Some Oceanographic Features of the Inside Passage Between Vancouver Island and the Mainland of British Columbia

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SOME OCEANOGRAPHIC FEATURES OF THE INSIDE PASSAGE BETWEEN VANCOUVER ISLAND AND THE MAINLAND OF BRITISH COLUMBIA

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INTRODUCTION

Extensive studies of the Strait of Georgia have already been carried out by Waldichuk (1957) and by Tully and Dodimead (1957). It is the purpose of this paper both to review some of the conclusions of these works in the light of data obtained subsequently and to extend the description of the consistent features and of the mechanisms to the entire length of the waterways separating Vancouver Island and the British Columbia mainland. The results may be of considerable use in ecological studies involving the "variability" in, and movement of, plankton, fish eggs, and larval and juvenile fish.

SOME NON-MARINE FACTORS AFFECTING INSIDE PASSAGE OCEANOGRAPHY

I. Geography and Topography

The "Inside Passage" between Vancouver Island and the British Columbia mainland (Fig. 1) is considered for the purposes of this paper to extend southeastward from Queen Charlotte Sound through Queen Charlotte Strait, Johnstone Strait, Discovery Passage, the Strait of Georgia, Boundary Passage and Haro and Rosario Straits, then northwestward through Juan de Fuca Strait to the open Pacific coast; hereafter it may be called simply "the Passage". It is approximately 480 km (300 mi) long.

The varied and complex bottom topography of the region is adequately described in the charts of the Canadian Hydrographic Service (e.g. Canadian Hydrographic Service, 1960). Figure 2 depicts the primary features of the bottom, which is characterized by a series of sills. Some sills are very shallow, e.g. that in Discovery Passage - 67 m (36 fm) deep, shoaling to 13 m (7 fm) mid-channel - and some quite deep, e.g. that in Stevens Passage in the Strait of Georgia - 200 m (110 fm). The sills divide the Inside Passage into a number of basins, Queen Charlotte Strait being the deepest and Haro Strait the shallowest.

The northern entrance to the Strait of Georgia consists of three narrow interconnecting channels. To the north again, these reduce to a single narrow channel, characterized by a width of only 2.4 km (1.5 mi) - Johnstone Strait. Beyond this channel, the passage is divided by a group of islands. To the north and northwest of these islands is situated Queen Charlotte Strait, which is about 16 km (10 mi) wide. The Passage is then again somewhat constricted by a maze of small islands and reefs before opening into Queen Charlotte Sound.

The southern entrance to the Strait of Georgia also consists of a number of interconnecting channels, the principal one being Boundary Passage - Haro Strait.

The entire Inside Passage is bordered on the mainland side by the mountains of the Coast Range - height to 3000 m (10,000 ft). These mountains are indented by valleys and inlets perpendicular to the coastline. The Vancouver Island mountains which border the Passage to the west are not as high - less than 1800 m (6000 ft) - but are also indented by valleys which, however, are not in general perpendicular to the shore.

II. Climate

In the area of interest to this report, quite exhaustive data on a large number of meteorological variables are obtained by the Meteorological Branch, Canada Department of Transport. These data are summarized monthly in: Monthly Record, Meteorological Observations in Canada. Summaries on temperature, precipitation and sunshine only are published annually by the Department of Agriculture, Province of British Columbia. The major features of the climate of the area have been summarized by Kendrew and Kerr (1955). For completeness a brief account of the climatic characteristics believed to be of special relevance to this report has been prepared from the above sources.

A. Air temperature

The air-temperature cycle throughout the Passage is in phase with the annual heating and cooling cycle occurring along the entire British Columbia coast. However, the annual range of temperature varies throughout the system, typically as shown in Fig. 3 (which displays data obtained in 1962 - Department of Agriculture, Province of British Columbia, 1963). The seasonal cycle is shown for five locations: Pachena Point, assumed to be an open coastal location and thus representative of the approaches to Juan de Fuca Strait; Victoria, representative of inner Juan de Fuca Strait; Nanaimo, of the Strait of Georgia; Chatham Point, of Johnstone Strait; and Bull Harbour, of the approaches to Queen Charlotte Strait. The means indicate that, during the period May through August, the air temperature in the Strait of Georgia is warmer - by as much as about 3C° (6F°) in 1962 - than in either the northern or southern approaches. The greatest difference occurs in mid-July. In the winter, on the other hand, the Strait of Georgia area can be colder (January and February) than the northern and southern approaches - by 1C° (2F°) in 1962. In July, air temperatures reach a maximum throughout the entire Inside Passage except in the northern approach, in which the maximum occurs about one month later. In all parts of the Passage the lowest temperatures are generally recorded in December or January.

B. Precipitation

The annual precipitation cycle possesses the same phase throughout the Passage, but the degree of precipitation varies considerably (Fig. 4); the same year and locations as in A. are involved in this figure. North of Discovery Passage (Chatham Point), and also, apparently, in the approaches to Juan de Fuca Strait (Pachena Point), the precipitation is greater than that in the other areas, markedly so from October through February. Throughout the Passage precipitation tends to attain an annual "major" maximum in December-January and a minimum in July-August. However, less pronounced maxima appear to occur both in late winter and in early summer. At lower altitudes most of the precipitation occurs as rain; that which falls as snow seldom lies longer than a month. The precipitation at high levels is stored throughout the winter as snow or ice. Orographic effects are indicated by the fact that precipitation generally decreases from west to east, except in Juan de Fuca Strait, where it decreases from north to south. Precipitation tends to increase with altitude; therefore it should be noted that the data which have been obtained at or near sea level, will usually provide values smaller than those actually relevant in considerations of snow and ice storage.

Digressing momentarily from the discussion of the Inside Passage climate, it may be noted that <u>runoff</u> into the Passage will, of course, be a direct function of the precipitation (rain and snow) characterizing the drainage area affecting the Passage. This area is considered to include the east and south coasts of Vancouver Island and the southwest mainland of British Columbia. On the basis of topographic features, primarily "divides", the area is assumed to be composed of six drainage "basins" (Fig. 5). An estimate of drainage for each of these basins has been obtained by considering the flows and the drainage areas of what are believed to be "representative" rivers: i.e. the Salmon River for Basin 1, the Homathko for Basin 2, the Squamish for Basin 3, the Cowichan for Basin 4, the Dungeness for Basin 5, and the Fraser for Basin 6. The runoff from an entire basin is assumed (roughly) equal to the following quantity:

$$\frac{\text{Area of entire basin}}{\text{Drainage area of representative river}} \times \text{flow from representative river}$$

The monthly-mean runoff values so obtained for each of the six basins, for the 12-month period October 1960 through September 1961, are shown in (1) through (6) of Fig. 6; the corresponding monthly-mean totals for the six basins are shown in (7). Data utilized in the calculations were provided by the Canada Water Resources Branch (1964) and by the United States Department of the Interior (1961, 1962).

Some of the basins, e.g. those associated with the Fraser or the Homathko rivers, consist mostly of mountainous areas in which winter storage plays a major role in regulating the runoff. Precipitation - as snow - is greatest in winter, but massive drainage does not occur until the following spring thaw. As a result of the delay, the major rivers (which drain the higher levels) do not commence to rise until about early April, and their discharge does not attain a maximum until June or July (Fig. 7). Some of the smaller mainland coastal rivers - and all of the Vancouver Island rivers, e.g. the Salmon (Fig. 7) - draining into the Inside Passage are primarily rain fed, and do not exhibit a marked increase in flow in spring and summer.

C. Cloud cover and fog

Figure 8 shows the percentage prevalence, in each month, of "high" cloud cover (as distinguished from fog) greater than 8/10 at four representative locations along the Inside Passage. The data were obtained from Kendrew and Kerr (1955). The mean-monthly values displayed involve periods ranging from 8 years (Port Hardy) to 10 years (Pachena Point, Vancouver and Victoria). It appears that, in the northern Passage (Port Hardy), cloud cover greater than 8/10 occurs between 60 and 80% of the time in each month of the year; this fact may be attributed primarily to the modification of eastward-moving maritime air masses by orographic effects. In the Strait of Georgia itself (Vancouver and Victoria) the occurrence of cloud cover greater than 8/10 is marked by a pronounced minimum in July and August. In the southern approaches, near the entrance to Juan de Fuca Strait (Pachena Point), cloud greater than 8/10 occurs between 60 and 70% of the time during each month from January through August; during the remainder of the year the occurrence decreases to about 50% and then increases to about 70%.

As for fog, the Passage itself is most free during late winter and spring (averaging only 1 to 2 days of fog per month). In the Strait of Georgia the occurrence of fog is, throughout the year, low relative to the remainder of the Passage; it is a maximum in September and October (6 to 8 days per month) and a minimum throughout the remainder of the year (e.g. April, about 1 day). Throughout the southern approaches, fog occurs most often in summer (August, average about 20 days).

D. Winds

The prevailing winds along the open British Columbia coast are southeasterly in winter and northwesterly in summer, parallel to the coastline. In the spring and autumn the winds are, in general, variable. However, within the Inside Passage, modifications to this relatively simple régime occur.

Mean-monthly characteristics of wind speed at three locations within the Passage, for the 10-year period 1955-64, are displayed in Fig. 9 (Summary of Hourly Winds: Mileage - Canada Department of Transport, Meteorological Branch; unpublished data). Means for the "total" wind and for northwest and southeast components are presented. Port Hardy and Comox are assumed basically to represent the northern and central portions, respectively, of the Passage. Victoria represents the southern extreme of the "Queen Charlotte Sound - Strait of Georgia" part of the Passage (no other "southern" locality providing a significant amount of data during 1955-64).

The means suggest that the "total-wind" speed generally is greater in the "south" (Victoria) than elsewhere in the Passage (Fig. 9A); the difference is most marked during the spring and summer months. Southeast wind strengths appear to undergo a well-defined annual cycle throughout the "entire" Passage, minimum values occurring in summer (Fig. 9B). Strengths at corresponding times are (roughly) the same at "all" locations. An annual cycle also features northwest strengths, although (with the marked exception of Victoria) the amplitude is much smaller; in contrast to the preceding case, the summer is characterized by a maximum. These winds are strongest in the "south" throughout the year, the feature being most apparent during spring and summer. It is indicated from these considerations that winds at the northern and "southern" ends of the Passage are similar in that they generally blow into the Passage during spring and summer and out during autumn and winter; the trend during the former period is the most marked.

OCEANOGRAPHIC DATA UTILIZED

During 1930-1932, monthly observations of water properties in the Strait of Georgia were made by Carter and Tully; the data were published by the Pacific Oceanographic Group (1953). The results are used here to illustrate the general features in the annual cycle of temperature and of salinity from the surface to the bottom in the Strait; supporting data were obtained in the Strait from 1949 through 1953 (Pacific Oceanographic Group, MS, 1954). Even more recently, in 1959, the Pacific Oceanographic Group included the Passage in their Coastal-Seaway Project cruises (Pacific Oceanographic Group, MS, 1959a, b). In 1962 the entire Passage was surveyed longitudinally within a period of 24 hours both in spring (April) and in summer (June) during cruises conducted by the Pacific Naval Laboratory (Herlinveaux, MS, 1963). The Passage was also monitored within a two-day period during the autumn (October) of 1960 (Lane _et_ _al_., MS 1960). These "intensive" data are considered to provide a very nearly synoptic representation of the gross longitudinal distribution of properties. Daily seawater observations are carried out at a number of lightstations in the Passage; the results, as reported by Hollister (MS, annual), have also been utilized.

