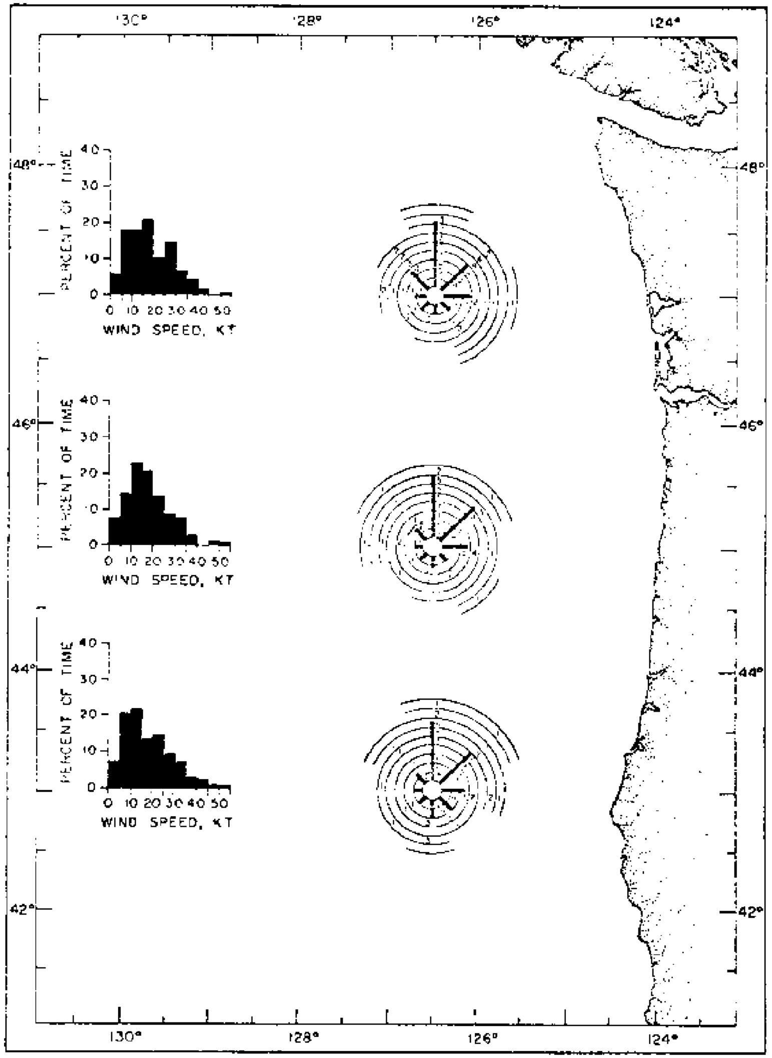

Fig. 5-5. Average direction and velocity of February winds for 1961-1963.

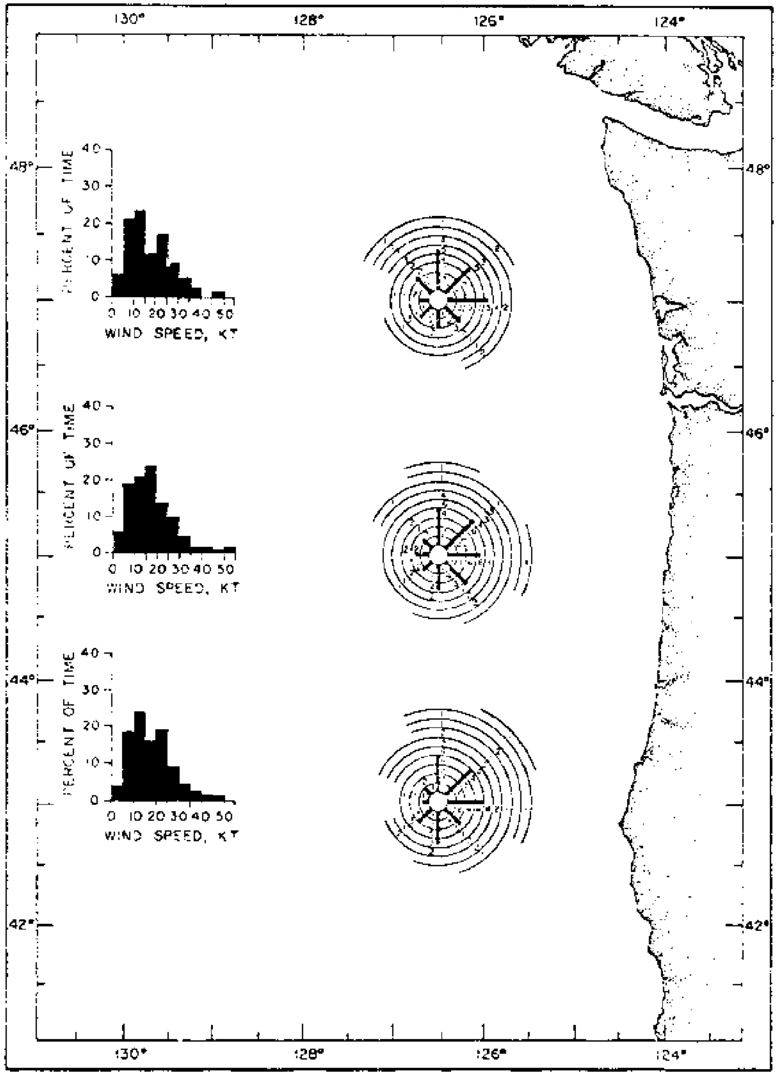

Fig. 5-6. Average direction and velocity of March winds for 1961-1963.

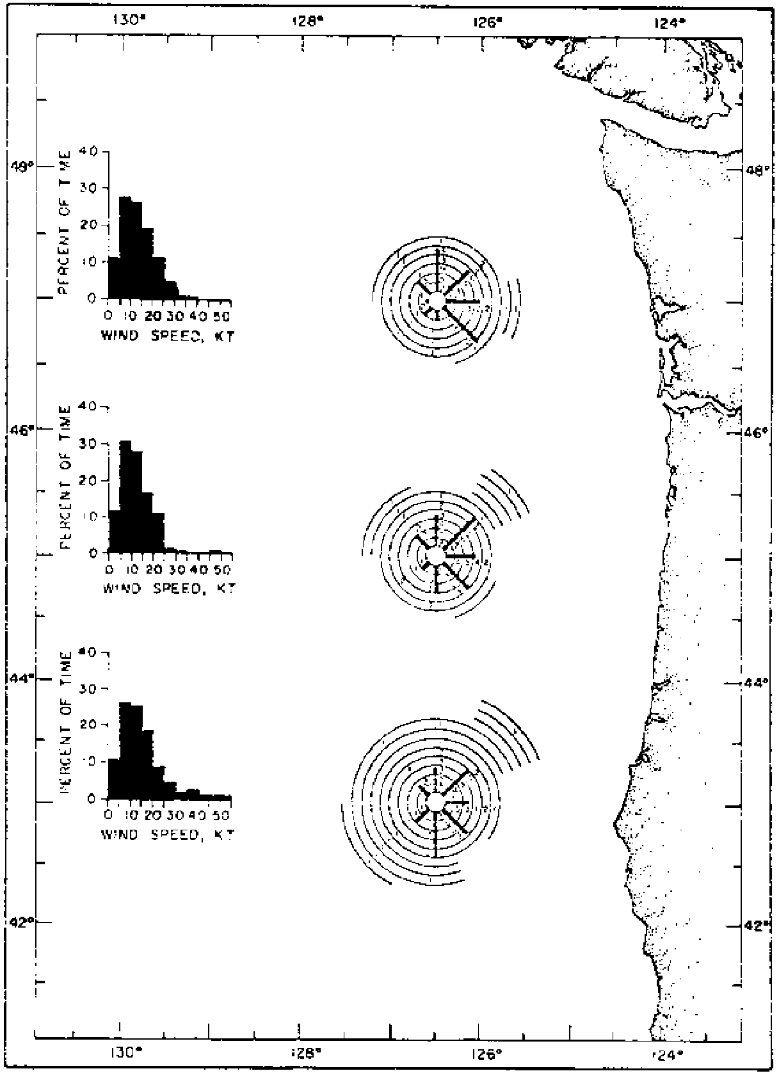

Fig. 5-7. Average direction and velocity of April winds for 1961-1963.

(from Duxbury, et al., 12)

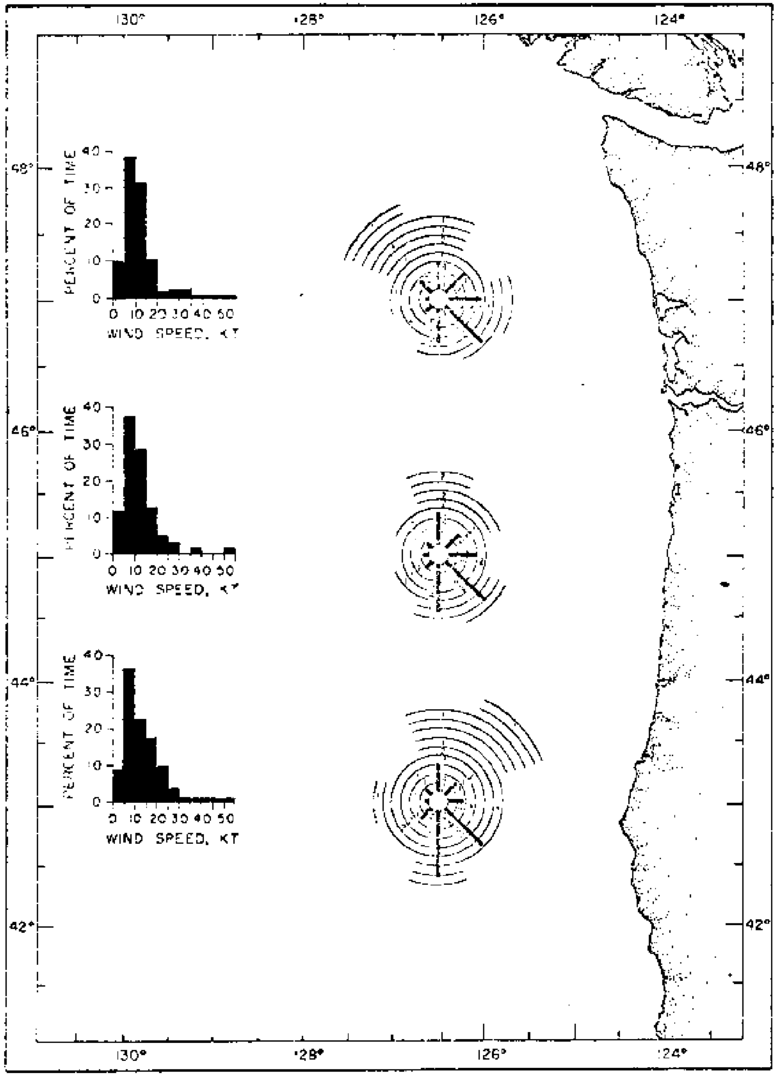

Fig. 5-8. Average direction and velocity of May winds for 1961-1963.

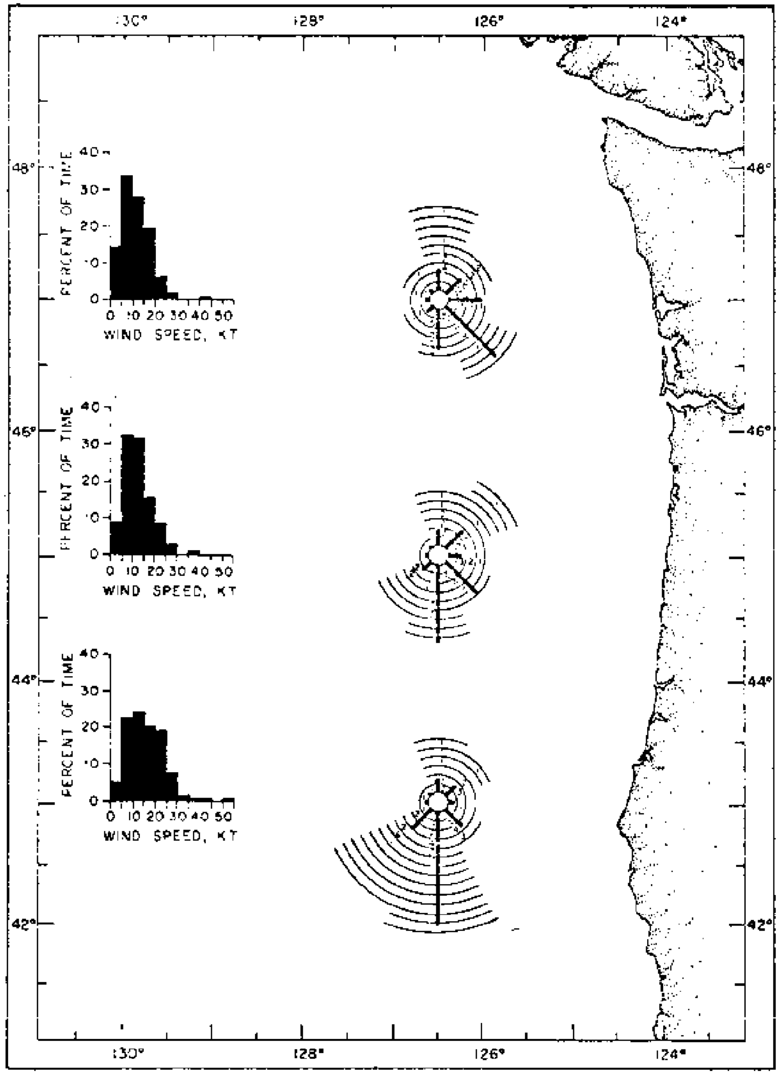

Fig. 5-9. Average direction and velocity of June winds for 1961-1963.

(from Duxbury, et al., 12)

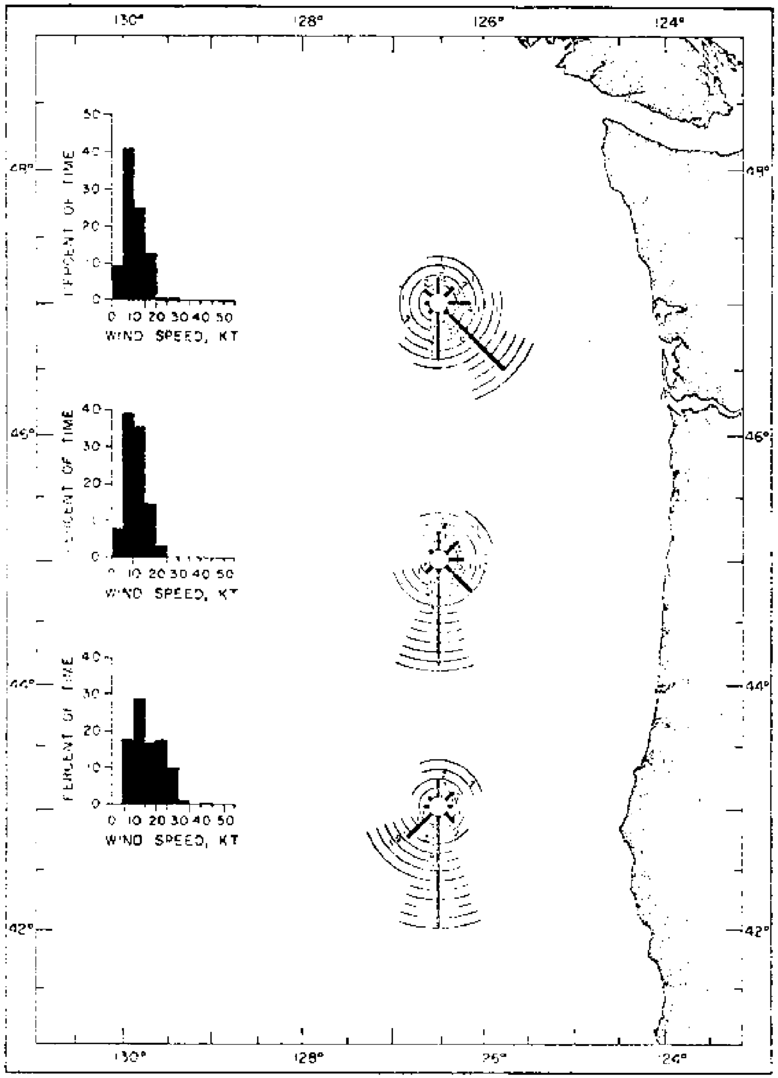

Fig. 5-10. Average direction and velocity of July winds for 1961-1963.

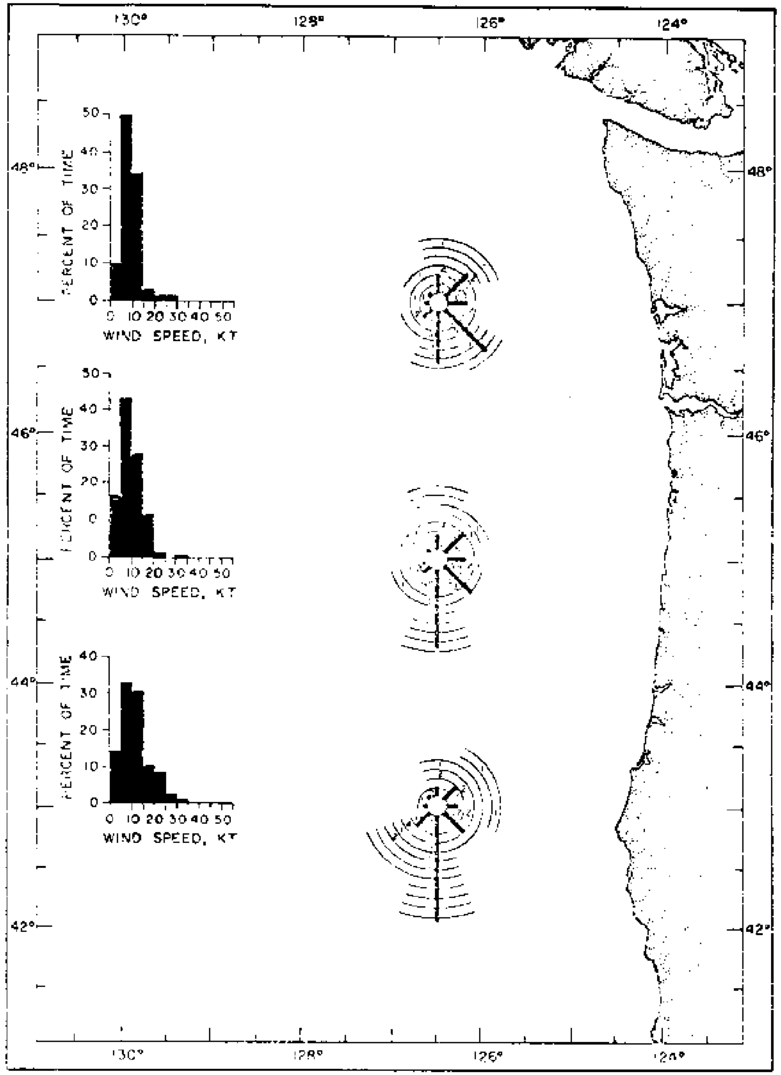

Fig. 5-11. Average direction and velocity of August winds for 1961-1963.

(from Duxbury, et al., 12)

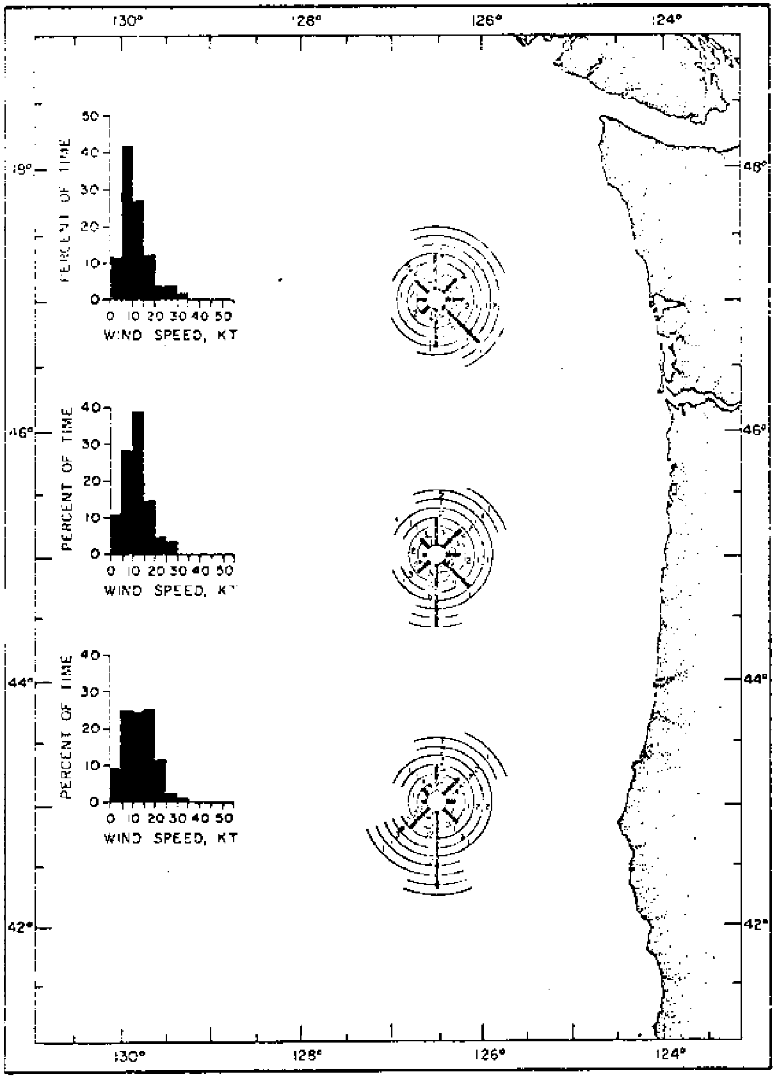

Fig. 5-12. Average direction and velocity of September winds for 1961-1963.

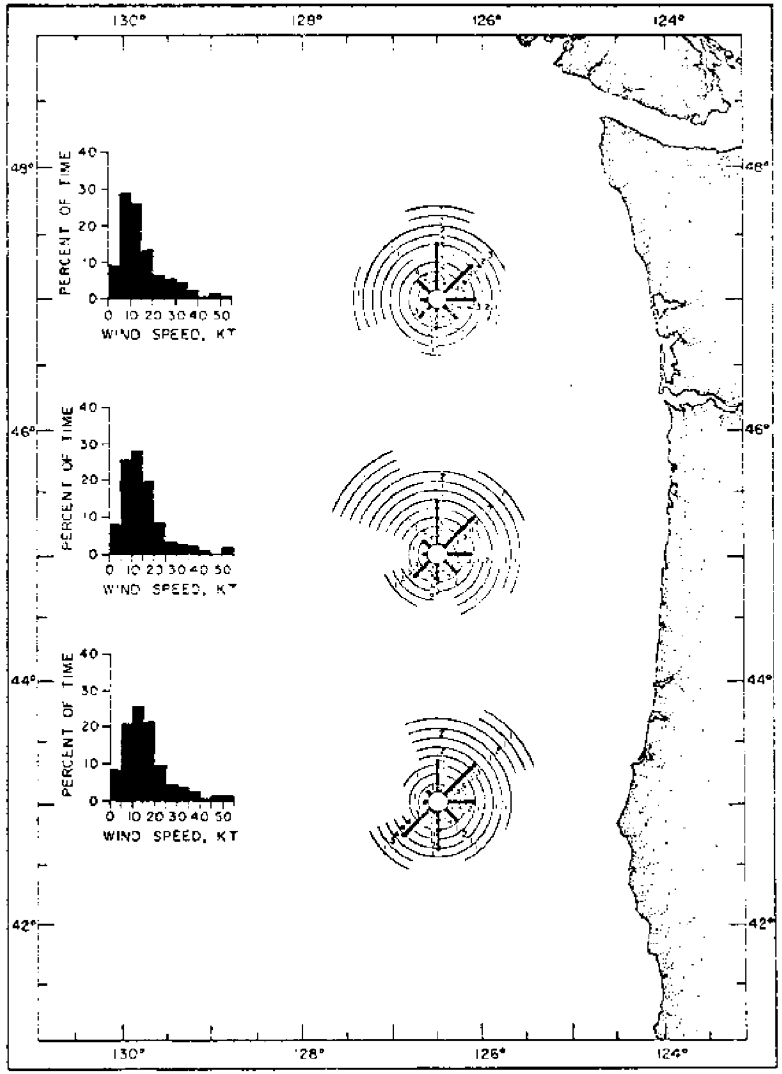

Fig. 5-13. Average direction and velocity of October winds for 1961-1963.

