PART IV
OCEANOGRAPHY OF INSHORE WATERS

Chapter 10. Strait of Georgia

The Strait of Georgia is by far the most important marine region of British Columbia. More than 70% of the population of the province is located on its periphery and its shores provide a foundation for expanding development and industrialization. The Strait is a waterway for a variety of commercial traffic and serves as a receptacle for industrial and domestic wastes from the burgeoning urban centers of greater Vancouver. Salmon runs to the rivers that enter the Strait of Georgia are the basis for one of the world's largest commercial salmon fisheries; its resident coho and chinook salmon form an important and ever-increasing recreational fishery. The Strait also provides an area for the spawning and growth of herring and is the largest overwintering location for waterfowl in Canada. Widespread recreational use of the Strait by boaters, sports fishermen, bathers, and campers make tourism in British Columbia a major industry. In short, the Strait of Georgia constitutes a multiple-use aquatic environment that must be considered a national asset worthy of utmost consideration and protection.

Physiography

The Strait of Georgia occupies an inundated portion of the northwest–southeast trending Georgia Depression that lies between the intrusive rocks of the Coast Mountains and the intrusive, metamorphic, and sedimentary rocks of Vancouver Island (Fig. 10.1). On the average, it is about 222 km (120 nm) long and 28 km (15 nm) wide; islands occupy roughly 7% of its total surface area of 6800 km^2 (200 nm^2). The average depth within the Strait is around 155 m, and only 5% of the total area has depths in excess of 360 m. The maximum recorded depth of 420 m is immediately south of the largest island in the Strait, Texada Island, and is rather shallow compared with soundings obtained in some of the adjoining inlets (depths in Jervis Inlet reach 730 m).

To the north, the Strait of Georgia is linked to the Pacific Ocean via several narrow but relatively long channels, notably Discovery Passage and Johnstone Strait, and by the broader Queen Charlotte Strait. To the south it is linked to the ocean via Juan de Fuca Strait and a few comparatively wide channels between the San Juan and Gulf Islands (Fig. 10.2). Of these, Haro Strait and Rosario Strait have a cross-sectional area appreciably larger than all other channels combined. Along the eastern margin of the Strait of Georgia, erosion by ice moving

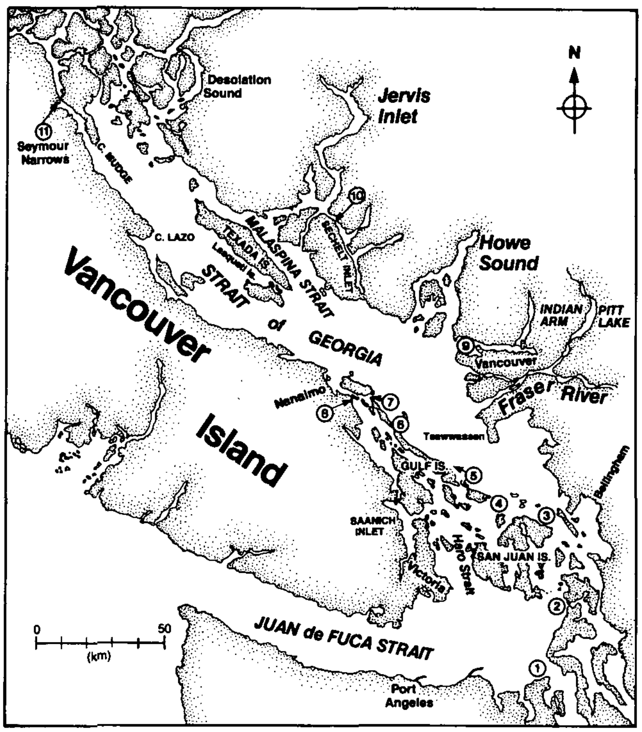

FIG. 10.1. Major geographical features of Strait of Georgia. Circled numbers: 1, Admiralty Inlet; 2, Deception Pass; 3, Rosario Strait; 4, Boundary Passage; 5, Active Pass; 6, Porlier Pass; 7, Gabriola Passage; 8, Dodd Narrows; 9, Burrard Inlet; 10, Skookumchuck Narrows; 11, Discovery Passage.

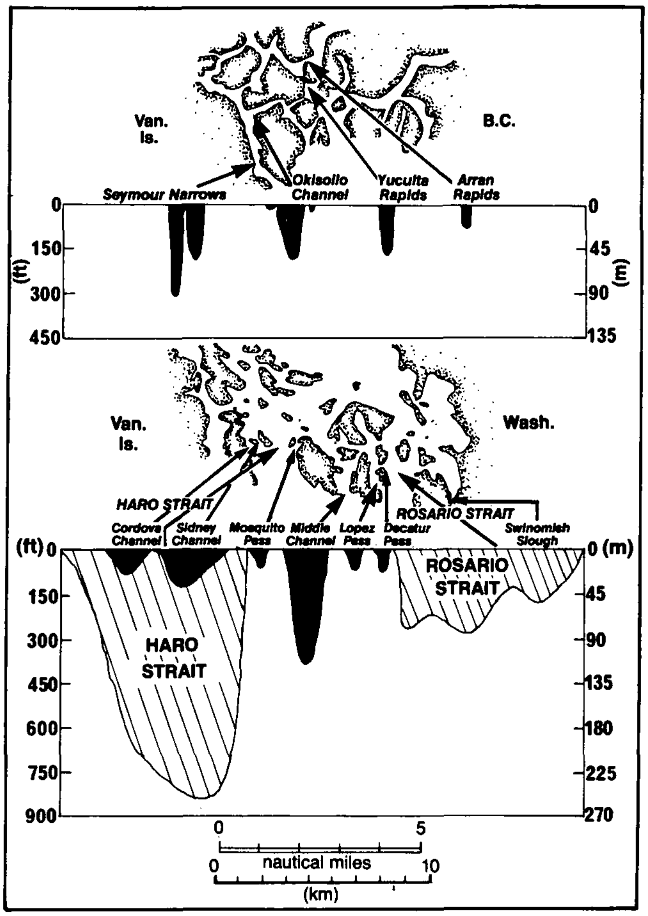

FIG. 10.2. Cross-sections of channels leading into Strait of Georgia, (*top*) northern approaches, (*bottom*) southern approaches. (From Waldichuk 1957)

down former rivers during repeated periods of glaciation created long, steep-sided valleys that were later flooded to form fiords as sea level rose following the last glacier retreat. The longest of these, Jervis Inlet, cuts back more than 61 km (33 nm) into the Coast Range. The combined effect of glacial scouring and subsequent flooding has further created a complex of islands, sounds, and passages along the eastern coastline of the basin. By contrast, the western side of the Strait has few inlets and a more regular coastline. The distinctive Gulf Islands in the southwest corner of the region were originally part of Vancouver Island but have since been detached through glacial erosion of the poorly resistant sedimentary rocks. Freshwater discharge into the Strait comes mainly from the Fraser River, which empties directly into the basin near Vancouver, with an important secondary contribution from the Squamish River that enters the Strait via Howe Sound. Appreciably smaller freshwater discharges come from the rivers of Vancouver Island, such as the Cowichan, Chemainus, Nanaimo, and Courtenay and from the rivers that empty into the inlets on the eastern coast.

Temperature and Salinity Distributions

The temperature of the water within the Strait of Georgia varies with depth, proximity to the Fraser River delta, and season. For simplicity the water column in the Strait can be divided into two layers; the upper layer, shallower than about 50 m, and the lower layer below this level to maximum depths of around 400 m. In the lower layer observed temperatures are nearly uniform throughout the year, typically 8–10°C over the entire basin from Cape Mudge to Haro Strait. Winter values tend to be higher than summer values but only by about 1C°. There is also a slight tendency for temperatures to decrease northward along the channel at depth.

It is in the upper layer that most seasonal and along-the-strait variation in water temperatures takes place, and this can be quite pronounced (Fig. 10.3a, b). Beginning in late fall, cool air begins to rapidly lower the temperature of surface waters. Due to storm winds and cooled water sinking as it becomes more dense than the water beneath, temperatures also begin to decrease throughout the upper 50 m or so of the Strait. By late winter (February–March), near-surface waters are coldest, sometimes falling to as low as 5–6°C, but below 50 m there is a gradual increase in temperature to around 9°C at the bottom. The coldest water in the Strait of Georgia at this time is frequently associated with Fraser River runoff, which loses heat as it flows through the wintery British Columbia interior.

With the advent of spring, air temperatures rise and storm activity abates to permit increased retention of solar energy in the upper waters of the Strait. By the middle of May sufficient warming has taken place in the top 10–20 m for near-surface temperatures to reach around 15°C in certain areas. The Fraser River freshet starts around this time and forms a brackish layer over large portions of the Strait. Increased stability of the top few metres of the water column allows further warming to occur, aided by longer periods of more intense solar radiation and warmer air temperatures. In July it is not unusual to find patches of water in mid-Strait that exceed 20°C. Similar water temperatures occur in protected areas, such as Departure Bay near Nanaimo and Burrard Inlet off Vancouver, and in numerous small coves and bays along both sides of the Strait. Only near tidally mixed regions at the northern and southern approaches to the Strait of Georgia do water temperatures remain consistently low (around 10°C) throughout the summer. However, when winds are offshore even areas like Departure Bay can have cool surface waters as the warmer water is driven offshore and colder deeper water upwells to replace it (see Chapter 5).

Maximum surface temperatures in the Strait of Georgia generally occur around the first week of August. By the end of the month substantial cooling sets in and surface water temperatures again fall to around 15°C over most of the region. Near the end of autumn, enhanced storm activity, combined with decreased solar heating, relatively low freshwater runoff, and cool wintery air, creates nearly uniform surface temperatures of about 9°C within the entire Strait. The upper layer continues to cool until late winter and the cycle is repeated, with slight variations from year to year due to annual fluctuations in local climate.

Like temperature, the salinity distribution in the Strait of Georgia has a marked two-layer structure (Fig. 10.4a, b). The top of the lower layer lies approximately 50 m deep and is delineated by a salinity of 29.5‰; below this, salinities gradually increase to near-bottom values of 30.5‰ in summer and 31.0‰ in winter. Above 50 m, on the other hand, salt content varies considerably with season and distance from the mouth of the Fraser River estuary, where salinities are always comparatively low. Very localized regions of low-salinity surface water are also often associated with the smaller rivers that empty into the Strait.

During the period of consistently low Fraser River discharge and strong wind mixing from early December to early April, freshwater runoff in the upper layer is generally confined to a region well south of Texada and Lasqueti islands. In this portion of the Strait of Georgia, regions with nearly uniform salt content form in the upper layer, where salinities increase from surface values of 27–28‰ to 29.5‰ near 50 m depth; other areas under more direct influence of the Fraser River may at the same time have salinities of 25‰ or less at the surface. Within the northern Strait, the overall range of salinity is consistently small in winter and near uniform salinity conditions always prevail.

With the Fraser River freshet in late May, a layer of brackish water with salinities of less than 15‰ forms the top few metres over most of the central and southern sectors of the Strait of Georgia. The surface water during this period often has a sweet taste and is drinkable. However, in the northern portion of the Strait the surface water is typically saltier than 25‰. By August, the peak runoff from the Fraser River is over and salinities in the upper 50 m begin a gradual increase in value. Localized regions of nearly brackish surface water still occur, but their extent and persistence continue to diminish with the approach of winter.

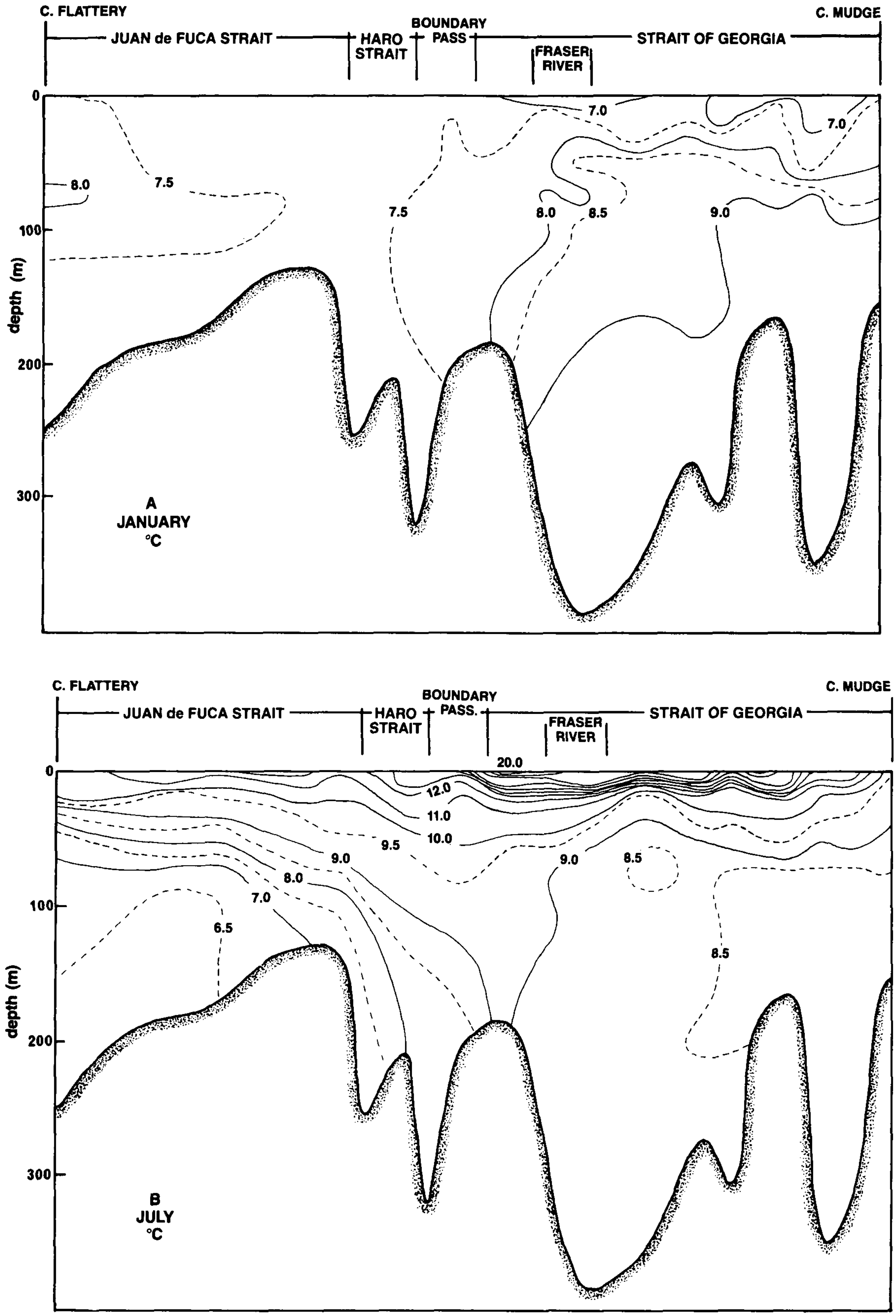

FIG. 10.3. Along-channel sections of water temperature from western end Juan de Fuca Strait to northern end Strait of Georgia (A) January 1968, (B) July 1968. (From Crean and Ages 1971)

