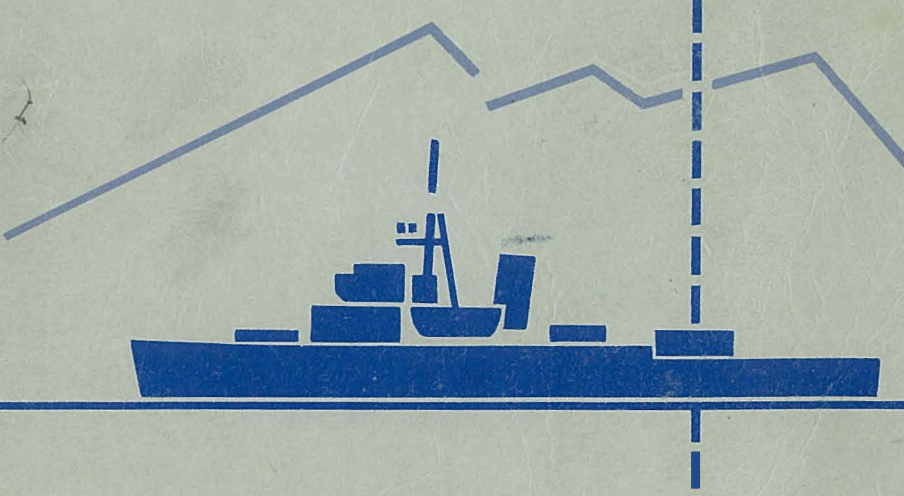
Bulletin No. 156

Physical Oceanography of Dixon Entrance, British Columbia

by P. B. Crean



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PHYSICAL OCEANOGRAPHY
OF DIXON ENTRANCE,
BRITISH COLUMBIA

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Fisheries Research Board of Canada
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ABSTRACT

Annual cycles in the long-term averages of monthly mean precipitation, runoff, surface salinity, winds, Ekman transport, sea level, net heat transfer at the sea surface, and sea surface temperature have been enumerated. The major features of seasonal behaviour pertinent to the oceanography of Dixon Entrance may be summarized as follows. Spring (April–May) is characterized by decreasing monthly mean southeast winds, onshore components of Ekman transport, and sea levels. The runoff increases. Net heat transfer at the sea surface is small. In summer (June through August) monthly mean southeast winds, onshore components of Ekman transport, and sea levels are minimal. The runoff reaches a maximum in June. There is a net heat gain at the sea surface. In autumn (September–October) monthly mean southeast winds, onshore components of Ekman transport, and sea levels increase. There is a secondary maximum in runoff. Net heat transfer at the sea surface is small. In winter (November through March) monthly mean components of southeast winds, onshore components of Ekman transport, and sea levels attain maximal values. The runoff is low. There is a net heat loss at the sea surface.

Oceanographic data appropriate to each of the four seasons show the persistence of three basic regimes of surface salinity. The lowest salinities are associated with Clarence Strait, the northern shores, and the west central part of Dixon Entrance. An irregular area of higher-salinity water generally occurs near Hecate Strait. Higher salinities again are found across the seaward approaches. This trichotomy is most pronounced in August. There is a persistent halocline, which rises in the spring to minimal depths in summer, sinking in the autumn to attain maximal depths in winter.

In summer and autumn there is a marked thermocline coincident with the halocline. A weak temperature inversion in the winter halocline gives way to near isothermal conditions in the spring.

The effects of tides, winds, runoff, and heat transfer are examined and discussed.

Observations in a tidal hydraulic model and in nature show that the dominant feature of the net tidal circulation is a cyclonic vortex which results from the meeting of the Dixon Entrance and Queen Charlotte Sound tides in northern Hecate Strait.

Long-term monthly mean Ekman transport vectors in the offshore waters from Washington to Alaska indicate the importance of the convergence of oceanic surface water, associated with winter southeast winds, in the waters to the north, including Dixon Entrance. (As shown by these vectors, the divergence of coastal waters associated with northwest winds is relatively insignificant.) The "relative" current occasioned by the convergence moves northward along the eastern shores of Hecate Strait and, given a sufficiently well-developed system of

southeast winds, seaward along the northern shores of Dixon Entrance. If the southeast winds are weak, the "relative" current finds primary egress through Clarence Strait.

The main source of brackish water is Chatham Sound. This water moves seaward through Clarence Strait and Dixon Entrance. Flushing is strong in early summer when the final relaxation of the convergence of the previous winter acts in concert with the major efflux of fresh water in spring to produce a marked discharge of brackish water from Dixon Entrance. Strong flushing is also occasioned by the "relative" current in winter.

The growth and decay of the thermocline is generally similar throughout most of Dixon Entrance. Two important advective effects modify the heat budget. The first of these is the intrusion of cool water at depth in summer resulting from the relaxation of the winter convergence. The second is the northerly advection of warm water by the "relative" current in winter.

The above considerations are summarized in a general model of oceanographic behaviour.

INTRODUCTION

The oceanography of the coastal waters of British Columbia is contingent on oceanic processes and on the local effects of winds, tides, runoff, heat flux at the sea surface, and coastal morphology. In this study the major oceanographic characteristics of Dixon Entrance are examined and the primary causal sequences establishing these characteristics are discussed and elaborated into a general model of seasonal oceanographic behaviour.

Previous Studies

In discussing previous studies on the coastal waters of British Columbia pertinent to the present investigation, it is useful to distinguish between the more extensive surveys concerned with defining the attributes of the adjacent ocean, and local studies of particular regions.

Considering initially the dominant oceanographic features of the adjacent ocean, the subarctic Pacific, it has been shown that the vertical distribution of salinity is characterized by three distinct layers or "zones" (Doe, 1955; Tully and Barber, 1960). Major seasonal changes, with respect to both salinity and temperature, are largely confined to the upper zone, which is approximately 100 m in depth. Below this, a permanent halocline extends for another 100 m and involves a salinity increase of about 1‰. In the lower zone, both temperature and salinity change gradually with depth to the bottom. In the upper zone the temperature distribution is characterized by the growth and decay of the seasonal thermocline (Tully and Giovando, 1963). From mid-April through mid-September, there is a net heat gain which results in the formation of transient thermoclines. The water associated with these thermoclines is mixed downward, through an otherwise isothermal layer, to the limit of wind mixing. There it accumulates to form the seasonal thermocline. Throughout the remainder of the year there is a net heat loss; the seasonal thermocline weakens until the isothermal layer above the halocline is again established by about February.

The mean monthly distributions of temperature in the Gulf of Alaska and in the northeast Pacific over the period 1941–52 have been described by Robinson (1957).

The coastal region as defined by Doe (1955) included all surface waters subject to appreciable dilution by land drainage. The western limit of this region was given approximately by the 32.5‰ surface salinity isopleth. Within this coastal region, the distribution of salinity in the upper zone is considerably less uniform than that in the offshore region. Substantial gradients of salinity are encountered even in late winter and spring when virtual homogeneity characterizes the upper zone in the offshore waters.

Currents in both coastal and offshore regions were found to be persistently northward, and, though generally weak and sinuous, better developed during the winter than in summer (Doe, 1955). Evidence of upwelling was noted off the coast of Vancouver Island in summer, and attributed to the influence of northwesterly winds.

Local studies, of interest to the present investigation, include the following. On the basis of drift experiments, the presence of a net northward flow through Hecate Strait, and of a seasonal movement of oceanic water into Dixon Entrance, has been concluded by Thompson and Van Cleve (1936). Haight (1926) has inferred a net northward flow through Clarence Strait.

A well-developed winter northward flow along the west coast of Vancouver Island (Lane, 1963), and its entry into Queen Charlotte Sound (Barber, 1957) have been reported. Marked changes in the salinity and temperature of the deep water in Queen Charlotte Sound have been attributed to the depression of the oceanic halocline along the coast during winter southeast winds, while in summer, light, or northwest winds, and strong runoff are associated with a rise in the coastal halocline (Barber, 1957). Similar changes in the deep water have been observed in the Strait of Georgia by Waldichuk (1957) and in the Juan de Fuca Strait by Herlinveaux and Tully (1961). In June, marked tongues of low-salinity water move seaward from Queen Charlotte Sound and Dixon Entrance (Barber, 1957; Favorite, 1961). The net velocity at 10 m depth associated with the tongue from Queen Charlotte Sound was about 20 km per tidal day. In contrast, at a depth of 125 m there was a shoreward velocity of about 15 km per tidal day. A complete renewal of the bottom water could therefore occur in a period of about 2 weeks (Barber, 1957).

Seasonal changes in the distribution of fresh water in, and brackish outflow from, Chatham Sound (Fig. 1) have been described by Trites (1956). The dominant feature is the spring freshet of the Nass and Skeena, at which time there is a strong brackish discharge between all the islands bordering the Sound. The average heat budget in the vicinity of Triple Island over a period of several years has been determined by Tabata (1958). Advective inferences from this heat budget include a deep intrusion of oceanic water in summer, and wind drifts moving northward from Hecate Strait into Dixon Entrance in winter.

Waldichuk (1964) has shown a marked seasonal cycle in monthly mean sea levels at Prince Rupert, and attributed fluctuations in mean sea level primarily to changes in atmospheric pressure and to the dynamic influence of winds. A similar conclusion appears implicit in the work of Saur (1962).

The strong coherence of winter day-to-day fluctuations in mean sea level at four locations along a stretch of the Alaska coast, extending some 400 naut. miles northward from Ketchikan to Yakutat, has been reported by Groves (1957). This emphasizes the widespread oceanic origin of these fluctuations in the northern coastal seaways. The influence of winds on the sea surface temperature in Dixon Entrance and Hecate Strait has been discussed by Ketchen (1956), Eber (1957), and Stewart et al. (1958).

GEOGRAPHY

Dixon Entrance itself (Fig. 1) is a coastal seaway located on the borders of southeastern Alaska and the northern coast of British Columbia. The western and central parts of Dixon Entrance are bounded to the north by Dall and Prince of Wales islands, and to the south by Graham Island. Three important seaways adjoin the eastern part of Dixon Entrance. To the north, Clarence Strait extends for some 112 miles to its junction with Sumner Strait, which links it to the open ocean. To the south lies Hecate Strait, some 140 miles in length, connected to the open sea by the broad sweep of Queen Charlotte Sound. To the east, separated by an irregular chain of islands, lies Chatham Sound. Eastern Dixon Entrance is thus part of a continuous coastal seaway along the mainland shores.

Throughout the region, coastal lowlands are generally narrow, and frequently eliminated by abrupt ascents to uplands, on both islands and mainland. Prince of

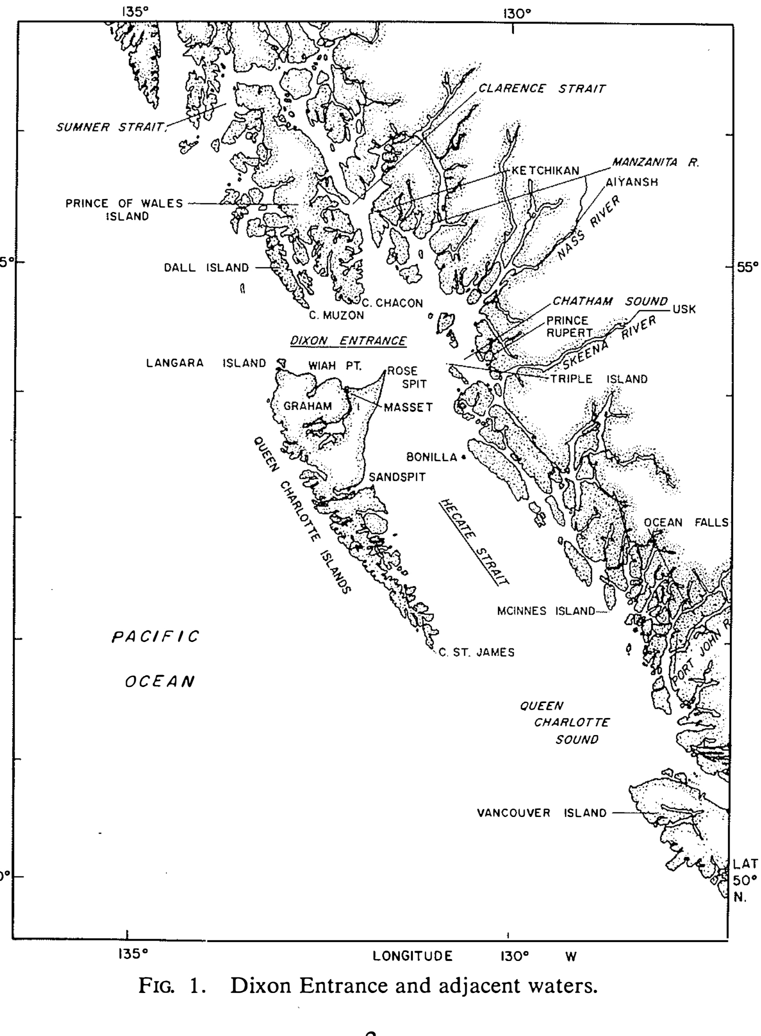

FIG. 1. Dixon Entrance and adjacent waters.

Wales and Dall islands are characterized by mountains ranging from 300–1500 m in elevation. Graham Island constitutes an exception in that its eastern part is relatively low lying. The western part of the island comprises the northern section of a mountain chain, 300–1500 m in elevation, which extends the full length of the Queen Charlotte Islands. It is apparent that Dixon Entrance is a gap between the mountain barriers on Dall and Graham islands which give initial check to the oceanic weather systems approaching the coast of Northern British Columbia. The mainland coasts of northern British Columbia and southeastern Alaska are cleft by numerous fjords cutting back into the high mountains of the Coast Range. Two major rivers, the Skeena and Nass, drain into Chatham Sound.

Bathymetry

The major bathymetric features pertinent to the present study may be summarized as follows, (Fig. 2). The mouth of Dixon Entrance is divided into two channels (350–400 m in depth) by Learmonth Bank, which rises to within some 35 m of the surface. These channels join to form the deep channel of Dixon Entrance. From the mouth, the bottom of this deep channel slopes gradually upward to a sill, some 270 m in depth, south of Cape Chacon. From there, the depths increase as the channel swings northward into the deep trench of Clarence Strait.

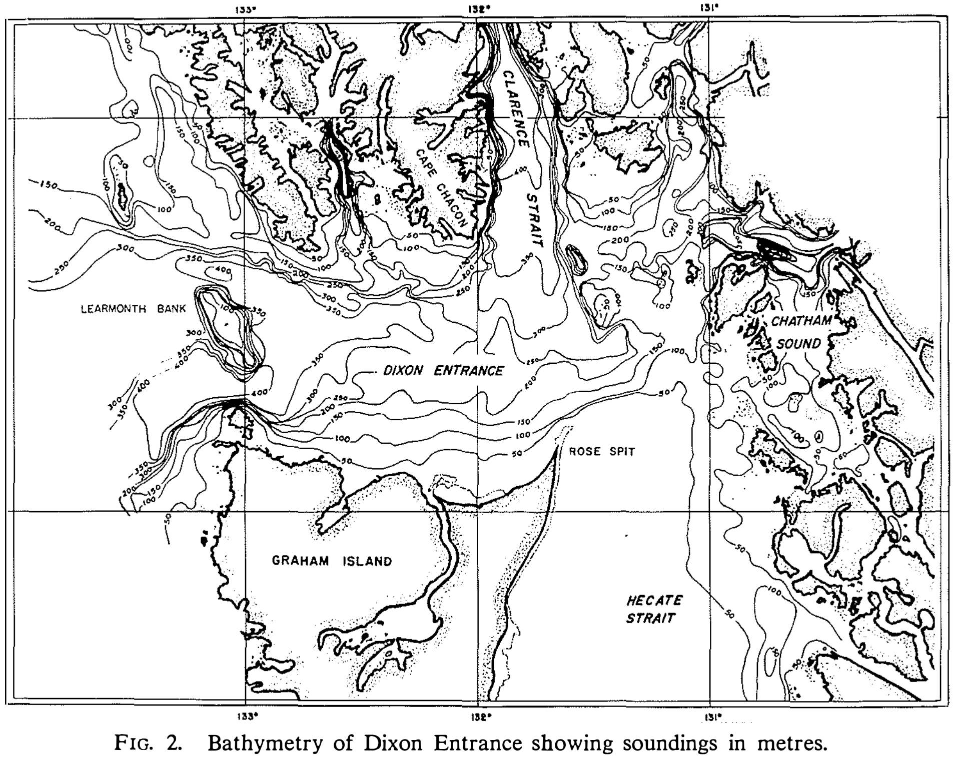

Fig. 2. Bathymetry of Dixon Entrance showing soundings in metres.

Chatham Sound is separated from Dixon Entrance by a submarine ridge, supporting a chain of shoals and islands. At its northern end, this ridge is broken by a deep, irregular channel, which extends westward to join the deep trench of Clarence Strait. The effective sill depth in this channel is about 170 m.

The northern part of Hecate Strait consists largely of a shallow bank less than 50 m in depth. Near, and approximately parallel to the eastern shores, a narrow channel of minimum depth 82 m affords the deepest passage between Queen Charlotte Sound and Dixon Entrance. The southern end of Hecate Strait is considerably broader and deeper. Thus, there occurs a marked reduction in cross-sectional area from south to north along the strait.

Clarence Strait is long, narrow, and about 400 m deep over the greater part of its length. At its northern end, the channel divides and the bottom topography is complex. For present purposes it is sufficient to note that these connections with Sumner Strait have a total width of about 5 miles, with depths of about 30 m, but include a narrow channel about 70 m deep.

Heuristic Approach

In recent years, the advances which have taken place in the acquisition and analysis of oceanographic data strongly emphasize the necessity of considering carefully the length and time scales of the phenomena under investigation, with respect to both the density and frequency of observations over the region of interest (Stommel, 1963; Pickard, 1963). In view of the scarcity of data available for the present study, it is thus desirable to comment on the heuristic approach employed.

Use has been made of the long-term averages of available monthly mean data to establish characteristic annual cycles. Based on these cycles, oceanographic behaviour is inferred and shown to be consistent with the available data, though these are insufficient in themselves to yield a simple deductive model. The results presented are thus, in some instances, contingent on analogical inference.

Two different types of data have been employed in this study. The first type consists of time-series data, usually obtained on a daily basis, which have been accumulated over a period of years and include information on both causal features, such as weather and river discharge, and on responsive features, such as sea level, Ekman transport, surface temperatures and salinities, of the overall system.

The second type comprises data obtained by conventional "synoptic" oceanographic surveys. Most of these data were obtained in the course of the Hecate Surveys (Pacific Oceanographic Group, MS, 1954, MS, 1955) and the Monitor Survey, (Crean et al., MS, 1962a,b). In addition a special detailed survey of Dixon Entrance was made in September–October 1962 (Crean et al., MS, 1963). The cruise plans are illustrated in Fig. 3. These data have been augmented by occasional observations in Dixon Entrance made in other surveys. Such ancillary data are introduced in context.

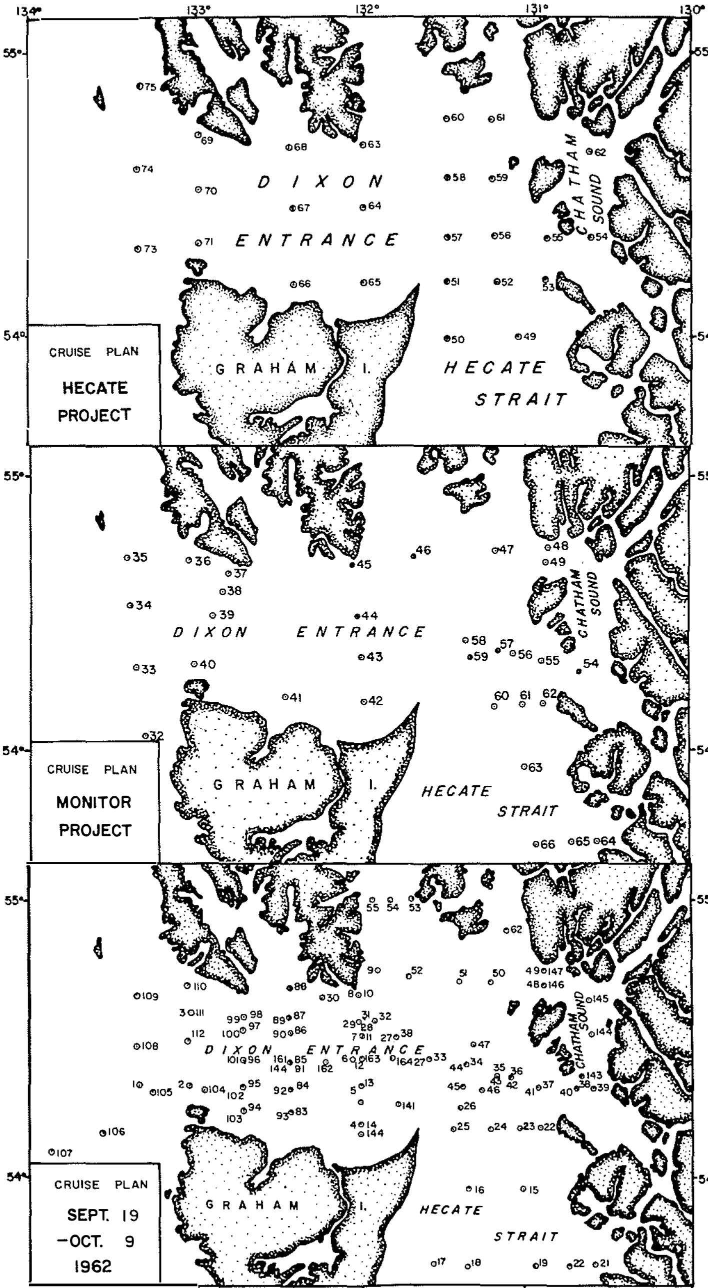

FIG. 3. Locations of oceanographic stations for the five Hecate (May 11–13, 1954; July 6–15, 1954; August 22–23, 1954; February 10–13, 1955; April 14–15, 1955), four Monitor (July 31 to August 3, 1961; October 6–13, 1961; January 18–21, 1962; March 15–17, 1962) and September 19 to October 9, 1962 surveys.

The two main bodies of cruise data, the Hecate and Monitor data (see below) excel, respectively, in geographical coverage of the region and in the frequency of station data at particular locations over an annual cycle. Thus, the Hecate data, augmented by a single special cruise in September–October 1962, have been used to present the general characteristics of the salinity and temperature distributions in Dixon Entrance for each of the four seasons. Special attention is paid to comparisons with the long-term monthly means of surface salinities and temperatures as observed at various locations in the vicinity.

