Queen Charlotte Sound, Hecate Strait, and Dixon Entrance form a continuous coastal seaway over the continental shelf of the Canadian west coast (Fig. 14.1). Except for the broad lowlands along the northwest side of Hecate Strait, the region is typified by a highly broken shoreline of islands, isolated shoals, and countless embayments which, during the last ice age, were covered by glaciers that spread seaward from the mountainous terrain of the mainland coast and the Queen Charlotte Islands. The irregular countenance of the seaway is mirrored by its bathymetry as re-entrant troughs cut landward between shallow banks and broad shoals and extend into Hecate Strait from northern Graham Island. From an oceanographic point of view it is a hybrid region, similar in many respects to the offshore waters but considerably modified by estuarine processes characteristic of the protected inland coastal waters. Deep-sea processes, tides, winds, and river discharge are all important factors in the establishment of the currents and water structure in this semiexposed marine environment.

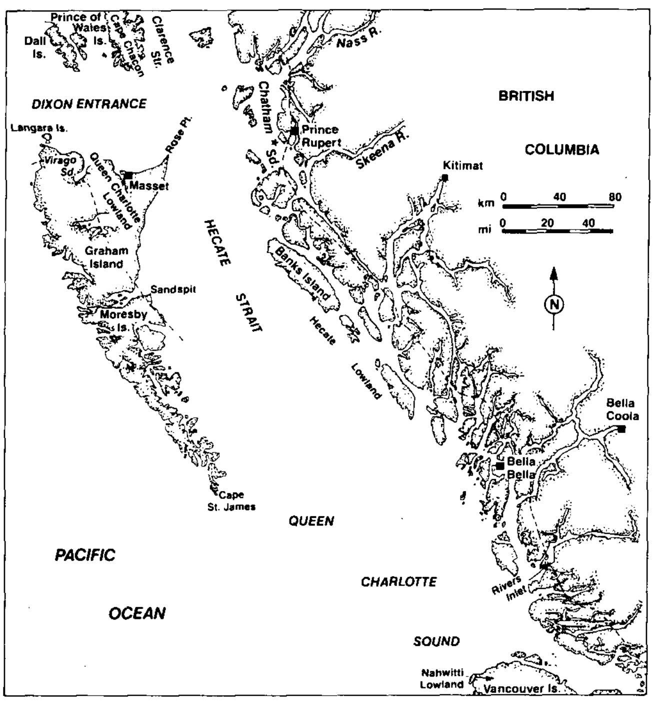

FIG. 14.1. Map of northwest Pacific coast. Broken lines show extent of coastal lowlands; wave measurements taken at star near Prince Rupert.

A Brief History

Long before the arrival of the "discoverers," the north coast Indians had evolved one of the most distinctive and sophisticated cultures in the Americas. The Haida, or "people" of the Queen Charlotte Islands, were especially skillful seamen and fishermen, whose sleek war canoes were almost as long as the ships of the early Spanish and British explorers. The Haida also were gifted carvers and produced a volume of art work which, like that of the mainland tribes of the Kwakiutl and Tsimshian, is only now becoming appreciated by the general public.

The first Europeans to sail the west coast of British Columbia were Spaniards. Under the command of Juan Perez they reached the vicinity of the Queen Charlotte Islands in 1774 before returning to a landfall at Nootka Sound on Vancouver Island. Quadra followed in 1775, but it was not until after Cook's voyage of 1778 with the *Resolution* and *Discovery* that the white man, or "Yets-haida" (iron men) as the Haida called them, began to explore in earnest the northern coastal waters. During his sojourn at Nootka that year Cook had received a number of soft, luxuriant sea otter furs which, after his death in Hawaii, members of his crew sold for high prices on arrival in China in 1779. News of his ships' windfall caused trading ships of several nations to sail to the coast to obtain sea otter furs for the China market.

It was the search for furs that brought about most of the early exploration of the coast. Dixon Entrance, for example, was named after Captain George Dixon, master of the 200-t *Queen Charlotte*, that passed the mouth of the channel in 1787 during a trading expedition for sea otter furs. (The channel was named in 1788 by Sir Joseph Banks who had been botanist and naturalist on Cook's round-the-world voyage in the *Endeavour* from 1768 to 1771 and in whose honor Banks Island in Hecate Strait is named.) "As he sailed southward Dixon met with a large island or islands, where he purchased a large number of sea otter skins. Rounding the southern termination of the land which he named Cape St. James, he sailed northward along the eastern shore until he recognized ahead the high mountains seen some days before, northward of a large opening in the coastline. Dixon thus ascertained the land he had been trading along was a large island or islands, and gave them the name of his vessel, Queen Charlotte isles. In 1789 Captain Gray, of the American trading sloop *Washington*, visited these islands, and named them after his vessel. As the ownership of the islands was established in Great Britain . . . the group has long been known by their present name." (Walbran 1971)

Hecate Strait received its name in 1861 after H. M. surveying vessel *Hecate*, a paddle-wheel sloop, 780 t, 5 guns, and brigantine rigged that worked the British Columbia coast from December 1860 to December 1862. The name for Queen Charlotte Sound was given in 1786 by the commander of the *Experiment* after the wife of George III of England, and adopted by Vancouver during his charting of the coast between 1792 and 1794.

Shoreline Features

The coastal seaway lies within the Hecate Depression, a segment of a continuous, low-lying area that extends from Puget Sound to Alaska (Fig. 1.11, 14.1). This depression includes the narrow, 20–50 km wide plain along the island-strewn mainland coast (the Hecate Lowland), the low relief northeast corner of Graham Island (the Queen Charlotte Lowland), and the rocky flatlands of northern Vancouver Island (the Nahwitti Lowland). To the east lie the Coast Mountains, to the west the open Pacific Ocean and the insular mountains of the Queen Charlotte Islands. The latter are especially rugged and plunge steeply into the sea off western Moresby Island. Nearly vertical sea cliffs over 200 m high are common and the short gravelly beaches that have managed to form are mostly associated with the numerous fiords that indent the outer coastline. The contrast between this area and the inner coast is striking.

The shoreline of the Nahwitti Lowland consists of shallow, open embayments, rocky intertidal zones, long stretches of gravelly beaches, and numerous small river deltas. Within the Hecate Lowland, the coastline is characterized by discontinuous sand, gravel, and boulder beaches between low rocky headlands. The Skeena River which enters these lowlands some 20 km south of Prince Rupert, has the second largest delta in British Columbia, and extends about 30 km to the west into Chatham Sound and adjoining channels. Unlike most deltas in British Columbia, it is neither at the head of an inlet nor directly exposed to a large body of open water, and exhibits no extensive tidal flats. However, the river sediments have effectively broadened the delta by "cementing" together the various islands situated seaward of the river mouth. Also, currents at the mouth of the river, which may attain speeds in excess of 1.5 m/s (3 kn), have formed extensive bars. The bars have megarippled surfaces with heights to 0.5 m and spacings over 10 m.

