THE TEMPERATURE AND SALINITY CHARACTERISTICS OF PUGET SOUND AND STRAIT OF JUAN DE FUCA BASED ON THE M. V. CATALYST OBSERVATIONS OF 1932 to 1942

by Teodoro G. Megia

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by

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A thesis submitted in partial fulfillment

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Department______________________________

Date______________________________

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In the course of this work the author has been deeply conscious of his debt of gratitude to the staff of the former Oceanographic Laboratories, now the Department of Oceanography, University of Washington, who collected the temperature and salinity data which formed the foundation of this study. He is even more immediately aware of his debt to those he has consulted personally, seeking advice and information and always finding it freely and generously given. It is impossible to name these people individually, but a few must have special mention.

Dr. Clifford A. Barnes has given him generous help and invaluable advice in the preparation of this thesis. Without the patient guidance and constant encouragement of Dr. Barnes this work would not have been possible.

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TABLE OF CONTENTS

	PAGE
LIST OF FIGURES	v
LIST OF TABLES	vii
Section	
1. INTRODUCTION	1
1.1 History and Purpose of the Investigation	1
1.2 Description of Area	2
1.3 Subdivisions of Puget Sound	5
1.4 Location of Sampling Stations	8
1.5 Sampling and Data	9
2. BACKGROUND PHYSICAL OCEANOGRAPHY AND INFLUENCING FACTORS	10
2.1 Circulation in Puget Sound and the Strait of Juan de Fuca	10
2.2 Local Precipitation and Runoff	12
2.3 Wind Systems	13
2.4 Coastal and Offshore Circulation	15
2.5 Coastal and Offshore Temperatures and Salinities	16
3. TEMPERATURES AND SALINITIES IN PUGET SOUND AND THE STRAIT OF JUAN DE FUCA	18
3.1 General Consideration of the Distribution of Water Mass Characteristics	18
3.2 Correlation of Surface Temperatures with Air Temperatures	18
3.3 Temperature - Salinity Relationship at Different Locations	21
3.4 Variations of Temperature with Season	33

TABLE OF CONTENTS (Continued)

PAGE

3.5 Variations of Salinity with Season 43

3.6 Variations of Temperature and Salinity with Depth 54

3.7 Harmonic Analysis of Temperatures 60

3.8 Comparison of Observations Taken During Different Periods of Years 67

4. SUMMARY AND CONCLUSIONS 75

BIBLIOGRAPHY 78

APPENDIX (TABLES) 80

LIST OF FIGURES

FIGURE		PAGE
1.	Map of Puget Sound and Adjacent Ocean Waters.	3
2.	Station Location Map Showing Station Positions in Relation to the Location of Principal Sills and Basins of Puget Sound.	6
3.	Profiles Along Main Channels.	7
4.	Temperature Cycles of Surface Water and Air.	20
5.	Temperature-Salinity Relationships for Pillar Point.	23
6.	Temperature-Salinity Relationships for Port Townsend.	24
7.	Temperature-Salinity Relationships for Tala Point.	25
8.	Temperature-Salinity Relationships for Point No Point.	26
9.	Temperature-Salinity Relationships for Point Jefferson.	27
10.	Temperature-Salinity Relationships for Green Point (Carr Inlet).	28
11.	Temperature-Salinity Envelopes.	32
12.	Annual Temperature Cycles for Pillar Point.	34
13.	Annual Temperature Cycles for Port Townsend.	35
14.	Annual Temperature Cycles for Tala Point.	36
15.	Annual Temperature Cycles for Point No Point.	37
16.	Annual Temperature Cycles for Point Jefferson.	38
17.	Annual Temperature Cycles for Green Point.	39
18.	Annual Salinity Cycles for Pillar Point.	44
19.	Annual Salinity Cycles for Port Townsend.	45
20.	Annual Salinity Cycles for Tala Point.	46
21.	Annual Salinity Cycles for Point No Point.	47

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1.4 LOCATION OF SAMPLING STATIONS

Of the many stations sampled by the M. V. CATALYST in Puget Sound and contiguous waters, five were occupied repeatedly and at quite regular intervals throughout most of the period 1932 to 1942. (See Figures 2 and 3). These stations were selected for detailed analysis and were spaced from Pillar Point in the Strait of Juan de Fuca to Jefferson Head in the central portion of the main basin of Puget Sound. The locations of the stations, bottom depths, and number of times each station was visited during the period 1932 to 1942 are given below:

	Latitude North	Longitude West	Depth to Bottom (meters)	Times Visited
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These stations are selected as representative of the Strait of Juan de Fuca which is the immediate source of relatively undiluted ocean water; Admiralty Inlet which is a turbulent zone where waters of the Strait mix with those discharging from Puget Sound; transition zones at the entrances to Hood Canal and the main basin of Puget Sound; and lastly the

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Sampling was carried out routinely, using reversing water bottles fitted with deep-sea reversing thermometers. A protected thermometer was paired with an unprotected thermometer at appropriate levels as a means of checking the depth of sampling indicated by the meter wheel. Sampling intervals were spaced more closely in the upper part of the water column where the gradients of properties are usually greater, and farther apart with increasing depth. The last bottle in the line was lowered to only a few meters from the bottom.

The observations were taken irrespective of the stage of the tide. The raw data were reduced by graphical method to correspond to every first and fifteenth of the month for all the standard levels selected for analysis. Mean values were computed from the scaled numbers. These mean values are based on the observations made in 1934-41. CATALYST data collected in 1932, 1933, and 1942 were not included in the analysis because of considerable gaps in the observations.

3. TEMPERATURES AND SALINITIES IN PUGET SOUND AND THE STRAIT OF JUAN DE FUCA

3.1 GENERAL CONSIDERATION OF THE DISTRIBUTION OF WATER CHARACTERISTICS

In general, the observed distribution of subsurface water properties is the result of advection and diffusion. Where large-scale exchanges were involved, the advective transfer is associated with the mean motion and the non-advective transfer - diffusion - with the random or turbulent motion. At the surface, changes in water properties are not limited to interchange between the water parcels themselves but interchange can also occur between the sea surface and the overlying air. In the tidal waters of the Puget Sound area the greatest and most abrupt changes in local water characteristics are generally associated with water movement and not with surface interchange (Barnes, Collias, and Paquette, 1955). Both lateral and vertical movements occur but at a given location and depth the lateral flow is more likely to cause the larger changes. This is usual in coastal tidal systems where vertical movement is restricted by the development of a stable water column such as occurs during periods of high runoff and heating. In stratified water, the density gradient acts as a barrier to vertical interchange of properties and permits the surface layer to respond freely to the wind which may drive it in a different direction from the underlying layer.

3.2 CORRELATION OF SURFACE TEMPERATURES WITH AIR TEMPERATURES

It is recognized that knowledge of the quantitative interchange of heat across the water surface is fundamental to a full explanation of the

The accuracy of the measurements conforms with the customary requirements in oceanographic work. The temperature measurements are accurate to within $\pm 0.02^{\circ}$ C. The salinities are believed to have an accuracy better than 0.05 o/oo.

2. BACKGROUND PHYSICAL OCEANOGRAPHY AND INFLUENCING FACTORS

2.1 CIRCULATION IN PUGET SOUND AND THE STRAIT OF JUAN DE FUCA

Puget Sound is one of the deep, fjord-like, glacially modified embayments contributing to the Northeast Pacific. It is primarily characterized by a deep inner basin in communication with outside waters across a sill deep enough to provide continuing but somewhat restricted ventilation of its deeper waters. The gross water movements are driven predominantly by the changes in water level associated with the tides. The area, however, is one in which precipitation and runoff exceeds evaporation. The resultant hydrostatic head leads to a net surface outflow of less saline water overriding a net inflow of relatively high salinity water at depth. Winds also drive the surface waters to some extent, but in general their effect is small compared to that of the tide. The very irregular bathymetry of the channels and basins influences the local currents, and sills restrict the depth of free water interchange. The effect of the deflecting force of the earth's rotation has been discerned, particularly in the Strait of Juan de Fuca. In response to the driving and modifying forces both the oscillating tidal currents and the net circulation varies greatly from time to time and from place to place within the area.

In considering the layered circulation the outflowing surface water is a varying mixture of fresh water from precipitation and runoff and

seawater entrained from the lower layer. This salt water entrainment would result in progressive freshening of the Sound waters were it not for the compensating net inflow of seawater in sub-surface layers (Paquette and Barnes, 1951). The two-layer system may persist throughout the year, but at times and places of intensive tidal and wind mixing, the stratification may break down affording mass exchange throughout the water column.

Paquette and Barnes (1951) conclude from current measurements made at 22 stations in Puget Sound from an anchored ship, that the local deep currents are associated primarily with the tides and guided locally by the submarine topography. The surface currents, on the other hand, are also appreciably affected by winds, and vary considerably with location. Observations made in Puget Sound show currents up to 6 to 8 knots in narrow constrictions like Deception Pass and Tacoma Narrows. In the Admiralty Inlet currents run up to 6 knots on the basis of measurements made by the U. S. Coast and Geodetic Survey on July 7-11, 1952. In most of the bays, circulation is relatively sluggish as observed in a tidal model of Puget Sound. Prominences like Admiralty Head generate a series of eddies in tidal currents which may persist after the change of tide.

In model studies Barnes, Lincoln, and Rattray (1954) observed that the rate of flushing is largely governed by the salinity of the inflowing deep water, the type of entrance, and the amount of runoff. An increase in the source salinity in the Strait of Juan de Fuca quickly increased the salinity at depth in the main basin of Puget Sound, and that in the subsidiary basins more slowly. A new equilibrium structure was reached at all depths throughout the area in about 90 days prototype time. A decrease in the source salinity resulted in a quick decrease in the

upper layers to a depth of 50 to 100 meters in the main basin and also in Hood Canal, but deeper waters were still changing after 100 days. In Hood Canal, water below 70 meters changed only slightly in 166 days. This is attributed to a combination of shallow entrance sill, relatively small tidal prism, and relatively great depth of the canal. Thus, the deep waters of Hood Canal are flushed out only slowly and Dabob Bay at the deeper end may not flush every year (University of Washington Department of Oceanography, 1959). The model studies have also shown that flushing is most rapid in the fall accompanying the intrusion of high-salinity water from the sea and not during periods of maximum runoff.

2.2 LOCAL PRECIPITATION AND RUNOFF

Fresh water addition comes principally from precipitation which amounts to only about 35 to 40 inches annually. In Seattle about 44 per cent of the annual precipitation occurs in winter and 72 per cent in autumn and winter. Taking this location as representative of conditions in the Sound, the precipitation falling during the rest of the year is only a small fraction of the total annual amount. This is attributed to the infrequent occurrence of cyclonic storms over the Sound, especially in summer.

Regional precipitation variations in a number of key stations of the general area are strikingly large as shown below:*

Key Station	Years of Record (1910-1940)	Winter	Spring	Summer	Autumn	Yearly
Tatoosh Island	30	31.28	15.88	6.16	22.28	75.61
Port Angeles	30	11.41	3.85	1.86	6.69	23.82
Port Townsend	30	6.53	3.77	2.51	4.59	17.42
Quilcene	30	17.61	8.22	3.57	10.68	39.89
Seattle	30	14.24	6.57	2.67	8.74	32.21

* Taken from Table 2-2, page 65, Volume I, Puget Sound and Approaches - A Literature Survey, University of Washington Department of Oceanography, (1953a).

LIST OF FIGURES (Continued)

FIGURE		PAGE
22.	Annual Salinity Cycles for Point Jefferson.	48
23.	Annual Salinity Cycles for Green Point.	49
24.	Vertical Distributions of Temperature in Winter and Summer.	55
25.	Vertical Distributions of Salinity in Winter and Summer.	56
26.	Computed Surface and Bottom Temperature Cycles of Pillar Point Based on Harmonic Analysis.	62
27.	Computed Surface and Bottom Temperature Cycles of Port Townsend Based on Harmonic Analysis.	63
28.	Computed Surface and Bottom Temperature Cycles of Tala Point Based on Harmonic Analysis.	64
29.	Computed Surface and Bottom Temperature Cycles of Point No Point Based on Harmonic Analysis.	65
30.	Computed Surface and Bottom Temperature Cycles of Point Jefferson Based on Harmonic Analysis.	66
31.	Comparison of CATALYST and BROWN BEAR Data for Pillar Point and Port Townsend.	68
32.	Comparison of CATALYST and BROWN BEAR Data for Tala Point, Point No Point, and Point Jefferson.	69
33.	Deviations of Surface Temperature Measured by the BROWN BEAR from CATALYST Norms.	71
34.	Deviations of Bottom Temperature Measured by the BROWN BEAR from CATALYST Norms.	72
35.	Deviations of Surface Salinity Measured by the BROWN BEAR from CATALYST Norms.	73
36.	Deviations of Bottom Salinity Measured by the BROWN BEAR from CATALYST Norms.	74

LIST OF TABLES

TABLE		PAGE
I.	Bi-Monthly Averages of Temperature and Salinity at Standard Depths.	80
II.	Deviations of Temperature Measured by the BROWN BEAR from CATALYST Norms.	86
III.	Deviations of Salinity Measured by the BROWN BEAR from CATALYST Norms.	87

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I. INTRODUCTION

1.1 HISTORY AND PURPOSE OF INVESTIGATION

Until recent years the temperature and salinity characteristics of Puget Sound and adjacent waters have been known only in a general way. This was in part due to lack of facilities for making a series of continuous observations of a detailed nature. In 1931 the former Oceanographic Laboratories, now the Department of Oceanography of the University of Washington, was established and in 1932 an oceanographic vessel, the M. V. CATALYST, was put into service. Subsequently temperature, salinity, and other water properties were measured, at first intermittently, but on a more or less regular and continuing basis until early 1942. The oceanographic program was inactive during the war years 1942 to 1946. Beginning in 1948 field work was resumed on a limited scale using the School of Fisheries vessel M. V. Oncorhynchus, and this program was intensified with the acquisition of the M. V. BROWN BEAR in 1952, ten years after the withdrawal of the CATALYST. The coordination of the early CATALYST findings has been needed to elucidate the physical oceanography of the region and to serve as a guide to future studies.

The study outlined herein was started in 1949-50 and resumed in 1955-56 and is intended as a contribution to the coordination and analysis

of the temperature and salinity data which have been collected. It is a descriptive study of the time and space distributions of the temperature and salinity of Puget Sound and adjacent waters. Its aims are three: (1) To organize and process the available data collected from 1932 to 1942 into a convenient form to aid other workers on the physical structure of the waters of the region; (2) To determine and interpret the seasonal changes that occur in different parts of the water column and area; and (3) To set up a basis for comparing future similar observations and to serve as a background for their detailed use. With this three-fold purpose, the limits of the study were arbitrarily set to exclude details which will merit separate studies as supplementary data become available. Although certain of the observations made during the period 1948-55 are referred to in explaining or extending the earlier information, no analysis of these later data *per se* has been attempted.

1.2 DESCRIPTION OF AREA

Puget Sound and the Strait of Juan de Fuca is a portion of the fjord-like system debouching into the Northeast Pacific Ocean at Cape Flattery, about 48° 30' N (Figure 1). South of Cape Flattery the coast is quite regular without any major break for several hundred miles. To the north the mainland is flanked by off-lying islands, and both island and mainland coasts are deeply indented with numerous fjords. The continental shelf within 200 miles of Cape Flattery is relatively narrow, the distance of the 100-fathom (183 meter) contour varying from 15 to 50 miles off the coast and averaging about 30 miles off. The 1000-fathom contour in this area lies from 30 to 75 miles offshore with an average distance of 50 miles.

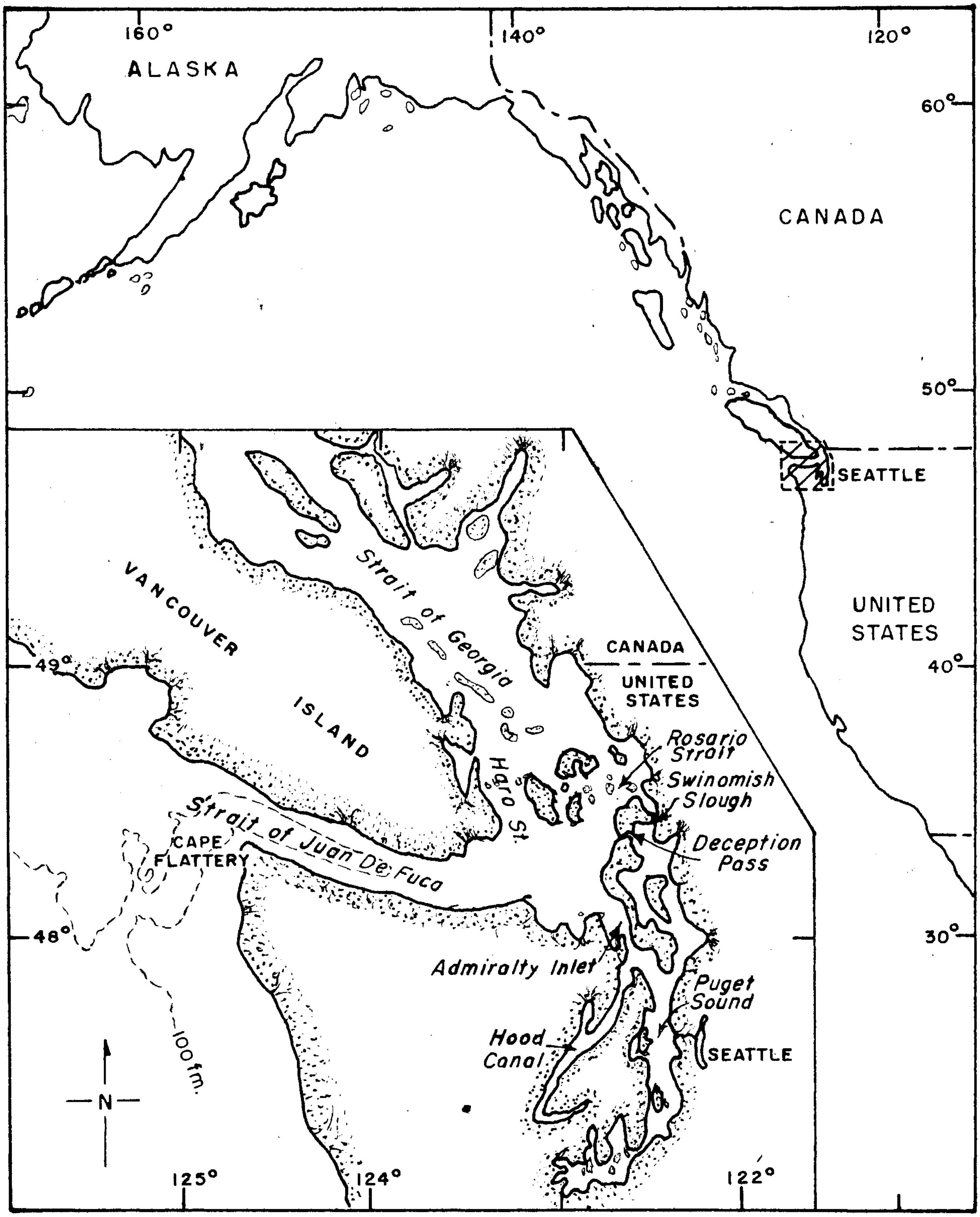


Figure 1. Map of Puget Sound and Adjacent Ocean Waters.

A submarine valley about 4 miles wide and roughly 100 meters deeper than the flanking bottom extends from the mouth of the Strait of Juan de Fuca southwesterly across the continental shelf and continues down the slope. It attains a maximum depth of 380 meters before crossing a 230-meter sill some 30 miles from Cape Flattery. Seaward of this sill the bottom drops to 100 meters within a distance of 15 miles. Inshore the Strait of Juan de Fuca continues eastward as an extension of this valley to Whidbey Island, a distance of 80 miles. Over most of its length the Strait is quite uniform varying from 9 to 13 miles wide, with mid-channel depths decreasing rather gradually from about 300 meters near Cape Flattery to 100 meters near its head.

Puget Sound extends southwestward from the head of the Strait of Juan de Fuca and is connected to it primarily through Admiralty Inlet, a constricted channel having a sill depth of about 73 meters and least width of 2-1/2 miles (University of Washington Department of Oceanography, 1953b). Deception Pass of 12 meters sill depth and 100 yards least width provides a secondary connection. Lastly, Swinomish Slough, roughly 100 yards wide and 3 meters dredged depth, provides an indirect and very minor connection. Puget Sound is divided into a number of sub-basins and contributing channels. Estuaries of eleven prominent rivers and a number of smaller streams are scattered along its heavily dissected coastline. It has an area of 767 square nautical miles at mean high water and has a shoreline, including islands, of 1,157 nautical miles (McLellan, 1954). Its average depth is about 63 meters and maximum depth 284 meters which occurs in the main basin off Point Jefferson.

The Strait of Georgia, the northern lobe of this inland water system is approximately 2,000 square nautical miles in area and 155 meters average depth, with a maximum depth of 420 meters. It connects to the head of the Strait of Juan de Fuca through Haro and Rosario Straits and the lesser passages through the San Juan Islands.

1.3 SUBDIVISIONS OF PUGET SOUND

For convenience in considering the local oceanography, subdivisions of Puget Sound have been selected as shown in Figure 2. The sections are in general delimited by sills or by lateral constrictions in the channels. The principal sills are shown in plan view in Figure 2, and profile in Figure 3. In the latter, maximum channel depths are shown for along-channel profiles extending into the Strait of Juan de Fuca from the southern reaches of Puget Sound proper, and of tributary Hood Canal.

Admiralty Inlet, Section I of Puget Sound, connects the Strait of Juan de Fuca to the main basin of Puget Sound, Section II, and to Hood Canal, Section III. A threshold sill about 73 meters in depth lies at the outer extremity of Admiralty Inlet, but only a lateral constriction marks its entry into the main basin. Hood Canal, with a maximum depth of about 185 meters, opens into Admiralty Inlet, and thus indirectly into the main basin and the Strait, through a rather long, narrow channel. This channel has inner and outer sills of approximately 50 and 70 meters in depth, respectively. The southern basin, Section IV, with a maximum depth of about 165 meters, connects to the main basin through the Tacoma Narrows which has a sill depth of 47 meters. It comprises numerous branching channels and small inlets. The northeastern part of the main basin of Puget Sound connects to Section V

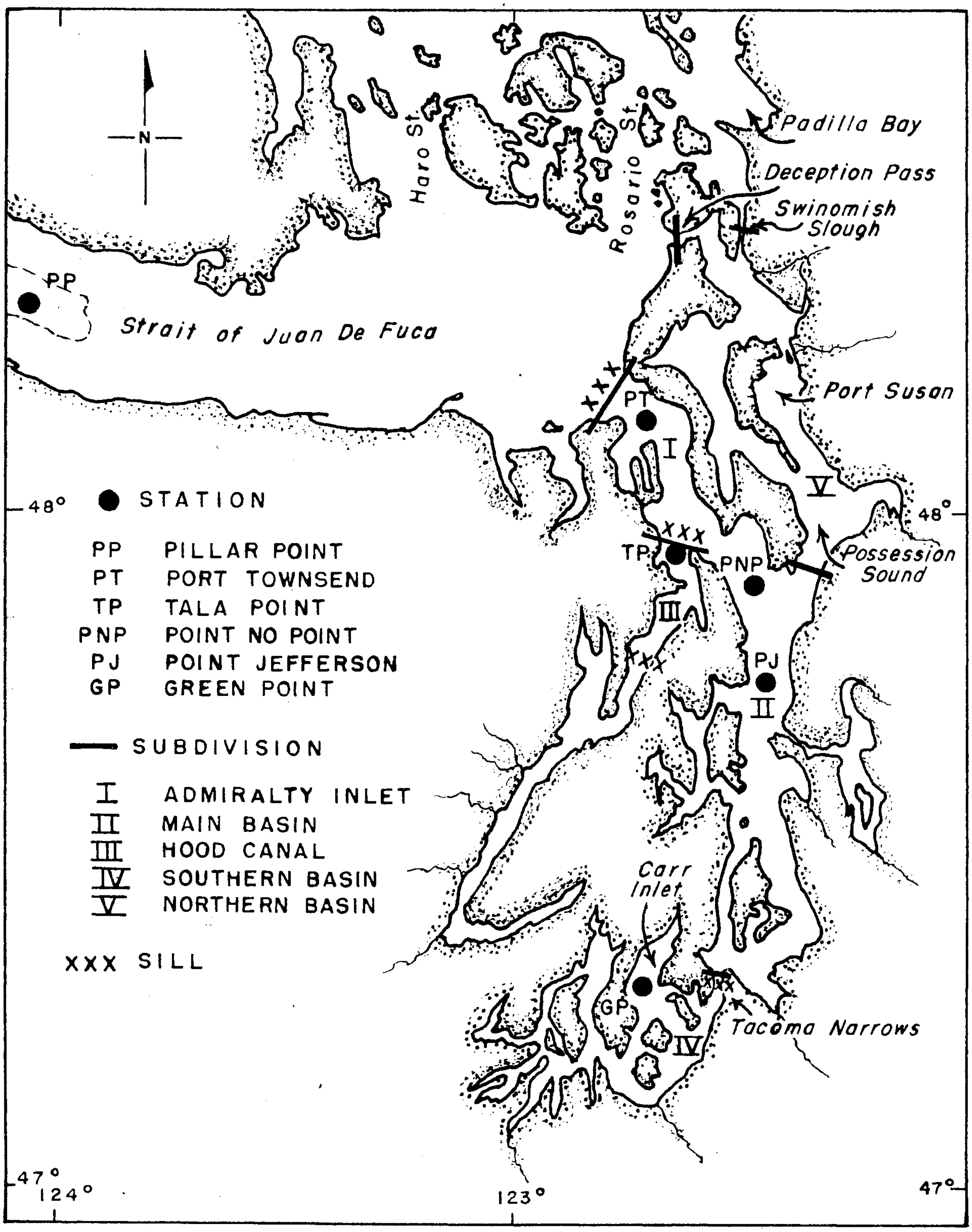
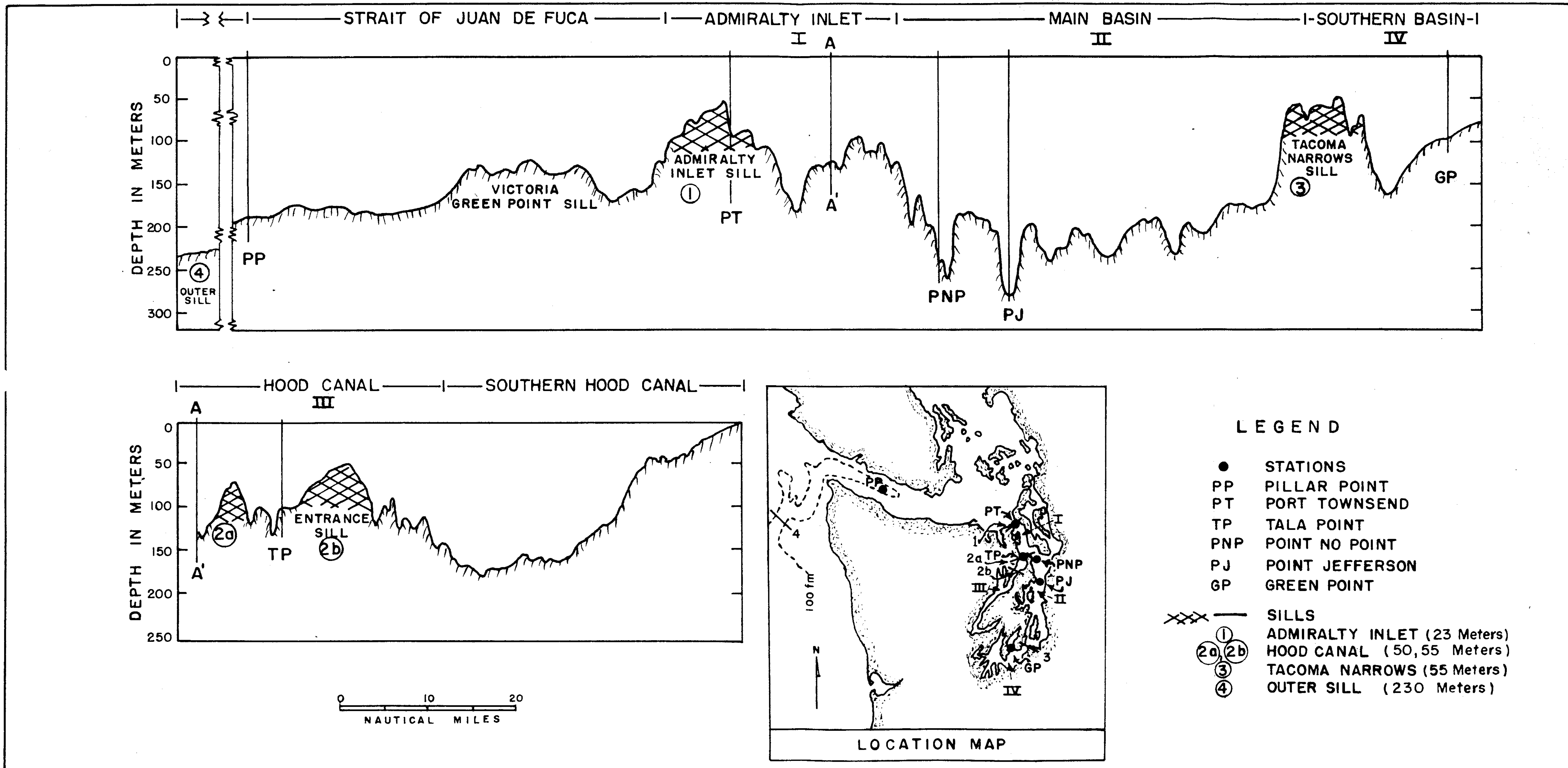


Figure 2. Station Location Map Showing Station Position in Relation to the Location of Principal Sills and Basins of Puget Sound.