Observations made in a tidal hydraulic model of the Dixon Entrance, Hecate Strait, and Queen Charlotte Sound region have also been introduced.

TIME-SERIES DATA

The data of this type, significant to the oceanography of Dixon Entrance, may conveniently be considered in three natural groupings. The first group includes precipitation, river discharge, and surface salinities; the second group includes winds, the components of Ekman transport in the offshore waters, and sea level at Prince Rupert; and the third includes heat transfer at the air–sea interface and sea surface temperatures.

Descriptive of mean conditions and the degree of variability, these data are presented, where possible, as long-term averages (solid lines) and standard deviations (dotted lines) of the monthly means.

PRECIPITATION

The geographical distribution of the mean annual precipitation over British Columbia (B.C. Natural Resources Conference, 1956) together with major drainage areas, are shown in Fig. 4. The heaviest precipitation is associated with the coastal drainage area, which consists primarily of the exposed seaward slopes of the Coast Mountains. The annual cycles of precipitation in this area may be described using the records of precipitation as observed at three different representative locations: Masset, Prince Rupert, and Ocean Falls.

Masset is located on the northern shores of Graham Island (Fig. 4) and lies effectively in the rain shadow of the island's west coast mountains. The mean annual precipitation is 56 inches (Kendrew and Kerr, 1955). The mean monthly precipitation averaged over the years 1956–63 (Fig. 5) is characterized by an annual cycle of relatively small amplitude, with maximal precipitation occurring during the winter months.

Prince Rupert is located on an island immediately adjacent to the mainland coast, and hence reflects to some extent the influence of the coast mountains. The mean annual precipitation is 96 inches (Kendrew and Kerr, 1955). The annual cycle in mean monthly precipitation, averaged over the years 1956–63 displays a greater amplitude than that observed at Masset, though again with maximal precipitation during the winter months.

Ocean Falls is located at the head of an inlet extending some 30 miles into the coast mountains. The mean annual rainfall is 166 inches. The mean monthly rainfall averaged over the years 1956–63 is characterized by an annual cycle of much greater amplitude than that at either Masset or Prince Rupert, though again maximal precipitation occurs during the winter months.

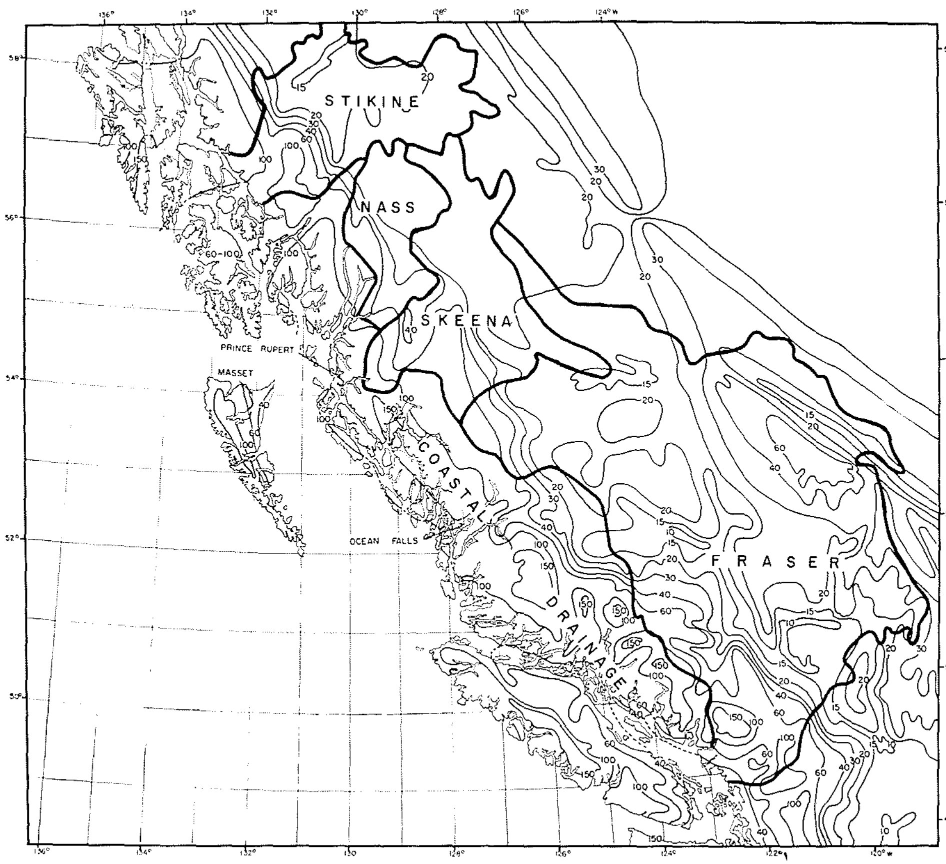

FIG. 4. Distribution of mean annual precipitation in inches, and major drainage areas. (B.C. Natural Resources Conference, 1956)

It is clear from these considerations that the greatest input of fresh water into these northern coastal seaways, resulting directly from local precipitation on the land during the months of October, November, and December, must occur into the articulated complex of channels that lie along the eastern boundary of Hecate Strait. It has, however, been noted by Kendrew and Kerr (1955) that from November to March the bulk of the precipitation is generally retained as snow almost down to sea level on the mountain slopes. It may thus be inferred that the maximum direct freshwater contribution of this type will be released into the coastal seaways in October.

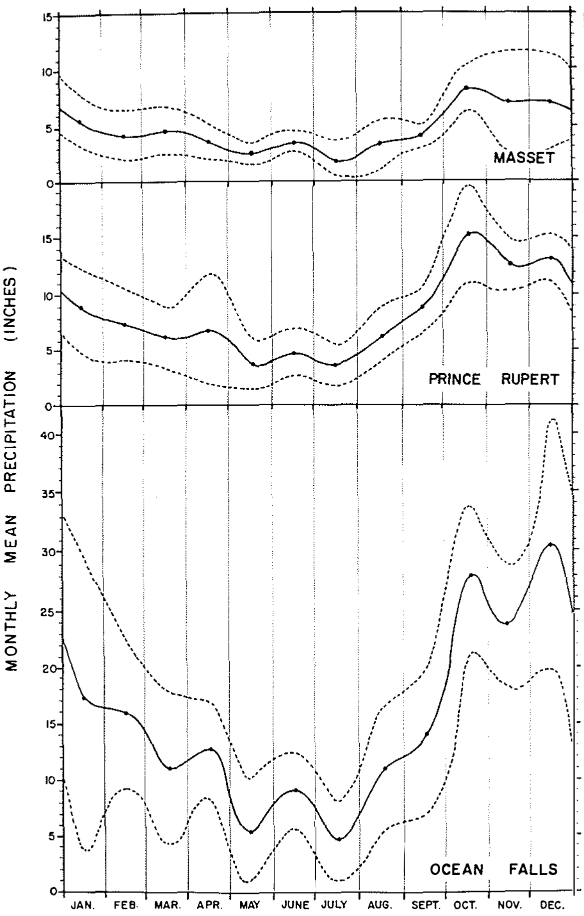

FIG. 5. Monthly mean precipitation in inches and standard deviations at Masset, Prince Rupert, and Ocean Falls, 1956 through 1963.

RIVER RUNOFF

Discharge from rivers in the northern coastal region of British Columbia may be expected to display an annual cycle in monthly mean discharge dominated by two maxima associated, respectively, with the heavy precipitation of early winter and with the spring thaw. The relative magnitudes of these maxima will depend on the location and average elevation of the drainage basin, and also on the annual cycle of monthly precipitation appropriate to that particular area.

Two large rivers of major consequence, the Skeena and the Nass, drain into this northern coastal region. The combined drainage area (Fig. 4) of these rivers is about 27,500 sq miles and is located in the mountainous hinterland. Discharge records of these rivers are maintained from gauge readings on the Skeena River at Usk, 90 miles upstream, and on the Nass at Aiyansh, 45 miles upstream from the mouth. The average monthly mean flows over the years 1953–62 for the Skeena

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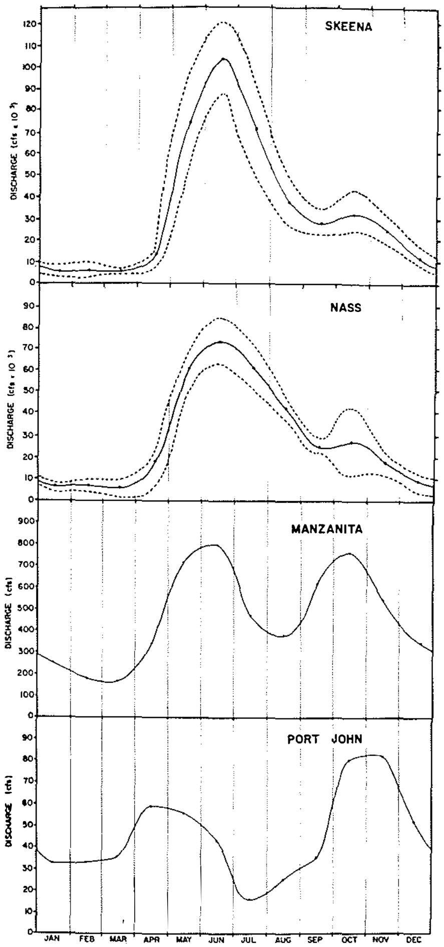
and 1956–62 for the Nass (Canada Department of Northern Affairs, personal communication) are shown in Fig. 6. The annual cycles are clearly dominated in June by the major peaks associated with the spring thaw. A weak secondary peak in October is attributable to the high precipitation of that month as described above. The location of the gauges some distance upstream, not being affected by much of the heavy precipitation near the coast, must contribute to some extent to the apparent weakness of this secondary maximum.

Along the coast there are many small local rivers which, in the aggregate, account for much of the freshwater input to the northern coastal seaways. As



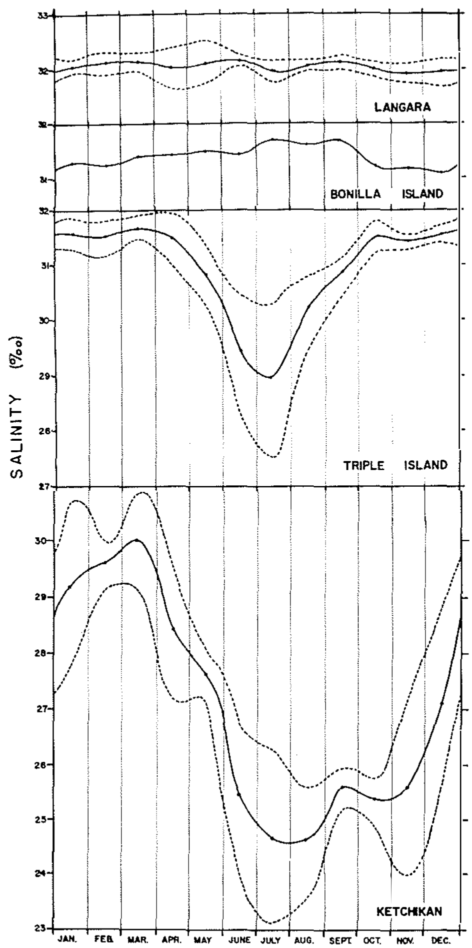


FIG. 6. *(Left)* Grand means and standard deviations of monthly mean river discharges of the Skeena River, 1953 through 1962, the Nass, 1956 through 1962, and grand means of the monthly mean river discharges of the Manzanita River, 1948 through 1953, and the Port John, 1948 through 1952.

FIG. 7. *(Right)* Grand means and standard deviations of monthly mean surface salinities at Langara, Bonilla, Triple Island, 1950 through 1959, and Ketchikan, 1951 through 1960.

examples, the annual cycles in monthly mean discharge for two of these rivers, the Manzanita and the Port John (Fig. 1) averaged over the years 1948–52 (United States Department of the Interior, personal communication; Canada Department of Northern Affairs, 1952) are illustrated in Fig. 6. In the case of the Manzanita, the cycle is clearly dominated by peak discharges of comparable magnitude in June and October. The Port John River shows the greatest monthly mean discharges in October–November and in April–May.

Surface Salinities

The marked variations in runoff which occur over the year may be expected to result in changes in the distribution of surface salinity throughout the coastal waters. Daily observations of surface salinity have been made at a number of locations along the British Columbia coast (Hollister, MS, 1960, MS, 1964; United States Department of Commerce, 1962). It has been shown that, over the year, the monthly mean salinities at these various locations conform to three major classifications (Pickard and McLeod, 1953). The first of these includes those stations where the changes in monthly mean salinity are small because the dominant influence is oceanic. The second classification applies to those locations dominated by a marked salinity minimum in summer, associated with the release of water stored as snow during the winter. Lastly, certain locations are characterized by a marked salinity minimum in winter, associated with direct runoff resulting from the heavy winter precipitation.

The long-term average of monthly means of surface salinity at four locations in the vicinity of Dixon Entrance is shown in Fig. 7. At Langara, the long-term monthly mean salinities averaged over the years 1953–62 show little change in magnitude throughout the year. Therefore, it may be inferred that this location is dominated by oceanic influence.

At Bonilla Island, observations are available only for the years 1961–63. Again there is relatively little change in salinity through the year, though there is some evidence of a weak salinity minimum in winter. Salinities are persistently less than those at Langara. Again there is evidence of oceanic influence.

The long-term average of monthly mean salinities at Triple Island over the years 1953–62 shows a strong minimum which is clearly related to the peak discharge of the Skeena River in June (Fig. 6). Throughout the remainder of the year, October through March, salinities are similar to those at Bonilla Island.

At Ketchikan, the average monthly mean salinities during the years 1951 through 1960 differ markedly from those at the three previous locations. Month for month, the salinities are much less. The annual cycle is characterized by minimal values from June to November. It would thus appear that salinities at this location are strongly affected by the runoff maxima associated, respectively, with snow melt and with local precipitation.

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WINDS

The distribution of winds in the coastal region of British Columbia depends primarily on the orographic modification of the major wind systems originating over the North Pacific. It is thus convenient to consider the oceanic and the inshore winds separately.

OCEANIC WINDS

The following discussion is based on a review of the climatology of British Columbia by Kendrew and Kerr (1955).

The oceanic winds are determined primarily by the field of barometric pressure which is dominated, in winter and in summer respectively, by characteristic mean surface pressure distributions. The mean winter distribution, generally extant from October to April, is illustrated in Fig. 8a. It is apparent from the closeness and orientation of the isobars that winds are relatively strong, and generally from directions between south and west. Along the coast, there is a high proportion of southeasterlies. The mean summer distribution (Fig. 8b) is usually dominant from May to September. Winds are lighter, and predominantly from directions between north and west. It is apparent that in winter the proportion and intensity of southeasterlies should be greater over the northern coastal region of

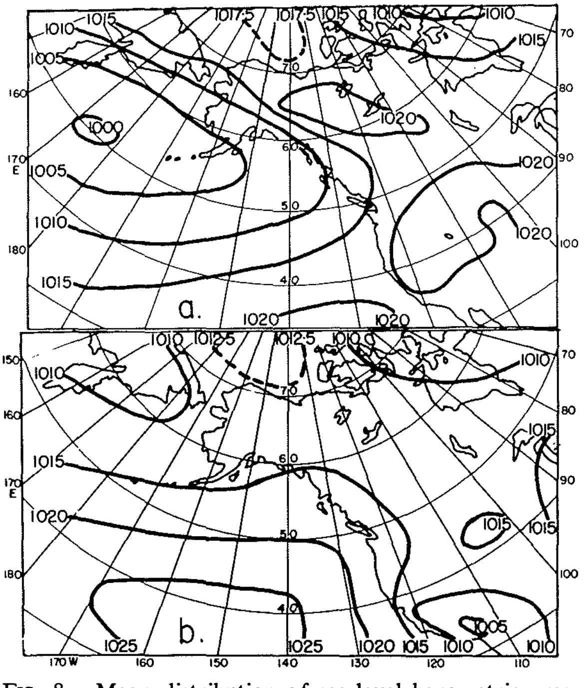

FIG. 8. Mean distribution of sea-level barometric pressure in millibars over the eastern North Pacific Ocean in (a) January, (b) July. (Kendrew and Kerr, 1958)

British Columbia than to the south. In summer, the proportion and intensity of northwesterlies should be greater in the south than in the north.

The major pressure systems which have been described above are mean distributions. It must be noted, however, that the actual pressure systems are changing persistently with respect to both intensity and position. These short-term changes are often the immediate cause of local weather along the coast. In particular, the strong depressions moving onto the coast in winter are both frequent and relatively slow moving, often coming in a series which may hold sway for a fortnight or more.

INSHORE WINDS

The directional dependence and the seasonal cycles of winds in Dixon Entrance and Hecate Strait are now discussed in terms of wind data from the four instrumented observing stations in the northern coastal region of British Columbia: Prince Rupert, Sandspit, McInnes Island, and Cape St. James (Canada Department of Transport, 1954–64, personal communications). It has been noted above that the dominant winds are parallel to the axis of the coastal mountain barriers which lie in a general southeast–northwest direction. Hence, illustrative of the mean annual cycles at each of the four locations, the 10-year averages of the monthly total mileages of wind are shown resolved along the southeast–northwest axis (Fig. 9).

The station at Prince Rupert occupies a somewhat sheltered location. Throughout the year, the southeast component clearly dominates, but shows a marked annual cycle. The wind mileages increase rapidly from September to maximal values in October, November, and December. From January on, there occurs a gradual decrease in wind mileage to a minimum in July.

Though Sandspit occupies a more exposed location, the wind mileages are considerably less than at Prince Rupert. The southeast component is still dominant throughout the year. The monthly mean mileages show an annual cycle similar to that at Prince Rupert, though the increase from September to October is more gradual than that at the latter location.

McInnes Island is located near the foot of the Coast Mountains, with a full exposure to the southeast. This station probably offers the best indication of winds in Hecate Strait (Walker, 1954, personal communication). The southeast component clearly dominates, except in July when a weak northwest component is apparent. The amplitude of the annual cycle is greater than at either Prince Rupert or Sandspit.

Cape St. James is located at the southern end of the mountain barrier which extends along the west coasts of the Queen Charlotte Islands. The cycle of winds at this location is dominated by strong components of northwest wind in summer, and thus differs markedly from those at the other three locations. This is probably attributable to the effect of the mountain barrier, which will tend to deflect winds into the direction parallel to its own northwesterly axis, and thereby increase the

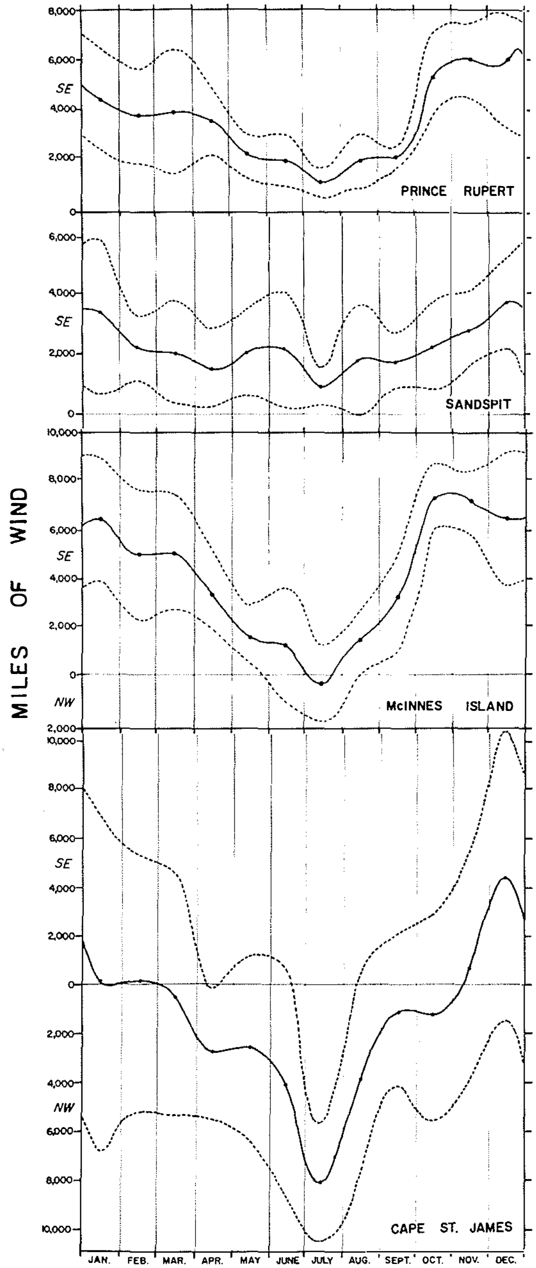

FIG. 9. Grand means and standard deviations of monthly total miles of wind resolved along the southeast axis at Prince Rupert, 1954 through 1962, Sandspit, 1955 through 1964, McInnes Island, 1955 through 1963, and Cape St. James, 1955 through 1963.

proportion of winds from this direction. A contributory factor to the relatively high mileages may be the location of the anemometer which is on a promontory 89 m above mean sea level.

Synoptic estimates of winds are also available for three locations in the immediate vicinity of Dixon Entrance—Langara, Masset, and Triple Island. These data (not given here) conform in most respects to the pattern of winds developed above. At Langara, winds from between southwest and southeast predominate throughout the year (Kendrew and Kerr, 1955), a probable consequence of its location near the northern end of the mountains along the west coasts of the Queen Charlotte Islands. In summer there is also a high proportion of westerlies at this location. This is consistent with the mean summer orientation of the isobars shown in Fig. 8b.

Ekman Transport

Using the monthly mean distributions of barometric pressure, Fofonoff and Dobson (MS, 1963) calculated the monthly mean meridional and zonal components of Ekman transport for an array of locations in the North Pacific Ocean. The theoretical model employed by Fofonoff (1962) assumes a balance, in the horizontal plane, of Coriolis force and the forces due to pressure and stress gradients. Horizontal accelerations are neglected, and vertical forces are assumed to be in hydrostatic equilibrium. These monthly mean components of Ekman transport are subject to a number of limitations implicit in the assumptions underlying their derivation. For present purposes, it is sufficient to note that they may be regarded as indices of the relative range and frequency of variations applied to the ocean by the atmosphere. Thus, for example, strong winds, highly variable with respect to direction over a given month, will not result in strong monthly mean vectors of Ekman transport.