ANNUAL VERTICAL DISTRIBUTIONS OF PROPERTIES IN THE STRAIT OF GEORGIA

I. Salinity

The vertical distribution of salinity at Station 1 (between Nanaimo and Vancouver - Fig. 2) throughout 1931 is shown in Fig. 10A. Subsequent data indicate that the conditions indicated in Fig. 10A can be considered as broadly representative of those occurring throughout the central part of the Strait of Georgia, which body of water comprises the major portion of the Inside Passage.

The smallest salinities in the water column occur at the surface, and attain minimum values in June-July. These values are associated with the annual maximum in the discharge of the Fraser River. One or more secondary minima occur in the winter; these are related to the contribution by "local" rain-fed runoff. Below 50 m, seasonal variations are small throughout the year. At 400 m a maximum in salinity apparently can occur in October (31.5‰), and a minimum in May (31.0‰).

Tully (1958) has shown that there are unique features of the salinity profile associated with estuarine systems and that these features distinguish the régimes of fresh and sea water. He also indicated that a reasonable way to illustrate the régimes involves the use of a logarithmic profile of properties. This profile quite unambiguously delineates the thickness of a low-salinity surface layer (hereafter termed the "upper zone"), and of a halocline characterized by a relatively rapid increase of salinity with depth. Figures 10B and C reveal the (expected) presence of such an estuarine-type salinity structure at Station 1; such structure is found throughout much of the Passage. However, the upper zone is seen to vary in thickness both with time and with location (Fig. 11). In some areas (e.g. Queen Charlotte Strait and the central Strait of Georgia), the thickness varies in an annual cycle. In other areas (e.g. the southern Strait of Georgia and Juan de Fuca Strait) this cycle is not present.

Figure 12 has been prepared from data obtained within the upper 60 m at Station 1 in 1931. It suggests for how long, and to what depth, events of dilution may be followed in the Strait of Georgia. The curved lines in Fig. 12A indicate the lower limits of haloclines, and the hatched sections the depth intervals occupied by the haloclines. Areas not hatched are to be considered isohaline. The lower limits of the haloclines can be determined by careful consideration of the "major discontinuities" in the logarithmic profile of salinity. (The intensity of the hatching crudely represents the "magnitude" of a halocline.)

In winter a halocline (1) is present and persists till April, gradually deepening and dissipating; it is dependent both on the runoff from winter precipitation and on the degree of mixing induced by tidal and meteorological effects. In late winter or early spring another halocline (2) may be formed by runoff occurring after a cold dry spell in February. It progressively deepens and has generally vanished by late April. In spring a further halocline (3) forms, presumably as a result of early summer precipitation (Fig. 4) and runoff; in its early stages it deepens because of surface-induced processes. From late May to September an extremely pronounced halocline (4) is maintained within the upper 20 m primarily by the large snow-fed discharge from the Fraser River. During the presence of this pronounced freshwater effect, halocline (3) is indicated to deepen by subsurface mixing processes. The downward movement of halocline (4) by advective and convective processes can be followed throughout the succeeding autumn and winter.

The major features present in the vertical salinity distribution in 1931 are indicated by subsequent data to occur during most years. Figure 12B represents the salinity "profile" observed at the time indicated by the dashed line in Fig. 12A; it provides some indication of the salinity gradients to be expected throughout the upper portion of the water column at this time.

II. Temperature

The monthly sequence of temperature from the surface to near the bottom at Station 1 in 1931 is shown in Fig. 13A. The corresponding logarithmic structures are given in Fig. 13B and C.

There is seen to be an annual cycle in the surface waters (with temperatures in 1931 varying from 5.5°C to 17.5°C); maximum temperatures occur in August and minimum temperatures in December to February. The cycle is distinguishable to a depth of about 40 m; however, the time of occurrence of the maximum lags increasingly with depth.

In winter (November to March) the surface waters are generally colder than the deep waters; hence a "positive" gradient (temperature increasing with depth) prevails. Surface heating commences near the end of March, creating a near-surface "negative" thermocline (temperature decreasing with depth), which attains its maximum "magnitude" in July-August. Below this seasonal thermocline a temperature minimum persists between 75 and 100 m throughout the summer. (This minimum is considered to represent the remnants of water cooled during the previous winter.)

An increase in temperature below the sub-thermocline minimum would not appear to be explainable by the effect of surface heating; it is believed to be due to subsurface advective movements which are associated with flushing through the southern passages. This effect will be discussed in a later section (page 11). In 1931 the increase was most noticeable in October (Fig. 13B). In the deepest waters (about 400 m) the temperature appeared to reach a maximum in November-December and a minimum in March-April. It is indicated that in summer (e.g. in July) the thermocline may intercept the surface. This indicates very light winds during the particular interval. However, in winter a nearly isothermal layer may extend to appreciable depths.

In addition to these seasonal changes, short-term variations can occur in the temperature structure in the Strait at all times of the year. These are greatest in the near-surface waters and least, but still apparent, in the depths. It is suggested (Tully and Dodimead, 1957) that the former are attributable to the interplay between surface heating and cooling and wind effects, whereas the latter result from tidal and other advective motions or from internal waves.

Figure 14 indicates what is believed to be the seasonal distribution of thermoclines in the upper 60 m in the Strait of Georgia. The curved lines in Fig. 14A indicate the lower limits of the various thermoclines present throughout the year; the hatching indicates both the vertical extent, and the positive or negative nature of the thermocline. The hatching composed of crosses indicates the presence of a positive thermal gradient. The other (dotted) shadings represent negative gradients. The darker the shading, the stronger the gradient. The blank areas represent isothermal water. The lower limits of the thermoclines are (cf Fig. 12A) determined from the logarithmic profiles of temperature with depth. Figure 14B represents the analog, for temperature, of Fig. 12B.

The character of thermal structure appears generally to be governed by the salinity structure. In winter the halocline is deep; therefore cooling by "surface-induced" convection can occur to like depths and may at times result in a positive temperature gradient, in the upper brackish layer. In early spring the halocline is shallow and not too intense; as a result surface heating generates a shallow thermocline which becomes progressively deeper with time. By late spring the Fraser River freshet has developed and the resulting intense halocline (and accompanying great stability in the water column) confines the summer thermocline to above comparable depths. This thermocline gradually deepens because of mixing processes (due to cooling) and can be followed to a depth of about 50 m by November.

III. Dissolved oxygen content

Logarithmic profiles for the dissolved oxygen content (in mℓ/ℓ) at Station 1 during 1931 are displayed in Fig. 15A and B. The monthly sequence corresponding to that of Fig. 10A or of Fig. 13A (for salinity and temperature, respectively) is not provided in this report. Data for the deeper water were not available during either April or September of 1931 and, unfortunately, it so happened that this deficiency did not permit a meaningful representation of the oxygen content for a depth range similar to that characterizing Fig. 10A or 13A.

The oxygen content of the surface waters apparently does not undergo an annual cycle. The range of values during the year generally is modest; in 1931, the great majority of the values lay between 9.0 and 10.5 mℓ/ℓ. An "iso-oxygenated" surface layer is present during the winter; during January and February of 1931, it was about 20 m thick. In the late spring and in the summer, a subsurface maximum is often present (ca. 5 m, May-July, 1931); this is believed to be associated primarily with phytoplankton production in the Strait, page 10). At all times of the year, a marked decrease in dissolved oxygen content with depth (an "oxycline") occurs between about 10 (or 20) and 50 m. A more gradual decrease generally occurs in the deep water; even in these strata, considerable variability throughout the year is indicated. Stagnation apparently does not occur at depth in the Strait (values of dissolved oxygen content in 1931 were indicated to be always greater than 4 mℓ/ℓ).

SEASONAL LONGITUDINAL DISTRIBUTIONS OF PROPERTIES WITHIN THE ENTIRE INSIDE PASSAGE

I. Salinity

The longitudinal salinity distributions throughout the Inside Passage at four times of the year are shown in Fig. 16. The sections were not all obtained during the same year, but rather, over a period of four years (2 in 1959, one in 1960, and one in 1962). However, it is believed that the annual sequence so obtained is a generally representative one. Throughout the entire year the smallest surface-layer salinities in the Passage are recorded in the Strait of Georgia. In the Strait itself, the lowest salinities of the year are observed in summer (June), and result from the maximum in the Fraser River discharge. (On the other hand, in Queen Charlotte and Juan de Fuca Straits the smallest salinities of the year occur in December and January (data not shown in Fig. 16), and result from a maximum in winter precipitation.) The largest surface salinities occur simultaneously throughout the entire Passage and are generally found in early autumn (October).

In the deeper water, the maximum salinities of the year are generally attained in the Passage in autumn; throughout the year, the smallest salinities at depth in the Passage are observed in the first basin north of the Strait of Georgia.

On the basis of information already provided, the packing of the isohalines provides a good indication of vertical stratification. Such stratification is pronounced above 50 m, especially in the Strait of Georgia. Although prominent throughout the year, it attains a maximum in summer because of the large Fraser River outflow. It is least in the basins north of Discovery Passage (Fig. 16), and in Haro Strait, because of the presence of intense tidal mixing. Some shallow stratification develops towards the mouth of Juan de Fuca and Queen Charlotte Straits in the spring and summer, and is believed due primarily to runoff from the areas bordering these straits.

Throughout the year the isohalines in the Strait of Georgia generally slope upward toward the northern and southern approaches.

II. Temperature

In Fig. 17 are shown the longitudinal temperature distributions throughout the Inside Passage for the same four times associated with Fig. 16. An annual cycle in the surface layers is evident, the highest temperatures being recorded in summer (June) and the lowest in winter (February), in phase with the annual cycle of insolation. The warmest summer temperatures and the coldest winter temperatures in the Passage generally occur in the Strait of Georgia. The cycle of temperatures in the intermediate water lags that at the surface by as much as 4 months; for example, in Queen Charlotte and Juan de Fuca straits the water at 150 m attains its maximum temperature in spring and its minimum in summer. In the deep water of the Strait of Georgia the maximum is recorded in autumn and the minimum in summer. This is in fair agreement with data obtained at Station 1 in 1931 (Fig. 13). Below about 100 m the highest temperatures in summer and the lowest in winter appear to occur in the basin immediately north of Discovery Passage.

Temperature maxima or minima are often found at depth within the system, except in Haro Strait and Discovery Passage. These maxima and minima are assumed to be due both to successions of heating and cooling events in the surface layers and to exchange mechanisms (page 11).

At modest depths (20-50 m) the isotherms are continuous throughout the whole system in the surface waters for a short period in summer. Throughout the remainder of the year vertical homogeneity occurs in Discovery and Haro straits because of tidal mixing action upon water that is less stable due to the reduced freshwater input. Fairly marked stratification is often generated seaward of these straits because of the general effect of local heating and the weakening of tidal mixing.

III. Dissolved oxygen content

Figure 18 presents the longitudinal distributions of dissolved oxygen content (in mℓ/ℓ) throughout the Inside Passage for the same four times of the year. The maximum surface values of dissolved oxygen (11.0 mℓ/ℓ) were recorded during the spring in the Strait of Georgia (Sabine Channel). The minimum surface values (4.0 mℓ/ℓ) occurred in late autumn in Haro Strait and Discovery Passage. This condition is believed related to the processes which mix deeper less-oxygenated water with that from the surface layers.