The Queen Charlotte Lowland has some of the most fascinating beach forms in British Columbia. Along Virago Sound, large beaches have been created through wave erosion and onshore current-induced movement of offshore bottom sediments. Between Massett and Rose Point to the east, similar processes have led to the formation of a continuous sand beach with a 200-m wide foreshore that slopes gently into Dixon Entrance (Fig. 14.2) The backshore is characterized by a series of dunes and ancient beach forms to 10 m above present sea level. In addition to widening the beach, the vast nearshore supply of sediment is transported eastward in the littoral zone, where it eventually contributes to the growth of Rose Spit that projects more than 12 km to the northeast of the trees on Rose Point. The beach-type environment continues some 65 km south of Rose Spit, but with a foreshore that is steeper,

Fig. 14.2. Broad sandy beach, McIntyre Bay, facing Dixon Entrance, Graham Island, Queen Charlotte Islands. Beaches on northeast Graham Island are unlike most on British Columbia coast. Sediment is plentiful, beaches wide, with sandy and extensive backshore dunes. (Courtesy J. Harper.)

narrower, and of coarser sediment than along the north coast. Sea cliffs in this region range from 15 to 60 m high and dunes are present 100–200 m inland of the backshore (see Fig. 8.11). In contrast to the north coast, beach sediments are actively being removed by littoral processes, which then carry them northward to Rose Spit.

Another pronounced depositional feature within the confines of the Queen Charlotte Lowland is Sand Spit which curves for nearly 5.5 km half way across the entrance to Skidegate Inlet. As with the gradually eroding beaches to the north, it suggests the presence of a net northward surface drift along the western shores of Hecate Strait.

Bathymetry

Dixon Entrance is an east–west depression in the continental shelf bounded over most of the 170-km length by the mountainous Dall and Prince of Wales islands to the north and by Graham Island to the south. At the seaward end it is split into two 400-m deep channels by Learmonth Bank, a shallow ridge that rises to within 35 m of the surface (Fig. 14.3). To the east, these channels recombine to form a single depression that gradually shoals to 270 m over a sill south of Cape Chacon, followed by more rapid shoaling over the submarine ridge that separates Dixon Entrance from Chatham Sound. The main axis of the depression continues into Clarence Strait, a 400-m deep trench leading 200 km seaward through the Alaska Panhandle.

Hecate Strait is the shallowest of the major channels that make up the Hecate Depression. It is also the least exposed and has the most regular bathymetry. The axis of the Strait is a narrow, 220 km long submarine valley that hugs the mainland flank, with depths that diminish from around 300 m in the south to about 50 m in the north. The northwest side of the Strait is a broad platform of glacial sands and gravels less than 100 m deep, adjacent to the flat coastal plain or strandflat of east Graham Island.

The bathymetry of Queen Charlotte Sound is considerably more complex than either Hecate Strait or Dixon Entrance because of shallow banks and three broad troughs that slice inland across the continental shelf from depths of 350–400 m (Fig. 14.3). Of these, the northern trough is the most irregular and most extensive and trends 270 km northward along faulted, ice-deepened depressions to form the deep channel of Hecate Strait. The central and southern troughs, on the other hand, shoal rather smoothly toward the mainland coast; the southern trough divides about 60 km from the shelf edge to send a branch into Queen Charlotte Strait to the southeast. All three troughs have low sills at the seaward entrances and are separated by wide shallow banks that are heavily fished by draggers. These sills and banks appear to have glacial origins and are made up in part by recessional moraines and stream outwash deposits left by retreating ice sheets. Exploratory oil wells drilled on the banks in the 1960s often encountered 3 km of marine sediment.

Due to the seaward funneling of land-derived sediments from the coastal mountains, the continental slope off Queen Charlotte Sound is comparatively gentle. There is also some evidence to suggest that the Queen Charlotte Islands once abutted Vancouver Island and effectively sealed off the Sound from any direct exposure to the Pacific Ocean. The subsequent northward movement of the Queen Charlottes along the Queen Charlotte fault created the present-day configuration.

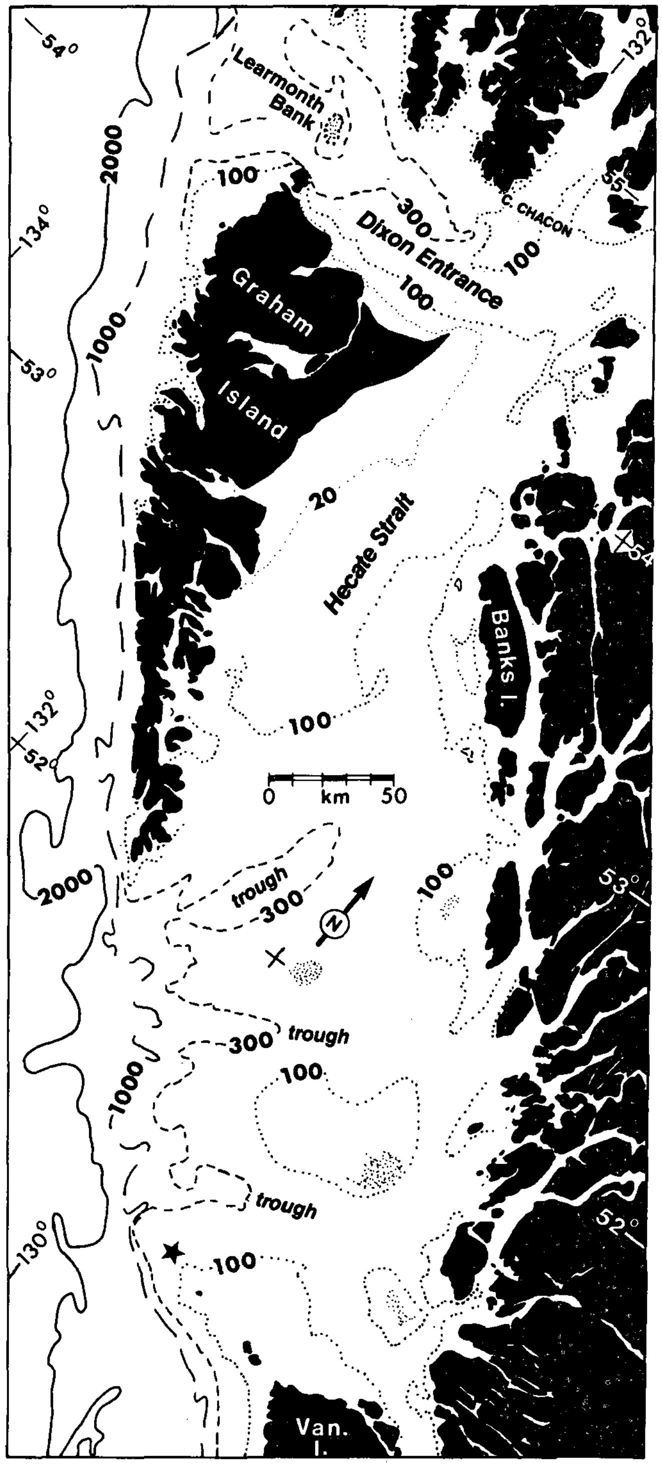

FIG. 14.3. Bathymetry of northwest coastal waters (m). Speckled areas denote shallow portions of banks. (Adapted from Chase et al. 1975)

Glaciation

On numerous occasions over the last million years, the coastal seaway has been inundated with vast ice sheets that spread from the mountainous terrain at the times of world-wide climatic cooling. During the nonglacial intervals the thick layers of debris deposited by the advancing and retreating glaciers were reworked by rivers, waves, and tidal currents to help produce the diverse littoral sediments, landforms, and bathymetry of the region.