(from Duxbury, et al., 12)

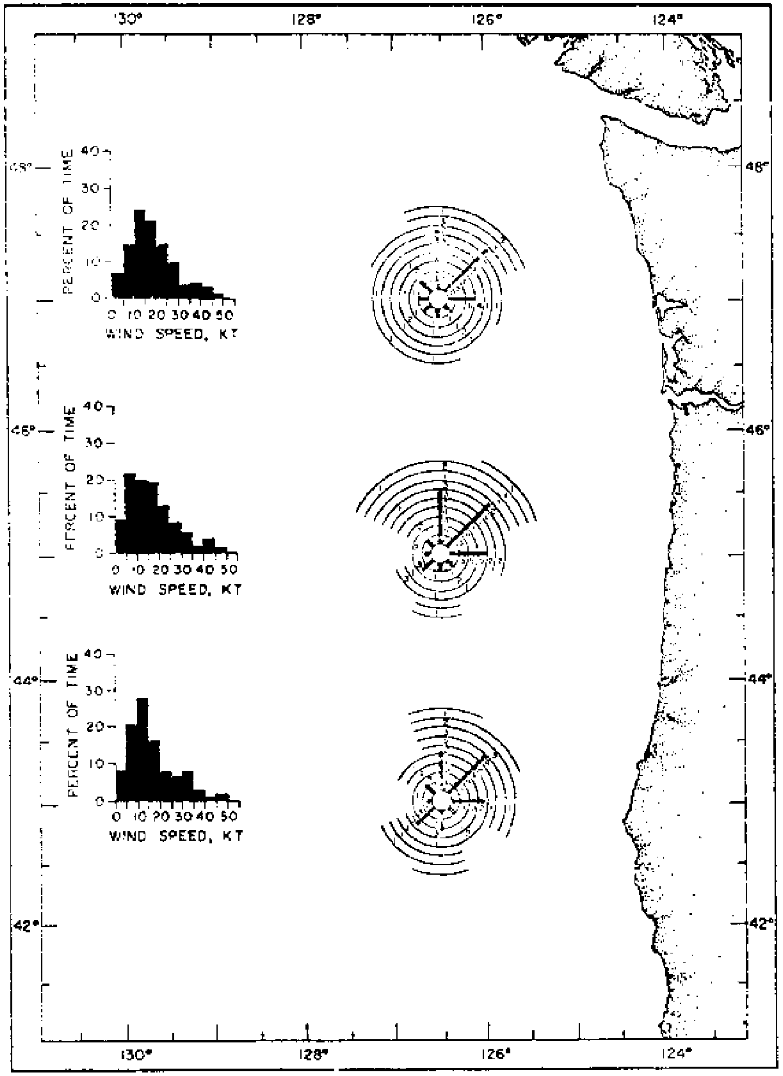

Fig. 5-14. Average direction and velocity of November winds for 1961-1963.

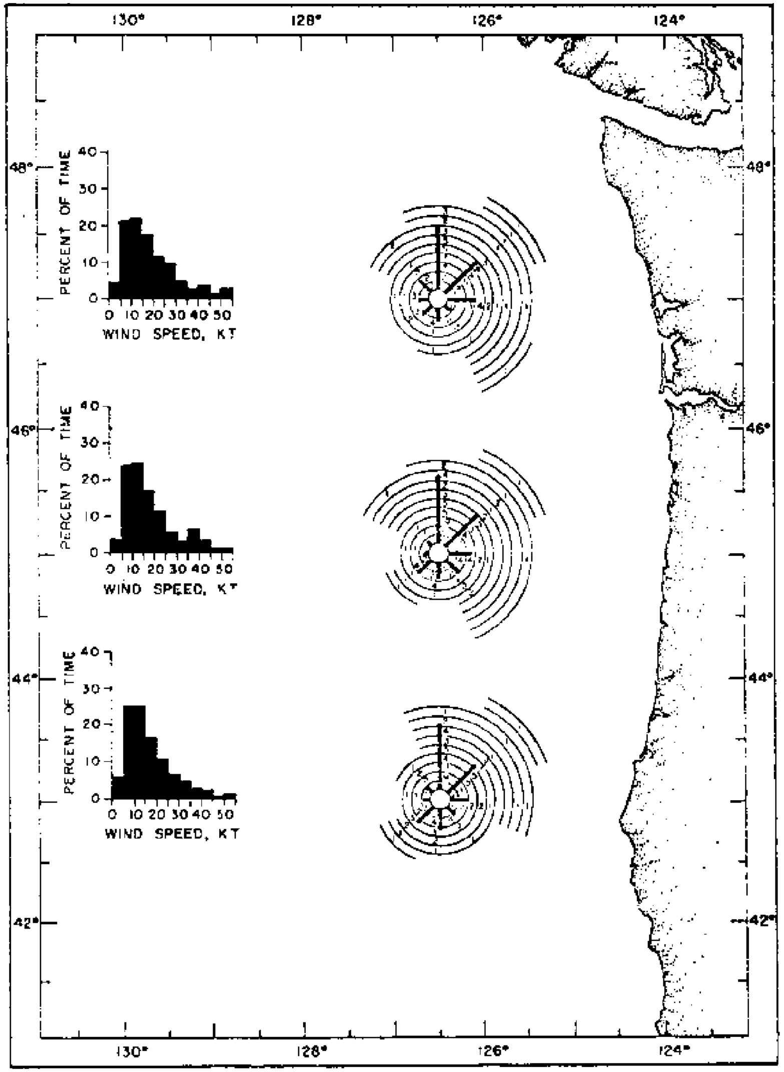

Fig. 5-15. Average direction and velocity of December winds for 1961-1963.

(from Duxbury, et al., 12)

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Chapter 6. TEMPERATURE AND SALINITY

Shore Station and Lightship Observations

Observations of surface temperature and salinity have been made at selected shore stations and from three lightships along the Pacific Northwest Coast. Daily observations have been reported from the Blunts Reef Lightship off Cape Mendocino since 1923 and from Crescent City, California since 1934 (U.S. Dept. of Commerce, 1). The Department of Oceanography at Oregon State University began reporting weekly observations from shore stations along the Oregon Coast in 1961 (OSU, Dept. of Ocean., 2). Since 1964 all observations from reporting stations have been made daily (OSU, Dept. of Ocean., 3). Data from the Umatilla Lightship are listed in a similar publication of the Scripps Institute of Oceanography (4). The location of each reporting station is shown in Figure 6-1 and Table 6-1.

Additional temperature and salinity samples have been collected from other sites along the Pacific Northwest Coast. Some of these data have been published (Burt, et al., 5; Gonor, 6; Neal, et al., 7; Pearson and Holt, 8; Skeesick, 9) and some exist as unpublished laboratory reports (Frolander, 10; Snow, 11). The majority of these observations were taken during a single season or month in conjunction with research concerning the ecology of organisms living in the surf zone. These records were not considered sufficiently long to establish annual trends and were not included in the analyses to follow.

Tables 6-2 and 6-3 list by month the average mean, average maximum, and average minimum surface temperature and salinity and the total number of observations for each reporting station computed over the period of record. Salinities were determined from hydrometer readings; the few stations reporting salinities in excess of 34.5‰ are probably in error (3).

Figures 6-2 through 6-5 are graphs of the monthly mean temperatures for the three lightship stations and for several stations along the Oregon - California coastline. At all locations there is a 4 to

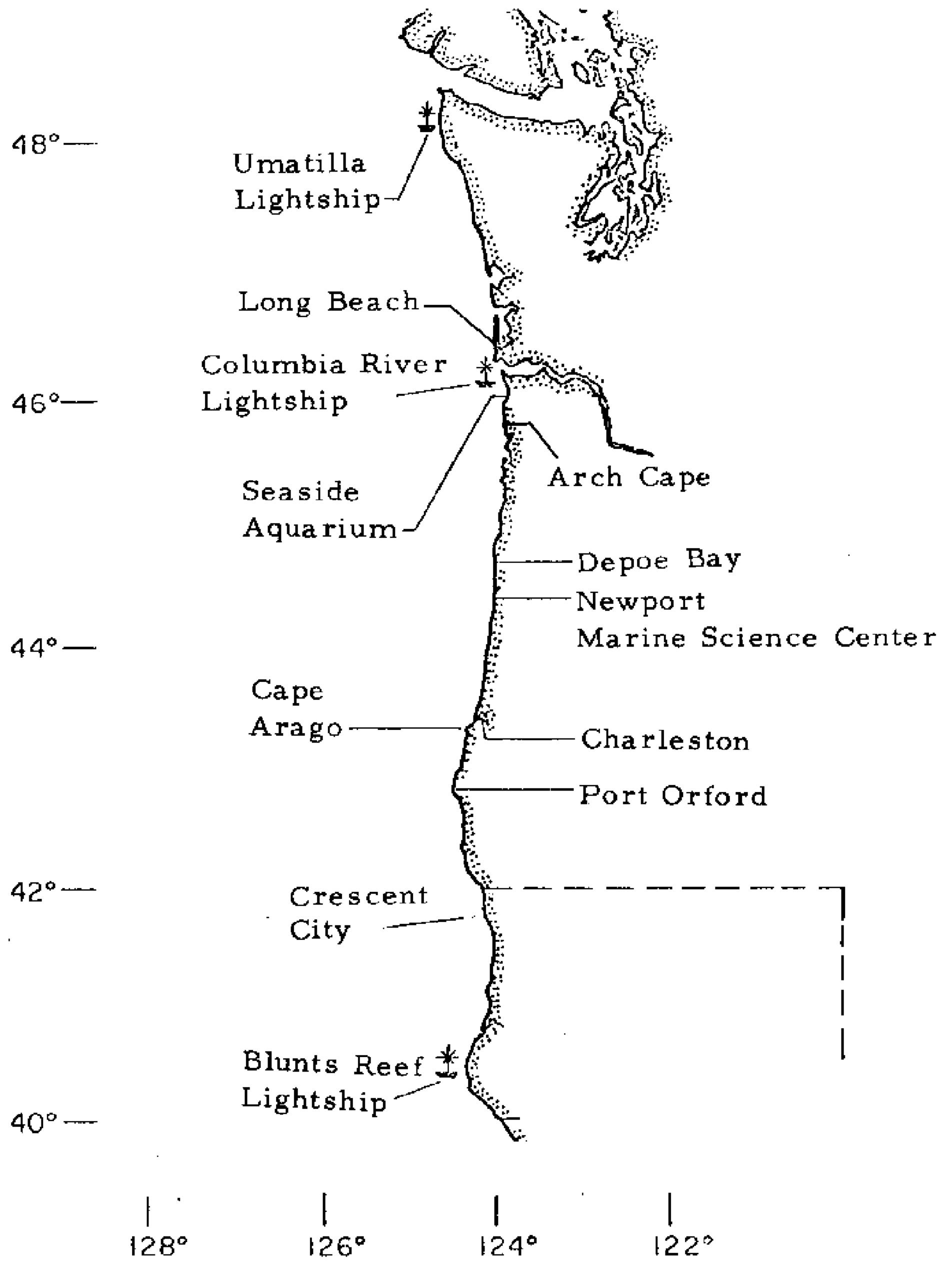

Figure 6-1. Location of shore stations and lightships along the Pacific Northwest coast.

Table 6-1. List of shore stations and lightships in geographical order.

Station Name	Position	Location
Washington		
Umatilla Lightship	48°10.0'N, 124°50.0'W	Off Cape Alava
Long Beach	46°23.0'N, 124°04.0'W	In surf on sand beach, 10th Street approach
Oregon		
Columbia River Lightship	46°11.2'N, 124°11.0'W	Mouth of Columbia River
Seaside Aquarium	45°59.7'N, 123°55.6'W	At pump outlet into Aquarium settling tank from surf inlet pipe
Arch Cape	45°48.0'N, 123°58.0'W	In surf on a sand beach
Depoe Bay Aquarium	44°49.4'N, 124°04.0'W	At pump outlet into Aquarium settling tank from surf inlet pipe
Newport Marine Science Center	44°37.2'N, 124°01.5'W	At pump outlet into Laboratory from bottom of Yaquina Bay
Charleston	43°21.0'N, 124°19.0'W	From surface of bay
Cape Arago Light Station	43°20.3'N, 124°22.5'W	Off the rocks below the Light Station
Port Orford	42°44.6'N, 124°30.6'W	Off east side of Port Orford River
California		
Crescent City	41°44.6'N, 124°11.7'W	USCGS Tide Guage Station, Crescent City
Blunts Reef Lightship	40°26.0'N, 124°30.0'W	Off Cape Mendocino

Table 6-2. Average monthly temperature (°C) and salinity (‰) of the surf measured at selected sites on the Pacific Northwest coast. Salinities enclosed by ( ) indicate average computed from fewer observations than listed in total.

Station and Period of Record		Monthly Avgs. & Total No. Obs.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Long Beach, Washington 1962-1963	T	Avg. Mean	-----	-----	-----	8.10	10.58	11.55	14.86	15.06	13.47	12.96	11.10	9.00
		Avg. Maximum				8.40	12.50	14.30	15.81	17.07	14.38	15.10	11.90	9.60
		Avg. Minimum				7.80	7.50	9.40	13.61	13.71	12.43	11.90	10.10	8.40
		Total No. Obs.				2	5	4	12	15	4	5	4	2
	S	Avg. Mean	-----	-----	-----	26.02	21.98	30.62	25.65	29.20	28.54	28.93	27.36	27.36
		Avg. Maximum				26.46	25.07	31.88	27.36	33.08	30.00	30.62	30.14	29.14
		Avg. Minimum				25.58	18.40	29.23	24.46	24.71	27.15	27.25	24.38	25.58
		Total No. Obs.				2	5	3	6	6	4	5	4	2
Seaside Aquarium 1966-1969	T	Avg. Mean	9.44	9.27	9.78	11.05	12.32	15.04	15.08	14.63	15.26	13.73	12.49	10.82
		Avg. Maximum	10.65	9.95	10.55	12.03	14.33	16.97	17.68	16.61	16.12	15.30	13.77	12.07
		Avg. Minimum	8.42	8.73	8.89	9.97	10.59	12.97	12.14	12.17	14.22	12.25	11.16	9.58
		Total No. Obs.	72	54	79	66	64	78	79	72	45	46	50	44
	S	Avg. Mean	28.14	28.23	28.39	28.52	29.11	26.83	28.98	31.19	30.41	29.79	30.15	28.95
		Avg. Maximum	29.81	30.34	30.36	30.41	31.69	30.92	32.70	32.48	31.64	30.85	30.52	29.79
		Avg. Minimum	26.09	25.65	24.48	24.67	24.83	21.65	23.22	29.48	27.56	27.95	28.25	27.75
		Total No. Obs.	69	55	77	66	64	78	79	72	45	46	50	44
Arch Cape 1960-1963	T	Avg. Mean	9.35	9.85	9.33	10.55	12.29	12.80	14.18	12.76	12.15	11.84	10.57	9.43
		Avg. Maximum	10.20	10.27	10.70	11.99	13.61	15.20	17.56	15.88	14.78	12.74	12.03	10.10
		Avg. Minimum	8.11	9.07	8.21	9.37	10.62	10.19	9.85	9.77	9.65	9.15	8.82	8.73
(1961 dominates salinity data)		Total No. Obs.	44	37	51	41	41	42	67	72	83	41	37	66
	S	Avg. Mean	30.68	30.51	30.22	29.12	28.70	31.30	31.52	32.76	32.46	32.31	31.53	30.13
		Avg. Maximum	31.45	31.64	31.70	32.43	31.46	33.62	33.45	33.89	33.41	33.35	32.96	31.57
		Avg. Minimum	28.87	30.00	27.55	26.65	26.52	27.75	28.77	30.99	31.44	30.93	29.75	26.98
		Total No. Obs.	8	7	25	38	44	32	40	40	42	36	29	41

Table 6-2. continued

Station			Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Depoe Bay Aquarium	T	Avg. Mean	9.23	9.28	9.33	10.35	10.66	13.10	12.06	15.81	14.48	12.83	11.28	9.96
1965-1969	T	Avg. Maximum	9.94	9.84	10.05	11.31	11.84	15.14	13.43	16.84	15.90	13.70	12.26	10.89
	T	Avg. Minimum	8.48	8.65	8.28	9.50	9.67	11.47	11.00	14.25	13.05	11.61	10.06	8.87
(July and August	T	Total No. Obs.	82	69	74	80	60	49	23	44	55	48	58	85
salinity averages	S	Avg. Mean	30.90	31.33	31.04	31.40	32.31	32.08	31.97	30.33	32.32	32.82	32.38	31.51
based on one year	S	Avg. Maximum	31.93	32.11	32.31	32.57	33.10	33.82	33.00	30.99	33.00	33.83	33.19	33.00
only)	S	Avg. Minimum	29.53	30.42	29.67	31.05	31.33	30.41	30.10	28.28	31.00	31.91	31.70	30.16
	S	Total No. Obs.	82	69	74	59	40	48	3	23	32	40	58	85
Newport Marine Science Center	T	Avg. Mean	9.33	9.44	9.75	10.27	12.38	13.39	12.60	12.30	13.38	11.53	11.96	10.94
1965-1969	T	Avg. Maximum	10.27	10.74	10.32	11.21	13.61	13.82	15.46	14.92	15.30	13.54	13.75	11.97
	T	Avg. Minimum	8.55	8.63	8.96	9.42	9.68	12.30	9.57	9.90	10.63	10.76	10.85	9.63
	T	Total No. Obs.	74	64	65	64	78	78	54	66	43	43	68	70
	S	Avg. Mean	29.40	30.06	30.00	31.28	31.98	31.87	32.59	33.31	32.83	32.59	31.27	29.54
	S	Avg. Maximum	31.69	31.78	31.93	32.89	33.59	33.16	33.73	33.74	33.41	33.15	32.48	31.41
	S	Avg. Minimum	25.83	24.94	26.75	29.39	29.49	28.61	29.86	32.51	31.97	31.73	29.75	26.07
	S	Total No. Obs.	85	75	64	77	81	79	58	77	63	65	70	70
Charleston	T	Avg. Mean	9.37	9.89	10.64	11.17	11.60	13.05	12.92	12.43	13.66	12.41	11.20	10.26
1966-1969	T	Avg. Maximum	10.80	11.28	12.04	12.38	13.81	15.71	15.33	13.96	15.70	14.62	12.68	11.50
	T	Avg. Minimum	7.70	8.81	9.51	9.71	9.98	11.57	10.54	10.45	11.35	10.74	9.47	9.06
	T	Total No. Obs.	64	35	42	46	55	65	76	44	45	64	41	63
	S	Avg. Mean	30.07	29.28	30.20	30.65	31.60	32.19	32.57	32.83	32.58	31.58	30.56	29.91
	S	Avg. Maximum	31.88	31.56	31.44	31.79	(33.16)	(33.48)	(33.42)	33.42	33.51	32.90	32.75	32.07
	S	Avg. Minimum	25.32	27.26	27.58	27.55	28.78	30.26	31.21	31.93	30.93	30.27	27.54	27.05
	S	Total No. Obs.	64	34	42	46	54	65	71	33	47	57	41	63
Cape Arago Light Station	T	Avg. Mean	9.52	9.55	9.81	10.45	11.37	12.47	12.74	13.29	13.00	12.75	12.34	10.96
1963-1966	T	Avg. Maximum	10.54	10.20	11.93	11.98	12.95	14.47	15.04	16.08	15.13	14.02	13.44	12.72
	T	Avg. Minimum	7.61	8.90	8.24	9.55	9.95	11.05	10.30	10.81	10.49	11.32	11.20	9.00
	T	Total No. Obs.	41	25	68	84	91	85	88	88	64	84	67	52
	S	Avg. Mean	30.86	32.48	32.17	32.05	31.72	32.90	33.32	33.53	33.35	32.84	32.53	31.78
	S	Avg. Maximum	32.61	33.58	(33.20)	(32.87)	(32.82)	(33.70)	>34.00	>34.00	>34.00	(33.55)	(32.96)	32.98
	S	Avg. Minimum	27.74	31.36	30.69	29.96	28.72	31.73	32.10	32.36	32.43	32.14	31.35	29.59
	S	Total No. Obs.	39	25	67	84	73	85	88	88	64	84	67	52

Table 6-2 continued

Station			Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Port Orford 1964-1969	T	Avg. Mean	9.76	10.24	9.85	9.88	9.89	10.89	10.90	11.58	12.35	11.83	11.12	10.71
		Avg. Maximum	10.73	11.05	10.89	11.00	11.29	12.76	13.96	14.10	14.41	12.87	11.52	11.58
		Avg. Minimum	8.32	9.75	8.93	8.62	8.48	9.33	9.14	9.40	10.43	10.89	10.45	9.71
		Total No. Obs.	99	101	126	107	113	90	110	97	90	70	25	76
	S	Avg. Mean	31.68	31.73	32.08	32.36	33.34	33.61	33.71	33.71	33.30	32.94	32.59	31.20
		Avg. Maximum	32.68	32.75	(33.10)	(32.62)	(33.76)	>34.00	>34.00	>34.00	(33.49)	(33.42)	33.27	32.20
		Avg. Minimum	29.97	30.26	30.17	31.20	32.20	32.60	33.02	32.99	32.83	32.20	31.83	30.02
		Total No. Obs.	99	98	126	107	113	89	110	96	90	80	25	75
Crescent City, California 1934-1964	T	Avg. Mean	9.7	10.0	10.2	10.8	11.7	12.5	13.5	14.2	13.5	12.1	11.1	10.3
		Avg. Maximum	11.0	11.2	11.6	12.2	13.4	14.7	15.3	15.8	15.2	13.6	12.5	11.6
		Avg. Minimum	8.1	8.4	8.7	9.5	10.0	10.6	11.4	12.3	11.7	10.8	9.5	8.7
1963-1969	S	Avg. Mean	28.30	28.98	29.69	28.84	30.40	31.77	32.54	32.33	32.75	32.60	30.90	29.64
		Avg. Maximum	31.99	(32.07)	(32.63)	32.35	33.75	(33.71)	(32.77)	33.08	33.62	33.33	32.74	32.31
		Avg. Minimum	22.90	23.05	23.55	22.14	25.00	29.08	30.42	31.28	31.56	31.71	28.01	25.49
		Total No. Obs.	106	102	90	81	51	71	60	61	99	96	96	55

Table 6-3. Average monthly surface temperature (°C) and salinity (‰) from three lightships off the Pacific Northwest coast. Salinities enclosed by ( ) indicate average computed from fewer observations than listed in total.