Phytoplankton are probably the main contributors to the oxygen content of the surface layers in the Strait of Georgia. Hutchinson, Lucas and McPhail (1929) showed that the horizontal distribution of phytoplankton at any time was "cloud-like". This has been also indicated by Stephens (1968). Hutchinson et al. (op. cit.) also found that the vertical distribution of phytoplankton was associated with the salinity distribution, and that a subsurface maximum of dissolved oxygen in the upper 15-20 m was probably associated with a subsurface maximum of phytoplankton. Maxima in dissolved oxygen concentration (in the upper 20 m) are indicated by the data to occur throughout the system, although they are not evident (Fig. 18) because of the small scale used. These maxima did not occur in winter, as would be expected.

Below 20 m oxygen maxima and minima are present throughout the Inside Passage and are assumed to be associated with water exchange at depth (maxima) and with biological demand (minima). Figure 18 indicates that during most of the year a dissolved oxygen minimum (about 4.0 to 5.0 $m\ell/\ell$) appears to exist between depths of 75 and 150 m in the Strait of Georgia, shallowing to the south. Simultaneously, beneath this minimum there is a maximum (about 5.0 to 5.5 $m\ell/\ell$) which is most intense in the spring; it appears also that the oxygen level reaches an annual maximum throughout the entire water column in Haro Strait at this time. This is due presumably to the movement of highly-oxygenated surface water from the Strait of Georgia into Haro Strait, and the subsequent downward mixing (page 11).

IV. Density (σ_t)

In Fig. 19 are shown the four longitudinal density (as σ_t) distributions through the Inside Passage. The distribution (both vertical and longitudinal) of the isopycnals exhibits the same general pattern as do those of the isohalines. The distribution has been exhibited primarily because of its utility in the consideration of water exchange in the Strait of Georgia (page 11).

The packing of the isopycnals indicates the degree of stratification in density throughout the year in the whole passage. The slope of the isopycnals and their continuity suggest that a subsurface movement of water from the southern approaches into the Strait of Georgia can occur, at any time, to considerable depths. However, subsurface movement into the Strait from the northern approaches is severely limited below about 13 m by the shallowness of Discovery Passage.

V. Sound speed

The value of sound speed integrates several properties of the water, thereby providing a useful indication of changing characteristics. The speed of sound in the sea increases by about 4 ft/sec* (1.3 m/sec) for an increase

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*Feet per second (ft/sec) is still generally used (in the literature of English-speaking countries) to indicate the magnitude of sound speed.

of 1‰ salinity and by about 6 ft/sec for an increase in depth of 330 feet (1.8 m/sec for 100 m). There is an increase with temperature of about 5.5 ft/sec/°F (3 m/sec/°C) in "average" surface layer conditions. In the open ocean, changes in temperature usually dominate the sound velocity structure. However, in areas affected by strong river outflow, the velocity characteristics are at times dominated by changes in salinity.

In Fig. 20 are shown the longitudinal sound speed distributions through the Inside Passage, corresponding to the distributions of Fig. 16 through 19. The vertical gradient of sound speed is seen generally to be positive (increasing with depth) in the Strait of Georgia, but negative in Queen Charlotte Sound and in Juan de Fuca Strait. The vertical gradient is generally greatest in the Strait of Georgia and least in the northern and southern approaches (Johnstone Strait and Haro Strait).

Throughout the spring and early summer (April-June), as surface heating intensifies, the sound speed increases in the surface layers throughout the Passage. A sound speed minimum underlies these large surface values, being most marked in the Strait of Georgia and in Queen Charlotte Sound. It occurs at about the depth of the layer of water cooled during the previous winter. The minimum is to all intents and purposes, however, non-existent in Johnstone and Juan de Fuca straits and Discovery Passage. In the autumn (October), as surface cooling intensifies, the sound speed in the surface waters decreases in the Strait of Georgia. A shallow maximum is associated with the remnants of the underlying summer-heated water.

Also during the autumn, a subsurface temperature minimum is evident in the northern Strait of Georgia (Fig. 17); this results in a sound speed minimum at depths between 50 m and 100 m.

A subsurface sound-speed maximum may also be present in the southern Strait throughout much of the year; this is believed to be due to the effect of water exchange. From 100 m to the bottom the vertical gradient of sound speed is positive throughout the year from Haro Strait through Johnstone Strait. In Juan de Fuca Strait and Queen Charlotte Sound this is true during the winter and spring, but the reverse condition obtains during summer and autumn. These features are believed to be associated with the subsurface intrusions.

In summary, in any one season a variety of sound propagation conditions may be encountered within the Inside Passage.

WATER EXCHANGE IN THE STRAIT OF GEORGIA

It was mentioned earlier (pages 9 and 10) that maxima and minima noted in the vertical distribution of various properties in the main body of the Strait of Georgia might be associated with, among other things, intrusion (i.e. advection) of water into the Strait from the approaches. In the present section this suggestion is explored somewhat more fully, by consideration both of the vertical distributions of property already described and by "surface-water" data obtained at various lightstations.

Use of vertical distributions

The vertical distribution of density (or of salinity) in Juan de Fuca and Georgia straits indicates that subsurface water movement can take place into the latter Strait from its southern end throughout the entire year, at "intermediate" depths at least (Fig. 16 and 19). It is believed that details of such "penetration" can be somewhat further clarified by examination of the vertical temperature and dissolved oxygen distributions for the area (Fig. 17 and 18).

Both the winter (February) and spring (April) temperature sections in the Strait of Georgia (Fig. 17) can apparently be featured by a layer associated both with a temperature minimum and with a dissolved oxygen maximum. This layer is present between depths of about 100 and 200 m and generally is much more pronounced in the southern part of the Strait. It is suggested that the layer results from intrusion of water through Haro Strait. This so-called "intermediate intruding" water is presumed to be formed by tidal mixing - primarily in Haro Strait - of deep water from Juan de Fuca Strait and the surface-cooled, less-saline and better-oxygenated water above. On the other hand the directly-overlying layer, associated with a temperature maximum, is believed composed of the "descended" remnant of water warmed by surface heating during the previous spring and summer; it is also marked by an oxygen minimum, which has resulted from such factors as biological demand. This layer is termed here "intermediate resident" water.

By the autumn the subsurface temperature structure above about 200 m has undergone marked modification. The temperature profile is now featured by a "temperature-minimum" layer overlying a depth interval associated with a temperature maximum. The shallower layer, featured also by an oxygen minimum, is believed to have evolved, by processes such as diffusion, from the intruding intermediate water of the previous winter and spring; it has now become "intermediate resident" water. By contrast, the underlying layer, associated also with an oxygen maximum, represents newer "intruding intermediate" water. It has presumably been formed primarily in Haro Strait by late-summer mixing of deeper, high-salinity water with warm surface water (Waldichuk, 1957).

Tully and Dodimead (1957) suggest that, because of the loss of deeper water (and its salt) in the Strait by entrainment into the (outflowing) surface water, there must be a compensatory subsurface transport of some type into the Strait. The (slow) intermediate inflow, together with any advection of bottom water in winter - as suggested by Waldichuk (1957) - could maintain the water and salt balance in the Strait.

"Intermediate" flow originating at the northern end of the Strait was not indicated for the times involved in Fig. 17, and is believed not to be common, in great part because of the extreme shoaling characterizing Discovery Passage. However, such flow apparently can occur during very cold winters (Waldichuk, 1957).

Subsurface maxima and minima in both temperature and dissolved oxygen content can apparently occur in the northern part of the Passage also. However, the structures seem to be somewhat more complicated than those in the Strait of Georgia and will be dealt with separately in a later report.

In summary, during the "winter" a subsurface temperature maximum is indicative of resident intermediate water, whereas a (deeper) minimum is indicative of intruding intermediate water. During "summer", on the other hand, a temperature maximum is associated with intruding intermediate water, and a minimum with resident intermediate. In winter, a temperature minimum is usually associated with an oxygen maximum and a temperature maximum with an oxygen minimum; in summer an oxygen maximum is associated with a temperature maximum and an oxygen minimum with a temperature minimum.

The concept of maxima and minima being indicative of horizontal movement at intermediate depths is further supported by nutrient data collected in 1931 (Pacific Oceanographic Group, 1953). The surface layer, of course, goes through a seasonal cycle involving depletion by phytoplankton growth and replenishment by advection and/or diffusion. Below this, at the intermediate resident level, the nutrients are always abundant, since utilization by production will be small and some regeneration by bacterial means could take place. Below this again, the intruding intermediate water is characterized by nutrient concentrations smaller than those in the resident intermediate, because of the former's origin in Haro Strait (being a mixture of deep and surface waters). Below the intruding intermediate water the nutrient concentrations increase, probably at least partly because of regeneration.

Additional qualitative indication of the presence of distinct subsurface layers might be provided by variability exhibited in the water velocity profile. Such profiles would portray any speed "biases" in the system, and would thus demonstrate any distinctive shears that might occur across the boundaries between water masses. A number of such profiles have been taken at two locations in the southern basin of the Strait of Georgia (at the southern end, off Patos Island, and at the northern end, near Ballenas Island [Fig. 2]). These observations were obtained by "following" a free-falling metal container by means of an underwater 3-dimensional-tracking apparatus (Garrison and Linger, 1962).

Observed water speed profiles are shown in Fig. 21. There were marked subsurface shears indicated; it is to be noted that the major shears occur in the general depth interval in which the intermediate layers ("resident and intruding") have been indicated to occur.

Use of lightstation data

Surface-water salinities and temperatures have been monitored daily at several lightstations along the British Columbia coast for varying periods of time. Figures 22 and 23 display the variability in salinity and temperature observed, during the year 1959, at 5 stations within the Inside Passage. Several authors (e.g. Hollister, 1949; Pickard and McLeod, 1953) have suggested that the data from these stations can be used to indicate various features of oceanographic properties in the surface layers, such as annual cycles at any location. The utility of the lightstation data is suggested by the fact that monthly-mean values (obtained in 1959 and 1962) for summer (June) and winter (February) - Fig. 24 - are found to provide good agreement "longitudinally" with surface values from the sections of Fig. 16 and 17.

Figures 22 and 23 appear in addition to provide evidence of the existence of semi-monthly variations in the surface temperatures and salinities. Herlinveaux (1957) had earlier noted similar features at Race Rocks, and concluded that these variations were due, in large degree, to a semi-monthly cycle (associated with the moon's phase) in the strength of tidal currents. The salinities increased during the intervals from neap (equinoxial) tides to spring (tropical) ones. In summer the surface temperature decreased, and in winter increased, during these intervals. Herlinveaux concluded that these effects were caused by mixing of the near-surface and deeper waters, and that the degree of this mixing (excluding the effect of wind) varied as the speed of tidal flow.

Results thus indicate that, at Race Rocks, surface-layer stratification would in general intensify during small tidal movements ("neaps") and would diminish during large tidal movements ("springs"). Therefore, the upper zone would tend to be more homogeneous (and deeper) during large tidal movement than during small. It may, therefore, be concluded that observations of salinity and temperature (especially of the former) taken at the surface during a time of large tidal velocities would be reasonably representative of conditions at the bottom of the upper zone at that time. Figures 22 and 23 indicate that similar semi-monthly variations in salinity and temperature due to tide are also present to a marked degree in the Strait of Georgia (e.g. at Cape Mudge, Entrance Island and East Point), and to a lesser degree in the northern approaches (e.g. at Pine Island). To what extent this variation is affected by other factors than tide is still to be investigated. The most likely other contributing factor is the wind. Wind-induced transport can move water onshore or offshore. Surface water moved onshore would tend to decrease both the salinity and the temperature of the "near-shore" water in winter and to decrease salinity and increase the temperature in summer. The offshore transport, on the other hand, would result in an increased salinity and an increased temperature during winter at the shore, and an increased salinity and decreased temperature during the summer. The onshore or offshore wind transport could appear to have the same effect on the surface water as tidal mixing. However, the two effects could generally be distinguished because of the periodicity of the tidal effect. This modification could occur anywhere throughout the Passage.