The present-day structure of the seaway was well established by the end of the last glacial period, but because of the isostatic depression of the earth's crust by the weight of the ice, the Hecate Depression and adjoining fiords remained submerged as the glaciers withdrew from the coast. The marine and glaciomarine muds deposited over the region at this time were then raised far above present sea level as the crust eventually rebounded upward to its new equilibrium. In general, the maximum elevation to which marine deposits are now found on land decreases from the inner coast toward the outer coast, in correspondence with the seaward decrease in past ice thickness. At Kitimat, for example, marine deposits are at elevations in excess of 200 m; on the outer coast of the Queen Charlotte Islands they are less than 20 m above sea level.

The position of sea level relative to the land has undergone several major variations since the last glaciation. In the Terrace–Kitimat area, for instance, the coast attained maximum submergence about 11,000 yr ago (compared to about 13,000 yr ago in the Strait of Georgia region), whereas the outer coast of the Queen Charlotte Islands around this time was raised some 30 m above present sea level. According to marine geologists, the latter condition stems from the fact that the removal of water from the oceans to create the world glaciers (eustatic effect) was of greater importance in this area than the depression of the crust (isostatic effect) by a regionally thin ice sheet. The difference in vertical movement between the inner and outer coasts as a result of the interaction of crustal plates also has contributed to their different sea-level histories. Aside from the outer coast, deglaciation was accompanied and succeeded by isostatic rebound, and with it a relative fall in sea level. The land–sea boundary on the inner coast reached a position similar to that of today about 9,000–10,000 yr ago, but continued to fall a further 10 m over the next few thousand years. Except for a few minor fluctuations, sea level has been on the rise ever since, and will continue to rise with the worldwide shrinkage of glaciers. An exception to this trend is the north coast of Graham Island where prograding beaches give evidence of tectonic uplift and an accompanying seaward advance of the shoreline. This evidence is supported by nearly 40 yr of tide-gage records from Sitka and Juneau in the Alaska Panhandle where sea levels are observed to be falling at average rates of 2.3 mm/yr and 11.5 mm/yr, respectively. However, at Prince Rupert, much further to the east, sea level is rising at about 0.5 mm/yr. These rates may be compared with observed falls in sea level at Tofino and Neah Bay of approximately 0.8 mm/yr and 1.3 mm/yr, or with rises in sea level at Victoria and Seattle of 0.6 mm/yr and 1.9 mm/yr, respectively.

Temperature and Salinity

Temperature and salinity of the surface waters within the coastal seaway vary seasonally in accordance with the amount of incoming solar energy and the input of freshwater runoff. Over most of the region the annual range of surface salinity is from 28 to 32‰, with maximal values in winter and minimal values in summer. Water on the western side of the seaway tends to be saltier than on the mainland side, due to drainage from the mainland mountains. This effect is most pronounced in Chatham Sound and along the northern side of Dixon Entrance, which receive most of the silty outflow of the Nass and Skeena rivers. The combined discharge of these rivers of around 5700 m^3/s (200,000 ft^3/s) during early June rivals that of the Fraser River.

Average sea surface temperatures vary from about 6°C in April to around 14°C in August; waters of Dixon Entrance are consistently colder than those of Hecate Strait and Queen Charlotte Sound. The temperature of surface waters can depart conspicuously from the average for a given month (Table 14.1). And, unlike the situation in midocean, maximum sea-surface temperatures in the coastal seaway do not occur at the end of the heating season in mid-August, nor minimum temperatures at the end of the cooling season in March, because wind-driven currents bring in relatively cold water in summer and relatively warm water in winter to partially counteract the effect of solar heating. There is also a reverse seasonal variation in the deep waters of the seaway, which are colder and more saline in summer than in winter. Two processes can account for this reversal in trends; first, northwest winds along the outer coast in summer move surface waters seaward and thereby cause deeper oceanic water to move onto the continental shelf, and second, the increased outflow of brackish water from the seaway in summer strengthens the deep inward flow of the estuarine circulation.

TABLE 14.1. Ranges of monthly averaged sea-surface temperature, wind speed, and air temperature for the northwest coast waters (50–55°N). Minimum values of water temperature are typically at northern end, maximum values at southern end of seaway for each month. Maximum speeds are along outer coast, minimum speeds along mainland coast of the seaway each month. Minimum values of air temperature are typically at northern end, maximum values at southern end of the seaway. (Adapted from U.S. Department of Commerce 1978)

Month	Sea Surface (°C)	Wind Speed (*m/s*)	Air (°C)
Jan.	3–11	6–9	3–6
Feb.	3–11	9	4–6
Mar.	2–12	6–9	4–6
Apr.	3–12	6–8	6–8
May	5–14	5–6	8–10
June	7–16	4–6	11–12
July	9–18	4–6	13–15
Aug.	10–20	4–6	14–16
Sept.	9–18	4–7	13–15
Oct.	7–17	5–9	10–14
Nov.	5–14	7–10	6–10
Dec.	4–13	6–10	4–8

The influence of freshwater discharge is most strongly felt in Dixon Entrance in late spring and summer when runoff from the Nass and Skeena rivers tends to flow seaward within a comparatively warm brackish layer 10–20 m thick that hugs the northern side of the channel. In contrast, cooler, saltier oceanic water generally prevails over the southern half of the channel at this time.

Winds

Prevailing wind conditions over the inland waterway are associated with the same semipermanent, large-scale pressure systems that govern the deep-sea wind regimes, namely the Aleutian Low of winter and the North Pacific High of summer. Major differences in the winds over the two regions exist, nonetheless. Winds over the seaway, for example, commonly blow parallel to the coast because of the channeling effect of the bordering mountains. And there is a marked drop in average wind speeds toward the mainland shore, due perhaps to dissipation of wind systems as they cross the coast and to enhanced frictional drag caused by the surrounding terrain. A further generalization is that the frequency and intensity of southeasterlies is greater over the northern sector of the seaway than over the southern sector, whereas the frequency and intensity of northwesterlies is greater in the south than in the north.

The most pleasant months to cruise the coastal seaway are June, July, and August. Mean winds at this time range from 5.5 m/s (11 kn) at the seaward approaches to 4.0 m/s (8 kn) near the mainland coast, and speeds in excess of Force 8 (34 kn) occur less than 5% of the time (Table 14.1). Prevailing winds are from the west in Dixon Entrance and from the northwest in Queen Charlotte Sound. Conditions usually remain favorable until early September, but by October deteriorate rapidly with the onset of storm activity. The prevailing winds shift to the southeast and sharply intensify. Average wind speeds in October range from around 9.5 m/s (19 kn) along the outer coast to 6 m/s (12 kn) along the eastern side of the seaway and exceed Force 8 about 5–10% of the time. From November to February winds blow at Force 8 or greater more than 10% of the time. Throughout most of this period average wind speeds vary from 10 m/s (20 kn) at the seaward approaches to Dixon Entrance and Queen Charlotte Sound to about 7.5 m/s (15 kn) along the mainland side. Although southeast winds are most frequent (20% occurrence), winds from the south, southwest, and west occur with almost equal regularity. From April to June there is a gradual abatement in the strength of the wind and a return to more frequent westerlies.

In addition to gale force winds associated with migrating depressions and their attendant frontal systems, strong Squamish winds periodically blow seaward along the mainland inlets of the seaway during periods of clear winter weather. Usually triggered by a fall in pressure offshore, these outflows of cold interior air may attain speeds in excess of 25 m/s (50 kn) and penetrate many kilometres beyond the mouth of the inlet before their momentum is diffused by lateral spreading. Williwaws (a somewhat similar phenomenon that originates from the seaward drainage of cold air from more local areas of high ground) are violent, squally winds of short duration that frequently blow down the narrow inlets and valleys of the west coast of the Queen Charlotte Islands.