.igure 3. Profiles Along Main Channels.

through a relatively deep, narrow channel. This section comprises Possession Sound which leads into two arms, Port Susan, a terminal basin, and gradually shoaling Saratoga Passage. The latter leads to Deception Pass which in turn connects to the Strait of Juan de Fuca.

1.4 LOCATION OF SAMPLING STATIONS

Of the many stations sampled by the M. V. CATALYST in Puget Sound and contiguous waters, five were occupied repeatedly and at quite regular intervals throughout most of the period 1932 to 1942. (See Figures 2 and 3). These stations were selected for detailed analysis and were spaced from Pillar Point in the Strait of Juan de Fuca to Jefferson Head in the central portion of the main basin of Puget Sound. The locations of the stations, bottom depths, and number of times each station was visited during the period 1932 to 1942 are given below:

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upper layers to a depth of 50 to 100 meters in the main basin and also in Hood Canal, but deeper waters were still changing after 100 days. In Hood Canal, water below 70 meters changed only slightly in 166 days. This is attributed to a combination of shallow entrance sill, relatively small tidal prism, and relatively great depth of the canal. Thus, the deep waters of Hood Canal are flushed out only slowly and Dabob Bay at the deeper end may not flush every year (University of Washington Department of Oceanography, 1959). The model studies have also shown that flushing is most rapid in the fall accompanying the intrusion of high-salinity water from the sea and not during periods of maximum runoff.

2.2 LOCAL PRECIPITATION AND RUNOFF

Fresh water addition comes principally from precipitation which amounts to only about 35 to 40 inches annually. In Seattle about 44 per cent of the annual precipitation occurs in winter and 72 per cent in autumn and winter. Taking this location as representative of conditions in the Sound, the precipitation falling during the rest of the year is only a small fraction of the total annual amount. This is attributed to the infrequent occurrence of cyclonic storms over the Sound, especially in summer.

Regional precipitation variations in a number of key stations of the general area are strikingly large as shown below:*

Key Station	Years of Record (1910-1940)	Winter	Spring	Summer	Autumn	Yearly
Tatoosh Island	30	31.28	15.88	6.16	22.28	75.61
Port Angeles	30	11.41	3.85	1.86	6.69	23.82
Port Townsend	30	6.53	3.77	2.51	4.59	17.42
Quilcene	30	17.61	8.22	3.57	10.68	39.89
Seattle	30	14.24	6.57	2.67	8.74	32.21

* Taken from Table 2-2, page 65, Volume I, Puget Sound and Approaches - A Literature Survey, University of Washington Department of Oceanography, (1953a).

The major runoff comes from rivers originating in the Cascade Mountains -- the Skagit, the largest river draining into the Sound, Stillaguamish, Snohomish, Duwamish, Nisqually, and Puyallup; and in the Olympic Mountains - the Skokomish, Duckabush, and Dosewallips.

For most of the rivers that flow from the higher mountains, two high-water periods are usual, one period occurring in winter and the other in the spring. In the Skagit River, which contributes approximately 35 per cent of the total mean runoff of Puget Sound, the maximum monthly runoff occurs in May and June. The discharge ranges between 2,740 and 94,300 cubic feet per second (c.f.s.) and averages about 14,345. During floods the discharge may increase from 5,000 to 75,000 c.f.s. within a period of two weeks.

These floods are not unusual in the Skagit River. Those that occur in November and December are caused by winds known locally as the "chinooks". The spring-early floods, on the other hand, are the result of the melting snow caused by the vernal warming.

In the shorter streams that drain relatively low elevations, no such destructive floods are on record. From the low-water period in the autumn the runoff starts to peak in November, reaching a maximum in December or January. These high-water periods are the direct result of precipitation in the form of rain. Once the ground reaches saturation, more than 80 per cent of the rain precipitation becomes runoff.

2.3 WIND SYSTEMS

The wind patterns for Puget Sound and the Strait of Juan de Fuca are to some extent governed by the prevailing air mass circulation off-shore,

the local topography modifying the flow patterns over land. This observation is confirmed by a recent work of Harris and Rattray (1954) on the surface winds over Puget Sound and the Strait of Juan de Fuca.

Wind circulation along the Pacific Coast is largely governed by two distinct types of pressure distribution found in the North Pacific Ocean. Normally a Pacific high is located near latitude 30° N longitude 140° W, and the Aleutian low centers near latitude 50° N and longitude 180° W. The high pressure cell intensifies in summer and dominates wind conditions during this period. The anticyclonic winds during this period are predominately northwest along the Washington coast, and west over the Strait of Juan de Fuca. Upon reaching Admiralty Inlet the surface winds intrude southward to the lower end of the Sound (Harris and Rattray, 1954). In winter the Aleutian low intensifies simultaneously with the weakening of the anti-cyclone, resulting in a reversal of the wind systems along the coast. The change in direction usually commences in October when the prevailing flow becomes southerly again. At times during the period from October to March a closed counter-clockwise circulation develops in the region north of the Olympic Mountains. Thus the local wind patterns cannot be explained solely on the basis of the changing atmospheric pattern over or near the region but local topography must also be considered.

Spring and autumn are periods of transition in the annual wind structure. Shifting winds from directions other than northwest and southeast generally prevail but, again, these are guided by the local topography.

The total wind movement at the ocean coast is quite large except in summer, while inland it is comparatively small due to influence of the

terrain. The highest recorded wind velocity in Western Washington was 84 miles per hour at Tatoosh Island and 95 miles per hour at North Head, registered on January 29, 1921.

2.4 COASTAL AND OFFSHORE CIRCULATION

In winter, when southerly and southeasterly winds prevail, the movements of the waters off the Washington coast are dominated by the north setting Davidson Current. Thompson and Robinson (1934) report a velocity of about two-thirds of a knot. Fleming (1955) notes that the current is close to the coast and is present only during the winter months. Seaward from the Davidson Current some 300 to 400 miles the cold California Current sets south to the latitude of Lower California.

Tully (1942) observes that under approximately steady conditions the non-tidal circulation in the area of the approaches to the Strait of Juan de Fuca represents a dynamic balance between the drift currents and the land drainage flow from the Strait, and that between these two currents is a region of maximum density indicative of "upwelling". Part of the water leaving the Strait turns northwestward along the coast, but some is deflected to the left and southward by the character of the bottom topography. Marmer (1926) showed that the tidal currents of this coastal area are rotary, continuously turning clockwise, and continuously varying in strength.

In the Strait of Juan de Fuca a predominating surface ebb maintained by excess of precipitation and river runoff is superimposed on the oscillating tidal currents (Redfield, 1950). At depth a prevailing flood current carries the deep ocean waters through the submarine valley and into

the Strait. The turbulence in the Strait, especially at vertical or lateral topographic constrictions, results in extensive mixing, increasing the density of the surface waters seaward and decreasing that of the deeper current landward. The resultant density of the outflowing surface waters may be as high, and at times higher, than the surface ocean waters near the coast (Tully, 1942).

2.5 COASTAL AND OFFSHORE TEMPERATURE AND SALINITY

In the open ocean the origin of the water masses and the relation of the currents to the general circulation of the water should be considered in discussing the local factors influencing temperature and salinity.

In the Pacific north of about the 43rd parallel, Sverdrup (1946) recognizes a large body of water of low temperature and salinity. This water mass results from the admixture of the warm waters of the Kuroshiwo and the cold Oyashio. Both the processes of mixing and dilution by excessive precipitation are so thorough that to the south of the Aleutian Islands, and between the depths of 100 and 1,000 meters, water of a rather constant temperature, 2.5° C, and salinity, 33.8 to 34.5 o/oo, is found over wide areas. As this water moves eastward, its characteristics change significantly at about 160° West. Goodman and Thompson (1940) found that at approximately the latitude of Puget Sound both the isotherms and isohalines dipped gradually from 160° W to about 130° W, some 300 miles off the coast of Washington. Eastward these contours showed a reverse trend, rising towards the surface near the coast. Tibby (1941) describes the character of the water masses off the west coast of North America in some detail.

The modification in the general trends of the isotherms and isohalines near the continental margins is attributed to the effects of currents and to dilution (Fleming, 1955). Within these margins at about the latitude of Puget Sound, the salinities are generally lower and the temperature generally higher in summer than in winter.

Along the Washington coast in winter when southerly winds predominate, offshore water is pushed towards the coast. This in turn crowds the surface coastal water close inshore and tends to preserve its identity. In summer, however, when northerly winds prevail, the deflecting force of the earth's rotation (force of Coriolis) tends to push the surface water seaward. Low coastal salinities, however, are still maintained from the mouth of the Columbia north past the entrance to the Strait of Juan de Fuca. This would not be the case if the rate of local runoff and discharge from the Strait of Juan de Fuca were less than the rate at which the surface water was driven seaward. Such deficiency would lead to the appearance of relatively high salinity, low temperature water at the surface, characteristic of upwelling. Such water does appear inshore at the surface south of the Columbia River where replenishment from local streams is small in late summer (Barnes and Paquette, 1954). Although upwelling at the very surface is partially masked at the mouth of the Strait of Juan de Fuca by surface discharge and mixing, the sublying waters are colder and more saline in summer than in winter indicating its probable occurrence. Previously Marmer (1926), Tully (1942), and others have recognized that changes in the temperature and salinity structure at the entrance to the Strait of Juan de Fuca are considerably influenced by topography, friction, runoff, and tides in addition to the winds and currents which affect the offshore waters.

temperature structure within the water mass. Unfortunately such information does not exist, and lacking it, first attention will be given to the water surface temperatures and air temperatures which, together with the subsurface temperature distribution, should give some qualitative insight of the surface interchange.

For purposes of comparison, air temperatures for Seattle and Tatoosh Island are shown together with surface water temperatures at five stations (Figure 4). The Seattle weather station is located at an elevation of 14 feet, and is sheltered. That at Tatoosh is at an elevation of 101 feet and is fully exposed to the influence of the open sea. The air temperatures are for the period from 1934 to 1941 and are based on the mean daily temperature observed by averaging the daily maximum and minimum temperatures by month. The water temperatures are based on observations by the CATALYST taken at varying intervals during the period from 1934 to 1941, and averaged for monthly intervals. Data at Green Point taken over a shorter and different period have not been included.

Summer is characterized by maximum air and surface water temperatures with the seasonal peak occurring about the end of July at both Seattle and Tatoosh (Figure 4). Minimum air temperatures occur in early spring and late fall, the period when the temperatures at both locations become nearly identical. From the minimum in winter the surface water temperatures rapidly increase as summer is approached reaching a maximum in August after which they drop at a rather uniform rate until February. The air temperatures, compared to the nearby water temperatures, are much higher during periods of maximum solar heating and lower during the coldest

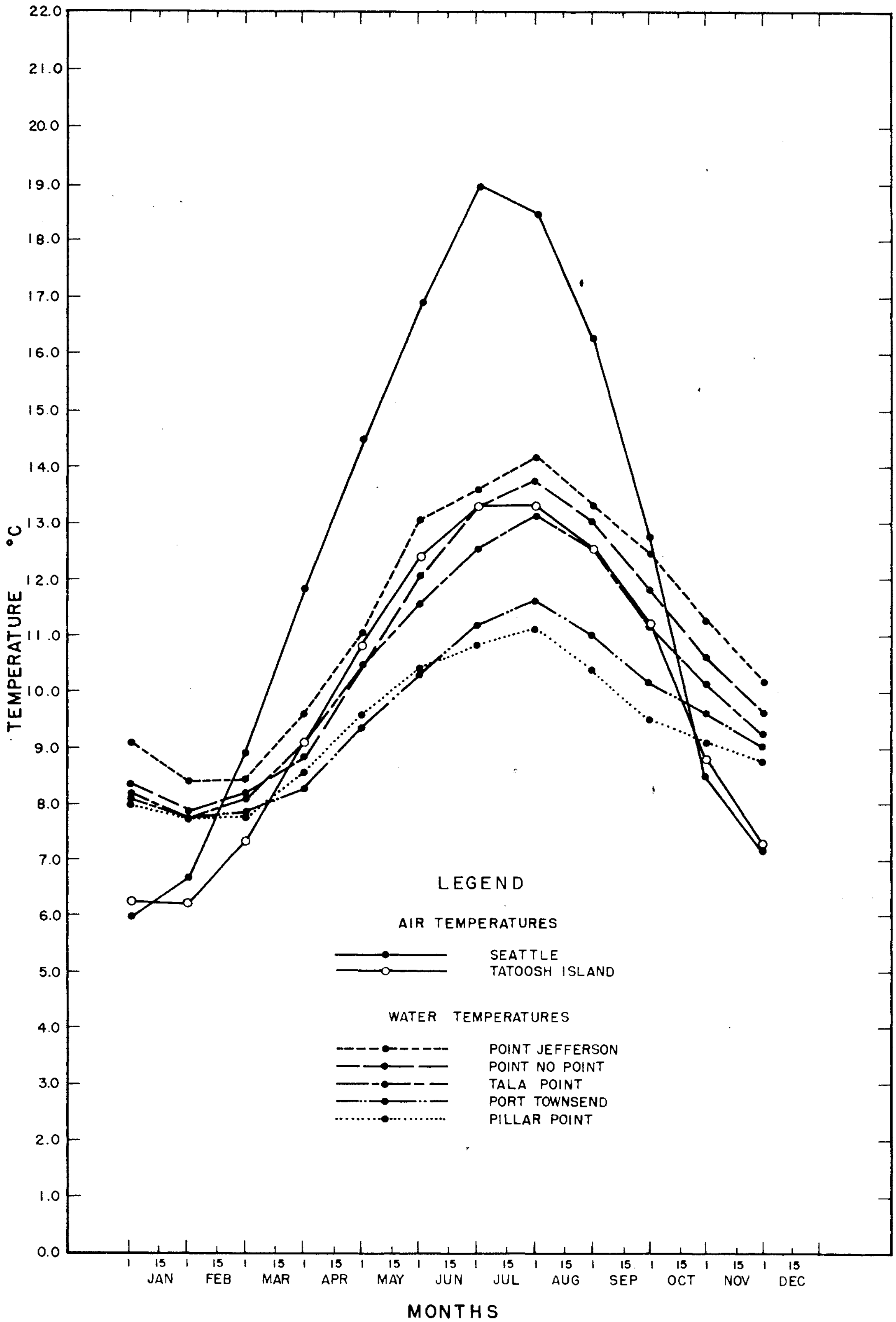

Figure 4. Temperature Cycles of Surface Water and Air.

periods. As would be expected, changes in water temperature lag somewhat behind those of the air.

The summer maximum surface temperature at the various stations increases in going from sea inland. The increase amounts to about 3° C from Pillar Point to Point Jefferson, compared to about 6° C increase in air temperature from Tatoosh Island (off Cape Flattery) to Seattle. The increase going inland in summer is the normal situation, but what may appear anomalous is the higher winter minimum at Point Jefferson contrasted to the stations lying seaward. This occurs despite a slightly lower Seattle air temperature. It appears that heat accumulated in the deeper water during summer is effective in maintaining this higher average surface temperature at Point Jefferson. The annual cycle of subsurface temperatures discussed later supports this view. It is suggested that the relatively large difference, 1° C between Point Jefferson and nearby Point No Point, stems in part from the effect of mixing in Admiralty Inlet which at times directly affects the surface water at the latter station. The surface water at Point Jefferson is under a more direct influence of the mixing which occurs in Tacoma Narrows.

3.3 TEMPERATURE-SALINITY RELATIONSHIPS AT DIFFERENT LOCATIONS

In order to interpret water structure and changes which are occurring in the temperature and salinity of subsurface waters recourse is frequently made to temperature-salinity (T-S) relationships. In shallow inshore regions surface interchange of mass and energy masks the results of mixing and distorts the temperature and salinity relationships from what would have prevailed in a system conservative within the water boundaries. In effect a time factor is introduced as the properties of the surface water,

one of the mixing types, are continuously changing with season. However, within a tidal system of complex bathymetry the mixing and flow rates may be high compared to the rate of surface interchange, thus the T-S relationships may be useful in identifying and in tracing the movements and mixing of the waters over short periods. Water masses in different sections of Puget Sound have been identified and compared to those at a representative station in the Strait of Juan de Fuca. Figures 5 to 10 show the T-S relationships at the six stations considered.

The curves are based on mean values of temperature and salinity and therefore show the average conditions to be expected rather than the extremes. Further, they may not represent the true slopes of the individual curves with respect to the sigma-t surfaces. However, the fact that the slopes between points in most part of the curves do not differ much from layer to layer is an argument in favor of the averaging. Linearity of the T-S relationships from top to bottom is specially striking for the curves of Pillar Point.

Figure 5 shows the mean monthly T-S diagrams for the Pillar Point station in the Strait of Juan de Fuca, the immediate source of deep water contributing to Puget Sound. Three distinctive features of the T-S pattern are easily recognized. A grouping of curves is enclosed in a primary envelope composed of two wedge-shaped secondary envelopes joined at the constriction of the curves at approximately 75 meters depth. The large envelope on the left is characterized by relatively low density water with a wide range of temperature and salinity. This envelope shows the considerable seasonal variability of the surface layer of the two-layer system in the Strait. The envelope on the right characterizes the cold more saline ocean

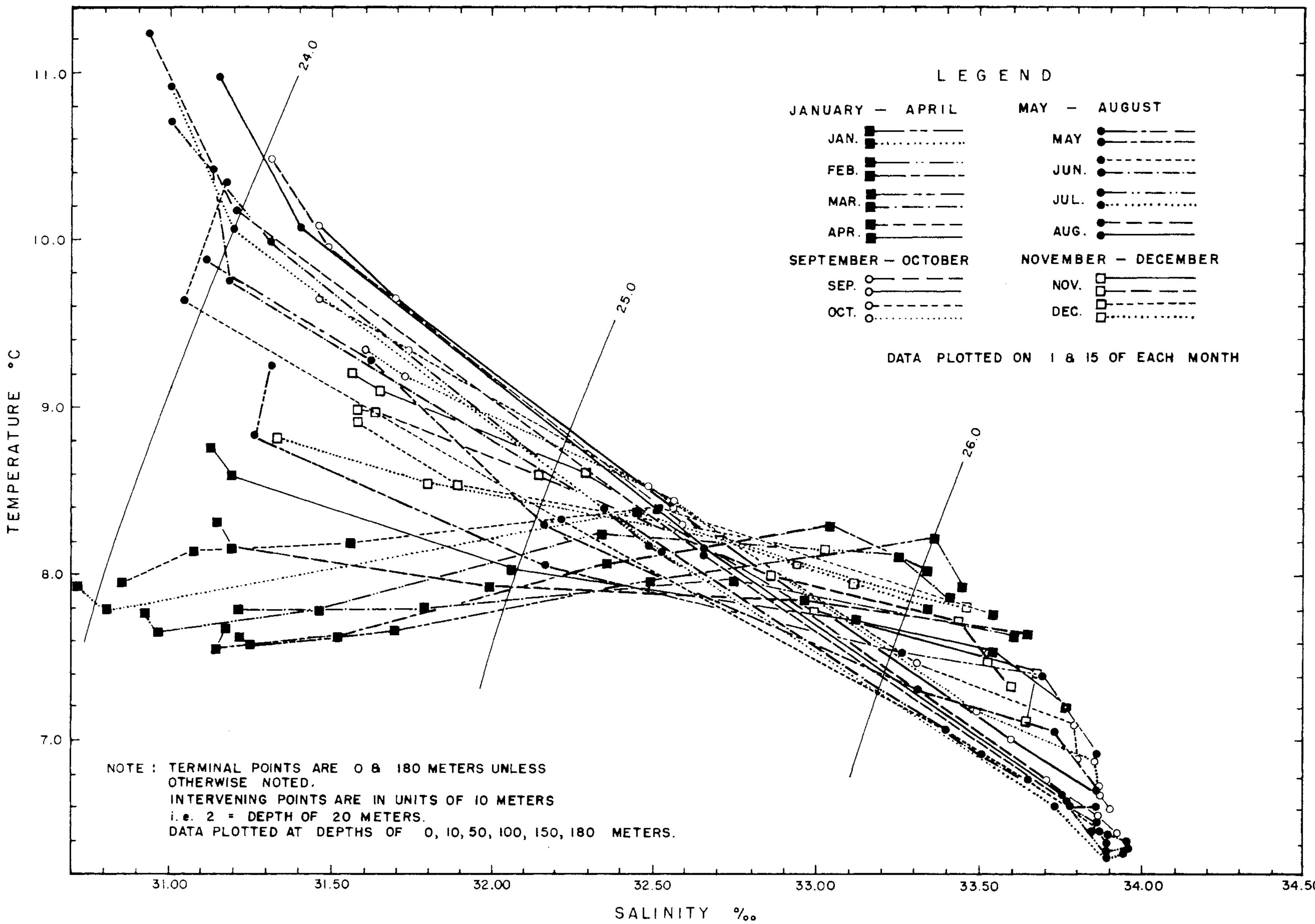

Figure 5. Temperature-Salinity Relationships for Pillar Point.

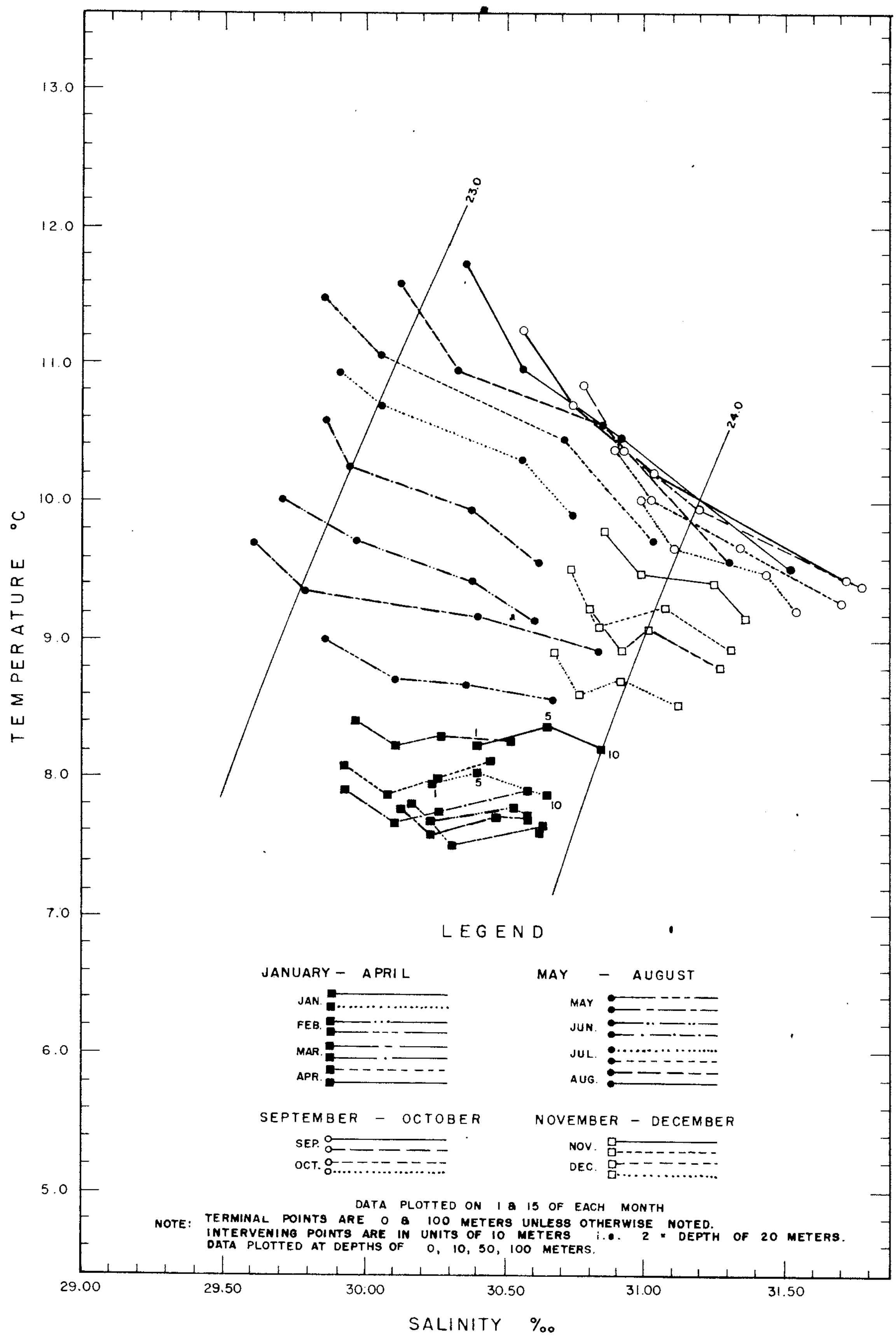

Figure 6. Temperature-Salinity Relationships for Port Townsend.