Figure 25C shows the monthly-mean surface salinity values observed at East Point and Cape Mudge for the 10-year period 1954 through 1963. These observations were taken at the beginning of the ebb. It is apparent that values at the southern approaches to the Strait of Georgia (East Point) were usually less than those at the northern (Cape Mudge) during the period 1956-1960. Tully and Dodimead (1957), as would be expected, reached opposite conclusions on the strength of 1954 data only since, during that year, East Point surface salinities were generally greater, the degree being indicated by the shaded area.

In Fig. 25A and B are shown the monthly-mean discharge data for the Fraser and Homathko rivers. It is evident that the difference in salinity between East Point and Cape Mudge is not related in any regular fashion to the volume of fresh water discharged into the Strait of Georgia by these two major rivers.

It has been suggested by Tully and Dodimead (1957), on the basis of data from 1954, that there is a greater accumulation of fresh water in the northern approaches than in the southern. It would appear from subsequent data that this is not a permanent situation. A greater accumulation of fresh water in any area may come about either by more of such water moving through the area or by it being retained because of meteorological conditions. Barber (1957) noted that during periods of southeast winds, Queen Charlotte Sound experienced a retention of fresh water (and a resultant thickening of the surface layer). Such an effect could be registered as a difference in mean sea level between two areas. The difference therefore could be construed as an indicator as to whether there is a retention in, or an expulsion from, water from part of the system. The determination of the relationship between daily seawater observations at the lightstations and the expulsion or retention of fresh water in the Strait of Georgia awaits further investigation of sea-level differences between various areas.

OCEANOGRAPHIC DOMAINS OF THE INSIDE PASSAGE

In preceding sections the variability in oceanographic properties throughout the year within the Inside Passage has been discussed in some detail. In order to summarize more conveniently these findings, the Passage is considered to be divided into six "domains" (Fig. 26). The concept of a domain used is that provided by Dodimead, Favorite and Hirano (1963); it ".... contains the ideas of consistent properties, structure, behaviour (flow, heating and cooling, etc.) climatic locality and continuity .... it depends .... on a rational consistency in all aspects." (Sundry features which have been reported in other studies and are considered to be important characteristics of one or more of the domains are also noted.)

The approximate extent of each of the six domains is shown in Fig. 26. Two of the domains - the Central and the Northern - are considered to be located entirely within the Strait of Georgia. The Central Domain is believed to be limited essentially to the southern basin of the Strait (Fig. 2) - and to be bounded to the north by the line running north from Nanaimo to the British Columbia mainland, and to the south by a line joining Point Roberts and Active Pass. Its surface layers are dominated throughout the year by the outflow from the Fraser River, the effect being especially marked during the "large-runoff" period (approximately May through September). The surface waters are characterized during this time by a thin brackish layer ("plume") resulting from this outflow (e.g. Giovando and Tabata, 1970); as a result, vertical stratification in salinity (and in temperature as well) is pronounced in the shallower layers. More than one marked halocline can be present within the first few tens of metres. Excluding the effect of wind, the surface currents are in general composed of both tidal and non-tidal components (the latter resulting from river runoff); they can attain speeds of over one knot (Pickard, 1956). The speeds of deep currents can attain half a knot. Renewal of water between about 100 and 200 metres depth can apparently occur throughout the year; the intruding water originates in the deep passages of the American Gulf Islands (e.g. Haro Strait). These (slow) intrusions are recognized primarily by the presence of maxima and minima in the profiles of temperature and of dissolved oxygen content. Internal waves are evident, especially at the boundary between the Fraser River "plume" and the surrounding waters (Shand, 1953). The bottom sediments are almost exclusively soft muds deposited as silt by the outflow from the Fraser (Waldichuk, 1953).

The Northern Domain includes the northern basin of the Strait and a small portion of the southern basin. It can be considered to be bounded to the north by Discovery Passage and by the deeper channels to the east. A halocline always exists in this domain. It is enhanced for a short period during June and July by fresh water originating from the Fraser and from major rivers (e.g. the Homathko) at the heads of the large inlets situated to the northeast of the domain. There is believed to be relatively little tidal movement, except in the vicinity of Discovery Passage. Temperature inversions are present at intermediate depths, but are not in general as pronounced as those in the Central Domain. The effect of frequent (or continuous) renewal of both intermediate and deep water in the Northern and Central Domains is indicated by the magnitude of the dissolved oxygen content (never less than about 3 $m\ell/\ell$ in the data treated in this report). The bottom sediments are featured by the presence of sand as well as of mud (Waldichuk, 1953).

There are two Homogeneous Domains. The Southern is considered to extend from the Central Domain to a sill running southward from Victoria, Vancouver Island. The entire area is characterized by intensive tidal mixing; this is especially marked in the island passages (Haro and Rosario Straits) but possesses considerable strength in the remainder of the area also, as evidenced, for example, by the presence of "tidal rips" (Tully and Dodimead, 1957). As a result the subsurface waters tend on the whole to be homogeneous throughout the year, although inversions in temperature or in dissolved oxygen content appear occasionally to be present at depth.

Bottom water is exchanged to some degree on each tide. The surface layers can be featured by a halocline structure during the freshet of the Fraser River. The tidal flow predominates over any (non-wind-induced) "residual" flow; surface speeds can attain values of 3-5 knots in the major passages between islands. Internal waves are often evident, at least in the vicinity of the passages in the northern portion of the domain.

The Northern Homogeneous Domain extends south from Weynton Passage near Alert Bay through Discovery Passage (Fig. 2). Tidal mixing is intense throughout this domain, especially over the three major sills of this sytem. As a result the water tends towards homogeneity. Stratification is always absent in Seymour Narrows, in which the speeds may reach 15 knots; however, throughout the year, it can occur in the vicinity of Queen Charlotte Strait because of freshwater contribution from local drainage. Bottom water is replenished at least partially on each tide.

Two Coastal-Seaways Domains can also be specified. The southern one extends from the sill off Victoria to the mouth of Juan de Fuca Strait. Stratification in the uppermost layers is generated by outgoing "Southern-Homogeneous-Domain" water modified by local runoff. An upper zone is evident throughout the year, being most marked during the summer. An intruding offshore water mass underruns this zone. Temperature maxima and minima appear at times to be present at a depth of about 100 metres. Surface currents of up to 3 knots have been observed.

The Northern Coastal-Seaways Domain extends from Weynton Passage to the northern tip of Vancouver Island. In this domain stratification is most noticeably generated by the combining of outgoing Northern-Homogeneous-Domain water from Johnstone Strait and the contribution from local runoff. This action forms an upper zone which is deepest in winter and shallowest in summer. This zone is underrun by an intruding offshore water mass which can frequently replenish the bottom water. Maxima and minima in the temperature structure are evident above 150 metres.

It may be noted that annual changes in the coastal waters of British Columbia have recently been discussed by Dodimead and Pickard (1967).

SUMMARY

On the basis of data obtained between 1931 and 1962, distinctive characteristics of the vertical and horizontal distributions of physical and chemical properties throughout the Inside Passage have been demonstrated. These characteristics suggest a mechanism for the renewal of water at intermediate depths in parts of the Passage. The Passage has been divided into six "domains" which categorize, by area, the prevailing oceanographic conditions. These various results should be of considerable importance in ecological studies within the Passage.

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LIST OF FIGURES

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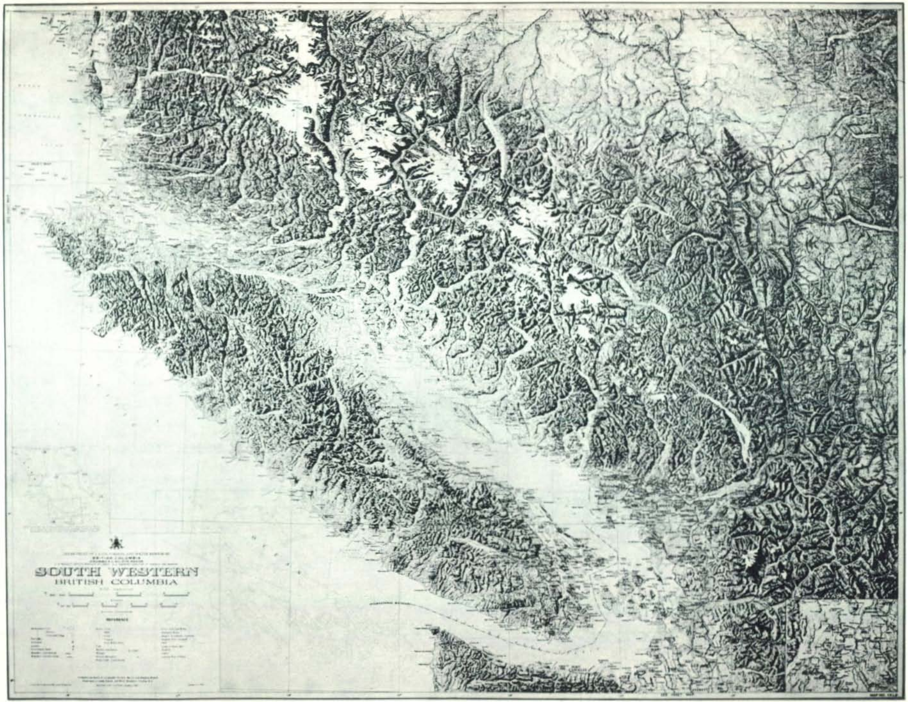


Figure 1

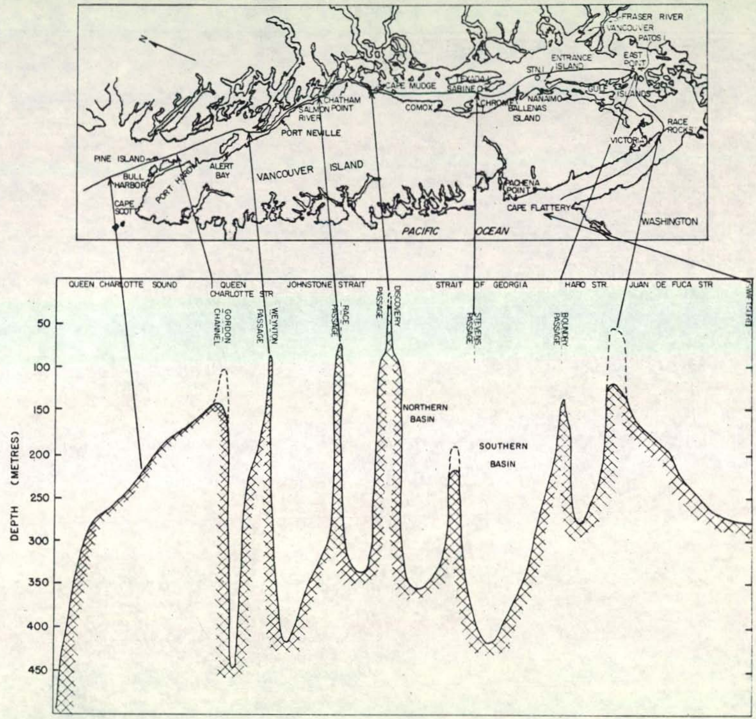

FRASER RIVER
VANCOUVER
PATOS I.
ENTRANCE ISLAND
EAST POINT
STN I
CAPE MUDGE
TEXADA I.
SABINE
CHATHAM POINT
SALMON RIVER
COMOX
CHROME
NANAIMO
BALLENAS ISLAND
GULF ISLANDS
PORT NEVILLE
RACE ROCKS
VICTORIA
PINE ISLAND
BULL HARBOR
ALERT BAY
PORT HARDY
VANCOUVER ISLAND
PACHENA POINT
CAPE SCOTT
CAPE FLATTERY
WASHINGTON
PACIFIC OCEAN
N
QUEEN CHARLOTTE SOUND
QUEEN CHARLOTTE STR
JOHNSTONE STRAIT
STRAIT OF GEORGIA
HARO STR.
JUAN DE FUCA STR
SWIFTSURE
GORDON CHANNEL
WEYNTON PASSAGE
RACE PASSAGE
DISCOVERY PASSAGE
STEVENS PASSAGE
BOUNDRY PASSAGE
NORTHERN BASIN
SOUTHERN BASIN
DEPTH (METRES)
50
100
150
200
250
300
350
400
450