Fog

Table 14.2 gives the seasonally averaged days of fog at four locations over the north coast waters. In concert with the outer coasts of Vancouver Island and western Washington, the percentage occurrence of sea fog over the coastal seaway is greater during summer (June through September) than during autumn or winter (October through February). Fog tends to be more prevalent over the seaward approaches to Queen Charlotte Sound and Dixon Entrance than over the mainland side or over Hecate Strait, although due to the absence of intense upwelling in these regions there is nothing that resembles the persistent summer fogs of the exposed coast to the south (Table 14.2).

TABLE 14.2. Number of days of fog during 3-mo intervals at four locations on northern coast. (From British Columbia Sailing Directions, Vol. II, 1977)

Location	Jan.–Mar.	Apr.–June	July–Sept.	Oct.–Dec.
Prince Rupert	1	4	10	1
Cape St. James	5	7	11	7
Langara	1	3	6	1
Sandspit	2	2	2	2

The foggiest months are August and September at 10–15% of the time. Fog occurs less than 5% of the time from October through February, about 5% of the time in March and April, and around 10% of the time during May, June, and July. Fresh winds that sometimes accompany foggy conditions in summer may effectively lift the moisture to a very low deck of stratus clouds with a slight improvement of visibility but, in general, near zero visibilities are likely to persist for many days over wide areas of the seaway.

Waves

Because of the limited extent and partially sheltered nature of the seaway, wave conditions are typically less severe than in the open ocean to the west. There is also a gradation within the seaway itself, with average wave heights in Dixon Entrance somewhat lower than those in Queen Charlotte Sound but higher than in Hecate Strait.

Dixon Entrance is protected from ocean waves that arrive from the southern quadrant, and Queen Charlotte Sound from waves that arrive from the northern quadrant. Swell entering the inland seas from the west, on the contrary, travel a considerable distance before the height is noticeably reduced by refraction and breaking in the gradually shoaling waters; over the shallow banks in Queen Charlotte Sound and Learmonth Bank in Dixon Entrance swell may in fact be amplified by the focussing effect of the bottom contours (see Chapter 6). Learmonth Bank, in particular, is noted for its sizable rips formed when such amplified waves move against an accelerated ebb current over the bank.

Queen Charlotte Sound and the southern end of Hecate Strait are especially vulnerable to deep-sea waves from the southwest which, when aided by favoring winds, undergo little attenuation as they propagate northward. In addition, frontal systems are known to rapidly generate steep mountainous seas over the broad shoal area adjacent to the east coast of the Queen Charlotte Islands and leave the hapless mariner no choice but to ride them out.

On a seasonal basis, wave conditions are most severe in autumn and winter and mildest in spring and summer. Hazardous wave heights in excess of 3.5 m occur on the average 20–30% of the time along the outer reaches of the seaway from October through January, but diminish in frequency to around 10% along the mainland side. From February until March the frequency of seas over 3.5 m reduces to 15% on the outer coast and 5% on the mainland coast. By late spring, the chance of encountering hazardous seas anywhere in the region is less than 5%, a condition that prevails until late September when storms again begin to lash the coast with renewed vigor. The "sudden" jump in wind strength and wave activity that transpires between September and October is, of course, characteristic of the entire coast.

The suddenness at which extreme autumn wave conditions can arise in the coastal seaway was made abundantly clear to workers on the Shell Drill Rig (SEDCO 135F) in 137 m of water off Cape St. James in Queen Charlotte Sound in 1968. Beginning in mid-October the rig was battered by heavy seas for 16 days, as one storm after another generated waves of 9–15 m. Between storms, seas never fell below 3 m. "On October 22, a rapidly moving storm with gusting winds of 80 kn produced the worst conditions experienced. Sea and swell from the southeast and southwest combined to form significant waves exceeding 65 ft (20 m) in height. On at least one occasion, a wave close to 100 ft in height smashed against the rig. The height of this monster was reliably observed since the wave trough exposed a lower support form of the rig while the wave crests passed just below a control room extending below the main deck. The standby ship *Gulf Jean* reported solid walls of spray over the main deck with passage of the larger waves.

"The most dangerous aspect of these storms is not the magnitude of the waves generated but the rapidity with which operating conditions change from difficult to dangerous or impossible. At 1500 on October 22 the seas were reported 10 ft in height. Within 8 hr the waves were 60 ft in height and were extremely dangerous for all ship operations. Shortly after this, there was an even more rapid decrease in wave height." (James 1969). Figure 14.4 shows the wave heights reported by personnel of Southeastern Drilling and Shell of Canada, aboard the rig during the storm.

The cause of the rapid onset of extreme waves in this case was twofold. First, the storm was advancing eastward as quickly as the larger waves it was generating, and thereby caused a build-up of wave energy at the leading edge. Second, arrival of the waves coincided with an opposing ebb current out of Queen Charlotte Sound. The 30.5-m "monster" was likely a freak wave created for that single brief moment when the larger waves were in step in the vicinity of the rig.

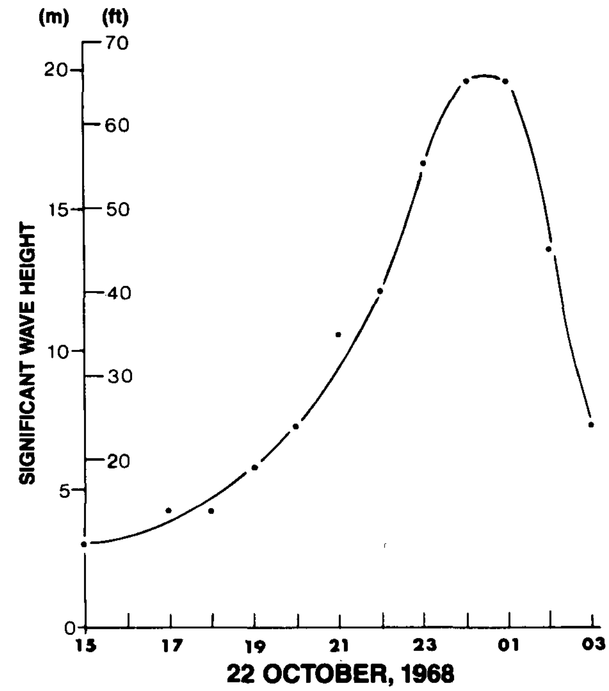

FIG. 14.4. Wave heights reported from SEDCO 135F drilling rig anchored off Cape St. James in 137 m water. (From James 1969).

Chatham Sound

From September 1972 to June 1973 wave measurements were obtained from a waverider buoy moored in 90 m of water approximately 2 km west of Prince Rupert Harbour. It represents one of the few attempts to determine wave height distributions within the north coast waters, although, because of the sheltered nature of the region, results are not representative of the seaway as a whole.

Most waves were found to be lower than 1 m in height and to have short periods of 2–5 s, typical of locally generated seas in Chatham Sound. Low swells that entered the Sound after propagating the 150 km length of Dixon Entrance were, nevertheless, common, and swell periods in the range of 8–10 s accounted for 20% of the wave observations. By the time such swells reached the inner portion of the coast, however, the effects of refraction and dissipation had considerably reduced the heights, so that only 10% were higher than 1 m. During the observation period, the significant wave heights remained below 3 m. In winter, conditions of eastward propagating swell often persisted for 2–3 days, but with wave heights in excess of 2 m for less than a day each time.