The average monthly mean resultant vectors of Ekman transport during the years 1950 through 1959, for four different latitudes, off the coasts of Washington, British Columbia, and Alaska are shown in Fig. 10. From May to September, (Fig. 10a), weak offshore components generally predominate at 45 and 50°N lat, weak onshore components at 55 and 60°N lat. In marked contrast are the strong onshore components which are present from October to April (Fig. 10b) and which increase markedly from south to north.

At the location 55°N, 135°W, 70 naut. miles seaward of Dixon Entrance, the seasonal cycle in the intensity of these onshore movements is conveniently illustrated by the long-term monthly mean zonal components of Ekman transport during the years 1950 through 1959, as shown in Fig. 11. There is a rapid decrease in this component from January to March, generally small values from April to September, and a rapid increase in October to maximal values in November, December, and January.

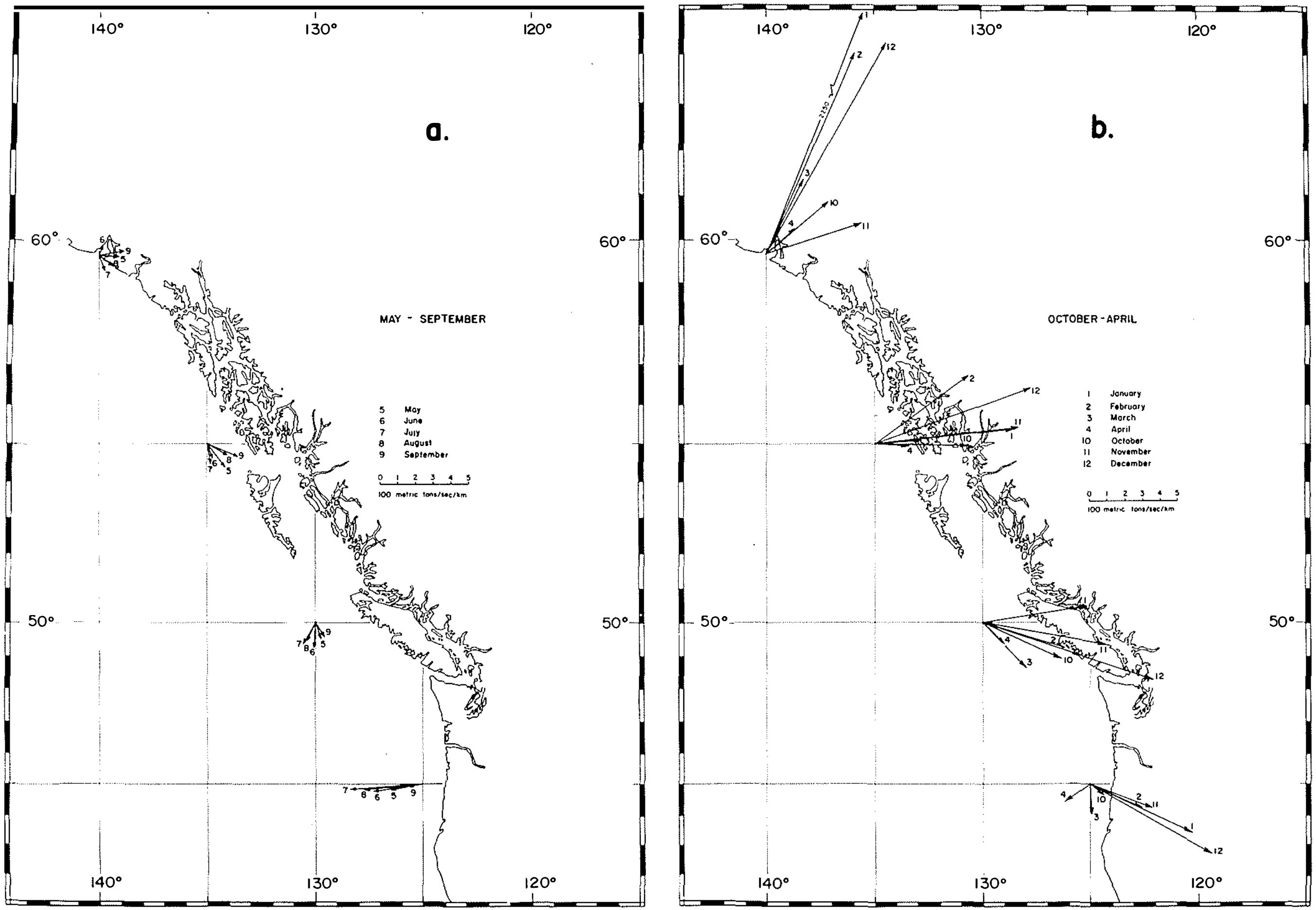

FIG. 10. Grand means of monthly mean vectors of Ekman transport, (a) May through September, (b) October through April, 1950 through 1959.

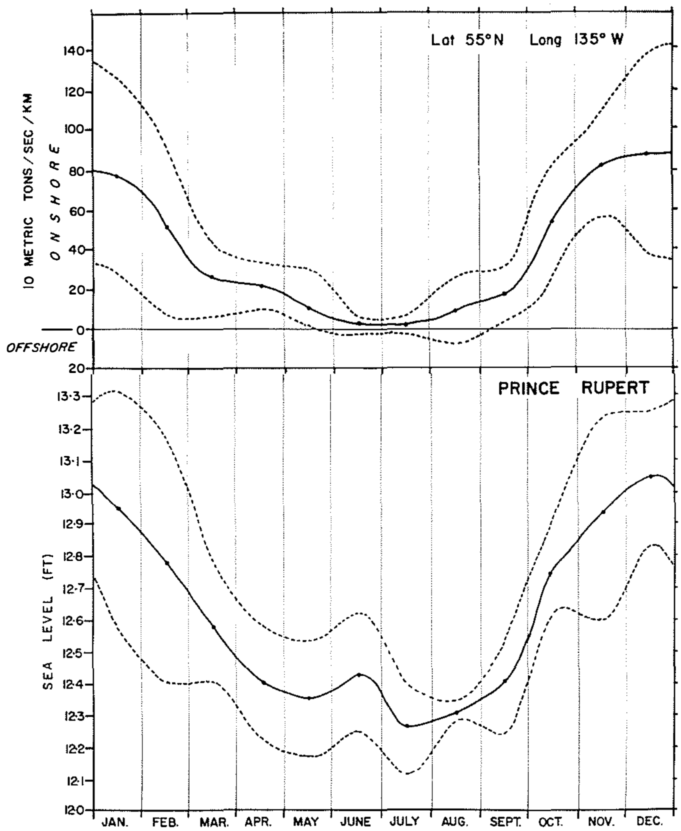

FIG. 11. Grand means and standard deviations of the monthly mean zonal components of Ekman transport at 55 N lat, 135 W long, and grand means and standard deviations of monthly mean sea levels at Prince Rupert, 1950 through 1959.

SEA LEVEL

From a study of monthly mean sea-level fluctuations at Prince Rupert, Waldichuk (1964) concluded that the changes in atmospheric pressure and the dynamic influence of winds were primarily responsible, while steric effects were of relatively little significance. It has been noted by Saur (1962) that the variance of monthly mean sea level at Ketchikan, for each month over a 28-year period, is largely accounted for by direct and indirect effects of atmospheric pressure. A strong coherence in winter sea-level fluctuations at four locations along the coast of southeast Alaska–Ketchikan, Sitka, Skagway, and Yakutat—has been shown by Groves (1957). This is considered to be an indication of their widespread oceanic origin. It has been suggested by Stewart et al. (1958) that the coherence of anomalies in the monthly means of sea water temperatures and sea level along the coast from California to Alaska is due to the common influence of winds.

Low-pressure systems, through the inverted barometer effect, tend to elevate sea level. Such systems moving onto the coast of British Columbia are generally associated with southeast winds, an onshore movement of oceanic surface water and, consequently, a further elevation of sea level. Conversely, high-pressure systems, and associated northwest winds, move water off the coast and tend to depress sea level.

It may thus be inferred that fluctuations in mean sea level afford an approximate index of major wind activity in the coastal waters of British Columbia.

The average monthly mean sea levels at Prince Rupert over the years 1953 through 1962 are shown in Fig. 11. The annual cycle is clearly evident with maximal values occurring during the winter and minimal values during the summer.

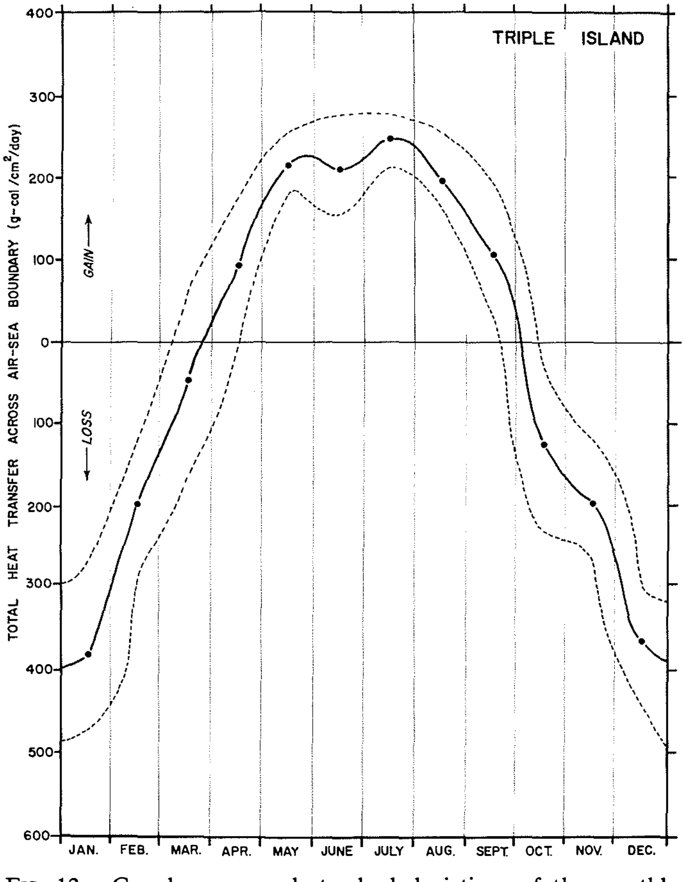

FIG. 12. Grand means and standard deviations of the monthly mean heat transfer at the air-sea interface, at Triple Island, 1947 through 1954. (Tabata, 1958)

Heat Transfer Across the Sea Surface

On the basis of local meteorological and oceanographic data, the average monthly mean net heat transfer across the sea surface, over the years 1947 through 1955, has been determined for the vicinity of Triple Island by Tabata (1958). These data (Fig. 12) show that the heating period generally extends from April to September, with maximal values of heat input to the water from May to August, while the cooling period lasts from October to March, with the greatest heat loss occurring in December and January.

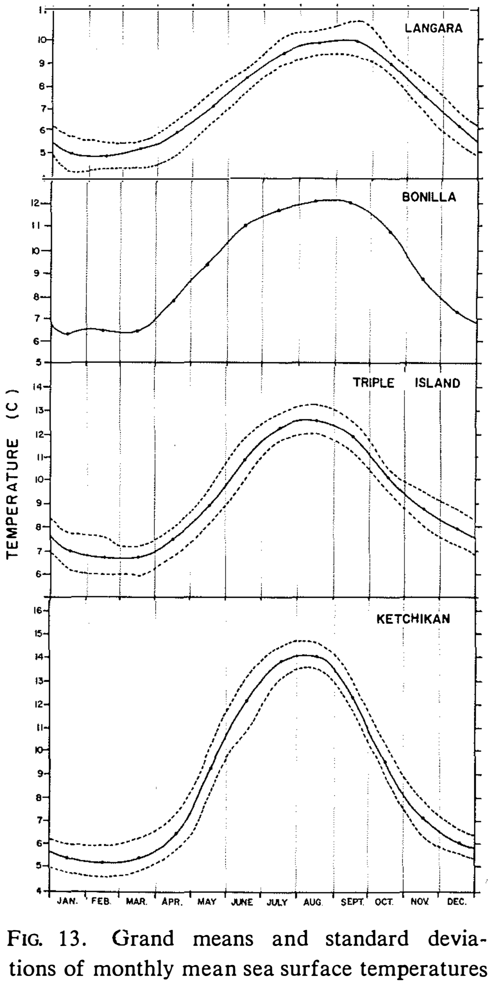

FIG. 13. Grand means and standard deviations of monthly mean sea surface temperatures at Langara, Bonilla, Triple Island, 1950 through 1959, and at Ketchikan, 1951 through 1960.

Surface Temperatures

The long-term averages of the monthly mean temperatures, and standard deviations for Langara, Triple Island, and Ketchikan for the years 1953 through 1962 are shown in Fig. 13. At Bonilla Island the average temperatures over the relatively short period of observations (1959 through 1963) are presented. At all locations, an essentially similar annual cycle is apparent, though differences are encountered between amplitudes and times of the maxima and minima at the various locations. A comparison of these data with the salinity cycles shown in Fig. 7, indicates that the greater temperature maxima are associated with the locations showing the lower salinities in summer. It has been suggested that this is due to the high stability of the surface waters, and consequent reduction in the downward dissipation of heat by eddy diffusion (Pickard and McLeod, 1953).

It is of interest to note that neither the maximum nor the minimum monthly mean surface temperatures correspond to the period of minimal heat transfer. This was attributed by Tabata (1958) to the advection into the region of cold water in summer, and of relatively warm water in winter. The effect is in marked contradistinction to the relation between sea surface temperatures and heat transfer as observed at Station P (Tabata, 1961), where the maximum temperatures occur at the end of the heating, and the minimum temperatures at the end of the cooling period.

Summary

On the basis of the foregoing, the more important aspects of seasonal behaviour affecting Dixon Entrance may be summarized as follows:

Spring (April and May), is characterized by decreasing values of southeast winds, onshore component of Ekman transport, and monthly mean sea level. The freshwater discharge into the region increases rapidly. Heat transfer at the air–sea interface is small.

In summer (June through August), values of southeast winds, onshore components of Ekman transport and mean sea levels are minimal. The discharge of fresh water reaches a peak in June, declining throughout July and August. There is a net heat gain at the sea surface.

In autumn (September and October), values of southeast winds, onshore components of Ekman transport, and monthly mean sea levels all rapidly increase. A secondary maximum in freshwater discharge occurs. Heat transfer at the sea surface is small.

In winter (November through March), values of southeast winds, onshore components of Ekman transport, and monthly mean sea levels are maximal. The freshwater discharge is relatively small. There is a net heat loss at the sea surface.

OCEANOGRAPHIC CHARACTERISTICS

Prior to a discussion of mechanisms, it is desirable to present the major characteristics of the distributions of salinity and of temperature for each of the four seasons. For this purpose it is necessary to select data adequate with respect to geographical coverage and appropriate in time. It has thus been necessary to employ autumn data based on the September 19 to October 9, 1962, cruise plan (Fig. 3) differing from the Hecate cruise plan employed for the other three seasons. This presents little difficulty in illustrating distributions of surface salinity and temperature. In describing the distribution of subsurface salinity and temperature, however, a series of transverse and longitudinal sections have been employed, thus necessitating a selection of autumn sections comparable with those used for the other seasons. In Fig. 14, the sections used to depict conditions in the spring, summer, and winter are indicated by solid lines and lettered A–F, while the autumn sections, where they depart geographically from the former, are represented and lettered respectively from A to E.

SURFACE SALINITIES

Distributions of surface salinity during each of the four seasons are illustrated in Fig. 15, using observations in the range of 3–5 m depth to eliminate short-term surface effects. Throughout the year the salinities in Dixon Entrance are less than those in the adjacent ocean, and are generally characterized by three persistent features.

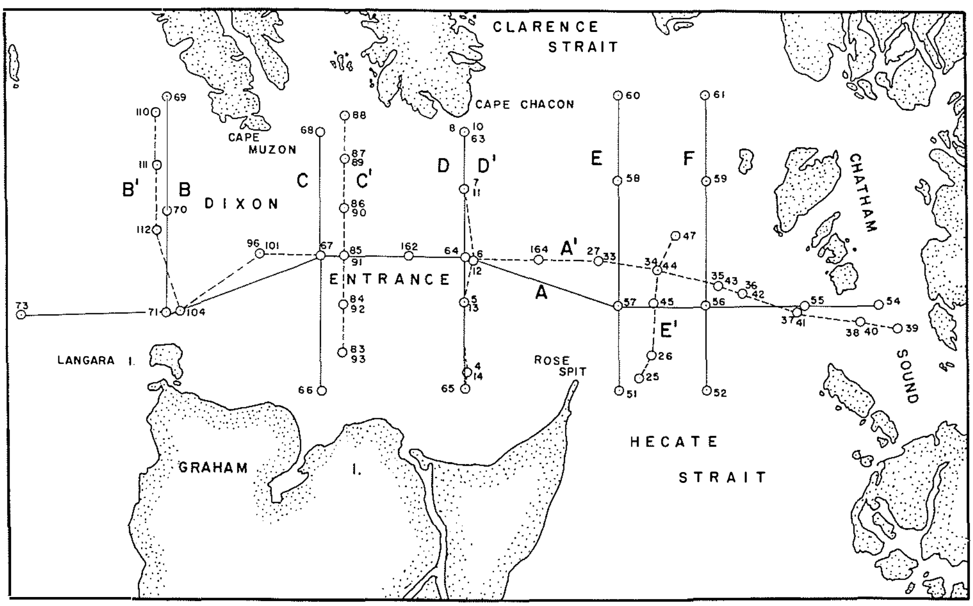

FIG. 14. Locations of sections illustrating seasonal subsurface salinities and temperatures.

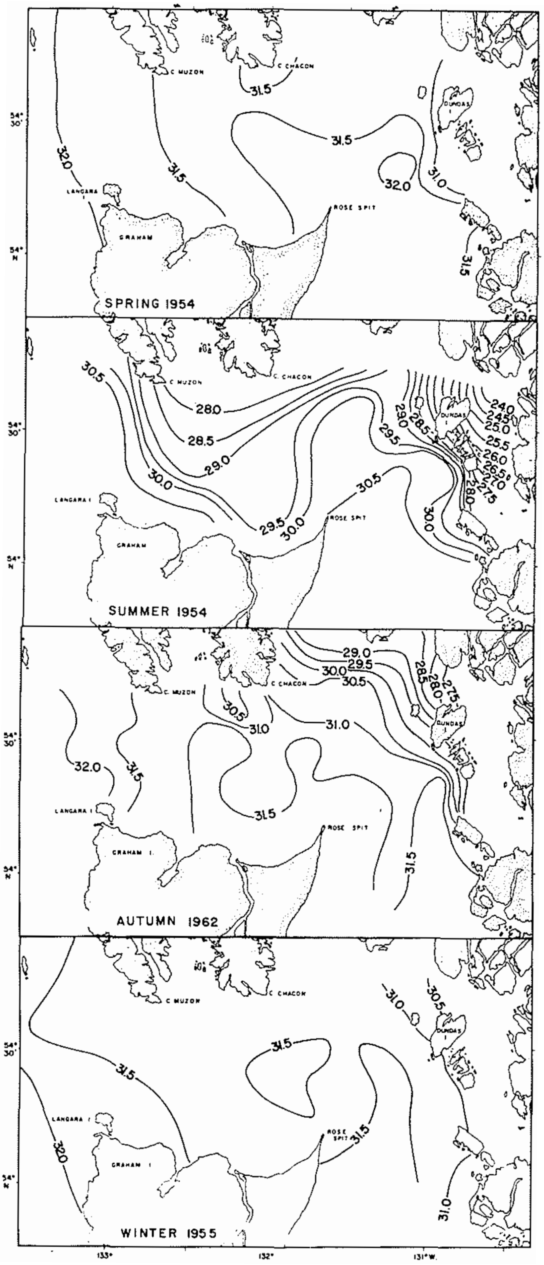

FIG. 15. Seasonal surface salinities (‰) in spring (May 1954), summer (August 1954), autumn (September–October 1962), winter (February 1955).

The first of these features is an area of low-salinity water associated with Chatham Sound, Clarence Strait, the northern shores, and the west-central parts of Dixon Entrance. In summer, the reduction in salinities apparent throughout the whole region is especially marked in this particular area, and is clearly attributable to the peak discharge of the Nass and Skeena rivers in June. Throughout the remainder of the year, the salinity distributions show relatively little change and this area may be approximately delineated as that enclosed by the 31.5‰ isoline.

The second feature is the horizontal gradient of salinity at the mouth of Dixon Entrance. In summer, salinities associated with this gradient are low, but the gradient itself is greater than at any other period. Throughout the other three seasons, the area associated with this gradient may be conveniently defined as that enclosed between the 31.5 and 32.0‰ isolines. In autumn, the gradient is still relatively strong, but in winter and spring it weakens and extends further to seaward.

The third feature is an irregular area of water, associated with the northern part of Hecate Strait, and displaying higher salinities (>30.5‰ in summer, >31.5‰ during the remaining seasons) than the remainder of Dixon Entrance. Though a general dilution is apparent in summer, this water shows relatively little change in salinity throughout the remainder of the year.

From these considerations it may be concluded that the major annual change in surface salinity is a consequence of dilution in summer due to the spring freshet in the Skeena, Nass, and Coastal drainage areas (Fig. 4). The trichotomy of the Dixon Entrance region and its immediate environs into three areas also prevails during the other seasons, though with much reduced salinity ranges. This is consonant with the monthly mean salinities presented above (Fig. 7); those at Langara Island are high throughout the year, those at Bonilla are less than those at Langara, and are subject to little seasonal change, while those at Triple Island and Ketchikan show a marked seasonal dilution.

Subsurface Salinities

The vertical sections of salinity (Fig. 16) indicate the presence of a persistent halocline throughout the greater part of Dixon Entrance. There is, however, a seasonal change in the depths of the isohalines associated with this halocline, the change being more pronounced in the western part of Dixon Entrance. The intense shallow summer halocline contrasts sharply with the deeper and weaker halocline of the winter.

The subsurface characteristics of the three distinctive areas of surface salinity described above are now considered. The horizontal gradient of salinity across the mouth of Dixon Entrance is clearly reflected in the intersection of the surface by the isohalines at the western end of the longitudinal sections A and A′ (Fig. 14).