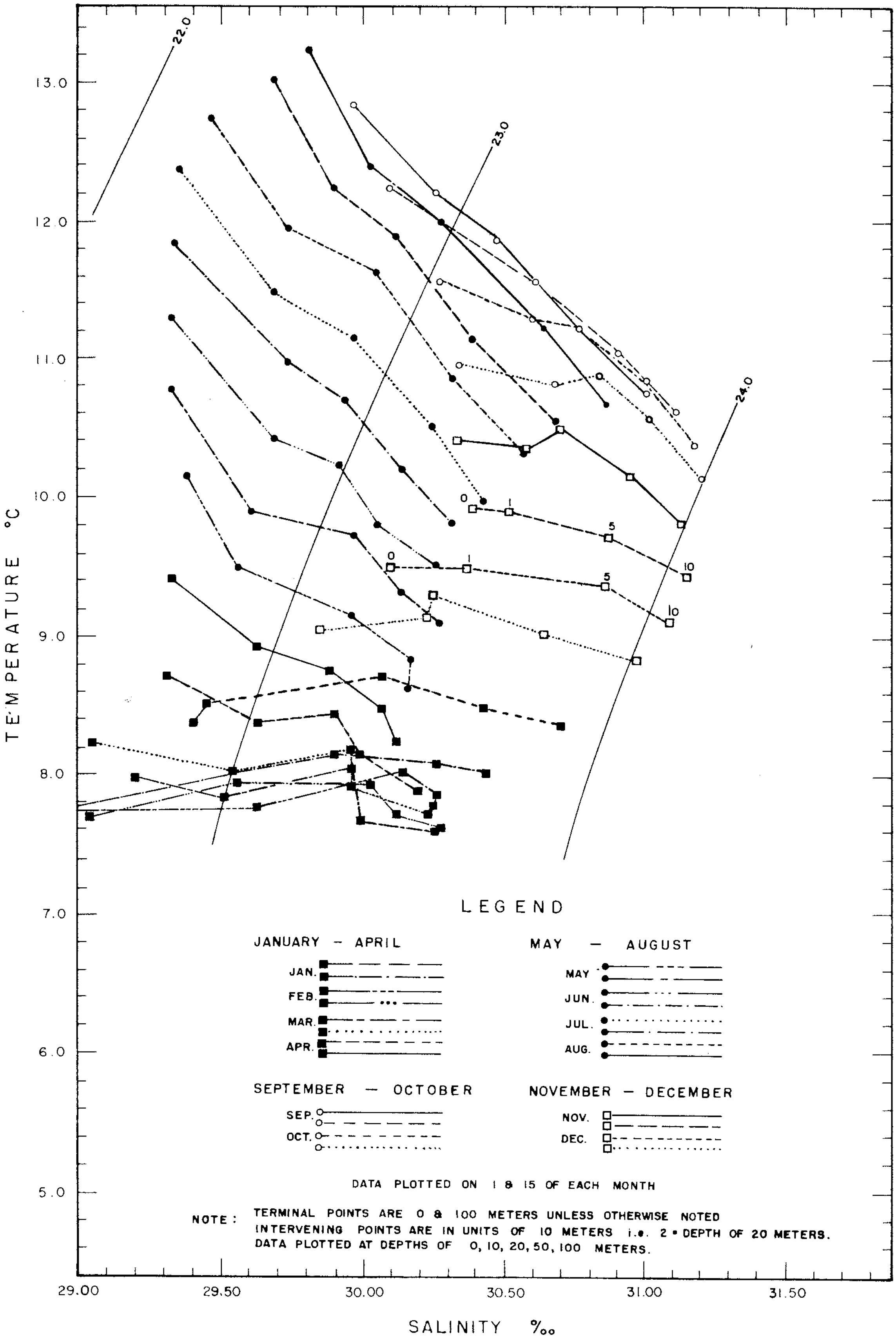

Figure 7. Temperature-Salinity Relationships for Tala Point.

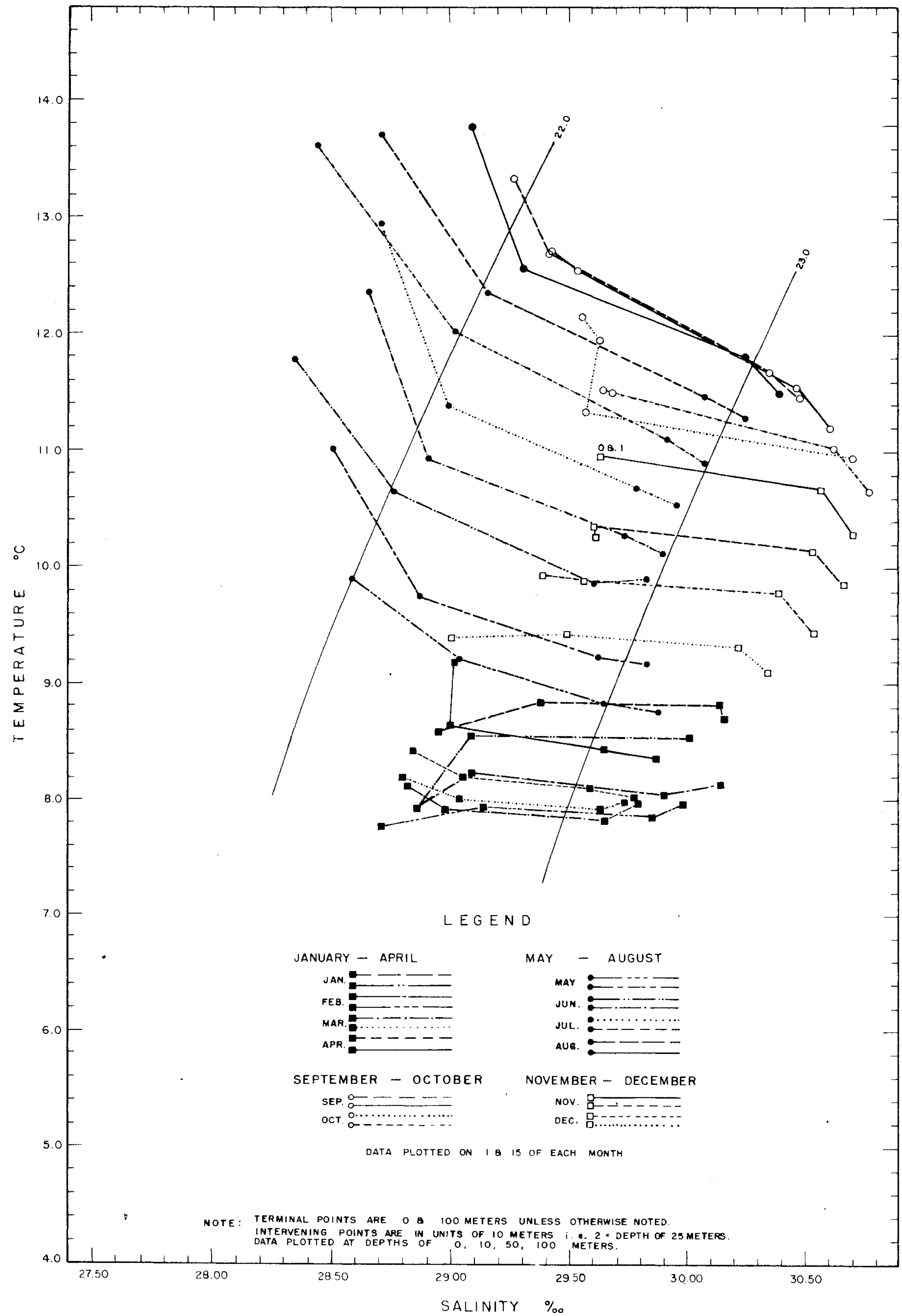

Figure 8. Temperature-Salinity Relationships for Point No Point.

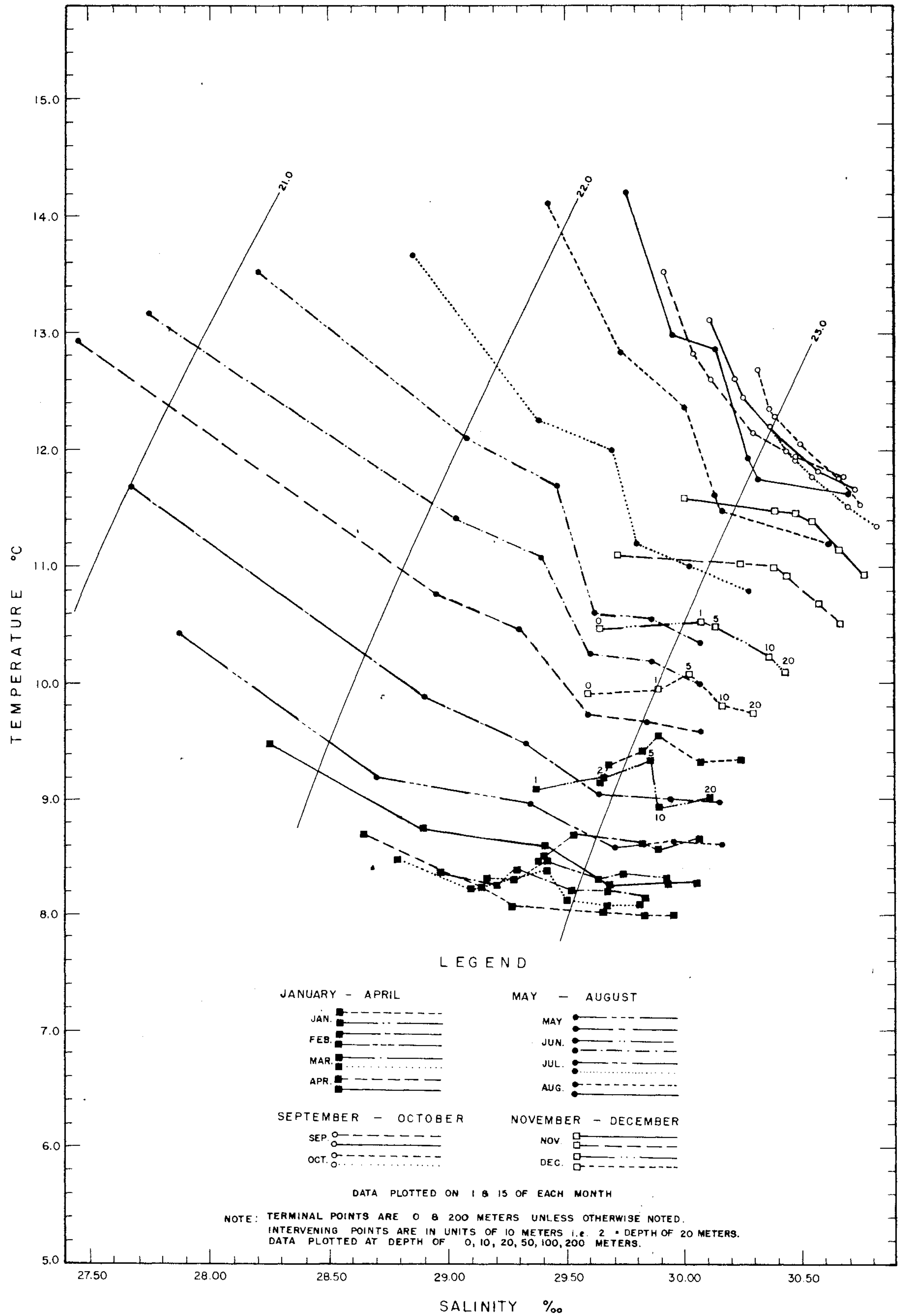

Figure 9. Temperature-Salinity Relationships for Point Jefferson.

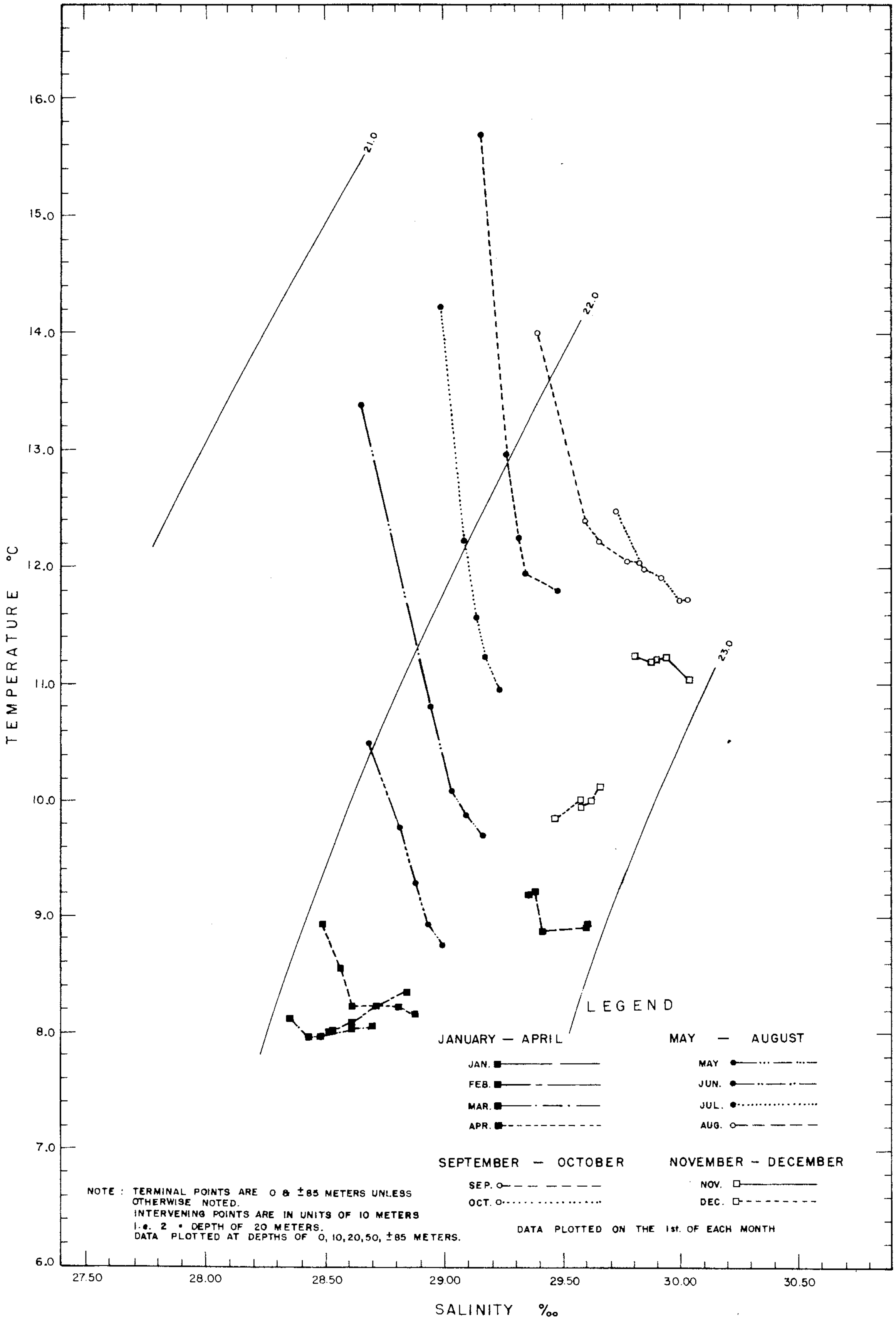

Figure 10. Temperature-Salinity Relationships for Green Point (Carr Inlet).

water which has a net flow landward towards Puget Sound, and which is relatively uniform throughout the year. At Pillar Point this layer of dense bottom water is of greater thickness than the surface layer, and the two are separated by a thin transition layer of intermediate properties.

At Pillar Point the water layers at the different levels indicate a uniform thermal distribution during the cold months. Water in the salinity range of 32.2 to 33.2 °/oo is nearly isothermal at 8° C, and is found from a few meters below the surface down to depths near bottom. As this subsurface water moves inland it mixes with the less saline upper waters, which themselves are a mixture of waters from the Strait of Georgia and Puget Sound with ocean waters that have intruded at an earlier date. Over and approaching the entrance sill of the Puget Sound basin the mixing reduces the salinity of the deeper water which can penetrate Admiralty Inlet and reach the Sound. At Port Townsend (Figure 6) the salinity is from 30.0 to 30.6 °/oo, the water containing about 7 per cent more fresh water than that at Pillar Point. Landward from Port Townsend water of approximately the same characteristics feeds into both the entrance of Hood Canal and the main basin as indicated by the similarity of much of the deeper water at Tala Point (Figure 7) and Point No Point (Figure 8). The higher average salinity and density at Tala Point reflects its more seaward position in the Admiralty Inlet mixing zone. At Point No Point the salinity of the water ranges from 28.9 to 29.9 °/oo, thus containing about 10 per cent more fresh water than at Pillar Point. The reduction in salinity within the short distance from Port Townsend to Point No Point suggests that considerable mixing of the incoming Straits water with the less saline

water coming from river estuaries is occurring here. This is to be expected at this confluence of waters discharging from both the northern and southern reaches of Puget Sound.

At Point Jefferson (Figure 9) the salinity of the water differs little from that at Point No Point but the temperatures are significantly higher. This suggests some retention of the warmer and more saline water which filled the main basin the previous autumn and its subsequent mixing with the colder and less saline surface water formed during late autumn and early winter.

In the southern basin as shown by the conditions off Green Point in Carr Inlet (Figure 10) the characteristics of the water column differ considerably from those in the main basin. The winter temperatures appear to be about the same but the salinity ranges from about 28.4 to 28.9 °/oo. The annual temperature range is somewhat higher than in the main basin due to the higher summer values, but the salinity and density values are lower and their annual ranges much narrower. The comparatively uniform salinity conditions throughout the year are attributed to the intensive mixing which occurs in the Tacoma Narrows, the source of the bottom water for the southern sound, and to the lack of any sizeable streams feeding directly into Carr Inlet. Such rivers as do feed into the southern sound largely ebb through the Tacoma Narrows and are quite thoroughly mixed before feeding into Carr Inlet on the returning flood. The entire water column in Carr Inlet apparently changes continuously and quite rapidly throughout the year. In summer the steep slope of the T-S curves shows thermal stratification to the bottom. This is attributed in part to local heating

superimposed upon water carried in at depth from the Tacoma Narrows. In the absence of this local heating the water characteristics in Carr Inlet should reflect those of the upper 47 meters of the main basin as mixed to that sill depth in the Tacoma Narrows with variable quantities of the discharge from the entire southern sound.

During summer the regional distribution of temperature and salinity presents an interesting picture. The waters at Pillar Point bear a close resemblance with the offshore water only at depths below about 75 meters. The isothermal conditions found in winter have disappeared and the thermocline characteristics of summer heating has developed. The resulting increase in the stability of the water column is enhanced by the reduction in salinity of the upper layers. This salinity reduction is a consequence of the heavy increase in the land drainage in late spring through summer.

In general the Puget Sound stations show a common T-S relationship with respect to season. In summer, during the heating cycle, the T-S curves become more nearly perpendicular to the sigma-t curves. This is attributed to the combined effects of salinity and temperature changes in density. In winter, largely as a result of surface cooling, the slopes of the individual T-S curves become more nearly horizontal and the water becomes less stable. At Pillar Point the same processes are in operation, but the entry at depth of cold offshore water results in lower bottom temperatures in summer.

The generalized picture of increasing temperatures and decreasing salinities landward is presented in Figure 11 where the T-S envelopes of the five key stations in Puget Sound are plotted beside that for the waters of Pillar Point. The BROWN BEAR data collected in 1953 and 1954 at Green Point in Carr Inlet are entered to include conditions obtaining near the

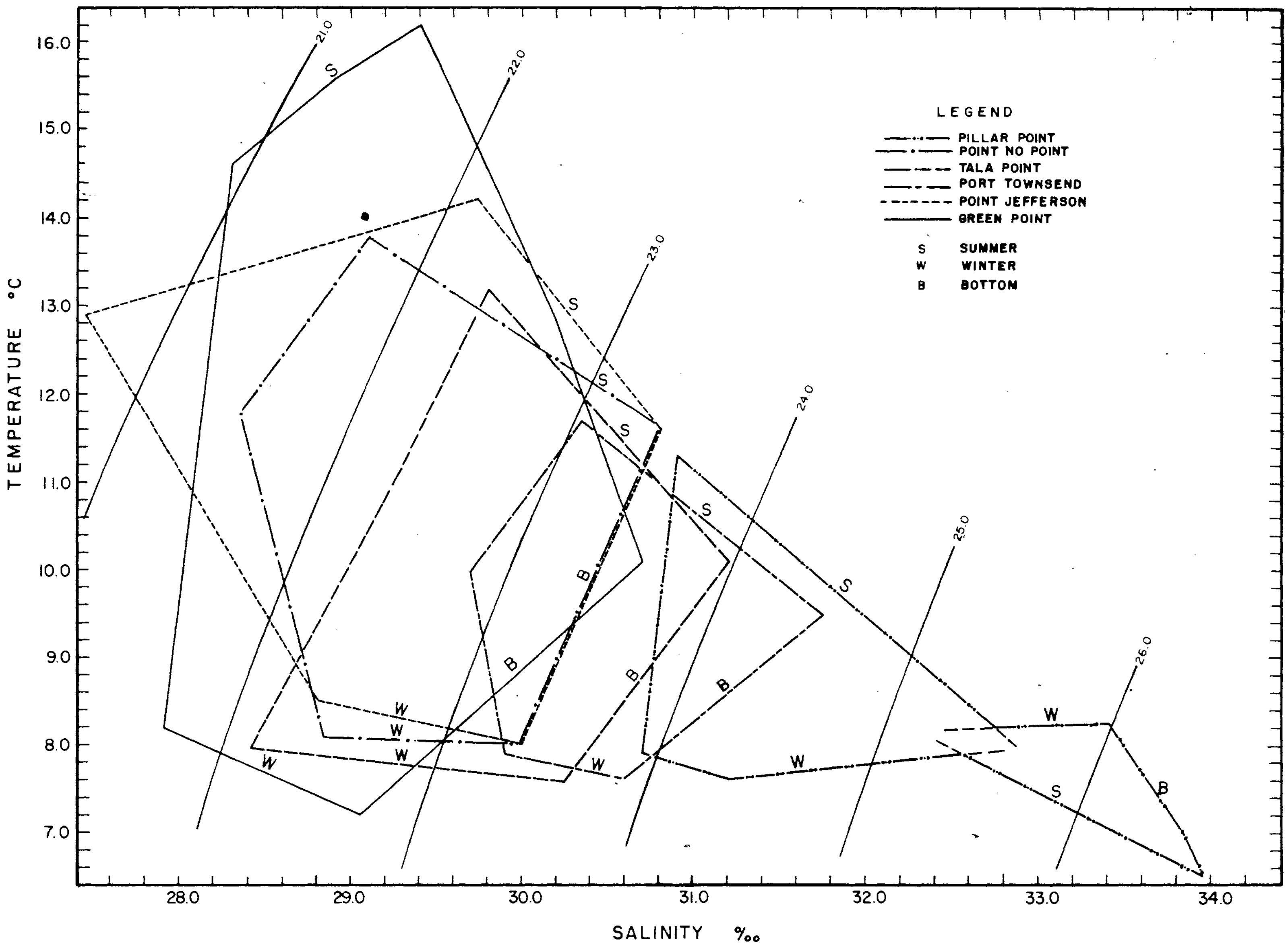

Figure 11. Temperature-Salinity Envelopes.

southernmost extension of the Sound beyond the Tacoma Narrows. The lower side of each envelope labeled W marks the winter temperature limits for each station throughout the entry water column. Near horizontality of the lines indicates almost uniform temperatures from top to bottom. The outer upper sides each marked S are the summer boundary curves for each station. Normality to the drawn sigma-t lines in general indicates high stability. The bottom temperatures throughout the year are formed by the base line marked B. Of the five base lines that of the T-S envelope for Port Townsend shows a rapid increase in density from winter to summer and early fall when maximum penetration of ocean water of a density expressed as sigma-t of about 24.5 occurs. Water of sigma-t greater than 24.0 apparently does not reach Hood Canal.

The wider spread of the Green Point envelope indicates a greater range in temperature for the year. The water column there, however, is subject to less change in salinity because of the absence of large rivers draining into the inlet. Surface waters from the main basin that may get through the Tacoma Narrows on the flood and reach Carr Inlet get mixed enroute with more saline waters from below, resulting in a narrower range of salinity changes for the waters reaching Green Point.

3.4 VARIATIONS OF TEMPERATURE WITH SEASON

For convenience, the account of the seasonal march in temperature is started with the late winter and early spring when the water has cooled to its minimum for the year and before vernal warming has proceeded appreciably. Figure 12 to 17 show the average annual temperature cycles at different standard depths for the five stations where observations have been made.

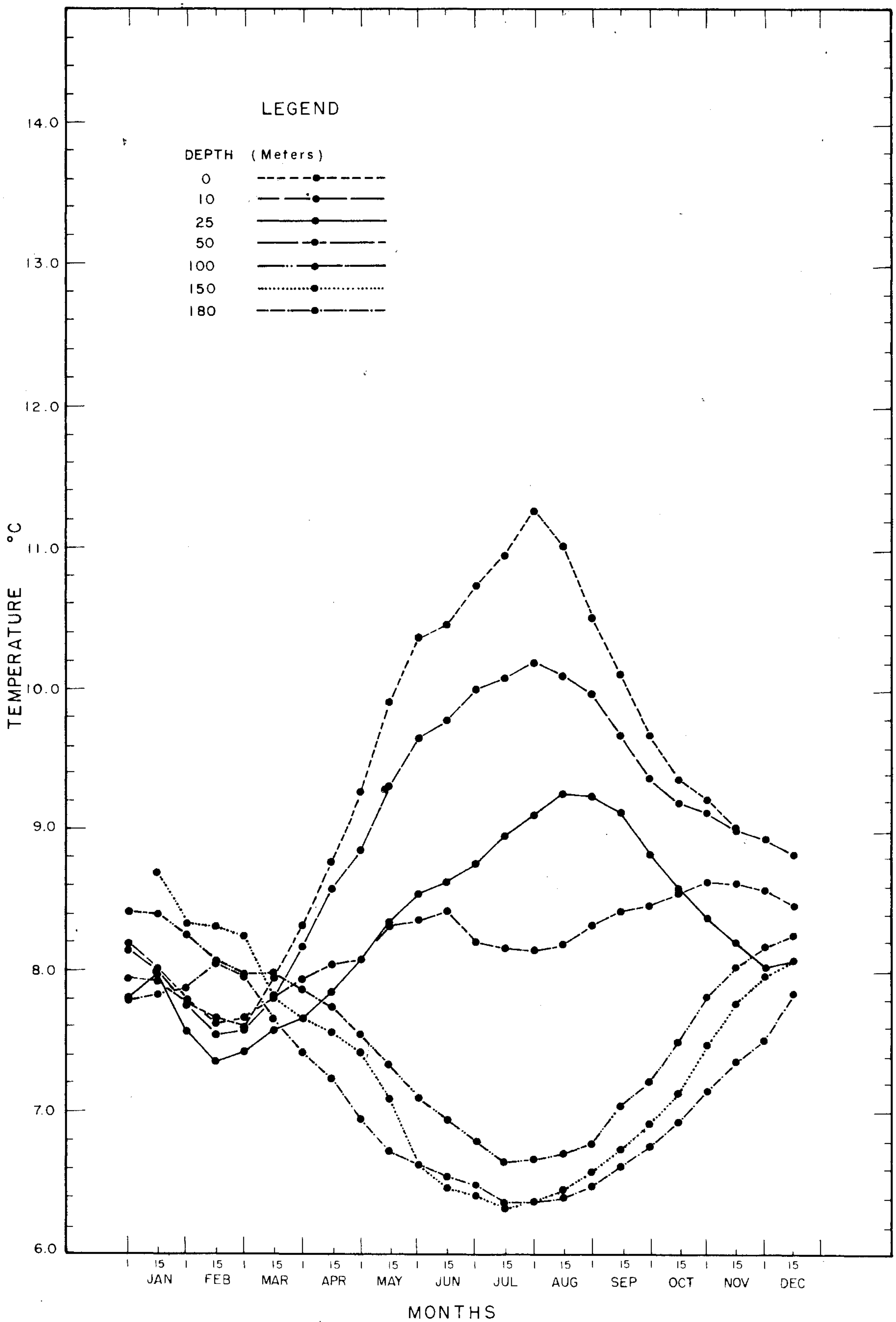

Figure 12. Annual Temperature Cycles for Pillar Point.