Tides

Tides within this region are mixed, predominantly semidiurnal, and co-oscillate with tides in the adjoining North Pacific Ocean. Shoaling effects cause the range of the semidiurnal tide to increase from about 2.4 m across the mouth of Queen Charlotte Sound to around 3.0 m midway along Hecate Strait, and from 2.4 m at the mouth of Dixon Entrance to 3.7 m along its eastern shore including Chatham Sound (Fig. 14.5). Corresponding values for the mean tide are from 3.0 m at the entrance to Queen Charlotte Sound to 4.8 m midway along Hecate Strait, and from about 3.5 m at the entrance to Dixon Entrance to 5.0 m at Prince Rupert. Tidal ranges over 7 m are encountered on large tides within Skidegate Channel that separates Graham and Morseby islands and in the vicinity of Prince Rupert. There is an amplification of the mean range to as much as 4.9 m as it moves up the deep narrow inlets of the mainland coast.

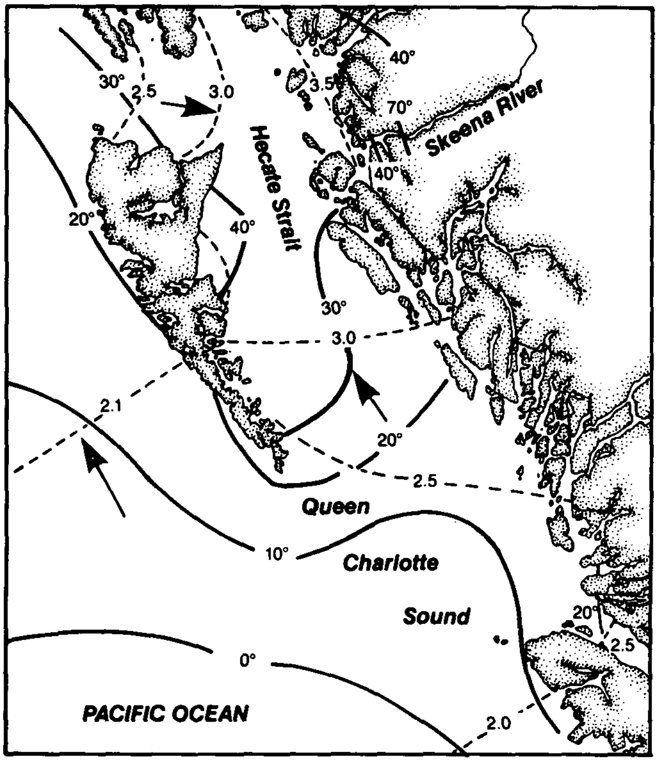

FIG. 14.5. Corange and cotidal values for semidiurnal tide. Tidal range (broken line) in metres; tidal phase (solid line) in degrees. Difference of 29° corresponds to time difference of 1 h. Arrows give direction of tide propagation.

In connection with the Strait of Georgia tides that propagate from the north and south meet at the northern end of the Strait. A similar situation occurs in the northern sector of Hecate Strait, where the north-going flood in Queen Charlotte Sound meets the south-going flood from Dixon Entrance. This confluence of the tides takes place over a somewhat ill-defined region, but appears to occur some 45–55 km further north in winter than in summer. Because the tidal waves will be partly reflected in this region, tides in Hecate Strait and Dixon Entrance are expected to behave like modified standing waves.

It takes about 30 min for the tide to reach the northern end of Hecate Strait from either of the two oceanic approaches, then the combined tide swings westward across the Strait to arrive at the shores of Graham Island some 15 min later. Consequently, a particular stage of the tide within the entire seaway differs by at most 1 h, not too unlike the 30 min difference that characterizes the Strait of Georgia tides. This fact, combined with recent current observations, supports the notion that the tides within the open seaway closely resemble standing waves.

Circulation

Surface water motions within the seaway are dominated by semidiurnal tidal streams that consistently undergo modification by the effects of wind, runoff, bathymetry, and shoreline configuration. During certain times of the year, wind-generated currents and seaward-moving brackish water may be strong enough to temporarily mask the normal ebb and flood of the surface streams, and result in persistent directional sets for durations of days. As expected, such conditions are particularly well established in many adjoining inlets and passages during spring and summer, when river discharges create a persistent ebb bias in the surface layer and a weaker flood bias at depth.

Tidal Streams

In the absence of vigorous winds or runoff, surface currents within Hecate Strait and Queen Charlotte Sound consist of clockwise-rotary tidal streams that alter direction and speed in a regular manner over a cycle of about 12½ h. The rotary nature of the tidal flow is best developed in the outer reaches of Queen Charlotte Sound, where horizontal motions are comparatively unrestricted by the land. Principal floods are to the northeast and principal ebbs to the southwest in this area (Fig. 14.6). During spring tides, maximum speeds are of the order of

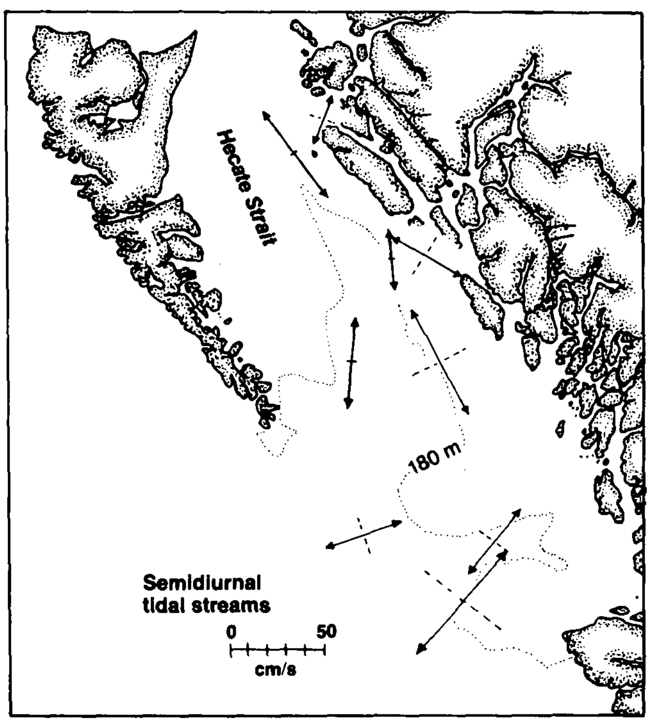

FIG. 14.6. Observed semidiurnal tidal streams at a depth of 15 m in Queen Charlotte Sound and Hecate Strait. Solid lines and arrows give orientations of major ebb and flood directions; broken lines at right angles give minor flow directions for rotary tidal currents. Scale measures speed relative to midpoint of each axis. (Courtesy S. Huggett).

50 cm/s (1 kn) but decrease to around half this value during neap tides. Slack water is nonexistent, as the effect of the earth's rotation causes the current vectors to cyclically alter direction with little change in speed. Nearer the shore, the tidal ellipses generally become increasingly rectilinear with major axes aligned parallel to the trend of entrant channels. In many cases, the flow is accelerated as it negotiates the constricted mouths of these inland leading waterways. As always, there are exceptions. It appears that tidal streams in the central portions of some broader openings that adjoin Queen Charlotte Sound retain their rotary nature because of the curvature of the shoreline and the splitting of the streams into still further channels. (Readers wishing more detailed information on currents within the inland channels are referred to *Sailing Directions British Columbia Coast (North Portion)* Vol. II, 8th ed. 1981.)