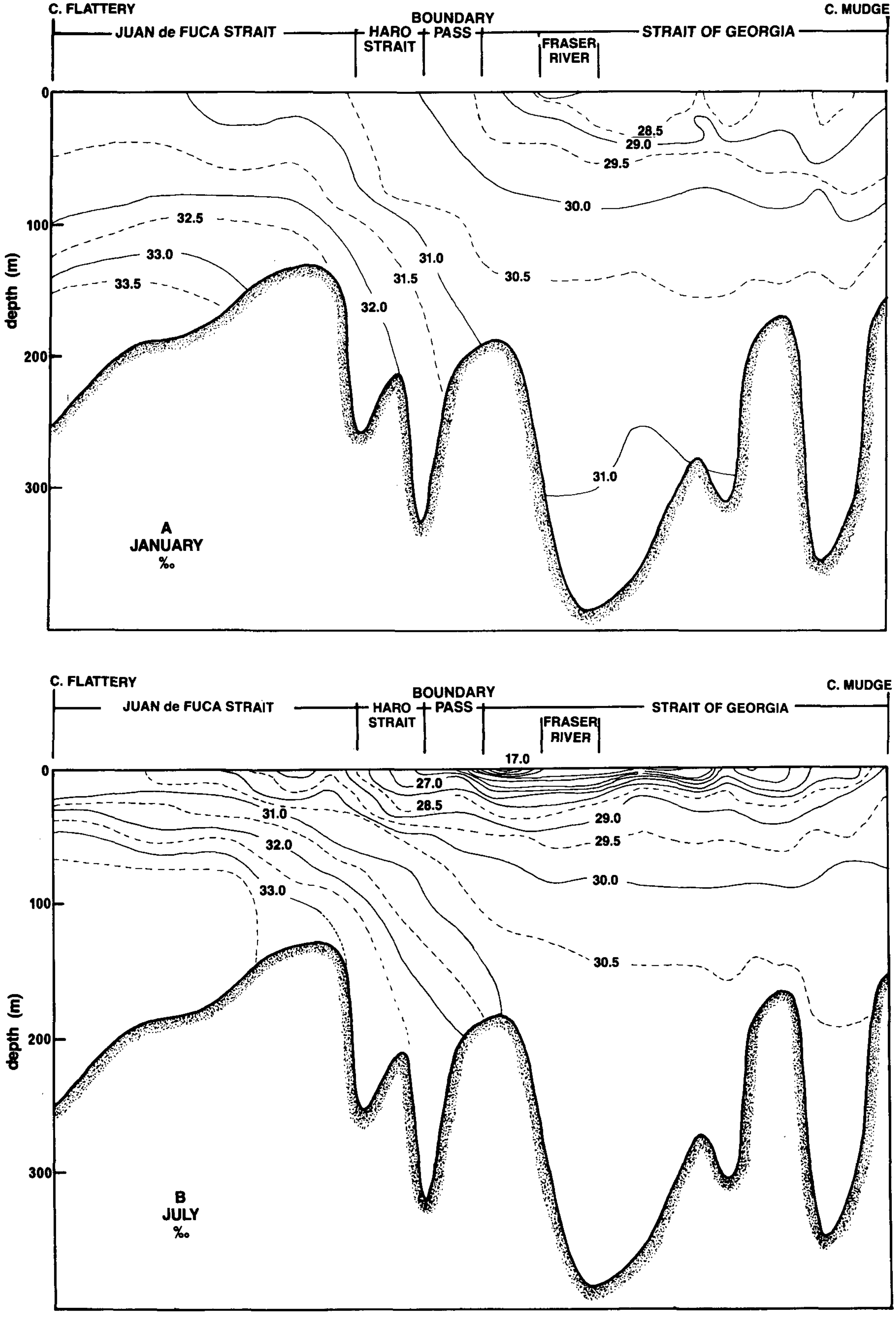

FIG. 10.4. Along-channel sections of salinity from western end Juan de Fuca Strait to northern end Strait of Georgia (A) January 1968, (B) July 1968. (From Crean and Ages 1971)

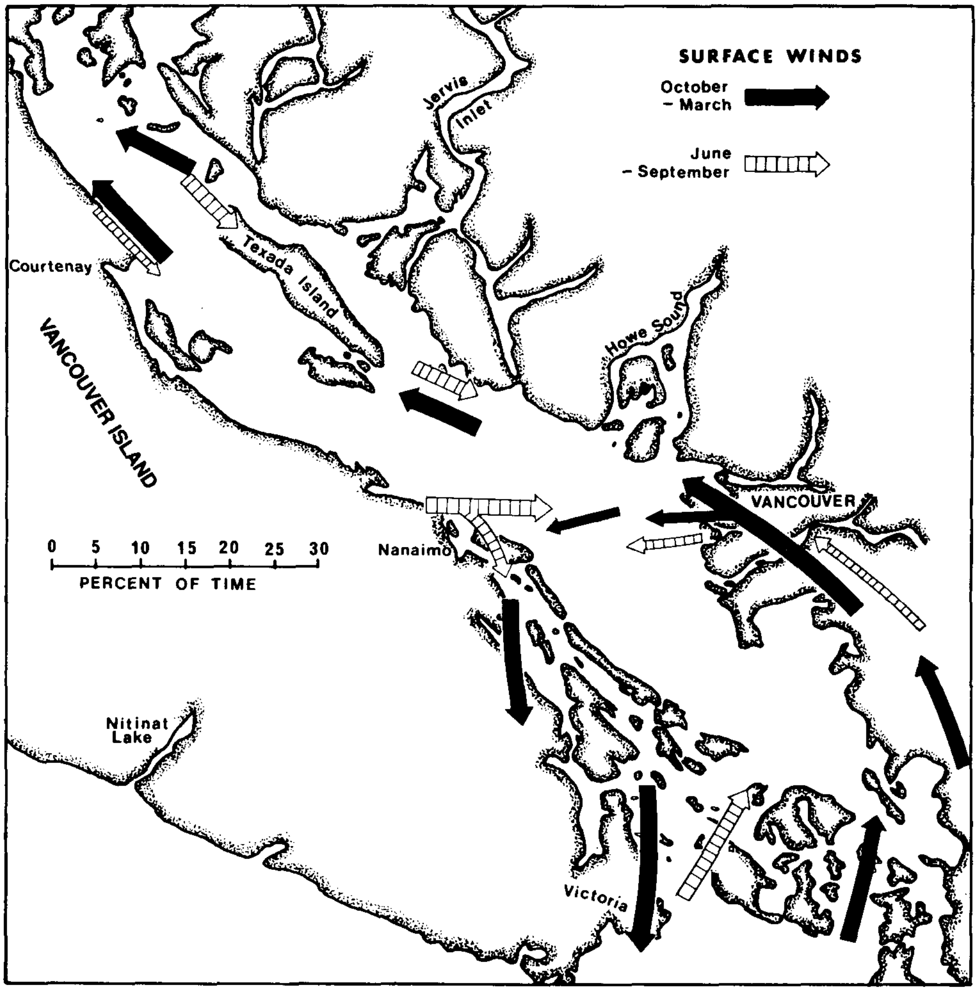

FIG. 10.5. Prevailing surface wind patterns over Strait of Georgia in winter (solid arrows) and summer (hatched arrows). Thick arrows correspond to speeds 4.5–9 m/s (8.7–17.5 kn); thin arrows less than 4.5 m/s. Comparison of length of arrow to scale on left yields frequency of occurrence of particular wind. (Modified after Barker 1974)

Wind Patterns

In the exposed areas of the Strait of Georgia, prevailing winds are predominantly from the northwest in summer and the southeast in winter. The northwesterlies are associated with the clockwise motion of air around the North Pacific High, which centers west of California in midsummer; the southeasterlies are associated with the strong anticlockwise flow of air around the Aleutian Low, which develops just south of Alaska in winter (see Fig. 2.14). Significant modifications of this general pattern are produced by the complicated topography of the surrounding land. The funneling effects of Juan de Fuca Strait, Puget Sound, and the Fraser Valley play important roles in governing the overall wind pattern in the Strait of Georgia. In the southern Strait, for instance, there appears to be a closed anticlockwise wind pattern from October to March (Fig. 10.5), and a turn from southeasterlies to easterlies of winds off the Fraser River, because of the influence of the Fraser Valley. By spring, the winds are predominantly southeasterly to easterly. In summer, winds are typically lighter and more confused than in other seasons. Southeasterlies and southwesterlies dominate the southern Strait but northwesterlies dominate the northern Strait, where they conform more to the oceanic wind pattern.

The winter wind pattern is altered further by the invasion of polar continental air funneled onto the Strait through the inlets and valleys that lead from the B.C. interior. As this air descends toward the coast, its speed is often sharply increased to produce the gale strength Squamishes that howl forcefully down inlets like Howe Sound. These winds have some important effects on the wind structure in the Strait of Georgia. For example, if the Squamishes occur when there is a low-pressure area over northwestern Washington, northwest winds instead of southeast winds occur over the northern and central regions of the Strait (Fig. 10.6). An interesting feature for Vancouver sailors is that, although Howe Sound Squamishes are usually associated with strong easterly winds through the Fraser Valley, the accompanying winds in Burrard Inlet are often light and variable. In other words, it is possible to have gale force winds in Howe Sound and at Abbotsford, but nearly becalmed conditions in the

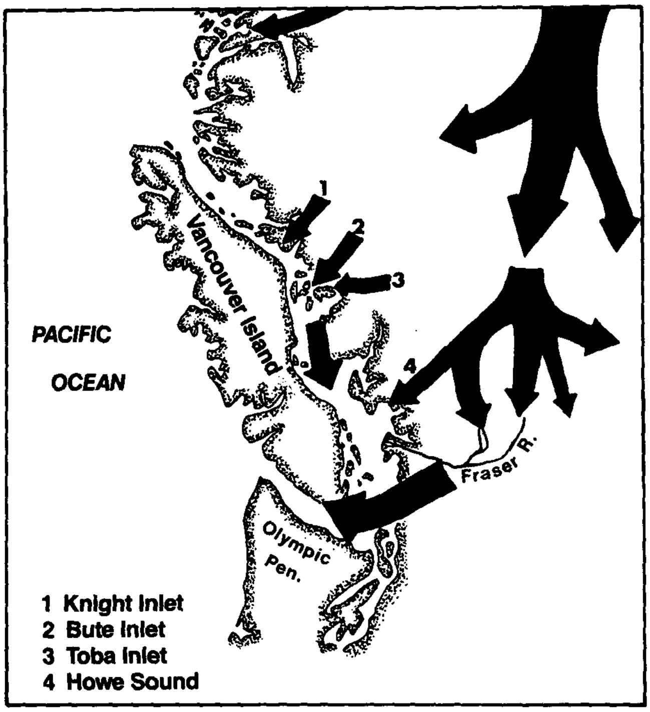

FIG. 10.6. The main paths of cold air in polar outbreaks. Seaward flow along mainland inlets is responsible for Squamish-type winds. (From Tyner 1951)

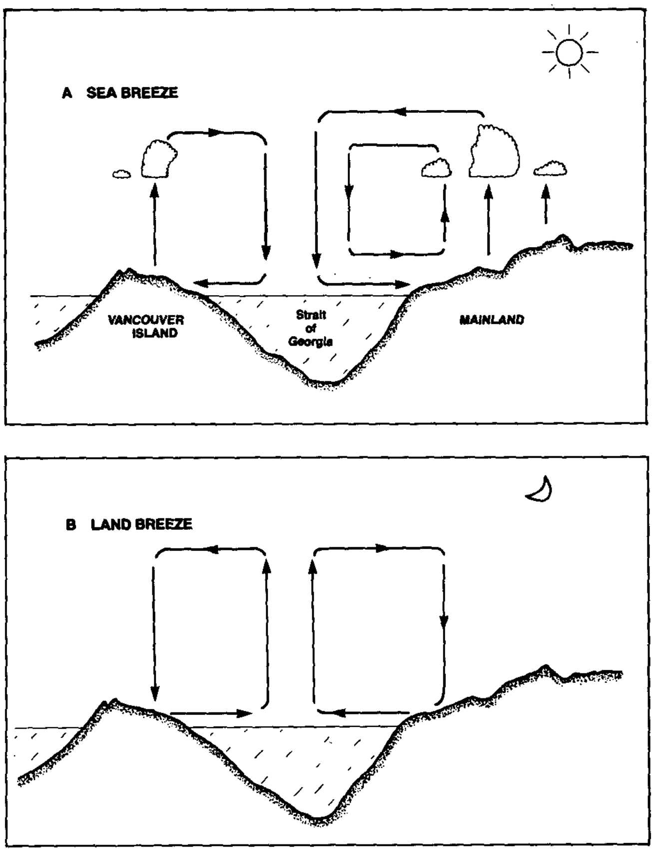

FIG. 10.7. Day sea breeze and night land breeze over Strait of Georgia region in fine weather.

sailing areas around Vancouver. Squamishes were reported on one occasion to reach 130 km/h in Dean Channel in the vicinity of Ocean Falls. Strong winds are most often associated with the passage of active frontal disturbances, however. The more vigorous storms are preceded by southeast gales, which tend to follow the trend of the Strait of Georgia and the Coast Mountains. Moreover, strong southeasterly winds that precede southwest–northeast oriented cold fronts frequently veer to strong northwesterly winds as a ridge of high pressure strengthens behind the advancing front.

In summer, the differential heating of the land and water generates breezes that significantly alter the prevailing wind regime during periods of fine weather. There are two types: (a) the sea breeze from the water to the land, produced by the greater heating of the land than the water during the day (Fig. 10.7a), and (b) the land breeze from the land to the water, produced by the greater cooling of the land than the water at night (Fig. 10.7b). Over the eastern side of the Strait of Georgia, the sea breeze generally sets eastward onto the mainland around 10 a.m., strengthens to about 4–7 m/s (8–14 kn) at midafternoon and then dies away before sunset. Consequently, the time of least chop begins about 2 h before sunset, and the smoothest crossings of the Strait begin in the late afternoon to early evening. (See *Small Craft Guide*, Vol. 1, 1979, p. 28–29, published by the Canadian Hydrographic Service.) Often in summer, the combination of the sea breeze and prevailing northwest winds (associated with large-scale westerly flow of air over the coast) results in strong (over 8 m/s) onshore winds on the eastern side of the Strait. Near gale force winds in summer can occur in Burrard Inlet if each of these two wind systems is intense enough. On the western side of the Strait the sea breeze will partially counterbalance any pattern of prevailing northwest winds, and produce weaker, more northerly, winds.

During the evening, the land breeze develops and winds blow onto the eastern half of the Strait from the mainland at speeds that peak near midnight to less than 4 m/s. On the western side of the Strait, a similar system of onshore and offshore breezes develops as a consequence of the daily heating and cooling of Vancouver Island. These winds, of course, are in the opposite direction to their counterparts on the mainland side.

Waves

Wave heights in the Strait of Georgia are limited by the fetch of the wind and to a lesser degree by its strength and duration. The total fetch is further limited by obstructions like Texada and Lasqueti islands, which make it almost impossible for wind waves to propagate and grow unimpeded along the entire length of the basin. No one who has been out in the Strait during a strong blow would argue that wave heights cannot at times be quite appreciable. But claims such as one boater made that he had "just survived 30-foot rollers off Nanaimo" during a gale are exaggerations (5–10 ft waves were seen in the same area from the research vessel *Richardson*). Had he claimed to have endured such conditions south of Cape Mudge or off the main arm of the Fraser River where large rips can develop, his story would have been more believable.

Some of the first scientifically recorded wave measurements in the Strait of Georgia were made in 1968–69 by the B.C. Research Council, to assess wave effects on the first "stretched" B.C. ferry, MV *Queen of Esquimalt*, between Swartz Bay and Tsawwassen. These were followed by similar studies at Halibut Bank prior to the first stretched ferry sailings between Nanaimo and Horseshoe Bay. More recent investigations of the wave climate of the Strait have been undertaken by Environment Canada and the Department of Public Works using bottom-moored waverider accelerometer buoys. Wave records from these buoys have been obtained off West Vancouver in Burrard Inlet in 40 m of water, off Sturgeon Bank near the Iona Sewage Outfall in 139 m, and off Roberts Banks near the coal port in 110 m (Fig. 10.8a). Observations were made for 17 mo off West Vancouver and 26 mo at the other localities, with continuous readings over a span of 20 min, each 3 h. Sturgeon and Roberts Bank are especially well exposed to waves from the northwest generated over a possible wind fetch up to 120 km (63 nm) and, therefore, should yield extreme wave data indicative of other exposed areas in the Strait.

Heights

Wave statistics from the three locations are presented in Fig. 10.8a, b; 10.9. During the entire period of observations in the Strait, significant wave heights never exceeded 2.1 m off Roberts Bank or 2.7 m off Sturgeon Bank, while corresponding maximum heights were always less than 3.3 and 4.0 m. Only 10% of the time did average wave heights at both localities exceed 0.8 m and maximum wave heights exceed 1.2 m; however, 60% of the time the maximum waves exceeded 0.3 m. Calm conditions prevailed 31% of the time at Roberts Bank and 27% at Sturgeon Bank. The curves for West Vancouver reflect the protected nature of Burrard Inlet where maximum probable waves rarely exceeded 1.8 m and maximum wave heights were greater than 0.6 m only 10% of the time. Fewer than 30% of the latter records showed waves higher than 0.3 m.