The greatest depths of low-salinity water are generally associated with Chatham Sound, Clarence Strait, and the northern shores of Dixon Entrance. Of particular interest is the persistent presence of low-salinity water in the west-central part of Dixon Entrance, as shown in the longitudinal sections A and A′ in the vicinity of, respectively, stations 67 and 96/101.

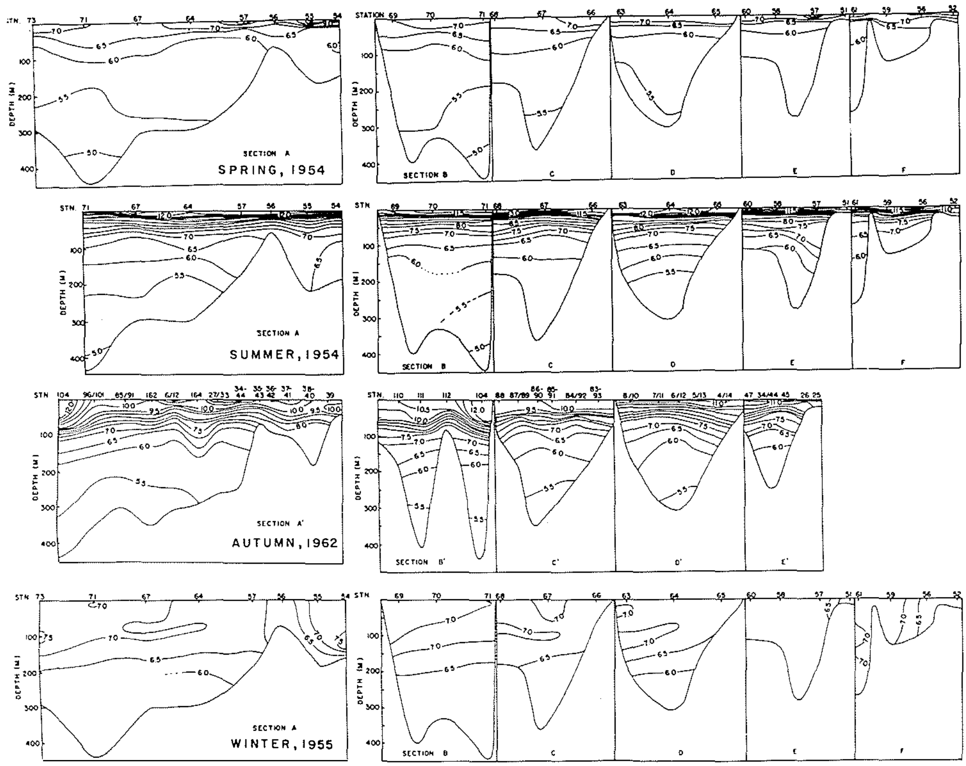

FIG. 16. Subsurface salinities (‰) in spring (May 1954), summer (August 1954), autumn (September–October 1962), winter (February 1955). The letters denote sections shown in Fig. 14.

Salinity changes at depth in the area of intermediate-salinity water adjacent to the northern end of Hecate Strait show a striking seasonal dependence. In summer and autumn (sections E, E′, and F) there is a relatively small shallow volume of near-isohaline water immediately adjacent to the edge of the bank. In winter and spring this volume has increased greatly in extent.

Two other important features are apparent in these sections. The first of these concerns the cross-channel slope of isohalines in the winter and spring, at sections B and C, respectively. The second involves the marked salinity "dome" in winter, evident in sections A and D. Both of these features are discussed in detail later.

SALINITY STRUCTURES

The specific features of salinity structure in a "positive" deep fjord have been discussed by Tully (1958). Usually there is a near-homogeneous upper zone, attributable to surface mixing processes, surmounting a halocline formed by mixing usually associated with the tidal flows. In the absence of surface mixing, the halocline will extend to the surface. Below the halocline there is a near-uniform lower zone of undiluted sea water.

As noted above, some measure of dilution exists along the northern shores and in the west-central part of Dixon Entrance throughout the year. Such a dilution must be maintained by a persistent seaward movement of fresh water, although strong seasonal changes in the intensity of this flow may be anticipated. The salinity structures (Fig. 17) in the west-central region are probably as representative as any of water in Dixon Entrance. For this purpose, the two closest locations, stations 67 and 85/91 (Fig. 14), with depths of approximately 300 m, have been employed.

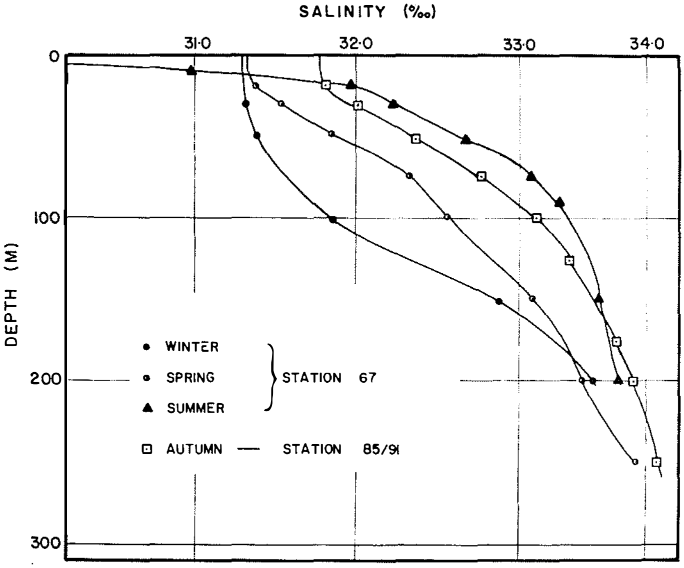

FIG. 17. Seasonal salinity structures in west-central Dixon Entrance.

Throughout the year, there is a marked variation in the depth of the halocline; this is a minimum in summer and deepens throughout the autumn to a maximum in winter, becoming shallower again in the spring. Salinities at depth are greater in the summer and autumn than in the winter and spring. It is apparent that the zones referred to above are poorly defined in Dixon Entrance, and that in winter and in spring the halocline virtually extends from the surface to the bottom. This is to some degree similar to the structures encountered in the shallow "coastal-plain" estuaries of the eastern United States (Pritchard, 1952).

SURFACE TEMPERATURES

In presenting the general seasonal distributions of temperature in Dixon Entrance, the same arrangement of stations and sections (Fig. 14) has been employed as those used in connection with salinities.

In spring, the differences in surface temperature (Fig. 18) in Dixon Entrance and its environs are relatively small. The warmest water during this period is associated with northern Hecate Strait. This is consonant with the more rapid

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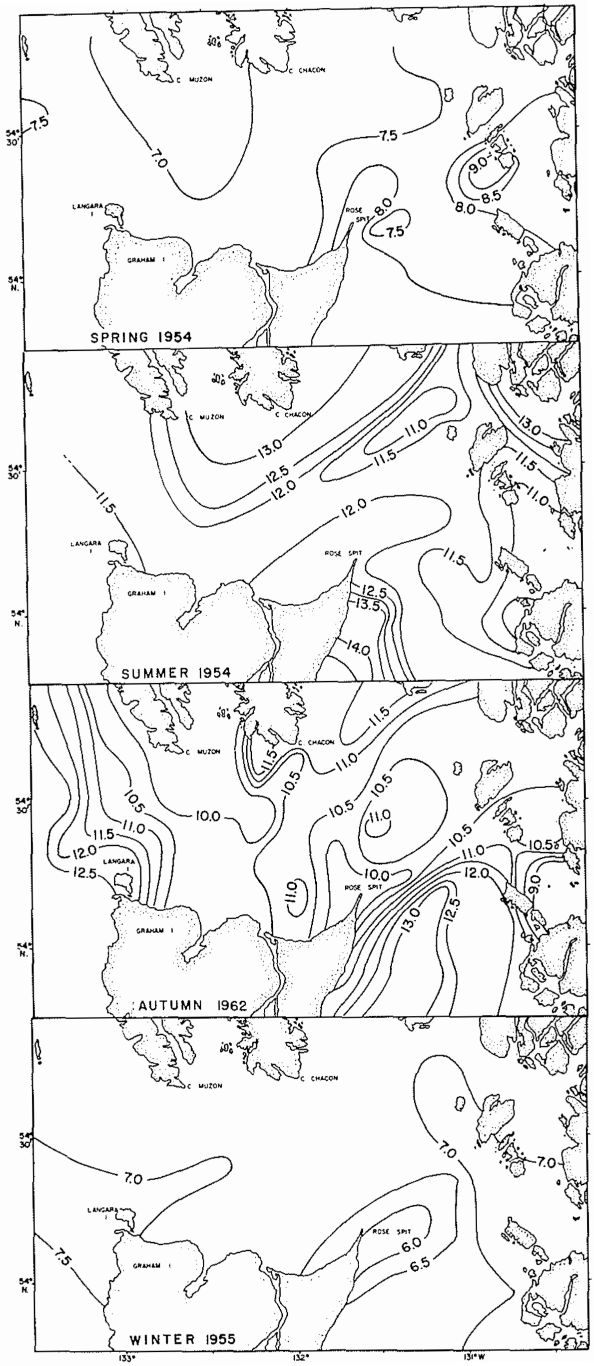

FIG. 18. Seasonal surface temperatures (*C*) in spring (May 1954), summer (August 1954), autumn (September-October 1962), winter (February 1955).

increase of monthly mean surface temperatures at Triple Island and Bonilla than at Langara (Fig. 13).

In summer, the higher surface temperatures are associated with the area of low-salinity water found along the northern shores of Dixon Entrance and in the southern reaches of Clarence Strait. This agrees with the occurrence of higher monthly mean surface temperatures at Ketchikan than at Triple Island, Bonilla, and Langara (Fig. 13).

In autumn, surface temperatures are generally lower throughout Dixon Entrance than to seaward or in Hecate Strait. Again, this is in agreement with the more rapid decrease in monthly mean surface temperatures at Ketchikan than at the other stations.

In winter, surface temperature differences throughout the region are small. At Triple Island, Bonilla, and Langara, monthly mean surface temperatures have similar values (Fig. 13), though at Ketchikan temperatures are lower than at the other locations.

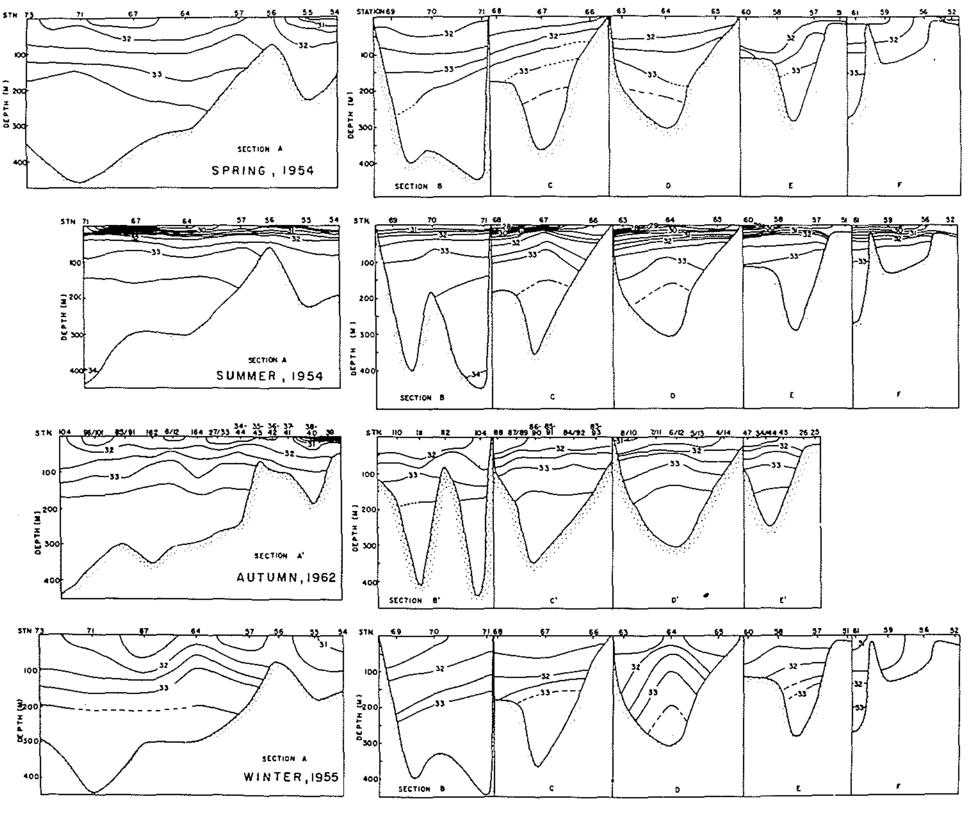

FIG. 19. Seasonal subsurface temperatures (*C*) in spring (May 1954), summer (August 1954), autumn (September–October 1962), winter (February 1955).

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Subsurface Temperatures

The temperature sections show that the growth of the thermocline from spring to summer and its decay from autumn to winter, are similar throughout Dixon Entrance (Fig. 19). It is of interest to note that the temperatures of the deep water are somewhat higher in winter than in any other season. The vertical near-homogeneity apparent in the winter salinities north of Hecate Strait (Sec. F, Fig. 16) is also present in the temperatures.

Temperature Structures

The temperature structures shown in Fig. 20 correspond to the four seasonal salinity structures presented in Fig. 17 for stations 67 and 85/91.

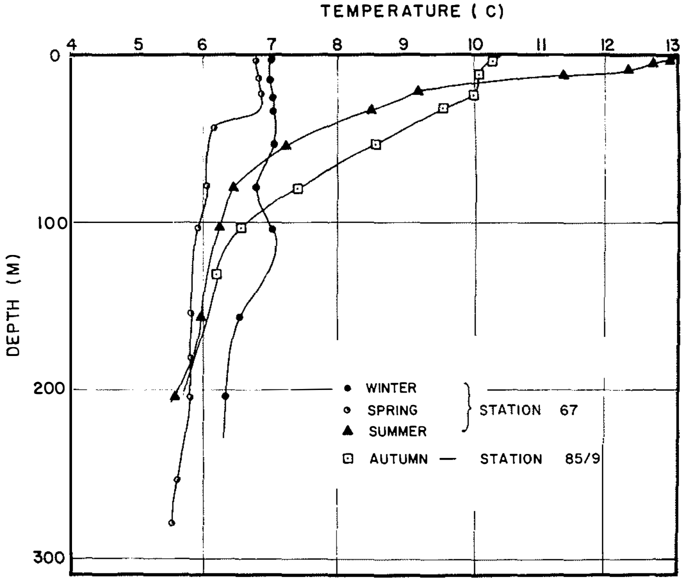

Fig. 20. Seasonal temperature structures in west-central Dixon Entrance.

The most distinctive feature is the strong thermocline which is coincident with the halocline in the summer and autumn. This persistent coincidence of the thermocline with the halocline is a characteristic feature of coastal waters dominated by estuarine discharge, and differs from the adjacent ocean, where the growth and decay of the thermocline occur within the upper zone above the halocline (Dodimead, 1961). Below the halocline, the temperatures are higher in the winter than in the remaining seasons. These features have also been observed in Juan de Fuca Strait (Herlinveaux and Tully, 1961) and in Queen Charlotte Sound (Barber, 1957). In winter there is evidence of a weak inversion and the water at depth is warmer than in any of the other seasons. In the spring, a shallow layer of warm water is apparent at the surface, while below this the changes of temperature with depth are small.

DENSITY STRUCTURES

The density (σ_t) structures derived from the salinities and temperatures shown in Fig. 17 and 20 are illustrated in Fig. 21. The marked resemblance between the density and salinity profiles shows that throughout the year, salinity rather than temperature plays the dominant role in determining the density. This

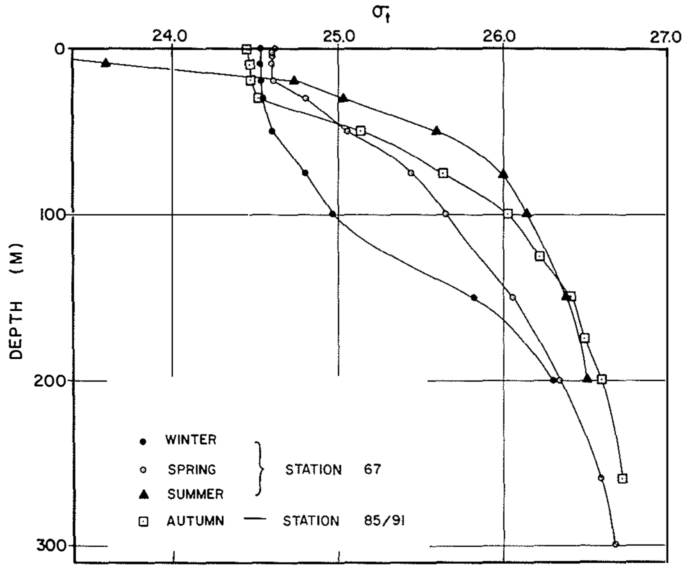

FIG. 21. Seasonal density (σ_t) structures in west-central Dixon Entrance.

has been noted elsewhere in the coastal waters of British Columbia by Herlinveaux and Tully (1961) and by Pickard and Trites (1957). In winter, the gradient of density is almost solely determined by salinity. In summer the main effect of surface warming is to further enhance the strong density gradient associated with the estuarine discharge.

TIDAL MECHANISM

TIDES

In the northern coastal seaways of British Columbia, the observed tide, which includes both diurnal and semi-diurnal components, co-oscillates with the oceanic tides of the adjacent North Pacific. Considerable changes with respect to both range and phase occur within the areas. These have been summarized (Canada Department of Mines and Technical Surveys, MS, 1963) and may be illustrated by the co-phase and the co-range lines for the largest component, the M2 component (Fig. 22). The flood coming from the south through Queen Charlotte Sound and along the mainland shores meets the flood coming through Dixon Entrance in the northern part of Hecate Strait, some 30 min after high water in Queen Charlotte

Sound. The combined tides swing westward across Hecate Strait, reaching the southeastern shores of Graham Island some 15 min later. The greatest ranges are encountered along these shores and in the vicinity of Prince Rupert, where the ranges of the largest tides are about 24 ft. This meeting of the tides in Hecate Strait occurs some 25-30 miles farther north in the winter than in the summer. It has been observed that along the eastern shores of the relatively narrow northern part of Hecate Strait, the strongest set is northwestward with the ebb, while the flood southward is much weaker. This suggests a net tidal flow northward through Hecate Strait and into Dixon Entrance. The deflection, by Coriolis force, of water movements due to runoff and wind would tend to augment such a flow.

Due to the complicating effects of wind and land drainage, a program of field observations in terms of present methods of current measurement required to

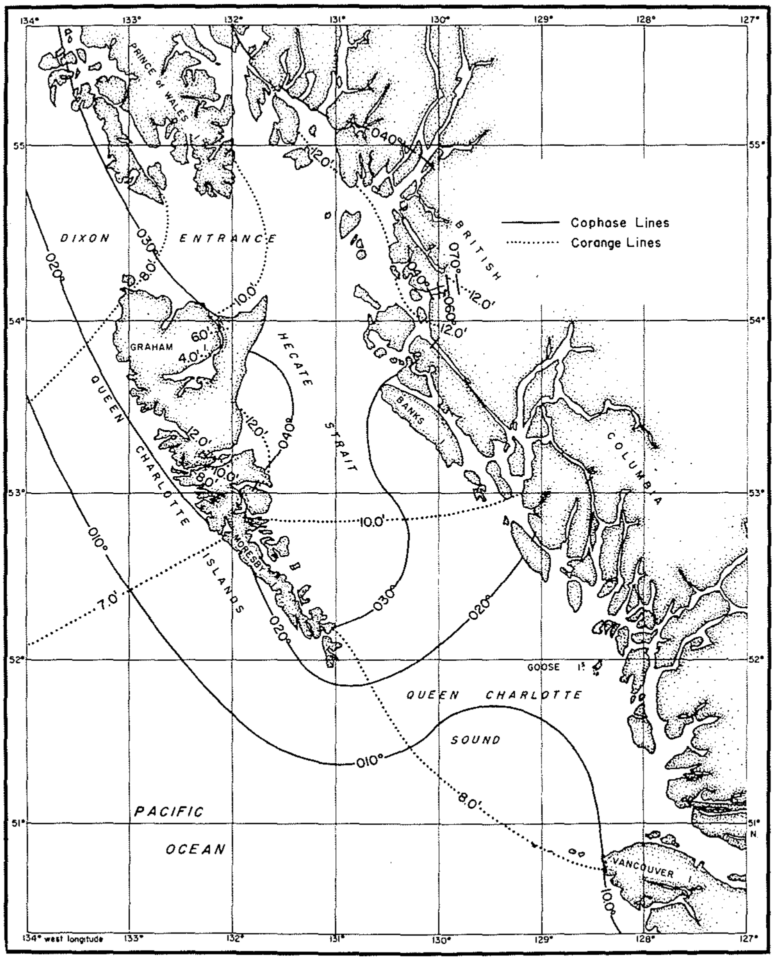

FIG. 22. M2 cotidal lines, Queen Charlotte Sound to Dixon Entrance. (Canada Department of Mines and Technical Surveys, MS, 1957)

describe the tidal movements would be prohibitive. Thus tidal aspects of the region have been studied with the aid of a hydraulic model.