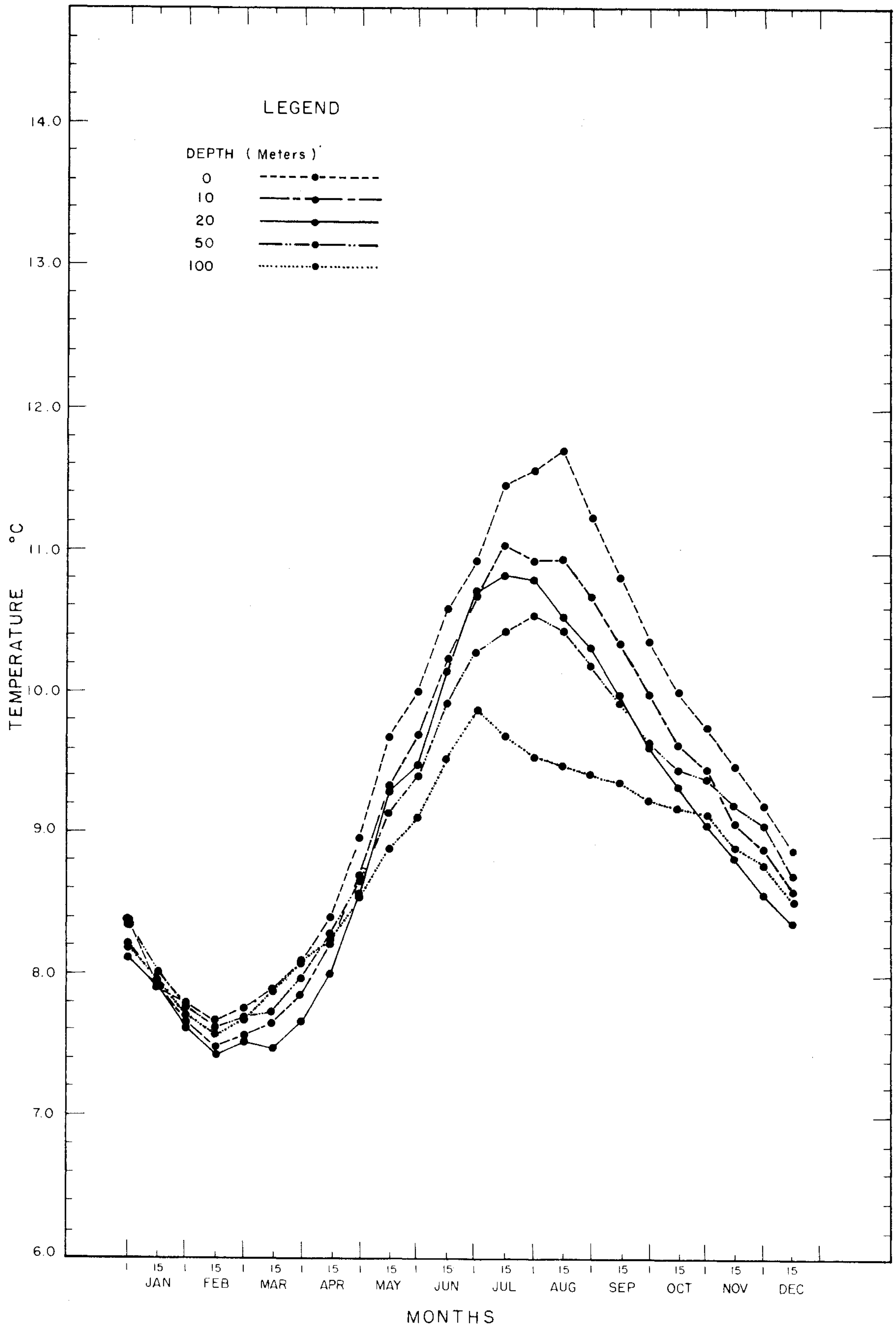

Figure 13. Annual Temperature Cycles for Port Townsend.

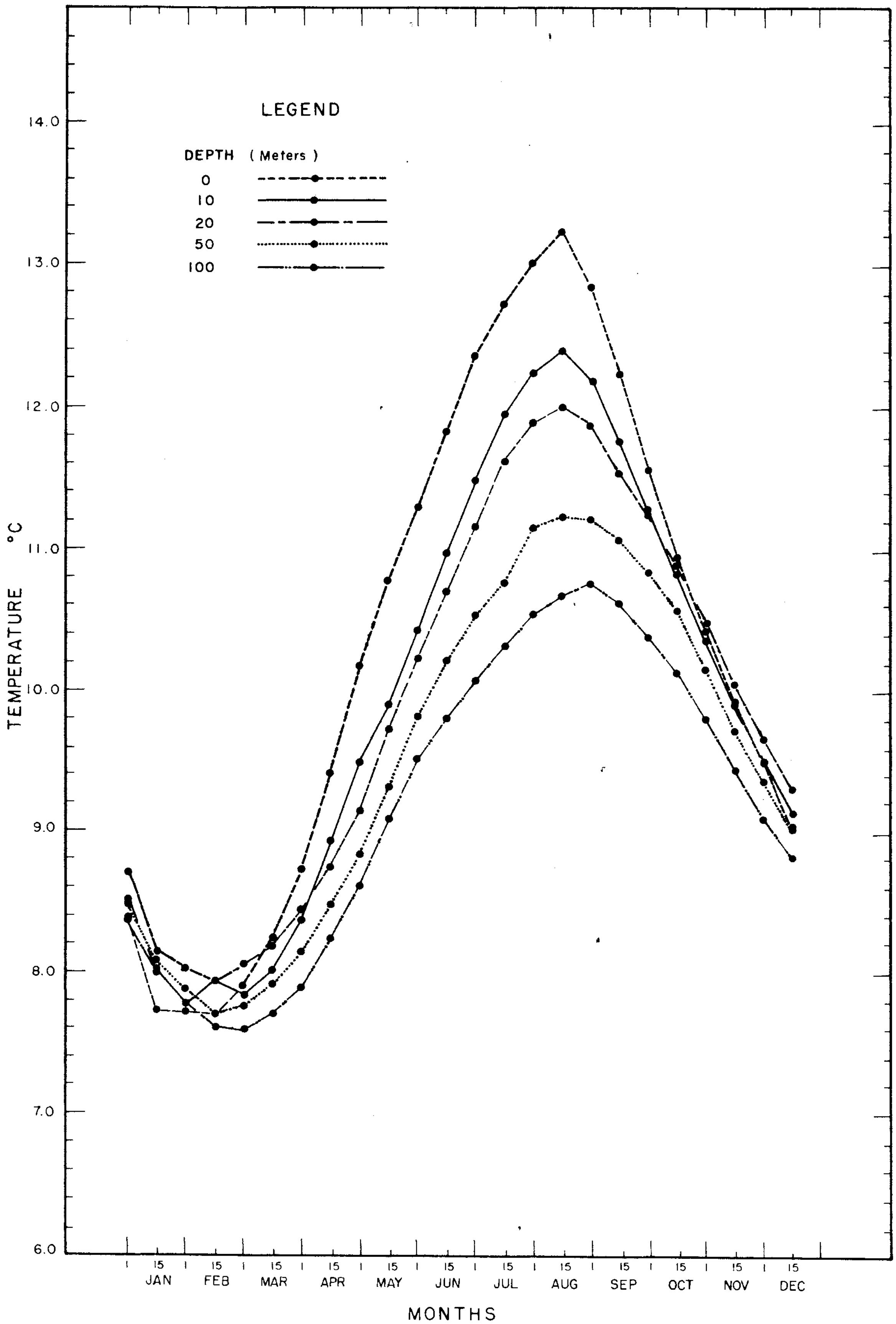

Figure 14. Annual Temperature Cycles for Tala Point.

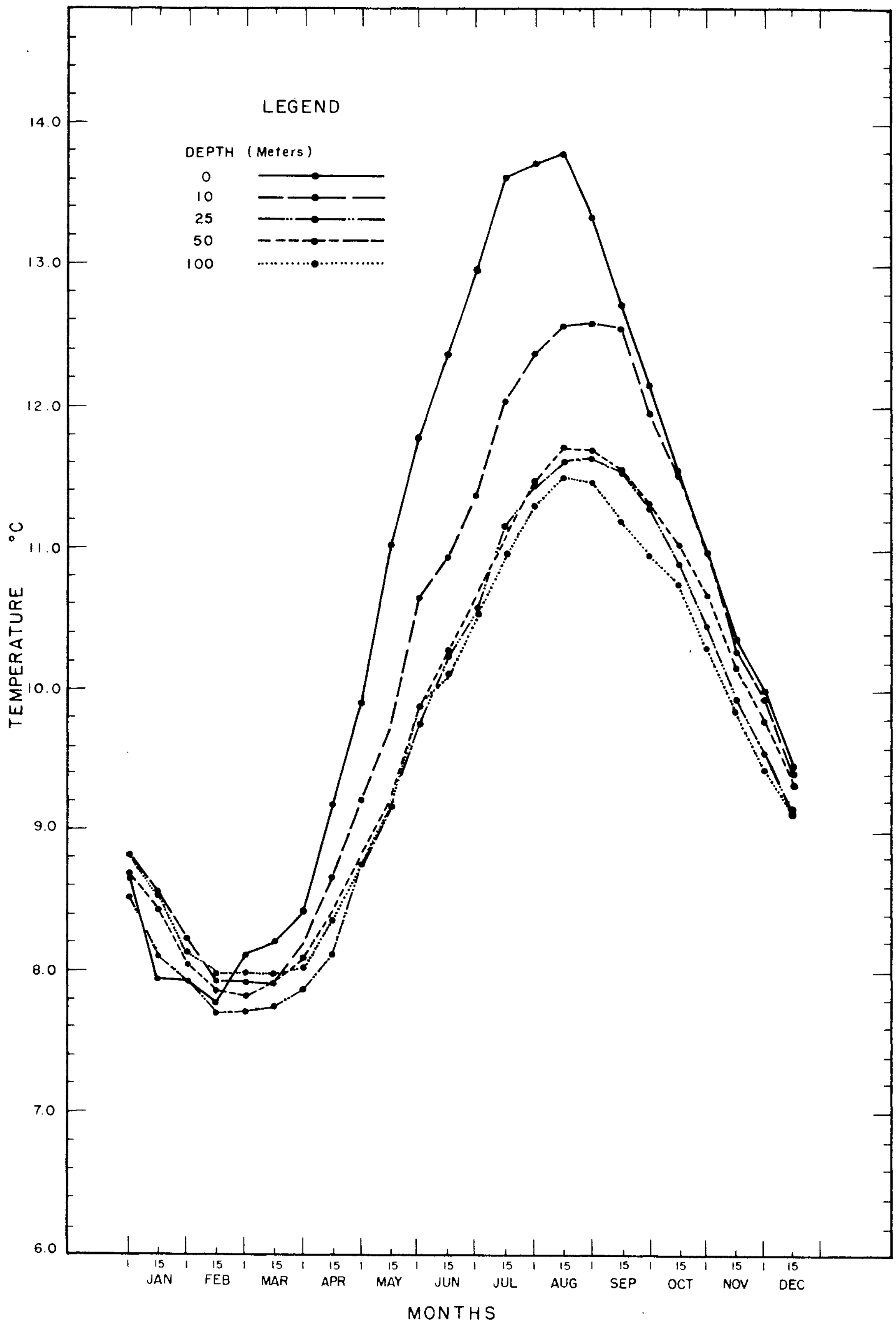

Figure 15. Annual Temperature Cycles for Point No Point.

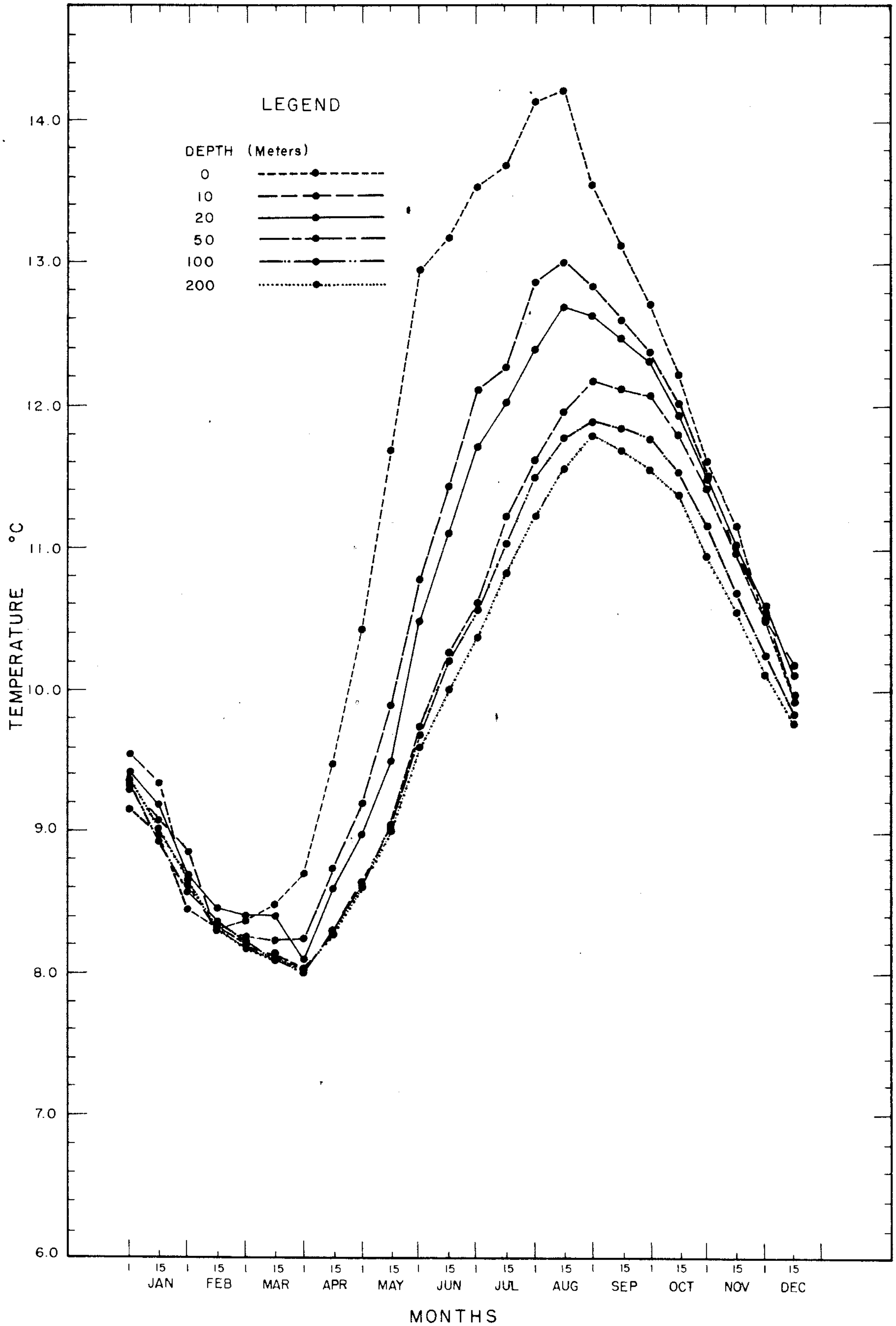

Figure 16. Annual Temperature Cycles for Point Jefferson.

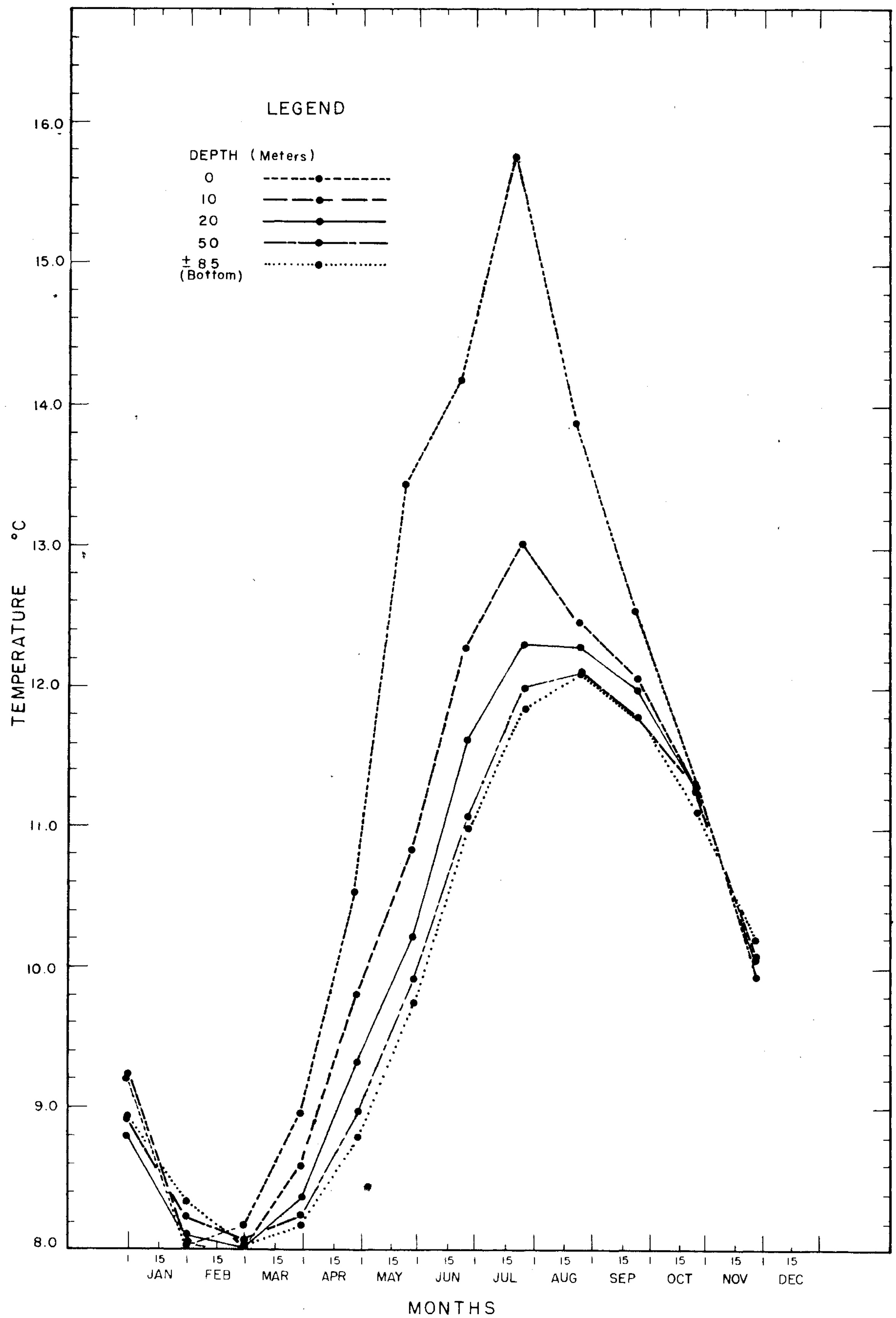

Figure 17. Annual Temperature Cycles for Green Point.

February - March

February - March is the period of minimum temperatures for the waters of Puget Sound at all levels. In the Strait of Juan de Fuca, at Pillar Point (Figure 12) minimum temperatures for the upper 50-meter layer and maximum temperatures for the deeper levels occur at the same time. Thus in the two-layer system of this place during this period a cold upper layer overrides a warm lower layer. This condition, however, does not last long as vernal warming of the upper layer, and concurrent movement of deeper colder water into the Strait of Juan de Fuca soon result in a column nearly uniform in temperature from top to bottom. As these two processes combine through the spring and summer the temperature of the upper layer increases rapidly with respect to that in the lower layer, simultaneously strengthening the stability of the interfacial density layer separating the two.

At the five stations in Puget Sound the water column at all levels attains minimum temperature during this period. Surface minimum temperatures were lowest at Port Townsend (Figure 13) and bottom minimum temperatures highest at Green Point. In the two stations of the main basin the surface layer becomes colder earlier than the underlying layers. Once vertical warming commences, the surface layer warms up rapidly while the lower layers are still losing heat or are maintaining steady temperature.

The minimum average temperatures at the five stations are as follows, the figures in the first column corresponding to the surface and those in the second column to the bottom or lowest layer sampled:

Port Townsend	7.67° C	7.58° C
Tala Point	7.69	7.59
Point No Point	7.77	7.98
Point Jefferson	8.30	8.00
Green Point	8.02	8.05 (two years average)

Thus, nowhere within the Sound does the average minimum surface temperature differ by more than 0.7° C, and that of the bottom water by more than 0.5° C.

May

This month is characterized by a rapid rise in the water temperatures at all levels.

Vernal warming comes much faster at Pillar Point than at Port Townsend, and at Tala Point than at Point No Point. After the land drainage reaches its peak in June, the rise in temperature at Pillar Point advances more slowly while that at Port Townsend increases at an even rate. As the season advances from May the water temperature at Point No Point increases more rapidly than at Tala Point, but in no period during the year does it exceed the increase at Point Jefferson or at Green Point.

July - August

In summer when the surface temperatures in the six stations reach their maximum the order of decreasing temperatures is as follows: Green Point, Point Jefferson, Point No Point, Tala Point, Port Townsend, and Pillar Point. The highest temperature for the last was 11.26° C (Table 1), and 15.72° C for the first, or a difference of about 4.4° C. It is likely that the cold upwelled waters at Pillar Point contribute to this great difference in the maximum summer temperatures.

At Pillar Point the waters reach their highest temperature earlier than at the other stations. The highest temperature for the waters at Pillar Point is attained in early August and that of the waters at the other stations about half a month later. This lag for Green Point is not shown because the observations were taken only at monthly intervals. Because upwelling at Pillar Point apparently occurs during this period following the advent of the summer winds, it is suggested that it may be one of the principal factors contributing to the early occurrence of maximum

November

In late fall there is a pronounced regularity in the rate of decrease in water temperatures at Green Point, Point Jefferson, Point No Point, and Tala Point. At Pillar Point and Port Townsend temperatures decrease faster following the occurrence of the summer maximum but advances more slowly after November.

It is interesting to note that there is a rather uniform difference in temperature of about 0.5° between any two adjacent stations. At no other time during the annual temperature cycle does this occur.

The seasonal trend in the surface temperature off Pillar Point shows good agreement with the temperature changes observed across the Strait of Juan de Fuca at William Head at Vancouver Island. The latter observations were taken from samples collected at the lighthouse during the corresponding period (Fisheries Research Board of Canada, 1947, 1948). They differ only in the order of magnitude of temperatures during the extreme seasons and in annual range. The annual temperature range for William Head is 4.33° C, about 0.9° higher than at mid-strait, the greater range for the former being

due to higher temperatures in summer and lower temperatures in winter. The seasonal variation of temperature and salinity at various stations along the British Columbia coast are discussed by Pickard and McLeod (1958).

3.5 VARIATIONS OF SALINITY WITH SEASON

Variations in salinity with the season are characteristic of coastal and embayed waters, the water freshening during the spring and early fall freshets and then gradually increasing in salinity again as this river runoff is mixed through the action of waves, winds, and tides. The coastal and tide waters of Washington are no exception to this rule. The annual range is generally widest in regions close to river deltas and farther away from the sea. The annual salinity cycles are shown in Figures 18 to 23.

February - March

It is logical to choose this period as a point of beginning in discussing the seasonal variations in salinity as it parallels that of the temperature changes. It is a period when variations in salinity, both regional and vertical, are least.

A comparison of the figures shows that the values at Pillar Point (Figure 18) do not represent the typical distribution of salinity in the upper layers of coastal and tide waters in boreal regions. The lowest salinities throughout the year are found in winter with readings as low as 31.7 ‰ at the surface and as high as 33.5 ‰ at the bottom. At Pillar Point the salinity maximum is reached progressively earlier with depth, a feature not found in the inner Puget Sound stations. This is attributed to sea water intrusion. This more saline water apparently does not penetrate

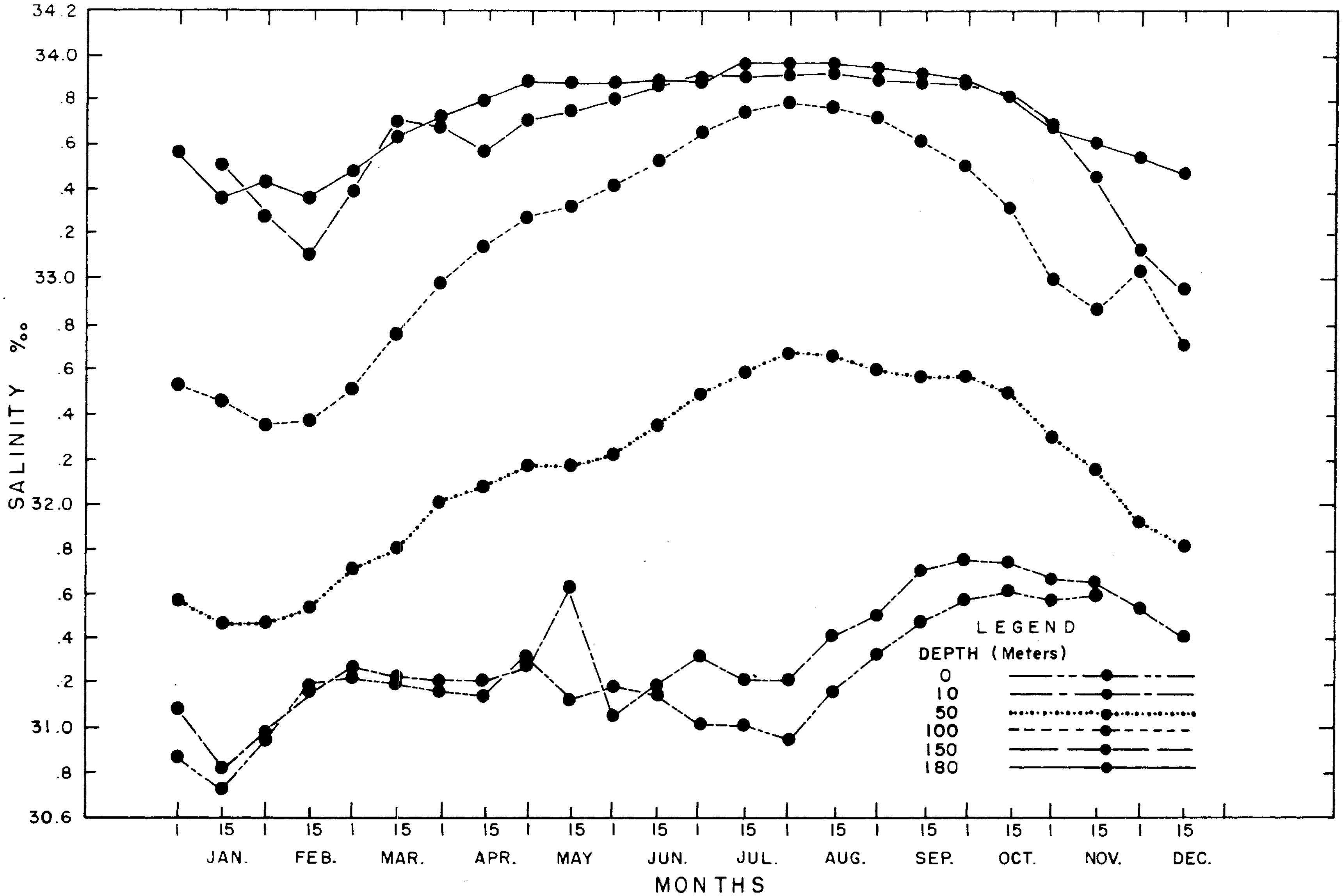

Figure 18. Annual Salinity Cycles for Pillar Point.