Periods

A comparison of wave heights and wave periods reveals other facets of the wave climate in the Strait of Georgia. At the two exposed locations, for example, there is a tendency for significant wave heights to increase as the period increases, at least up to periods of around 5 s. A typical 5-s wave will have a significant wave height of 0.5–1.0 m or a maximum wave height of 0.8–1.6 m, suggesting that waves with periods of 5 s or less are seas actively worked on by the winds. Wave periods of 5–6 s represent a transition from sea to swell-type waves, when both large and small wave heights occur with almost equal regularity. At periods exceeding 6 s, the observed wave heights are generally small and indicative of long, low, swell-like waves, which for a period of 6 s would have a wavelength of approximately 55 m based on Table 6.3.

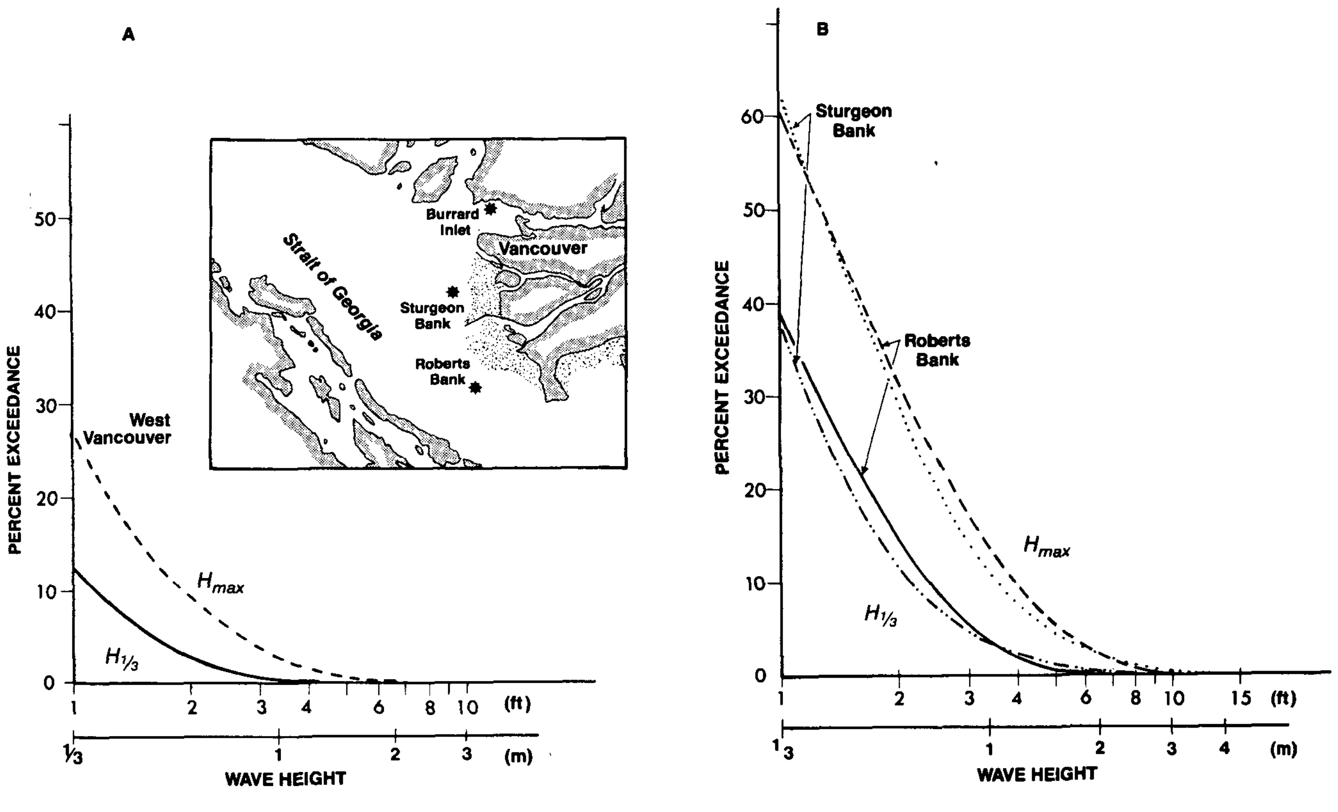

FIG. 10.8. Measured wave-height distributions for three locations (*) Strait of Georgia. Upper curves (A) (B), percentage of time maximum probable wave, H_{max}, exceeds given height; lower curves percentage exceedance for significant wave, $H_{1/3}$. Statistics based on observations March 1973–May 1974 West Vancouver, and February 1974–April 1976 Sturgeon and Roberts Bank.

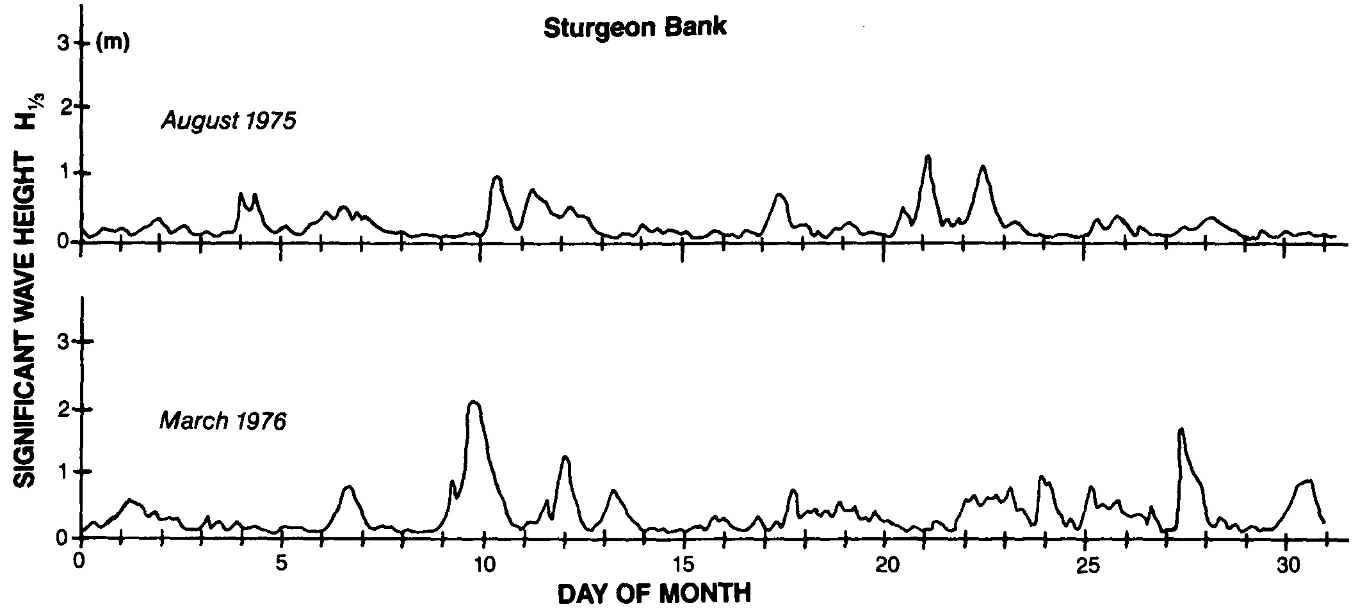

FIG. 10.9. Significant wave height versus time at Sturgeon Bank for 2 mo. Height in metres based on measurements taken every 3 h. (Adapted from Canadian Marine Environmental Data Service reports)

Nevertheless, seas with significant wave heights up to 2.5 m and periods of 7–8 s occur on occasions. Such sea conditions are more likely to occur at Sturgeon Bank than at Roberts Bank because of a steepening effect by opposing currents from the North Arm of the Fraser River.

The vast majority of waves in the open Strait off the Fraser River estuary have periods clustered in the range of 2–4 s and maximum probable heights below 1.5 m. The most probable maximum wave period according to the observations off Sturgeon and Roberts Bank is 9 s which, for low sinusoidal swell in deep water, would correspond to a maximum wavelength of about 125 m. Periods of 5–6 s occur as much as 30% of the time off Sturgeon and Robert Banks.

Wave records off West Vancouver are noticeably different from those within the Strait. Significant wave heights off West Vancouver are always less than 1.0 m, but span a surprisingly wide range of wave periods of up to 7 s, indicating that both sea and swell have comparable heights within Burrard Inlet.

Of course not all wave conditions in the Strait of Georgia are represented by the above statistical results. On one ferry crossing the author took between Swartz Bay and Tsawwassen on a blustery spring day, northwest winds were gusting to 25 m/s (50 kn) and huge breaking seas seemed to engulf the Strait in foaming white water. Onboard the spray-drenched MV *Queen of Sidney*, babies cried and many passengers ended up on the deck. The cafeteria was closed soon after the boat left Active Pass, though many patrons were too seasick to notice. A few later sailings that day were canceled, but not because of the 3–4 m high waves. As attested to by the minimal amount of wave shelter provided by the small breakwaters at Tsawwassen, the occasions when sailings are canceled are usually due to adverse winds when docking rather than the sea state.

Rips

The highest and steepest waves in the Strait of Georgia occur in rips where strong currents oppose wind waves generated over long fetches during gale force winds. Waves in these regions can be devastating and small craft should make every effort to avoid them.

Particularly dangerous rips occur at three locations in the Strait (see Fig. 10.1): (1) in the vicinity of Boundary Passage during periods of strong northwest winds and large flood streams. The sea state is further confused in this area by intense upwellings and eddies associated with tidal mixing in the channel. In the large backeddy that forms north of Tumbo Island on the flood, the seas will be more subdued; (2) seaward of Steveston Jetty and North Arm Jetty of the Fraser River delta during times of west to northwest gales. Extremely dangerous rips for such winds are created during periods of substantial river discharge (summer freshet) or near times of low tides when entrant speeds of the river can reach 2.5 m/s (5 kn) in the main channel. Near the river mouth, shoaling of the bottom causes a further amplification of the wave heights and invariably the water is rougher than in adjacent regions of the Strait. Numerous boats have capsized and their occupants drowned when attempting to enter the river in a northwest blow, and the number will undoubtedly grow unless the increasing number of boaters on the lower mainland are made more fully aware of the risks; and (3) south of Cape Mudge during strong southeast winds and a flood stream. The region from Cape Mudge to about Willow Point is locally renowned for some of the most awesome rip conditions in the Strait of Georgia, and owes this distinction to the relatively long wind fetch and strong tidal currents that surge southward out of Discovery Passage. The author can personally attest to the validity of this reputation. On the homeward leg of a March 1977 cruise, the CSS *Parizeau* encountered an area of high seas roughly 1.5 km south of Cape Mudge at the time of a 3 m/s (6 kn) flood and a southeast gale with winds gusting to 30 m/s. The currents had literally stopped the waves at the leading edge of the advancing tidal stream. The waves steepened into sharp, white-water peaks over 5 m high, churning and foaming in their effort to propagate against the flow. With the passage of each standing crest, the bow of the *Parizeau* would drop suddenly and plow almost immediately into the next wave, sending a blinding spray of water over the bridge and leaving stomachs suspended in air. After a few kilometres the ride ended, and the 2- to 3-m seas south of the tide rip seemed like the proverbial millpond.

From the air, flood waters that intrude into the Strait of Georgia via Discovery Passage appear as a slowly widening jet, whose axis lies roughly parallel to the 90-m bottom contour (Fig. 10.10). As the intense rips occur near the leading edge of this intruding jet where its currents first begin to oppose waves from the southeast, they can be avoided by keeping well to the east of midchannel or by waiting for a turn to ebb.

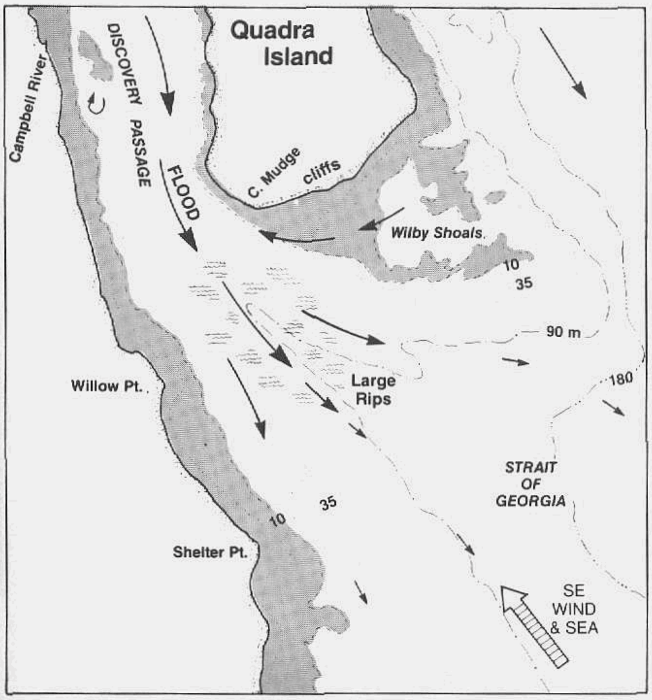

FIG. 10.10. Approximate extent of large rips south of Cape Mudge during a flood current and moderate-to-high seas from southeast. Area covered by rips varies according to velocity of current and strength and duration of wind. Depths in metres (for location see Fig. 10.1.)

Substantial rips can also form at the Strait of Georgia entrances to Porlier Pass and Active Pass during a flood stream and northwest winds. If the flooding jet of water curves northward when it leaves the pass, as it has been observed to do on occasions at Porlier Pass, there can be a further steepening of the waves in the rip. Southeast winds generally produce less intense rips due to the comparatively short wind fetch, especially at Active Pass.

Tides

As noted in Chapter 3, the inward progressing ocean tide enters the Strait of Georgia via Juan de Fuca Strait and is reflected from the constricted northern end of the channel. This southward reflected portion of the tidal wave then combines with the northward advancing portion of the tide to produce a standing wave in the Strait of Georgia, with distinct features from the more progressive-type tidal wave traveling along Juan de Fuca Strait. The fact that the reflected portion of the semidiurnal tide is partly attenuated by frictional effects before it can reenter Juan de Fuca Strait confines the pure standing wave pattern to the Strait of Georgia.

The standing wave nature of the tides causes the entire water level along the Strait of Georgia to move up and down in unison roughly every 12 h, 25 min, as if it were pivoted at an imaginary line drawn eastward through a point south of Saturna Island (see Fig. 3.25). As a consequence of this teeter-totter arrangement, the tidal ranges of both the main semidiurnal constituent (the M_2 tide) and the main diurnal constituent (the K_1 tide) increase from south to north (Fig. 10.11a, b). Moreover,

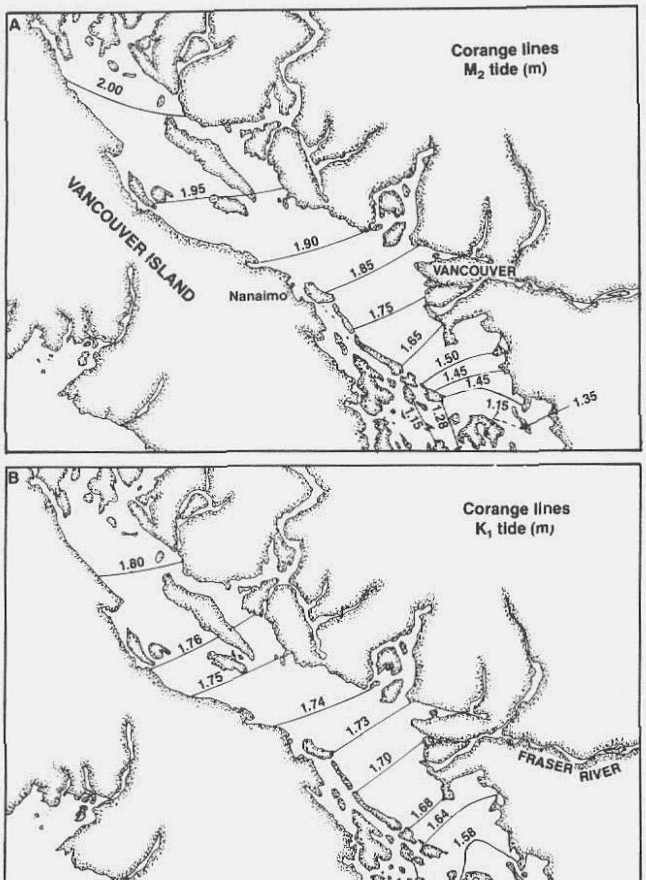

FIG. 10.11. Lines of equal tidal range for (A) main semidiurnal constituent, M_2, and (B) main diurnal constituent, K_1, in Strait of Georgia. (After Parker 1977)