Tidal streams in Hecate Strait are basically rectilinear due to restrictions on cross-strait flow by the valleylike bathymetry (Fig. 14.6). Therefore, floods are directed to the north and ebbs to the south at maximum rates of roughly 50 cm/s. Again, there is considerable distortion of surface tidal streams near the broken shorelines of the mainland and Moresby Island coasts. The times of a particular stage of the current along Hecate Strait (for example, maximum ebb or flood) are progressively delayed from those at the seaward entrance to Queen Charlotte Sound, and reach a maximum delay of just over 2 h at the latitude of Banks Island (Fig. 14.7). The fact that the tide itself is delayed by less than 1 h over the same distance would suggest it gradually departs from a standing-type wave as it travels the length of the Strait. This is ineed what happens as the northward propagating tide in Hecate Strait merges with the portion of the tide that advances along Dixon Entrance. From a practical point of view, the times of maximum flood or ebb in northern Hecate Strait are 2–3 h later than the times of local high or low water.

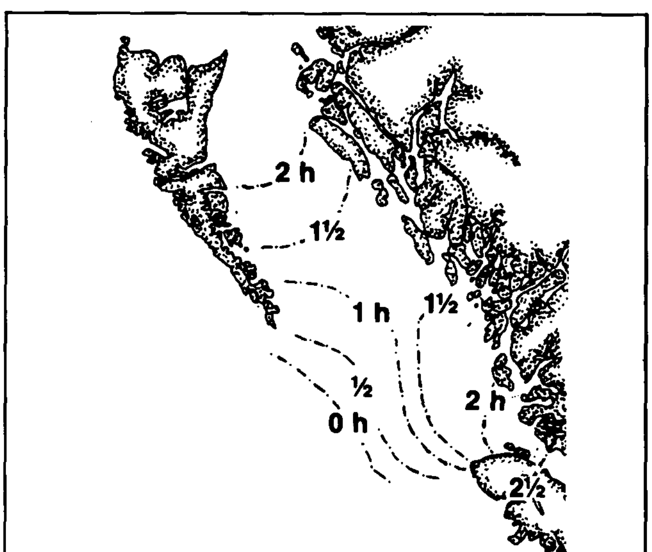

Fig. 14.7. Times of particular stage of tidal streams, relative to open coast. For example, off Banks Island maximum flood occurs 2 h after maximum flood at entrance to Queen Charlotte Sound. (Courtesy S. Huggett)

To the north of the meeting area of the tides, there is a reversal in the ebb and flood directions as principal ebbs are directed to the north and principal floods to the southeast. The confluence of tides in combination with the right-angle geometry of the coastline further complicates the tidal streams within the central portion of Dixon Entrance. Instead of near uniform strength, flood streams are decidedly stronger on the southern side of Dixon Entrance and ebb streams stronger on the northern side (Fig. 14.8). As a consequence, a net counterclockwise vortex is established over a tidal cycle with its center about half way between Cape Chacon and Rose Spit. Currents within this vortex attain greatest speeds (50–100 cm/s) around the outer circumference approximately midway between high and low water, as measured at the shore, and diminish inward to the vortex core. An intense westward setting stream is formed south of Cape Chacon where the ebb from Clarence Strait converges with the ebb that originates from northern Hecate Strait. Similarly, on the flood there is comparatively strong eastward flow north of Graham Island at a time when weak and variable currents exist off Cape Chacon. Further toward the mouth of Dixon Entrance, tidal streams run parallel to the trend of the channel axis and eventually merge with the northward setting flood and southward setting ebb along the outer coast.

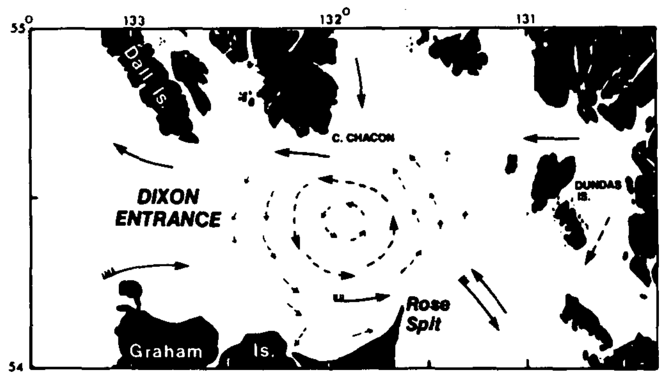

Fig. 14.8. Tidal streams in Dixon Entrance. Flood streams strongest on south side of channel, ebb streams strongest on north side. Broken arrows show net (resultant) cyclonic circulation created by asymetric tidal current pattern. (Adapted from Crean 1967)

Near-bottom tidal motions within the seaway are weaker than their surface counterpart and differ slightly in direction because of the more immediate constraints of the bathymetry. Speeds of 15–25 cm/s appear to be characteristic of the region.

Nontidal Currents

Until now, the important influences of wind and runoff have been ignored. When added to the tidal streams (which must be done to obtain a truly representative picture of the circulation) they may radically alter the characteristics of the tidally induced currents and even suppress them completely. The difficulty with these nontidal components of the circulation is they are often subject to rapid spatial and temporal variations associated with transient fluctuations in wind and runoff patterns. On a short period basis their predictability is almost nil and attention must be confined to prevailing seasonal conditions. As noted in Chapter 4, inertial currents have an important, albeit intermittent, influence on the currents in Queen Charlotte Sound and southern Hecate Strait. Whether they are a factor in Dixon Entrance has yet to be determined. A brief description of inertial currents in the Queen Charlotte Sound–Hecate Strait region is presented in the next subsection.

During November through February, the low freshwater drainage from the land has but a minor influence on currents in the seaway. The reverse is true of the winds, which commonly blow with considerable vigor from the southeast over the entire north coast. To appreciate fully the importance of these winds to the long-term, nontidal component of the flow within the seaway, the study should begin along the outer coast. In this region, southeast winds initially generate a downwind surface drift which is then deflected to the right by the earth's rotation. This, in turn, leads to a net onshore Ekman transport within the top 100 m or so of the water column. Where this transport is blocked by the coast there is an onshore accumulation of surface waters and a depression of the nearshore isopycnals, with only a partially compensating offshore transport at depth. Resulting pressure gradients are then balanced by the establishment of northward coastal currents in the upper layer. If the winds die, the piled-up surface waters collapse seaward and the current disappears. If the winds reverse to the northwest, the antithesis occurs; the surface Ekman transport is offshore, isopycnals are raised (upwelling), and the ensuing coastal current is southward.

At the entrance to Queen Charlotte Sound there is no coastal barrier and surface waters that would normally converge over the continental shelf under the influence of persistent southeast winds are directed northward into the Sound. Aided by the direct action of southeast winds over the seaway, they then flow northward into Hecate Strait as a well-defined, relatively warm surface current (see Fig. 13.19a). Typical speeds of this current are presumably of the order of 3% of the wind speed averaged over several days, but can be expected to vary markedly over periods of half a day or longer and be slightly faster on the eastern side of the channel. If the winds are weak-to-moderately strong, the wind-induced flow will bear northward across the eastern portion of Dixon Entrance into Clarence Strait. The remaining portion of Dixon Entrance will continue to be dominated by the tidal vortex. If, on the other hand, the winds are strong over the coast, the northward transport of surface water through Hecate Strait will create a concentrated seaward flow around Cape Chacon and along the northern side of Dixon Entrance in addition to the northerly set through Clarence Strait. At the mouth of Dixon Entrance the westward progressing surface current veers sharply to the northwest as it merges with the prevailing currents along the outer coast of Alaska.