Station and Period of Record		Monthly Avgs. & Total No. Obs.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Umatilla Reef Lightship 1966-1969	T	Avg. Mean	9.11	8.16	8.49	9.26	10.29	12.40	12.67	12.56	14.05	12.00	10.97	9.40
		Avg. Maximum	10.40	9.10	9.11	11.68	13.07	15.50	14.60	14.58	16.39	14.11	12.04	11.03
		Avg. Minimum	7.97	7.49	7.68	7.62	8.85	12.82	11.22	10.18	11.79	10.64	9.53	8.42
		Total No. Obs.	93	57	65	73	88	119	94	88	83	80	80	78
	S	No data.												
Columbia River Lightship 1965-1969	T	Avg. Mean	9.30	8.82	9.20	10.10	11.50	13.64	14.56	14.91	14.92	13.83	12.14	10.00
		Avg. Maximum	10.61	10.63	10.06	11.37	13.07	15.56	16.50	17.07	16.48	15.17	13.46	11.89
		Avg. Minimum	7.55	7.53	8.03	9.22	12.39	11.41	12.71	12.65	12.89	12.29	10.56	7.90
		Total No. Obs.	77	118	112	109	123	151	152	117	93	89	112	103
	S	Avg. Mean	27.99	26.90	26.69	24.17	25.18	22.76	23.07	27.27	31.15	30.35	27.80	22.72
		Avg. Maximum	(33.20)	32.11	32.04	29.72	29.43	29.88	26.90	30.60	(33.50)	(33.43)	30.48	30.94
		Avg. Minimum	19.29	21.23	17.02	16.18	19.95	14.80	12.55	21.48	23.00	21.36	24.12	13.18
		Total No. Obs.	55	55	95	78	96	107	117	81	58	63	94	53
Blunts Reef Lightship 1923-1964	T	Avg. Mean	11.0	10.8	10.4	10.2	10.3	10.3	10.2	10.8	11.3	11.6	11.7	11.5
		Avg. Maximum	12.1	11.8	11.6	11.4	12.0	12.2	11.9	12.7	13.3	13.6	13.3	12.9
		Avg. Minimum	10.1	9.9	9.1	8.9	9.1	8.9	8.9	9.4	9.9	10.1	10.1	10.1
1966-1968	S	Avg. Mean	33.16	33.08	32.86	33.26	33.73	33.75	33.84	33.59	33.42	33.52	33.20	33.06
		Avg. Maximum	33.68	33.62	33.52	(33.[illegible]4)	> 34.00	> 34.00	> 34.00	> 34.00	33.89	33.87	33.73	33.49
		Avg. Minimum	32.23	32.12	31.39	32.10	33.07	33.36	33.24	32.91	33.02	32.98	32.70	32.55
		Total No. Obs.	62	57	89	84	90	89	92	86	88	93	89	55

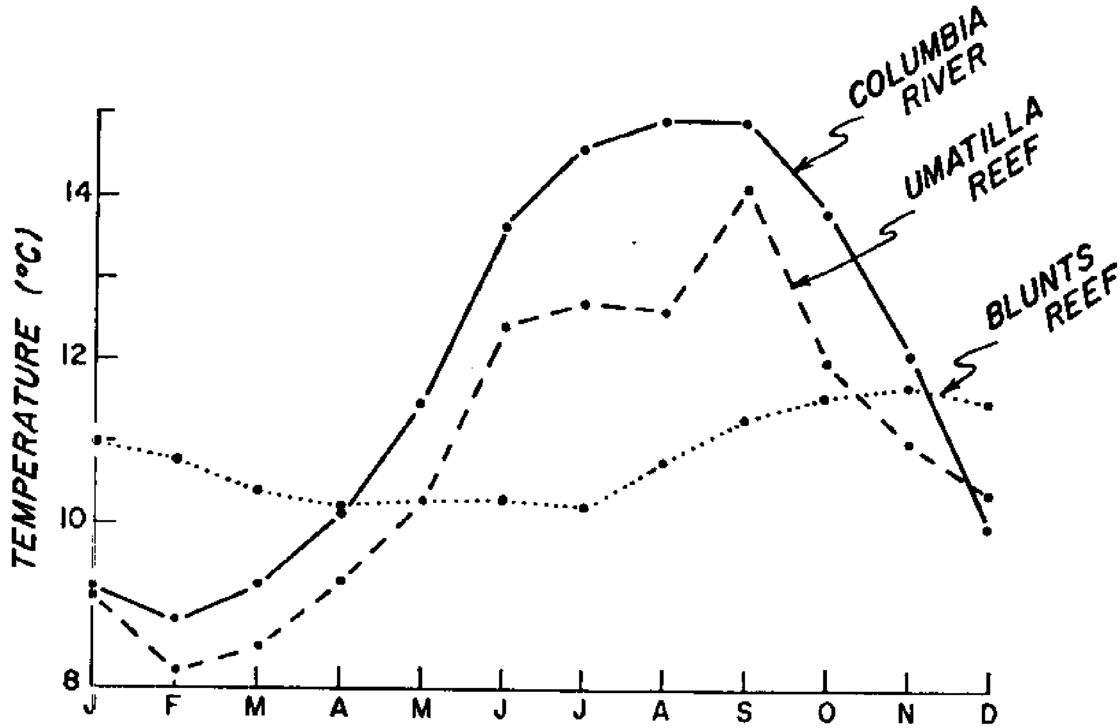

Figure 6-2. Mean monthly surface temperatures recorded at three lightships along the Pacific Northwest Coast. Monthly means were computed from daily observations taken over the periods listed in Table 6-3. Note that the annual range for the southernmost lightship is much less than that of the more northerly stations.

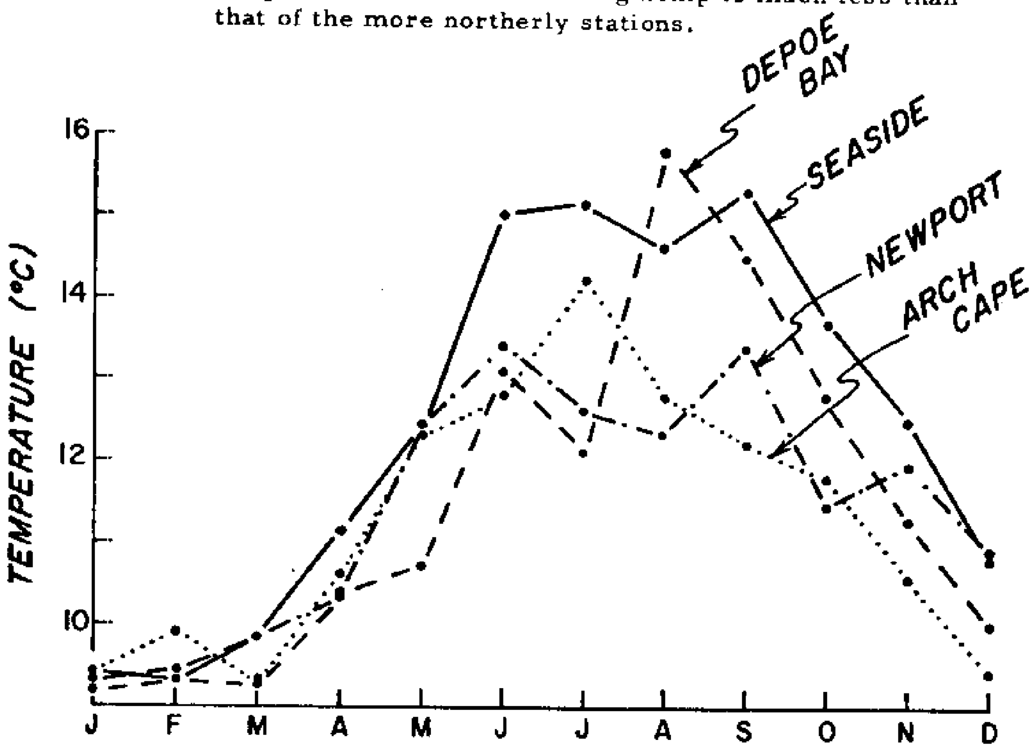

Figure 6-3. Mean monthly surface temperatures recorded at four northern Oregon shore stations. Monthly means were computed from daily observations taken over the periods listed in Table 6-2. The high summer temperatures reflect the influx of the warm Columbia River discharge.

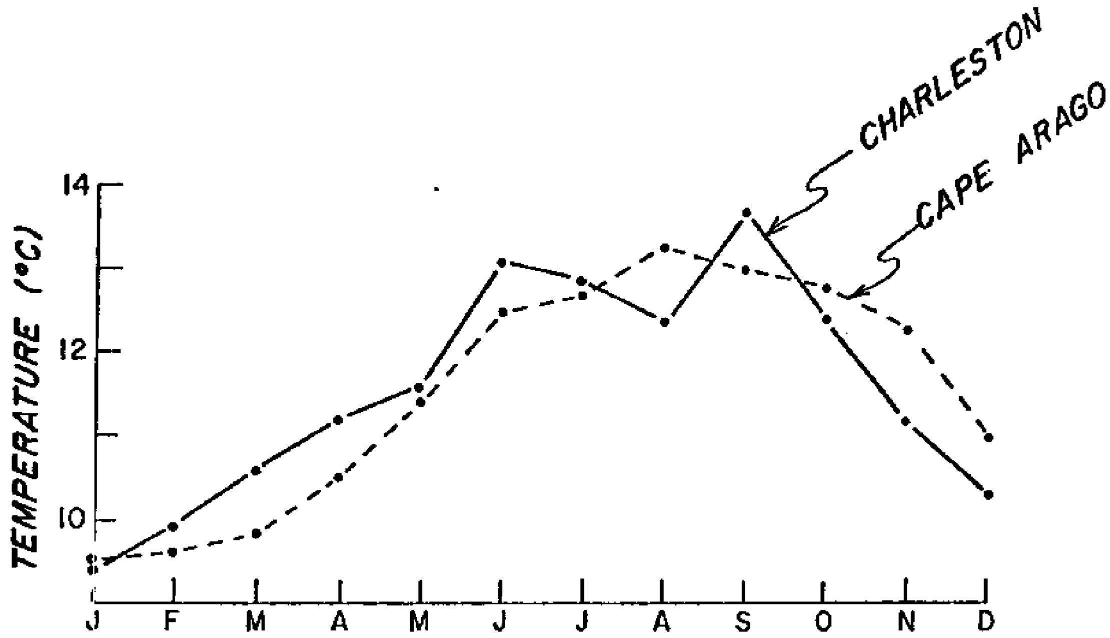

Figure 6-4. Mean monthly surface temperatures measured at shore stations in Coos Bay area. Monthly means were computed from daily observations over a four year period (Table 6-2).

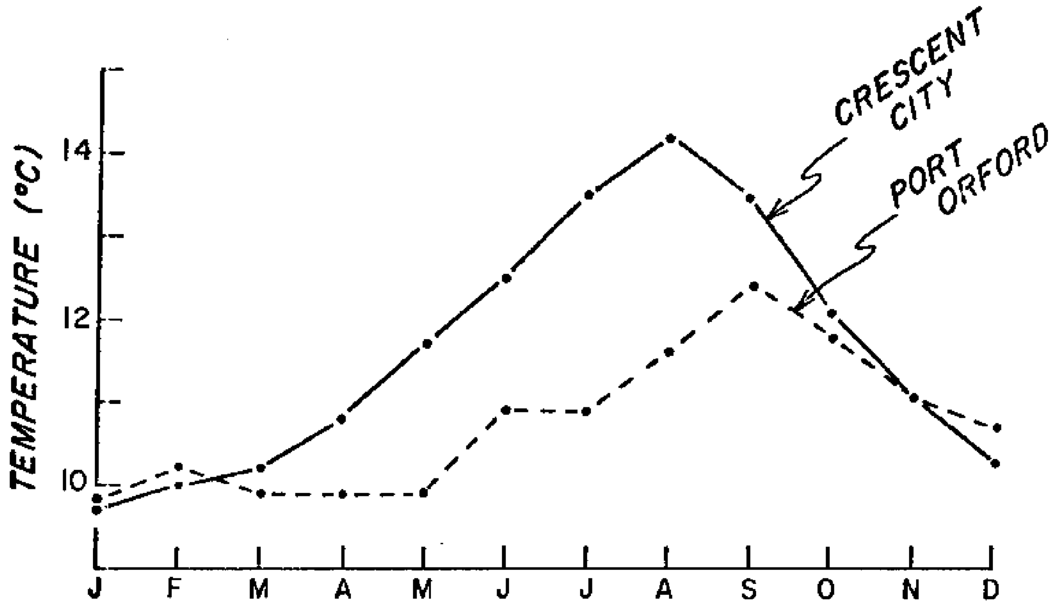

Figure 6-5. Mean monthly surface temperatures measured at shore stations south of Cape Blanco. Monthly means were computed from daily observations taken over the periods listed in Table 6-2. Note that the intense upwelling characteristic of the Cape Blanco area is reflected in the low summer temperatures at Port Orford.

5 C° increase in temperature during the summer months. The northern stations experience a larger range in annual temperatures than do the southern stations (Tables 6-2 and 6-3). Maximum temperatures are usually achieved during August or September. The surface waters are coldest from December through March.

The range between average maximum and minimum monthly temperatures is larger during summer than winter. Summer temperatures can be expected to fluctuate approximately 2.5 to 3.0 C° about the monthly mean temperature; during winter this fluctuation is approximately 0.5 to 1.0 C°.

The surface temperatures observed during summer from the Columbia River Lightship, 5 miles offshore, are influenced by the river discharge temperature as indicated by the anomalously high average mean and average maximum temperatures of 14.9°C and 17.1°C, respectively. The three northerly stations on the Oregon Coast also had average maximum temperatures in excess of 17°C; at the southerly stations maximum temperatures were usually 14 to 15°C. The high summer temperature of the Columbia River discharge undoubtedly caused the higher temperatures observed at these northern stations. This corroborates the findings of Pattullo and Denner (12) based on a shorter observation period.

The temperature patterns observed from the Blunts Reef Lightship off Cape Mendocino and at Port Orford just south of Cape Blanco are unlike those observed at other stations. These stations are located in regions of extremely active upwelling. During periods of upwelling (June-September) the near surface waters of these regions can be expected to be relatively cool and quite saline. Average minimum temperatures are low, 8 to 9°C, and surface salinities often exceed 34‰. The increase in summer temperatures observed at the other stations does not occur. Maximum temperatures occur in October and November, two months after the other stations have reached their maximums. The range in temperature at these two stations is small, approximately 1 C° in winter and 2 C° in summer.

Offshore Temperature and Salinity Observations

Temperature and salinity observations from vessels at sea are on file at the National Oceanographic Data Center (NODC). These data are filed by 10° Marsden square numbers (Schuyler, 13); number 157 encompasses the region of the study area. Data from one degree squares 40° to 48°N latitude and 124° to 125°W longitude within Marsden square 157 were obtained from NODC. Since this report is concerned with the data observed within 10 miles of the coast (the distance between 124° W and 125° W longitude is about 48 miles), a computer program was written to exclude all data observed more than 10 miles from shore. About 25 percent of the original data was found shoreward of this 10-mile boundary. After arranging the data by month and latitude, it was apparent that an extreme paucity of data existed and that most observations were clustered about the major coastal towns or off prominent headlands. More than 50 percent of the observations were from the vicinity of the Columbia River mouth.

Monthly means of temperature and salinity, maximum and minimum values, and number of observations have been computed for the standard depths of 0, 10, 20, 30, and 50 meters for the clustered data areas. Table 6-4 is a listing of average surface conditions. Similar statistics for the remaining depths are listed in Appendix 2 of Renfro, et al. (14).

Care should be exercised when using the data in Table 6-4 since:

1. Very few observations were available to compute a meaningful average. Frequently only 1 to 3 observations were used to compute the monthly averages.

2. The observations for a given month are not necessarily from the same year, but may have been taken over a span of 10 years.

3. The data represent average surface conditions over an area about 5 miles wide. Airborne infrared surveys have shown temperatures to increase with distance from the coast in this 5-mile wide zone.

With the above in mind, the following observations seem significant regarding the offshore temperature and salinity distribution:

1. a. For the Coos Bay, Brookings, and Trinidad Head offshore areas, coldest temperatures (7-9°C) occur in June. Salinities are also high in June (> 33.6‰) indicating strong upwelling.

b. Maximum temperatures at the above three offshore stations are reached in September and October (12-13°C). Salinities remain high throughout the summer (> 33 ‰).

c. For the Yaquina Head and Tillamook Bay offshore areas, low temperature (8-9°C) and high salinities (> 33‰) are observed in July. Upwelling is dominant during July. Maximum temperatures (13-15°C) occur in September and October after the cessation of upwelling.

Area		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Humboldt Bay Area 40°49' to 40°51'	Mean Temp.	11.04	11.19	10.31	9.14	11.72	12.21	12.80	13.24	12.76	11.49	-----	11.34
	No. of Obs.	10	3	5	6	3	13	3	7	7	6		7
	Mean Salinity	32.76	30.16	30.60	33.73	31.68	33.55	33.38	33.33	33.65	33.32	-----	30.67
	No. of Obs.	10	3	5	6	3	12	3	7	7	6		8
Trinidad Head Area 41°03' to 41°04'	Mean Temp.	-----	-----	-----	10.93	-----	9.47	13.66	12.63	13.32	12.42	-----	-----
	No. of Obs.				1		3	10	2	8	1		
	Mean Salinity	-----	-----	-----	32.12	-----	33.93	33.35	-----	33.56	33.15	-----	-----
	No. of Obs.				1		3			8	1		
Brookings Area 42°00'	Mean Temp.	-----	-----	10.86	-----	11.66	6.50	11.08	11.48	12.66	11.05	-----	9.71
	No. of Obs.			1		5	1	1	1	1	1		1
	Mean Salinity	-----	-----	-----	-----	31.57	34.06	33.62	33.85	33.53	33.00	-----	32.72
	No. of Obs.					5	1	1	1	1	1		1
Coos Bay Area 43°20' to 43°21'	Mean Temp.	9.20	-----	10.10	11.19	11.71	8.46	10.60	11.05	13.24	13.46	10.79	10.44
	No. of Obs.	1		7	1	1	1	3	2	2	3	2	3
	Mean Salinity	32.36	-----	31.95	30.93	32.17	33.58	33.23	33.46	33.02	32.83	32.68	31.67
	No. of Obs.	1		7	1	1	1	3	2	2	3	2	3
Yaquina Head Area 44°38' to 44°41'	Mean Temp.	9.68	9.45	10.55	10.52	10.75	11.47	9.65	11.80	12.97	12.15	11.94	10.41
	No. of Obs.	6	7	4	7	6	7	11	6	5	10	9	7
	Mean Salinity	32.17	31.03	31.13	31.03	32.05	32.13	33.06	33.14	32.71	32.53	32.14	31.66
	No. of Obs.	6		4	7	6	7	11	6	5	10	10	7
Tillamook Bay Area 45°30' to 45°46'	Mean Temp.	10.26	8.16	10.29	9.42	13.25	12.01	8.44	12.76	14.18	15.33	-----	11.71
	No. of Obs.	1	1	1	1	4	6	1	2	4	3		2
	Mean Salinity	32.00	27.41	31.08	25.84	30.18	30.06	33.16	31.76	31.87	31.82	-----	31.53
	No. of Obs.	1	1	1	1	3	6	1	2	4	3		2
Seaside Area 45°58' to 46°05'	Mean Temp.	-----	8.02	9.33	9.24	12.05	12.72	15.04	14.56	14.86	15.98	10.41	-----
	No. of Obs.		3	5	2	1	11	1	3	7	4	1	
	Mean Salinity	-----	24.76	27.74	27.36	30.31	24.71	29.05	28.80	27.35	31.38	32.16	-----
	No. of Obs.		3	5	2	1	11	1	3	7	4	1	
Columbia River Mouth Area 46°07' to 46°22'	Mean Temp.	8.93	7.61	8.94	9.67	12.02	13.62	14.68	14.41	13.84	14.24	10.26	9.84
	No. of Obs.	5	37	28	11	10	110	2	51	155	10	9	5
	Mean Salinity	27.74	20.16	24.30	22.09	21.65	16.57	25.40	25.21	27.80	28.08	29.71	25.86
	No. of Obs.	4	37	27	11	9	117	2	51	156	10	9	6
Long Beach to Ocean Park Area 46°22' to 46°36'	Mean Temp.	8.17	8.00	8.65	9.18	12.97	13.49	-----	13.58	13.90	14.91	11.60	8.84
	No. of Obs.	3	6	8	6	3	15		4	9	5	5	2
	Mean Salinity	27.92	26.29	27.37	27.40	30.24	21.87	-----	30.71	29.80	29.37	30.64	26.10
	No. of Obs.	3	6	8	6	3	15		4	9	5	5	2
Pacific Beach Area 47°00' to 47°19'	Mean Temp.	9.28	8.24	9.26	9.49	-----	13.99	10.30	-----	15.00	14.70	-----	6.92
	No. of Obs.	1	2	3	1		4	1		3	1		1
	Mean Salinity	28.26	27.67	27.23	25.65	-----	27.19	33.43	-----	30.97	30.09	-----	26.96
	No. of Obs.	1	2	3	1		4	1		3	1		1

Table 6-4 Mean monthly surface temperatures (°C) and salinities (‰) for selected offshore areas. Data are from that on file at NODC.

d. Maximum temperatures at shore stations in these 5 areas occur two months earlier - in August and September.

2. a. At Seaside and for the Long Beach-Ocean Park areas, surface temperatures remain relatively high throughout the summer (14-15° C). Salinities rarely exceed 30‰. In June, the Columbia River flood is reflected in extremely low surface salinities (21-25‰).

b. Upwelling then, as measured by low temperatures and high salinities, does not appear to be a dominant factor in these two areas.

3. a. Examination of subsurface temperatures (14) indicates that isothermal conditions (constant temperature with increasing depth) exist from November through March-April. This may permit surface temperatures to be inferred from subsurface temperature recorders during the winter months when it may be difficult to obtain continuous surface temperatures. A weak thermocline (less than 2° C) exists during the summer at a depth of less than 20 meters.

Continuous temperature measurements are available from thermograph records made 3 to 10 miles off the central Oregon coast near Depoe Bay and Yaquina Head. Observational periods include May and June, 1967; April through September, 1968; and July through September, 1969. Analysis of the 1967-1968 data is completed and will be published (Pillsbury, et al., 15).

Sea Surface Temperature from Infrared Surveys

The airborne infrared radiometer (radiation thermometer) has proven useful for mapping mesoscale distributions of sea surface temperature. Large scale features such as upwelling fronts or the plume from the Columbia River are readily apparent.

Since August 1963 the Tiburon Marine Laboratory of the Bureau of Sport Fisheries and Wildlife, Department of the Interior, in cooperation with the U.S. Coast Guard has conducted monthly infrared radiometer surveys for three Pacific coast areas. The recently modified northern flight pattern (the only area within the limits of this study) extends from Cape Elizabeth, Washington, to Newport, Oregon, and offshore to the 6000 foot (1000 fathoms) contour (approximately 60 miles offshore). Figure 6-6 is an example of the monthly temperature pattern constructed from one such survey.

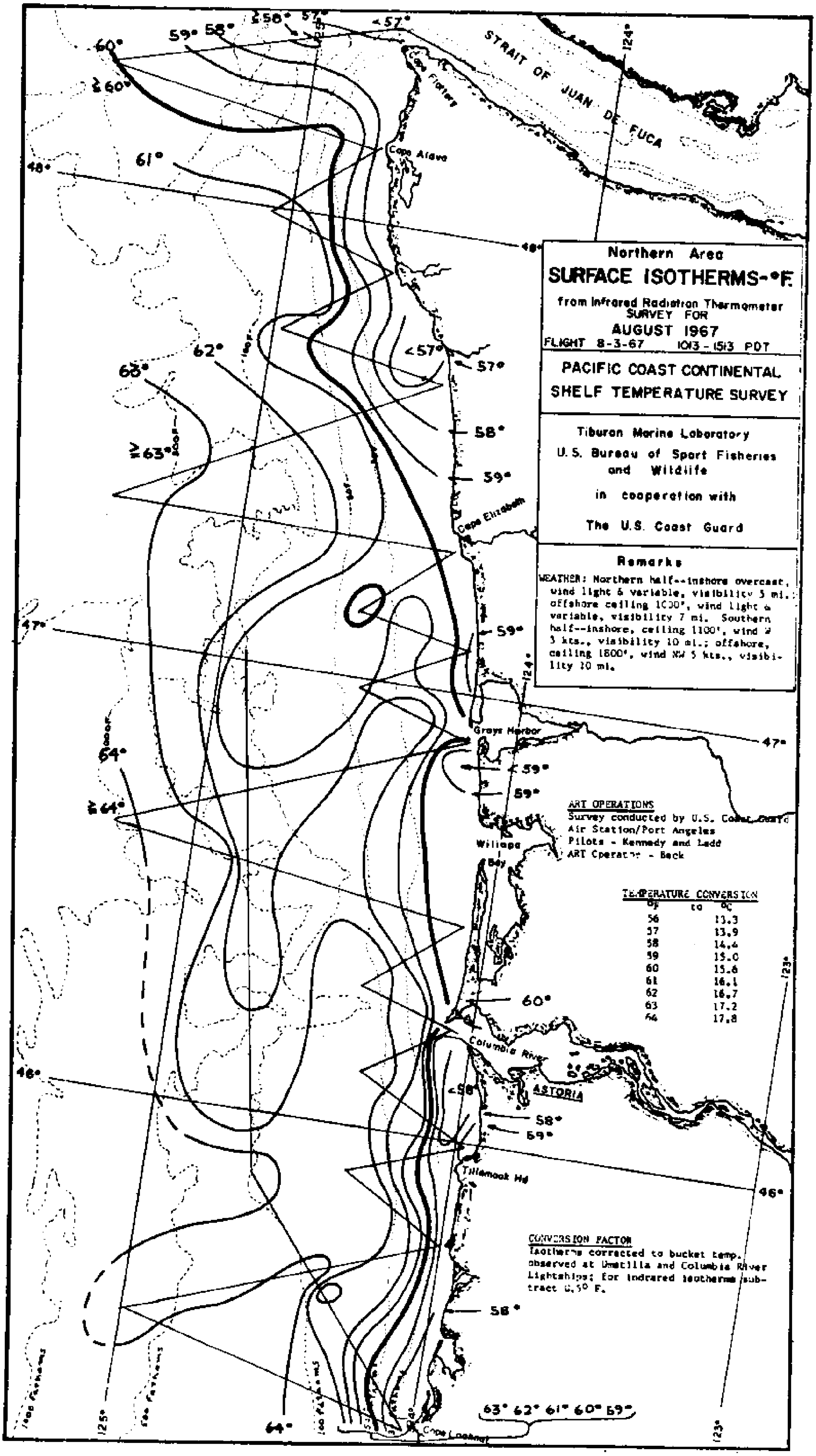

Figure 6-6. Example of a typical infrared survey conducted by the Tiburon Marine Laboratory of the Bureau of Sport Fisheries and Wildlife. Note that insufficient data prevents drawing temperature contours within five

During the summer of 1969 the Department of Oceanography, Oregon State University in conjunction with OSU's Sea Grant project, "Albacore Central," conducted daily infrared radiometer surveys, along the Oregon Coast to approximately 30 miles offshore. Temperature contours from a typical flight are shown in Figure 6-7.