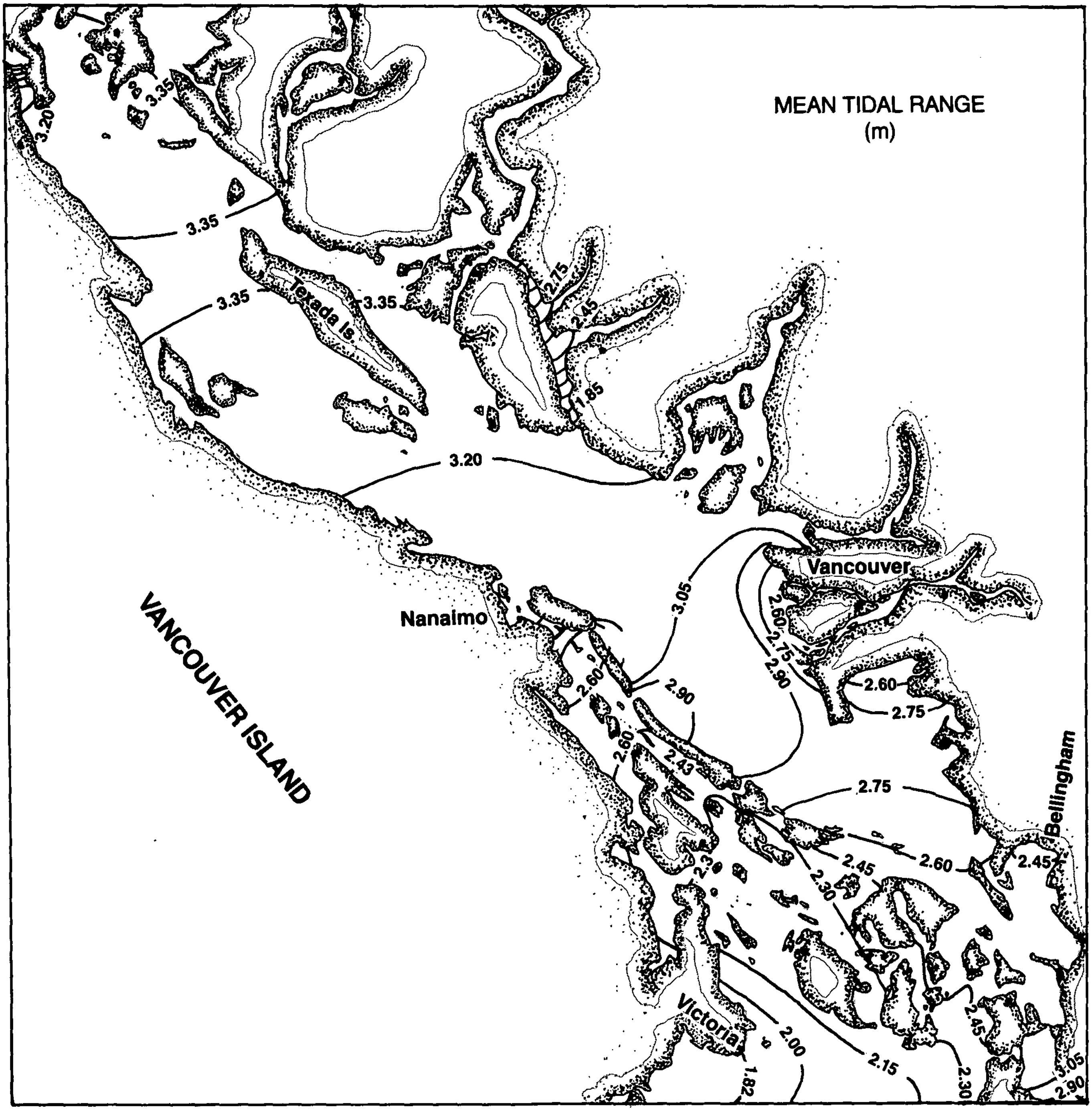

FIG. 10.12. Lines of equal mean tidal range in Strait of Georgia. (From Barker 1974)

between any two places within the Strait, the difference in time between identical stages of the tide never exceeds 30 min, quite unlike the situation in Juan de Fuca Strait. The actual tide is largely a combination of the M_2 and K_1 constituents and behaves in the same manner (Fig. 10.12). As semidiurnal elevations are slightly more important than diurnal ones, tides in the Strait are mixed, mainly semidiurnal. Consequently, there are differences in elevation between successive high waters and between successive low waters, the diurnal inequality. The diurnal inequality for successive high waters is always less than that for successive low waters. Moreover, the sequence of the tide always follows the pattern of Higher High Water, Higher Low Water, Lower High Water, Lower Low Water illustrated in Fig. 3.5 for Point Atkinson near Vancouver.

In addition to its daily inequality in height, the tidal range in the Strait of Georgia undergoes a biweekly variation due to cyclic changes in the declination and phase of the moon, with the declinational influence decreasing northward along the channel. Spring tides each 15-day period occur almost exactly 26 h following a new or full moon, which compares to a corresponding delay of about 15 h in the eastern portion of Juan de Fuca Strait.

Each year maximum tidal ranges occur during the summer and winter solstices when both the sun and moon attain their greatest north–south declinations at the same time. Minimum ranges occur during the spring and autumn equinoxes. Therefore, beginning in March, when Lower Low Water in the Strait is in the late afternoon, the low water begins to occur earlier each day and to become more extreme. By late June, lowest daylight tides take place at midday when the sun is overhead and a new moon coincides with the maximum lunar declination south of the equator. If one wishes to swim at Spanish Bank in Vancouver in the summer it is best to wait until evening after the water has been warmed as it crosses the broad sand flats on the rising tide.

The Coriolis effect produces only slightly greater tidal ranges at the boundaries of the Strait compared to those at interior regions. This is expected because, except in the southern portion, currents in the main body of the Strait of Georgia are weak and, therefore, subject to negligible deflection as a result of the earth's rotation. On the contrary, the across-strait difference in the tidal range in Juan de Fuca Strait is much more pronounced because of appreciably stronger tidal currents in that channel. Finally, the "centrifugal" force on the tidal wave that turns the corner into the Strait of Georgia from Haro Strait causes the tides to occur a few minutes earlier on the American side south of Boundary Bay than elsewhere in the southern portion of the Strait. Generally speaking, however, the large-scale curvature of the channel has a minor effect on the flow compared to that of local bends and points of land.

Tidal Streams

As with other coastal regions, currents in the Strait of Georgia are affected by tides, winds, river discharge, the Coriolis force, centrifugal forces, and channel bathymetry. Because of along-channel changes in the relative importance of these factors, the Strait actually possesses a diversity of circulation patterns superimposed on the tidal flow pattern. The Fraser River runoff, for instance, is of more direct importance to the flow structure in the surface layer of the central and southern portions of the Strait than to the northern sector. Although tidal streams are the predominant form of motion, their strength varies considerably over the length and depth of the Strait to further complicate an already complex oceanographic regime.

Measured tidal streams within the Strait of Georgia exhibit the characteristics of a standing wave where maximum flood occurs roughly 3 h before high water and maximum ebb around 3 h before low water (Fig. 10.13).

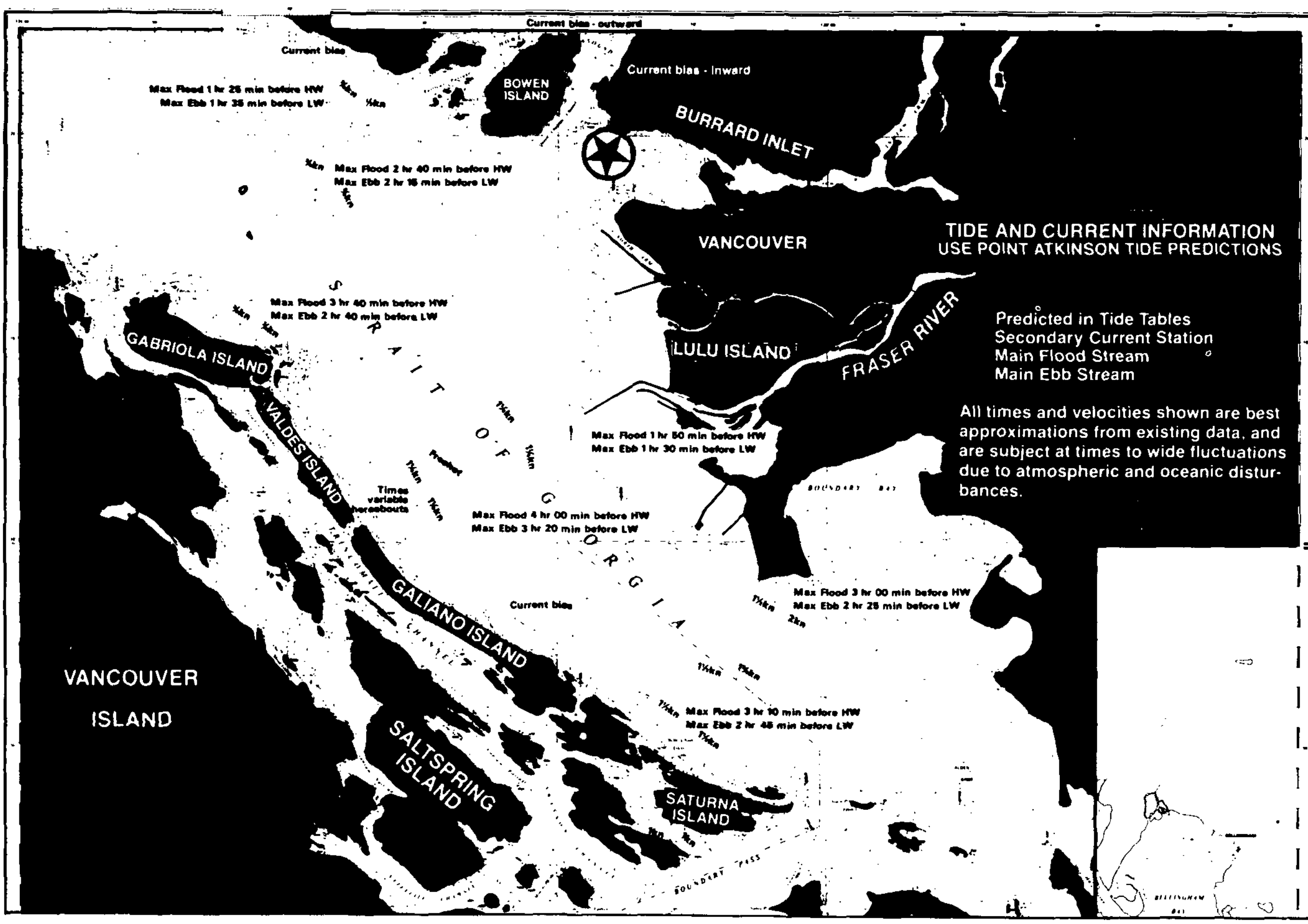

FIG. 10.13. Tidal streams and times of maximum ebb and flood relative to tide heights at Point Atkinson (star). Except near Fraser River delta, maximum surface tidal currents occur approximately midway through a semidiurnal tidal cycle, 2–4 h prior to high or low water. (Courtesy S. Huggett and P. Crean)

This correspondence between tide and tidal currents is best established within the northern part of the Strait and weakens slightly southward where the progressive nature of the ocean tide becomes more prevalent. Like the tides, tidal streams in the Strait can be classified as mixed, mainly semidiurnal with a diurnal inequality in the strengths of successive floods and successive ebbs. The sequence of tidal streams is stronger maximum ebb, stronger maximum flood, weaker maximum ebb, weaker maximum flood, which is consistent with the tide height sequence described in the previous section. In terms of constituents, the semidiurnal (M_2) tidal streams are generally much stronger than the diurnal (K_1) tidal streams. The main reason is that, although both the semidiurnal and diurnal streams transport roughly the same volume of water, the more rapidly varying semidiurnal streams must transport the water in half the time of the diurnal streams.

The following general features of the tidal flow are found during a flood stream. As the flow turns the corner toward the San Juan Islands, the water is deflected slightly eastward by centrifugal forces that produce a high water that is higher and earlier on the U.S. side than the Canadian side. A large portion of the flow then floods into Haro Strait while the rest moves northward through Middle Channel and Rosario Strait. Increased friction in these relatively constricted passageways greatly retards the flow and forces a partial backing up of water into Puget Sound (see Tidal Streams, Chapter 3). Although the transport of water in and out of the Strait of Georgia by the tides takes place at either end, the exchange through the southern channels is about 15 times that through the northern ones. For the most part then, the tides enter and leave the Strait of Georgia via Haro Strait and Rosario Strait, the volume through the former about 3 times that through the latter.

Most water that floods into Haro Strait continues along the main channel and eventually enters the Strait of Georgia through Boundary Passage. However, a significant portion surges northwestward via Swanson Channel, then into Trincomali Channel, where it piles up between the Gulf Islands as a sort of head box, an engineering term for a partially enclosed container used to maintain a hydraulic head. As a consequence, the water streams through the passes into the Strait of Georgia to produce the strong flood currents associated with Gabriola Pass, Porlier Pass, and Active Pass (Fig. 10.1). Dangerous rips often appear in the eastern ends of these passes at this time.

Within the main portion of the Strait of Georgia, the flood streams set to the northwest more or less parallel to the orientation of the shore. To the north of Point Roberts, the tidal flow undergoes a marked decrease in speed due to an appreciable increase in the cross-sectional area of the channel. Because the Strait is fairly wide, currents are also influenced by the Coriolis force, which deflects them very slightly to the right. This produces a small tilt of around 10 cm across the Strait toward the mainland side, enough to generate slightly stronger currents on that side than on the Vancouver Island side. Somewhere south of Quadra and Cortes islands the northward propagating tide encounters the southward propagating tide through the northern channels, so the tidal patterns in the northern part of the Strait are confused and highly variable. Within the northeastern sector, the tidal motions apparently swirl round and meet near Lund, Desolation Sound.

Consistent with the standing wave nature of the tide, there is slack water at high tide within the Strait of Georgia and a reversal in flow direction with the ensuing ebb. In contrast to the flood, the ebb is to the southeast and deflected slightly toward the Vancouver Island side, whereby tidal streams on the western side of the Strait are a few centimetres per second stronger and have a slightly longer duration than those on the mainland side. Tidal currents in the passes and inlets that adjoin the Strait are also reversed on the ebb and rips are infrequent. There is an acceleration of the ebb in the narrow portion of the Strait south of Point Roberts.

Except in passes and narrows, tidal streams in the Strait of Georgia are typically weak, their presence in the surface waters often masked by wind-generated currents and river runoff. For this reason, it is sometimes impossible to know what fraction of the observed current is actually due to the tides. To accurately determine the tidal flow throughout the entire Strait, current measurements over a broad area at many different depths and stages of the tide would be needed. This would be expensive, difficult, and time-consuming. Fortunately, there is a way around the problem, and that is to develop a computer-simulation of the tides and associated tidal streams. Pat Crean, of the Institute of Ocean Sciences, Sidney, B.C., has developed such a model for the waters of the Strait of Georgia–Juan de Fuca Strait system.

More than a decade of full-time effort was required to bring Crean's model to its present high level of sophistication. During that time, the model has undergone considerable modification to include increasing numbers of physical mechanisms that can affect the tides, and to make use of improved computer technology and numerical analysis techniques. Moreover, it has been necessary to measure tides and currents at selected locations in the two Straits to check the validity of computer-simulated results. Because results from the present model consistently reproduce actual measurements for a wide variety of tides, the ability to accurately predict the tides and tidal streams has improved immeasurably. It is now possible, for example, to simulate the tidal flow over the entire seaway at a given time and to estimate the long-term, tidally induced movement of pollutants, such as oil. The computer model further assists scientists to establish which physical processes most affect the oceanic variability of the inside coastal waters. Ultimately, it is hoped that the model will be refined to the point where it will be possible to simulate the influence of winds, Fraser River runoff, and conditions in the open Pacific on the circulations in the Strait of Georgia and Juan de Fuca Strait.