By early to late spring (March–May), the strength of the southeast winds begins to moderate. This is accompanied by a reduction in the onshore convergence of oceanic surface water and a weakening of the northward wind-generated current that moves through Hecate Strait into Clarence Strait. During the summer (June–August) southeast winds are minimal and there is negligible wind-induced flow within the coastal seaway. Regeneration of the northerly set follows the reestablishment of intense southeast winds some time between September and October and the cycle is completed.

In contradistinction to the winds, freshwater runoff can be expected to modify the circulation of the northern seaway most effectively from late spring to early summer, when large volumes of snow melt are discharged from the multitude of coastal estuaries. The fresh water spreads laterally over the denser salt water where it reaches the seaway and soon becomes mixed to near uniform salinity by winds and tidal currents. This results in the formation of an upper zone of brackish water that is forced to move seaward because of the hydraulic pressure head set up by the accumulation of fresh water along the mainland shores of the seaway. As it progresses, the upper zone becomes increasingly more saline through entrainment of oceanic water from below. To compensate for this loss of salt, sea water intrudes inward at depth, but at a considerably slower rate than the surface outflow.

Therefore, the effect of the runoff is to superimpose a measurable, albeit highly variable, estuarine-type circulation on the tide and average wind-generated circulations. Among other factors, the strength of the brackish outflow over the seaway will, in the absence of winds, vary in accordance with the amount of runoff from contiguous waterways and the degree of lateral spreading. For these reasons the most well-defined estuarine circulation is within Chatham Sound and the fairly confined eastern sector of Dixon Entrance into which pour the voluminous discharges of the Skeena and Nass rivers. Throughout the rest of the seaway, significant estuarine flow is generally limited to the immediate vicinity of mainland shores. Runoff has only a marginal influence on the surface currents in Queen Charlotte Sound and Hecate Strait, which are at all times dominated by tidal streams and wind drift. Attention will be focused on the Dixon Entrance region.

Beginning in late April, there is a rapid rise in the discharge from the Nass and Skeena rivers until respective peaks of 3000 and 4200m^3/s (105,000 and 150,000 ft^3/s) are attained about the beginning of June, a 10-fold increase over midwinter values (Fig. 14.9). The freshet is then followed by a gradual reduction in outflow until October when a secondary peak associated with winter precipitation occurs. After leaving Chatham Sound the freshwater discharge advances in a general northwesterly direction into the southern reaches of Clarence Strait and the adjoining passages. In summer the flow divides in this region, one branch continues northward through Clarence Strait, the other turns southward around Cape Chacon into Dixon Entrance (Fig. 14.10). The latter branch then spreads into the west central portion of the channel as a result of the indigenous tidal vortex before eventually making its way seaward via the deep channel north of Learmonth Bank. Because the seaward discharge of fresh water acts in concert with the last stages of the westward wind-driven currents in this region, there is a major flushing of brackish water into the Pacific Ocean, and a strong intrusion of cold, saline oceanic water at

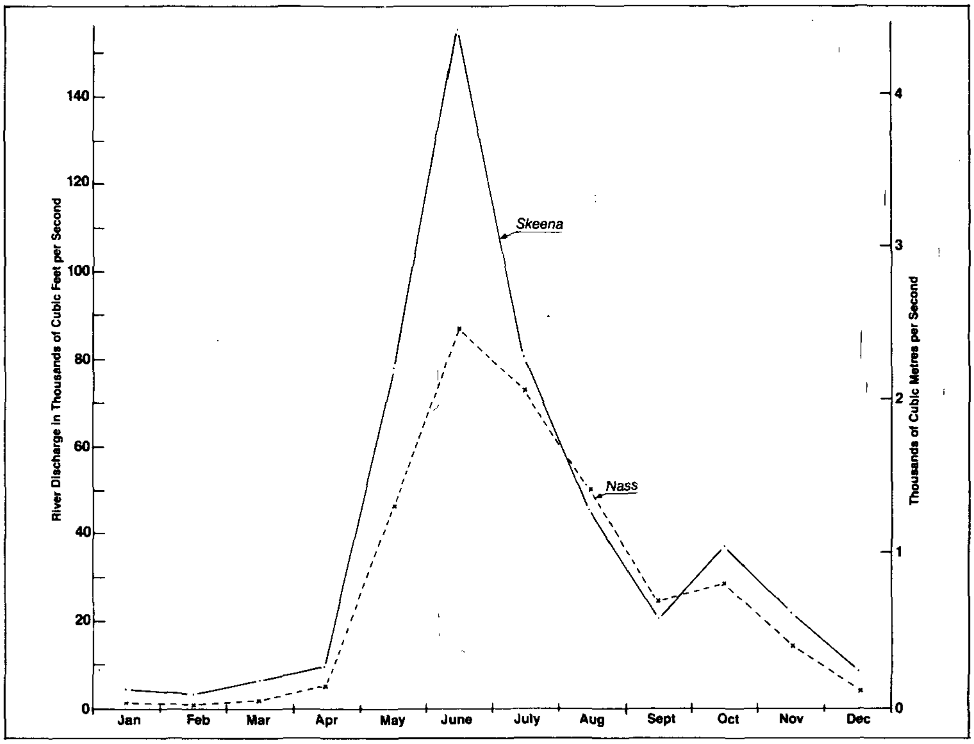

FIG. 14.9. Average monthly volume discharges for Skeena and Nass rivers, 1972. Skeena measurements were taken at Usk, 145 km upstream, and Nass River at Aiyansh, 70 km upstream. Significant volume is added to Skeena downstream of Usk, so values shown underestimate amount of fresh water entering Chatham Sound. (From Water Survey of Canada 1974)

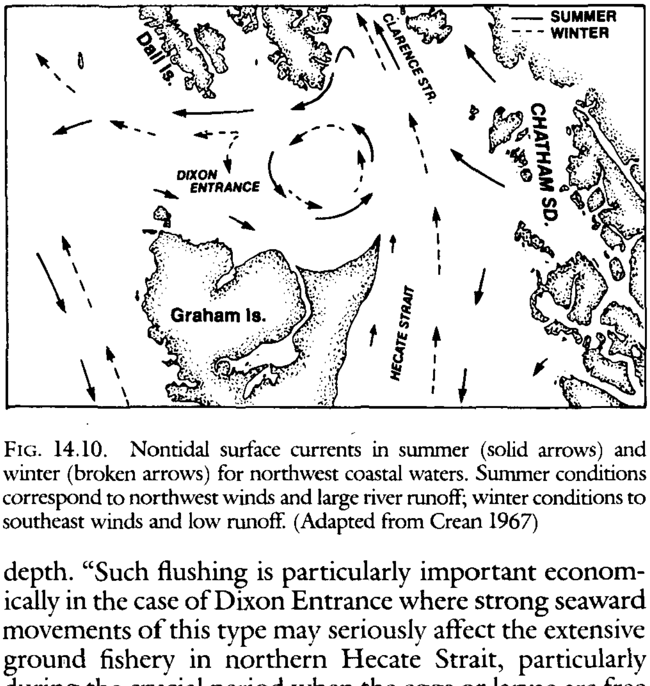

FIG. 14.10. Nontidal surface currents in summer (solid arrows) and winter (broken arrows) for northwest coastal waters. Summer conditions correspond to northwest winds and large river runoff; winter conditions to southeast winds and low runoff. (Adapted from Crean 1967)

depth. "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." (Crean 1967)

With a subsequent fall in discharge from these rivers by late summer, the outward flow of brackish water becomes mainly confined to Clarence Strait and to the northern shores of Dixon Entrance. On the other hand, westerly winds at this time probably enhance the net inflow of high-salinity surface water along the southern side of Dixon Entrance. By late autumn the nontidal component of the circulation becomes dominated by winds, and what remains of the brackish upper zone is flushed seaward through Clarence Strait. This condition prevails throughout the winter and early spring until the return of warmer weather and melting of snow in the high elevations of the coastal mountains.