Temperature profiles constructed from airborne infrared surveys within 5 miles of the coast are quite subjective. Figure 6-8 shows profiles from a segment of a typical survey conducted by OSU. The horizontal temperature gradient changes rapidly and unpredictably within the first 5 to 10 miles off the coast. Discontinuities marking temperature fronts are present and can be corroborated by abrupt changes in water color. In order to construct representative sea surface temperature contours with some degree of confidence, closer spacing of the flight track is required than that shown in Figure 6-8.

Conclusions

1. An abundant source of surface temperature and salinity data is available from coastal shore stations and the three offshore lightships. Few measurements have been made, however, inside of this five mile wide zone.

2. Surface temperatures range from an average high of 17.7° C to an average low of 7.6° C. More variability is observed in summer than in winter. Summer temperatures fluctuate within a 4 to 6 C° band while winter temperatures are constrained within a 1 to 2 C° band.

3. Summer temperatures are about 5 C° warmer than winter temperatures. Mean summer temperatures peak in August and September (12 to 14° C); average maximum temperatures, however, peak in July and August (15.5 to 17.5° C). Winter mean temperatures are uniformly low (about 9.5° C) during the period December through March. Average minimum temperatures (7.5 to 8.3° C) generally occur in January.

4. Summer temperatures in the northern portion of the area (from Willapa Bay, Wash. to Tillamook Bay, Oregon) are 2 or 3C° warmer than temperatures observed at the more southerly stations. This is undoubtedly due to the warming influence of the Columbia River.

5. In areas where coastal upwelling is intense, summer temperatures are suppressed below those of the more northerly stations. Average minimum temperatures of 9.5 to 10.5° C are observed in upwelling regions

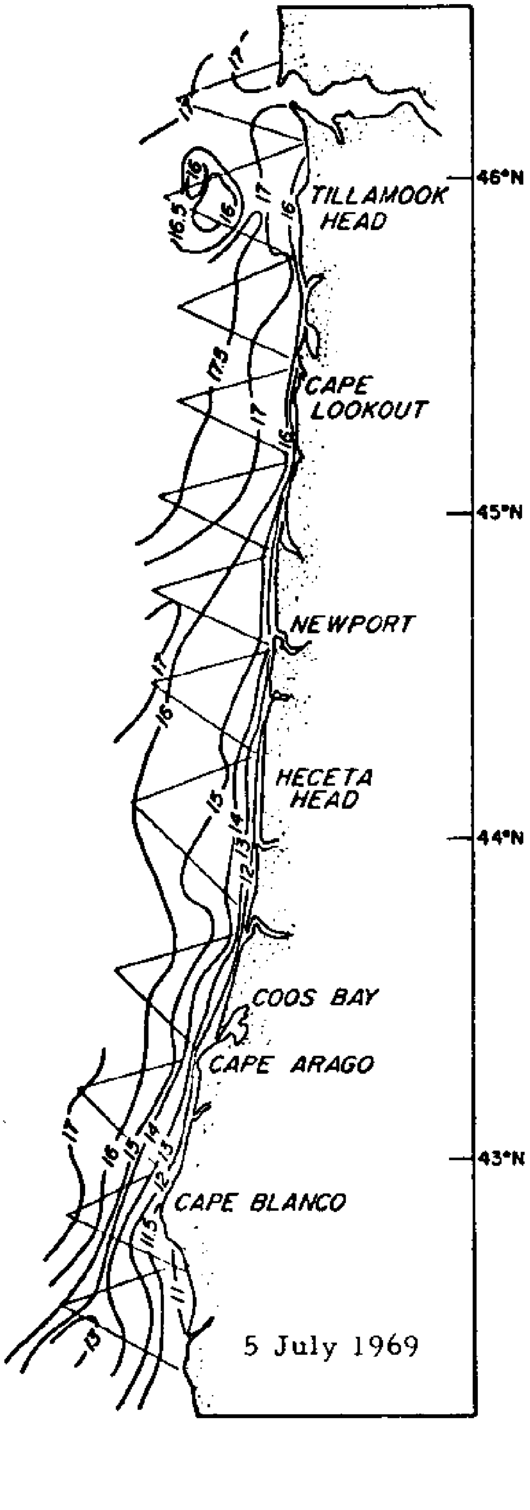

Figure 6-7. Temperature contours from a typical infrared survey conducted by Oregon State University's Sea Grant project "Albacore Central." Note closer spacing of flight track provides capability to construct contours closer to shore than that shown in Figure 6-6.

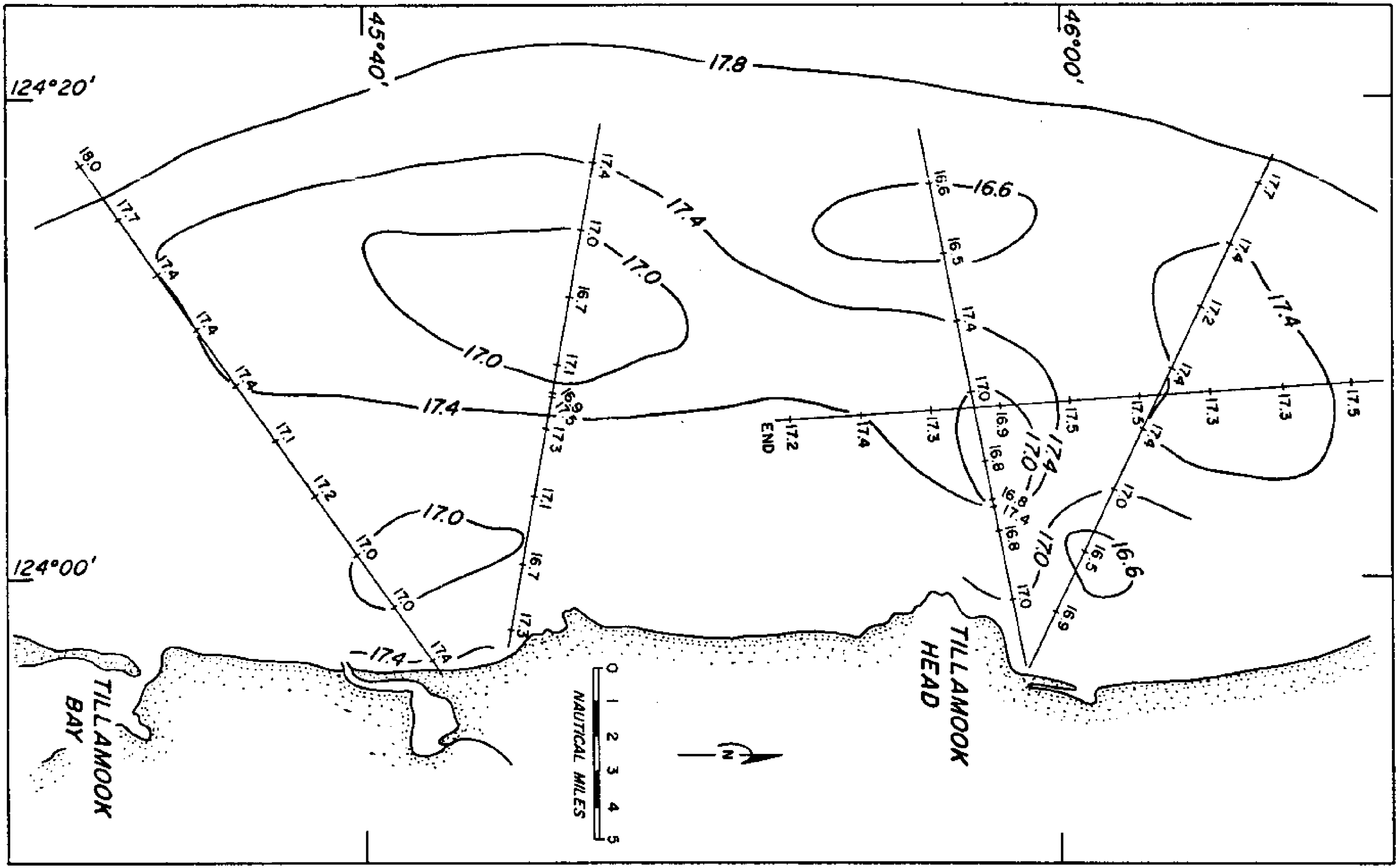

Figure 6-8. Segment of a typical infrared survey conducted by Oregon State University's Sea Grant project, "Albacore Central." Note that construction of temperature contours is highly subjective even for this relatively narrow strip.

whereas minimum temperatures of 12 to 14° are found in regions of little or no upwelling.

6. Due to extensive wind mixing of these shallow waters in winter, isothermal conditions exist from November through March-April.

7. Surface salinities are higher in summer (approximately 33.5‰) than in winter (approximately 32‰). Coastal upwelling tends to keep salinities elevated during the summer while winter rains and high river run-off tend to lower surface salinities.

8. Where coastal upwelling is prevalent, salinities in excess of 33.8‰ are frequently observed. However, during periods of weak or inactive upwelling, surface salinities may be reduced to 32.5 to 33‰.

9. In winter the discharge from the Columbia River flows north close to the Washington coastline. Mean salinities observed along the southern Washington coast are low (25 to 28‰) with maximum salinities rarely exceeding 30‰. During periods of peak discharge (June) salinities below 20‰ are not uncommon. During summer when the Columbia River plume flows offshore to the southwest, its freshening influence is still felt along the southern Washington coast. Surface salinities average about 30‰ occasionally reaching 33‰ in July and August.

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Chapter 7. HEAT BUDGET

Introduction

A heat budget study for the coastal area of the Pacific Northwest has been completed by Lane (1). He investigated the area from 40 to 50° North Latitude and from the coastline to 130° West Longitude. A further subdivision narrowed this area to include only the region within 60 nautical miles of the coastline. This subdivided region was established to provide a comparison between a coastal upwelling region and one free from the effects of upwelling. Measured values of sea surface temperature, wet and dry bulb air temperature, wind velocity, solar radiation, and cloud cover were used to compute the terms in the heat budget equation. The data used by Lane were from records of naval vessels for the period 1952-1962. These records are on file at the National Weather Records Center in Asheville, N. C. Each heat budget term was averaged month by month over a ten-year period (Table 7-1). The monthly variation of the total net heat exchange across the air-sea boundary was computed from the simplified heat budget equation: $Q_t = Q_s - Q_b - Q_h - Q_e$ 7-1

where Q_t is net heat transfer; considered positive when the sea receives heat energy,

Q_s is net short wave solar radiation incident on the sea surface,

Q_b is heat loss due to effective back radiation,

Q_h is heat conduction; considered positive when there is a net exchange of heat from the sea to the atmosphere,

Q_e is heat loss due to evaporation.

All terms are measured in langleys (calories/cm^2).

Empirical Methods

Direct measurement of terms in the heat budget equation (equation 7-1) is presently limited to laboratory experiments with the possible

Table 7-1. Average monthly values (langleys) for the major heat budget terms for a region where coastal upwelling is seasonally present. $Q_{t\ overall}$ includes this region as well as areas further offshore not affected by coastal upwelling.

	Q_b	Q_h	Q_e	$Q_{s\ net}$	Q_t	$Q_{t\ overall}$
Jan	82	38	225	116	-229	-191
Feb	70	30	200	140	-160	-100
Mar	70	41	167	264	- 14	20
Apr	73	-10	118	423	242	198
May	63	- 5	129	486	299	277
June	72	- 7	150	528	313	304
July	51	-22	93	419	297	366
Aug	63	-15	100	447	299	274
Sept	75	-42	110	386	243	119
Oct	113	10	185	272	- 36	- 89
Nov	80	24	155	126	-133	-205
Dec	95	- 6	106	105	- 90	-203

(modified from Lane, 1)

exception of the radiative terms. In practice, empirical methods are used to compute the heat budget terms. Spatial and temporal measurements of sea surface temperature, wet and dry bulb air temperature, wind velocity, solar radiation, and cloud coverage are observed from which diurnal, monthly, or annual means are computed. A variety of empirical relationships have been established for the computation of each heat budget term utilizing the above measurements. A discussion of the methods employed by Lane follows.

Monthly mean values of the total daily solar radiation incident on the surface of the earth, Q_s, were obtained from the U. S. Weather Bureau at Astoria, Oregon. These monthly means were corrected for latitude and cloud cover. The percent of the incident solar radiation reflected from the sea surface, i.e., the albedo, was determined by slightly modifying and averaging the albedos as determined by Burt (2, 3). The net solar radiation was calculated as the difference between the incident and reflected values. Monthly means of net solar radiation are listed in Table 7-1 and plotted in Figure 7-3.

The effective back radiation or the net loss of heat due to long wave radiation from the sea surface is a function of the surface water temperature and several atmospheric characteristics (temperature, vapor pressure, and cloud coverage). Lane used the relationship developed by Anderson et al. (4) to compute Q_b.

$$Q_b = 1.141\ K_s^{\,4} - K_a^{\,4}\ [\ (0.74 + 0.025\ C\ e^{-0.0584h}) + (0.0049 - 0.00054\ C\,e^{-0.06h})\ e_a\ ]\ 10^{-7}\ \text{ly/day} \qquad 7\text{-}2$$

where K_s and K_a are, respectively, absolute sea surface and air temperatures in °K,

C is cloud cover in tenths, and

h is height of the clouds above sea level in meters.

The heat loss due to evaporation, Q_e, is primarily a function of the wind speed, V (m/sec), and the difference between the saturation vapor pressure and the vapor pressure of the air, $(e_s - e_a)$. A number of equations have been developed, but none are able to predict the evaporation from the oceans with great confidence or accuracy. The equation chosen by Lane originated with Sverdrup

(5) and is of the form:

$$Q_e = 6.13\ V\ (e_s - e_a)\ \text{ly/day} \qquad 7\text{-}3$$

The conduction of sensible heat from the sea surface to the atmosphere occurs when the sea is warmer than the overlying air. Convective cells are created due to the instability within the air column resulting in cooling of the sea surface. If the air is warmer than the sea, a condition of stability is approached resulting in negligible exchange of heat. In general, the conduction process favors the removal of heat from the sea. The standard technique for estimating Q_h is by use of the Bowen ratio, i.e., $R = Q_h/Q_e$. Once the heat loss due to evaporation has been determined, Q_h can be found by

$$Q_h = \frac{0.61(K_s - K_a)\,Q_e}{(e_s - e_a)} \quad \text{ly/day} \qquad 7\text{-}4$$

where the terms are the same as those previously defined.

A comprehensive review of the heat budget including evaluation of the numerous empirical relationships, methods of data analysis, and techniques and equipment for obtaining the required meteorological variables may be found in several reports of which Edinger and Geyer (6), Raphael (7) and a TVA report (8) are the most complete. Average monthly values of the heat budget terms for the Pacific Northwest may also be determined from the heat budget Atlas edited by Budyko (9).

Discussion of Results

Over the ten-year period of investigation the total net heat transfer varied considerably from one year to the next. The range was appreciable, varying from over 42,000 langleys gained by the sea in 1956 to almost 2,000 langleys lost by the sea in 1959 (Figure 7-1). Lane was able to show that annual fluctuations in both solar radiation and evaporation were the major contributors to the observed net heat differences.

From January through March the net heat transfer was negative indicating a release of heat from the ocean to the atmosphere (Figure 7-2). During March through May the direction of exchange reversed resulting in a warming of the ocean. During the summer the warming process continued at a relatively constant rate. However, further offshore beyond the upwelling zone, the mid-summer atmospheric warming of the ocean decreased due to high surface temperatures

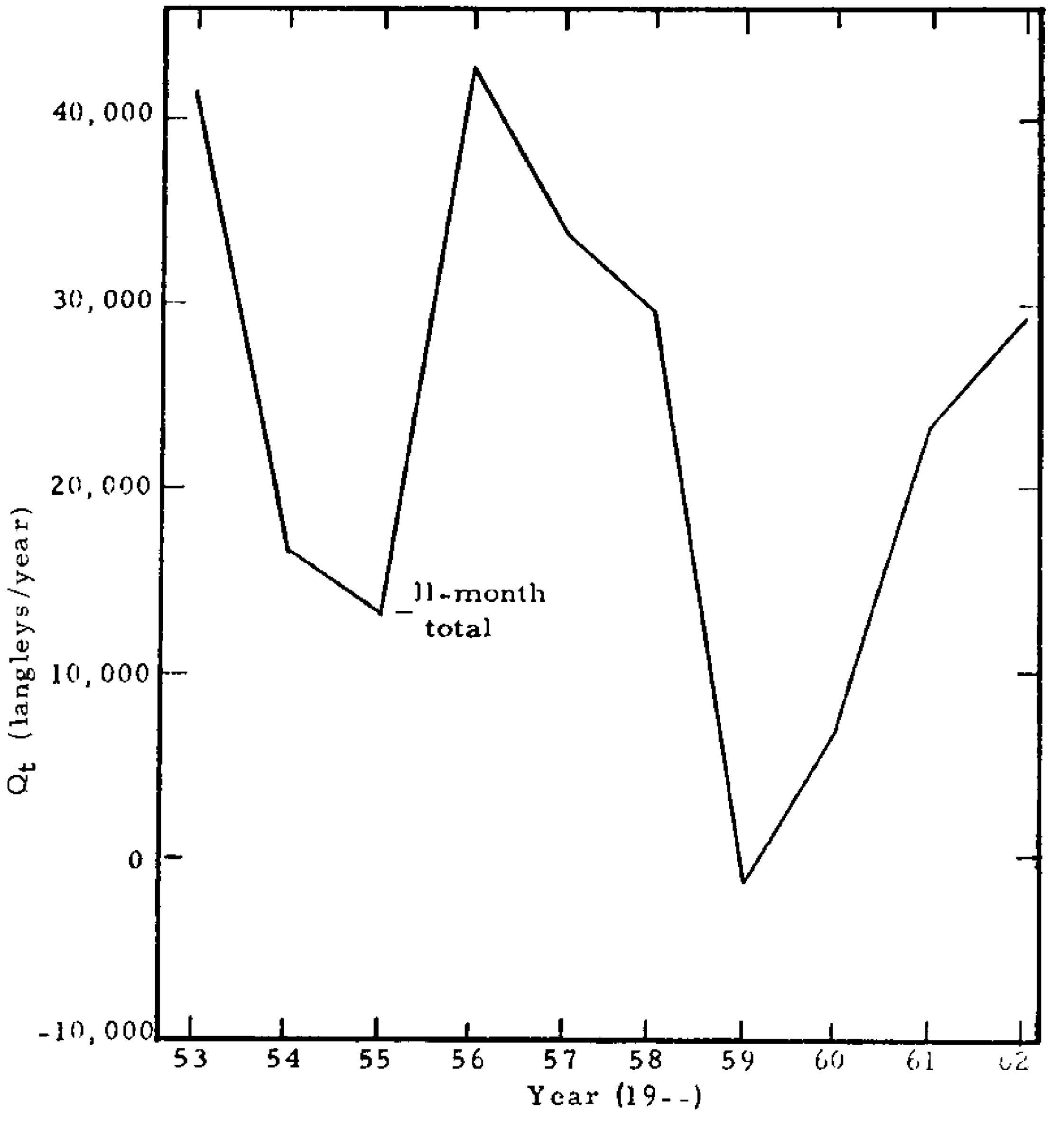

Figure 7-1. Variation of annual heat exchange (Q_t) from 1953 to 1962 for the region 40 to 50 N. Lat. and from the coastline to 130 W. Long. Note the extreme fluctuations in heat gained and lost by the sea in 1956 and 1959, respectively (from Lane, 1).

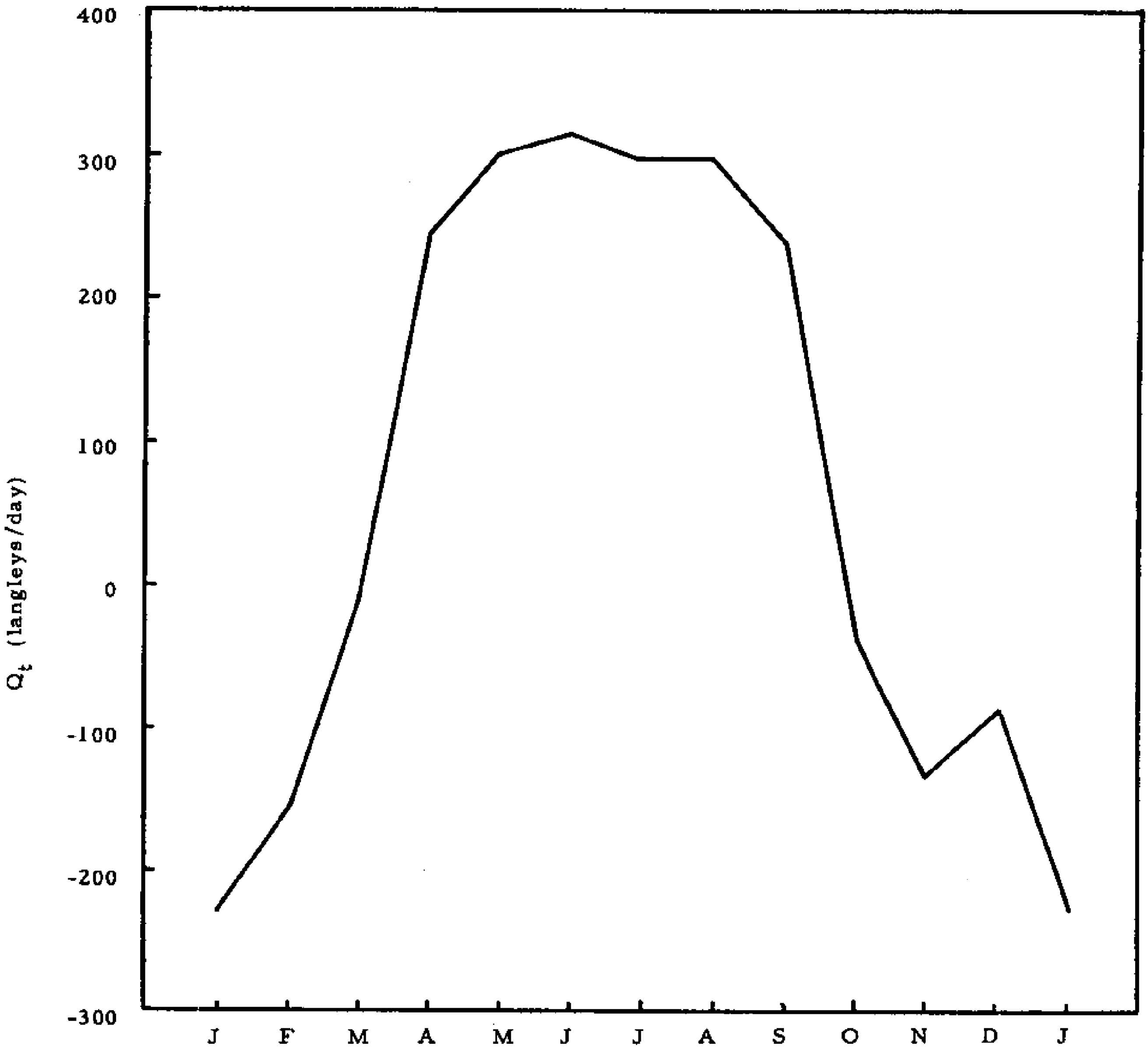

Figure 7-2. Monthly mean values of net heat transferred across the air-sea interface for the area, from the Oregon coastline to 60 nautical miles offshore. From March through October net heat is transferred from the atmosphere to the ocean. (modified from Lane, 1).

caused by warm Columbia River water and high values of cloud cover which reduced the incident solar radiation. By October the net heat exchange again reversed and the ocean continued to release heat at an increasing rate through December and January.