Figure 2

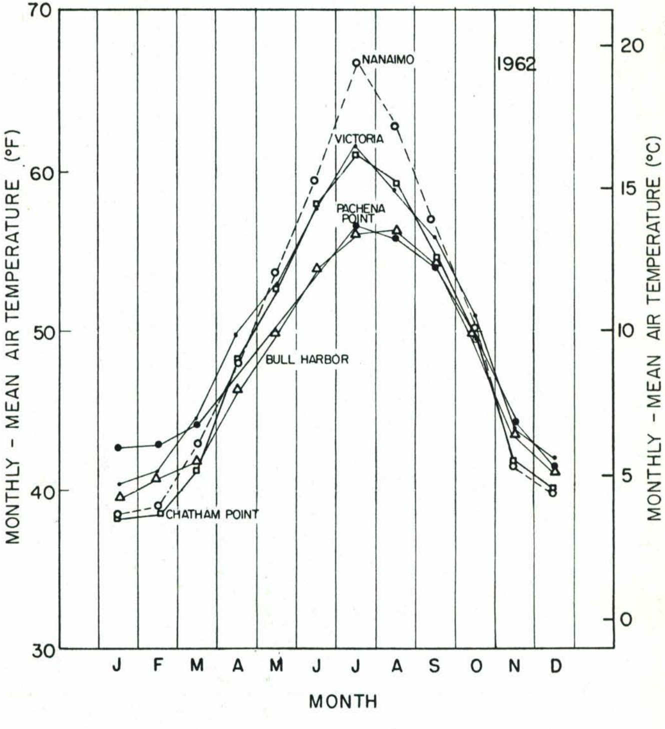

70
60
50
40
30
20
15
10
5
0
MONTHLY - MEAN AIR TEMPERATURE (°F)
MONTHLY - MEAN AIR TEMPERATURE (°C)
NANAIMO
1962
VICTORIA
PACHENA POINT
BULL HARBOR
CHATHAM POINT
J
F
M
A
M
J
J
A
S
O
N
D
MONTH

Figure 3

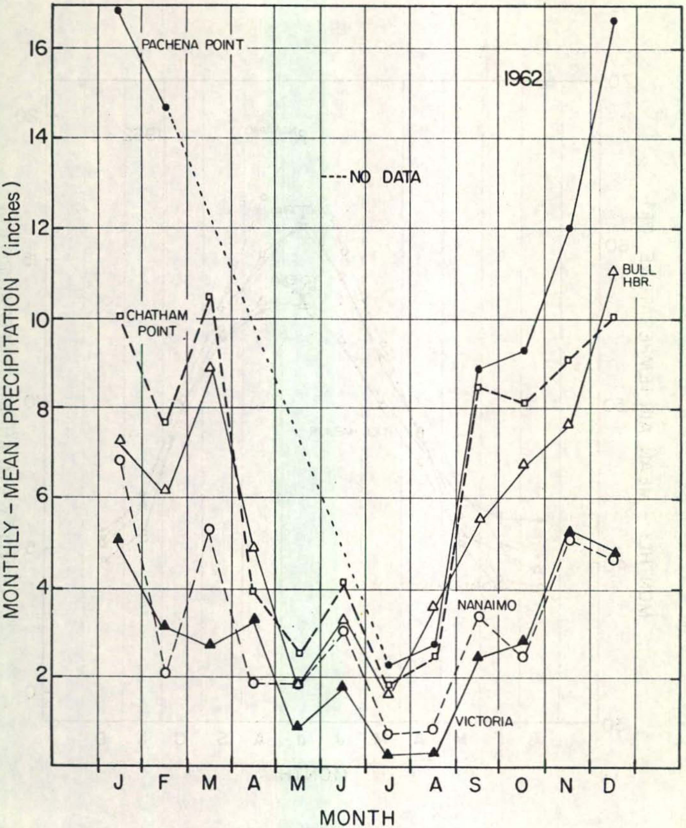

MONTHLY - MEAN PRECIPITATION (inches)
16
14
12
10
8
6
4
2
J
F
M
A
M
J
J
A
S
O
N
D
MONTH
1962
---- NO DATA
PACHENA POINT
CHATHAM POINT
BULL HBR.
NANAIMO
VICTORIA

Figure 4


-20 - ANNUAL PRECIPITATION (inches)
GREAT DIVIDE
HOMATHKO RIVER
SALMON RIVER
SQUAMISH RIVER
FRASER RIVER
COWICHAN RIVER
DUNGENESS RIVER
VANCOUVER I.
STRAIT OF GEORGIA
STR. OF JUAN DE FUCA
1
2
3
4
5
6
128°
126°
124°
122°
120°
118°
55°
53°
51°
Lat. 49° N.
47°
126
124
122
Long. 120° W
20
40
60
80
100
120
140
160
180
200

Figure 5

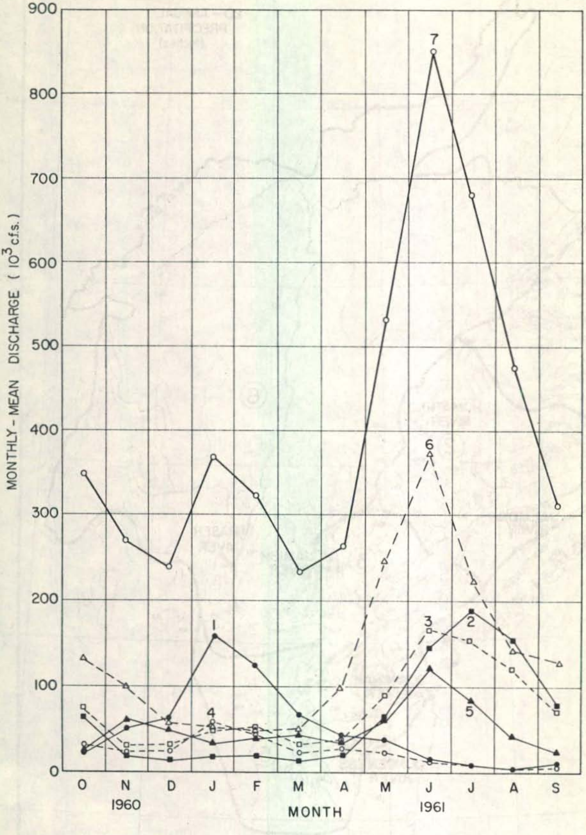

MONTHLY - MEAN DISCHARGE (10^3 c.f.s.)
900
800
700
600
500
400
300
200
100
0
O
N
D
J
F
M
A
M
J
J
A
S
1960
MONTH
1961
7
6
1
2
3
4
5

Figure 6

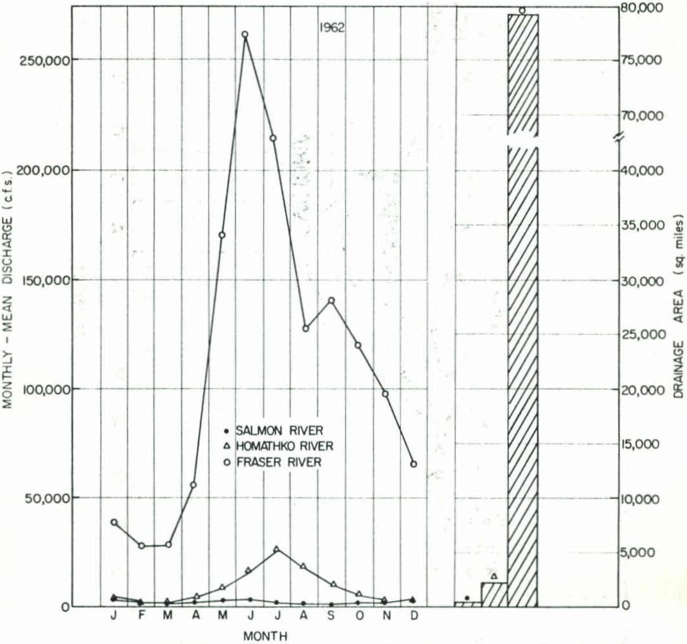

1962
MONTHLY - MEAN DISCHARGE (c.f.s.)
0
50,000
100,000
150,000
200,000
250,000
J
F
M
A
M
J
J
A
S
O
N
D
MONTH
● SALMON RIVER
△ HOMATHKO RIVER
○ FRASER RIVER
DRAINAGE AREA (sq. miles)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
70,000
75,000
80,000

Figure 7

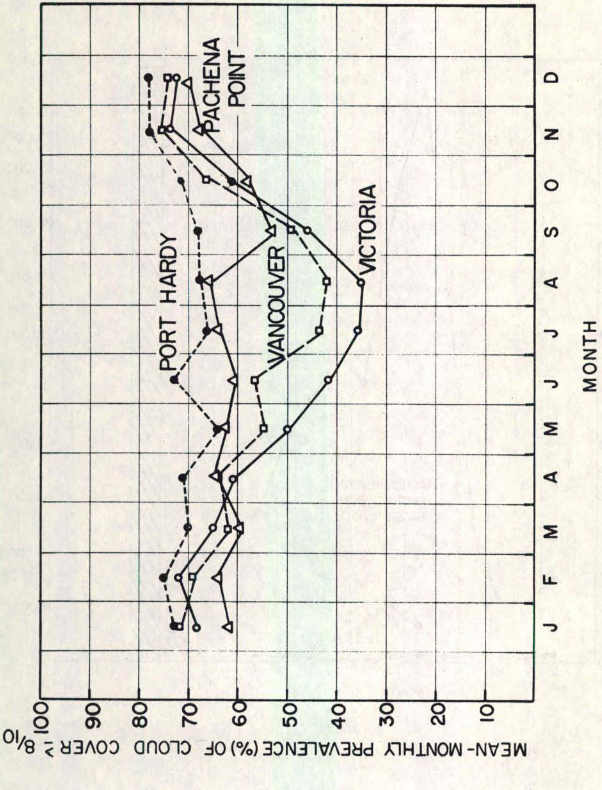

MEAN-MONTHLY PREVALENCE (%) OF CLOUD COVER ≥ 8/10
100
90
80
70
60
50
40
30
20
10
J
F
M
A
M
J
J
A
S
O
N
D
MONTH
PORT HARDY
PACHENA POINT
VANCOUVER
VICTORIA