Inertial Currents

Current meter observations from the nine mooring sites shown in Fig. 14.6 reveal that intermittent, wind-generated inertial currents frequently dominate the surface circulation within Queen Charlotte Sound and Hecate Strait. Weak remnants of these motions also occur near the bottom to depths of 260 m and within the entrances to the larger channels (e.g. Browning Entrance and Caamaño Sound) that open into the seaway on the mainland side.

Generation of inertial currents in this region is principally by moderate-to-strong, southeast frontal winds that accompany passage of extratropical cyclones ("storms") across the north coast (Fig. 14.11). The current vector necessarily rotates in the clockwise direction (looking downward) and its tip traces out a circular path approximately every 15½ h (1 inertial period at 51° latitude). The latter feature can be verified by noticing that the north–south velocity component of the inertial current in Fig. 14.11 leads the east–west component by 90° (i.e. by $90°/360° \times 15.5 = 3.9$ h) and that the strengths of the two components are always about equal. Because of this rotation, especially strong inertial currents result if the southeast winds veer to southwesterly at about20–30°/h following passage of the front so they remain

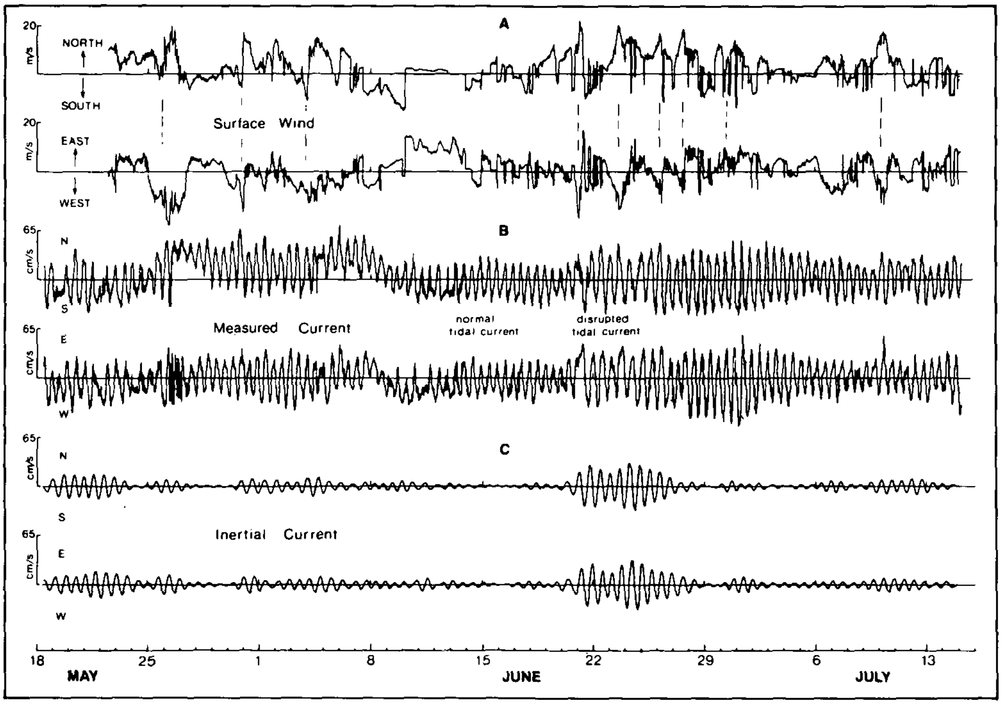

FIG. 14.11. Winds and currents in Queen Charlotte Sound from May to July, 1977. (A) North–south and east–west components of the wind according to oceanographic convention, i.e. direction to which wind is blowing. For example, on May 26 winds were *toward* the northwest or *from* the southeast at over 20 m/s (40 kn). (B) North–south and east–west components of the actual current measured at a depth of about 15 m (50 ft) at a location 70 km west-northwest of Cape Scott (star in Fig. 14.3). Winds were measured from a mooring 100 km northwest of current meter location. (C) North–south and east–west components of inertial currents, extracted from the observed records in (B) using digital filtering methods. (In the observed curret records, inertial currents were masked by tidal and estuarine currents and had to be isolated using computational techniques.) Note that each onset of strong inertial currents was roughly coincident with passage of a frontal system marked by vertical dashed lines in (A).

aligned with the current during its inception. The near-surface speed of the current is highest roughly 15–20 h after onset and may exceed 50 cm/s (1 kn) within the exposed western half of Queen Charlotte Sound; a speed of 75 cm/s was recorded on June 22, 1977, at an exposed mooring site 130 km northwest of Cape Scott. Through a combination of turbulence, mixing processes, and dispersion, the downward propagated kinetic energy of these motions is rapidly attenuated with depth and wind-generated inertial currents are mainly confined to the upper 50 m or so.

The speeds of near-surface inertial motions are greatest near the entrance to Queen Charlotte Sound and decrease in a generally northeastward direction over the seaway. Typical maximum speeds of 50 cm/s at the Pacific entrance diminish to less than 20 cm/s off Banks Island in northern Hecate Strait and 30 cm/s in the eastern sector of the Sound. Moreover, because the storms that generate the currents travel to the northeast, there is a corresponding delay in the time of onset of the current toward the northeast. The inertial currents produced by a particular storm usually persist locally for about 2½ days and represent transient oceanic responses to rapid variations in the wind. However, if the time between successive storms is a multiple of the inertial period and less than 3 days, the gradually decelerating currents generated by one storm will be given an accelerating boost by the following storm in the sequence, and the current will persist. This was the case beginning on June 21 in Fig. 14.11, where four successive storms, each with peak winds about four inertial periods (2½ days) apart, kept the inertial currents going for more than a week; the much stronger motions about 50 km northwest of this location lasted nearly 12 days. (Instances where successive storms are "out of sync" lead to rapid deceleration of established inertial flows by adverse winds.)

In the previous chapter it was noted that the most common time delay between successive winter storms in the Northeast Pacific is 2½ days. This, in conjunction with the greater strength of winter winds, suggests that extended periods of intense inertial oscillations are a common feature of the Queen Charlotte Sound–Hecate Strait region from late autumn to early spring.

As demonstrated by the observed currents in Fig. 14.11, inertial currents in excess of 10 cm/s effectively disrupt the normal rhythm of the rotary tidal streams. Current-table predictions would be useless at such times as both the strength and direction of surface flows are modified by the wind-generated currents. A less obvious, but equally important, facet of inertial motions is that they are a prime mechanism for transferring wind energy downward into the water column and, therefore, are a major source of energy for mixing processes within the upper layer of the ocean.