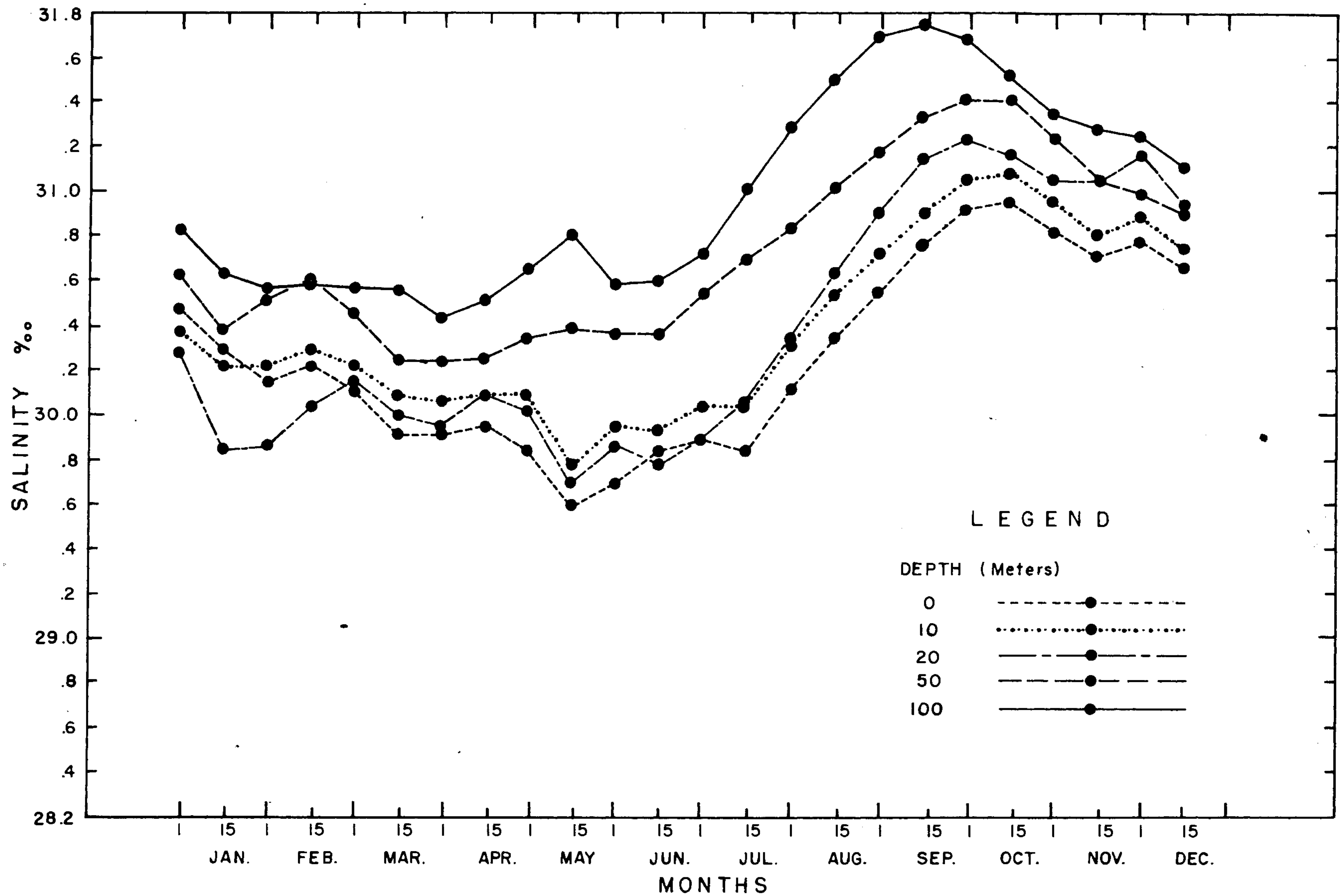

Figure 19. Annual Salinity Cycles for Port Townsend.

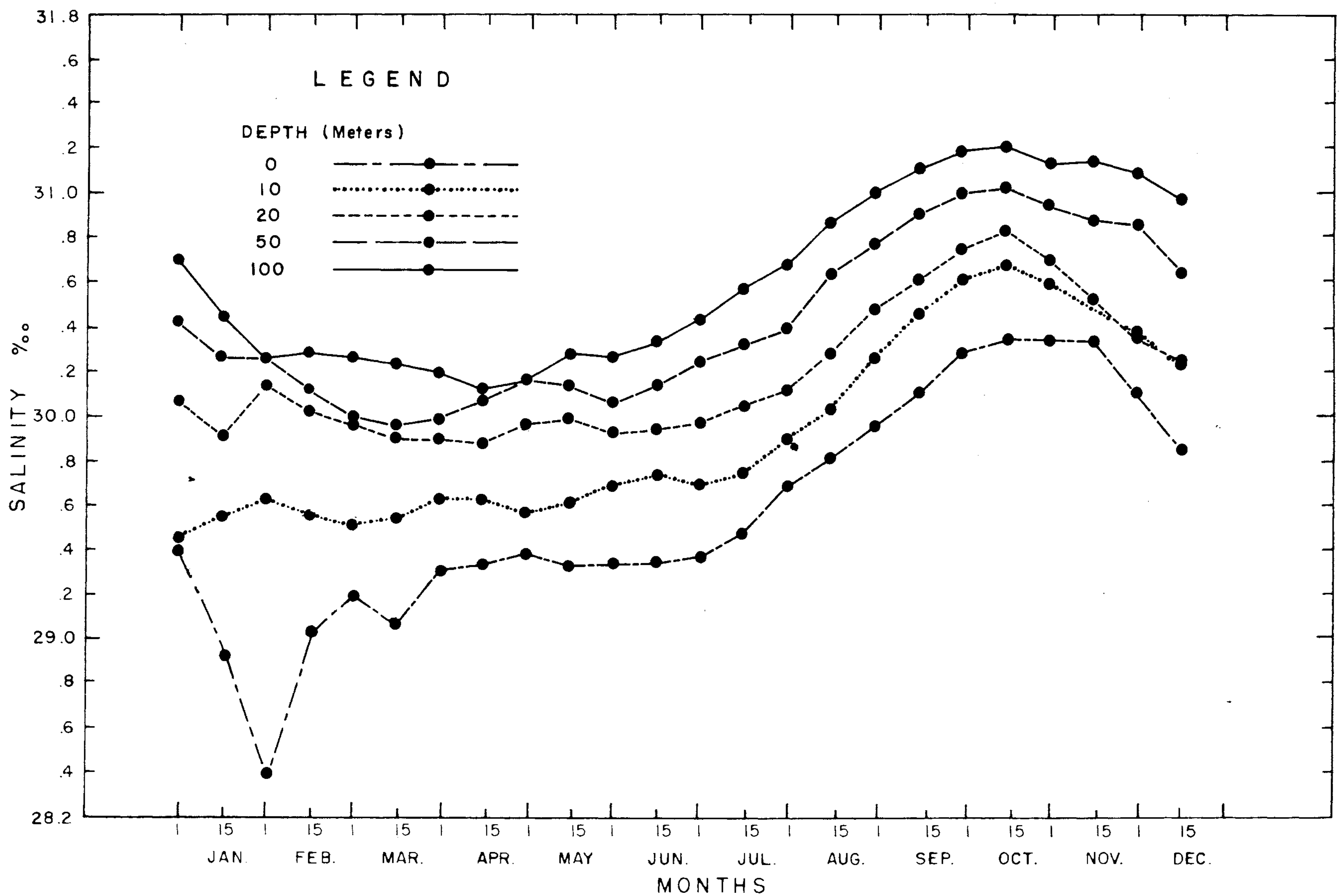

Figure 20. Annual Salinity Cycles for Tala Point.

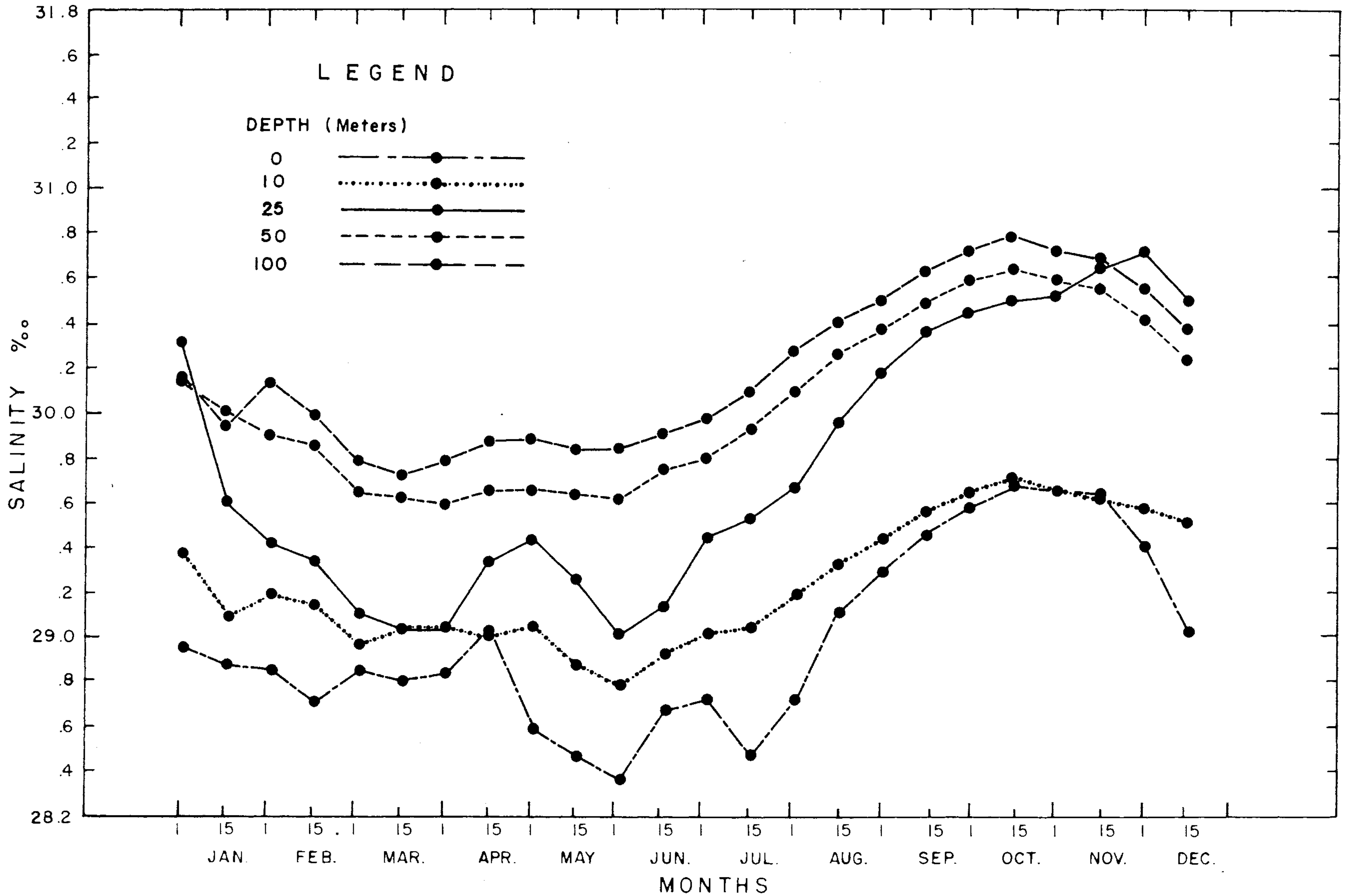

Figure 21. Annual Salinity Cycles for Point No Point.

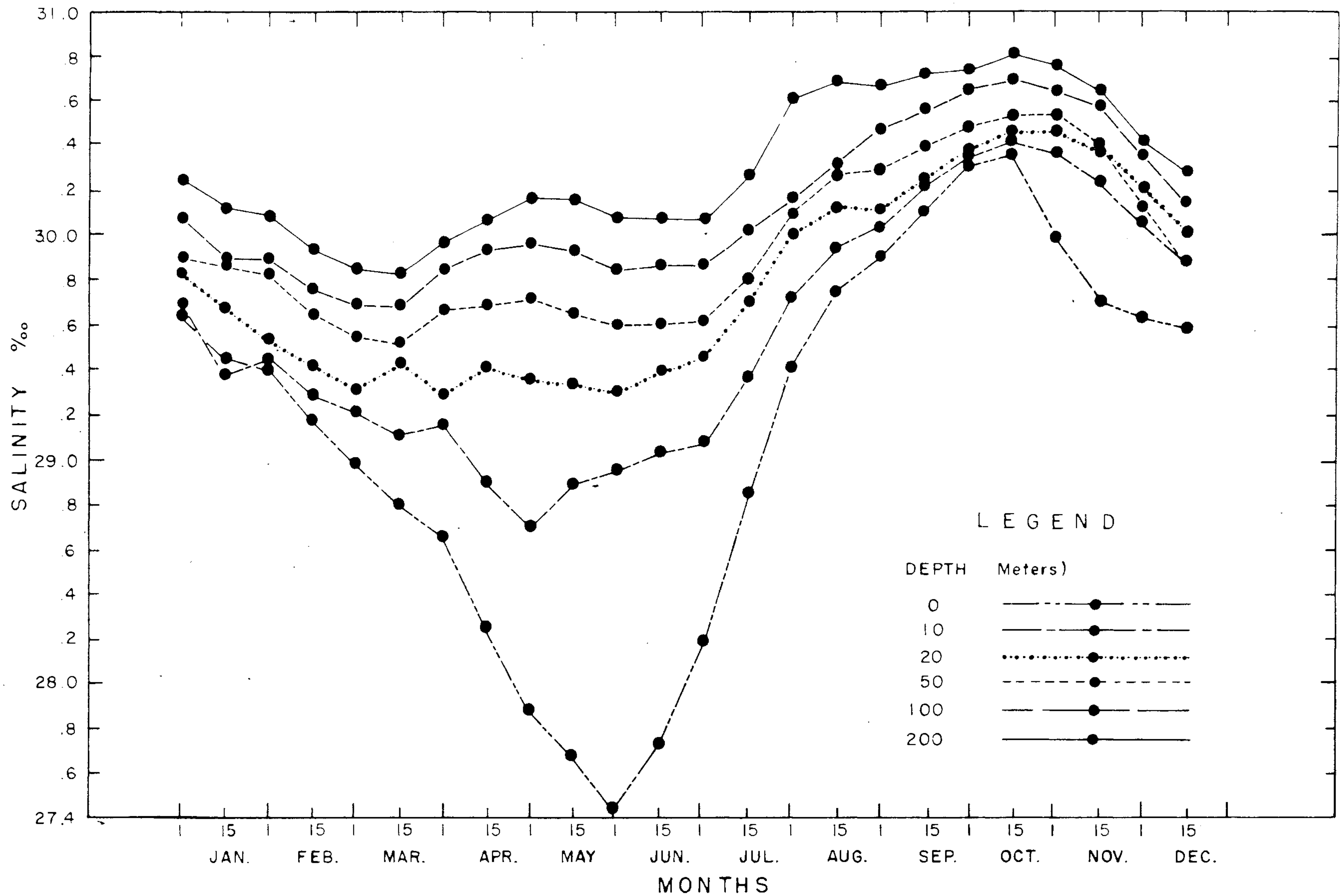

Figure 22. Annual Salinity Cycles for Point Jefferson.

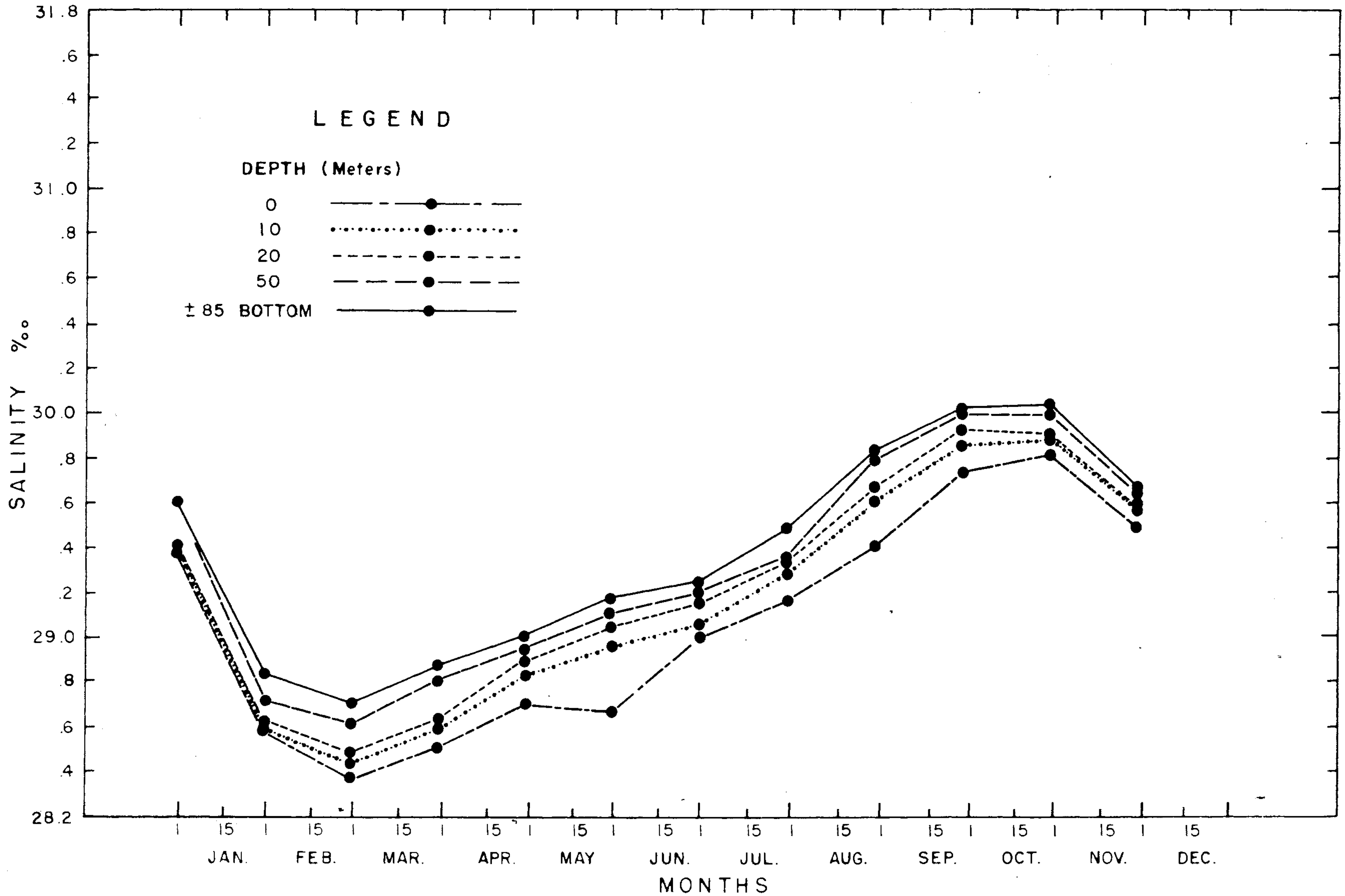

Figure 23. Annual Salinity Cycles for Green Point.

into the Sound at this season without considerable intermixing with local more dilute water and its effect is not noticeable beyond Port Townsend (Figure 19).

During this period a rapid drop in salinity is found at all depths to 200 meters in the waters off Point Jefferson (Figure 22). The drop in surface salinities reflects the high penetration and runoff of the period. This fresh water is mixed vertically in such turbulent tideways as Admiralty Inlet and subsequently its effect is felt after more or less delay at all depths in the basin. At Point Jefferson low salinities persist at the surface until the end of spring.

May

During this month the incoming ocean waters show less influence on the salinity of the waters landward of Pillar Point. Inland waters which are fed more or less directly by the melting snows become increasingly dilute as the sun rises in altitude. This flood of snow water results in a pronounced drop in salinity of the upper layers, particularly off Point Jefferson (Figure 22) where mixing processes are slow to disperse the accumulating lens of surface water. As a consequence of the "refluxing" of mixed water from Admiralty Inlet, however, some dilution is evident in the bottom waters at Point Jefferson by the last of May. Surface dilution is also marked at Point No Point (Figure 21) and to a lesser extent at Port Townsend (Figure 19), whereas the bottom layers at both stations show but little change. At Tala Point (Figure 20) near the center of the mixing zone salinities change very little at any depth during May.

June

June may well serve as the starting point to account for the salinity minimum that occurs in summer. This salinity minimum precedes the maximum surface temperatures by about a month. This choice of an earlier period corresponds to the month of highest runoff.

Of the waters at the six stations, only the deeper water at Pillar Point does not appear to be under the diluting influence of the heavy runoff in late spring and early summer. If influenced at all, the intruding ocean water masks it. In the upper ten meters of water, however, dilution effects are quite evident. The rather striking uniformity in salinity from late winter to early June appears to be an evidence of the maintenance of the salt balance, for as the volume of land drainage increases so also does the amount of sea water penetration. It appears probable that the north and northeasterly winds which blow in increasing intensity with the coming of summer and the coincident increased land drainage flow contribute significantly to the forces that maintain this mechanism.

In contrast to the conditions at Pillar Point, the waters at the other stations display significant reductions in salinity at all levels. From a salinity of 29.6 $^{o}/oo$ in January the surface waters off Point Jefferson decrease about 2 $^{o}/oo$ by June, a period of five months. The reduction in salinity is most noticeable in the upper 10 meters of water, but is significant at all depths.

The location of the Point Jefferson station within the central part of the main basin, where tidal mixing is less vigorous than at the constricted entrances, favors the accumulation of runoff from local rivers in the surface layers and a resultant lowering of the salinity.

It is interesting to note that although the more saline source water of the southern section of Puget Sound comes from the main basin, the mean salinities for corresponding depth increments throughout the entire water column in the former (Figure 23) not only are higher but the minimum occurs in February - March. At Point Jefferson, below 20 meters, the salinity trends correspond to those for the Carr Inlet waters. This suggests thorough mixing over the sill at the Tacoma Narrows. That the salinity trends shown by the curves for Green Point should follow the precipitation cycle is to be expected. The river systems draining into the southern basin are small and almost entirely rain-fed.

At stations seaward of Point Jefferson the diluting influence of river freshets is not felt appreciably beyond a depth of about 100 meters at Point No Point and not lower than 20 or 25 meters at Port Townsend and Tala Point.

During the height of vernal warming the soft top snow is melted rapidly, resulting in a significant change in the rate of river discharge. This condition is reflected in the secondary salinity minimum for the upper layers at all stations.

The combined influence of outside waters on the inland waters and decreased runoff is shown by the salinity increase throughout the entire water column at Port Townsend (Figure 19). The salinity of the bottom water peaks in about the middle of September and that of the surface layer about a month later.

Fall

At Pillar Point in the fall the water increases in salinity in the upper layers to a depth of about 75 meters and decreases in salinity below that depth. The surface increase reflects the lower replenishment rate of fresh water from precipitation and runoff during that period. Not only does the maximum salinity of the bottom layer decrease, but the thickness of the relatively saline undiluted layer also decreases considerably. This decrease in the amount of salt present in the deeper layers could result from a change in water characteristics at sill level near the entrance to the Strait, a decrease rate of flow of the oceanic water towards the head of the Strait, or increased vertical mixing in the Strait itself. The change in water properties at the depth of the seaward sill appears quite likely and could come from reduced upwelling, the presence of a different water mass which had moved in laterally from another location, or local changes near the mouth of the Strait that might stem from vertical mixing. The pronounced stability of the coastal water mass during summer, the lesser winds at that period, and the rather considerable depth of the seaward sill, about 230 meters, suggest that vertical mixing with surface layers is not an important contributing factor. The persistently low oxygen and high salt content of the deeper waters at Pillar Point and the close conformity with which the concentrations repeat themselves at closely the same time from year to year point towards the motion directed vertically as a primary cause of the variation in the ocean type water as appears at Pillar Point. Thus the autumnal decrease in the amount of salt present in the lower layers may reflect the gradual decrease in the rate and extent of upwelling at the approaches to the Strait of Juan de Fuca.

3.6 VARIATION OF TEMPERATURE AND SALINITY WITH DEPTH

For representing the vertical distribution of temperature and salinity, the periods of maximum and minimum temperatures in the annual temperature cycle are chosen. These periods, taken to correspond to the heights of the summer and winter seasons for the waters of Puget Sound at the various locations, are approximately as shown below. Figures 24 and 25 present graphically the vertical distributions of salinity and temperature during the two periods.

Station	Winter Peak	Summer Peak
Pillar Point	Feb. 1 - Mar. 15	July 1 - Aug. 15
Port Townsend	Feb. 1 - Mar. 15	July 1 - Aug. 15
Tala Point	Feb. 1 - Mar. 15	Aug. 1 - Sept. 15
Point No Point	Feb. 1 - Mar. 15	Aug. 1 - Sept. 15
Point Jefferson	Feb. 1 - Apr. 1	Aug. 1 - Sept. 15
Green Point	February - March	August - September

In making comparisons at depth it is helpful to consider the average values. In averaging the temperatures and salinities at each depth for all stations, certain values did not fit into the monthly T-S relationships discussed in the preceding section. Most of the discrepancies were due to the uneveness in the number of measurements being averaged from one layer to another. The questionable values appear bracketed in Table I. The overall number of measurements rejected is small.