Figure 8

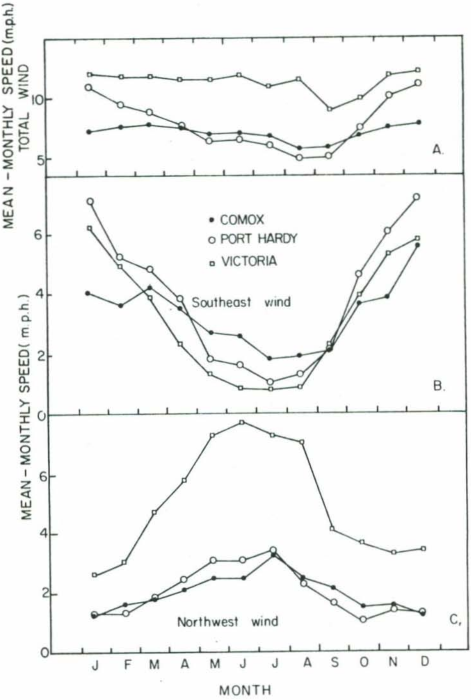

MEAN - MONTHLY SPEED (m.p.h.)
TOTAL WIND
10
5
A.
• COMOX
o PORT HARDY
▫ VICTORIA
Southeast wind
MEAN - MONTHLY SPEED(m.p.h.)
6
4
2
0
B.
6
4
2
0
Northwest wind
C,
J F M A M J J A S O N D
MONTH

Figure 9

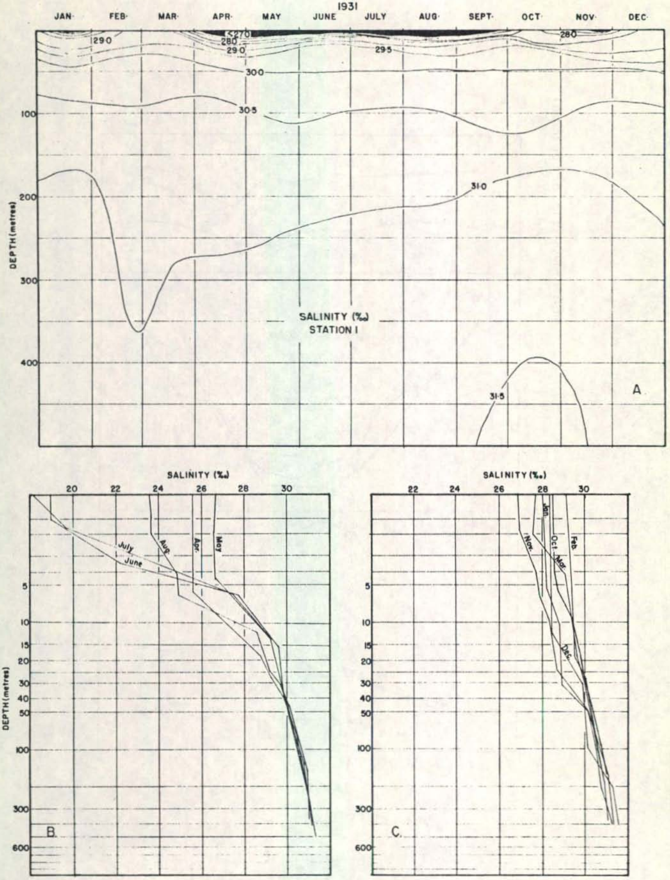

1931
JAN·
FEB·
MAR·
APR·
MAY
JUNE
JULY
AUG·
SEPT·
OCT·
NOV·
DEC·
<27·0
28·0
29·0
29·0
29·5
28·0
30·0
30·5
31·0
31·5
SALINITY (‰)
STATION I
A
DEPTH (metres)
100
200
300
400
SALINITY (‰)
20
22
24
26
28
30
July
June
Aug.
Apr.
May
DEPTH (metres)
5
10
15
20
30
40
50
100
300
600
B.
SALINITY (‰)
22
24
26
28
30
Jan.
Nov.
Oct.
Mar.
Feb.
Dec.
5
10
15
20
30
40
50
100
300
600
C.

Figure 10

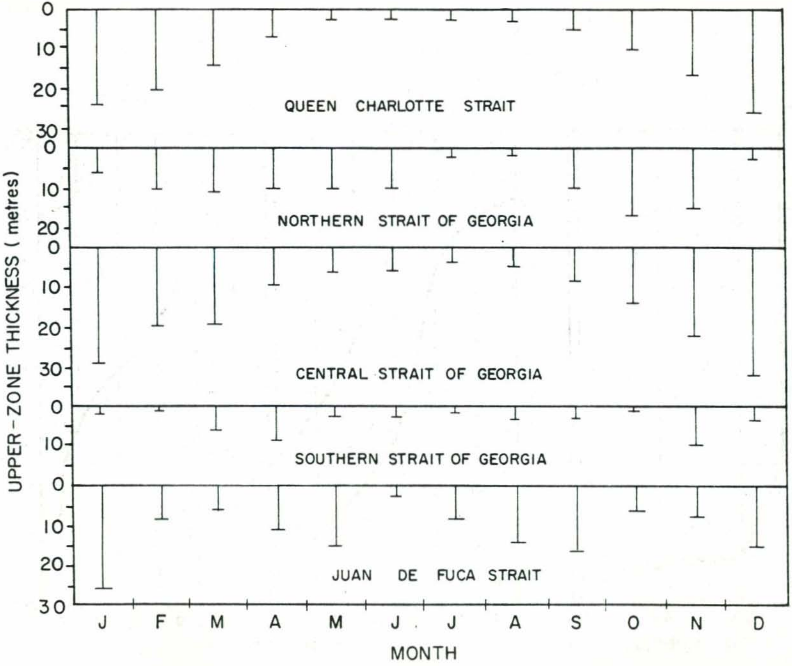

UPPER-ZONE THICKNESS (metres)
QUEEN CHARLOTTE STRAIT
NORTHERN STRAIT OF GEORGIA
CENTRAL STRAIT OF GEORGIA
SOUTHERN STRAIT OF GEORGIA
JUAN DE FUCA STRAIT
0
10
20
30
J
F
M
A
M
J
J
A
S
O
N
D
MONTH

Figure 11

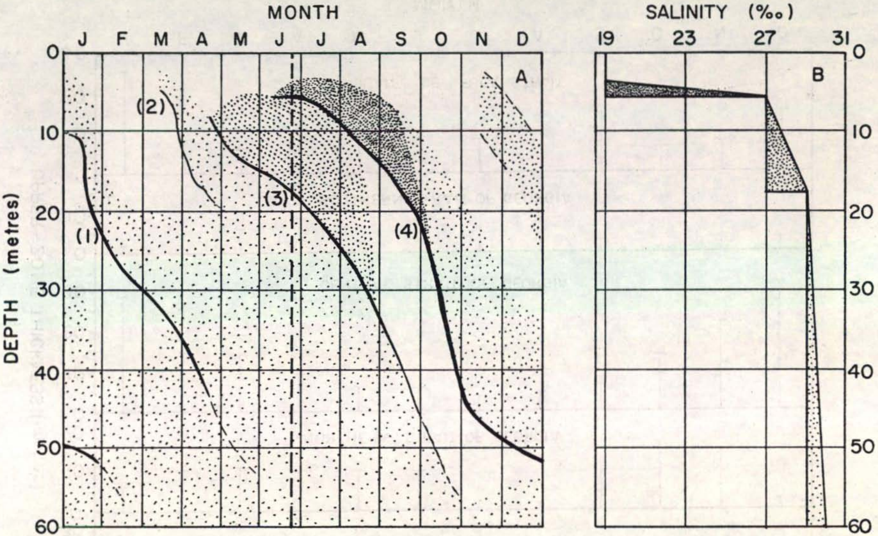

MONTH
J F M A M J J A S O N D
SALINITY (‰)
19 23 27 31
DEPTH (metres)
0
10
20
30
40
50
60
A
B
(1)
(2)
(3)
(4)

Figure 12

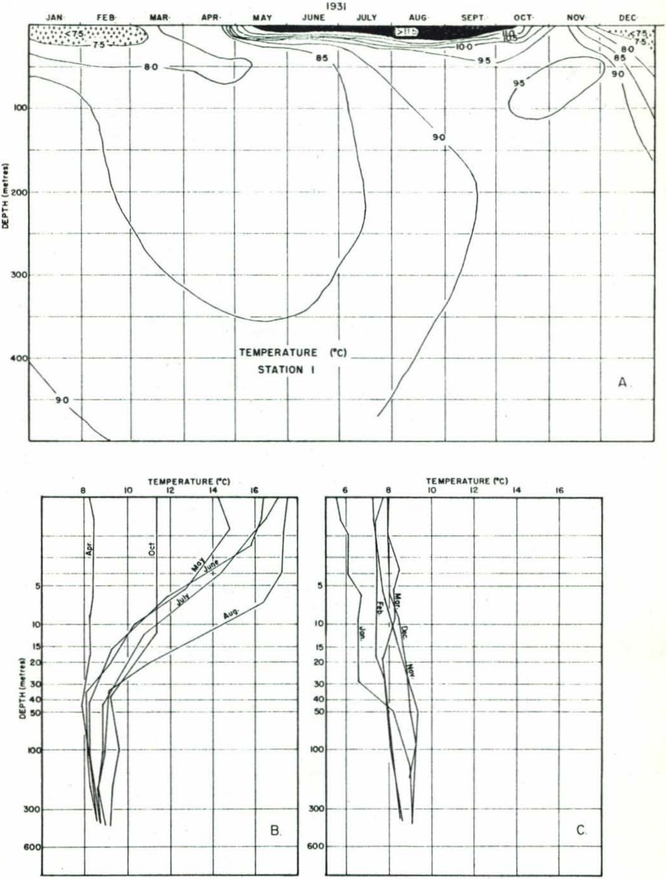
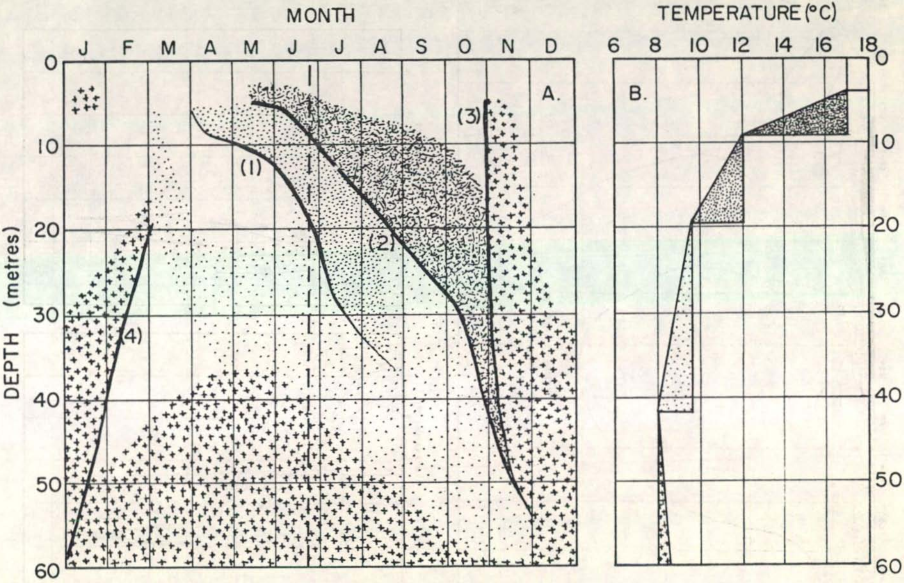

1931
JAN.
FEB.
MAR.
APR.
MAY
JUNE
JULY
AUG.
SEPT.
OCT.
NOV.
DEC.
<7.5
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
>11
DEPTH (metres)
100
200
300
400
TEMPERATURE (°C)
STATION I
A.
TEMPERATURE (°C)
8
10
12
14
16
Apr.
Oct.
May
June
July
Aug.
5
10
15
20
30
40
50
100
300
600
B.
TEMPERATURE (°C)
6
8
10
12
14
16
Jan.
Feb.
Mar.
Dec.
Nov.
C.