Net solar radiation and heat loss due to evaporation are the most significant factors affecting the total net heat exchange. The net solar radiation reaches its maximum during the summer months. April through September experience more than twice the insolation of the winter months (Figure 7-3). The heat loss due to evaporation is almost double that due to back radiation (Figures 7-4 and 7-5). However, during the summer months when upwelling is prevalent, the evaporative heat loss is suppressed from its winter maximum. The water transfer to the atmosphere during summer is less by approximately two inches per month compared to that in regions beyond the zone of upwelling. Cooling of the surface waters in summer due to upwelling also results in the conduction term, Q_h, being negative, i.e., a net conduction of heat to the sea (Figure 7-6). This lowering of the surface water temperature also results in a reduction of the effective back radiation during the summer months.

Direct Measurements

Direct measurements of net radiation and the evaporative and conductive heat fluxes will provide better knowledge of the heat transfer process across the air-sea interface. With increased understanding of the heat transfer process, the reliability of the empirical relationships should be improved. However, direct measurement of the heat budget terms is still limited to laboratory experiments with the exception of the radiative terms.

Solar radiation incident on the sea surface is usually measured with a pyrheliometer. Determination of the effective back radiation term is from empirical methods. The net radiation, both long and short wave, incident on the sea surface, however, can be measured with a net radiometer. Unfortunately, few of these devices are in operation at marine stations (1).

Both the conductive and the evaporative heat exchanges can be expressed as the sum of a slowly fluctuating average value and a rapidly fluctuating random value. The slowly fluctuating portion is that which is estimated by empirical methods since these methods are based on average values of wind,

Figure 7-3. Monthly mean values of net solar radiation incident upon the area from the Oregon coastline to 60 nautical miles offshore. The summer months experience more than twice the insolation of the winter months. (modified from Lane, 1).

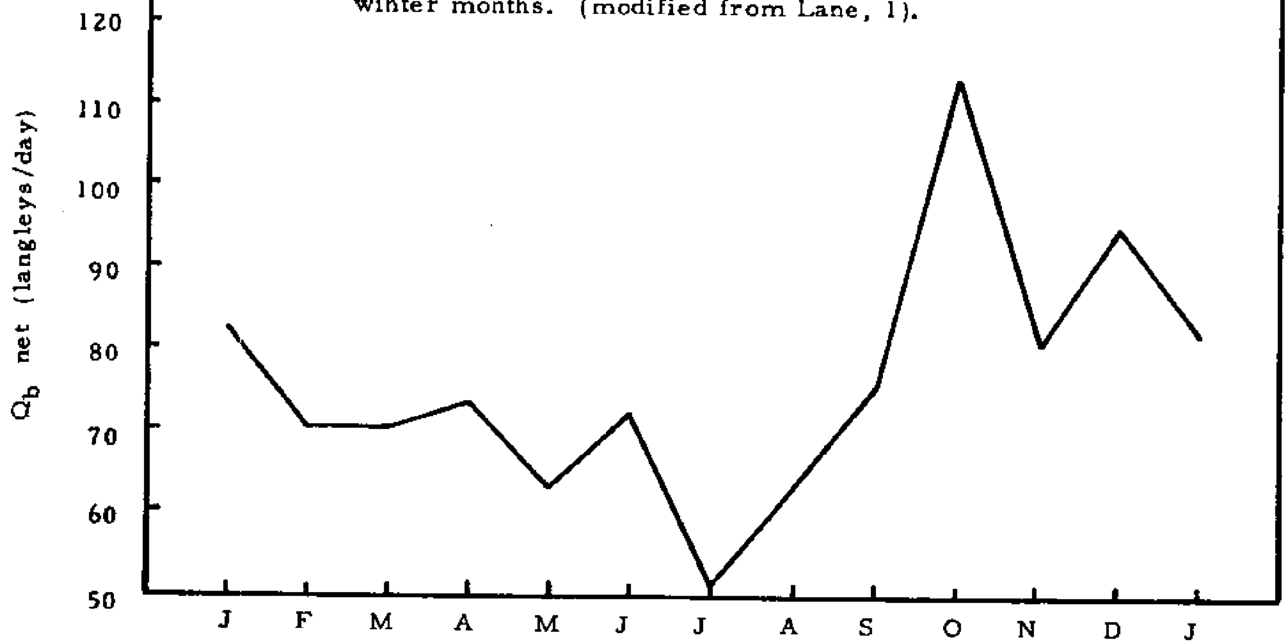

Figure 7-4. Monthly mean values of net back radiation for the area from the Oregon coastline to 60 nautical miles offshore. The low surface temperatures in summer resulting from coastal upwelling suppresses the net back radiation during this season. (modified from Lane, 1).

Figure 7-5. Monthly mean values of evaporative flux for the area from the Oregon coastline to 60 nautical miles offshore. In summer the evaporative heat loss is greatly suppressed from its winter maximum due to cooling effect of coastal upwelling. (modified from Lane, 1).

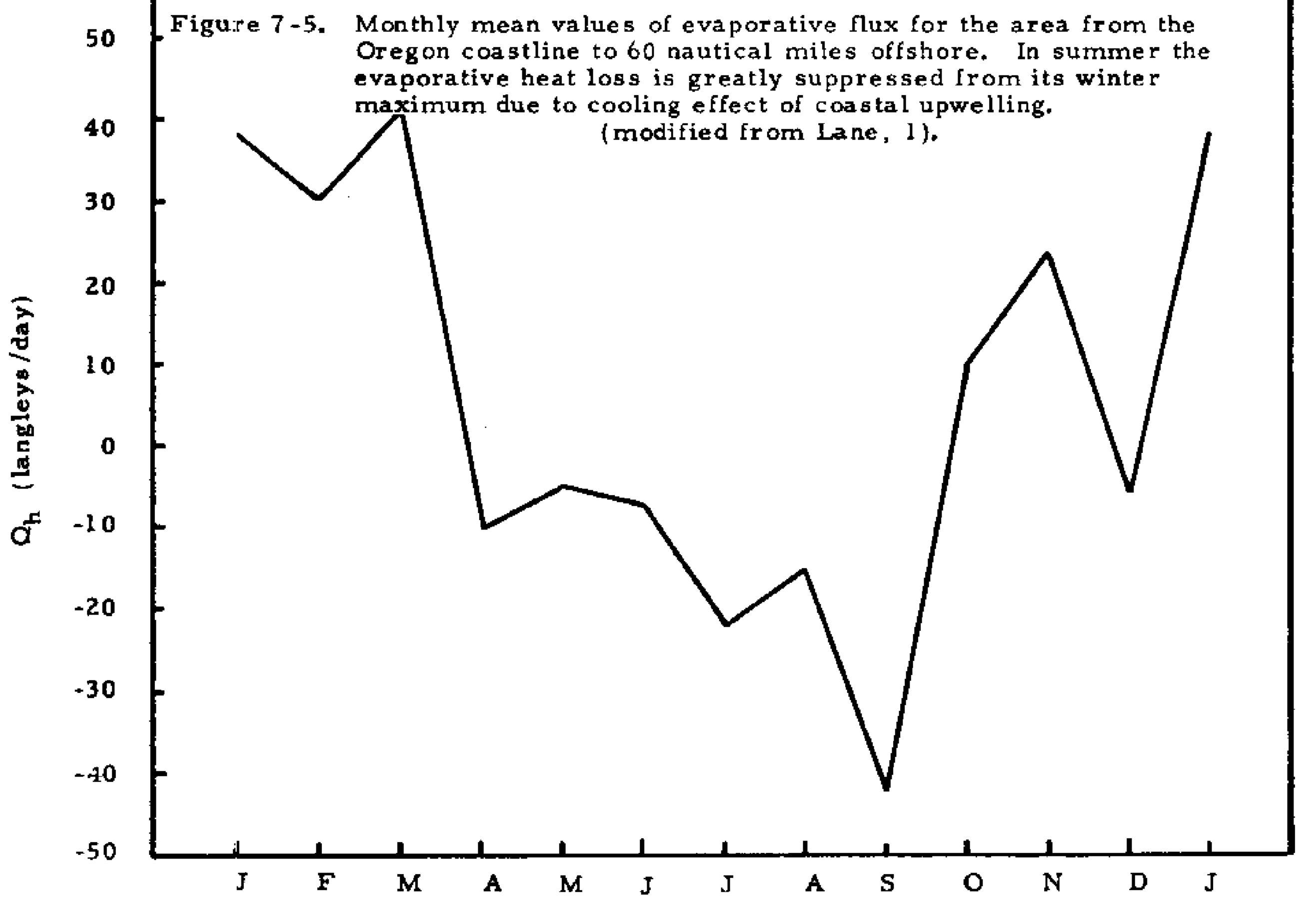

Figure 7-6. Monthly mean values of sensible heat conducted across the air-sea interface for the area from the Oregon coastline to 60 nautical miles offshore. Since surface temperatures are low in summer due to coastal upwelling, sensible heat is conducted from the atmosphere to the sea. (modified from Lane, 1).

temperature, vapor pressure, etc. The rapidly fluctuating values are the fluxes of evaporation and sensible heat. These fluxes need to be measured to obtain the true picture of the evaporative and conductive heat transfer processes. In the past, equipment with sufficiently fast response time to measure the rapid fluctuations was not available. Such equipment is now being developed in the laboratory. It will be some time in the future, however, before equipment reliability and cost will permit seasonal measurements encompassing a large area.

Summary

The direct measurement of the heat budget terms is generally limited to laboratory and field experiments. Empirical methods employing measurements of sea surface temperature, air temperature, humidity, wind velocity, solar radiation, etc. will have to suffice until direct reading instruments become available for practical use.

Based on empirical methods the following conclusions can be made concerning the heat budget for the coastal upwelling region off Oregon and Washington:

(1) The net heat exchange across the air-sea boundary varies considerably from year to year. In general, the sea receives a net annual input of heat from air-sea exchange.

(2) The factors most influential in altering the heat budget from year to year are variations in cloud cover, sea surface temperature, and wind speed.

(3) Coastal upwelling results in a lowering of air, sea, and wet bulb temperatures in the nearshore region. These reductions affect the heat budget by slightly reducing the back radiation, greatly reducing conduction from the sea to the atmosphere (conduction to the sea occurs frequently during the upwelling season), and greatly reducing the heat loss due to evaporation. Due to the relative magnitude involved, the reduction of the evaporative flux is the most important effect.

(4) The measurable effects of upwelling on the climate of coastal Oregon and Washington are a suppression of the summer and autumn air temperature values and an increase in relative humidity.

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Chapter 8. WAVES

Introduction

The importance of wave statistics has long been recognized by oceanographers and ocean engineers as necessary for design of ocean and coastal installations. Good wave data, however, are rare and the records are often such that the wide variability inherent in waves may not be adequately described. The wave climate off the Pacific Northwest coast displays a definite seasonal pattern in response to the wind regime requiring wave records which encompass all the seasons.

The basic statistics required to describe the wave regime are the deep water wave direction, wave period and wave height. From these statistics one can determine the wave length, wave steepness, energy content, and particle motion. In the analysis of wave data the significant wave height and period (H_o and T_o) are calculated rather than average values. The significant height and period are the average height and period associated with the highest one-third of the waves observed or measured. In order to eliminate the shallow water effects of shoaling and refraction, wave measurements or observations should be conducted in "deep" water, i.e., in water where the depth is larger than one-half the wave length.

The wave height, period and direction can be determined by observation from a moored ship in "deep" water, e.g., a lightship or instrumented buoy. The wave characteristics can also be inferred from observations of breaker height and period. Errors are inherent in both of these methods, but the chief difficulty lies in obtaining a complete annual record.

Wave statistics can also be calculated from the twelve hourly synoptic charts of the U.S. Weather Bureau. The fetch, duration, and velocity of the wind are determined and the wave characteristics are "hindcasted." Although this method relies heavily on one's ability to "read" or interpret the synoptic charts, it does provide a long and continuous record.

Data on wave height, period, direction, and frequency of occurrence over the yearly seasonal cycle are often important to power plant siting and design for several reasons. Some of these factors which are in part due to the wave climate are:

a) longshore current speed and direction
b) beach accretion and erosion
c) pressures and forces on bulkheads, pipelines, outfall, etc.
d) dispersal of the heated effluent from the outfall by wave turbulence.

Measured or Observed Waves

In the Pacific Northwest few deep water wave observations exist for extended periods of time. One such set of observations taken at the Columbia River Lightship from 1933 to 1936 was analyzed and reported by M. P. O'Brien in 1961 (1). The data were not obtained by trained observers and the methods used were rough, but O'Brien points out that the data are probably more accurate than most deep water observations since a limited number of observers on a relatively small anchored ship were used. The results are presented in Table 8-1.

O'Brien's analysis showed that the observed periods and wave lengths were less than the "correct" value. This conclusion was based upon comparative observations of the period of the breakers measured near the Columbia River mouth. O'Brien suggested that the reported wave lengths from the lightship should be increased by about one third to bring them into general agreement with those observed on the coast. The predominant wave direction (as a function of the square of the wave height) was found to be from west to southwest (Table 8-2). In general, the observations show that the higher and longer period waves occur in winter (October through March).

Neal, et al. (2) inferred the deep water wave statistics off Newport, Oregon, from observations on the beach of breaker heights and periods. The average value of the significant breaker height and period was determined from visual observations using the height of eye technique. From solitary wave theory the deep water wave height was related to the breaker height, H_B, by:

$$H_o = \left[\frac{H_B{}^3 \, dl_s}{0.027 \, L_o \, dl_o} \right]^{1/2}$$

Table 8-1. Dimensions and periods of waves observed at Columbia River Light Vessel

	Percentage of total observations exceeding figure specified								
	20			50			80		
	H_o	L_o	T	H_o	L_o	T	H_o	L_o	T
	ft	ft	sec	ft	ft	sec	ft	ft	sec
January	8.4	310	8.9	5.3	187	7.2	2.9	68	5.6
February	6.6	280	8.4	3.8	130	7.0	1.9	82	4.8
March	8.4	326	9.5	4.4	242	7.5	2.5	159	6.1
April	4.5	227	10.0	2.7	112	7.5	1.3	65	4.8
May	6.2	252	7.9	3.9	172	6.4	2.1	88	5.0
June	5.7	192	7.6	3.3	125	6.0	1.3	71	4.2
July	4.4	275	9.0	2.5	178	6.7	1.2	45	4.0
August	6.1	193	8.1	3.6	168	6.1	1.6	134	4.1
September	6.4	238	8.1	3.8	180	6.5	1.8	78	4.6
October	7.9	293	9.5	4.9	210	6.9	2.4	110	4.6
November	9.9	296	8.5	4.8	223	7.0	2.7	177	4.3
December	10.6	325	9.2	6.3	239	7.2	4.0	153	5.5

H_o = wave height; L_o = wave length; T = wave period between crests. (from O'Brien, 1).

Table 8-2. Observed wave direction

Direction	Percentage of total observations over 12 months	Percentage weighted in proportion to H_o^2
N	0.73	0.57
NE	1.80	1.44
E	3.18	1.26
SE	2.38	3.30
S	15.02	25.14
SW	18.74	36.36
W	30.03	23.70
NW	16.57	8.24
Calm	11.54	-----

(from O'Brien, 1).

where the refraction coefficient, dl_s/dl_o, was assumed close to unity and neglected. For the beach at Newport this assumption may not be valid due to the presence of both an offshore reef and physical barriers to the north and south which greatly influence the refractive pattern. The monthly averages of wave height, period and direction are listed in Table 8-3. The number of observations per month (from 3 to 9) permit only the most general conclusions to be drawn. The significant wave heights ranged from 2. 8 ft. in August to 14. 6 ft. in January averaging 7. 2 ft. with the highest waves generated during winter (December through April). The significant wave periods ranged from 5. 2 seconds in July to 17. 8 seconds in February averaging 10. 5 seconds for the year. The long period waves (11 to 12 seconds) occurred in winter from November to May. During the period September - April, the direction of wave approach was from the west; in summer (May-August) they approached from WNW-NW.

The Coastal Engineering Research Center of the U. S. Army Corps of Engineers has established a program to measure wave data at various coastal sites around the United States (Darling and Dumm, 3). The only site located within the study area is off the mouth of the Umpqua River where, in August 1964, a pressure type sensor was installed. Wave data from pressure sensitive devices can provide accurate information provided the pressure fluctuations can be properly converted to fluctuations of the sea surface. Recording is not continuous, however. The available records cover the periods of 13 August - 13 September 1964 and 16 June - 15 August 1966. No analysis has been made of these records as yet; pertinent wave statistics will be published as soon as the analysis is completed.

A prime source of deep water wave data is that measured from offshore oil rigs. These rigs are equipped with automatic wave recording instruments and have their vertical struts marked for visual observations as well. Several articles in industrial journals have reported the measurement of rather remarkable wave heights developed during intense winter storms off the Pacific Northwest coast. One rig survived a storm which generated 58-foot waves (Watts and Faulkner, 4), only to be subjected to another even larger storm which generated a 95-foot wave (SEDCO 135F, 5).

Table 8-3. Monthly wave averages, Newport, Oregon, September 1968-August 1969.

	1968				1969							
	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.
Direction from	272°	276°	268°	277°	280°	271°	282°	283°	292°	297°	320°	324°
Period (sec)	11.4	9.7	12.5	11.5	10.5	11.8	12.3	11.3	11.6	9.3	9.8	7.4
H_{o}(feet)	6.8	7.5	7.0	10.4	9.0	8.3	8.3	8.4	6.1	5.2	6.6	4.5
No. of Obs.	3	6	7	5	6	8	5	8	7	9	9	4

(from Neal *et al.*, 2).

Other large waves recorded from oil rigs are reported by Rogers (6). None of these very large waves represent average wave conditions during a severe storm, but are simply the chance increase in wave height due to constructive interference from several large waves.

Hindcasted Waves

One of the most detailed wave studies for the Pacific Northwest region was conducted by National Marine Consultants in 1960 (7) and 1961 (8). Since equipment to actually measure deep water wave characteristics was not available at the time of the study, the investigators resorted to wave hindcasting techniques employing the spectral energy method of Pierson, Neumann, and James (9). Wave prediction based on spectral theory is obviously not as accurate as prediction based on measured data, but it can provide indicative figures. The accuracy of the hindcast depends on the forecaster's experience and ability to interpret the synoptic weather charts produced by the U.S. Weather Bureau. The forecasters from National Marine Consultants had been making verified wave forecasts for four years prior to this study and were considered to be experienced.

The analyses of the deep water wave statistics were based upon meteorological records and charts for the years 1956, 1957, and 1958 which, when considered collectively, would represent an "average" year. The location of the four deep water stations shown in Figure 8-1 are:

Station	1	42°00'N,	125°00'W	(off California-Oregon border)
	2	44°40'N,	124°50'W	(off Newport, Oregon)
	3	46°12'N,	124°30'W	(off Columbia River)
	4	47°40'N,	125°00'W	(northwest of Grays Harbor, Washington)

The hindcasting method of wave forecasting has been shown to yield varied results based upon the individual judgments of the interpreters (Wiegel, 10). Because of this inherent variability in the results, the analysis by National Marine Consultants was considered to be too detailed for data based upon hindcasting techniques. Therefore, their analysis has been made more general by grouping the data over four octants (N-NW, NW-W, W-SW, SW-S)

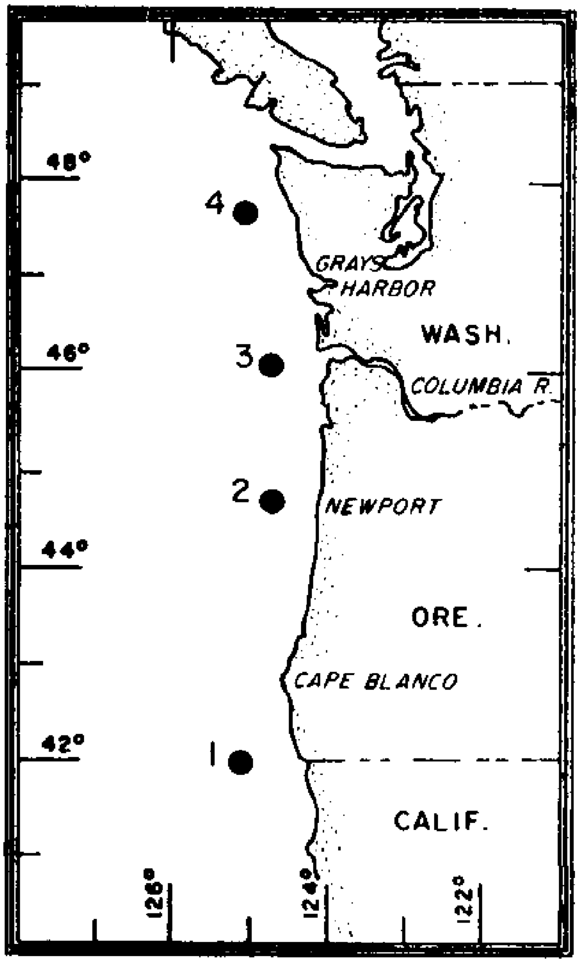

Figure 8-1. Location of deep water hindcast stations (from National Marine Consultants, 8).

and over four seasons (winter, spring, summer, fall). See Tables 8-4 and 8-5. The winter season includes the months of December, January, and February; spring - March, April and May; summer - June, July August and September; and autumn - October and November. These groupings were based on the seasonal wind pattern of this region. The spring and autumn seasons are transitional periods between the more stable climatic seasons of summer and winter. A further generalization was to report only the average value of the significant wave height and period for each octant and season. The standard deviation (S. D.) of each is also presented to provide a measure of variability. In addition, the probable frequency of occurrence for each condition is shown.

The National Marine Consultants' report listed the data in terms of sea and swell, the former being local waves of a random nature located within the storm generation area and the latter being the more uniform waves which were generated from distant storms. Several different trains of swell may be present at the same time; only the height and period of the dominant swell train is reported. Calm periods are those times when no storm was present in the area to generate local waves or "sea." These periods also include the infrequent occasions when the direction of wave approach was offshore.

Analysis of the data listed in Tables 8-4 and 8-5 indicates that general conclusions may be drawn which are common to all four stations. The most important of these are:

1. The predominant direction from which the swell approached was from the NW-W octant during all seasons.

2. The predominant direction from which local seas approached was from SW-SSE during autumn and winter and from N-NW during spring and summer. The frequency with which the seas approached from a particular direction showed more variability than did swell.