HYDRAULIC MODEL STUDIES

The Hecate Model includes Queen Charlotte Sound, Hecate Strait, and Dixon Entrance (Bell and Boston, MS, 1962). Since the modelled region extends over several degrees of latitude, a map projection was employed in which meridians were reproduced as straight lines and the scale was independent of direction. The time and length scales were selected to effect comparable Froude numbers in

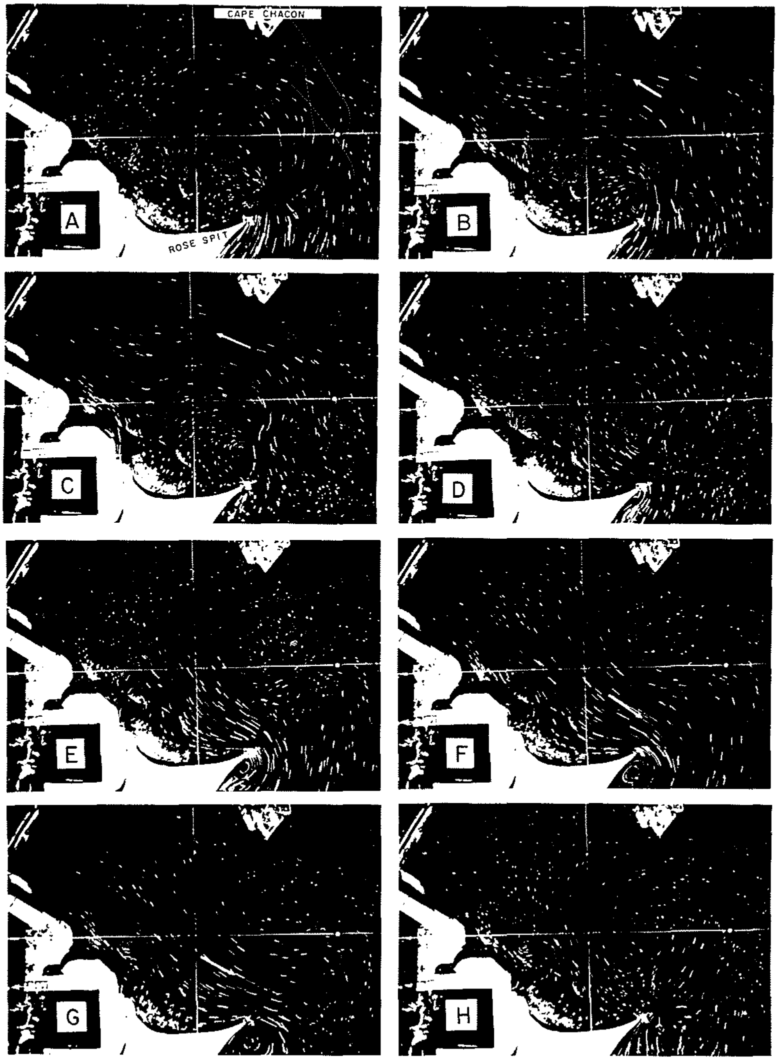

FIG. 23. Motions of confetti particles over different phases of a tidal cycle in the hydraulic model of Dixon Entrance.

model and in prototype. The depth scale was adjusted to ensure a Reynolds number such that turbulent flow occurs throughout the model. The tides were produced by electronically-programmed tilting plates located across the mouth of Queen Charlotte Sound and of Dixon Entrance. The resulting tides at different locations in the model were measured by electronic recording tide gauges.

Calibration of the model (Bell and Boston, 1963) was carried out by adjusting the phases and amplitudes of the tidal generators to reproduce prototype tide gauge data at two locations within the model.

In studies pertinent to the present discussion, attention was confined to the Dixon Entrance and northern Hecate Strait region. The following technique was employed (Bell, MS, 1963).

The water in the model was dyed a dark red and particles of confetti were scattered about the surface. A sequence of time exposures was then made of the particle movements. Each exposure lasted for 3 sec (equivalent to 1/20 of a day in nature), and was followed by a 1 sec interval for film transport.

A typical set of eight pictures, obtained over a tidal cycle, is shown in Fig. 23. The coastline at the lower left-hand corner in these plates corresponds to the northern shore of Graham Island. The promontory in the upper right-hand quadrant represents Cape Chacon. During the period of falling tide, pictures A–D, the dominant flow is in an anticlockwise sense, past Cape Chacon. During the period of rising tide, pictures E–H, the dominant flow is towards and around Rose Spit.

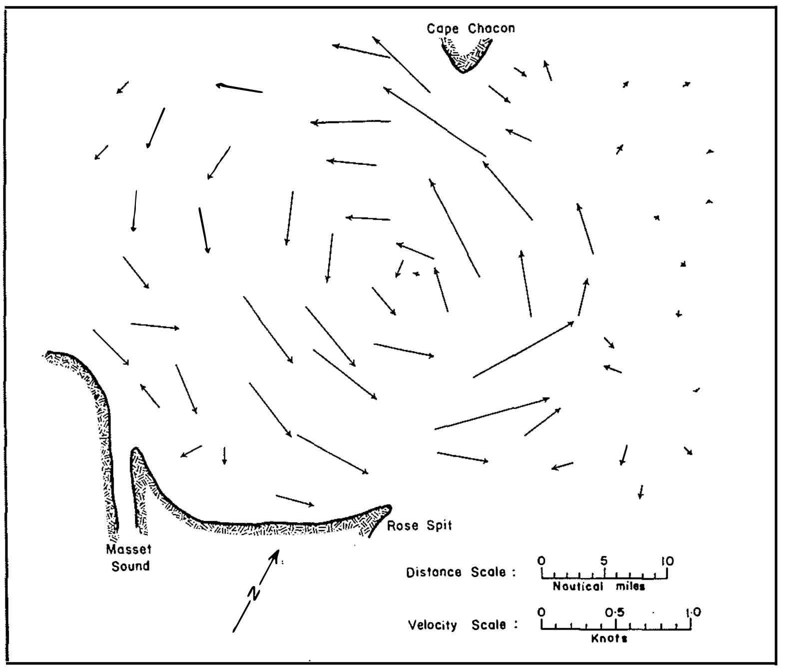

FIG. 24. Resultant current vectors over one M2 tidal cycle, using the method of Lagrange, in the hydraulic model of Dixon Entrance.

If the movements of particular particles are followed over any desired period through a series of these plates, the net particle displacements may readily be determined. Displacements obtained in this manner over one M2 tidal cycle are shown in Fig. 24. A strong net cyclonic vortex, centered approximately between Cape Chacon and Rose Spit, is clearly evident as the dominant feature of the surface circulation in Dixon Entrance.

A partial restriction of the flows adjacent to Rose Spit resulted in a major alteration in the pattern of circulation in Dixon Entrance. When the northern end of Hecate Strait in the model was blocked by sandbags, the vortex was totally eliminated. It would thus appear that the major factor in producing this net circulation is the strong tidal movements adjacent to Rose Spit (Bell, MS, 1963).

The experiments suggest, that if only a simple tidal hydraulic flow is involved, the basic surface circulation of Dixon Entrance would be a strong net cyclonic vortex, resulting from the meeting of the Queen Charlotte Sound and Dixon Entrance tides in northern Hecate Strait. It should be noted, however, that additional factors in nature, such as Coriolis force, will modify this feature.

Features of the Tidal Circulation in Dixon Entrance

On the basis of results from the tidal hydraulic model, a series of observations in the general region of the vortex was included in the September–October 1962 cruise (Fig. 3).

Prior to a discussion of these observations, it is desirable to review the properties of a vortex of this type. If the velocities associated with a cyclonic vortex in a stratified sea are greater in the upper part of the vortex than below, the sea surface will slope upward and outward from the axis of the vortex (Defant, 1961). The resulting pressure gradient at depth will lead to an accumulation of the deeper, denser water around the axis of the vortex. In consequence, a section through the vortex will show a characteristic "doming" of the isopycnals. If fluctuations in the velocity differential between the upper and lower parts of the vortex occur, concomitant fluctuations in the depths of isopycnals at the centre of the vortex also occur.

In the September–October 1962 cruise, sections, timed in the following manner, were run across the area of the vortex. The times of high or low water to the north (Cape Chacon) and to the south (Wiah Point) (Fig. 1) of the vortex area are separated by only 20 min (Canada Department of Mines and Technical Surveys, MS, 1963; United States Department of Commerce, MS, 1962a,b). Also, the maximum flows near Cape Chacon and in the vicinity of Rose Spit occur at about the same time, roughly midway between high and low water at Cape Chacon. The sections were run on the flood and ebb tides, such that the centre station was observed at a time midway between high and low water as predicted for Cape Chacon. The sections of density obtained in this manner are illustrated in Fig. 25. A well developed doming of the isopycnals is apparent in the section obtained during the flood tide. This partially collapses during the ebb.

If it is assumed that the axis of the isopycnal dome described above remains reasonably stationary, it should be possible to examine vertical oscillations of isopycnals associated with the dome by observing the changes of density with time at particular depths below a vessel anchored at the approximate centre of the vortex. The results from observations at depths of 50, 75, and 100 m respectively, taken at 2-hr intervals over a 54-hr period, are illustrated in Fig. 26, together with the predicted tides for Cape Chacon. The period in question was intermediate between the spring and neap tides. At these depths, the sequences are characterized by periods of relatively high density interspersed with brief density minima, the latter generally occurring shortly after high water. This would suggest that the "dome" is extant throughout the greater part of the tidal cycle. There is, however, a brief period of collapse in the early part of the ebb.

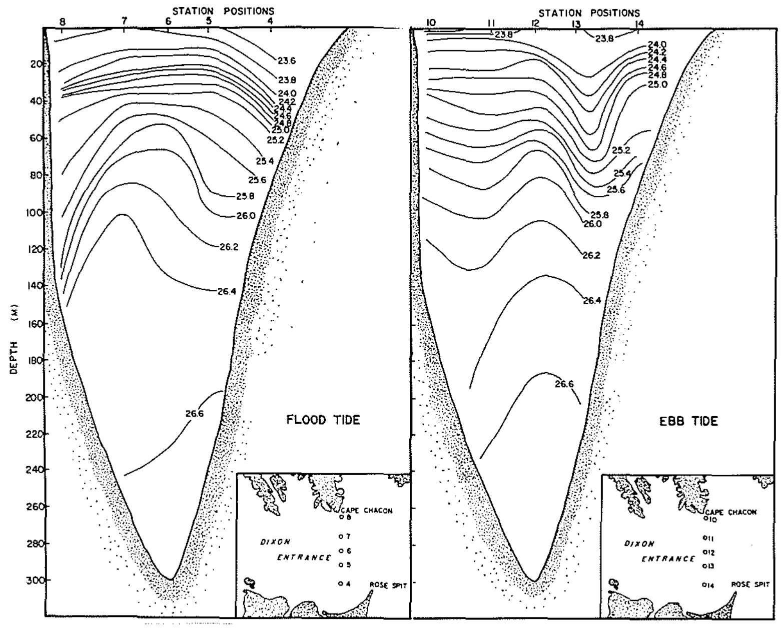

FIG. 25. Cross-sections of density anomaly (σ_t), obtained respectively on the flood and ebb, September 19, 1962.

Estimates of surface velocities using a drift pole, and of velocities at depth using an Ekman current meter, were made at three different locations across the vortex. At each location, observations of velocity were made at approximately 2-hr intervals. Anchor station A included three tidal periods, with observations at 0, 50, 100, 150, and 250 m, anchor station B five tidal periods, with observations at 0, 50, 100, 150, and 250 m, and anchor station C two tidal periods, with observations at 0, 50, 75, 100, and 150 m. The average velocity components, resolved along north–south and east–west axes, at each depth for each location over the period in question, are summarized in Fig. 27. It has been observed that although current speeds measured by the Ekman meter under sea-swell conditions of 2/3 are subject to considerable random variation associated with the rolling of the vessel, directions can be measured with an accuracy of some 10 deg (Tabata and Groll, 1956). Throughout each of the periods of observations sea-swell conditions were of this order. It is, however, apparent that the net components to the south and west at station A, to the north and west at station B, and to the north and east at station C, are clearly consonant with a vortex circulation as shown in the hydraulic model experiments.

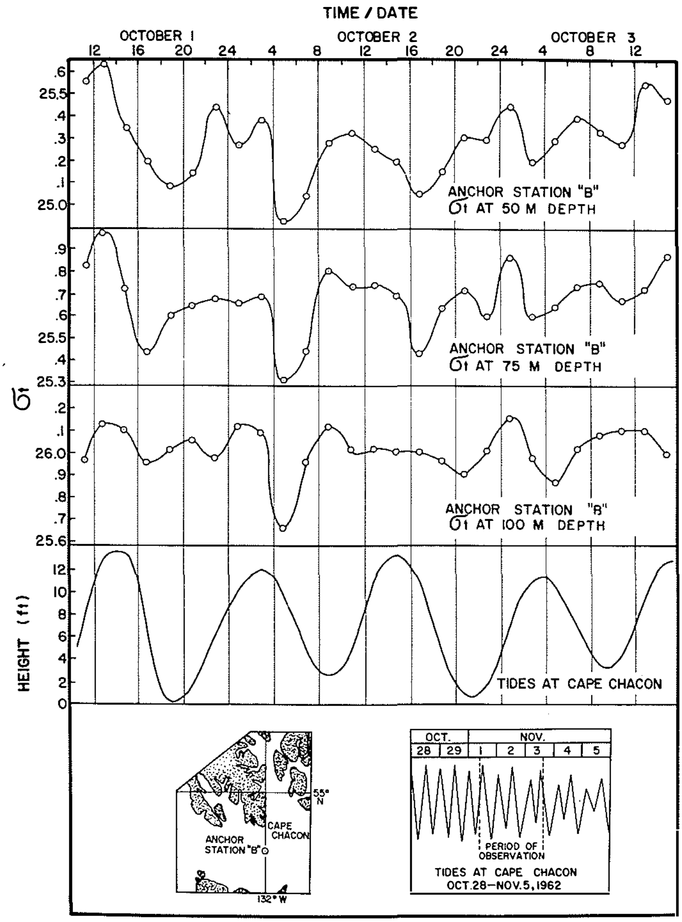

FIG. 26. Changes in density anomaly (σ_t) at depths of 50, 75, and 100 m near the centre of the gyre, October 1—3, 1962.

If it is assumed that a vortex results from the tides and geometry of the system, the mass field should be consonant with such a rotation. A comparison of the net flow directions at stations A and C (Fig. 27) with the distribution of dynamic height from 0 to 125 m (Fig. 28) shows reasonable agreement with respect to the general rotation. It would thus appear that this dynamic topography

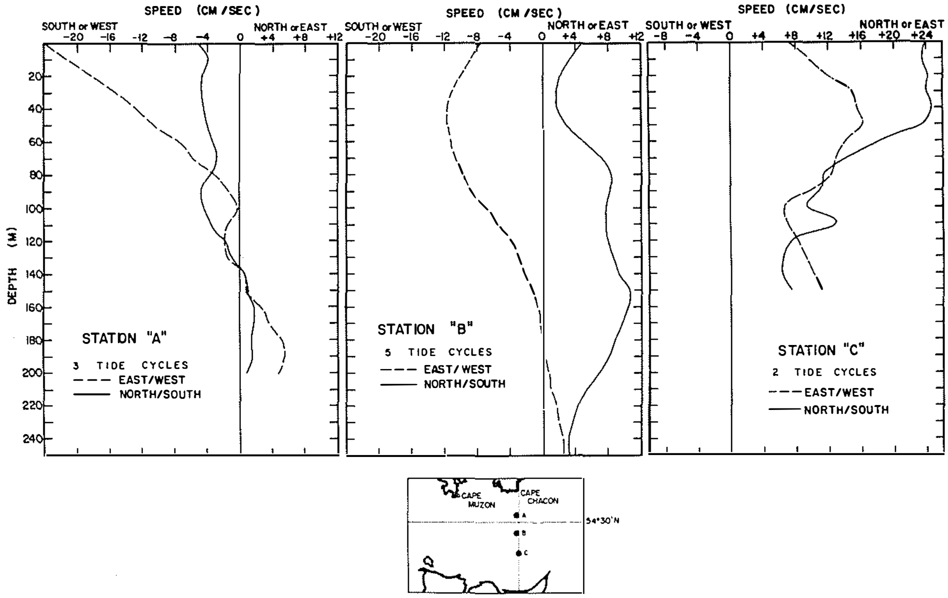

FIG. 27. Average current components at three locations across the vortex, September–October 1962.

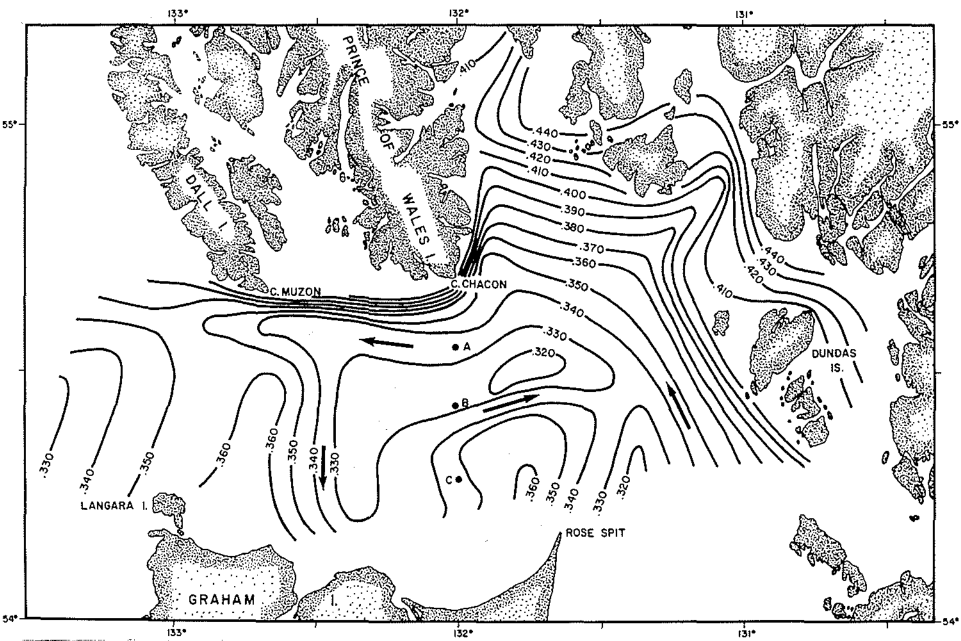

FIG. 28. Distribution of dynamic height anomaly (ΔD), 0/125 m September-October 1962.

may be employed to indicate the general extent of the vortex circulation. It is evident that the recirculation extends through the northern and central regions of Dixon Entrance, from westward of Cape Muzon to eastward of Cape Chacon.

If it can be assumed that little water is fed into the system, such a circulation is basically retentive. It is reasonable to suppose that the water thus involved might be characterized by a high degree of lateral uniformity. It is thus of interest to consider briefly the distinctive water masses in Dixon Entrance during the period September–October 1962, and in particular to note the remarkable lateral uniformity of the water mass associated with the vortex recirculation. This may be done conveniently in terms of a temperature-salinity diagram.

Figure 29 shows a classification of the region into five "domains" (inset) each domain representing that part of the region having similar temperature-salinity profiles contained within the shaded portions. To eliminate short-term variability associated with the surface layers, temperatures have been arbitrarily limited to those less than 10 C. This is roughly equivalent to excluding values in the upper 50 m (Fig. 16).

Since the water below the halocline showed little change of temperature and salinity with depth during September–October 1962, this diagram is predominantly descriptive of water masses occurring in the halocline. The domains ranged from the relatively brackish water in the southern reaches of Clarence Strait to the more saline water seaward of Dixon Entrance. Of particular interest, however, is the narrow envelope appropriate to domain 3, indicating a high degree of uniformity in the isopycnal surfaces. A comparison of the geographical extent of domain 3 with the recirculation apparent in the dynamic topography shown in Fig. 28 shows that this high degree of lateral uniformity is associated with the water in the vortex

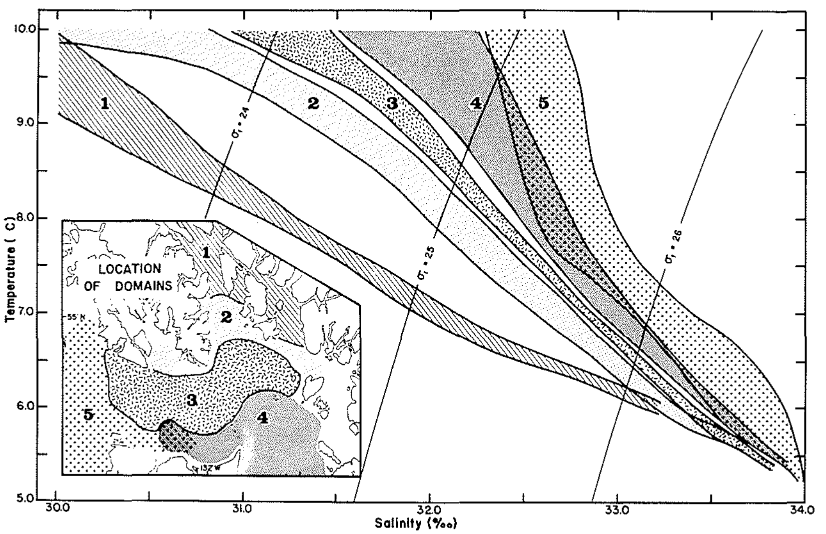

FIG. 29. Classification of the water in Dixon Entrance on the basis of temperature-salinity relations, and geographical extent of the resulting domains, September–October 1962.

and thus with an efficient recirculation during this period. It should be noted that factors such as wind and runoff may radically alter the characteristics of the vortex or even temporarily suppress it completely.

WIND MECHANISM

When the wind imparts momentum to the sea, the ensuing wind drift, with respect to both magnitude and direction, depends on the velocity and the duration of the wind, the fetch over which the wind acts, the depth and stratification of the sea, and on the restrictive influence of shore lines. It has been noted above that the dominant winds along the coast of British Columbia are from the southeast or northwest. Though Dixon Entrance is partially screened from the full force of these winds, it is reasonable to expect that the effect of these winds over the exposed waters to seaward, and over the long fetch of Hecate Strait, will have significant oceanographic consequences in Dixon Entrance.

In the northern hemisphere, the wind-driven transport of surface water occurs to the right of the wind direction, although in shallow water this deflection may be much reduced (Sverdrup et al., 1946). In the case of a stratified ocean bounded by a uniform coast, two important situations may be distinguished. When the coast is parallel to, and on the right of, the wind direction, there occurs both an onshore accumulation of surface water, and a depression of isopycnal surfaces near the coast. Some distance off the coast there will be a convergence. This onshore accumulation creates a related field of pressure with which must be associated a current (called by Sverdrup the "relative" current) running parallel to the coast in the same direction as the wind. When the wind drops, the shoreward accumulation of surface water dissipates seaward, and the isopycnals rise to depths comparable with those in the adjacent ocean. If the wind direction is reversed, a net offshore movement, or divergence, of surface water occurs, accompanied by a compensatory inshore movement of deeper water. Isopycnal surfaces in the vicinity of the coast are displaced upward. It has been observed that force 6 winds blowing along a coast for half a day can cause sufficient piling up of surface water to replace the water in the water column to a depth of 90 m at a location 10 miles offshore on the continental shelf (Longard and Banks, 1952).

The prevalence of southeast winds in winter and northwest winds in summer, is clearly conducive to changes of this type in the coastal waters of British Columbia. The mean seasonal cycle of Ekman transport has been calculated for various locations off the coast of British Columbia (Fofonoff, 1962). This has been related to seasonal changes in the seaward extent of brackish water and in the depths of isopycnal surfaces off the west coast of Vancouver Island (Fofonoff and Tabata, 1966). Seasonal changes in the depth of isopycnal surfaces in Queen Charlotte Sound and Dixon Entrance have been reported by Barber (1957).