Figure 13



MONTH
J
F
M
A
M
J
J
A
S
O
N
D
DEPTH (metres)
0
10
20
30
40
50
60
A.
(1)
(2)
(3)
(4)
TEMPERATURE (°C)
6
8
10
12
14
16
18
B.
0
10
20
30
40
50
60

Figure 14

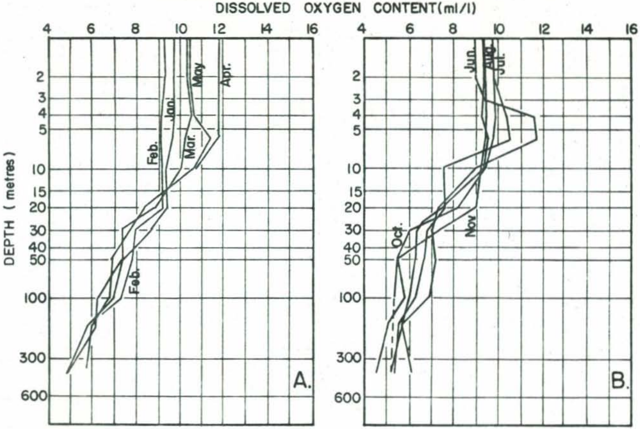

DISSOLVED OXYGEN CONTENT(ml/l)
4
6
8
10
12
14
16
DEPTH (metres)
2
3
4
5
10
15
20
30
40
50
100
300
600
Feb.
Jan.
Mar.
May
Apr.
Feb.
A.
Jun.
Aug.
Jul.
Oct.
Nov.
B.

Figure 15

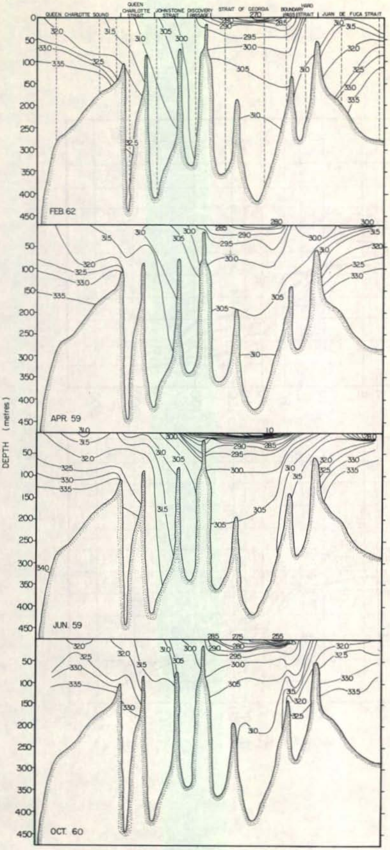

QUEEN CHARLOTTE SOUND
QUEEN CHARLOTTE STRAIT
JOHNSTONE STRAIT
DISCOVERY PASSAGE
STRAIT OF GEORGIA
BOUNDARY PASS
HARO STRAIT
JUAN DE FUCA STRAIT
DEPTH (metres)
0
50
100
150
200
250
300
350
400
450
FEB. 62
APR. 59
JUN. 59
OCT. 60
32.0
31.5
31.0
30.5
30.0
33.0
33.5
32.5
29.5
29.0
28.0
28.5
27.0
34.0
27.5
25.5
1.0

Figure 16

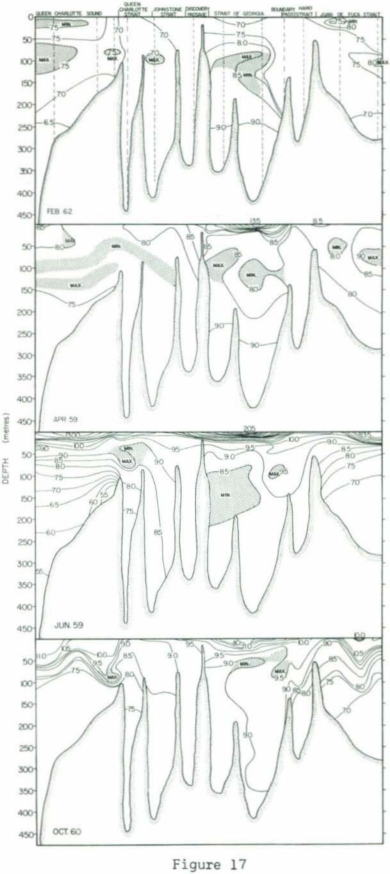

QUEEN CHARLOTTE SOUND
QUEEN CHARLOTTE STRAIT
JOHNSTONE STRAIT
DISCOVERY PASSAGE
STRAIT OF GEORGIA
BOUNDARY PASS
HARO STRAIT
JUAN DE FUCA STRAIT
DEPTH (metres)
0
50
100
150
200
250
300
350
400
450
FEB 62
APR 59
JUN 59
OCT 60
MAX
MIN
65
70
75
80
85
90
95
100
105
110
135
205

Figure 17

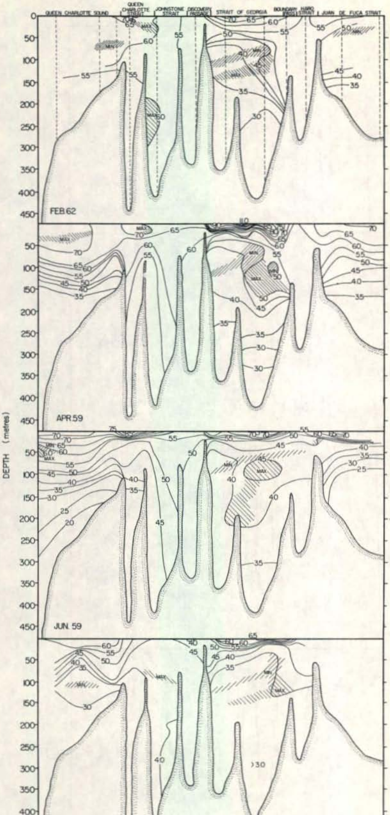

QUEEN CHARLOTTE SOUND
QUEEN CHARLOTTE STRAIT
JOHNSTONE STRAIT
DISCOVERY PASSAGE
STRAIT OF GEORGIA
BOUNDARY PASS
HARO STRAIT
JUAN DE FUCA STRAIT
DEPTH (metres)
0
50
100
150
200
250
300
350
400
450
FEB 62
APR 59
JUN 59
OCT 60
MAX
MIN

Figure 18

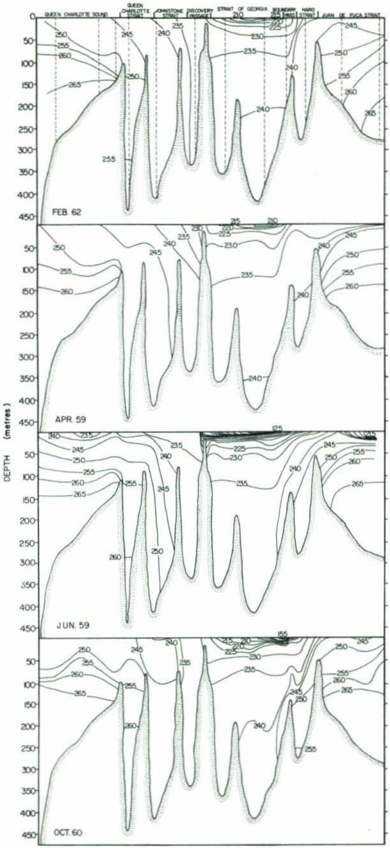

QUEEN CHARLOTTE SOUND
QUEEN CHARLOTTE STRAIT
JOHNSTONE STRAIT
DISCOVERY PASSAGE
STRAIT OF GEORGIA
BOUNDARY PASS
HARO STRAIT
JUAN DE FUCA STRAIT
DEPTH (metres)
0
50
100
150
200
250
300
350
400
450
FEB. 62
APR. 59
JUN. 59
OCT. 60
210
215
220
225
230
235
240
245
250
255
260
265
125
155

Figure 19

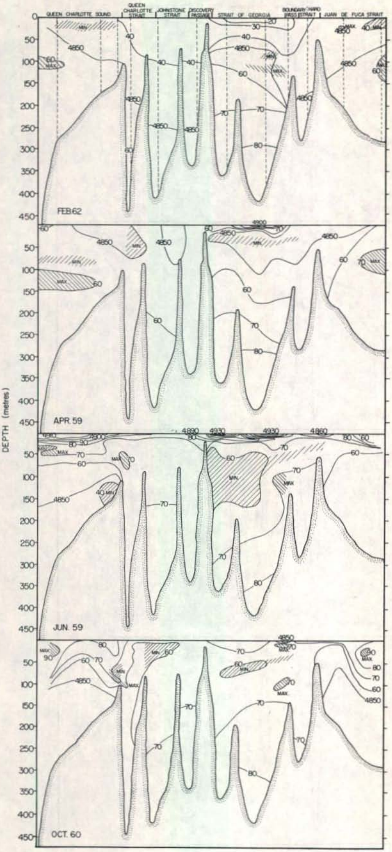

QUEEN CHARLOTTE SOUND
QUEEN CHARLOTTE STRAIT
JOHNSTONE STRAIT
DISCOVERY PASSAGE
STRAIT OF GEORGIA
BOUNDARY PASS
HARO STRAIT
JUAN DE FUCA STRAIT
DEPTH (metres)
0
50
100
150
200
250
300
350
400
450
FEB.62
APR. 59
JUN. 59
OCT. 60
MAX
MIN
4850
4890
4900
4930
4860
20
30
40
60
70
80
90

Figure 20

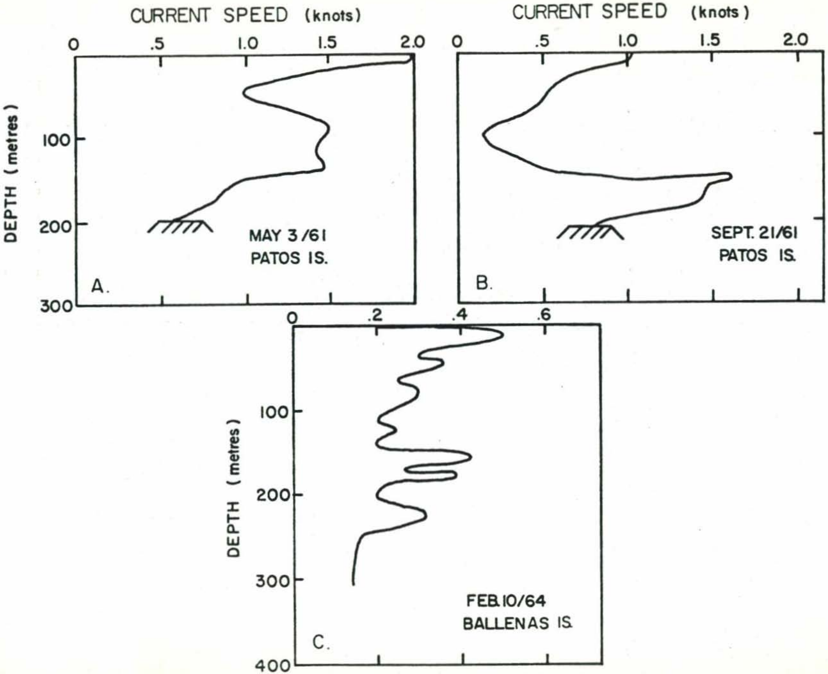

CURRENT SPEED (knots)
0
.5
1.0
1.5
2.0
DEPTH (metres)
100
200
300
MAY 3/61
PATOS IS.
A.
CURRENT SPEED (knots)
0
.5
1.0
1.5
2.0
SEPT. 21/61
PATOS IS.
B.
0
.2
.4
.6
DEPTH (metres)
100
200
300
400
FEB.10/64
BALLENAS IS.
C.