Selected tidal flow charts from the model have been reproduced in Fig. 10.14, 10.15. The first set of charts (Fig. 10.14a, b) gives instantaneous pictures, or "snapshots," of the surface tidal streams for maximum ebb and flood throughout the entire seaway from Cape Flattery to Cape Mudge. These so-called "coarse grid" charts are derived from an earlier version of the model. Figure

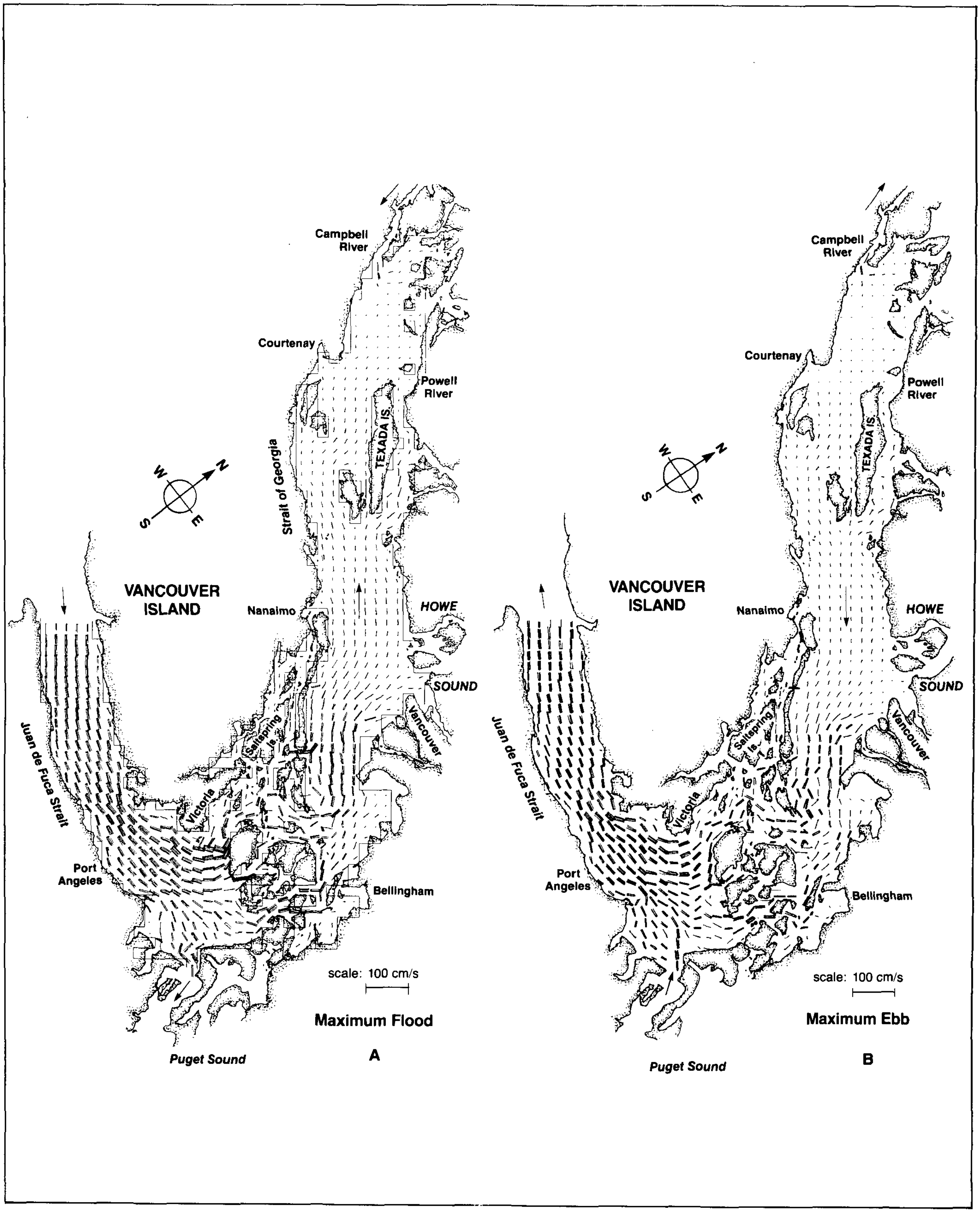

FIG. 10.14. Tidal streams in Strait of Georgia–Juan de Fuca Strait system calculated from Crean's coarse grid computer simulation model for large semidiurnal tide. Plots correspond to (A) maximum flood and (B) maximum ebb. Model calibrated by observed current and tide height data from the two straits. Direction of flow at center of each 4 × 4 km grid square is away from dot, total length of each line (vector) emanates from dot proportional to current speed (actual speed obtained from scale 100 cm/s or 2 kn long). Where current is strong and line too long to fit neatly on plot, it has been broken into segments and placed side by side. Actual coastline has been drawn over computer shoreline. (Courtesy P. Crean)

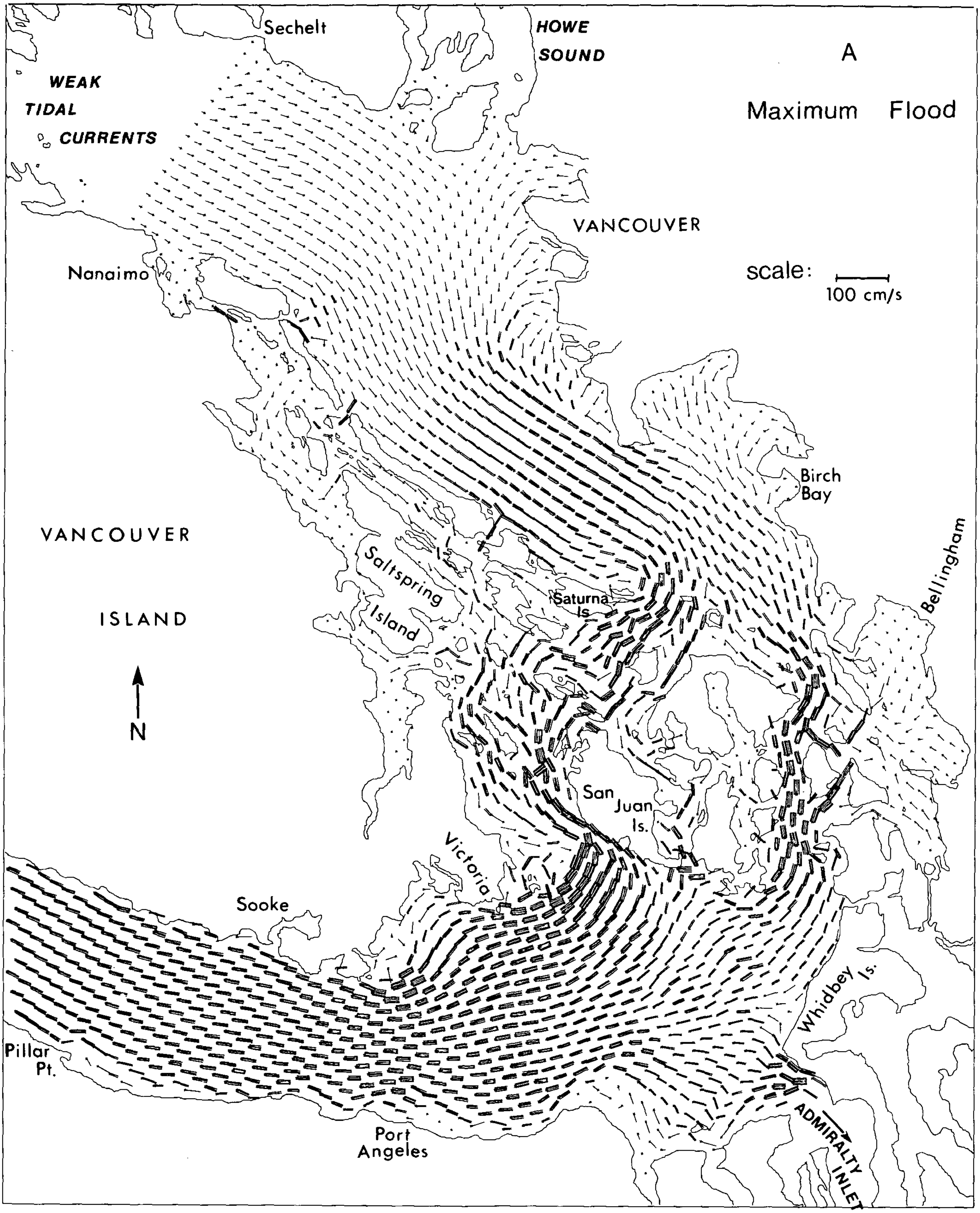

FIG. 10.15. Tidal streams in Juan de Fuca Strait and southern portion of Strait of Georgia calculated by Crean's fine grid computer simulation model. Plots correspond to three stages of mixed tide at Point Atkinson (A) maximum flood, (B) maximum flood plus 2 h, and (C) maximum ebb. Velocity vectors emanate from crosses and represent average surface currents over 2 × 2 km grid squares. Total length of vector at each location proportional to flow speed. Development of large counterclockwise eddy east of Race Rocks follows maximum flood; large eddies form east of Saturna Island and at southern end Haro Strait. (Courtesy P. Crean and A. Douglas)

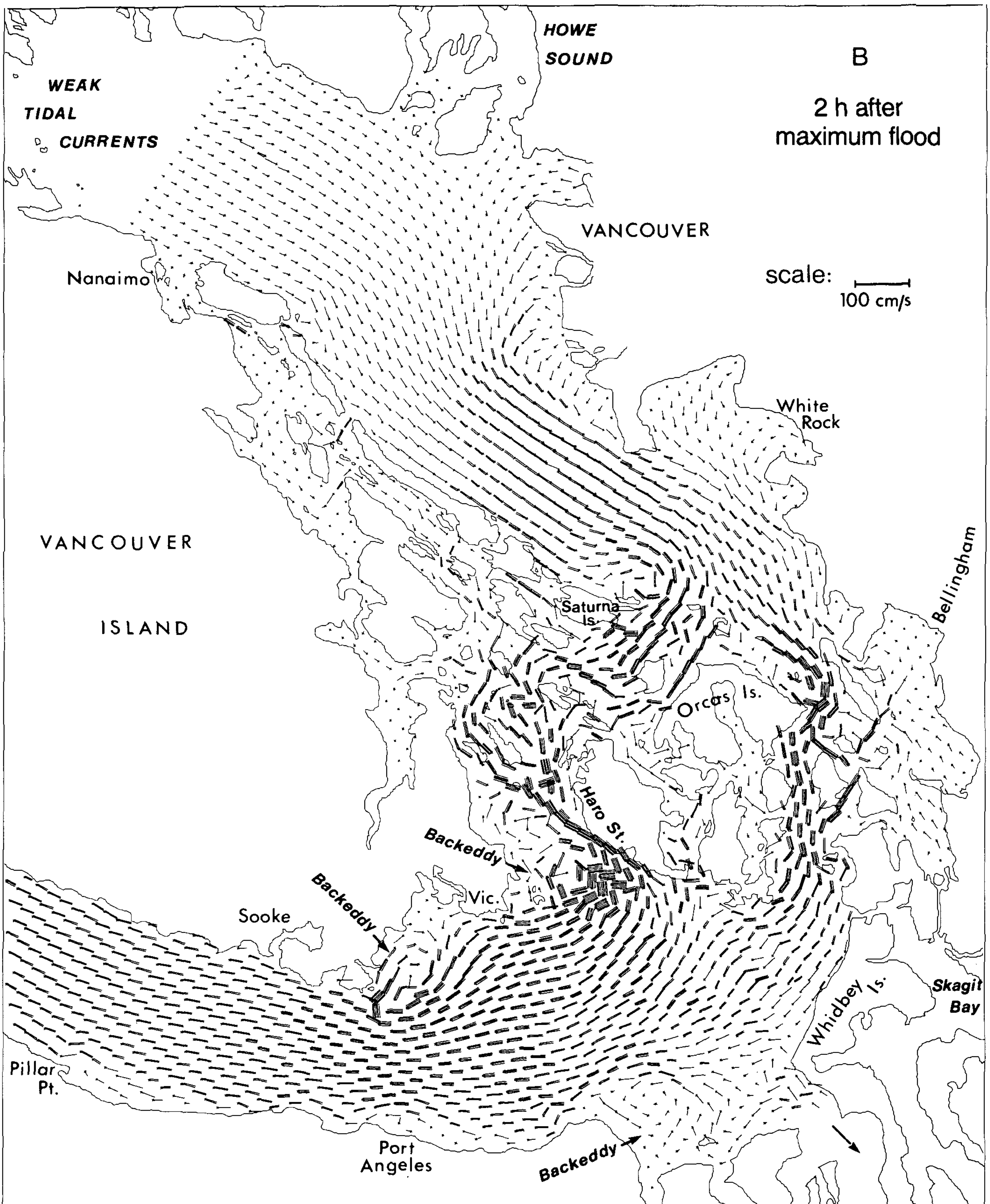

FIG. 10.15. Tidal streams in Juan de Fuca Strait and southern portion of Strait of Georgia calculated by Crean's fine grid computer simulation model. Plots correspond to three stages of mixed tide at Point Atkinson (A) maximum flood, (B) maximum flood plus 2 h, and (C) maximum ebb. Velocity vectors emanate from crosses and represent average surface currents over 2 × 2 km grid squares. Total length of vector at each location proportional to flow speed. Development of large counterclockwise eddy east of Race Rocks follows maximum flood; large eddies form east of Saturna Island and at southern end Haro Strait. (Courtesy P. Crean and A. Douglas)

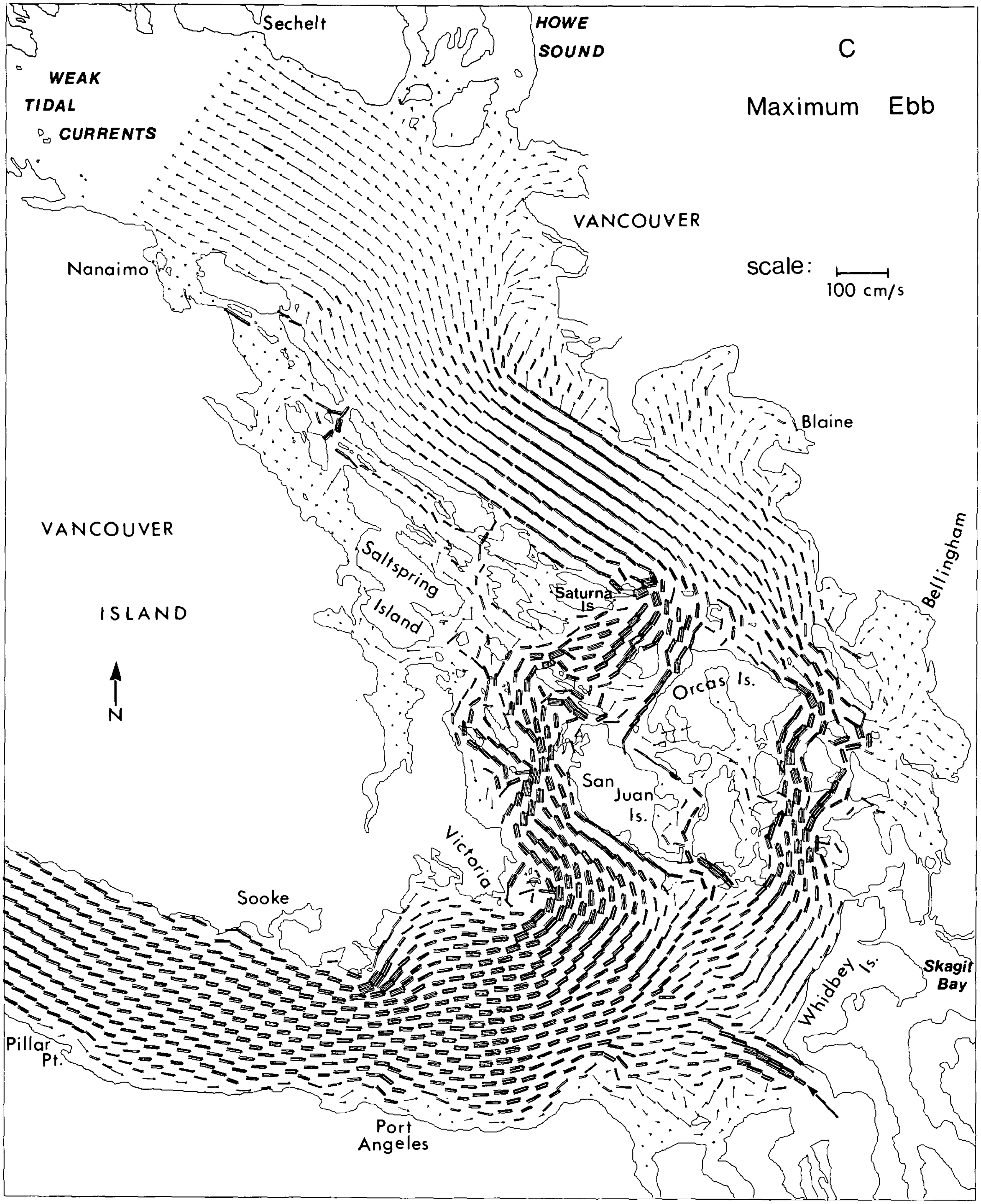

FIG. 10.15. Tidal streams in Juan de Fuca Strait and southern portion of Strait of Georgia calculated by Crean's fine grid computer simulation model. Plots correspond to three stages of mixed tide at Point Atkinson (A) maximum flood, (B) maximum flood plus 2 h, and (C) maximum ebb. Velocity vectors emanate from crosses and represent average surface currents over 2 × 2 km grid squares. Total length of vector at each location proportional to flow speed. Development of large counterclockwise eddy east of Race Rocks follows maximum flood; large eddies form east of Saturna Island and at southern end Haro Strait. (Courtesy P. Crean and A. Douglas)

10.15a–c, the more recent "fine grid" charts, give a much more detailed picture of the currents but are limited to the southern Strait of Georgia and eastern Juan de Fuca Strait. (Results from the coarse grid model are used as "input" to the fine grid model.) The times of the three tidal stream patterns correspond to maximum flood, 2 h after maximum flood and maximum ebb. In each case, the arrows (or vectors) denote the average velocity of the tidal streams from sea surface to seafloor at a particular locality for the specified stage of the tide. For the coarse grid charts, a velocity vector represents the average tidal stream at the center of a square grid of the water surface 4 km long by 4 km wide; for the fine grid charts, the average is over a smaller grid surface 2 km long by 2 km wide. A similar averaging procedure applies to the depth of water at each grid. (The expense of running programs for the computer model grows rapidly with decreasing grid spacing. Therefore, cost, aside from scientific limitations, becomes a major prohibiting factor to enhancing the detail resolvable by the tidal model.) The model takes into account the variable water depth and shoreline configuration, the earth's rotation (the Coriolis effect), friction effects, and the earth's gravity. It does not include the influence on the circulation of the winds, atmospheric pressure, river runoff, and variable water density.