Prior to considering the effects of these transports on the properties of water in Dixon Entrance, it is of interest to compare the winds and monthly mean components of Ekman transport in the northern and southern coastal waters of

British Columbia. It has been noted that the component of southeast wind in winter is generally stronger in the northern region than in the south, while the component of northwest wind in summer is stronger in the southern region than in the north. In comparing the long-term monthly mean vectors of Ekman transport (Fig. 10) at various latitudes off the west coasts of Washington, British Columbia, and southeastern Alaska (Fofonoff and Dobson, MS, 1963) it is apparent that the stronger onshore component (convergence) occurs at the higher latitudes in winter, while the stronger offshore component (divergence) occurs at more southerly latitudes in summer. This agrees with the observation by Doe (1955) of a stronger divergence in the southernmost of four lines of oceanographic stations, normal to the British Columbia coast in August 1950.

It would thus appear that in the northern coastal waters of British Columbia, the dominant aspect of this transport mechanism will devolve on the establishment of a strong convergence in winter, followed by its relaxation, and that divergence will, in general, be a secondary consideration. This relaxation of the convergence would appear analogous to the densimetric exchange flow described by Barr (1961), who on the basis of flume experiments infers that the flow in the upper layers would be somewhat more rapid than in the denser layers below. This agrees with measurement by Barber (1957) of a greater net seaward velocity near the surface than at depth off Queen Charlotte Sound in June.

The wind-induced convergence mechanism has been described above for the idealized case of a long straight coast. The probable oceanographic consequences in Dixon Entrance and contiguous seaways of such a mechanism are now considered. Hecate and Clarence straits and eastern Dixon Entrance afford a continuous route for the "relative" current associated with the onshore movement of surface water in the adjacent ocean.

Over the long fetch of Hecate Strait it is reasonable to suppose that such a current will be much enhanced in accordance with the action of winds in a sea strait. When the wind blows along a sea strait, the surface waters move initially in the same direction as the wind, but, in the northern hemisphere, Coriolis force will soon produce a deflection to the right (Defant, 1961). In consequence, a current develops along the right-hand shore of the strait, accompanied by a tilting of the mass field downward across the strait from left to right (when viewed downwind). If the strait is relatively shallow, this deflection to the right is reduced and the current will be closer in direction to that of the wind. Thus the "relative" current moving northward through Hecate Strait will generally be enhanced by the direct effect of winds associated with the weather system generating the convergence.

With respect to Dixon Entrance, two important situations may be distinguished. If the winds are weak, the "relative" current will be confined to Hecate and Clarence straits and the eastern part of Dixon Entrance. In this instance there will exist an essentially conservative situation, dominated by the tidal vortex, throughout the remainder of Dixon Entrance. If, however, the winds are strong, the northward movement of water through Hecate Strait will lead (in addition to the flow through Clarence Strait) to a strongly developed flow seaward around Cape Chacon and along the northern shores of Dixon Entrance.

The available oceanographic evidence is consistent with a general process of this type. Considering initially conditions seaward of Dixon Entrance, observations obtained over the period June 1961 to June 1962 afford the best available sampling frequency for the establishment of an annual cycle in the depths of isopycnals consonant with such a convergence mechanism. The monthly mean zonal components of Ekman transport over this period, as calculated for a location 70 miles to seaward of Dixon Entrance, are shown in Fig. 30. Also included in the figure, for purposes of comparison, are the corresponding long-term monthly averages and standard deviations as presented previously in Fig. 11. It is apparent that there was a net onshore movement of surface water during the winter, though this was generally weaker than usual.

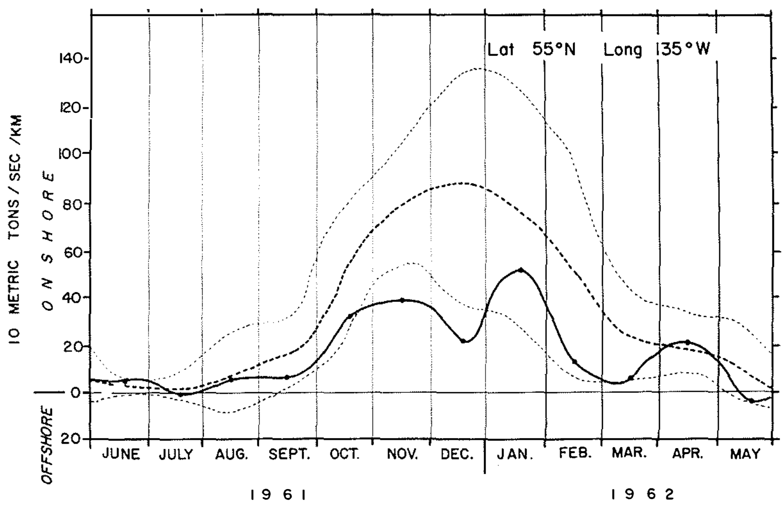

FIG. 30. Comparison of monthly mean zonal components of Ekman transport, June 1961 through May 1962, with the grand means and standard deviations, of the monthly mean zonal components, 1950 through 1959, seaward of Dixon Entrance.

The densities at three locations during this period are shown in Fig. 31. The rise in the deeper isopycnals ($\sigma_t = 26.6$ and 26.7) at stations 33 and 40 between June and August 1961, to depths comparable with those occupied by these isopycnals at station 200, is consistent with the relaxation of the convergence of the previous winter.

From October 1961 to January 1962 there was an onshore component in the monthly mean Ekman transport. The deeper isopycnals at stations 33 and 40 descended. From January to May 1962, there was a net decrease in the onshore component of the monthly mean Ekman transport. The deeper isopycnals at stations 33 and 40 ascended to depths comparable with those occupied by the same isopycnals at these locations in the previous June.

The annual cycle in the depths of isopycnals is thus clearly evident at station 40, and also at station 33, though with reduced amplitude. At station 200, the annual cycle is barely perceptible.

Considering now the water movements in Hecate Strait, the existence of a net northerly flow has been inferred on the basis of drift experiments by Thompson and Van Cleve (1936) and by Haight (1926). A strong predominance of the northward ebb over the southward flood along the northeastern shores of Hecate Strait has been noted above. Further evidence suggests that this persistent net flow

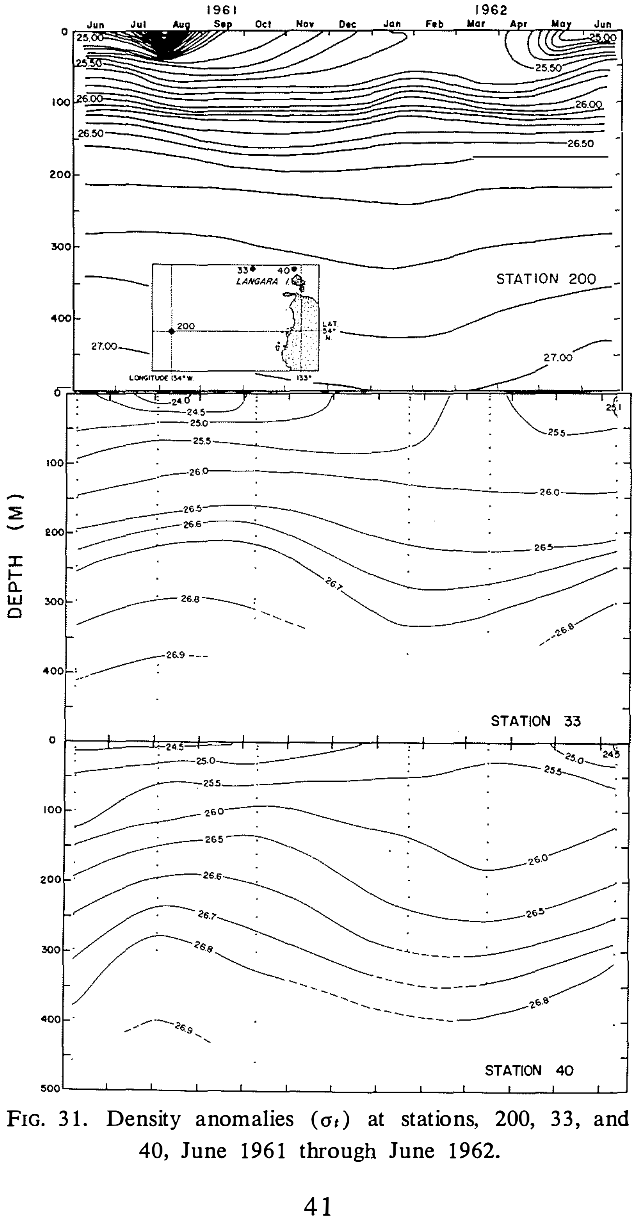

FIG. 31. Density anomalies (σ_t) at stations, 200, 33, and 40, June 1961 through June 1962.

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is best developed during the winter months. It has been observed that the meeting of the tides from Queen Charlotte Sound and from Dixon Entrance in northern Hecate Strait occurs some 25–30 miles further north in winter than in summer. The existence of a strong northward "relative" current along the west coast of Vancouver Island has been shown by Lane (1963) and by Waldichuk (MS, 1963). The entry of this current into Queen Charlotte Sound has been noted by Barber (1958). It may reasonably be inferred that much of this current continues northward through Hecate Strait.

Available winter oceanographic observations in Hecate Strait are consistent with such a well-developed net northerly flow. A density section across the central part of the Strait (Fig. 32), obtained in February 1955, affords a good illustration. The downward slope of isopycnals towards the eastern side of the Strait indicated a northerly flow through the section. Similar conclusions may be drawn from other transverse density sections observed in January 1962 across the eastern part of the strait (Crean et al., MS, 1962a,b). Two sections, occupied on consecutive ebb and flood tides in November 1958, indicated little tidal effect on the strength of this northerly flow (Herlinveaux et al., MS, 1960).

The occurrence of strong seaward flows from Dixon Entrance in early winter is indicated by observations obtained in the vicinity of the mouth in November 1955. A comparison of the isopycnal slopes in the density sections (Fig. 33) is consistent with such a flow veering northward on leaving Dixon Entrance. A similar flow was indicated by data obtained in February 1959 (Pacific Oceanographic Group, MS, 1959a,b,c).

It has been noted by Kendrew and Kerr (1955) that, during the winter months, storms are frequent in the northern coastal waters of British Columbia, often arriving in a series which may continue for a fortnight or more. In a study of the mean monthly frequency of such systems, over several years, as characterized by periods of southeast winds exceeding 25 mph for longer than 6 hr, it has been shown that the highest monthly mean frequencies occur in November (11), December (7), and January (8) (Benedictson, 1965, personal communication). Since the major oceanographic changes occurring in winter may reasonably be associated with these storms, it is of particular interest to examine conditions in Dixon Entrance following such a disturbance observed in January 1962.

Using the changes in daily mean sea level at Prince Rupert, (Fig. 34) as an approximate index of southeast wind activity over the three weeks preceding the cruise, it is apparent that a marked net drop in mean sea level indicated generally decreasing southeast winds. Peaks in sea level on January 4 and 10 coincided with southeast gales as recorded in the estimates of wind at Triple Island (Canada Department of Transport, 1962, personal communication).

In the eastern part of Dixon Entrance, there was a strong intrusion of relatively high-salinity water (Fig. 35). (It is shown in Fig. 39c that this water was continuous with a region of high salinity water occupying the full length of western Hecate Strait.) The salinities associated with this intrusion were comparable with those normally occurring to seaward, as typified by values near Langara

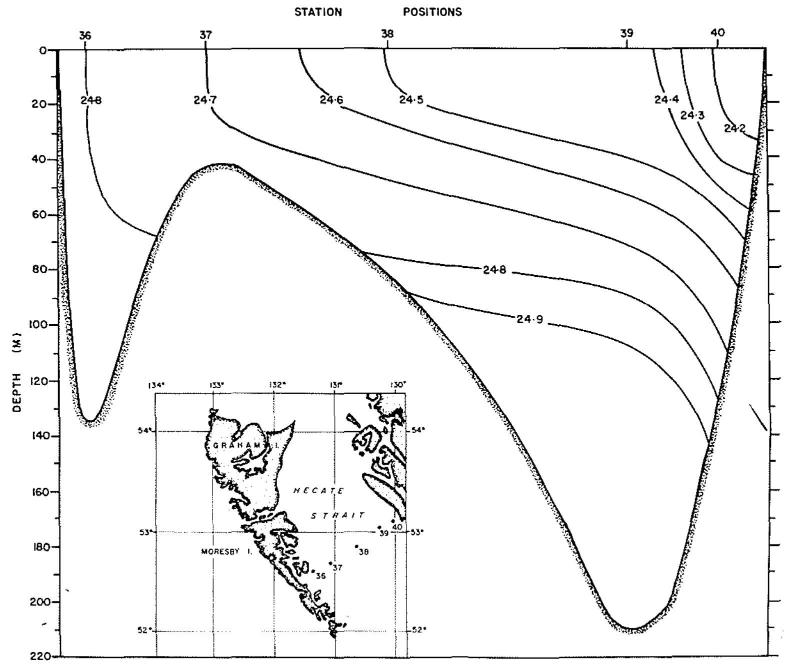

FIG. 32. Cross-section of density anomaly (σ_t) in Hecate Strait, February 6–13, 1955.

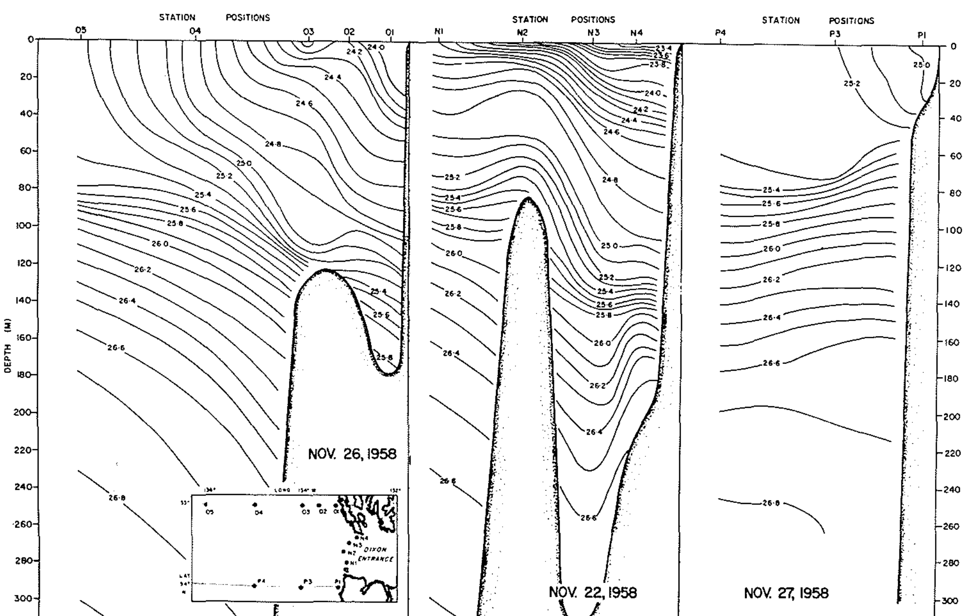

FIG. 33. Cross-sections of density anomaly (σ_t) at the mouth of Dixon Entrance, November 1958.

Island, (Fig. 7). Along the northern shores and in the western part of Dixon Entrance there was a large area of less saline water, with salinities approximating those normally found near Bonilla and Triple islands (Fig. 7) at this time of year. The slopes of isopycnals in the density sections across Dixon Entrance indicated a net seaward flow (Fig. 36).

The mechanism governing conditions in Dixon Entrance over this period undoubtedly represented a complex balance between a number of different factors. The following series of events would appear to offer a reasonable explanation. In the early part of January, the winter onshore convergence of surface waters in the adjacent ocean and the direct action of southeast winds engendered a northward flow through Hecate Strait. This flow was strongest along the eastern shores, and resulted in a marked northerly flow through Clarence Strait, and a westward flow along the northern shores of Dixon Entrance. In the western part of Hecate Strait, relatively high-salinity water was transported northward into the eastern part of Dixon Entrance. Mean sea levels throughout the region were high. With decreased southeast winds, a general relaxation flow seaward through Dixon Entrance occurred.

A further consideration concerning the action of winds in Dixon Entrance involves the effect of westerly winds during the summer. Such winds, as noted by Kendrew and Kerr (1955), are fairly common and may be expected to enhance the eastward flow, along the shores of Graham Island, associated with the net tidal circulation.

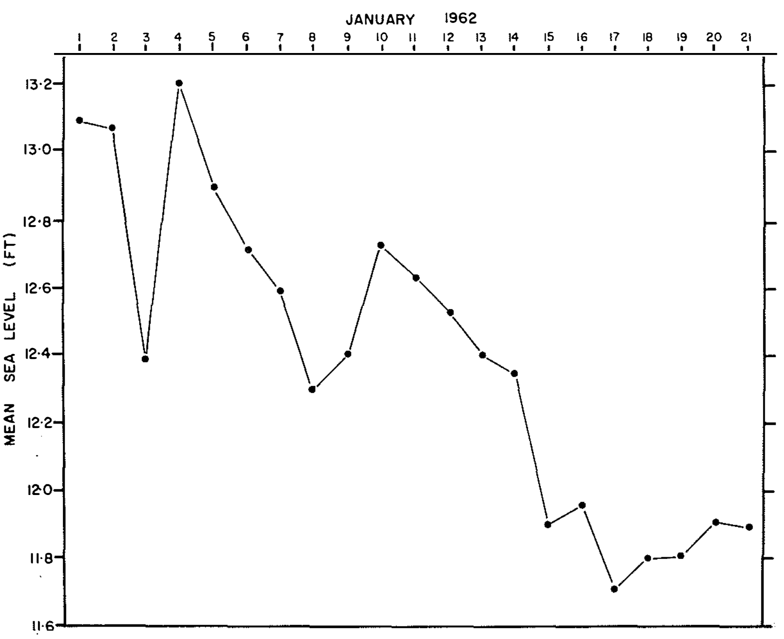

FIG. 34. Daily mean sea levels at Prince Rupert, January 1–21, 1962.

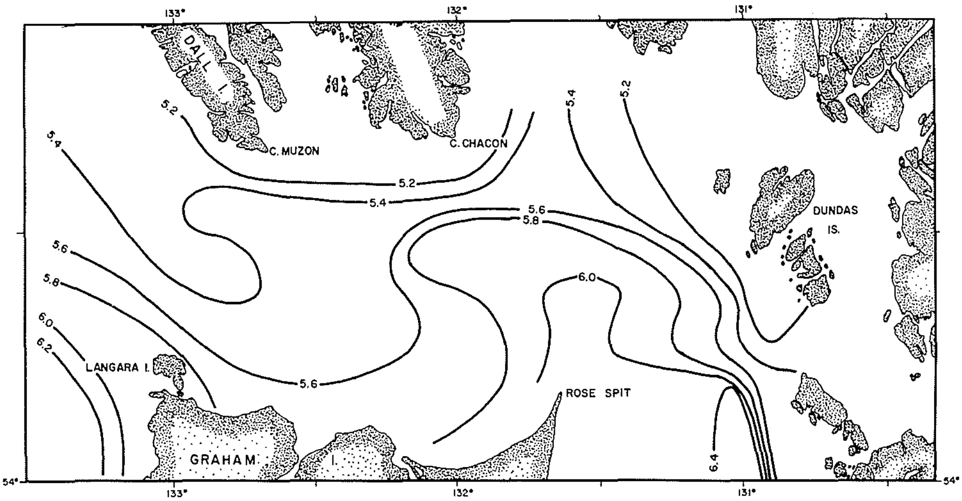

FIG. 35. Distribution of salinity (‰) at 5 m depth, January 1962.

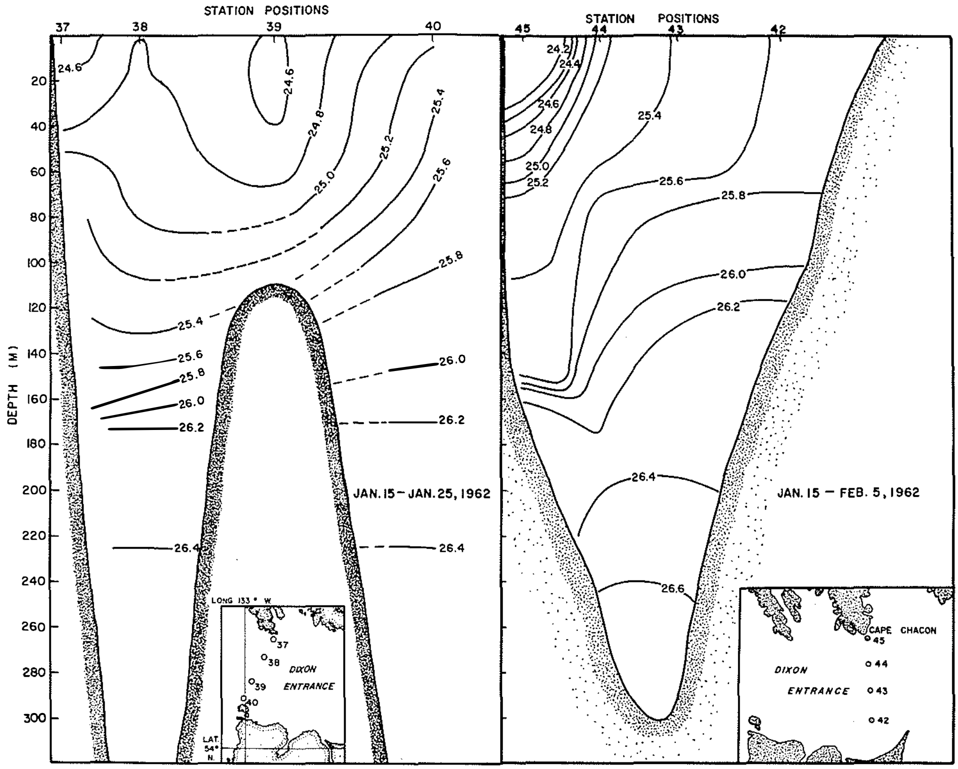

FIG. 36. Cross-sections of density anomaly (σ_t) in Dixon Entrance, January 1962.