3. Waves generated by local storms were generally higher than wave heights of swell.

4. The highest waves regardless of angle of approach always occurred in winter.

Table 8-4. HINDCAST DEEP WATER WAVE HEIGHTS (H_o) FOR THE OREGON AND WASHINGTON COAST

STATION	SEASON	TYPE	N - NW H_o	N - NW S.D.	N - NW %	NW - W H_o	NW - W S.D.	NW - W %	W - SW H_o	W - SW S.D.	W - SW %	SW - SSE H_o	SW - SSE S.D.	SW - SSE %	PERCENT OFFSHORE OR CALM
1	Winter	Swell	5.7	3.5	10.6	5.2	3.3	50.5	5.5	3.5	19.6	3.8	1.1	4.2	
		Sea	4.1	2.4	15.0	6.3	2.9	8.1	6.5	2.8	13.7	8.2	4.0	33.8	20.2
	Spring	Swell	2.9	1.2	15.7	4.8	3.3	65.8	2.7	1.4	13.4	3.3	2.2	5.0	
		Sea	4.5	2.1	41.1	3.5	2.0	4.7	4.5	2.4	10.1	4.0	2.3	17.3	26.9
	Summer	Swell	2.6	1.0	38.8	3.3	1.6	52.9	2.8	1.1	6.6	2.0	0.0	1.5	
		Sea	4.8	2.6	59.5	3.0	1.1	2.8	3.3	1.5	3.9	3.2	1.4	4.7	29.2
	Autumn	Swell	4.8	3.3	25.0	4.7	3.1	64.0	3.3	1.6	9.8	2.7	1.9	1.2	
		Sea	4.6	2.6	27.4	4.3	2.1	5.1	4.2	2.0	9.9	5.0	2.6	18.0	39.7
	Annual	Swell	3.7	2.8	24.8	4.7	3.2	59.4	4.2	3.2	12.7	3.3	2.0	3.1	
		Sea	4.6	2.5	38.3	4.5	2.7	5.0	5.0	3.0	9.1	6.6	4.7	17.3	30.3
2	Winter	Swell	4.5	2.7	10.1	5.4	3.7	52.2	5.2	3.6	24.7	5.6	3.9	13.0	
		Sea	5.6	4.4	7.5	6.9	3.8	10.8	6.2	4.0	14.5	7.9	4.8	37.0	30.1
	Spring	Swell	3.3	2.0	15.7	4.4	2.7	65.7	4.1	3.2	12.4	4.5	3.0	6.2	
		Sea	4.0	2.2	32.8	3.9	2.3	9.6	4.6	2.6	10.4	5.3	3.3	17.4	29.7
	Summer	Swell	2.9	1.7	33.3	3.3	1.7	59.5	3.2	1.4	4.4	3.5	1.3	2.8	
		Sea	3.8	2.1	51.4	2.7	1.0	4.8	3.2	2.4	5.6	4.2	2.7	8.8	29.5
	Autumn	Swell	4.8	3.2	17.8	5.1	3.6	68.4	3.7	2.5	7.1	3.8	2.6	6.7	
		Sea	4.2	2.8	17.4	5.1	2.4	7.1	4.7	3.1	15.7	5.9	4.1	25.1	35.3
	Annual	Swell	3.6	2.4	18.8	4.8	3.2	60.5	4.6	3.4	13.2	4.8	3.7	7.5	
		Sea	4.0	2.5	30.0	4.7	3.2	7.8	5.0	3.3	10.8	6.5	4.4	20.6	31.0
3	Winter	Swell	4.8	2.7	5.2	5.4	3.4	50.4	4.9	3.5	29.6	5.3	3.6	14.8	
		Sea	5.6	4.0	5.1	7.0	3.9	11.7	6.5	3.9	13.9	8.3	5.0	37.9	31.4
	Spring	Swell	3.3	2.0	11.5	4.3	2.6	63.7	3.8	2.4	16.3	4.1	2.7	8.5	
		Sea	3.9	2.2	27.6	4.1	2.3	11.4	4.6	2.7	10.0	5.4	3.5	19.0	32.1
	Summer	Swell	2.8	1.8	22.1	3.4	1.7	66.0	3.2	2.2	8.6	2.6	0.3	3.3	
		Sea	3.6	2.0	44.3	3.0	1.6	10.5	2.9	1.6	7.4	4.6	3.3	11.0	26.9
	Autumn	Swell	5.1	4.6	6.0	5.2	3.3	74.5	4.5	3.3	11.1	3.9	2.9	5.4	
		Sea	5.0	3.0	12.8	4.9	2.3	8.0	5.8	3.2	15.8	6.3	4.2	24.6	39.0
	Annual	Swell	3.3	2.5	11.1	4.5	3.0	52.4	4.3	3.2	17.4	4.6	3.4	9.1	
		Sea	3.9	2.8	25.0	4.6	3.2	10.5	5.2	3.3	11.0	6.7	4.5	21.9	31.8
4	Winter	Swell	4.1	0.7	0.5	5.4	3.4	46.9	4.5	2.6	33.1	5.0	3.3	19.5	
		Sea	5.1	3.0	5.6	7.1	3.7	11.6	6.8	3.2	11.1	8.1	4.8	46.9	24.8
	Spring	Swell	2.0	0.0	1.6	4.0	2.0	63.2	3.8	2.6	25.4	3.9	2.3	9.8	
		Sea	4.1	2.2	22.2	4.7	3.0	14.4	5.2	3.1	10.1	5.4	3.4	22.7	30.5
	Summer	Swell	3.2	1.4	3.1	3.3	1.8	72.7	2.9	1.5	16.1	3.3	2.6	2.5	
		Sea	3.7	2.1	33.6	3.6	2.0	14.5	3.0	1.6	11.5	4.6	3.0	16.6	23.9
	Autumn	Swell	—	—	—	5.4	3.5	73.0	3.9	2.9	17.8	4.3	3.3	9.4	
		Sea	5.4	2.8	10.7	5.7	3.5	9.7	5.5	3.2	13.6	6.3	4.2	35.5	30.2
	Annual	Swell	2.7	1.5	2.2	3.8	2.8	62.4	4.4	2.9	24.4	4.7	3.4	11.0	
		Sea	4.0	2.5	20.0	4.9	3.4	12.9	5.0	3.4	11.3	6.7	4.5	28.8	27.0

Table 8-5. HINDCAST WAVE PERIODS (T_o) FOR THE OREGON AND WASHINGTON COAST

STATION	SEASON	TYPE	N - NW T_o	N - NW S.D.	N - NW %	NW - W T_o	NW - W S.D.	NW - W %	W - SW T_o	W - SW S.D.	W - SW %	SW - SSW T_o	SW - SSW S.D.	SW - SSW %	PERCENT OFFSHORE OR CALM
1	Winter	Swell	9.8	2.2	19.6	10.5	2.6	56.6	10.4	2.6	19.6	9.4	1.2	4.2	
		Sea	6.9	1.5	15.0	7.1	1.6	8.1	7.6	1.8	13.7	8.1	1.9	33.8	29.2
	Spring	Swell	9.9	1.7	15.7	10.6	2.4	55.8	10.2	1.8	13.4	9.4	1.6	5.0	
		Sea	6.9	1.3	41.1	6.2	1.1	4.7	6.9	1.4	10.1	6.8	1.6	17.3	26.9
	Summer	Swell	9.9	1.4	38.8	10.3	2.2	52.9	9.3	0.3	6.6	11.0	0.0	1.5	
		Sea	6.9	1.7	59.5	5.6	0.7	2.8	5.9	1.1	3.9	5.9	1.1	4.7	29.2
	Autumn	Swell	10.2	2.2	25.0	10.6	2.5	54.0	9.5	1.4	9.8	9.3	0.5	1.2	
		Sea	6.9	1.6	27.4	6.7	1.5	5.1	6.7	1.5	9.9	7.1	1.6	16.0	39.7
	Annual	Swell	10.0	1.9	24.8	10.4	2.5	59.4	10.0	2.2	12.7	9.7	1.6	3.1	
		Sea	6.9	1.5	38.3	6.4	1.2	5.0	6.8	1.4	9.1	7.0	1.3	17.3	30.3
2	Winter	Swell	10.0	2.3	10.1	10.7	2.8	52.2	10.2	2.7	24.7	9.4	1.7	13.0	
		Sea	6.8	1.9	7.5	7.3	1.6	10.8	7.3	1.8	14.5	7.9	2.1	37.0	30.1
	Spring	Swell	10.3	1.8	15.7	10.7	2.6	65.7	10.5	2.0	12.4	9.1	1.2	6.2	
		Sea	6.3	1.4	32.8	6.2	1.3	9.6	6.6	1.4	10.4	6.8	1.6	17.4	29.7
	Summer	Swell	9.4	1.8	33.3	10.4	2.3	59.5	8.9	2.0	4.4	8.6	0.9	2.8	
		Sea	6.2	1.4	51.4	5.4	0.8	4.8	5.8	1.5	5.6	6.0	1.6	8.6	29.5
	Autumn	Swell	10.3	2.3	17.8	10.8	2.7	68.4	10.0	1.9	7.1	9.6	1.4	6.7	
		Sea	6.2	1.5	17.4	6.6	1.5	7.1	8.5	2.0	15.7	7.1	2.0	25.1	36.3
	Annual	Swell	9.8	2.1	18.8	10.5	2.8	60.5	10.4	2.4	13.2	9.4	1.5	7.5	
		Sea	6.3	1.5	30.0	6.6	1.7	7.8	6.8	1.6	10.6	7.3	2.0	20.8	31.0
3	Winter	Swell	10.0	2.4	6.2	10.8	2.7	50.4	10.9	2.4	29.6	9.6	1.8	14.8	
		Sea	7.0	2.1	5.1	7.6	2.0	11.7	7.6	1.6	13.9	8.1	2.0	37.9	31.4
	Spring	Swell	10.0	1.8	11.5	10.8	2.3	63.7	10.3	2.0	16.3	9.1	1.6	6.5	
		Sea	6.2	1.5	27.6	6.3	1.3	11.4	5.5	1.4	10.0	5.9	1.7	19.0	32.1
	Summer	Swell	9.4	1.6	22.1	10.2	2.3	66.0	9.7	1.8	8.6	8.2	0.5	3.3	
		Sea	6.0	1.3	44.3	5.6	1.0	10.5	5.6	1.0	7.4	6.6	1.7	11.0	26.9
	Autumn	Swell	10.1	2.3	6.0	9.6	3.2	74.5	10.6	2.4	11.1	9.6	1.4	6.4	
		Sea	6.6	1.6	12.6	6.9	1.4	6.0	6.9	1.6	15.8	7.2	2.0	24.6	39.0
	Annual	Swell	9.7	1.9	11.1	10.6	2.5	62.4	10.5	2.4	17.4	9.5	1.6	9.1	
		Sea	6.2	1.5	25.0	6.5	1.7	10.5	6.8	1.7	11.0	7.4	2.0	21.9	31.6
4	Winter	Swell	9.6	1.5	0.5	10.5	2.7	46.9	10.9	2.7	33.1	9.7	1.8	19.5	
		Sea	6.7	1.5	5.6	7.8	1.9	11.6	7.6	1.6	11.1	8.4	1.6	46.9	24.8
	Spring	Swell	8.8	1.4	1.6	10.6	2.5	63.2	10.7	2.3	25.4	9.4	1.3	9.6	
		Sea	6.4	1.4	22.2	6.6	1.6	14.4	6.9	1.6	10.1	7.0	1.7	22.7	30.5
	Summer	Swell	9.2	0.6	3.1	10.2	2.2	72.7	10.0	2.0	18.1	8.9	1.2	2.5	
		Sea	6.4	1.2	33.6	6.0	1.3	14.5	5.6	1.0	11.5	6.4	1.6	16.6	23.9
	Autumn	Swell	—	—	—	10.6	2.6	73.0	10.6	2.5	17.6	9.7	1.4	9.4	
		Sea	7.1	1.4	10.7	7.2	1.7	9.7	6.9	1.9	13.6	7.2	1.9	36.5	30.2
	Annual	Swell	9.0	1.5	2.2	10.6	2.5	62.4	10.6	2.5	24.4	9.6	1.7	11.0	
		Sea	6.3	1.5	20.0	6.7	1.8	12.9	6.7	1.8	11.3	7.4	1.9	28.8	27.0

5. Throughout the year the highest waves came from the SW-SSE octant.

6. The period of the swell was always greater than the period of the locally generated wind waves.

7. The shortest periods for both sea and swell occurred during summer.

8. The longest swell periods generally occurred during autumn; the longest sea periods occurred during winter.

9. Throughout the year the longest period swell generally approached from NW-W. At stations 2 and 3 long period swell also approached from the W-SW octant.

10. During all four seasons the longest period sea generally approached from the SW-SSE octant.

11. During all four seasons the periods of calm occurred with about the same frequency, 25-30%; the season of greatest calm was autumn.

Wave Steepness

Based on data from the National Marine Consultants' report (8) for a station 20 miles west of the Columbia River, Ballard (11) has calculated the wave steepness and its effect on sediment transport. The steepness of a wave is defined as the ratio of the wave height to its length (H_o/L_o) and is a critical factor in determining its capacity to move sediment (Saville, 12). The steepness values computed from annual average conditions for both sea and swell were divided into three groups and the relative frequency of occurrence within each group determined for various wave directions (Table 8-6). Most of the swell (81.5%) fell in the H_o/L_o range of <0.015 while local seas were dominant (90.3%) in the 0.015 to 0.025 range.

Waves with steepness values in the 0.015 to 0.025 range result in the greatest amount of sediment movement (12). Ballard has plotted the relative frequency of waves in this range for various wave directions

Table 8-6. Relative frequency of waves with given steepness (H_o/L_o) values from various directions. Values represent average annual conditions for the years 1956, 1957, and 1958.

H_o/L_o	Condition	Percent occurrence from various wave directions										
		N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	Σ
<0.015	sea	---	---	---	---	---	---	---	0.1	---	---	0.1
	swell	---	0.6	9.0	24.2	26.4	10.2	4.7	4.0	2.3	0.1	81.5
0.015-0.025	sea	4.8	6.9	22.2	5.9	8.5	4.8	9.4	10.2	13.8	3.8	90.3
	swell	---	0.1	1.3	5.6	4.9	1.9	1.4	1.7	0.9	0.1	17.9
>0.025	sea	0.4	0.5	1.7	0.6	0.5	0.8	1.3	1.2	1.8	0.8	9.6
	swell	---	---	0.1	0.1	0.2	0.1	0.1	---	---	---	0.6

(from Ballard, 11).

as shown in Figure 8-2. The predominance of local seas over swell in this range is evident. The inset of Figure 8-2 shows the effect of summing up the frequency of occurrence for both sea and swell from north-of-west and from south-of-west. The nearly equal frequencies of occurrence imply no net movement of sediment or a tendency to keep it localized.

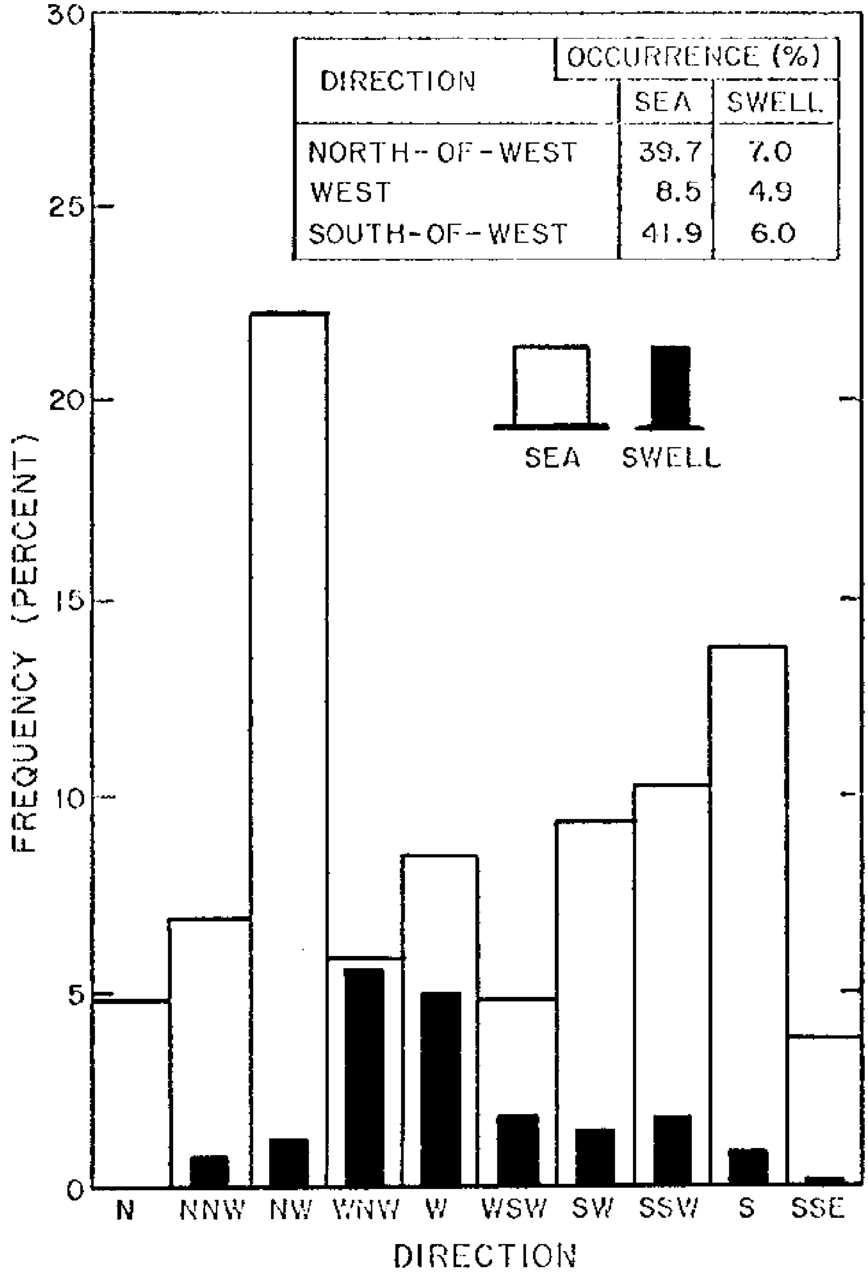

Figure 8-2. Relative frequency and direction of deep-water waves with steepness values of H_o/L_o = 0.015 to 0.025. All values represent average annual wave conditions. (from Ballard, 11).

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Chapter 9. COASTAL CURRENTS

Introduction

The circulation of ocean waters in the shallow coastal zone examined in this review (the area within 10 nautical miles of the coast) has not been investigated in any detail. Measurements of current velocities in these coastal waters are extremely sparse. Those measurements that have been made indicate that steady flow is not a common occurrence, but rather eddy flow and current reversals with tide or wind are more characteristic of the nearshore circulation.

Because of the many forces present to produce currents in coastal areas, current speed and direction are highly variable. Some nearshore currents have been found to respond to the changing forces on a time scale of about one hour (Neal, et al., 1). Due to this variability average spatial as well as temporal values are usually reported. In regions where local topography influences the interaction of the driving forces the current may move as an eddy fluctuating widely in both speed and direction. For such areas average values may be meaningless. This is perhaps the reason why some offshore oil spills have been found to disperse in directions quite different from that predicted.

The primary forces that produce coastal currents are winds, main ocean currents, and tides. Of lesser importance are the current contributions from waves and pressure gradients.

Wind currents take place mainly on the surface. The extent of this surface layer is still under investigation, but recent studies indicate wind driven water motion to a depth of about 10 meters. Tidal wave motion is a so-called "shallow water" phenomenon and extends theoretically to the bottom of the oceans. Tidal currents, therefore, are generally thought to be essentially constant with depth in nearshore regions. Currents due to wind waves (swell) decrease logarithmically with depth and are essentially negligible at a depth equal to one-half the wave length.

Main Ocean Currents

The circulation of the main ocean currents off the Oregon-Washington coast is known only in general terms. The detailed circulation pattern is still a topic demanding extensive investigation. In general, the California Current is a broad, slow, and shallow southward flowing current. It flows offshore as a diffuse band about 300 miles wide with an average speed of 0.2 knots (0.34 ft/sec). It attains maximum strength during the summer when surface winds are consistently from North-Northwest.

The Davidson current as reported by Schwartzlose (2) is a seasonal northward flowing current attaining speeds of at least 0.5 to 0.9 knots over extensive distances. It has a minimum width of 50 miles. The current develops off the Oregon-Washington coast in September and becomes well established by January. Towards spring it diminishes and disappears by May. The driving force of the Davidson Current is not well understood. Off Oregon it appears to result from local wind stress (Ingraham, 3), but Reid and Schwartzlose (4) report it as not due to the local winds but to some larger scale phenomenon. Their direct measurements indicate support for the concept advanced by Sverdrup, et al., (5) that the Davidson Current is a surface manifestation of a deeper northward flowing counter current that develops when the winds weaken seasonally.

Tidal Currents at Pacific Northwest Lightships

Coastal tidal currents found 5 miles (9 km) offshore, as observed by lightships along the Pacific Coast, are reported in the Tidal Current Tables (U.S.C. and G.S., 6). The currents are rotary, turning clockwise, with a 12.5 hour period. Spring and neap tides, which occur biweekly, increase and decrease, respectively, the average tidal current by about 20 percent. Frequently, wind driven currents and other nontidal currents are of such strength as to completely mask the tidal current. These nontidal currents must be vectorially added to the tidal current to obtain the resultant current.

The tidal currents measured at the Blunts Reef Lightship off Cape Mendicino show very weak rotary characteristics with average speeds of less than 0.1 knots (0.17 ft/sec). At maximum flood the current sets north; at maximum ebb it sets south. The tidal current is generally masked by a nontidal current averaging 0.2 knots (0.34 ft/sec) setting towards the southwest from March to November and towards the northwest from November to March. The greatest observed velocity at the lightship is 3.0 knots (5.1 ft/sec).

The tidal currents observed at the Columbia River Lightship are also rotary, but rather weak, averaging about 0.3 knots (0.51 ft/sec). The set of the maximum flood and ebb currents are 020° T and 200° T, respectively. The discharge from the Columbia River completely masks the flood current at the lightship. The set of the nontidal current created by the river flow changes from SW (235°T) during February through October to WNW (295°T) from October to February in response to the seasonal wind pattern. The nontidal current speed ranges from a monthly average of 15 cm/sec (0.45 ft/sec) in March to 39 cm/sec (1.28 ft/sec) in June (Duxbury, et al., 7). During periods of high river runoff the combined tidal and nontidal current frequently is 2.0 knots (3.4 ft/sec) or greater to the SW. The greatest observed velocity at the lightship is 3.5 knots (5.9 ft/sec). At the river mouth between the north and south jetties surface currents measured by the U.S. Army Corps of Engineers (8) were 300 cm/sec (9.8 ft/sec) on ebb and 120 cm/sec (3.9 ft/sec) on flood during June. In September these values had changed by 240 cm/sec (7.9 ft/sec) on ebb and 180 cm/sec (5.9 ft/sec) on flood.

The tidal currents at the Umatilla Reef Lightship off Cape Arago, Washington are weakly rotary. Maximum currents occur 15 minutes after maximum flood or ebb is observed at the entrance to the Straits of Juan de Fuca. The average velocity of flood and ebb currents is 0.3 knots (0.51 ft/sec) setting 345°T on flood and 165°T on ebb. Wind driven currents usually mask the tidal current. From November to April the flow is northerly (350°T) at 0.7 knots (1.2 ft/sec) peaking to 1.0 knots (1.7 ft/sec) during December; from April to November the current is variable, generally setting SE at an average speed of 0.4 knots (0.68 ft/sec). The strong southeasterly winds of winter produce a combined current of 2 to 3 knots. The greatest observed velocity at the lightship is 3.3 knots (5.6 ft/sec).

Because changes in wind direction and speed may alter the wind driven currents, tables have been prepared to account for these changes (6). Table 9-1 shows the increase in current speed due to increasing wind speeds. The number of degrees by which the wind driven current deviates to the right or left of the wind direction is listed in Table 9-2. This deflection of the wind driven current, as measured approximately 5 miles offshore, appears to be primarily due to coastline configuration rather than geostrophic effects.

Grays Harbor, Washington

A literature survey of this area conducted by the Oceanography Department of the University of Washington (9) describes the average flood and ebb currents at the harbor entrance as generally onshore-offshore at 2.5 knots (4.2 ft/sec). Velocities in excess of 5.0 knots have been reported. The estimated velocity at a depth of 120-180 feet off the harbor entrance is 0.4-0.5 knots. The littoral current is generally northward although affected by the prevailing winds. In summer there is an occasional flow to the south with a maximum velocity of about 1.5 knots (2.5 ft/sec). The maximum velocity in winter when the flow is northward is about 4.0 knots (6.8 ft/sec).

Table 9-1. Average speed of current due to winds of various strength.

Wind velocity (mph)	10	20	30	40	50
Average current (knots) due to wind					
Blunts Reef	.2	.3	.4	.7	.8
Columbia River	.4	.5	.6	.8	.8
Umatilla Reef	.2	.6	.9	1.0	.9

Table 9-2. Average deviation of current to Right or Left of wind direction.

Wind from (in degrees)	Blunts Reef		Columbia River		Umatilla Reef	
	L	R	L	R	L	R
N		20		35		44
NNE		6		27		18
NE		10		9		34
ENE		32		29		48
E		28		17		52
ESE		7		2		38
SE	11		8			25
SSE		13	7			6
S		1	19		6	
SSW	11		44		13	
SW	18		74		32	
WSW	28		121		52	
W	60			145	77	
WNW		2		105	6	
NW		31		78		37
NNW		43		53		25

(from Tidal Current Tables, 6).

Depoe Bay, Oregon

An extensive study was made of the nearshore water movement off Depoe Bay by Mooers, et al. (10) from moored current meters and thermographs during August and September, 1966. Three arrays were anchored at 5, 10, and 15 miles off the coast (DB-5, DB-10, and DB-15). The current meters were spaced at a depth of 20 meters and 60 meters from the surface.

When the current speed and direction vectors for each recording time increment are progressively summed (tail of one vector placed against tip of preceding vector), a progressive vector diagram (PVD) results. PVD's for DB-5 (20m and 60m), DB-10 (20m), and DB-15 (60m) are plotted in Figure 9-1. Several conclusions can be drawn from these PVD's: (a) The flow at 20 meters is to the south, and at 60 meters is to the north; (b) The flow tends to follow the local topography, except for DB-15 (60 meters) where a strong onshore component is present; (c) There are frequent wiggles in the curves associated with tidal-like motions; (d) Periods of acceleration and deceleration in speed and reversals in flow direction are easily seen, e.g., at DB-5 (60 meters) the current changed direction three times within 20 days.