The monthly maximum and minimum deviations from the temperature and salinity means corresponding to the surface and bottom layers (and also to 50 meters for Pillar Point) were analyzed for possible correlation with runoff, heating cycle, etc. The analysis showed that the range of the deviations from the mean, both for surface and bottom salinities, was confined to a narrow limit in late summer and early fall when maximum salinities

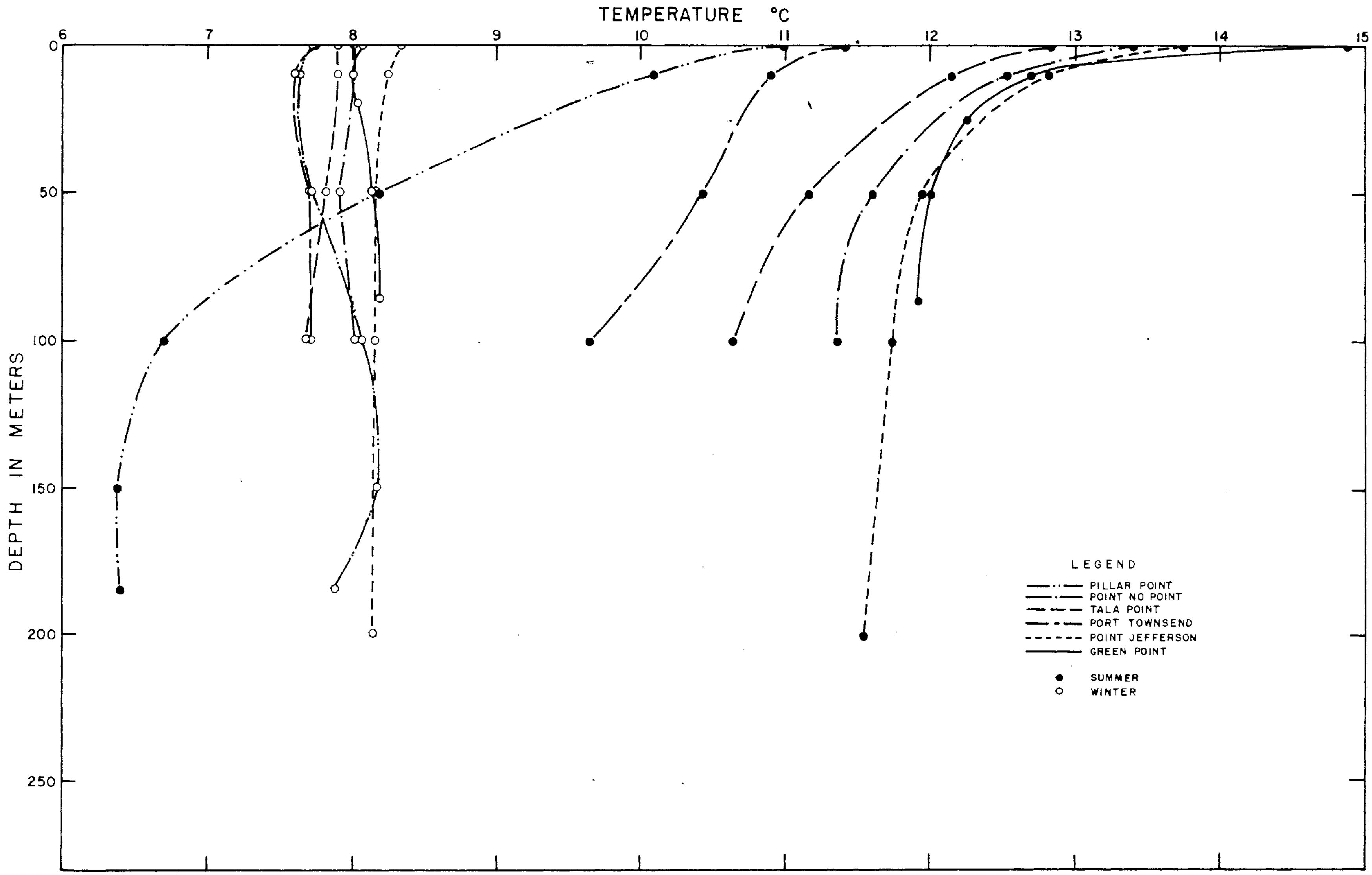

Figure 24. Vertical Distributions of Temperature in Winter and Summer.

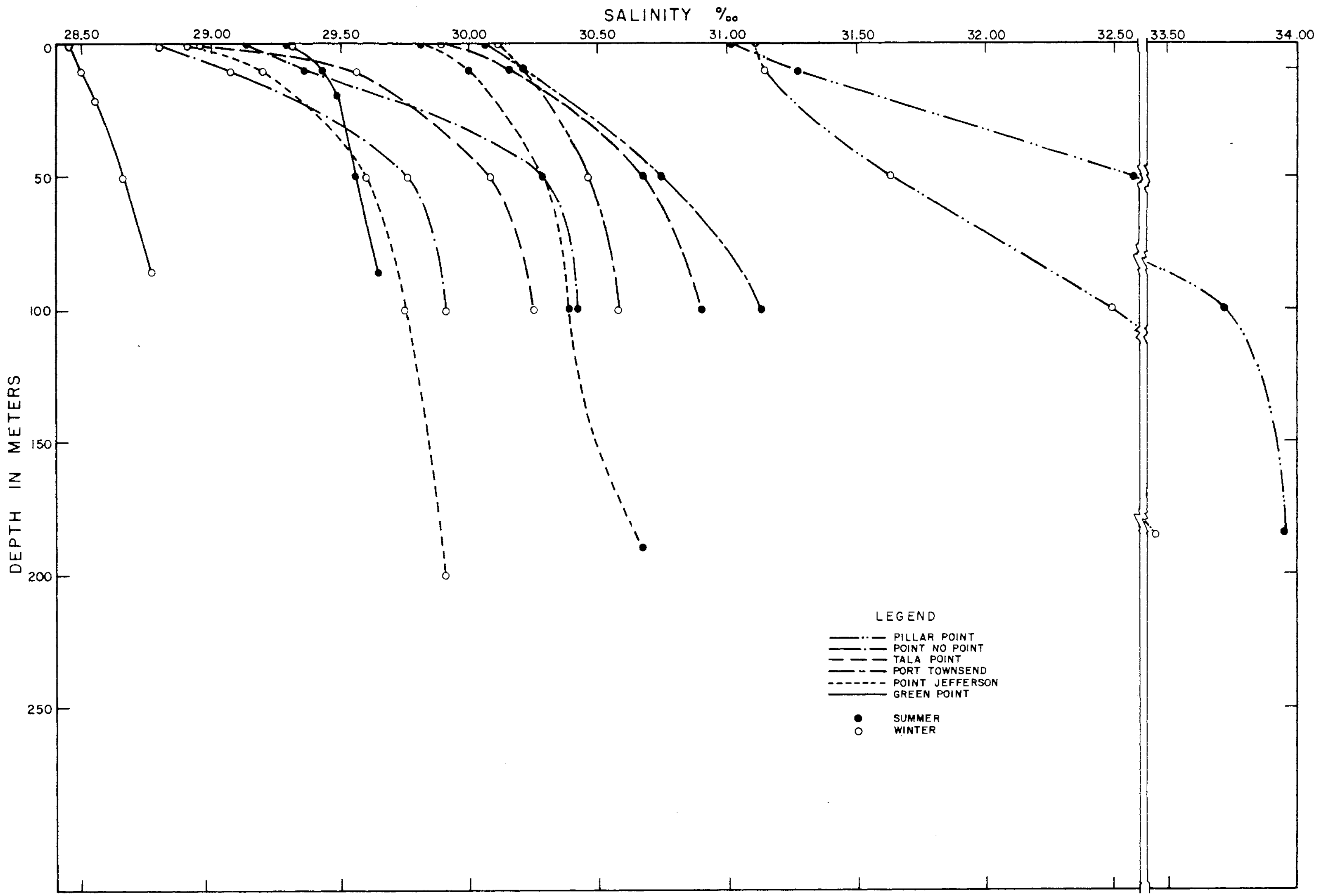

Figure 25. Vertical Distributions of Salinity in Winter and Summer.

occur. This may be taken as another indication of sea water intrusion at depth. The temperature deviations showed a narrow range of variation for the surface and bottom only for the waters off Point Jefferson.

The period of greatest deviations for both temperature and salinity appear to coincide with the period of high land drainage.

Surface

Temperature. In winter temperatures are everywhere uniformly low. Pillar Point registers 7.7° C, differing but 0.1° from that Port Townsend, which is 7.8° C. Point Jefferson has 8.3° C, about 0.3° higher than that at Point No Point. At Green Point the temperature is only 0.1° lower than at Point Jefferson. Thus the average temperature difference between the extremities of the area under study never exceeds 1° at any time.

In summer differences in temperature are well marked. Local heating in the proximity to land is important in changing the surface temperatures. The highest temperature at Green Point is 15.72° C as against 10.88° C at Pillar Point. The difference is about five times that observed in winter.

Salinity. The surface salinities in winter are useful in studying the effects of the ocean waters on the physical structure of the waters of the Sound. The absence of "upwelling" coincides with the period of lowest runoff.

Figure 25 shows that the salinity is higher at Point No P oint than at Point Jefferson, a normal situation considering that the salt source is the ocean and runoff the primary source of dilution.

In summer during the period of highest runoff, Pillar Point again shows the highest salinity although it lies in the direct path of the drainage systems of both Puget Sound and the Strait of Georgia. Discharges from both are intensively mixed over respective entrance sills, however, an additional entrainment of salt water from below occurs in the Strait of Juan de Fuca inside Pillar Point. The greatly reduced salinity of the waters off Point No Point compared to that for Point Jefferson is an indication of the effects of effluents from the Skagit and Snohomish rivers. Below that depth the salinity of the waters off Point No Point is only slightly higher than for corresponding depths off Point Jefferson.

10 Meters

Temperature. At this level the temperatures vary but slightly from the readings at the surface in summer, an inversion occurring at most of the stations. As shown in Figures 12 to 17, the temperatures at the surface and at a depth of 10 meters become nearly identical in early February at Pillar Point, the first days of March at Tala Point, toward the end of February at Point No Point, and in the middle part of February at Point Jefferson. At Green Point this condition occurs in February. Except at this station, this condition is attained much earlier at intensive mixing zone off Port Townsend than at any of the other stations.

Salinity. The salinity is everywhere higher at this depth than at the surface, except at Pillar Point where the waters show a subsurface minimum in winter. In summer this salinity minimum disappears.

<u>50 Meters</u>

Due to the relatively small number of observations taken at 20 to 25 meters, a discussion on the distribution of properties at this intermediate depth is not included. A smooth curve, however, was drawn to eliminate the discontinuity of observation at this important part of the water column. When used, these observations are found to fall closely to the interpolated curves.

<u>Temperature</u>. At this level in winter the temperatures at Pillar Point and Port Townsend nearly equal those corresponding to the surface. In summer the lower boundary of the thermocline at Point No Point and Point Jefferson appears to be limited to this depth and at Pillar Point down to about 100 meters. At Port Townsend and Tala Point the temperature gradient varies very little from layer to layer down to the bottom. In the upper layers at Green Point the temperature gradient is quite strong, on the average decreasing about 0.2° per meter within the upper 10-meters of water.

<u>Salinity</u>. At this depth in summer the regional distribution of salinity is well pronounced; it is lowest at Green Point and highest at Pillar Point. Waters at Port Townsend and Tala Point differ only by a little higher than 0.05 $^{o}/oo$, and at Point No Point and Point Jefferson have identical salinities. In winter the salinities decrease gradually upsound, the decrease roughly a function of distance from the source sea water entering the Sound at depth.

<u>100 Meters</u>

Seasonal variations in the temperature and salinity distributions are still evident at this depth and down to the bottom in the deeper stations.

Temperature. In winter the temperatures at this and greater depths in the Sound do not show significant variations from their values at the surface. At Pillar Point, however, there is an increase of 0.25° from its value at 50 meters. The rise in temperature continues down to 150 meters and then decreases to 7.88° C at the bottom. The corresponding temperature in summer is 6.40° C. There is thus a reversal of the seasons in the bottom waters of Pillar Point. This condition is not observed in any of the Puget Sound stations.

Salinity. At the deepest station in the Sound, off Point Jefferson, there is observed a gradual increase in salinity from this depth down to the bottom, irrespective of the season, the salinities being higher in summer than in winter. This suggests the effect of the ocean water entering the Sound in summer. At Pillar Point the salinity gradient in the layer below about 100 meters is very weak, suggesting "bulk" flow of offshore water at depth by way of the Strait of Juan de Fuca. This condition is not observed in winter when the salinity gradient is significantly strong down to the bottom layers at Pillar Point. The effects of the entry of ocean water in summer on the waters at Port Townsend are reflected in the early "peaking" of the salinity curves compared to those for the other Sound stations (Figure 12).

3.7 HARMONIC ANALYSIS OF TEMPERATURES

In the preceding discussions on the temperature characteristics of Puget Sound and Strait of Juan de Fuca waters the regularity in the temperature fluctuations was not emphasized, although the temperature cycles as shown in Figures 12 to 16 suggest it rather strongly. A harmonic

analysis has been made to test the regularity at all five stations for the surface and bottom layers. The results are presented in Figures 26 to 30.

The data suggested that the temperature could be represented by a Fourier series of the form:

$$T(X) = A_o + A_1\cos A + A_2\cos 2X + B_1\sin X + B_2\sin 2X + \dots$$

where T(X) is the temperature in °C and X is an angle taken at 15° intervals from 0° to 360°, thus completing a year's cycle starting at August 1st. Only the amplitude A (°C) and phase lag σ (days) for the surface and bottom layers were computed. In view of the magnitude of the year-to-year fluctuations it is doubtful if additional terms are significant.

Although the results of the analysis cannot disclose the causes of the regularity in the temperature fluctuations, they reflect the magnitudes of the amplitudes and phases of the temperature variations in different places in the region.

The computed values of A and σ are given below:

	Surface			Bottom		
	Mean T °C	A °C	σ Days	Mean T °C	A °C	σ Days
Pillar Point	9.30	1.60	0	7.12	0.79	-150
Port Townsend	9.52	1.85	15	8.77	1.18	15
Tala Point	10.32	2.60	15	9.20	1.53	30
Point No Point	10.66	2.89	15	9.62	1.71	30
Point Jefferson	11.16	2.87	15	9.86	1.83	30

The above data show that in Puget Sound the surface waters reach their maximum temperatures about 15 days later than at Pillar Point in the surface layer. In the bottom waters of Pillar Point maximum temperatures

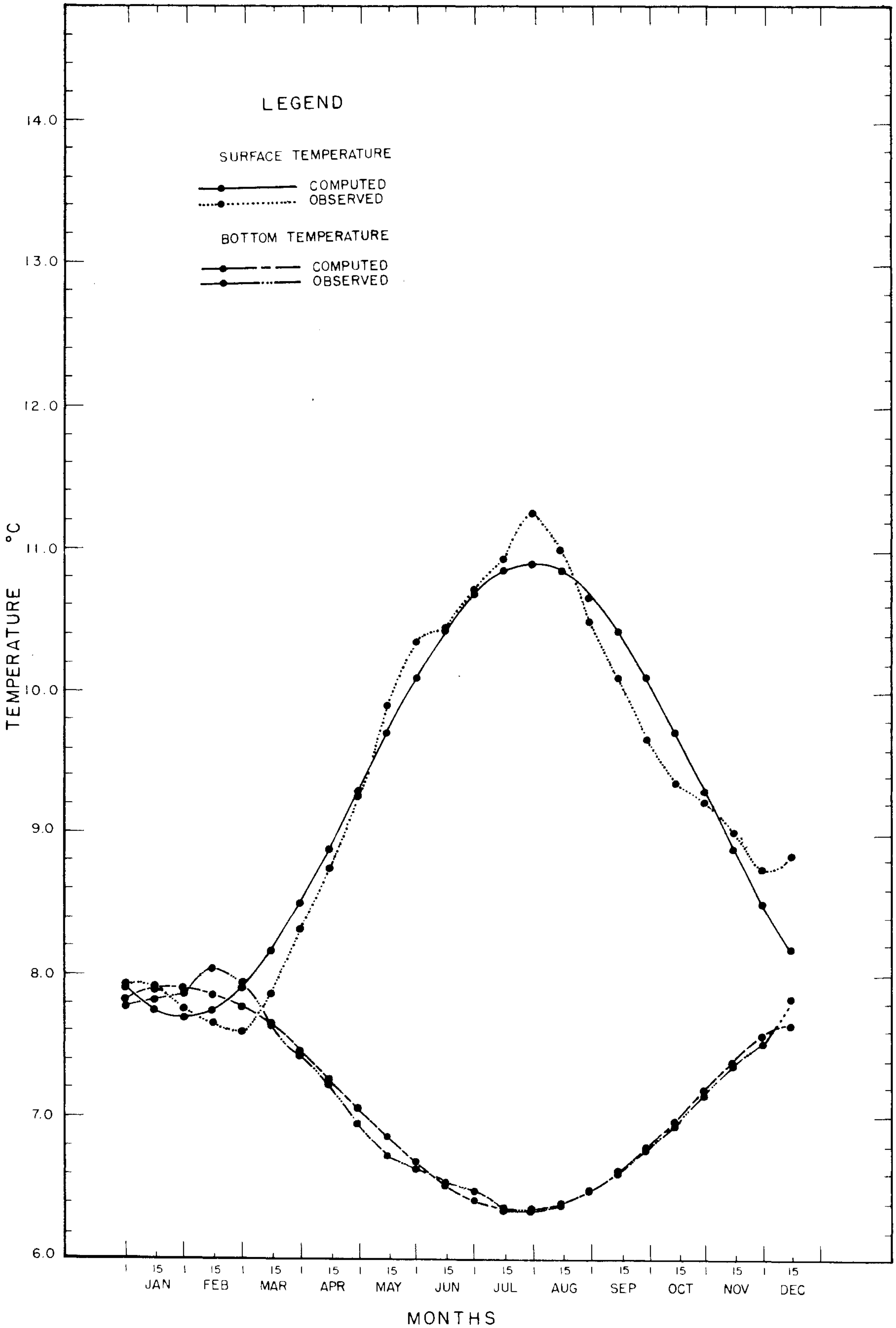

Figure 26. Computed Surface and Bottom Temperature Cycles of Pillar Point Based on Harmonic Analysis.

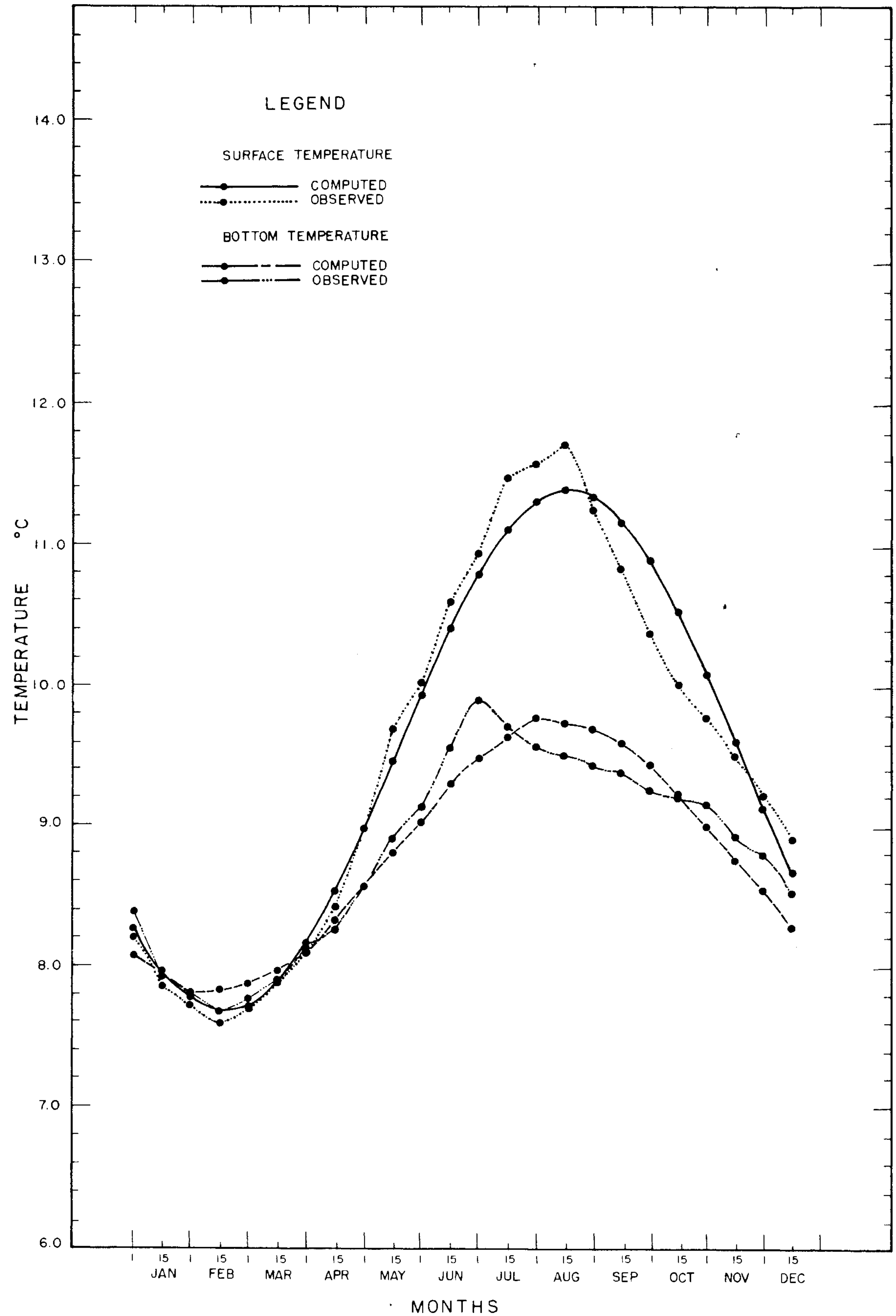

Figure 27. Computed Surface and Bottom Temperature Cycles of Port Townsend Based on Harmonic Analysis.

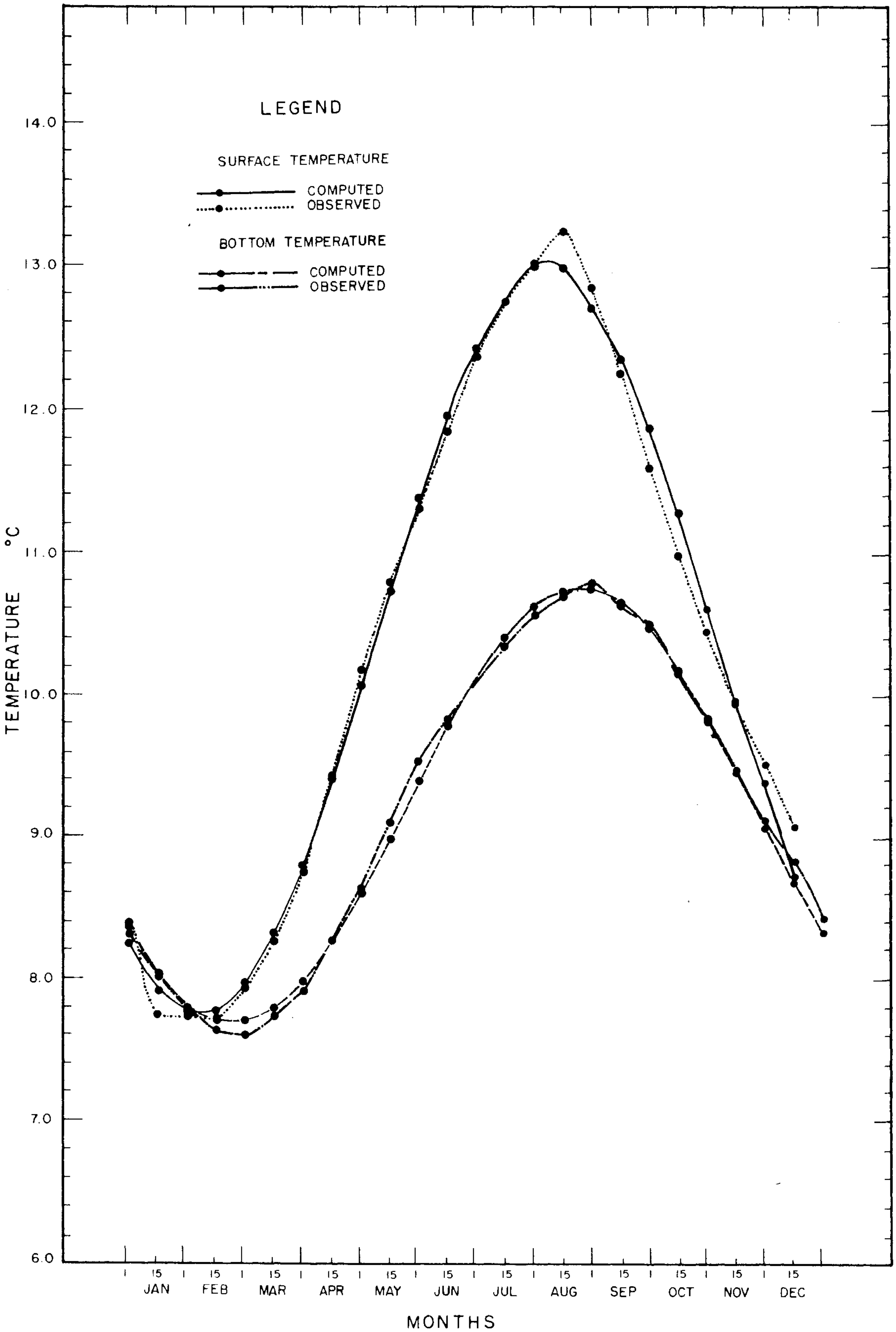

Figure 28. Computed Surface and Bottom Temperature Cycles of Tala Point Based on Harmonic Analysis.

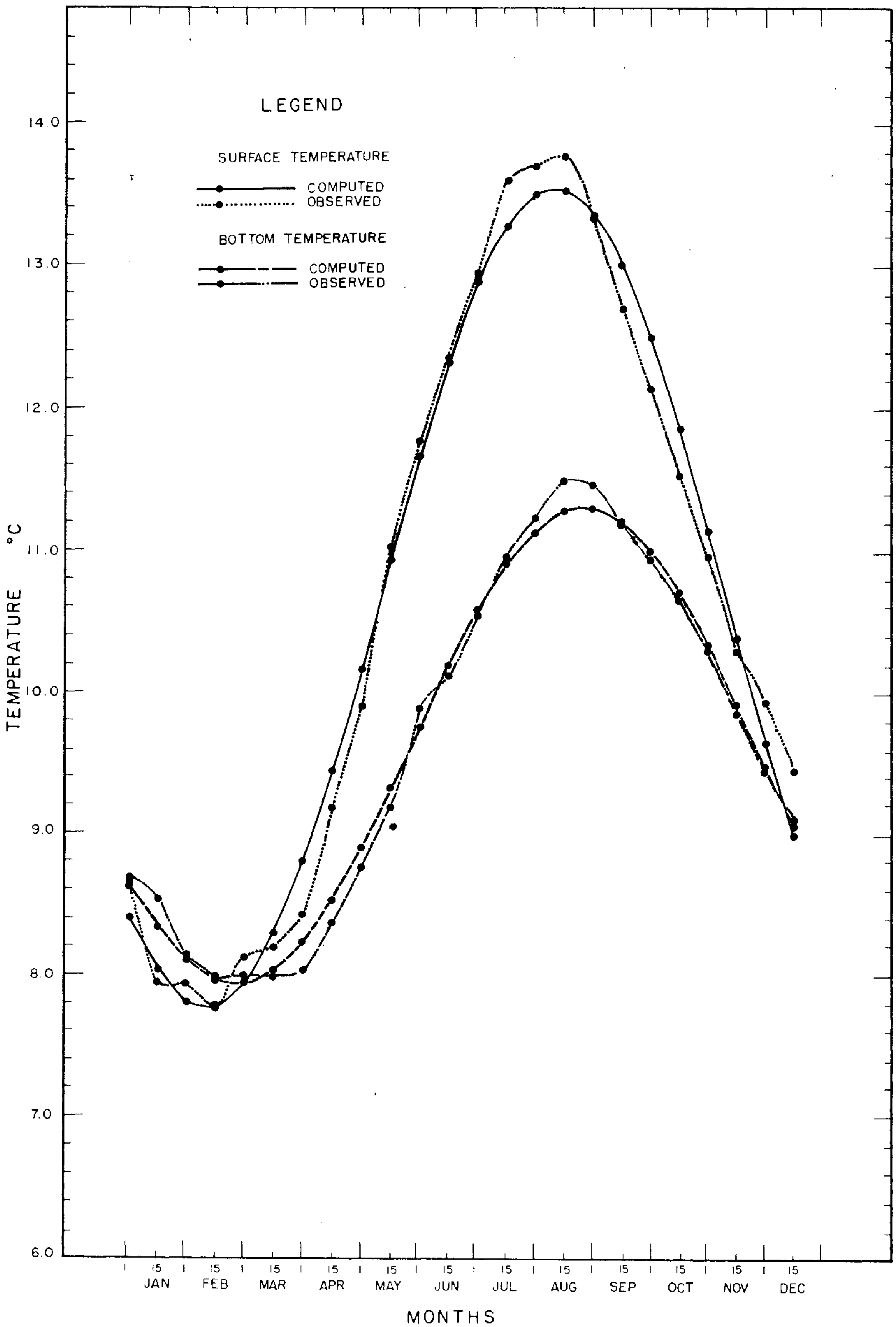

Figure 29. Computed Surface and Bottom Temperature Cycles of Point No Point Based on Harmonic Analysis.