The computer simulation deals only with the "pure" tidal streams so there can be considerable difference between observed and modeled surface currents currents due to the effects of runoff and winds. This will be particularly true at times of large Fraser River discharge or strong winds. The prudent reader should consider the current charts a guide to typical ebb and flood conditions but not assume them to be gospel. Furthermore, narrow channels like Dodd and False narrows are crudely approximated in the simulation. (Because the actual volume of water that moves through them is small, the passes are not critical to proper simulation of the tidal streams in the main channels, although they do possess considerable local importance.) Nor can localized backeddies be delineated by the model if their size is comparable to, or smaller than, the size of the grid squares over which the flow and depths are averaged. Also, the actual shoreline can be approximated, at best, by a series of short, straight lines corresponding to sides of the square computer grids along the land boundaries in the model. As a consequence, tidal streams near the shore may differ appreciably from reality. Finally, the model is not capable yet of simulating the strong onshore–offshore flow associated with drying tidal flats such as the Fraser River delta. In Fig. 10.15, the depth of these banks has been set arbitrarily at 5 m, so the currents only crudely model the true flow. Future models, however, will accurately include flow onto the banks as it can be a navigational hazard to vessels near the delta.

Despite its shortcomings, the computer simulation reveals numerous aspects of the tidal streams within the Strait of Georgia and Juan de Fuca Strait. (The latter region will be discussed in the next Chapter.) For example, the coarse grid charts (Fig. 10.14), show that tidal streams in the Strait of Georgia become progressively weaker to the north and eventually reverse where the flow from the south meets that entering the Strait via the northern channels. Although the currents tend to be in the same general direction throughout most of the Strait, those in the southern portion of Malaspina Strait to the east of Texada Island circulate in the clockwise direction during the flood. The fine grid charts (Fig. 10.15) reveal numerous large-scale eddy patterns in the Strait of Georgia, especially during the flood. The large counterclockwise eddy that forms north of Tumbo and Saturna islands during the flood appears to be one of the major circulation systems in the Strait.

The computer model is capable of simulating other facets of the tidal regime in the Strait of Georgia and Juan de Fuca Strait in addition to the currents. Figure 10.16 shows it is possible to obtain three-dimensional plots of the sea surface elevation relative to an arbitrary reference plane. The large drop in water level between the two Straits clearly shows the delaying effect the narrow channels between the San Juan and Gulf islands have on the passage of the inward propagating oceanic tidal wave. It is differences of this kind that account for the rapid tidal currents through the passages that connect the Strait of Georgia to Juan de Fuca Strait. The times of high and low water among the San Juan and Gulf islands coincide with those in Haro Strait, not those in the Strait of Georgia.

Measured Currents

Although there were a few observations of currents in the navigable tidal passages of southwestern B.C. as early as 1895, the measurement of currents in the Strait of Georgia proper only began fairly recently. This was perhaps due as much to a lack of effort and interest as to a lack of technology. In fairness, however, it should be pointed out that current measurements are neither easy nor inexpensive to obtain.

As any mariner knows, determination of the direction and speed of the surface current is not a simple task. So how is it done? One of the oldest and least expensive methods is to employ the "drift bottle" technique made famous by shipwrecked sailors in Hollywood films. For scientific purposes, sealed, nearly submerged bottles with an official card are used and offer a small reward to the finder, if the card is returned with the time and location of the find. A rough estimate of the surface drift can then be determined from a knowledge of the time it took the bottle to travel the distance between its release and recovery. During the summers of 1926 and 1929, 1636 such bottles were released throughout the Strait of Georgia. The 41% recovered indicated there was a net northwestward drift along the eastern side of the Strait and a southeastward drift along the western side over many tidal cycles. On the basis of this, Waldichuk (1958) suggested there was a general counterclockwise circulation in the Strait superimposed on the ebb and flood of the tidal streams. A smaller gyre that circulated in the same direction also seemed to exist to the south of a line drawn from Sand Heads to Active Pass.

The difficulty with this technique is that the bottles are not really an accurate way to measure currents, as winds and waves affect them in unpredictable ways, and

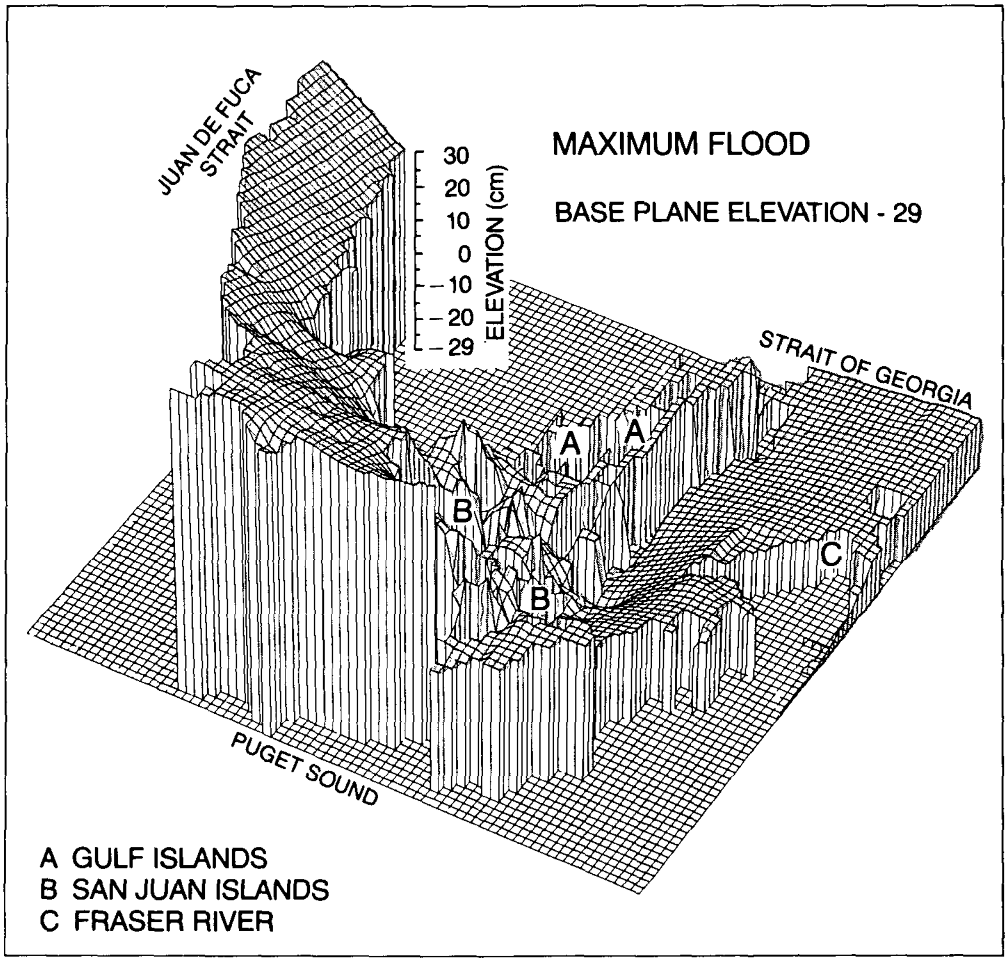

FIG. 10.16. Computer simulation of sea surface elevations during maximum flood, from seaward entance to Juan de Fuca Strait to northern end Strait of Georgia. Base plane is arbitrarily –29 cm; heights of water surface above this level in cm. Note slightly higher elevations on U.S. side of Juan de Fuca Strait due to Coriolis effect on flood streams and steep water slopes through islands. (Courtesy P. Crean)

they may lie on the shore a long time before being recovered. A more sophisticated method is to attach current meters (instruments that record the direction and speed of the current at a fixed position) at various depths on an anchored line. This works fine except near the surface, where logs and marine traffic can do considerable damage and the bouncing action of waves can cause the instrument to give meaningless readings. Consequently, observations of this type are usually not taken shallower than 5 m below the surface. Because there can be considerable difference in the speeds and directions of currents at different depths, especially in regions affected by river discharge, other methods are needed to further determine the behavior of surface currents.

Fortunately, there are two other methods especially applicable to measuring currents close to the surface. The first uses small drifting buoys called drift drogues, whose motion can be tracked day and night by ship or land-based radar. (In offshore regions, satellites are used to track drifting buoys.) An essential part of their construction is a structure with a relatively large surface area that hangs below the surface float to minimize the effect of winds and waves. Called a drogue, it ensures that the system as a whole doesn't move relative to the water, just as a sailboat's keel is meant to prevent leeway. Provided they don't run aground, the buoys will give a measure of the average speed and direction of the current over a depth comparable to the keel depths of most yachts (roughly 2 m). Some of the first measurements by tracked drifters in the Strait of Georgia were taken by Pickard in the summer of 1954. (He actually used "drift poles" that don't have a drogue, but the idea is the same.) Observations lasted 25 h (1 tidal cycle) and were taken at six positions between Point Roberts and Galiano Island, and at two positions in Trincomali Channel. Surface currents averaged 23 cm/s (0.45 kn) on the flood and 43 cm/s (0.85 kn) on the ebb, with maxima to 100 cm/s (2 kn) in each case. In the Strait, these flows were attributed to the tides and to the large Fraser River runoff, as the winds were generally less than 2.5 m/s (5 kn).

The second method uses the silty water from land drainage as a natural tracer of the surface water movement and is applicable to the regions of the Strait of Georgia directly affected by the Fraser River runoff. Aerial and satellite photographs are valuable in this regard although cloud cover can often be a nuisance (Fig. 10.17, Pl. 12).

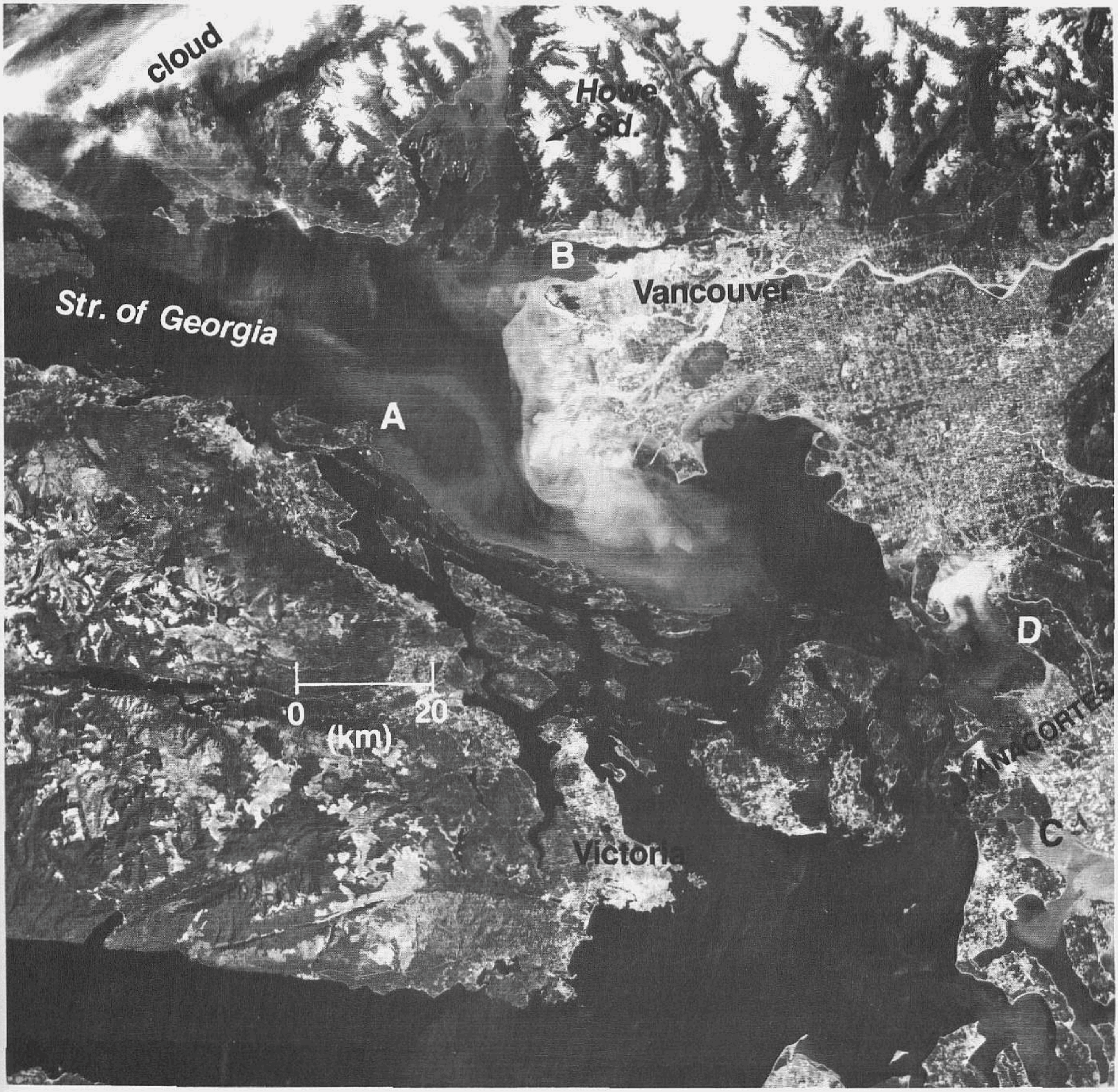

FIG. 10.17. Satellite (LANDSAT) image shows southeasterly movement of Fraser River sediments into southern Strait of Georgia, July 20, 1974. Sediment dispersal pattern (midway between maximum ebb and low water slack) suggests movement of surface water along Gulf Islands into Porlier Pass, with a cyclonic eddy to east of Gabriola Island (A). Suspended sediments from north arm of Fraser River flow into Burrard Inlet (B); sediment discharge of Skagit River into Skagit Bay (C), and Nooksack River into Bellingham Bay (D). (Courtesy R.A. Feely)

Because the surface can be expected to move primarily under the influence of tides, winds, and the Fraser River runoff, the question is, "How closely does the behavior of the observed surface currents resemble that of the currents expected to be produced by the local winds and tides?" To answer this question it is expedient to divide the Strait into its three somewhat different regions (Fig. 10.18).