From these considerations it may be concluded that the most important single effect of the winds in the northern waters of British Columbia is associated with the action of strong southeasterlies in winter over the exposed coastal waters and in the confines of Hecate Strait. A consequence of the ensuing onshore movement of surface waters in the adjacent ocean is a net northerly "relative" current flowing along the west coast of Vancouver Island and through Hecate Strait. This flow is increased by the direct action of southeast winds channelled northward between the mountain barriers which flank the Strait. Part of this flow continues northward through Clarence Strait, the remainder moving seaward through Dixon Entrance and veering northward again around Cape Chacon. Two important situations may be distinguished. A weak onshore convergence will produce a "relative" current which will be confined to Hecate and Clarence straits. A predominantly conservative situation will exist in Dixon Entrance. A strong onshore convergence, will lead to a "relative" current, probably much enhanced by the direct action of southeast winds in Hecate Strait, finding seaward egress through Clarence Strait and along the northern shores of Dixon Entrance.

ESTUARINE MECHANISM

A positive estuary may be defined as a coastal embayment having free connection to the open sea and a measurable dilution by land drainage (Pritchard, 1952). The mechanism and salinity structures associated with the movement of fresh water through a deep estuary have been discussed by Tully (1952) and Tully and Barber (1960). When the fresh water enters the head of such an estuary it spreads out over the denser sea water forming a halocline. Surface mixing may transform the upper part of this halocline into a mixed layer, of near-uniform salinity, termed the upper zone. With progress seaward, the surface salinity increases as sea water is entrained from below. This leads to a compensatory intrusion of sea water below the halocline which maintains a lower zone of undiluted sea water. These net water movements are superimposed on the tidal currents, which flood and ebb at all depths, and which are primarily responsible for the mixing in the estuary. The effect of Coriolis force on these flows is to produce a net transverse tilting of the mass field, consonant (in the northern hemisphere) with the persistent seaward transport of fresh water along the right-hand side of the estuary (Cameron, 1951).

The fresh water is generally distributed in the upper zone and halocline throughout the estuary by the natural processes of circulation and mixing. Under steady state conditions, the outflow of fresh water from the mouth of the estuary equals the input of fresh water at the head. The distribution of salinity throughout the estuary remains essentially independent of time.

The central problem in any estuarine study usually concerns the flushing of water from the estuary. In the present case the term flushing is considered synonymous with the seaward movement of water in the upper zone and halocline.

Such flushing is particularly important economically in the case of Dixon Entrance where strong seaward movements of this type may seriously affect the extensive ground fishery in northern Hecate Strait, particularly during the crucial period when the eggs or larvae are free floating.

A qualitative assessment of the flushing rates from Dixon Entrance may be made on the basis of salinity changes occurring over the year. The best available sequences of data for this purpose consist of six oceanographic stations, at each of four locations in Dixon Entrance and northern Hecate Strait, observed over the period June 1961 to June 1962. In relating the changes in salinity at each of these locations to the probable water movements in Dixon Entrance, it is desirable to consider the basic pattern of freshwater flow, and effects of the marked seasonal cycles in freshwater runoff and winds.

Freshwater Flow

On leaving Chatham Sound, the freshwater discharge moves in a general northwesterly direction into the southern reaches of Clarence Strait, and among the islands flanking the southeastern part of the Strait. Such a northwesterly set has been reported by the United States Department of Commerce (1952). The division of this flow, part moving northward through Clarence Strait, and part southward around Cape Chacon into Dixon Entrance, may be inferred from the distribution of dynamic height anomaly (Fig. 28). On leaving the vicinity of Cape Chacon, the flow moving seaward through Dixon Entrance spreads southward from the northern shores into the west-central part of Dixon Entrance probably because of the vortex described previously and possibly because of centrifugal forces associated with its passage around Cape Chacon. The persistent occurrence of low salinity water in the west-central part of Dixon Entrance has been noted (Fig. 16). This low-salinity water finds primary egress through the deep channel north of Learmonth Bank.

Seasonal Cycles in Runoff and Winds

The discharge rates of the two main sources of fresh water affecting Dixon Entrance, the Nass and the Skeena, are each subject to a marked annual cycle (Fig. 6). The changes in the vertical distribution of salinity in an estuary occasioned by changes in the freshwater flow rate have been discussed by Tully (1952) and by Waldichuk (1957).

In deep estuaries the predominant cause of mixing is the tides which, as a source of mixing energy, are effectively constant from month to month. If the river discharge is strong, high stabilities result and the time spent by the fresh water on passage through the estuary is short. The depth to which the fresh water is mixed will therefore be relatively small. Under these conditions, the halocline tends to be strong and shallow. Conversely, if the river discharge is small, the halocline tends to be deeper but of smaller magnitude.

Considering now the effects of southeast winds on the salinity field in Dixon Entrance, two important situations may be distinguished. If the southeast winds are strong, a marked "relative" current, northward through Hecate and Clarence straits and westward through Dixon Entrance, results. Under these circumstances, a comparison of salinities in the channels north and south of Learmonth Bank should show that a given value of salinity will occur at greater depth in the northern channel than in the southern one due to the distortion of the density field by Coriolis force. If the southeast winds are weak, the relative current will be largely confined to Hecate and Clarence straits. Under these conditions, the weak seaward flow through the channel north of Learmonth Bank should be characterized by a degradation of the halocline towards homogeneity, because of the increased time spent by the water on passage through the tidal mixing processes in Dixon Entrance. The salinity characteristics of the relative current should be apparent in observations from the eastern part of Dixon Entrance.

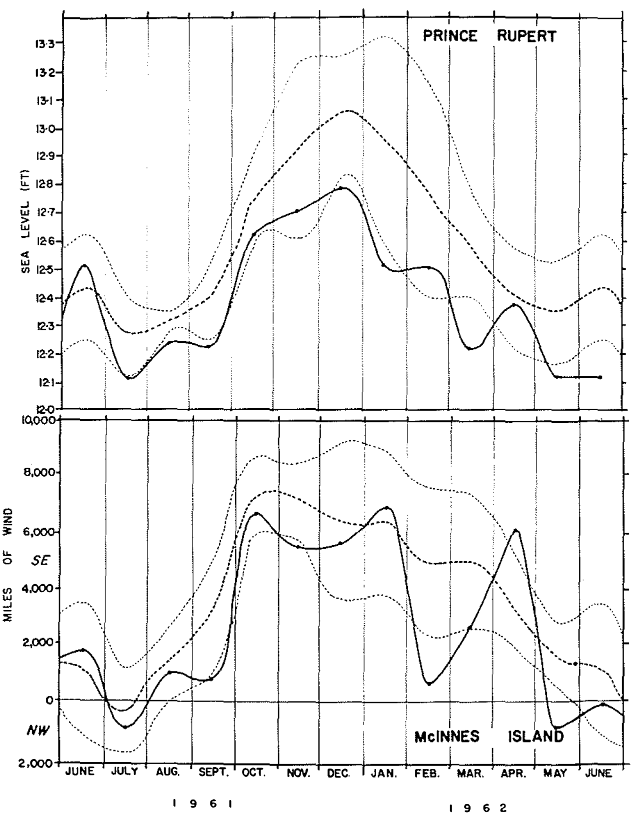

FIG. 37. Comparison of monthly mean sea levels, June 1961 through June 1962, with the grand means, and standard deviations, of monthly mean sea levels at Prince Rupert, 1950 through 1959, and comparison of monthly total miles of wind, resolved along the southeast axis, June 1961 through June 1962, with the grand means, and standard deviations, of the monthly total miles of wind at McInnes Island, 1955 through 1963.

The flushing of water from Dixon Entrance is now discussed using the best available sequences of oceanographic data, which extend over the period June 1961 to June 1962.

Flushing

The most changeable and important factor affecting the flushing of water from Dixon Entrance is the wind. It is thus desirable to examine the wind effects over the period June 1961 to June 1962, and to compare these with the average behaviour normally obtaining. It has already been shown (Fig. 30) that the annual cycle in the monthly mean zonal component of Ekman transport at a location 70 miles seaward of Dixon Entrance was present over this period, though characterized by considerably weaker winter onshore components than usual. In particular, the values in November and December were unusually low.

As noted above, monthly mean sea levels at Prince Rupert afford an approximate index of wind activity in the northern coastal waters of British Columbia. Monthly mean sea levels over the period June 1961 to June 1962, together with the 10-year averages and standard deviations for the same location, are shown in Fig. 37. The annual cycle was present but the values were generally lower than usual.

Indicative of the winds in Hecate Strait, the total monthly miles of wind at McInnes Island resolved along the southeast axis, for the period June 1961 to June 1962, are also shown in Fig. 37, together with the 10-year averages and standard deviations. It is apparent that the monthly mileages conformed approximately to the long-term cycle.

The oceanographic observations over the period June 1961 to June 1962, are presented in terms of salinity sequences, distributions of surface salinity and dynamic height anomalies. Seasonal changes in the salinity field are characterized by salinity sequences at four locations (Fig. 38), based on Monitor cruise data augmented by other data (Dodimead, 1961; Dodimead et al., MS, 1962) at virtually the same locations.

Station 40 is located in the deep channel south of Learmonth Bank. The estuarine flow seaward through this channel is small and salinity changes at this location are descriptive of conditions along the exposed coast. In particular, it will be shown that in winter this station is generally representative of the region of convergence between the onshore oceanic surface water movement, and the "relative" current along the mainland coast.

Station 38 is located in the deep channel north of Learmonth Bank which affords primary egress to fresh water, in the upper zone and halocline, moving seaward through Dixon Entrance. Since the water in Dixon Entrance is generally less saline than that to seaward, such a flow must persist, although large variations may be anticipated. An important feature of this location is the influence of that part of the "relative" current which moves through Hecate Strait in early winter but which does not continue northward through Clarence Strait.

Station 58 is descriptive of conditions in the eastern part of Dixon Entrance. Throughout most of the year the dominant influence is the northerly flow from Hecate Strait.

Station 61 is located at the northern end of the deepest channel linking Queen Charlotte Sound to Dixon Entrance, and is primarily descriptive of water moving into Dixon Entrance from Hecate Strait. Tides, wind, and runoff generally act in concert to maintain a new northerly flow at this location; again, marked variations may be anticipated.

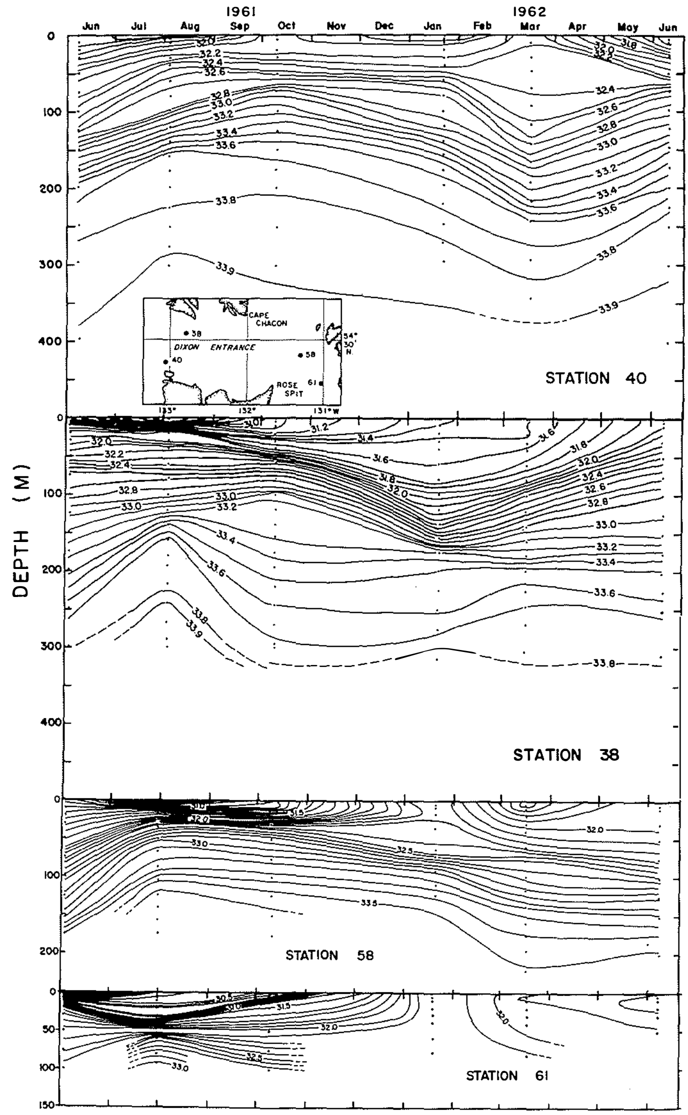

FIG. 38. Salinities (‰) at stations 40, 38, 58, and 61 in Dixon Entrance, June 1961 through June 1962.

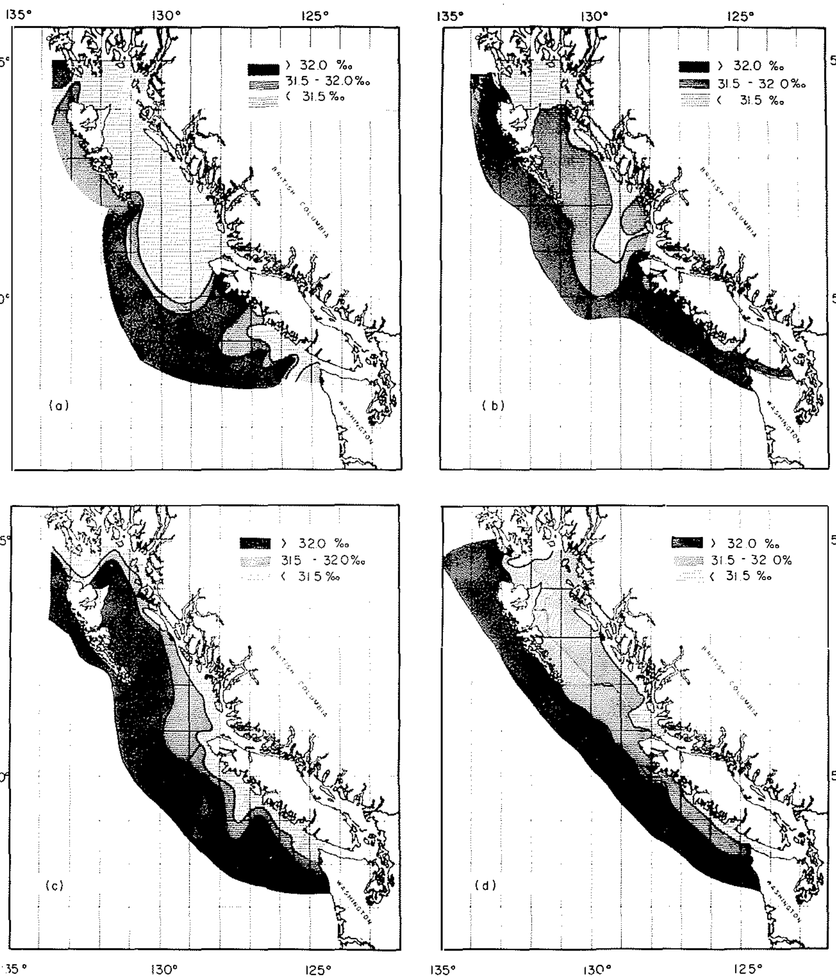

FIG. 39. Distributions of surface salinity (‰) in the coastal waters of British Columbia: (a) July 24—August 8, 1961; (b) September 21—October 17, 1961; (c) January 15—25, 1962; (d) March 12—21, 1962.

Complementary to the above changes in salinity at particular locations, Fig. 39 shows the general distributions of salinity at 5 m depth observed in July–August and October 1961, and January and March 1962. It has been noted above that the oceanographic properties of Dixon Entrance are contingent to a large degree upon processes extending well beyond the limits of its own boundaries. It is thus of interest to consider the major continuities of surface salinity in the coastal waters of British Columbia, with reference to conditions in Dixon Entrance.

Lastly, indicative of the major directional features of the circulation in Dixon Entrance, the dynamic height anomalies relative to 100 m for the months July–August, October 1961, and January and March 1962, are illustrated in Fig. 40.

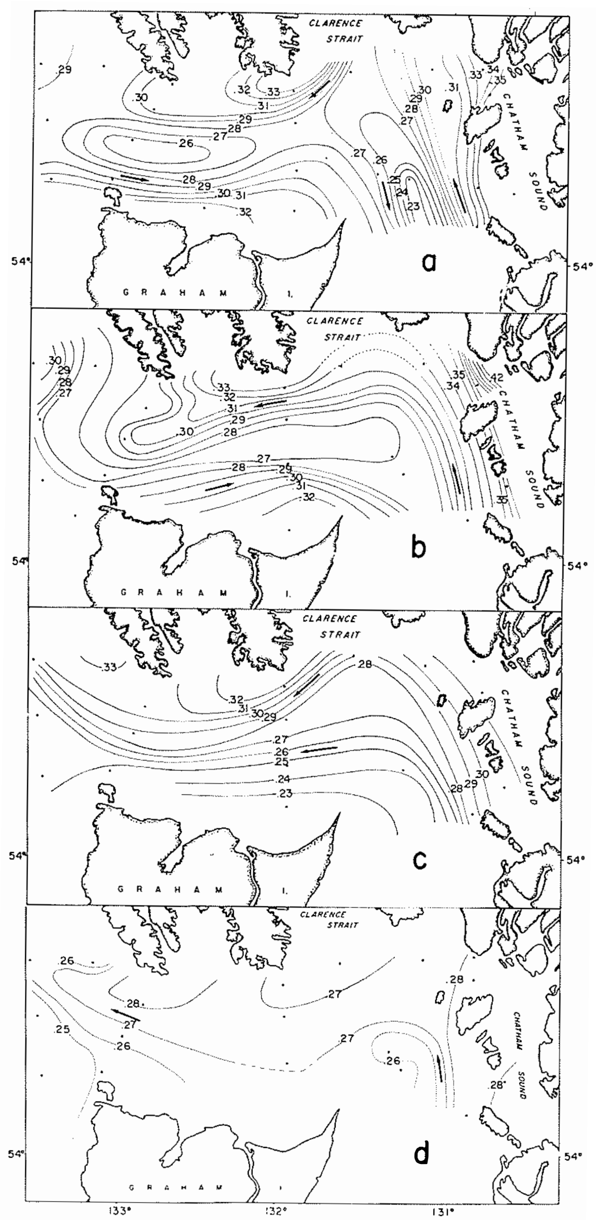

FIG. 40. Distributions of dynamic height anomaly (ΔD) in Dixon Entrance, 0/100 m; (a) July 31–August 3, 1961; (b) October 6–13, 1961; (c) January 18–21, 1962; (d) March 15–17, 1962.

Again, as in the discussion of the tidal vortex, it is assumed that dynamic heights may be used for this purpose. The selection of a 100 m rather than the 125 m reference surface, used in the previous case, was occasioned by the rather better coverage by stations of sufficient depth.

During the period June through August the monthly mean components of zonal Ekman transport were small (Fig. 30). At Prince Rupert, the monthly mean sea level (Fig. 37), though relatively high in June, fell to minimal values in July and August. In Hecate Strait, the monthly total mileages of wind were small.

Over the same period the upward movement of the deeper isohalines (below about 100 m) at all stations indicated a marked increase in the salinity of the deeper water throughout Dixon Entrance (Fig. 38). Surface freshening was apparent at stations 38, 58, and 61, although at station 40 there was little change.

In July–August, the salinities at 5 m depth (Fig. 39a) throughout the coastal seaways were low (less than 31.5‰), evidently a consequence of the major efflux of fresh water associated with the spring thaw. At the mouth of Dixon Entrance, the remainder of a tongue of this low-salinity water extended seaward in a southwesterly direction. Tongues of relatively low-salinity water were observed to extend over a hundred miles to seaward of Dixon Entrance in August 1958 and August 1959 (Favorite, 1961). In the present instance, low-salinity surface water was responsible for the low densities at station 200 (Fig. 31) in August 1961, and was consistent with the presence of such a tongue. It is of interest to note that, in July, the monthly mean meridional component of Ekman transport (Fofonoff, 1962) was southward, thus favouring a drift of this tongue towards the location of station 200.

The dynamic height anomalies relative to 100 m in July–August (Fig. 40a) showed that the flow in Dixon Entrance was largely dominated by the cyclonic vortex which, at this time, appeared to have shifted towards the mouth of Dixon Entrance. Evidence of such a seaward shift of this cyclonic circulation was also apparent in data obtained in June 1959 (Pacific Oceanographic Group, MS, 1959) and in August 1954 (Pacific Oceanographic Group, MS, 1955). From these considerations, it is reasonable to infer that between June and August 1961 two mechanisms, acting in concert, brought about a major change in the distribution of salinity in Dixon Entrance. The first of these was a densimetric exchange flow associated with the final relaxation of the convergence of the previous winter. The second was the major discharge of fresh water, which produced a strong seaward movement near the surface and compensatory intrusion of undiluted oceanic water at depth. The surface flow was strongest along the northern shores of Dixon Entrance, thus enhancing the natural tidal cyclonic recirculation. It has been estimated that a strong flushing of this type in Queen Charlotte Sound could occur over a 2-week period (Barber, 1957).

In September a relatively quiescent situation prevailed, as shown by minimal values of the monthly mean zonal component of Ekman transport (Fig. 30), the monthly mean sea levels at Prince Rupert (Fig. 37), and the southeast components of wind at McInnes Island (Fig. 37). In October there occurred a marked increase in all three variables.

At stations 40, 38, 58, and 61 (Fig. 38), surface salinities increased. At station 38, there was a rapid increase in the depth of the deeper isohalines (below 125 m). At station 61, there was evidence of mixing in the water column at depths greater than about 25 m. This suggests that the progress of fresh water seaward was retarded, and that there was a dominantly conservative situation.

In September–October, the region of low salinity was confined to the mainland shores and to Dixon Entrance (Fig. 39b). Hecate Strait was dominated by an extensive area of intermediate-salinity water (31.5–32.00‰). Across the mouth of Dixon Entrance, there was a strong horizontal salinity gradient.

The dynamic height anomalies (Fig. 40b) suggest the development of a strong flow northward along the eastern boundary of Dixon Entrance, and westward along the northern shores. Strong southerly winds were observed at McInnes Island during the week preceding these observations in Dixon Entrance (Canada Department of Transport, 1962, personal communication).

It may be inferred that there existed an essentially conservative situation in Dixon Entrance during August and September. In October, the onset of the winter southeast winds heralded the start of the strong northerly drifts through Hecate Strait.