A summary of the basic current data is presented in Table 9-3. The vector mean speed and direction at 20 meters depth, five miles off the coast, is 18.0 cm/sec (0.54 ft/sec) flowing southward (187°T). At 60 meters depth the mean vector speed has been reduced to a third of that at 20 meters and changed direction by almost 180° to 028°T. Histograms of current speed and direction and current velocity components for DB-5, 20 meters and 60 meters, are shown in Figures 9-2 and 9-3, respectively. These histograms are essentially unimodel indicating a predominance in velocity and direction.

Table 9-3. Mean current measured off Depoe Bay, 15 August-24 September, 1966 based on a 10-minute sampling rate. S. D. is standard deviation.

Depoe Bay Station	Depth (m)	N (No. of days)	U (cm/sec) Mean±S. D.	V (cm/sec) Mean±S. D.	Scalar Speed (cm/sec) Mean±S. D.	Vector Mean Speed (cm/sec)	Vector Mean Direction Deg. True
5	20	14.5	-2.1±11.4	-17.9±11.8	23.4±7.0	18.0	187
	60	35.4	2.7± 6.7	5.1±12.6	14.3±5.8	5.8	028
10A	20	37.1	-0.8±11.0	-13.6± 8.6	18.4±6.3	13.6	183
15	60	39.8	4.8± 7.6	3.9± 8.5	12.5±3.4	6.1	051

(modified from Mooers et al., 10)

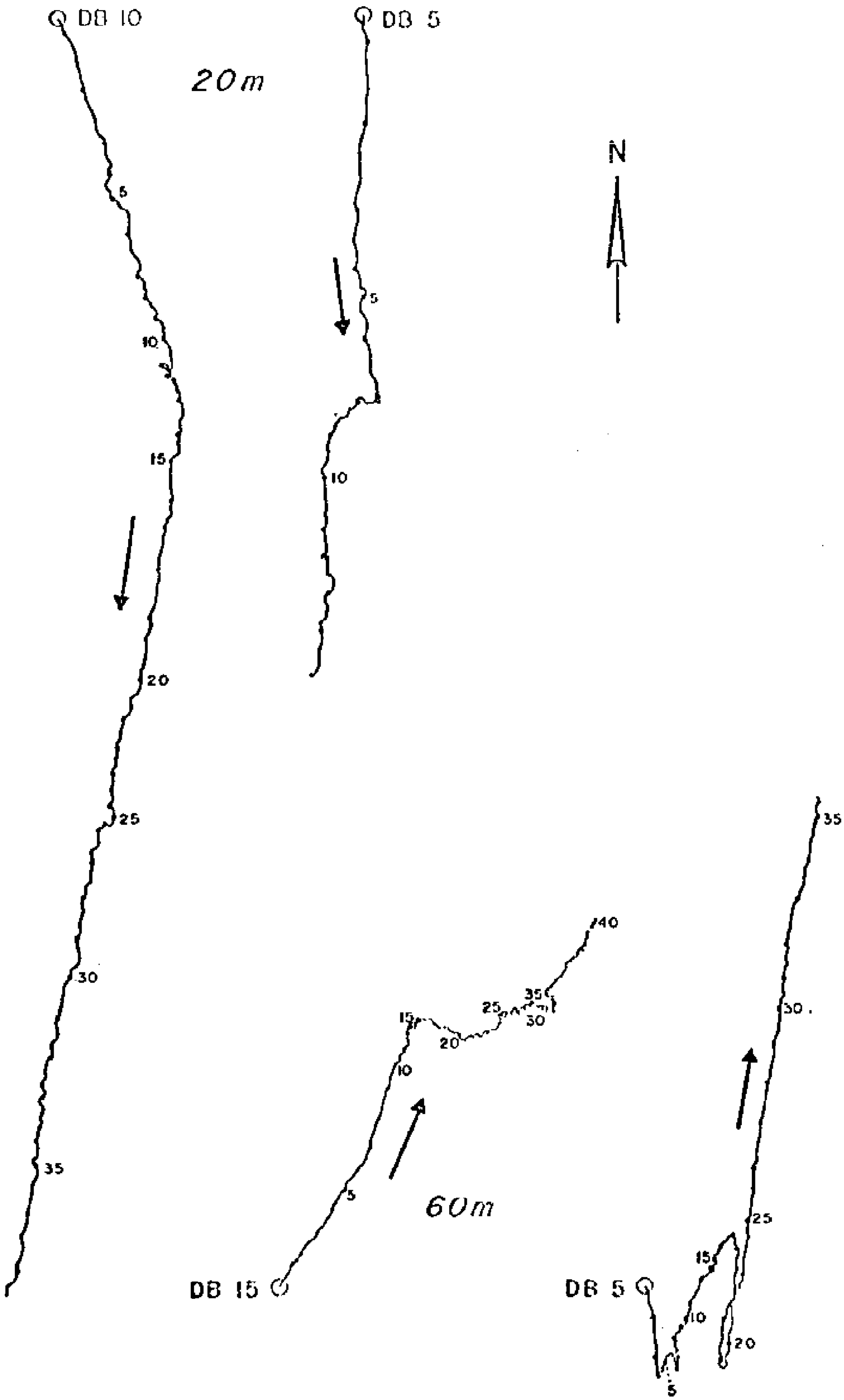

Figure 9-1. Progressive vector diagrams of currents, Depoe Bay array, 15 August-24 September 1966. The figures indicate the number of days since commencement of current meter recordings (from Mooers, et al., 10).

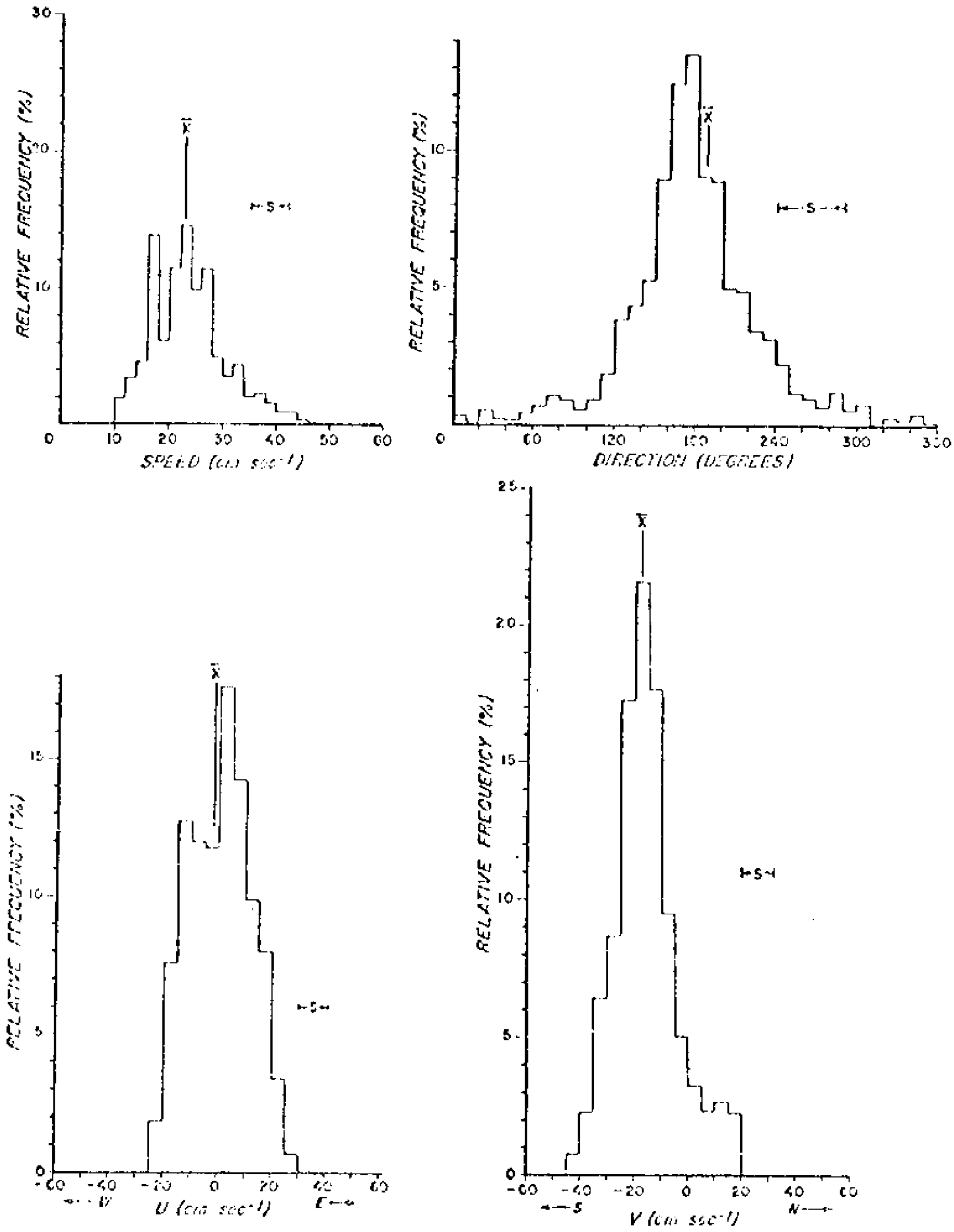

Figure 9-2. Histograms of current speed, direction, and velocity components measured 5 miles off Depoe Bay at 20 meters depth (from Mooers, et al., 10).

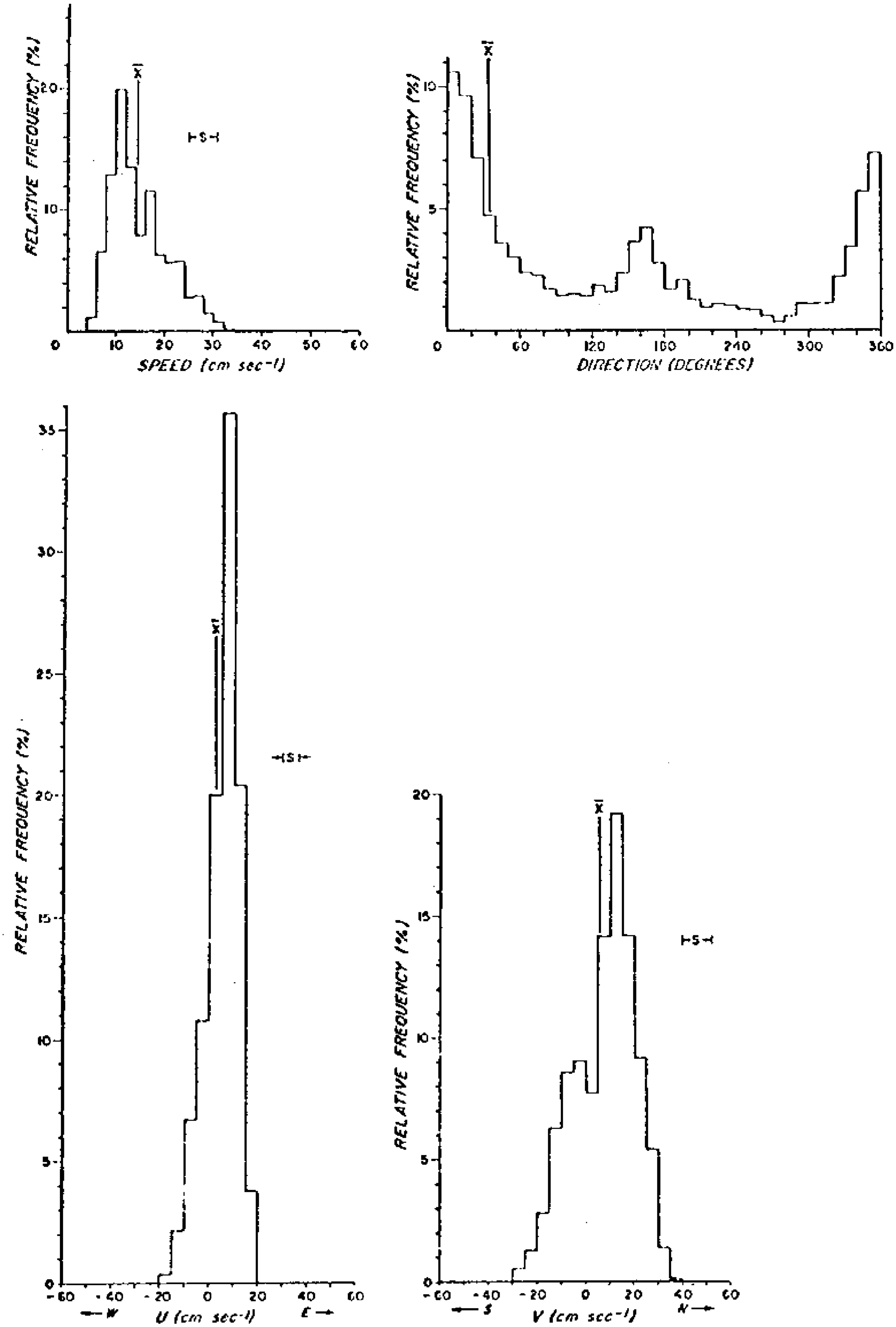

Figure 9-3. Histograms of current speed, direction, and velocity components measured 5 miles off Depoe Bay at 60 meters depth (from Mooers, et al., 10).

In order to establish the vertical structure of the horizontal current; vertical profiles of current velocity were made at DB-5, 10, and 15 using a Savonius rotor current meter. These profiles, as drawn in Figure 9-4, show that at each station a subsurface minimum and a deeper maximum exist. No directions are given as these are single profiles and current direction is known to be highly variable over a tidal cycle. The speed minimum occurs at a depth near the base of the thermocline while the depth of the deeper maximum is associated with the base of the permanent pycnocline.

Additional nearshore current data is available from current meter arrays located off Depoe Bay and Yaquina Head during the summers of 1967 through 1969. Analysis and conclusions for the 1967 and the 1968 surveys are nearly complete (Pillsbury, Smith, and Pattullo, 11). The analysis of the 1969 data is incomplete.

Newport, Oregon

A recent report by Neal, et al. (1) discusses the currents near an ocean outfall off Newport. Due to topographic features (a shallow offshore reef, a prominent headland to the north, and a long jetty to the south) the currents are quite variable and unpredictable exhibiting the characteristics of a large eddy. The dominant driving force appears to be the wind, but many exceptions are noted. The current appears to deviate to the left of the wind direction for wind speeds less than 10 knots and to the right for wind speeds greater than 10 knots. South of Yaquina Head the predominant current direction was towards the beach. Near the ocean outfall off Newport the flow was either northeast or southwest. North of the jetties current flow was generally to the west.

Off Newport the littoral drift varies seasonally although the dominant yearly drift along the coast is believed to be north (Kulm, et al., 12). From November-December to March the drift is northward reversing direction from April to October-November. Neal, et al. (1) however, report from drift bottle studies that the longshore currents are definitely not sustained since at times the currents are in opposite directions at different portions of the beach. They found that the currents were about evenly divided between northerly flow and southerly flow throughout the year except during summer (June-August) when the waves were consistently out of the NW. Measured values of the longshore current velocity ranged from zero to over 1.6 ft/sec.

Additional current data is available from the work of James and Burgess (13) who have used aerial photography and drift cards in plume dispersion studies off Newport. Surface current speed and direction can be calculated from this data, but at present no analysis has been undertaken for this purpose. Their aerial studies, however, do corroborate Neal, et al's findings that the outfall plume direction is quite variable and disperses in all directions.

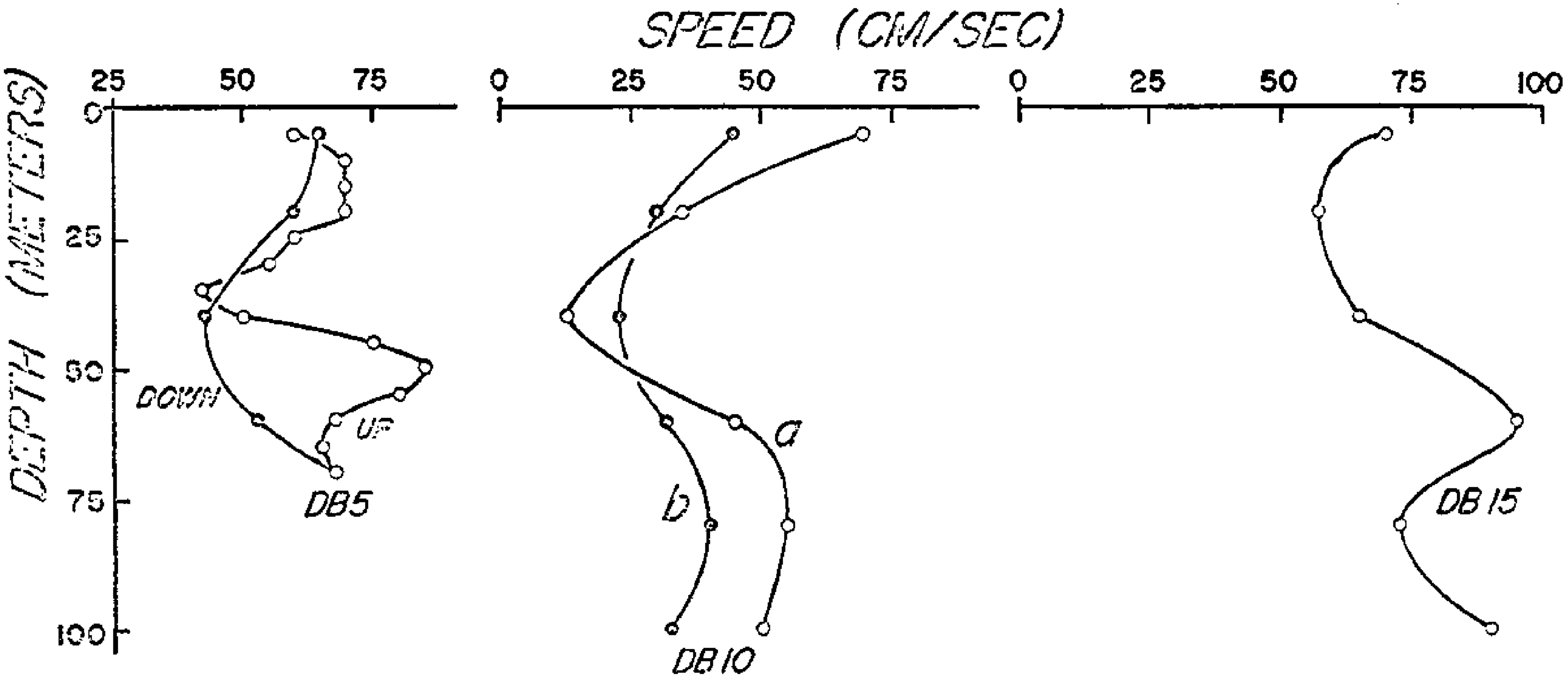

Figure 9-4. Vertical profiles of current speed 5, 10, and 15 miles off Depoe Bay, 23-24 September 1966 (from Mooers, <u>et al.</u>, 10).

Goodwin, Emmett and Glenne (14) measured tidal heights and currents in the Yaquina, Alsea and Siletz estuaries. Higher flood velocities than ebb velocities were observed, a characteristic typical of "choked" estuaries. In the Yaquina estuary entrance a maximum flood velocity of about 2.4 ft/sec was observed. Near Walport in the Alsea estuary a maximum flood velocity of about 3.0 ft/sec was measured. Near Taft in the Siletz estuary entrance a maximum flood velocity of about 6.7 ft/sec was found. In all three estuaries an approximate 90° phase lag existed between tidal heights and tidal currents. No attempts were made to track the estuary flows offshore.

Coos Bay, Oregon

From a literature survey similar to that undertaken for Grays Harbor, Washington (15), the average tidal current velocity is listed as 2.0 knots (3.4 ft/sec). Maximum ebb currents up to 7 knots (11.8 ft/sec) and flood currents of 3.5 knots (5.9 ft/sec) have been reported. The estimated velocity at a depth of 120-180 feet off the entrance is 0.4-0.5 knots. The littoral current is southerly in summer due to winds from the northwest and reversed in winter.

Trinidad Head to Eel River, California

From an investigation undertaken for the California Water Pollution Control Board, Humboldt State College has published a review of its oceanographic study of the nearshore area of Northern California (16). The current pattern of this region is one of eddies superimposed on the California and Davidson currents. The headlands of Cape Mendicino and Trinidad Head, the jetties of Humboldt Bay, and the Eel River canyon all contribute to a mixed circulation pattern. Tidal currents, most pronounced near the entrance to Humboldt Bay, dominate the flow when other influencing factors are minimal. Nearshore currents have been correlated with wind conditions, but a lag effect of unstated duration was noted when the correlation was poor. Based upon a variety of observational methods, the current direction for each month from January to June (1959-1961) is presented in Table 9-4. Throughout this period the predominant observed direction was southward. Northward flow was observed most frequently during winter (January-February).

Table 9-4. Summary of observations of surface current direction for January-June, 1959-1961, between Trinidad Head and Cape Mendocino

Flow Direction	Jan	Feb	Mar	Apr	May	June	Total
South	27	20	23	24	28	24	146
North	33	15	13	18	7	11	97
West	3	1	1	0	0	0	5
East	5	2	2	2	1	1	13
None	1	0	1	5	0	1	8

(from Humboldt State College, 16)

Bottom Currents

The scouring action and differential forces acting on structures and outfall pipes embedded in the ocean bottom are problems associated with near bottom currents (Brown, 17). When current velocities are of appreciable magnitude, the bottom sediment may be loosely compacted with considerable material in suspension. Such conditions invite severe scouring and sedimentation near industrial cooling water intake and outlet structures, piers, jetties, and other submerged structures.

Direct measurements of near bottom currents are difficult to make and usually require special equipment. Few direct measurements are available. Observations along the Pacific Northwest coast have been made from sea bed drifters and moored current meters.

As reported in the section under Depoe Bay (10), the direction of current flow measured at 60 meters (20 meters above the sea floor) was opposite to that measured near the surface (20 meters depth) (Table 9-3). At a point 5 miles off the coast for a period of 35 days during the summer the near bottom resultant current (vector mean current) was 5.8 cm/sec (0.19 ft/sec) at 028° T. The mean scalar speed was 14.3 cm/sec (0.47 ft/sec). Fifteen miles off the coast at 60 meters depth the resultant current was 6.1 cm/sec (0.20 ft/sec) at 051° T, an increase in the onshore component probably due to the increased depth. The mean scalar speed was 12.5 cm/sec (0.41 ft/sec).

Over the continental shelves of Washington and Oregon for water depths below 200 meters Dodimead, Favorite, and Hirano (18) reported the current flow to be northward based on geostrophic calculations. This deep northward flowing current was corroborated by Ingraham (3) who also employed the geostrophic technique.

The first direct measurement of the near bottom current off the Washington coastline was made by Gross, Morse, and Barnes (19) using sea bed drifters, a saucer-like disk and stem arrangement which drifts a few meters above the bottom. Data analysis is essentially the same as that employed with surface drift bottles. Over the inner continental shelf (waters < 40 meters deep) the flow was towards the coast apparently responding to the influence of waves and the ascending-shoreward motion of coastal upwelling. Speeds ranged from 0.7 to 2.5 km/day (0.03 to 0.09 ft/sec) averaging about 1.6 km/day (0.06 ft/sec). Within 10 km of the Columbia River mouth the flow was towards the river mouth at approximately 1.4 km/day (0.05 ft/sec). For shelf waters in excess of 40 meters depth the dominant flow was northward.

These measurements were made over a period of three years which indicates that these flows are persistent throughout the year. Seasonal variability in the flow of the near bottom current has not been determined.

The prediction of bottom currents may be calculated to an order of magnitude by investigating the relationship between current speed and the size of the sediment found on the sea bed. A review of previous investigations in this area and the development of a more general relationship is presented by Panicker (20). For currents over a downhill slope he proposes

$$U = V_s / K\alpha \qquad 9\text{-}1$$

where U is the average velocity of the bottom current,

V_s is the average velocity of the sediment,

α is the bottom slope, and

K is the portion of available turbulent energy released by the suspended particle to maintain it in suspension; proposed to be of the order of 0.1.

A calculation of maximum depths where wave motion tends to move sediments is carried out in Chapter 3 in the section on Sediment Motion.

Current Flow under the Influence of Coastal Upwelling

During the summer months, June through September, the process of coastal upwelling occurs along the Oregon coast (Bourke, 21). The north-northwesterly summer winds produce a southward flow in the surface layer and also an offshore surface flow due to the earth's rotation. This causes cold, saline water to upwell in eddies and form a rise in both the seasonal and permanent pycnoclines (Figure 9-5). The seasonal pycnocline (region of strong density gradients) breaks to the surface forming a surface front approximately 10 to 20 kilometers offshore. Shoreward of the surface front the waters take on the characteristics associated with upwelling - relatively low temperatures, low dissolved oxygen content, and high salinities. Seaward of the surface front the surface temperature may be 5 to 7C° warmer than the surface waters in the upwelling region. Other indicators of upwelled water would be increased alkalinity, inorganic phosphate, and hydrogen ion concentration (Park, et al., 22).