The Northern Strait

This portion of the Strait is typified by weak and variable tidal currents (see for example Fig. 10.14). Over most of the region these currents attain speeds of only around 10 cm/s, with the most marked exception at the southern approaches to Discovery Passage. Tidal streams through Sabine Channel between Texada Island and Lasqueti Island, and in Malaspina Strait, can reach 50 cm/s or

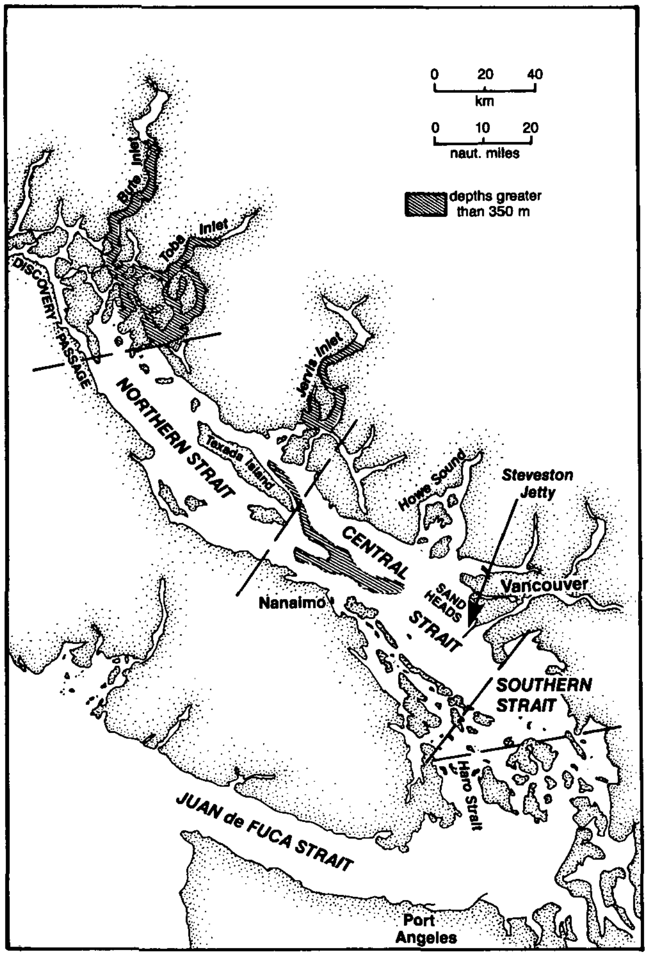

FIG. 10.18. Three oceanic regions of Strait of Georgia. Depths greater than 350 m (200 fa) indicated by hatched areas.

more on occasion, but in general are of the order of half this value.

Aside from a general knowledge of the tidal motions, little else is known about the surface currents in the northern Strait as so few observations have been reported. Although drift bottle studies in the 1920s indicated a general counterclockwise circulation in this area, with westward drift at the northern end and southward drift on the Vancouver Island side, this has yet to be confirmed. With the information in Chapter 4, however, the importance of wind currents in this region can be speculated as generally weak, despite the persistence and strength of the local winds. The reason is that the water does not normally have a distinct layering over most of the year. Consequently, the maximum speed of surface water under a steady, along-the-strait wind is only about 3% of the wind speed. Even for a persistently strong 10 m/s (20 kn) wind, this is only a current speed of 30 cm/s (0.6 kn) at best. For winds across the strait, or of short duration (less than about 12 h), the speed will be somewhat less.

In summer, the overall situation may be altered slightly when the sun warms the upper metre or so of water thereby making it lighter than the cold water beneath. This creates the "slippery water" situation discussed in Chapter 4 and permits the surface layer to slide downwind with greater ease. Provided the surface layer is not so churned up by wave action that it loses its identity, a 10 m/s wind could now generate surface currents that exceed 50 cm/s (see Fig. 4.3).

The Central Strait

This portion of the Strait is characterized by moderately strong tidal streams and by the influence of the Fraser River runoff. Its proximity to the densely populated areas of greater Vancouver makes it the most used marine passageway in British Columbia. As it receives most domestic and industrial waste from the lower mainland and is an important feeding area for migrating salmon, it has been the most studied region of the Strait. Hence, it is possible to see how the observed currents resemble those a mariner might expect according to the winds and tides. For this purpose, the findings of the drifting drogue studies made between 1966 and 1968 will be used. Reference will also be made to some recent aerial photographic studies.

To begin, it is necessary to appreciate the importance of the Fraser River runoff to water circulation in the Central Strait. Approximately 75% of freshwater runoff into the Strait of Georgia is from the Fraser River, which itself drains about 25% of the total land area of British Columbia. All but 30% of this discharge empties into the Strait from the main channel near Steveston. During the snow-melt period of late spring to summer the lighter water pouring from the river spreads over a portion of the Strait as a brackish, silt-laden layer with thickness from 1 to 10 m. Because the discharge from June to mid-July can exceed 11,000 m^3/s (390,000 ft^3/s) (Fig. 10.19), the total surface area covered by this murky water may be quite large, particularly when the numerous patches and fingers of fresh surface water that have broken from the main pattern are considered. In winter, on the other hand, the river outflow tends to be more confined to the nearshore region of the Fraser River delta; by mid-March the discharge has typically diminished to around 1000 m^3/s (35,300 ft^3/s) and is less able to spread over the central

FIG. 10.19. *Volume of water per second through cross-section of Fraser River in 4 different years. (Measurements taken at Hope, head of Fraser Valley.) Only portion of 1948 runoff curve shown. (Large runoff that year caused severe spring floods in Fraser Valley.)*

part of the Strait. Except under very rough wave conditions, the boundaries between the light colored brackish water and the darker salty water of more oceanic origin are usually very distinct. The runoff's importance is two-fold: first, the momentum of the river water flowing from the main arm causes it initially to be directed southwesterly toward the Gulf Islands; and, secondly, the river is a source for light surface water that produces the slippery water situation necessary for enhanced wind-generated currents. Superimposed on the currents produced by winds and river runoff is the more regular tidal streams that ebb to the southeast and flood to the northwest at speeds of about 50 cm/s (1 kn) half way through the normal tidal range of 3.2 m.

In summary, observations of the interplay of the various mechanisms that produce surface currents are:

1) Drift drogues released near the mouth of the Fraser River indicate that the speed at which the river water first overflows the Strait depends on the volume of runoff and the stage of the tide. During the summer runoff, outflow speeds to 2.5 m/s (5 kn) can occur near low water during large tides, and speeds of 1.0–1.5 m/s (2–3 kn) are not uncommon at less extreme low tides. These reduce to around 0.5 m/s within about 5 km of the river mouth as the buoyant plume of brackish water spreads laterally over the Strait.

At high tide the outflow speeds are typically below 50 cm/s. During winter when the runoff is low, currents are up-river as far as New Westminster during the later stages of a rising tide. This is normal so anyone who uses the river is advised to pick the tides to his advantage.

2) In the presence of light winds, the plume of fresh water leaving the river does one of two things, depending on the state of the tide. During an ebb, the plume will maintain its southwest direction despite the fact that the tidal currents are to the southeast (Fig. 10.20a). During a flood, on the other hand, the surface plume will turn sharply to the north at a greater rate than would be predicted from the tidal currents alone (Fig. 10.20b). Why these unexpected results? One possible explanation is that the Coriolis force, which attempts to turn the plume to its right, is able to balance the effort of the ebb currents to move the plume to its left. During a falling tide the ebb currents increase in speed but so does the speed the river runoff enters the Strait. As the Coriolis force on the runoff also increases with its speed, the effect of the tidal current is kept in check. Thus, even when the tide tables indicate an ebb current, a boat within the plume emanating directly from the river could drift to the southwest. If the ensuing flood is weak, this drift may extend all the way to the Gulf Islands. Usually, the Coriolis force begins to prevail over the weakening ebb and the plume turns northward. During the flood, the combined effect of the tidal currents and the Coriolis force turns the plume directly northward within about 15 km of the river mouth. It may then drift toward Burrard Inlet at speeds of 50–100 cm/s (1–2 kn) on a large flood.

3) Away from the direct influence of the river's discharge the surface currents are expected to be more dependent on local winds and tides. But this is not always the case. The drift drogue observations of 1966 and 1967 showed that a section of the plume that had been turned northward on a flood could continue to move northward at over 50 cm/s, even when the tidal currents were ebbing strongly to the southeast. This motion inevitably carried the surface water toward the western side of Howe Sound or toward the vicinity of Wilson Creek on the Sechelt Peninsula. The water then moved parallel to the shore or turned immediately westward toward Texada and Lasqueti islands. Although the brackish surface layer moved against the ebb, observations showed it did slow significantly at the time of maximum ebb, as would be anticipated. Similarly, maximum northward speeds occurred at times of maximum flood.

Because the winds were generally around 5.0–7.5 m/s (10–15 kn) from the southeast at the time of these particular drift drogue studies, it is natural to assume that the persistent northward drift of this particular portion of the plume was due solely to the influence of the wind. But the observed depth of about 3 m for the slippery brackish layer and Fig. 4.3 show that, at most, these winds would drag the surface layer along at 25–30 cm/s (0.5–1 kn). Obviously, this is not rapid enough to account completely for the movement of the top layer against the ebb, which is also about 50 cm/s. In other words, there are fairly strong currents in the Strait of Georgia that aren't directly relatable to local winds and tides. For want of a better term, oceanographers call these unpredictable motions residual currents. Although of little consolation to anyone who attempts to determine the surface currents, in retrospect the residual flow was to the north at about 50–100 cm/s in the present example. However, until there are more measurements and more concrete explanations for what produces such currents there is little to be said about them. One thing is fairly certain. The initially northward moving surface layer will start flowing nearly parallel to the shoreline once it reaches the vicinity of the Sechelt Peninsula, regardless of what mechanism is pushing it along. Moreover, it appears that surface currents generated by moderate winds, although at times significant, are not an over-riding factor in determining the speed and direction of the surface waters in the Central Strait.

4) Through the action of winds, tides, and residual flow, the silty river outflow has an irregular distribution over large areas of the central and southern portions of the Strait; the greatest area is covered in summer when runoff is greatest. The result is a surface patchwork of dark- to light-colored water; the darker areas correspond to salty oceanic water and lighter areas to recently added Fraser River outflow. Less recent Fraser runoff, which has become mixed to varying degrees with the oceanic water, appears in various shades of grey (Fig. 10.21). A sharp boundary between the dark- and light-colored water often marks the location of a rapid change in the speed of the surface current. Currents that flow parallel to the boundary on the darker side may, in fact, differ by as much as 1

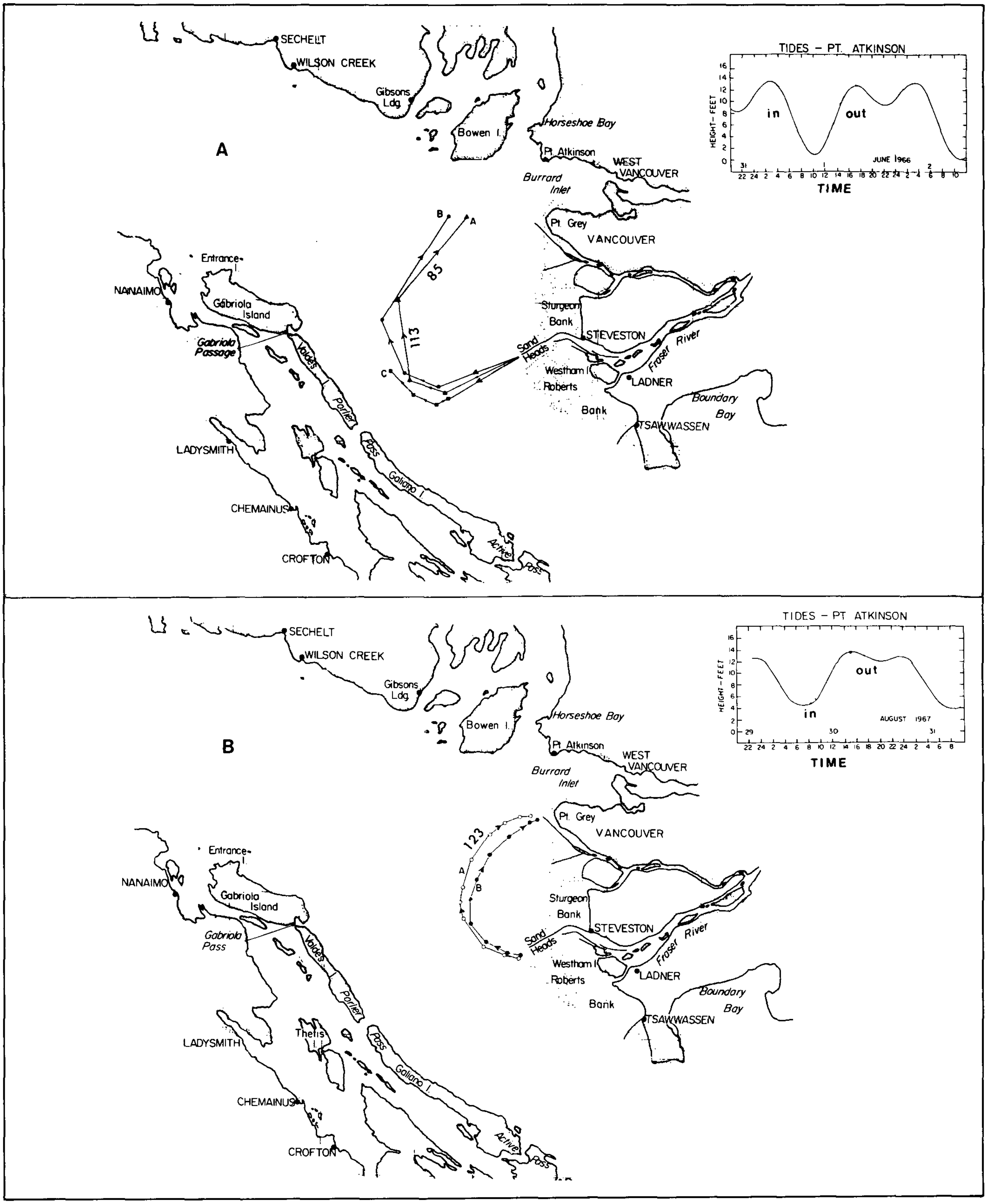

FIG. 10.20. Paths taken by surface drogues released near Sand Heads at mouth of main arm of Fraser River. Top inset gives times of release and recovery with stage of tide at Point Atkinson. (Point Atkinson tides lag those at Sand Heads by about 18 min.) (A) Three drogues released on ebb, June 1, 1966. Light winds. On flood, drogues moved northward attained speeds 85–113 cm/s. (B) Two drogues released at low water, Aug. 29, 1967. Light winds. Each dot (or circle) represents position of drogue on hour with 1 h between each position. Example shows drogue speed 123 cm/s on one leg of path. (Adapted from Giovando and Tabata 1970)