Figure 21

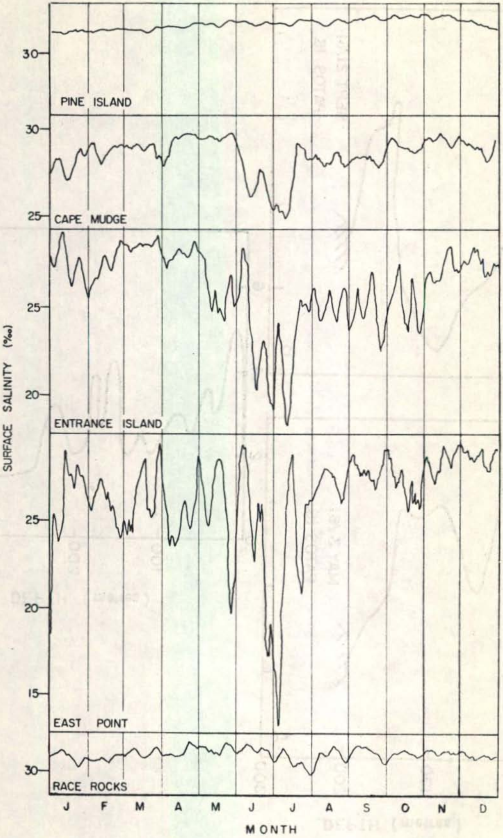

PINE ISLAND
CAPE MUDGE
ENTRANCE ISLAND
EAST POINT
RACE ROCKS
SURFACE SALINITY (‰)
30
30
25
25
20
25
20
15
30
J
F
M
A
M
J
J
A
S
O
N
D
MONTH

Figure 22

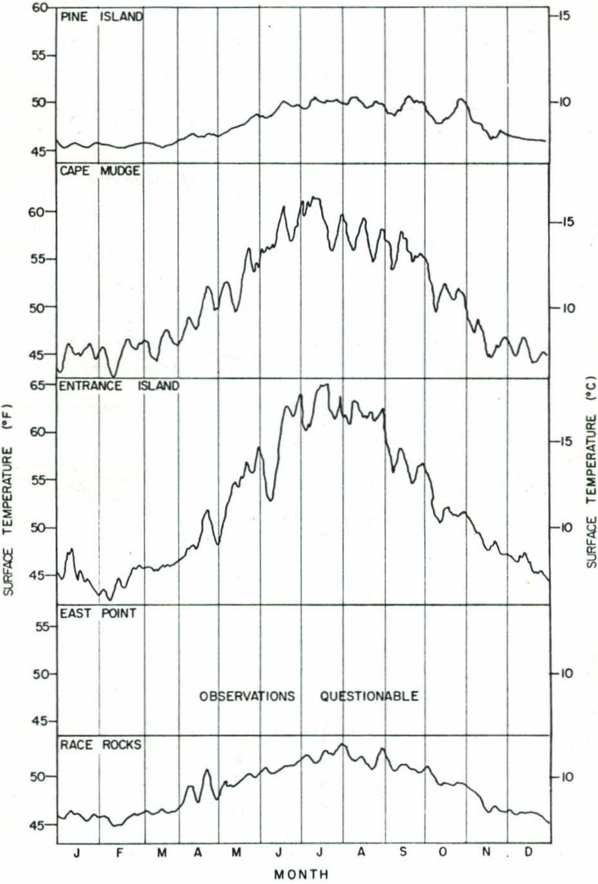

PINE ISLAND
CAPE MUDGE
ENTRANCE ISLAND
EAST POINT
OBSERVATIONS QUESTIONABLE
RACE ROCKS
SURFACE TEMPERATURE (°F)
SURFACE TEMPERATURE (°C)
60
55
50
45
65
15
10
J F M A M J J A S O N D
MONTH

Figure 23

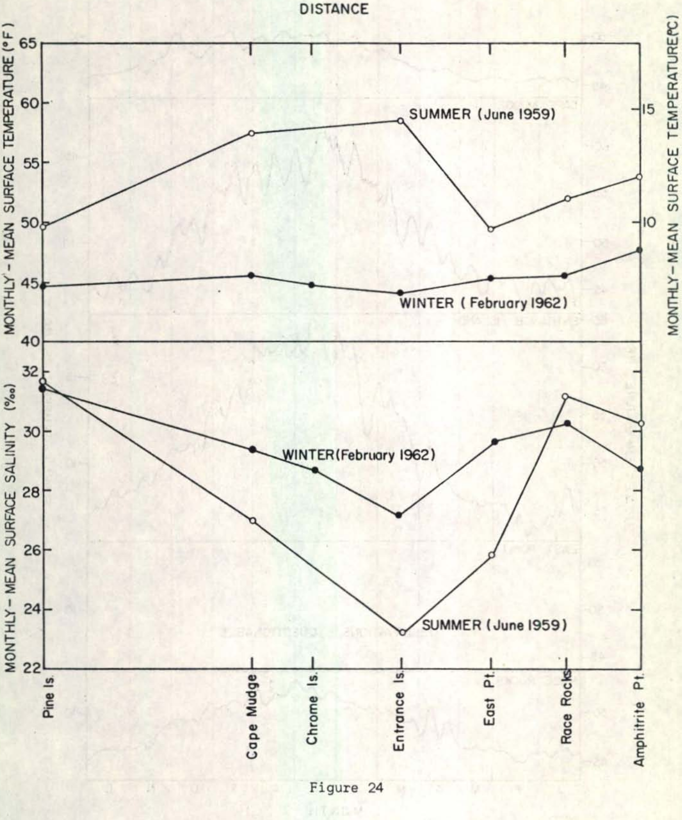

DISTANCE
MONTHLY-MEAN SURFACE TEMPERATURE (°F)
MONTHLY-MEAN SURFACE TEMPERATURE(°C)
65
60
55
50
45
40
15
10
SUMMER (June 1959)
WINTER (February 1962)
MONTHLY-MEAN SURFACE SALINITY (‰)
32
30
28
26
24
22
WINTER(February 1962)
SUMMER (June 1959)
Pine Is.
Cape Mudge
Chrome Is.
Entrance Is.
East Pt.
Race Rocks
Amphitrite Pt.

Figure 24

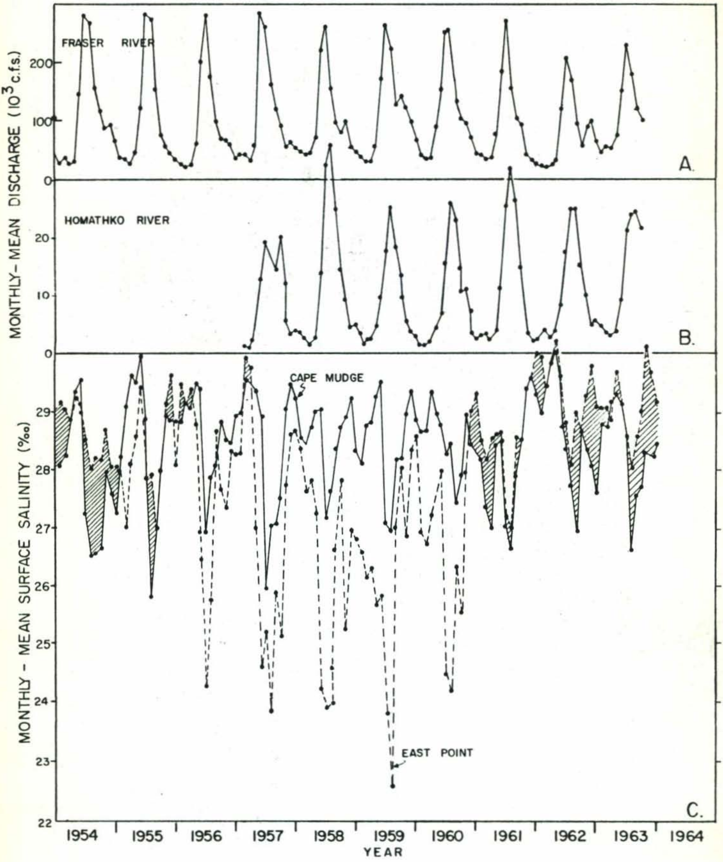

FRASER RIVER
A.
HOMATHKO RIVER
B.
CAPE MUDGE
EAST POINT
C.
MONTHLY-MEAN DISCHARGE (10^3 c.f.s.)
MONTHLY - MEAN SURFACE SALINITY (‰)
0
100
200
0
10
20
22
23
24
25
26
27
28
29
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
YEAR

Figure 25

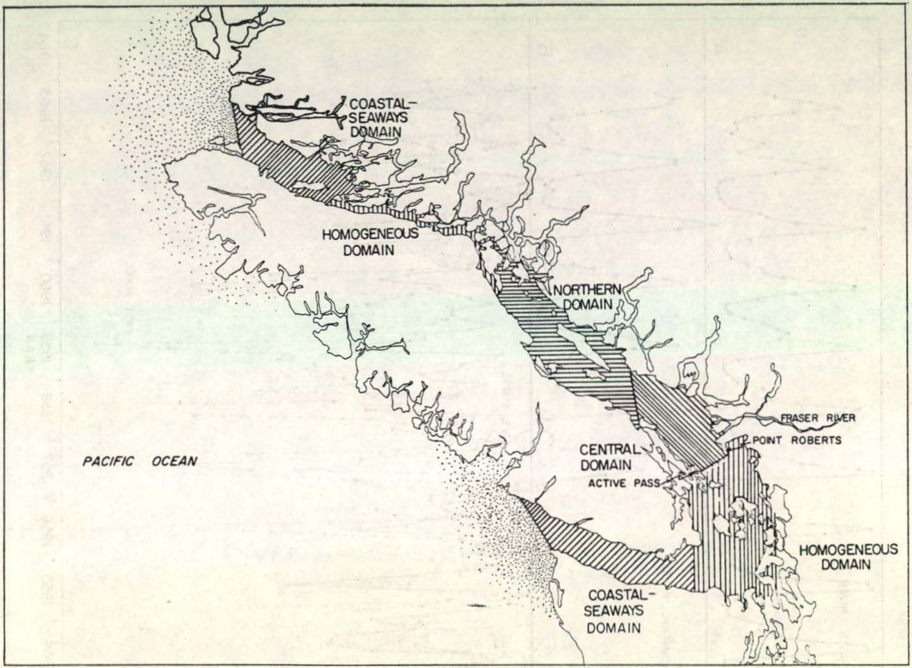

COASTAL-
SEAWAYS
DOMAIN
HOMOGENEOUS
DOMAIN
NORTHERN
DOMAIN
FRASER RIVER
POINT ROBERTS
CENTRAL
DOMAIN
ACTIVE PASS
PACIFIC OCEAN
HOMOGENEOUS
DOMAIN
COASTAL-
SEAWAYS
DOMAIN

Figure 26