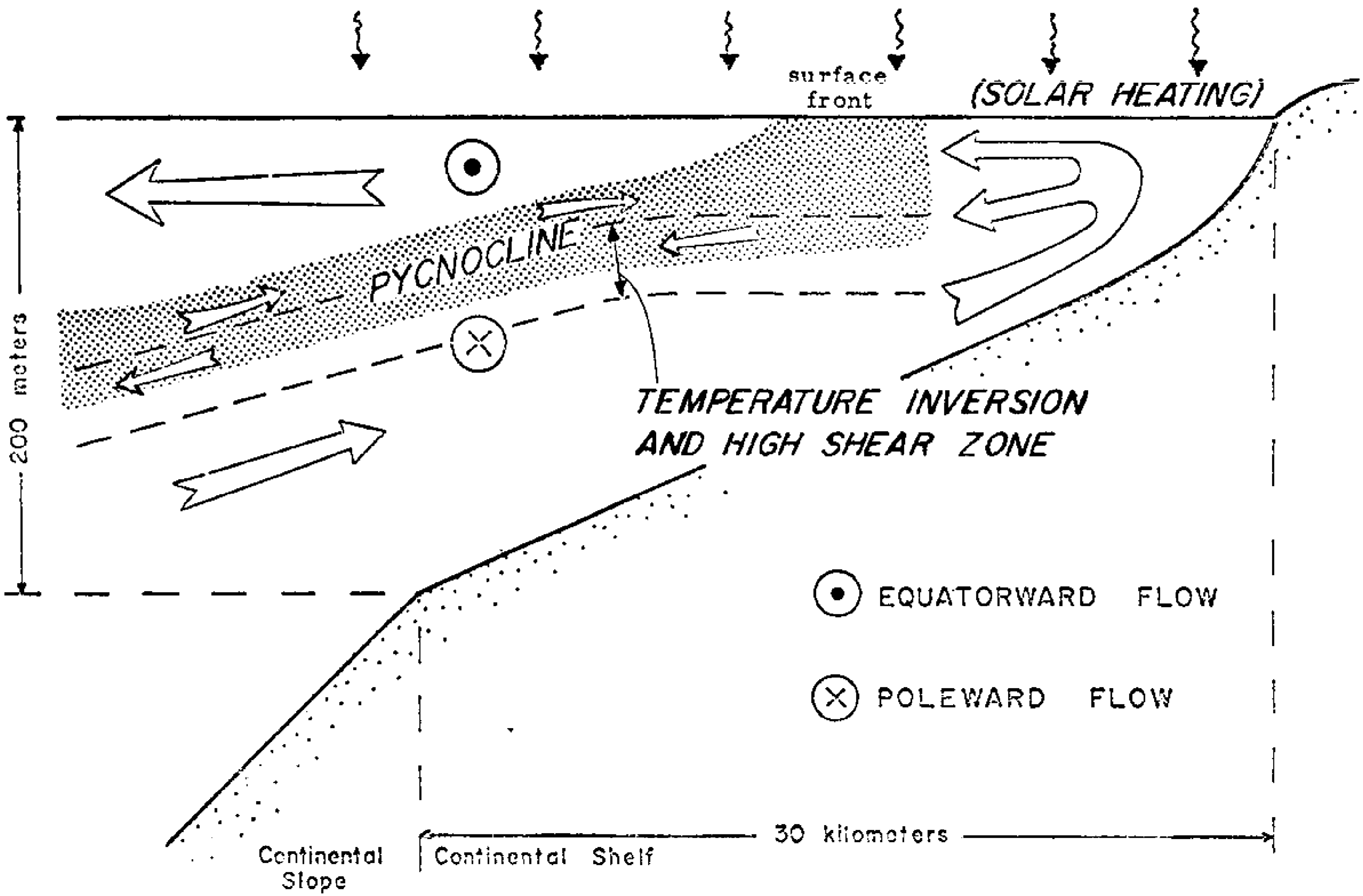

Figure 9-5. The mean current of the frontal zone in the coastal upwelling region off central Oregon (from Mooers, 23).

The following summary of the general flow pattern for the coastal upwelling region off central Oregon during the upwelling season (Figure 9-6) is taken from that postulated by Mooers (23).

1. The flow is southward in the upper 40 meters of the water column.

2. The flow is northward below 40 meters tending to concentrate beneath the inclined permanent frontal layer at about 100 meters.

3. The flow in the surface Ekman layer (a boundary layer in which frictional effects predominate in the equations of motion) is offshore. This transport layer is about 10 to 20 meters thick.

4. Within 10 to 20 meters of the bottom, the frictional effects of the bottom create a bottom Ekman layer where the flow is onshore.

5. Beneath the seasonal pycnocline (formed by summer heating and the influx of relatively fresh water from the Columbia River plume) the flow is offshore at a depth of 10 to 30 meters.

6. Within the upper portion of the permanent pycnocline from 20 to 60 meters the flow is onshore.

7. A new water mass formed near the surface possessing a characteristic temperature inversion sinks beneath the inclined permanent frontal layer and flows offshore in a layer at a depth of about 40 to 80 meters.

8. Between the above layer and the bottom Ekman layer the flow is onshore.

The process of coastal upwelling may go through the phases of inception, steady-state, and decay several times during the upwelling season since it is believed to be a process which responds to a wind field which is neither steady nor statistically stationary. Hence, these longitudinal and zonal flows fluctuate in depth and rate of transport commensurate with the current phase of upwelling.

The study of coastal upwelling undertaken by Mooers provides little information on the effects of the upwelling process for the region within 10 kilometers of the coast as the closest sensor was located

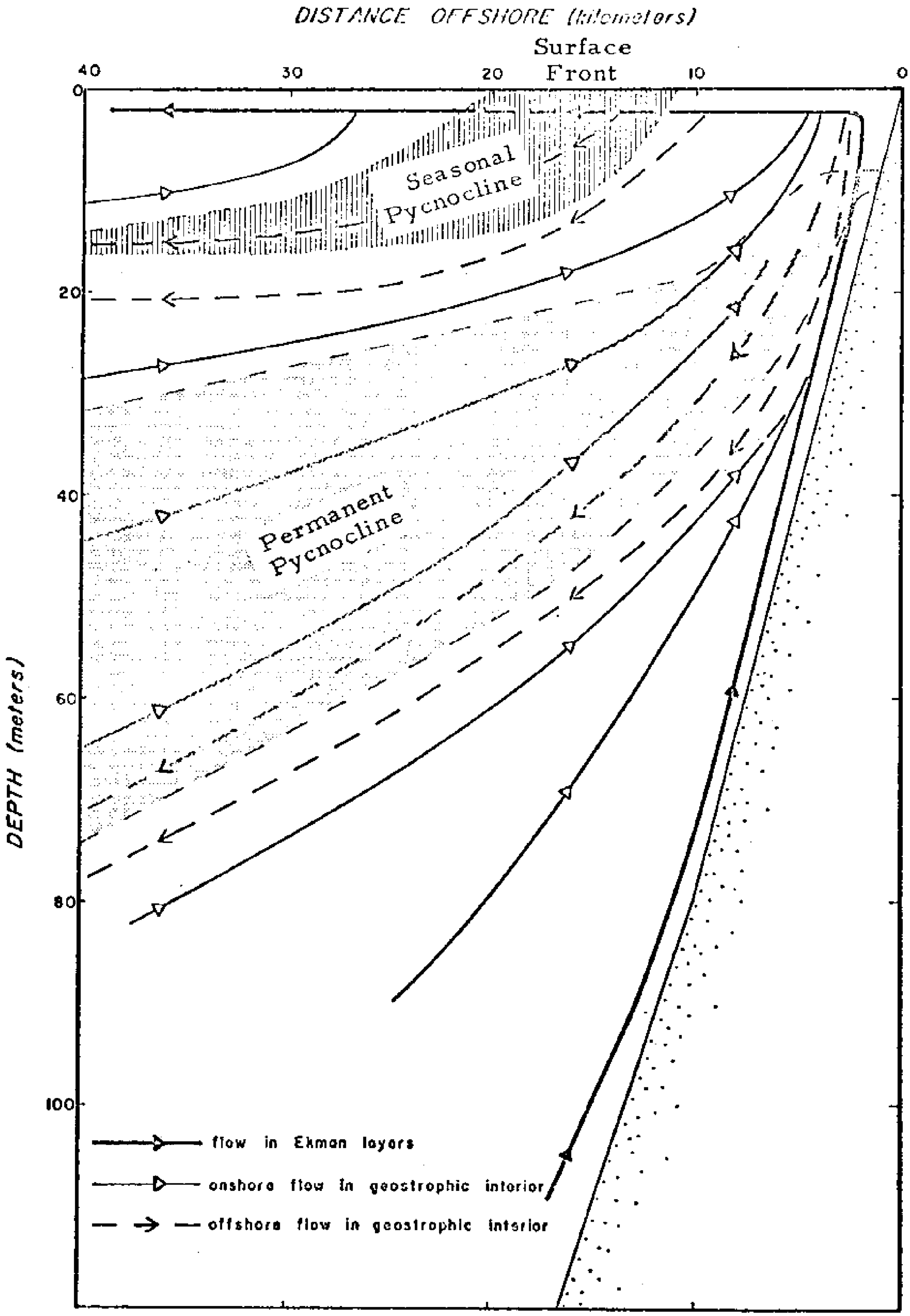

Figure 9-6. Inferred onshore-offshore flow over the continental shelf off Depoe Bay, Oregon during the summer upwelling season (from Mooers, 23).

10 kilometers offshore. He states that during the period of observation it was uncertain how the upwelling process affected this region, but believed it to be a region where mixing is dominant.

Analytical Approach to Coastal Currents

In lieu of the scarcity of observed current data approximate analytical methods may be used to determine current velocities. One such method would be to consider only the wind and tide as the driving mechanisms for the establishment of coastal currents and to vectorially add the contributions from each of these forces.

(a) Wind Driven Currents

The drag of the wind passing over the surface of the water produces a drift current. Much of the initial investigation in this area was done by Ekman (24). He found for a homogeneous body of water of infinite depth that the surface velocity of a pure drift current is proportional to the wind stress and, for an infinite ocean in the Northern Hemisphere, directed 45° to the right of the wind direction:

$$V = \frac{\tau}{\sqrt{\rho A f}} \qquad 9\text{-}2$$

where V is the surface current (cm/sec),

- τ is the wind stress (dyne cm^{-2}),
- ρ is the density of sea water (gm cm^{-3}),
- A is the eddy viscosity coefficient (gm $cm^{-1} sec^{-1}$), and
- f is the Coriolis parameter, $f = 2\Omega \sin\phi$ (sec^{-1}) where ϕ is the latitude and Ω is the rotation rate of the Earth.

For waters of finite depth the angle of deflection of the surface current from the wind direction is a function of h/D, the ratio between the water depth and Ekman's depth of frictional influence. In shallow water h/D decreases with increasing wind speed. Actual measurements have shown the deflection angle at the sea surface to vary between 25°-30° for low velocity winds (<4 m/sec) and approach the actual wind direction for high velocity winds (Neumann and Pierson, 25).

One must use an "effective" eddy viscosity coefficient, A, which is a function of wind speed, i.e., A must increase with increasing wind speed. The following table (Table 9-5) for A as a function of wind speed is from Neumann (26).

Table 9-5. Effective eddy viscosity coefficient as a function of wind speed.

Wind speed (m/sec)	4	6	8	10	14	18
A (gm/cm-sec)	58	161	332	577	1350	2520

Because of uncertainties in the values for wind stress and eddy viscosity coefficient, empirical formulae relating wind speed and current velocity directly have been postulated. These take the form

$$V = \frac{kW}{\sqrt{\sin \phi}} \qquad 9\text{-}3$$

where W is the wind speed in m/sec,

ϕ is the latitude, and

k is a coefficient which varies with wind speed; values used range from 0.76 to 2.59 (25).

Wind drift currents and the relationship between wind speed and current speed at the surface have been discussed and studied, but few systematic measurements are available. Wide variability exists between actual measurements and that predicted by theory. Wiegel (27) emphasizes that caution should be exercised when results based on theory are being used. Neither of the two preceding formulas consider the influence of a coast and should probably not be used in the nearshore region.

Bretschneider (28) has developed a relationship between wind speed, U, and the steady state mean longshore wind-driven current, $\overline{V}_{st}$, over the continental shelf. Assuming shallow water conditions and constant values of $k = 3.0 \times 10^{-6}$ and $K = 10^{-2} ft^{1/3}$ for the wind stress and bottom stress parameters, respectively, the steady state mean current may be expressed as:

$$\frac{\overline{V}_{st}}{U} = 0.0173\, D^{1/6} \sqrt{\sin \theta} \qquad 9\text{-}4$$

where θ is the angle of the wind measured from the perpendicular to the coastline or bottom contours,

D is the water depth (ft), and

$\bar{V}_{st}$ is in ft/sec and U in knots.

Figure 9-7 shows the relationship of $\frac{\bar{V}_{st}}{U}$ versus D for various angles θ. Exact values for the wind stress and bottom stress parameters have not been established.

(b) Tidal Currents

An approximate tidal current velocity can be found from the information listed in the Tide Tables (29) and the Current Tables (6). The time it takes a particular stage of the tide (e.g., HHW) to travel from the Farallon Islands off San Francisco to Cape Alava off the northern Washington coast has been determined from the Tide Tables for four periods of the year. The pertinent data are listed in Table 9-6 along with tidal heights at HHW. The approximate distance from the Farallons to Cape Alava is 628 n. mi.

Table 9-6. Time of higher high water (HHW) and tidal height for four periods in 1969 for Farallon Island, California and Cape Alava, Washington.

	11 Feb		15 May		23 July		26 Oct	
	Time	Height (ft)	Time	Height (ft)	Time	Height (ft)	Time	Height (ft)
Farallon Islands	0459	5.8	2153	5.6	1659	5.8	1041	5.9
Cape Alava	0640	8.0	2340	8.5	1840	8.0	1228	9.3
Travel time (min)	101		107		101		107	

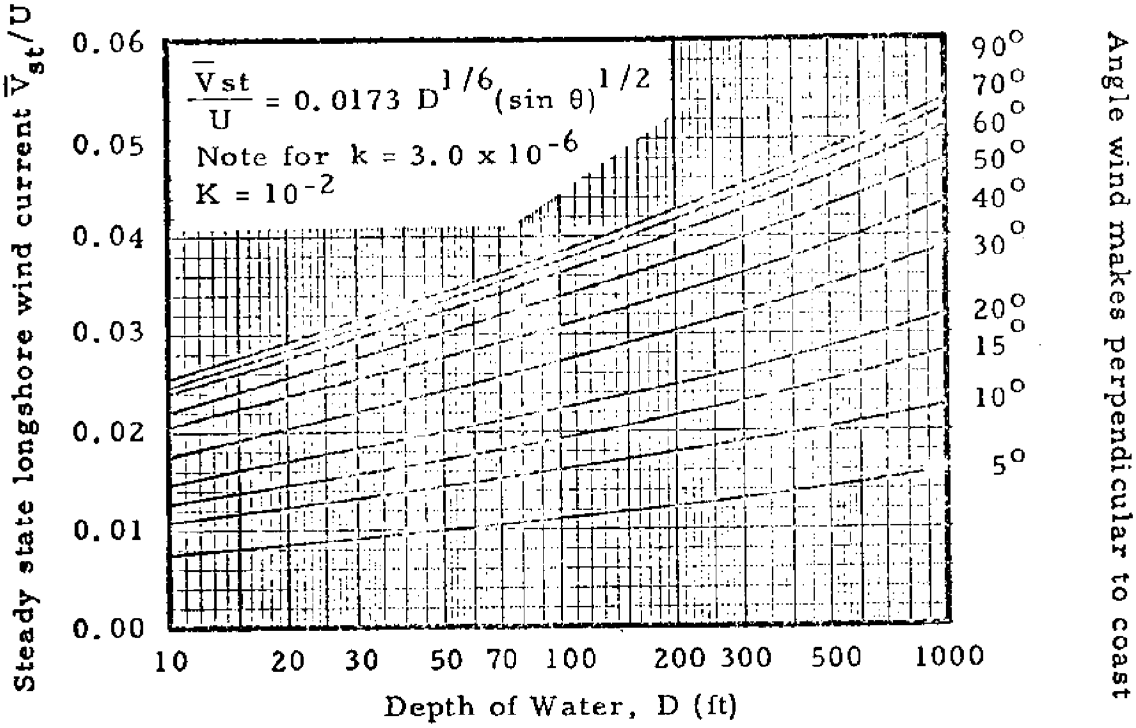

Figure 9-7. Relationship of $\overline{V}_{st}/U$ versus D for various angles θ. (from Bretschneider, 28)

Using a travel time of 104 minutes, the velocity of propagation up the coast is 610 ft/sec (362 knots). The Current Tables indicate that the current is rotary but rather weak all along the Pacific Coast, setting approximately 060° T on flood, 240° T on ebb. Multiplying the computed wave velocity by the cosine of 60° yields the resultant wave velocity for a wave approaching the beach at an angle 30° normal to the shoreline of 305 ft/sec.

The maximum horizontal particle velocity or the maximum velocity of the net tical motion is given by

$$u = g\, a/c \qquad 9\text{-}5$$

where u is the maximum horizontal particle velocity for a shallow-water progressive wave based on Airy wave theory (ft/sec),

g is the acceleration due to gravity, 32.2 ft/sec^2,

a is the tidal amplitude and from Table 9-6 is about

$$\frac{7.1}{2} = 3.55 \text{ ft},$$

c is the wave velocity, 305 ft/sec.

The above values yield a maximum net tidal current of approximately 0.37 ft/sec (0.2 knots) approaching the coast from 240° T. This speed compares veryfavorably with that reported in the Current Tables based on measured values at lightships five miles off the coast (6, p. 238).

Due to decreasing water depths as the tidal wave approaches shore, the speed decreases and the angle of approach becomes more and more parallel to the shoreline. The net onshore-offshore component of particle motion in this shallow coastal region can be computed from a simple tidal prism analysis. Assume that a flow of unit width perpendicular to the shoreline with period T and height H enters a tidal prism of volume ($L_{av}H$) in time T/2 (Figure 9-8). The average onshore-offshore particle velocity may be expressed as:

$$\bar{u} = \frac{2\, L_{av}H}{Td_{av}} \qquad 9\text{-}6$$

where d_{av} is the mixing layer thickness assumed to extend to the bottom.

The area between the sea surface and the bottom, $L_{av} \times d_{av}$, was calculated from the coastline to three miles offshore. This area was divided by the square of the water depth at three miles to yield the required L_{av}/d_{av} relationship in equation 9-6. Average net onshore-offshore tidal currents at selected areas along the Pacific Northwest Coast were computed using mean tidal heights from the Tide Tables (29). These average tidal currents are listed in Table 9-7. Of primary interest is a comparison of the magnitude of these currents with location. The largest currents appear to occur in regions where the beach slope is relatively flat.

Table 9-7. Average net tidal currents for the Pacific Northwest Coastline computed from tidal prism analysis.

Location	Mean Tidal Range (ft)	Average Onshore-Offshore Tidal Current (ft/sec)
Humboldt Bay entrance	6.2	0.08
Crescent City	5.1	0.12
Coos Bay entrance	5.2	0.05
Yaquina Bay entrance	5.9	0.06
Tillamook Bay entrance	5.7	0.05
Columbia River entrance	5.6	0.13
Long Beach, Washington	6.2	0.14
Grays Harbor entrance	6.9	0.25
Pacific Beach, Washington	6.5	0.13

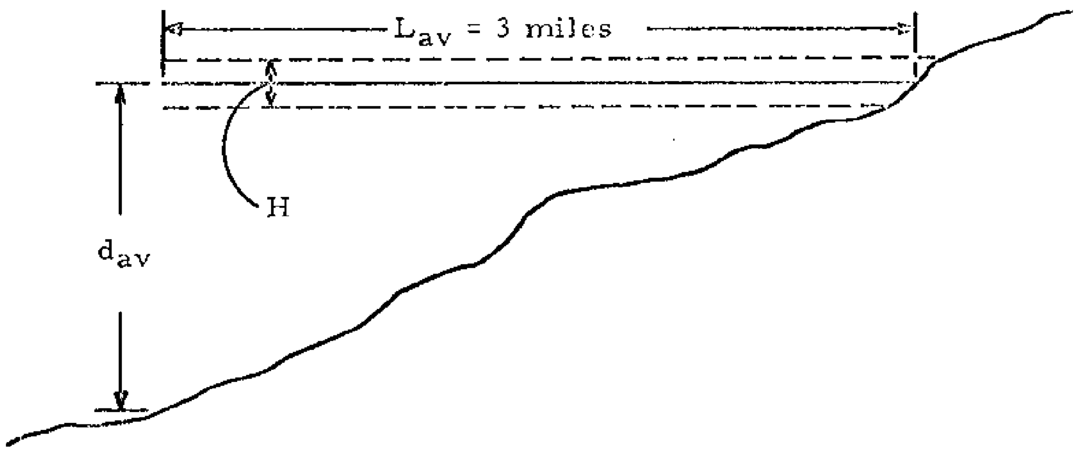

Figure 9-8. Sketch of tidal prism defining terms used in equation 9-6.

Longshore Currents

Most waves approach the coastline at an angle to the bottom contours. The effect of refraction tends to bend the angle of wave approach such that the wave crests are almost parallel to the shoreline by the time the waves break. However, when waves do break at an angle to the beach, the shoreward transport of water has a component parallel to the coast. This water motion parallel to the coast is the longshore current. These currents are the major mechanism of longshore sand transport. Most of the longshore sand transport takes place in the surf zone.

Longshore current velocities can be computed from the relationship listed by Eagleson (30)

$$V_L^2 = 3/8 \left(\frac{gH_b^2 n_b}{h_b} \right) \left(\frac{\sin\alpha \ \sin\theta_b \ \sin 2\theta_b}{f} \right) \qquad 9\text{-}7$$

where V_L is the mean longshore current velocity (ft/sec) assumed to be constant in the surf zone. The current will actually decrease with distance from the shoreline as the depth increases;

H_b and h_b are respectively, the wave height (ft) and water depth (ft) at the point of breaking;

n_b is the ratio of the group velocity to phase velocity;

α is the beach slope;

θ_b is the angle between the breaker crest and the original wave crest;

f is the Darcy Weisbach resistance coefficient = $[2 \log_{10} \frac{h_b}{k_e} + 1.74]^{-2}$;

k_e is the equivalent sand roughness, ft.

H_b and h_b can be computed from solitary wave theory using

$$h_b = 0.667 \, (H_o'T)^{2/3} \text{ and} \qquad 9\text{-}8$$

$$H_b = 0.78 \, h_b \qquad 9\text{-}9$$

where H_o' is the deep water wave height considering the effects of refraction, i.e. $H_o' = K_r H_o$

where K_r is the refraction coefficient.

H_b and h_b can more easily be determined from Figure D-54 in the U. S. Army Coastal Engineering Research Center Technical Report No. 4 (31). A sample calculation using conditions appropriate to the Pacific Northwest Coast follows:

Assume $H_o' = 8$ feet; $T = 10$ sec; $\alpha = 1°$; $\theta_b = 5°$; bottom sand roughness, $k_e = 0.0033$ ft.

then:

$$\left.\begin{array}{l} h_b = 12.3 \text{ ft} \\ H_b = 9.6 \text{ ft} \end{array}\right\} \text{ from eqs. 9-8 and 9-9}$$

$n_b = 0.95$ from linear wave theory tables

$$f = [2 \log_{10} \frac{h_b}{k_e} + 1.74]^{-2} = 0.013$$

$$V_L^2 = \frac{3}{8}[\frac{32.2 \times (9.6)^2 \times 0.95}{12.3}][\frac{0.0175 \times 0.0872 \times 0.1736}{0.013}]$$

$V_L = 1.26$ ft/sec.

This is in agreement with measured values off the central Oregon coast as reported by Neal, et al. (1)

Many attempts have been made to predict longshore current velocity. Galvin (32) in 1967 reviewed the theory and available data. More recently Longuet-Higgins (33) has suggested using the concept of radiation stress to more satisfactorily estimate the momentum of the incoming waves. However, the chief difficulty in estimating longshore current velocity is the inability to accurately measure the wave angle of approach.

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