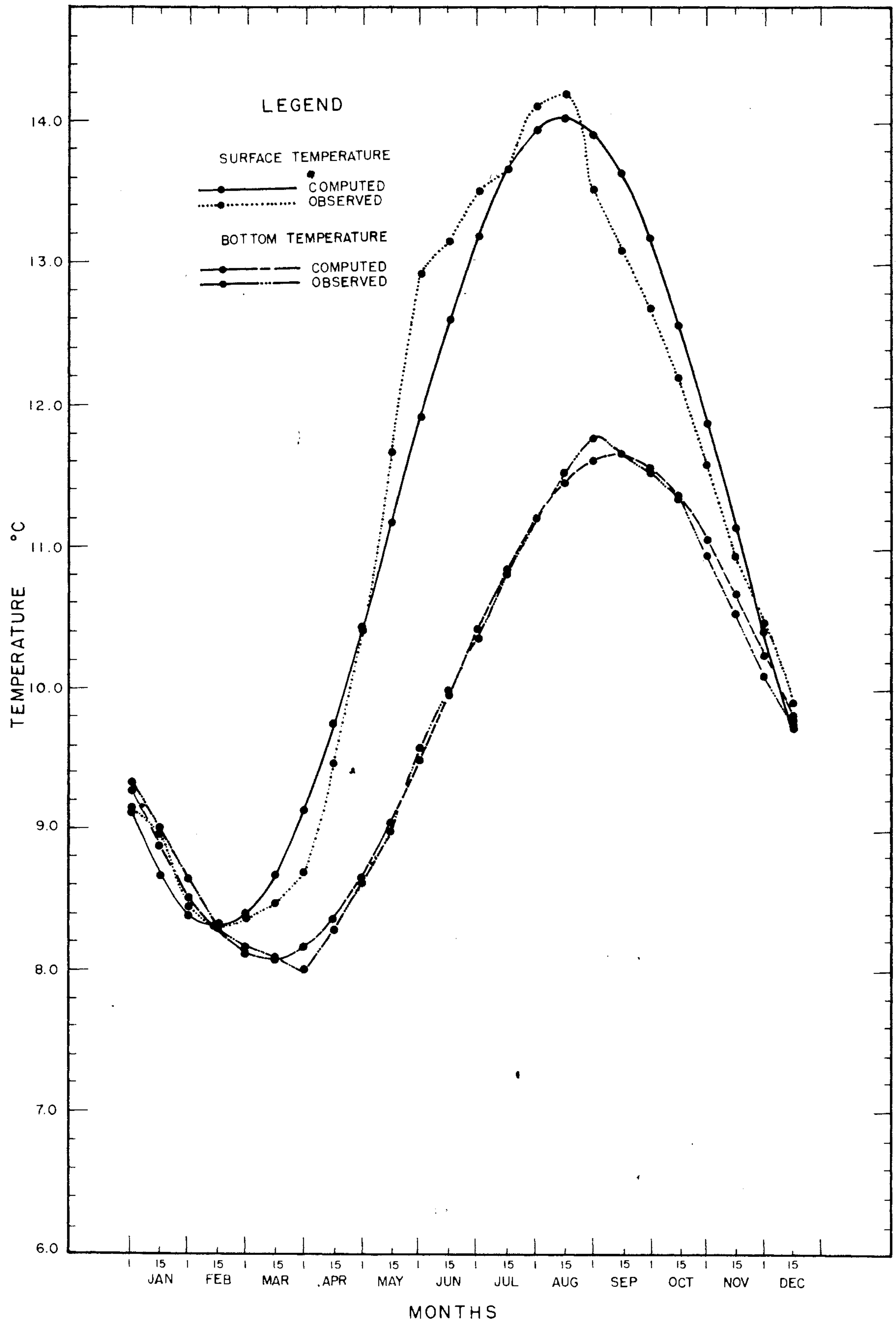

Figure 30. Computed Surface and Bottom Temperature Cycles of Point Jefferson Based on Harmonic Analysis.

are attained about 150 days or 5 months ahead of those for the surface. At Port Townsend the bottom waters reach their maximum temperatures at about the same time as the surface layers. At the other stations there is a lag of about 15 days compared with the corresponding surface values and about 180 days or 6 months compared to those for the bottom waters at Pillar Point.

As a means of comparing the surface temperature changes at Pillar Point with the available radiation data summarized by Waldichuck (1955) for the Strait of Georgia, the amplitude and phase of the latter were computed. The results of the computation show an amplitude of 84.1 gram-calories per cm^2 per day and, as expected, a phase lead of about 45 days compared to the surface water temperatures off Pillar Point. A similar comparison was made for the Seattle air temperatures mentioned in an earlier section and the surface water temperatures off Point Jefferson. The air temperature amplitude was about 0.36° C greater and the phase about 15 days earlier than the corresponding values for the surface water temperatures off Point Jefferson.

3.8 COMPARISON OF OBSERVATIONS TAKEN DURING DIFFERENT PERIODS OF YEARS

The results of the harmonic analysis suggest that it might be possible to consider the CATALYST observations as representing the average conditions of temperature and salinity in the region under study. On this premise an attempt has been made to analyze the observations taken by the BROWN BEAR in 1953 and 1954, using the CATALYST data as basis of comparison. Figures 31 and 32 show the comparison of surface and bottom temperature trends in all five stations.

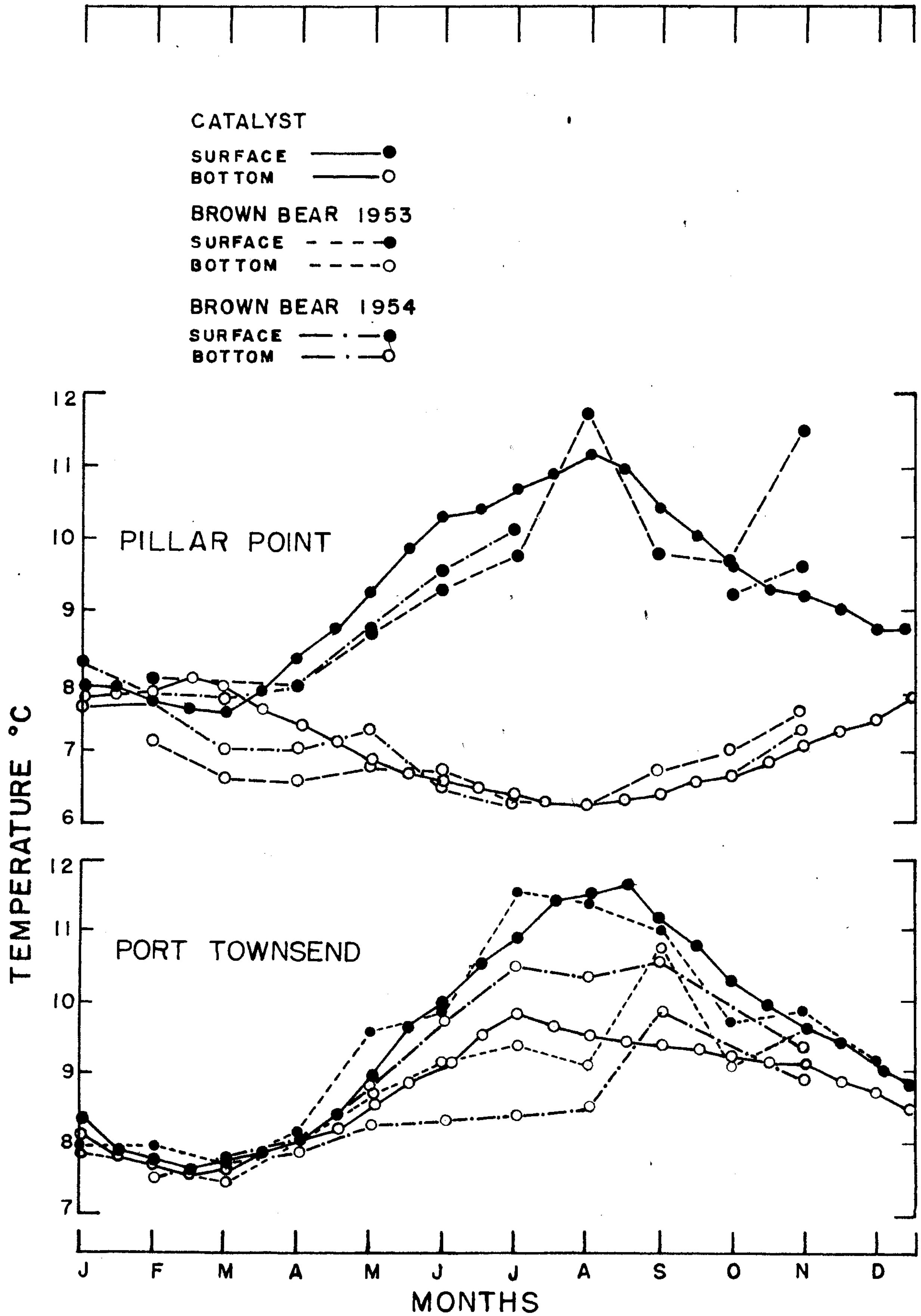

Figure 31. Comparison of CATALYST and BROWN BEAR Data for Pillar Point and Port Townsend.

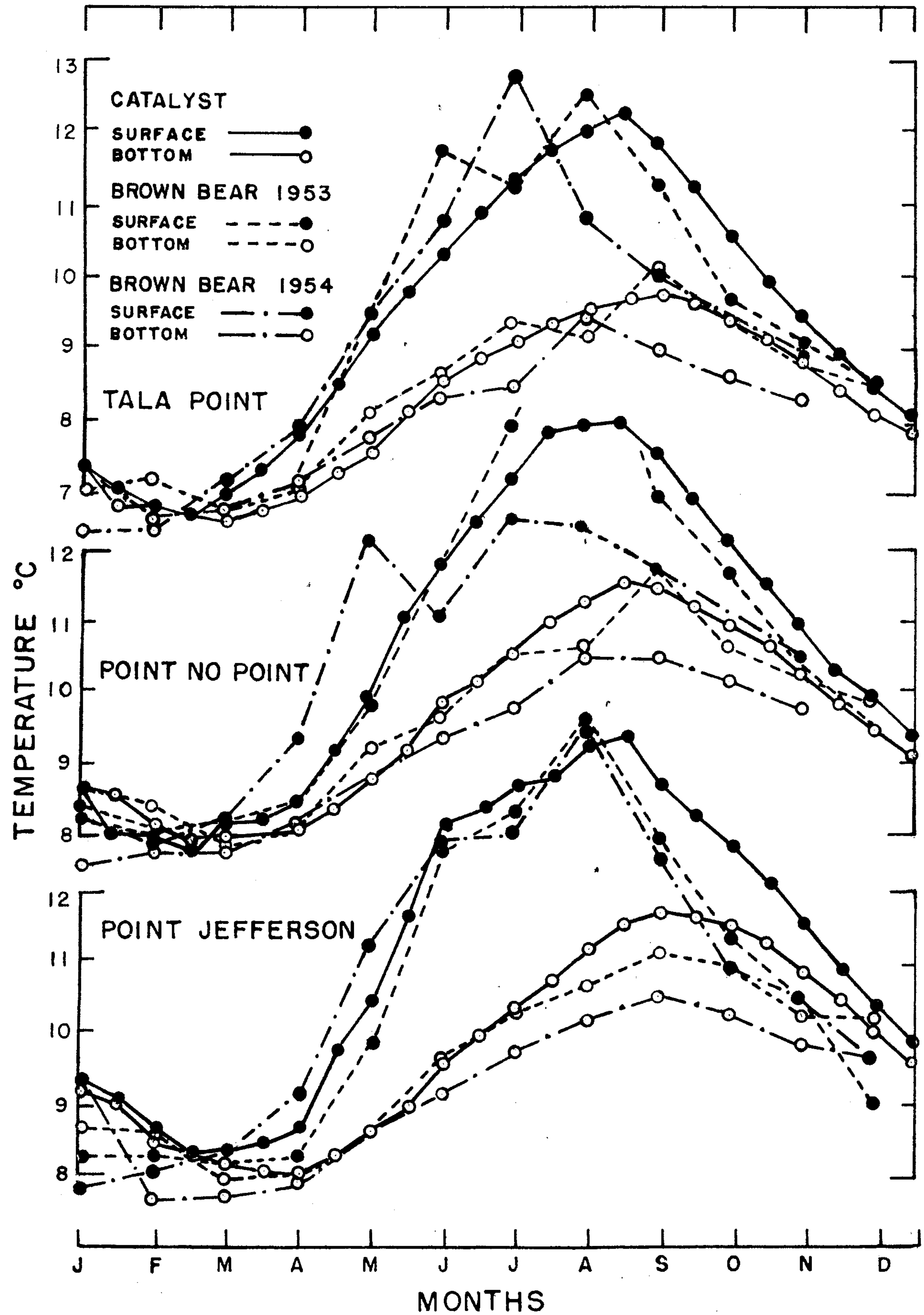

Figure 32. Comparison of CATALYST and BROWN BEAR Data for Tala Point, Point No Point, and Point Jefferson.

In all five cases the BROWN BEAR data show essential agreement with the reference data of the CATALYST shown herein. Close agreement between the two sets of data is especially striking in the bottom layers. Surface maximum temperatures in the Sound observed by the BROWN BEAR, however, occurred earlier than the CATALYST normal. No definite lag is shown in the curves for the bottom layers, and at Point Jefferson the timing was identical.

While the temperature trends are in close correspondence, the deviations (TABLE II) are erratic in their dispersion around the mean. The widest scatter of the deviations, as shown in Figures 33 and 35, occurs in the surface layers in summer when run-off and isolation act together in shaping the temperature structure during that season. Maximum deviations for surface temperature in Puget Sound range from 1.23° C to 1.85° C. The range of the maximum annual fluctuations from the mean for the CATALYST temperature observations is from 1.39° C to 1.89° C.

In the bottom layers (Figures 34 and 36) the dispersion is relatively small. At Pillar Point the deviations corresponding to the bottom layers are large when those at the surface are least. This is attributed to the effect of the two-layer system in the Strait of Juan de Fuca.

The maximum surface salinity deviations (Table III) are abnormally compared to the maximum annual fluctuations of salinity for the CATALYST data. This may be due to the greater precipitation in 1953 and 1954 which exceeded by about 15 per cent the mean of the years from 1934 to 1941. Corresponding ranges for the bottom layers are, however, within the range of maximum annual amplitudes for the CATALYST data.

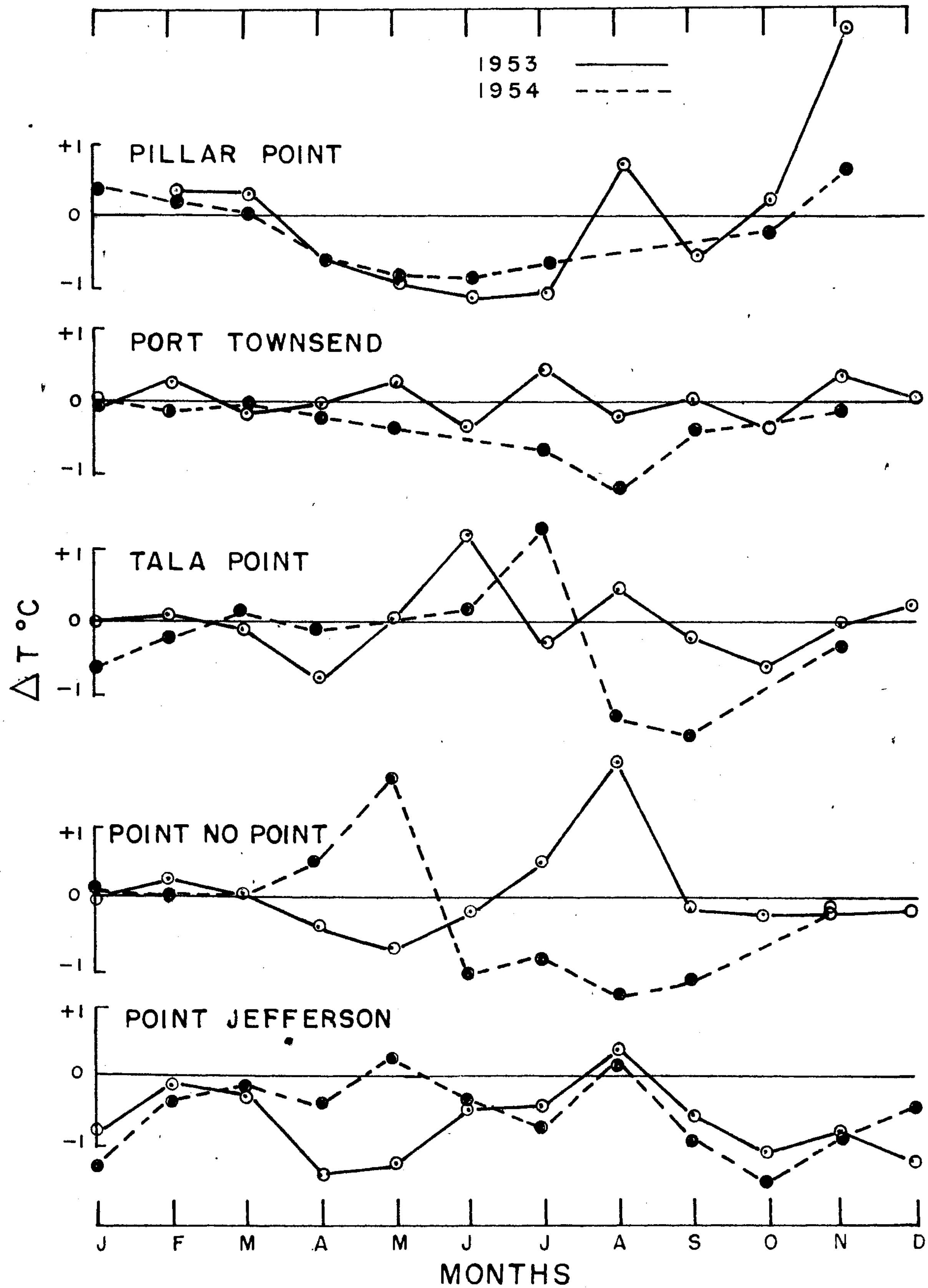

Figure 33. Deviations of Surface Temperature Measured by the BROWN BEAR from CATALYST Norms.

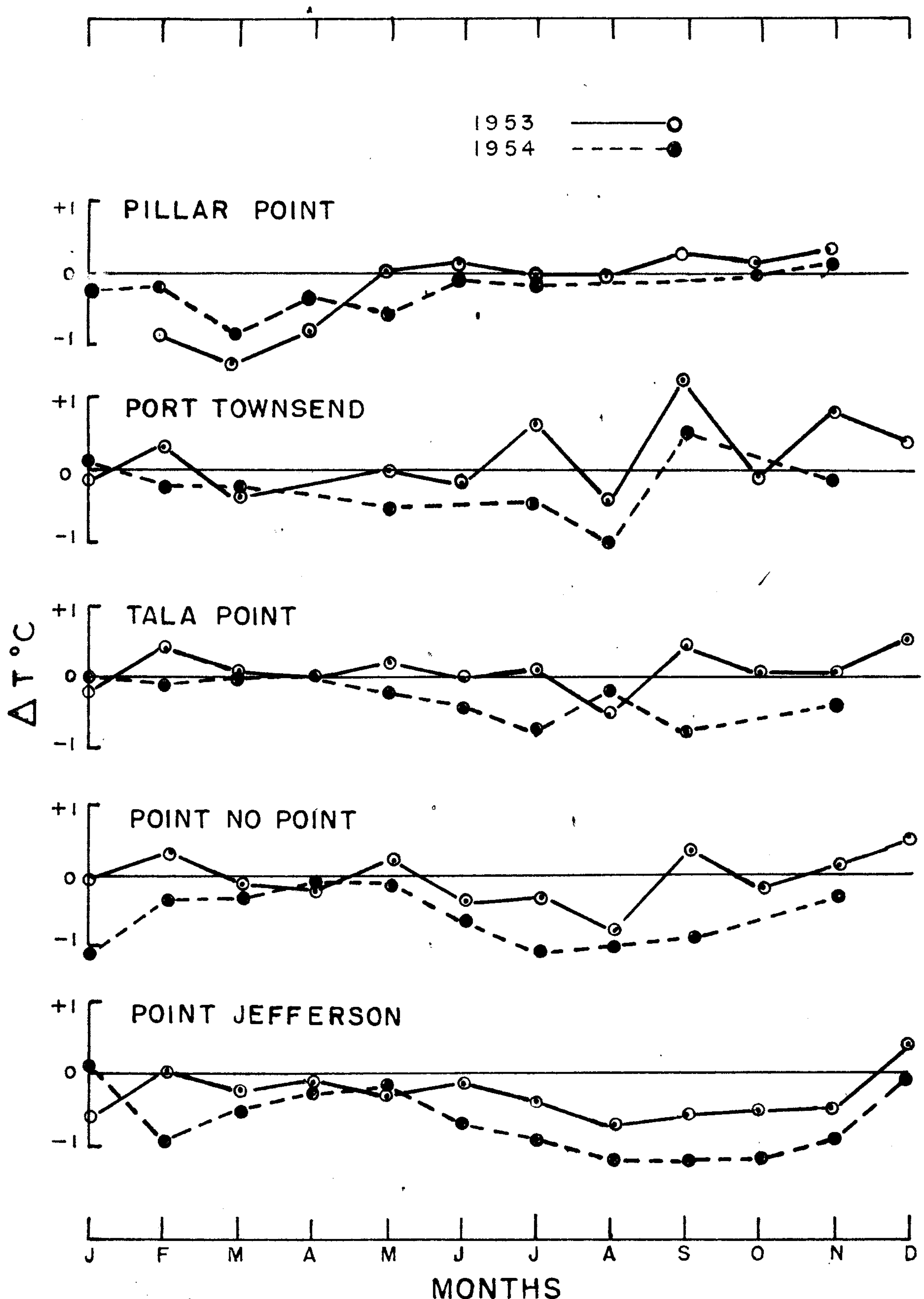

Figure 34. Deviations of Bottom Temperature Measured by the BROWN BEAR from CATALYST Norms.

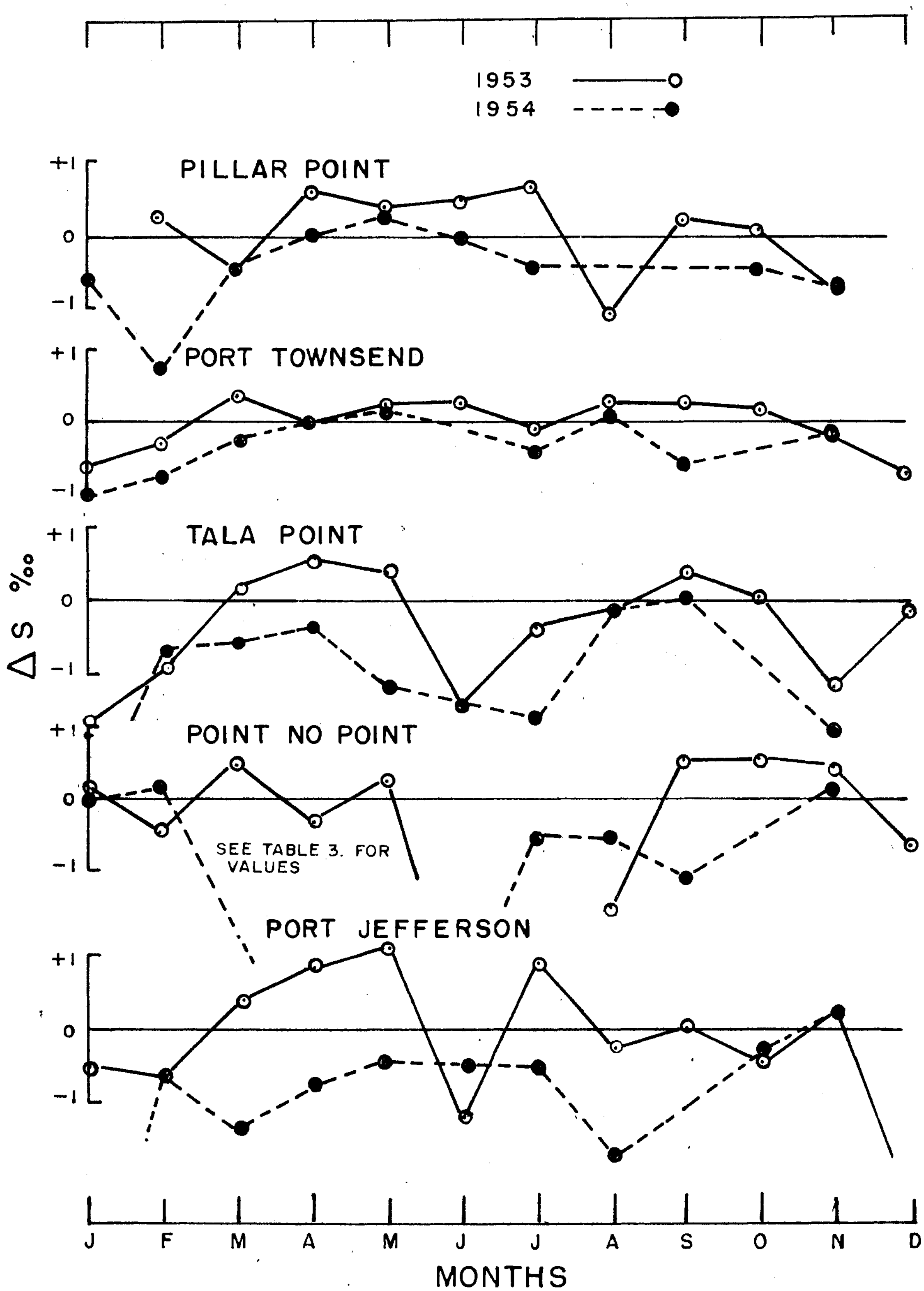

Figure 35. Deviations of Surface Salinity Measured by the BROWN BEAR from CATALYST Norms.