During the period November through January, the onshore component of Ekman transport, the monthly mean sea levels at Prince Rupert, and the wind mileages in Hecate Strait were generally high.

At station 40 (Fig. 38), the deeper isohalines (below 100 m) descended, indicating a general coastal convergence. At station 38, the isohalines in the upper part of the halocline (between 50 and 150 m depth) descended sharply and were surmounted by a deepening zone of near-isohaline water. Salinites at depth (below 150 m) showed negligible change. At station 58, there was also a deepening of the upper zone, associated with the descent of the deeper isohalines. At station 61 the halocline disappeared.

In January (Fig. 39c), there was a marked salinity gradient along the eastern shores of Hecate Strait. The greater part of the Strait itself was filled with high salinity water extending northward into the eastern part of Dixon Entrance. Along the northern shores, and in the western part of Dixon Entrance, there was still an extensive area of low-salinity water. Conditions prevailing at this time have been discussed already in connection with wind drifts in Hecate Strait, and probably typify the situation in Dixon Entrance between the frequent storms of early winter.

The dynamic height anomalies (Fig. 40c) suggest a well-developed seaward flow through Dixon Entrance.

Throughout this period, the inshore current associated with the general coastal convergence was well developed along the eastern shores of Hecate Strait and the northern shores of Dixon Entrance. This was essentially a continuation of the winter coastal current moving along the west coast of Vancouver Island (Lane, 1963) and into Queen Charlotte Sound (Barber, 1957). The heavy precipitation of early winter on the seaward slopes of the coast mountains had been confined along the eastern and northern shores of Hecate Strait and Dixon Entrance.

During this period, the marked intrusion of water from Hecate Strait could be expected to override the denser water at depth in Dixon Entrance, resulting in a strong flushing of less-dense water from the region. The actual mechanism of flushing during this period was probably one of great complexity, involving a buildup of sea level, in the inlets and seaways, under the influence of strong southeast winds, followed by strong relaxation currents when the wind dropped. Below this zone of strong flushing a largely conservative regime was maintained. (It will be shown later that temperatures as well as salinities in the deeper water at station 38 underwent relatively little change throughout the greater part of the year.) It was noted previously in connection with the tidal mechanism that the temperature-salinity relations of the water associated with the vortex (domain 3, Fig. 29) were characterized by a marked degree of lateral uniformity. The site of station 38 was located in this circulation. This suggests that a major change in the deeper water of the vortex only occurs during a brief interval in summer. The persistence of the halocline during the winter, however, must require some intrusion and mixing of oceanic water at depth.

One of the most interesting features during this period was the marked difference between salinity distributions at stations 40 and 38 (Fig. 38). This may be attributed to the location of the former in the region of coastal convergence, and the location of the latter in the relative current which was associated with this general coastal convergence and which, during this period, found seaward egress through Dixon Entrance as well as through Clarence Strait.

During the period February through March, there was a general decrease in the monthly mean onshore component of Ekman transport (Fig. 30), in the monthly mean sea levels at Prince Rupert, and in the monthly total mileages of southeast wind in Hecate Strait (Fig. 37).

At station 40 (Fig. 38), the deepening of the isohalines below 50 m indicated a continuation of the general coastal convergence. At station 38, the isohalines above about 175 m sloped steeply upward, while the deeper isohalines remained relatively level, indicating increased salinities in the upper part of the water column consistent with a basically conservative situation. At station 58, there was evidence of freshening near the surface, while at depth the isohalines continued to descend. This implied a net increase in the freshwater content of the water column, and hence the advection of low salinity water towards this location. At station 61, near-uniform salinities extended from the surface to the bottom.

In March, water of intermediate salinity (31.5–32.00‰) predominated throughout Hecate Strait and Dixon Entrance (Fig. 39d). A small tongue of low-salinity water extended from Clarence Strait westward along the northern shores of Dixon Entrance. Across the mouth of Dixon Entrance, there was a continuous regime of high-salinity water (>32‰).

The relatively small differences in the horizontal distribution of mass in the upper 100 m precluded any well-developed evidence of circulation being obtained from the dynamic topography (Fig. 40d).

Throughout this period, the general coastal convergence continued. The difference between the distribution of salinity in the water column at station 38 and those in the columns at stations 58 and 61 suggests that the current along the eastern shores of Hecate Strait moved northward through Clarence Strait, rather than seaward along the northern shores of Dixon Entrance. This was predominantly a period of retention, and flushing through Dixon Entrance was relatively weak.

In the period April through June, the general decreases in the monthly mean zonal component of Ekman transport (Fig. 30), the monthly mean sea levels at Prince Rupert (Fig. 37), and the monthly total mileages of southeast wind in Hecate Strait, were interrupted by secondary maxima in April. The absence of oceanographic data in April and May obviates the possibility of assessing the possible consequences with respect to the water in Dixon Entrance. For present purposes, it is probably sufficient to note the following. Between March and June the onshore monthly mean component of Ekman transport had been replaced by a weak offshore component. There was a net decrease in monthly mean sea levels at Prince Rupert. In Hecate Strait, the monthly total mileages of southeast wind had given way to a weak component of northwest wind.

At station 40 (Fig. 38), the deeper isohalines (below 100 m) rose to depths comparable with those of the same isohalines at that location in the previous June. There was evidence of freshening near the surface. This indicated a relaxation of the winter convergence. At station 38, salinities in the upper 150 m increased, suggesting a predominantly conservative mixing situation. At station 58, a freshening of the water column at depth again suggested a primarily conservative situation. At both stations 38 and 58, the depths of the isohalines in June 1962 were similar to those found in June 1961.

From these considerations, it may be inferred that there existed a predominantly conservative situation in Dixon Entrance over this period. The relaxation of the winter convergence had begun seaward of Dixon Entrance, and conditions were propitious to the onset of the major flushing of the region associated with the spring thaw and the final relaxation of the convergence.

Briefly, in summary, during the periods June–July and November through January, high flushing rates occur. During the remaining periods August through October, and February through May, low flushing rates may be anticipated.

HEAT TRANSFER MECHANISM

The distribution of temperature within the sea is primarily determined by heat transfer at the air–sea interface and by advective and turbulent processes beneath the sea surface. It has been shown (Fig. 12) that the heating season normally extends from the latter part of March to the latter part of September. Throughout the remainder of the year there is usually a net heat loss from the sea surface, the maximum loss occurring in January. Though the seasonal growth and decay of the thermocline is generally similar throughout Dixon Entrance, heat-budget studies have shown that there exist marked anomalies between the calculated heat transfer through the sea surface, and the actual heat content of the water (Tabata, 1958). It has, for example, been noted that the deeper water in Dixon Entrance is somewhat warmer in winter than in summer (Fig. 20). It has thus been inferred that advection is of considerable importance in determining the temperature field in Dixon Entrance. In the present section, the seasonal temperature changes will be discussed using sequences of temperature concomitant with those of salinity already presented for four locations in Dixon Entrance (Fig. 38) and aspects of the winter wind-induced advections in Hecate Strait. Initially, however, it is desirable to review the major features of the temperature distribution over the general coastal and offshore regions of British Columbia.

Based on the aggregate of temperature observations in the northeastern Pacific during the years 1941–52, the long-term averages of the monthly mean temperature distributions have been described (Robinson, 1957). Seaward of British Columbia the characteristic feature is a warm tongue extending northward with its axis roughly parallel to the coast. Temperatures defining the inshore side of this tongue are determined by processes on the continental shelf, which generally involve more rapid heating in spring, or cooling in autumn, than is the case in the oceanic waters. Close inshore the isotherms are approximately normal to the coast, with temperatures decreasing from south to north. The major axis of the surface tongue appears to be situated closer to the coast in winter than in summer. A comparable subsurface warm tongue is apparent at a depth 60–120 m only during winter and spring.

Temperature Sequences

Sequences of temperature, concomitant with the previous sequences of salinity during the period June 1961 to June 1962, are shown in Fig. 41.

From June to August, surface temperatures increased, and the formation of a strong shallow thermocline coincident with the halocline (Fig. 38) is evident at all four locations. Decreasing temperatures at depth were associated with the intrusion of oceanic water, and hence are in agreement with the strong flushing which occurred during this period.

From August to October, surface temperatures decreased at stations 38, 58, and 61, and the formation of a mixed layer near the surface became apparent. A downward slope of the deeper isotherms indicated a warming of the water at depth; it will be remembered that during this period the isohalines (Fig. 38) also deepened. This is consistent with the onset of the winter convergence.

From October to January at all locations, the cooling and deepening of the mixed layer near the surface proceeded rapidly. Such a deepening is in reasonable correspondence with the behaviour of salinity (Fig. 38). However, comparison of the distribution of isotherms at depth at stations 40 and 38 shows a marked difference. At station 40, a temperature maximum was located in the halocline. Below the halocline the water was notably warmer than during the preceding summer months. It is reasonable to infer that the deep estuarine compensatory intrusion required by the persistence of the halocline in Dixon Entrance was moving relatively warm water into the region at depth. By contrast, the properties of the deeper water at station 38 underwent relatively little change throughout the remainder of the period (Fig. 38 and 41). It has been noted that a temperature-salinity classification of the data obtained in Dixon Entrance in September–October 1962, showed that the vortex area (Fig. 29) included the location of station 38. This suggests that the deeper water associated with the vortex (below about 200 m) undergoes relatively little change throughout the greater part of the year.

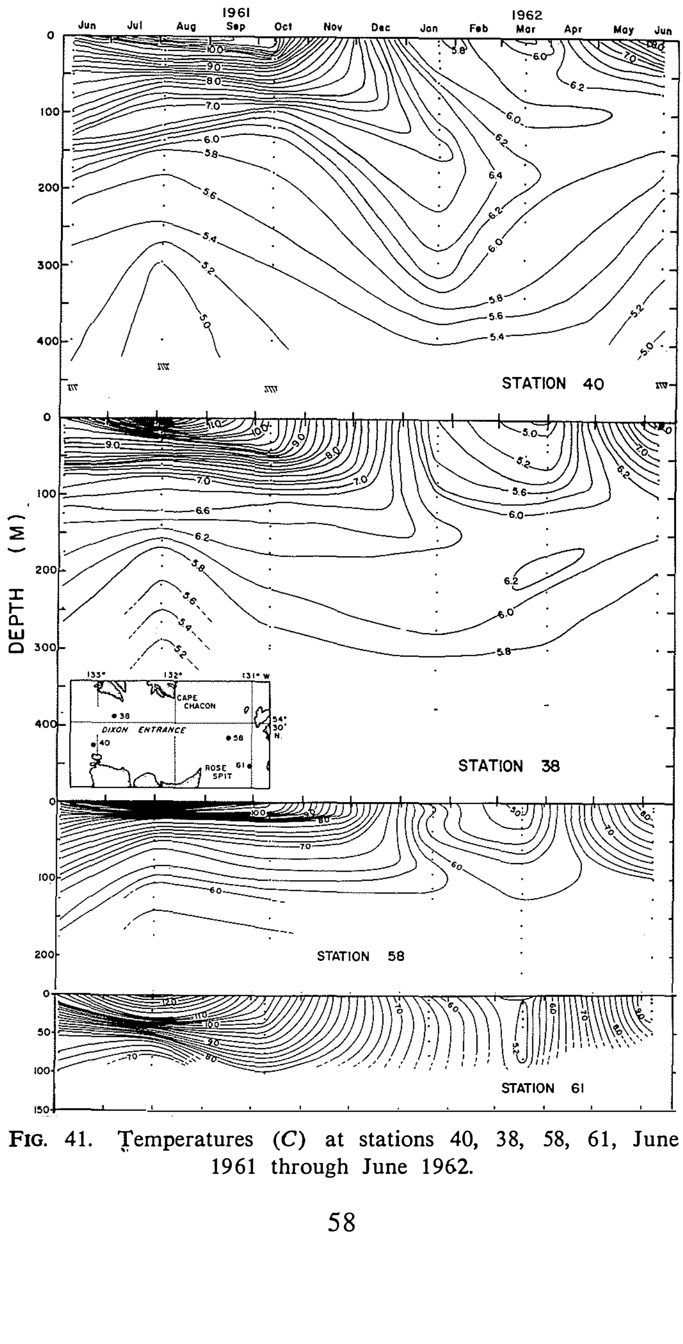

FIG. 41. Temperatures (*C*) at stations 40, 38, 58, 61, June 1961 through June 1962.

It is unfortunate that the gap in oceanographic data during this period did not permit a better assessment of the timing of changes brought about in Dixon Entrance by the winter current from Hecate Strait, moving seaward along the northern shores.

From January to March, surface temperatures continued to fall at stations 38, 58, and 61, although at station 40 there was relatively little change. The formation of a weak positive vertical gradient was apparent in the upper 100 m at stations 38 and 58. At station 61, temperatures were nearly uniform from surface to bottom, and continued to decrease. The deeper water at stations 38 and 58 showed little change in temperature. The contrast between the temperature inversions, at about 200 m depth, at stations 40 and 38 reflected the mixing effects associated with the vortex circulation. It is of interest to note that there was a general gradation of temperatures, in the upper 100 m, from station 61 (6.2–6.6 C), to station 58 (5.6–6.2 C), to station 38 (5.4–6.0 C). This is consistent with a warm advection from Hecate Strait and will be discussed further below.

From April to June, with the commencement of the summer heating period, sea surface temperatures increased and a thermocline began to form at stations 40, 38, and 58. At stations 40 and 38 the cooling at depth was consistent with the beginning of a relaxation of the winter convergence, as previously inferred from the salinity data at this location (Fig. 38). At station 61, near-uniformity of temperature still persisted throughout the water column.

Winter Flows in Hecate Strait

The temperatures associated with the winter flow through Hecate Strait will be determined by the degree of cooling encountered by the relatively warm water from the south during its passage northward. Initially, the strength of the northward flow is sufficient to maintain a relatively high temperature. The data of January 1962 showed a strong intrusion of high-salinity water into the eastern part

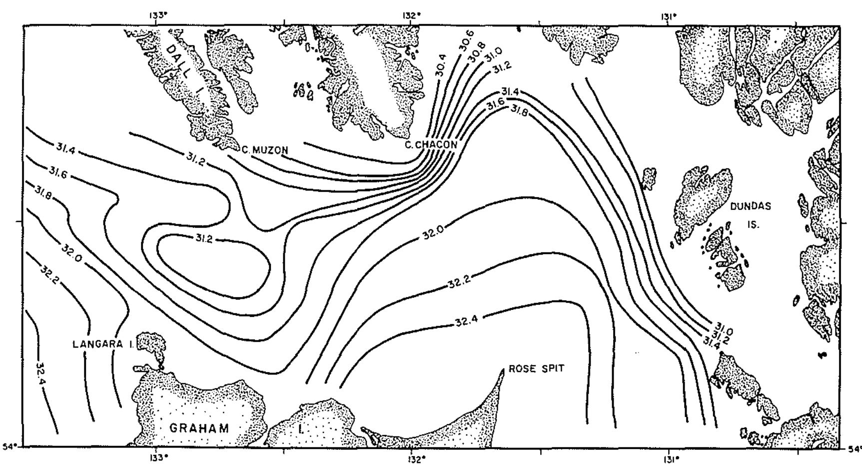

FIG. 42. Distribution of temperature (*C*) at 5 m depth, January 1962.

of Dixon Entrance (Fig. 35). The accompanying horizontal distribution of temperature at that time (Fig. 42) shows that this intrusion was substantially warmer than the water already in Dixon Entrance. A longitudinal section of temperature through the deep channel in the northeastern part of Hecate Strait (Fig. 43) affords an interesting illustration of the conditions then obtaining. It will be recalled that these observations in northern Hecate Strait and Dixon Entrance were made at the end of a general period of relaxation following strong winds during the earlier part of the month. A strongly mixed body of water, decreasing in temperature from south to north, is clearly evident in the central part of the section. It may be inferred that this water mass constitutes part of the strong northern intrusion which occurred during the previous weeks. The effect of local cooling has become apparent with the inception of a temperature gradient close to the surface.

From an examination of data for the months of January over a 19-year period, it has been shown by Eber (1957) that strong winds from the south are associated with high monthly mean sea surface temperatures at Triple Island, while weak southerly winds are associated with low mean monthly temperatures. He inferred that the marked loss of heat from the sea surface usually occurring in January (Fig. 35) is mitigated by the marked wind-induced advections coming

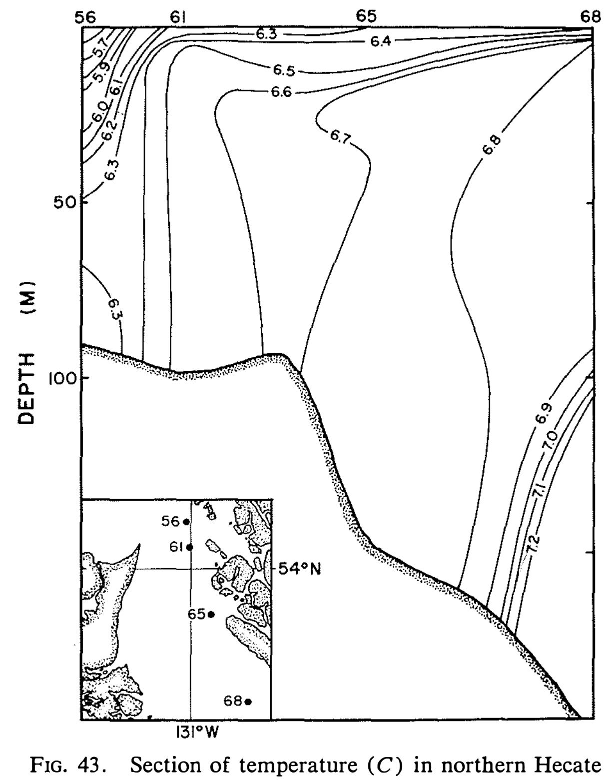

FIG. 43. Section of temperature (C) in northern Hecate Strait, January 1962.

from the south through Hecate Strait. Conversely, weak wind-induced advection northward will generally result in a greater degree of cooling and, consequently, in lower temperatures. Eber (1957) further noted that anomalous conditions occurring in January generally persisted through February and March. The wind indices used in this study reflect conditions over an extensive oceanic and coastal area to the south of Hecate Strait. Therefore, this persistence may readily be interpreted as a general lowering of the temperatures associated with the northward advections which occur during the latter part of winter. These conclusions agree with those deriving from other investigations. It has been shown that between August 1954 and February 1955 an intrusion of warmer water into Dixon Entrance must have occurred (Tabata, 1958). In a study of factors influencing the survival of lemon sole in Hecate Strait, Ketchen (1956) concluded that fluctuations in the strengths of year-classes are associated with the low temperatures prevailing in Hecate Strait when the northward flow is weak.

It may be concluded that the most important factors governing the field of temperature in Dixon Entrance are the heat transfer at the sea surface, the intrusion of cold oceanic water at depth in summer, and the advection of relatively warm water north through Hecate Strait in winter.

SUMMARY

Characteristic seasonal cycles associated with precipitation, runoff, salinities, winds, Ekman transport, sea level, sea surface temperatures and heat transfer, have been established using long-term monthly means of data regularly monitored in Dixon Entrance and vicinity. Of these data, the greatest lability is displayed by the winds. Major features of the seasonal distributions of temperature and salinity have been enumerated and discussed. Tidal, wind, estuarine, and heat-transfer mechanisms have been discussed and shown consistent with the available aggregate of data. These considerations lead to a general seasonal model of oceanographic behaviour, which may be summarized as follows:

By spring (April–May) the strong southeast winds of the preceding winter months have moderated considerably. The discharge of fresh water into the region increases rapidly with the onset of the spring thaw, both in the coastal drainage area and in the basins of the Nass and Skeena rivers. The net northward flow through Hecate Strait is reduced. Most of what flow does occur continues northward through Clarence Strait. The general onshore convergence of surface waters in the adjacent ocean begins to relax. In Dixon Entrance a basically conservative system is dominated by the net cyclonic circulation induced by the meeting of the tides in northern Hecate Strait.

In summer (June–August) the influence of southeast winds is minimal. In early summer, a strong discharge of fresh water from the Nass and Skeena rivers moves seaward through Dixon Entrance. The net northward flow through Hecate Strait becomes negligible.

The strong freshwater discharge seaward, acting in concert with a densimetric exchange flow occasioned by the final relaxation of the onshore convergence, engenders a major flushing of brackish water from the region, and a strong intrusion of cold, saline, oceanic water at depth.

Throughout the remainder of the summer the seaward flow of fresh water decreases and is largely confined to Clarence Strait, and the northern shores and west-central part of Dixon Entrance. The net cyclonic circulation includes in its extent the seaward approaches. The net inward flow, along the southern side of Dixon Entrance, may be enhanced by westerly winds.

In autumn (September–October) there is a marked increase in southeast winds. The freshwater discharge associated with high precipitation in the coast drainage area increases to a secondary maximum in October. This discharge is confined largely to Clarence Strait. The northward flow through Hecate Strait increases. A general onshore convergence of surface waters in the adjacent ocean begins. The net tidal cyclonic circulation dominates the central part of Dixon Entrance. The seaward flushing of brackish water through Dixon Entrance is weak.

In winter (November–March) two regimes of behaviour may be distinguished. In early winter, southeast winds are maximal. The discharge of fresh water is relatively small since most of the precipitation is retained in the mountains as snow. There is a marked onshore movement of oceanic surface water. Associated with this movement is a well-developed northward flow, or "relative" current, through Hecate and Clarence straits. In particular, in its passage through Hecate Strait, this flow is much enhanced by the direct action of winds channelled northward through the Strait. In consequence, a marked movement of water seaward through Dixon Entrance occurs. This water then resumes its northward course along the exposed coasts of southeastern Alaska. The water comprising the northward flow through Hecate Strait is relatively warm, due to the mitigation of local cooling by the rapidity of its northward translation.

In late winter, the southeast winds gradually decrease. The freshwater discharge remains small. The flow through Hecate Strait is reduced, most of it continuing northward through Clarence Strait. The onshore movement of oceanic surface water continues, but with diminished intensity. In Dixon Entrance, a basically conservative situation obtains, dominated by the net cyclonic circulation. The seaward flushing of brackish water is weak.

In conclusion it must be noted that the general model of behaviour described above undoubtedly represents a major simplification of the actual processes involved. Further understanding of the problem must thus involve the continuous recording of variables at strategic locations throughout the region, and the relating of these variables to the primary causal features.

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