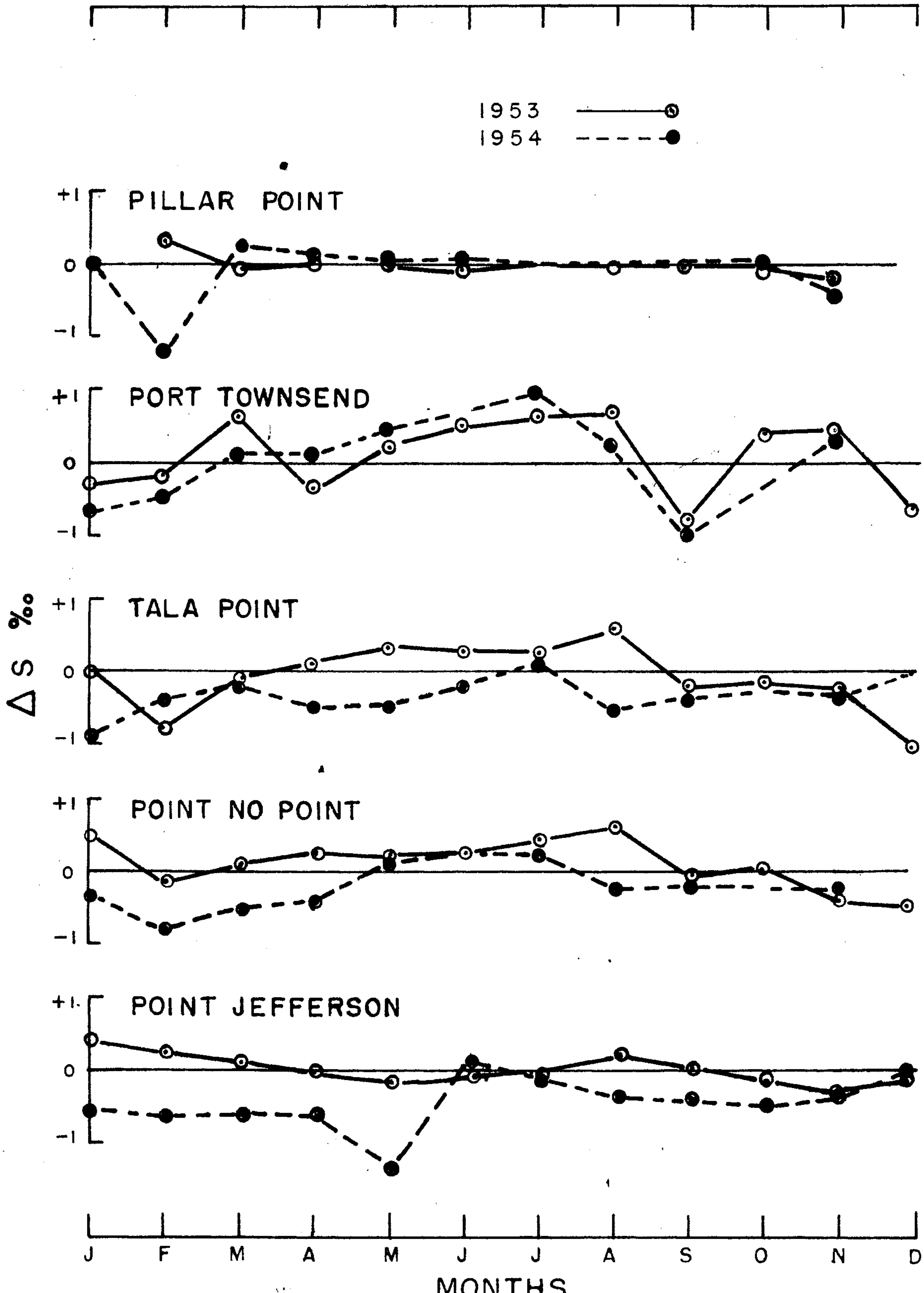

Figure 36. Deviations of Bottom Salinity Measured by the BROWN BEAR from CATALYST Norms.

A comparison between the surface temperature data for Green Point and Point Jefferson taken by the BROWN BEAR during the same period shows good agreement in the monthly trends. Except in winter when average surface temperatures at the former are about 0.2° C lower than the corresponding values at the latter station, the surface waters off Green Point are always warmer than those for Point Jefferson. The average maximum difference of about 1.2° C occurs when both curves peak in early August.

The results of the comparison indicate that the CATALYST observations may be used as tentative average conditions of temperature and salinity in the area to which future observations can be compared.

4. SUMMARY AND CONCLUSIONS

An analysis of the available temperature and salinity data for Puget Sound and the Strait of Juan de Fuca shows that there exist definite seasonal differences both in space and time distributions of these water properties.

Strait of Juan de Fuca

In the Strait there exists a contrasting seasonal distribution of properties between the upper 50 meters and the bottom layers. As a result of mass and energy exchange between the two layers, the seasonal changes in the transition layer separating the two are not well pronounced.

The upper layer attains maximum temperatures in summer when the bottom layers reach minimum temperatures. In the upper layer the

average annual maximum temperature of 11.3° C occurs in August and the average annual minimum temperature of 7.6° C is attained in February - March. In the bottom layer the average maximum temperature of 8.0° C is reached in February - March and the average annual minimum temperature of 6.4° C is attained in July - August.

Average salinities in the upper layer range from 30.7 ‰ in January to 31.6 ‰ in October; in the bottom layer from 33.4 ‰ in February to 33.95 ‰ in August.

Main Basin of Puget Sound

In winter, water temperatures in the main basin are everywhere uniformly low, the regional differences in the area under study never exceeding 1° C. In summer this difference is exceeded by about five times.

The average annual maximum surface temperature of 14.2° C is attained in August and the average annual minimum temperature of 8.3° C in February - March. The upper limit is about 3° and the lower limit about 0.7° higher than the corresponding values observed in the Strait of Juan de Fuca. In the main basin the maximum bottom temperatures are attained about a month later than at the surface. They are always higher than the corresponding temperatures in the Strait.

The lowest salinities are found in the winter period, both at the surface and bottom. At the surface Point No Point, the average salinities range from 28.4 ‰ in June and 29.7 ‰ in late October; and in the bottom layer off Point Jefferson the range is from 29.8 ‰ in March and 30.8 ‰ in October - November.

Southern Basin of Puget Sound

Off Green Point, Carr Inlet, the average annual maximum surface temperature of 15.7° C occurs in August and the average annual maximum bottom temperature of 12.0° C in September. There is a lag of about a month for the respective minimum values. In the surface layer the annual range is about 7.7° C; in the bottom layer the maximum summer temperature and the minimum winter temperature differ by about 4°.

As a rule, salinities in the southern basin are greater than those in the surface layers in the main basin. The salinity changes throughout the water column follow closely the precipitation cycle. The annual cycle of salinity shows an average minimum of about 28.4 °/oo in April and an annual average maximum of about 29.8 °/oo in November.

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TABLE I (Continued) STATION: TALA POINT (HOOD CANAL)

Date		Surface		10		20		50		100	
		Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.
Jan	1	8.38	29.40	8.52	29.45	8.71	30.07	8.48	30.43	8.36	30.70
	15	7.73	.22	.02	.54	.15	29.90	.08	.26	.00	.44
Feb	1	.72	28.96	7.77	.63	.33	30.14	7.88	.26	7.78	.23
	15	.69	29.63	.95	.56	7.93	.03	.71	.12	.62	.28
Mar	1	.91	.60	.84	.51	8.05	29.96	.76	29.99	.57	.26
	15	8.24	.05	8.02	.54	.19	.90	.91	.96	.71	.23
Apr	1	.73	.31	.38	.63	.44	.90	8.15	.99	.89	.19
	15	9.42	.33	.93	.63	.76	.88	.48	30.07	8.24	.12
May	1	10.16	.38	9.50	.56	9.15	.96	.84	.17	.62	.16
	15	.78	.33	.90	.61	.73	.97	9.32	.14	9.09	.28
Jun	1	11.29	.33	10.42	.69	10.23	.92	.81	.05	.51	.26
	15	.83	.34	.97	.74	.70	.94	10.20	.14	.81	.32
Jul	1	12.36	.36	11.48	.69	11.15	.97	.52	.25	10.07	.43
	15	.73	.47	.94	.74	.62	30.05	.86	.32	.32	.57
Aug	1	13.01	.69	12.23	.90	.88	.12	11.14	.39	.54	.68
	15	.23	.81	.39	30.03	.99	.28	.22	.64	.67	.86
Sep	1	12.84	.96	.19	.26	.87	.48	.21	.77	.75	31.00
	15	.23	30.10	11.75	.46	.54	.61	.06	.90	.61	.11
Oct	1	11.57	.28	.28	.61	.23	.75	10.83	31.00	.38	.18
	15	10.96	.35	10.80	.68	10.88	.84	.56	.02	.13	.20
Nov	1	.42	.34	.35	.59	.49	.70	.15	30.95	9.80	.13
	15	9.92	.34	9.89	.52	.04	.52	9.71	.88	.43	.15
Dec	1	.49	.10	.49	.37	9.66	.35	.36	.86	.09	.09
	15	.04	29.85	.13	.23	.30	.25	.01	.64	8.81	30.97

TABLE I. BI-MONTHLY AVERAGES OF TEMPERATURES (°C) AND SALINITY (o/oo) AT STANDARD DEPTHS (METERS) -- STATION: PILLAR POINT

Date	Surface		10		50		100		150		200	
	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.
Jan 1	7.94	30.86	8.14	31.08	8.19	31.56	8.41	32.52	7.74	32.23	7.78	33.55
15	.92	.72	7.79	30.81	.01	.46	.40	.45	8.69	.49	.82	.35
Feb 1	.76	.93	.65	.97	7.79	.47	.25	.34	.33	33.26	.87	.42
15	.66	31.18	.54	31.15	.62	.53	.07	.36	.31	.10	8.04	.35
Mar 1	.60	.22	.57	.26	.66	.71	7.97	.50	.24	.37	7.95	.46
15	(.87)	(.38)	.79	.22	.80	.80	.98	.75	7.80	.69	.65	.62
Apr 1	8.32	.15	8.16	.20	.93	32.00	7.86	.97	.66	.66	.43	.71
15	.76	.13	.59	.20	8.04	.07	.74	33.13	.56	.55	.23	.78
May 1	9.27	.31	.85	.26	.08	.16	.55	.26	.42	.69	6.95	.86
15	.91	.11	9.31	.62	.32	.16	.33	.31	.08	.73	.72	.86
Jun 1	10.36	.17	.65	.04	.35	.21	.09	.40	6.63	.78	.63	.86
15	.45	.13	.77	.18	.42	.34	6.94	.51	.46	.84	.54	.87
Jul 1	.73	.00	10.00	.31	.20	.48	.79	.64	.41	.89	.48	.87
15	.94	.00	.07	.20	.16	.52	.64	.73	.32	.89	.36	.95
Aug 1	11.26	30.93	.19	.20	.14	.65	.66	.77	.36	.89	.36	.95
15	.00	31.15	.09	.40	.18	.65	.70	.75	.44	.89	.39	.95
Sep 1	10.50	.31	9.96	.49	8.32	.59	.79	.71	.57	.87	.47	.93
15	.10	.46	.67	.69	.42	.56	7.04	.60	.73	.86	.61	.91
Oct 1	9.67	.56	.36	.74	.46	.56	.21	.49	.91	.86	.75	.87
15	.36	.60	.19	.73	.54	.48	.49	.31	7.13	.80	.92	.80
Nov 1	.22	.56	.12	.65	.63	.29	.81	32.99	.46	.68	7.14	.66
15	.01	.58	8.99	.64	.62	.14	8.02	.86	.76	.44	.35	.60
Dec 1	(8.74)	(.69)	.93	.53	.57	31.89	.16	33.03	.96	.12	.50	.53
15	(.84)	(.38)	.83	.33	.46	.80	.24	32.70	8.07	32.94	.83	.46

Bracketed figures are uncertain because of discontinuity of observation during some years resulting in abnormal averages.

TABLE I (Continued) STATION: PORT TOWNSEND

Date	Surface		10		20		50		100	
	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.
Jan 1	8.38	30.41	8.22	30.39	8.12	30.30	8.36	30.64	8.19	30.84
15	7.91	.30	7.94	.23	7.93	29.85	8.02	.39	7.85	.64
Feb 1	.80	.16	.67	.23	.62	.87	7.77	.52	.71	.57
15	.67	.23	.49	.30	.43	30.05	.63	.62	.58	.61
Mar 1	.76	.12	.57	.23	.52	.16	.70	.46	.69	.57
15	.90	29.92	.66	.10	.47	.01	.74	.25	.89	.57
Apr 1	8.08	.92	7.86	.07	.67	29.96	.98	.25	8.10	.44
15	.41	.96	8.22	.10	8.01	30.10	8.29	.26	.25	.52
May 1	.97	.85	.70	.10	.58	.03	.66	.35	.55	.66
15	9.69	.60	9.34	29.78	9.30	29.70	9.15	.39	.90	.82
Jun 1	10.01	.70	.70	.96	.49	.87	.41	.37	9.12	.59
15	.58	.85	10.24	.94	10.15	.79	.93	.37	.54	.61
Jul 1	10.93	.90	.68	30.05	.71	.90	10.29	.55	9.88	.73
15	11.46	.85	11.04	.05	.83	30.07	.43	.70	.69	31.02
Aug 1	.56	30.12	10.93	.32	.79	.35	.54	.84	.55	.29
15	.70	.35	.94	.55	.54	.64	.44	.91	.49	.51
Sep 1	.23	.55	.68	.73	.31	.91	.19	31.02	9.42	.71
15	10.82	.77	.35	.91	9.98	31.15	9.93	.18	.37	.76
Oct 1	.36	.93	.00	31.06	.61	.24	.65	.33	.24	.69
15	.00	.97	9.64	.09	.34	.18	.46	.42	.19	.53
Nov 1	9.76	.84	.46	30.97	.07	.06	.39	.42	.14	.35
15	.49	.72	.08	.82	8.83	.06	.21	.06	8.91	.29
Dec 1	.21	.79	8.90	.90	.57	.17	.06	.00	.78	.26
15	8.89	.66	.59	.75	.37	30.95	8.70	30.90	.51	.11

TABLE I (Continued) STATION: TALA POINT (HOOD CANAL)

Date	Surface		10		20		50		100	
	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.
Jan 1	8.38	29.40	8.52	29.45	8.71	30.07	8.48	30.43	8.36	30.70
15	7.73	.22	.02	.54	.15	29.90	.08	.26	.00	.44
Feb 1	.72	28.96	7.77	.63	.33	30.14	7.88	.26	7.78	.23
15	.69	29.63	.95	.56	7.93	.03	.71	.12	.62	.28
Mar 1	.91	.60	.84	.51	8.05	29.96	.76	29.99	.57	.26
15	8.24	.05	8.02	.54	.19	.90	.91	.96	.71	.23
Apr 1	.73	.31	.38	.63	.44	.90	8.15	.99	.89	.19
15	9.42	.33	.93	.63	.76	.88	.48	30.07	8.24	.12
May 1	10.16	.38	9.50	.56	9.15	.96	.84	.17	.62	.16
15	.78	.33	.90	.61	.73	.97	9.32	.14	9.09	.28
Jun 1	11.29	.33	10.42	.69	10.23	.92	.81	.05	.51	.26
15	.83	.34	.97	.74	.70	.94	10.20	.14	.81	.32
Jul 1	12.36	.36	11.48	.69	11.15	.97	.52	.25	10.07	.43
15	.73	.47	.94	.74	.62	30.05	.86	.32	.32	.57
Aug 1	13.01	.69	12.23	.90	.88	.12	11.14	.39	.54	.68
15	.23	.81	.39	30.03	.99	.28	.22	.64	.67	.86
Sep 1	12.84	.96	.19	.26	.87	.48	.21	.77	.75	31.00
15	.23	30.10	11.75	.46	.54	.61	.06	.90	.61	.11
Oct 1	11.57	.28	.28	.61	.23	.75	10.83	31.00	.38	.18
15	10.96	.35	10.80	.68	10.88	.84	.56	.02	.13	.20
Nov 1	.42	.34	.35	.59	.49	.70	.15	30.95	9.80	.13
15	9.92	.34	9.89	.52	.04	.52	9.71	.88	.43	.15
Dec 1	.49	.10	.49	.37	9.66	.35	.36	.86	.09	.09
15	.04	29.85	.13	.23	.30	.25	.01	.64	8.81	30.97

TABLE I (Continued) STATION: POINT NO POINT

Date	Surface		10		20		50		100	
	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.
Jan 1	8.69	28.96	8.84	29.38	8.53	30.32	8.82	30.14	8.70	30.16
15	7.94	.87	.56	.09	.12	29.61	.54	.01	.54	29.94
Feb 1	.93	.86	.24	.19	7.84	.42	.05	29.90	8.14	30.14
15	.77	.71	7.94	.14	.71	.34	7.86	.85	7.98	29.99
Mar 1	8.12	.84	.93	28.96	.72	.09	.83	.65	.99	.78
15	.20	.80	.91	29.04	.75	.04	.92	.63	.98	.72
Apr 1	.43	.84	8.20	.05	.87	.04	8.10	.59	8.03	.78
15	9.19	29.02	8.67	.00	8.13	.33	.44	.65	.36	.87
May 11	.91	28.59	9.22	.04	.77	.43	.84	.65	.76	.88
15	11.02	.46	.76	28.87	9.19	.25	9.24	.63	9.18	.83
Jun 1	.78	.35	10.65	.77	.77	.00	.87	.61	.89	.83
15	12.36	.66	.94	.91	10.24	.13	10.28	.74	10.12	.90
Jul 1	12.95	.71	11.38	29.00	10.58	.43	.68	.79	.54	.96
15	13.62	.44	12.03	.02	11.17	.51	11.10	.92	.96	30.08
Aug 1	.71	.71	.36	.16	.45	.65	.47	30.08	11.29	.25
15	.78	29.09	.37	.31	.61	.94	.71	.25	.50	.39
Sep 1	.34	.27	.59	.42	.63	30.16	.68	.35	.46	.48
15	12.71	.43	.55	.54	.54	.34	.55	.46	.19	.61
Oct 1	.14	.56	11.96	.63	.28	.43	.31	.57	10.94	.70
15	11.53	.65	.51	.69	10.89	.48	.03	.62	.65	.77
Nov 1	10.96	.63	10.96	.63	10.44	.50	10.67	.57	.29	.70
15	.30	.61	.36	.60	9.93	.62	.15	.53	9.85	.66
Dec 1	9.94	.38	9.89	.56	.55	.70	9.78	.39	.44	.53
15	.40	.00	.43	.49	.10	.48	.32	.21	.11	.34

TABLE I (Continued) STATION: POINT JEFFERSON

Date	Surface Temp.	Surface Sal.	10 Temp.	10 Sal.	20 Temp.	20 Sal.	50 Temp.	50 Sal.	100 Temp.	100 Sal.	200 Temp.	200 Sal.
Jan 01	09.15	29.65	09.29	29.69	09.41	29.83	09.54	29.90	09.32	30.08	09.35	30.25
15	08.96	.43	.07	.38	.18	.67	.33	.87	8.92	29.90	9.01	.12
Feb 01	.44	.40	8.50	.42	8.68	.54	8.61	.83	.56	.90	8.65	.08
15	.30	.18	.29	.29	.45	.42	.31	.65	.35	.76	8.30	29.94
Mar 1	.36	28.98	.25	.22	.39	.31	.20	.54	.21	.69	8.16	.85
15	.47	.80	.22	.11	.39	.43	.13	.52	.08	.69	.09	.83
Apr 1	.69	.66	.23	.16	.08	.29	.02	.67	.00	.85	.00	.97
15	9.47	.26	.73	28.91	.59	.42	.26	.70	.28	.94	.28	30.07
May 1	10.42	27.88	9.19	.71	.96	.36	.58	.72	.63	.97	.62	.17
15	11.67	.68	.88	.91	9.48	.34	9.04	.65	9.01	.94	.98	.16
Jun 1	12.93	.45	10.76	.96	10.47	.31	.73	.60	.67	.85	9.58	.08
15	13.16	.75	11.41	29.04	11.08	.40	10.25	.61	10.19	.87	.99	.08
Jul 1	.52	28.21	12.09	.09	.69	.47	.60	.63	.55	.87	10.35	.08
15	.66	.86	.25	.39	12.00	.70	11.20	.81	11.01	30.03	.80	.28
Aug 1	14.11	29.43	.84	.74	.37	30.01	.59	30.14	.48	.17	11.20	.62
15	.20	.76	.99	.96	.67	.14	.93	.28	.75	.32	.53	.70
Sep 1	13.53	.92	.82	30.05	.61	.12	12.15	.30	.87	.48	.77	.68
15	.10	30.12	.58	.23	.45	.26	.09	.41	.82	.57	.66	.73
Oct 1	12.69	.32	.35	.37	.29	.39	.05	.50	.75	.66	.53	.75
15	.20	.37	11.99	.44	11.91	.48	11.77	.55	.51	.70	.35	.82
Nov 1	11.59	.01	.48	.39	.46	.48	.39	.55	.14	.66	10.93	.77
15	10.93	29.72	10.93	.26	.00	.39	10.94	.43	10.66	.59	.53	.66
Dec 1	.46	.65	.53	.08	10.57	.23	.49	.14	.23	.37	.09	.44
15	9.90	.60	.02	29.90	.08	.03	.16	29.90	9.81	.17	9.74	.30

TABLE I (Continued) STATION: GREEN POINT (CARR INLET)

Date		Surface		10		20		50		Bottom	
		Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.
Jan	1	9.20	29.38	9.23	29.39	8.79	29.42	8.91	29.61	8.94	29.61
	15										
Feb	1	8.02	28.57	8.03	28.58	.09	28.61	.22	28.71	.33	28.84
	15										
Mar	1	.15	.36	7.98	.43	7.99	.48	.05	.61	.05	.70
	15										
Apr	1	.94	.50	8.57	.58	8.34	.62	.21	.81	.15	.87
	15										
May	1	10.50	.69	9.77	.82	9.30	.89	.94	.94	.76	29.00
	15										
Jun	1	13.40	.66	10.81	.95	10.18	29.04	9.88	29.10	9.70	.17
	15										
Jul	1	14.24	.99	12.24	29.09	11.58	.14	11.24	.18	10.95	.24
	15										
Aug	1	15.72	29.16	.97	.27	12.26	.32	.95	.35	11.80	.48
	15										
Sep	1	14.02	29.40	.41	.60	.23	.66	12.05	.78	12.04	.83
	15										
Oct	1	12.48	.73	.00	.85	11.92	.92	11.72	30.00	11.73	30.02
	15										
Nov	1	11.25	.81	11.19	.88	.20	.90	.23	29.99	.04	.04
	15										
Dec	1	9.85	.48	10.00	.58	9.97	.57	10.00	.63	10.12	29.66
	15										

TABLE II. DEVIATIONS OF TEMPERATURE (°C) MEASURED BY THE BROWN BEAR FROM CATALYST VALUES

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Pillar Point													
Surface	1953	--	.29	.23	-.65	-.94	-1.13	-1.05	.67	-.61	.19	2.47	--
	1954	.31	.11	-.03	-.63	-.89	-.87	-.70	--	--	-.24	.56	--
Bottom	1953	--	-.81	-1.18	-.73	.03	.16	-.06	-.05	.26	.19	.35	--
	1954	-.26	-.19	-.78	-.30	-.52	.02	-.12	--	--	-.06	.14	--
Port Townsend													
Surface	1953	-.14	.25	-.15	-.10	.26	-.36	.41	-.21	-.02	-.40	.31	.07
	1954	.01	-.14	-.08	-.23	-.37	--	-.65	-1.23	-.43	--	-.20	--
Bottom	1953	-.11	.33	-.34	-.17	.05	-.15	.70	-.40	1.22	-.08	.83	.48
	1954	.15	-.11	-.17	-.24	-.42	--	-.36	-.92	.57	--	-.06	--
Tala Point													
Surface	1953	-.03	.07	-.14	-.84	-.02	1.17	-.32	.40	-.28	-.62	-.08	.23
	1954	-.63	-.23	.06	-.18	-.03	.17	1.26	-1.32	-1.55	--	-.30	--
Bottom	1953	-.18	.41	.11	.01	.22	.00	.11	-.49	.44	.10	.09	.51
	1954	.04	-.10	.10	.04	-.14	-.36	-.74	-.15	-.71	--	.38	--
Point No Point													
Surface	1953	-.05	.22	.02	-.40	-.72	-.26	.43	1.85	-.16	-.21	-.23	-.19
	1954	.08	.04	.06	.54	1.67	-1.03	-.85	-1.36	-1.17	--	-.13	--
Bottom	1953	.06	.39	-.09	-.14	.27	-.32	-.24	-.7[illegible]	.39	-.13	.13	.58
	1954	-1.02	-.30	-.24	-.05	-.09	-.61	-1.01	-.91	-.84	--	-.29	--
Point Jefferson													
Surface	1953	-.83	-.14	-.27	-1.36	-1.24	-.48	-.46	.33	-.53	-1.08	-.74	-1.14
	1954	-1.30	-.35	-.14	-.46	.21	-.33	-.74	.21	-.83	-1.49	-.81	-.50
Bottom	1953	-.53	.06	-.20	-.06	-.21	-.08	-.31	-.67	-.55	-.47	-.45	.38
	1954	.18	-.85	-.43	-.26	-.19	-.66	-.82	-1.16	-1.17	-1.15	-.85	-.01

TABLE III. DEVIATIONS OF SALINITY (o/oo) MEASURED BY THE BROWN BEAR FROM CATALYST VALUES

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Pillar Point													
Surface	1953	—	.27	-.41	.61	.43	.52	.72	-1.07	.21	.10	-.74	—
	1954	-.52	-1.83	-.34	.01	.27	-.01	-.40	—	—	-.40	-.69	—
Bottom	1953	—	.34	-.02	.09	-.04	-.09	-.04	.00	-.07	-.05	-.22	—
	1954	.06	-1.16	.27	.10	.02	-.02	-.05	—	—	.03	-.42	—
Port Townsend													
Surface	1953	-.55	-.26	.38	-.03	.27	.29	-.10	.28	.25	.18	-.20	-.70
	1954	-.95	-.70	-.18	-.01	.17	—	-.36	.10	-.57	—	-.16	—
Bottom	1953	-.29	-.15	.65	-.32	.25	.51	.65	.66	-.73	.42	.49	-.60
	1954	-.66	-.48	.17	.13	.48	—	.95	.28	-.97	—	-.32	—
Tala Point													
Surface	1953	-1.87	-1.56	.00	.57	.43	-1.31	-.37	-.11	.40	.09	-1.12	-.15
	1954	-3.29	-1.28	-.81	-.34	-1.14	-1.34	-1.55	-.11	.07	—	-1.76	—
Bottom	1953	.04	-.73	-.07	.11	.37	.29	.28	-.59	-.22	-.17	-.23	-1.02
	1954	-.87	-.38	-.18	-.46	.03	-.14	.15	-.48	-.27	—	-.33	—
Point No Point													
Surface	1953	.20	-.40	.52	-.26	.31	-3.36	-3.13	-1.44	.54	.55	.46	-.63
	1954	.05	.20	-1.86	-3.55	-6.53	-2.72	-.48	-.51	-1.06	—	.16	—
Bottom	1953	.55	-.12	.14	.30	.26	.30	.49	.64	-.06	.09	-.38	-.47
	1954	-.26	-.75	-.46	-.39	.13	.30	.23	-.22	-.18	—	-.27	—
Point Jefferson													
Surface	1953	-.46	-.63	-.39	.87	1.14	-1.26	.92	-.23	.06	-.45	.24	-3.45
	1954	-4.31	-.65	-1.32	-.74	-.40	-.47	-.49	-1.67	—	-.26	.21	-.11
Bottom	1953	.41	.24	.13	-.02	-.13	-.02	.05	.24	.09	-.11	-.24	-.11
	1954	-.50	-.59	-.53	-.60	-1.28	.17	-.08	-.32	-.35	-.41	-.32	-.48