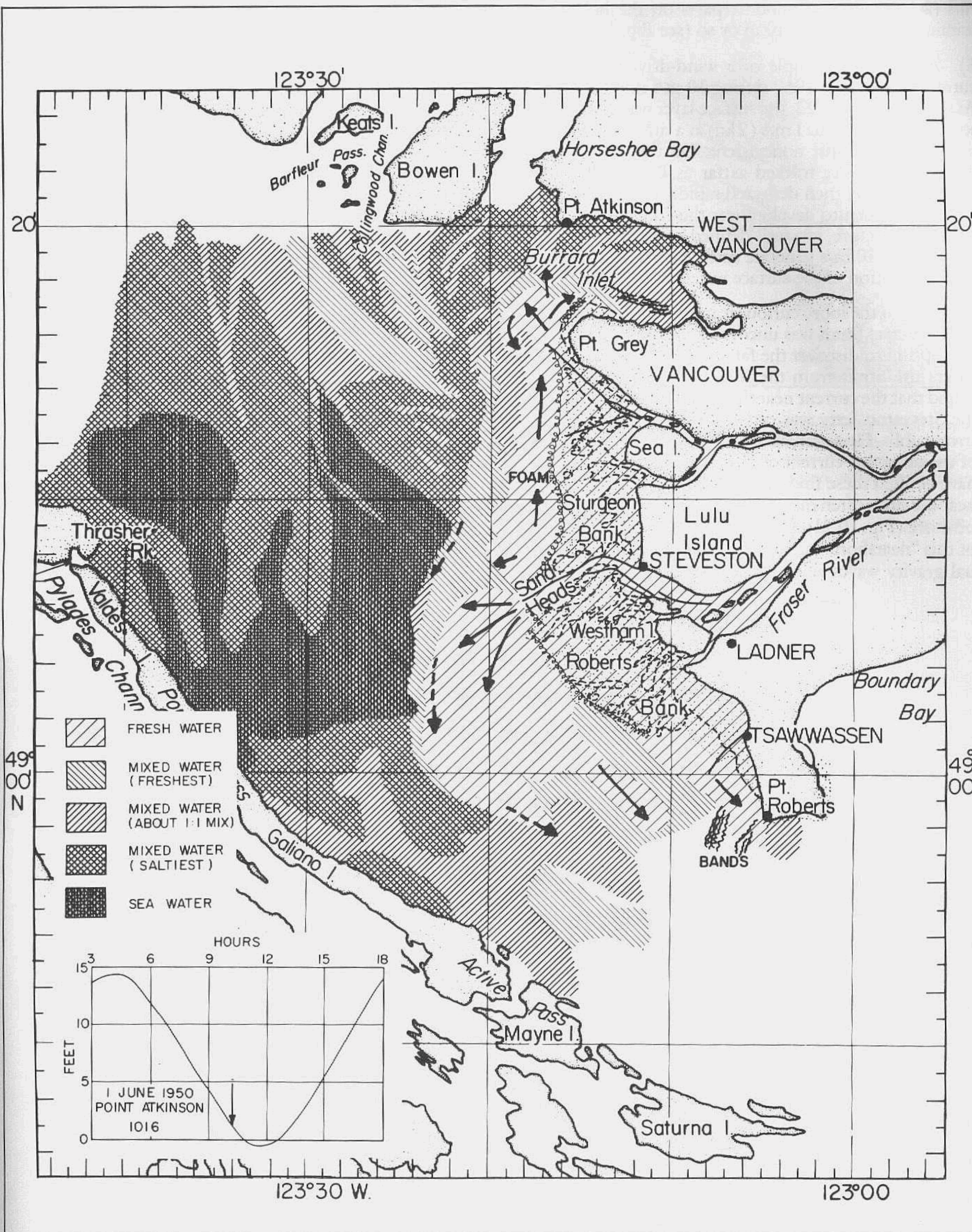

FIG. 10.21. Surface distribution of brackish and oceanic waters in central Strait of Georgia in final stage of large ebb, June 1, 1950 (deduced from series of aerial photographs). Note northward current at edge of Sturgeon Bank despite southeast ebb. Bands due to internal waves; spiral lines on delta represent foam associated with breaking wind waves. (From Tabata 1972)

m/s (2 kn) from their counterparts on the lighter side within a boat-length of 10 m or so (see Fig. 3.33).

5) An obvious example of a wind-driven current occurred in early June 1967 during 10 m/s northwesterlies. As shown in Fig. 10.22, the surface layer was driven to the southeast at speeds to 1 m/s (2 kn) at a time when the tidal streams were almost nonexistent. On this occasion, the drift drogues were tracked as far as Boundary Passage where they were then deflected rapidly to the east by the flood that began to develop near the end of the tracking session. Therefore, in a well-defined brackish layer, winds greater than 10 m/s generate surface currents that dominate the motion of the surface waters.

6) One of the more curious features of the residual flow in the central Strait was uncovered by studies in 1968. In attempting to discover the fate of the treated sewage that enters the Strait from the Iona outfall, oceanographers found that the current near the Fraser River delta north of the Steveston Jetty was often to the north, even during strong ebbs. However, about 2 km to the west of the edge of the delta this current disappeared. Aerial photographs have verified these findings and show that the silty water near the delta often moves in a different manner from that offshore (Fig. 10.21). One explanation for many features of this "nearshore" current is that it is generated by internal gravity waves as they break against the delta. Alternatively, the current may be driven by the along-shore hydraulic head due to the higher freshwater level at the entrance to the main arm relative to the north arm. As the speed of this current can be as much as 1 m/s (2 kn) about a kilometre from the edge of Sturgeon Bank, the mariner should choose his route accordingly. This is particularly true between May and September when the nearshore current is most likely to exist (Pl. 12).

The Southern Strait

As indicated by the computer-modeled charts in Fig. 10.14, 10.15, this region is characterized by relatively strong tidal currents that typically attain speeds of over 50 cm/s on normal tides. The influence of the Fraser River runoff is also important as most of the river water that accumulates in the Strait must eventually work its way toward the Pacific Ocean via the southern passes. Depending on the degree of mixing it has undergone, there is the possibility a well-defined brackish layer will extend into parts of the southern Strait, particularly in summer. Consequently, the southwesterly to southeasterly winds that dominate these regions could augment the flood currents and weaken the ebb currents. Northwesterlies would have the opposite effect. Near the extreme southern end of the Strait, on the other hand, the flood currents are so strong and the tidal mixing so intense that any surface wind effects should be completely overshadowed.

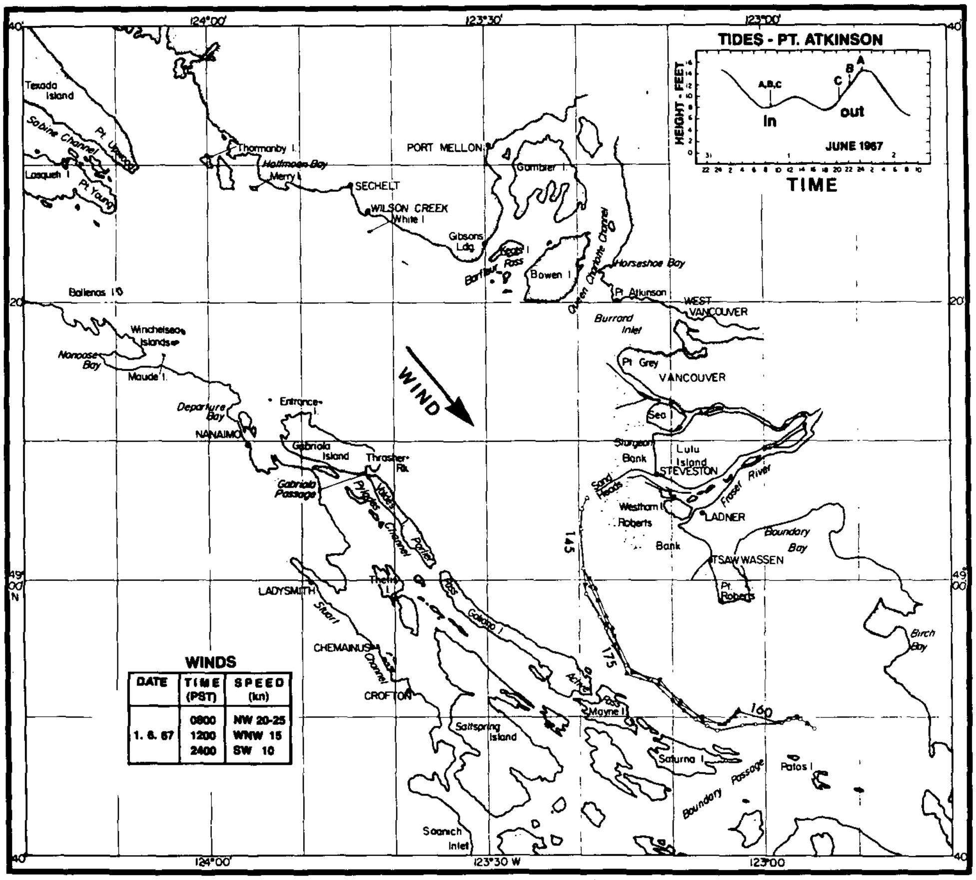

FIG. 10.22. Paths taken by three surface drogues released near Sand Heads during small tides but strong 10 m/s northwest winds (see inset, lower left). Drogue positions given for each hour. Maximum 175 cm/s (3.4 kn) for one drogue just north of Mayne Island. Near end of tracking session, flood entering via Boundary Passage appeared to deflect brackish water to east. (Adapted from Giovando and Tabata 1970)

Figure 10.23 is a crude schematic picture of the "average" surface currents in the Strait of Georgia based on the information just presented. It can be thought of as the resultant drift to be expected if the effects of tides, winds, and runoff were averaged over many months.

Water Renewal

Dilution of the Strait of Georgia waters by Fraser River runoff, together with intense tidal mixing in Haro and Rosario straits and inward movement of oceanic water along Juan de Fuca Strait, lead to water renewal within the deeper portions of the basin. This frequent flushing of the deeper basins is responsible for maintaining the present water quality throughout the Strait.

To understand this process, it is necessary to begin at the surface where fresh water forms a relatively thin brackish layer over much of the southern Strait. Because this fresh water cannot accumulate within the basin, most of it (typically 70–80%) slowly makes its way seaward toward the Pacific Ocean via the southern passes, where vigorous tidal action over the sills mixes it with the cold, salty oceanic water that moves inward along Juan de Fuca Strait (Fig. 10.24). Part of this newly formed mixture

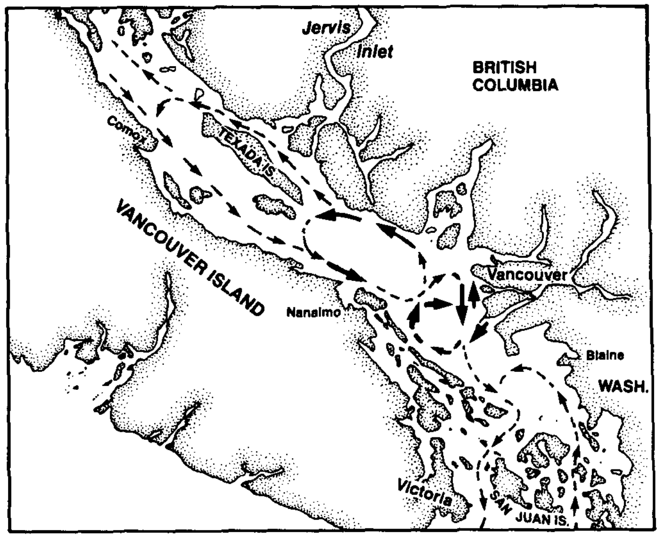

FIG. 10.23. Average (or net) surface circulation in spring and summer in Strait of Georgia as interpreted by author by a variety of oceanographic sources. Large arrows indicate currents measured by current meters and drift drogues; small arrows indicate currents measured by drift bottles.

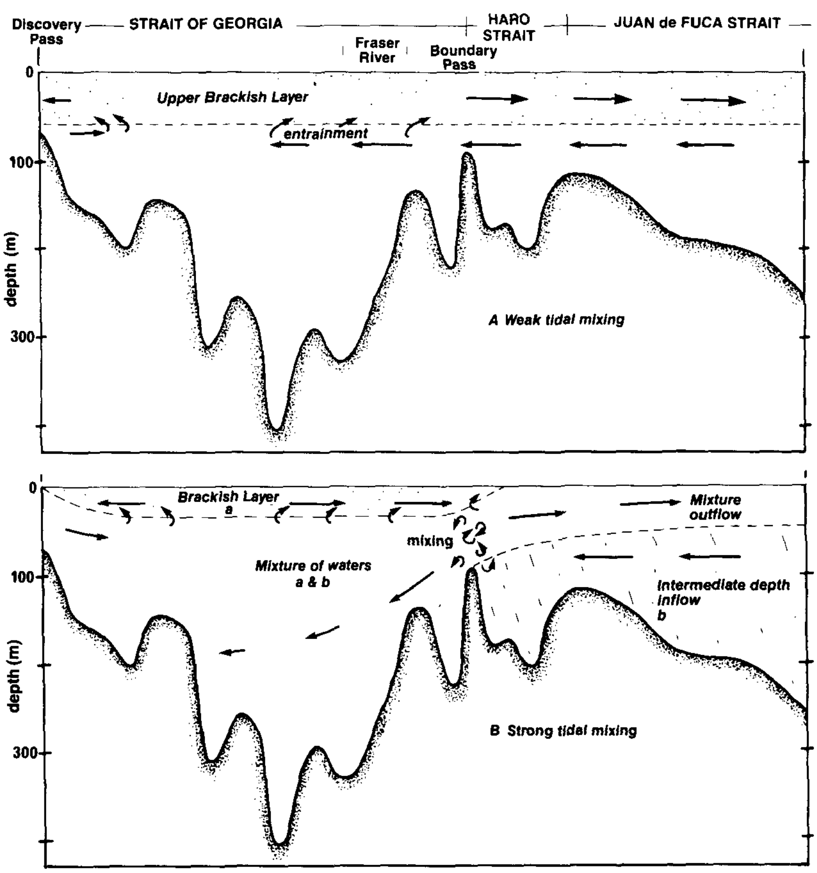

FIG. 10.24. Average circulation in the Strait of Georgia–Juan de Fuca Strait system. (A) Hypothetical circulation that would arise in the absence of strong tidal mixing in the southern and northern approaches to the Strait of Georgia. (B) Actual circulation from vigorous tidal mixing in passes. Brackish Fraser River water (a) mixes with saline oceanic water (b) entering at depth from Juan de Fuca Strait and Discovery Passage. Part of water mixture types (a & b) sinks in Strait of Georgia, rest moves seaward within upper layers of adjoining channels. (Modified after Waldichuk 1957)

(now less dense than the original oceanic water) continues its seaward advance through Juan de Fuca Strait as a more saline surface layer about 100 m thick. The remainder (now more dense than the brackish water flowing southward into the passes) sinks back into the Strait of Georgia at subsurface depths and flows slowly northward aided by pumping action of the tides.

It should be fairly obvious from the above description that the properties of water that flows back at depth into the Strait of Georgia are strongly determined by the properties of water present near the sills in Juan de Fuca and Haro straits. Observations show that relatively low-salinity, oxygen-rich water enters Juan de Fuca Strait from the Pacific in midwinter (December) and begins to move up-channel. About 2 mo later it has worked its way into Haro and Rosario straits. By early spring this oxygen-rich water mass has crossed the sills that tend to isolate the Strait of Georgia and has begun to sink into deeper basins, and gradually replaces older water whose oxygen levels have been depleted by biological activity and decay processes. Through the summer, oxygen levels begin to diminish at depth in the Strait because of the combined effects of internal consumption and lower dissolved oxygen values in Juan de Fuca Strait. Minimum values occur in early fall approximately 3 mo after the midsummer minimum at the seaward entrance to Juan de Fuca Strait. Dissolved oxygen levels then begin to increase again in the lower layer of the Strait of Georgia until the following spring. This process further demonstrates that oceanographic conditions on the continental shelf play a vital role in the replacement of bottom water in the Strait of Georgia. The same can be said of Puget Sound, Saanich Inlet, Bute Inlet, and other estuarine regions within the inshore waters. Similarly, the replacement of bottom waters in basins on the west coast of Vancouver Island, such as Alberni Inlet and Nootka Sound, depend on conditions on the shelf (see Chapter 13).

The situation in the northern Strait is slightly different. There, the waters are more homogeneous and overall tidal mixing is less intense. As a consequence, water renewal results mainly from convective overturning, when the surface water sinks after intense cooling by the air during unusually cold winters. Even then, the cooled surface water can only sink to intermediate depths. Therefore, water near the bottom of the northern Strait can only be replaced by the slow northward movement of the deep water from the southern Strait. (It is conceivable that relatively high density flood currents from Discovery Passage could, at certain times of the year, lead to bottom water formation in the northern Strait, although this has yet to be substantiated.)

In summary then, if there were no tides, no Fraser River, and a more restricted connection to the ocean, density currents in the Strait of Georgia would be far less intense and dissolved oxygen needed for marine life within the basin might soon be depleted below depths of around 30 m; above this depth, near surface mixing and convective overturning in winter would keep the water well supplied with air. In certain inlets this has already happened, sometimes because of natural causes, sometimes not. A case in point is Saanich Inlet north of Victoria. Because of a weak estuarine circulation (a combination of very little river inflow and weak tidal motions) and a sill separating the inlet from Satellite Channel (Fig. 10.25), there is no consistent replacement of the water below the sill depth of about 70 m. As a consequence, water below 200 m is usually deficient in oxygen and often contains hydrogen sulphide, "rotten egg" gas. Under such conditions, the deeper water will become devoid of higher forms of marine life, such as fish and squat lobsters, which can move to more suitable waters. Nonmobile animals such as anemones, sponges, and sea-squirts will die or, if the period of anoxia is brief, become seriously unhealthy. Such a situation does not exist in the Strait of Georgia because deeper waters are completely replaced by more oxygen-rich water over a relatively short period of a year or so, and water above 30 m is completely replaced roughly every month.

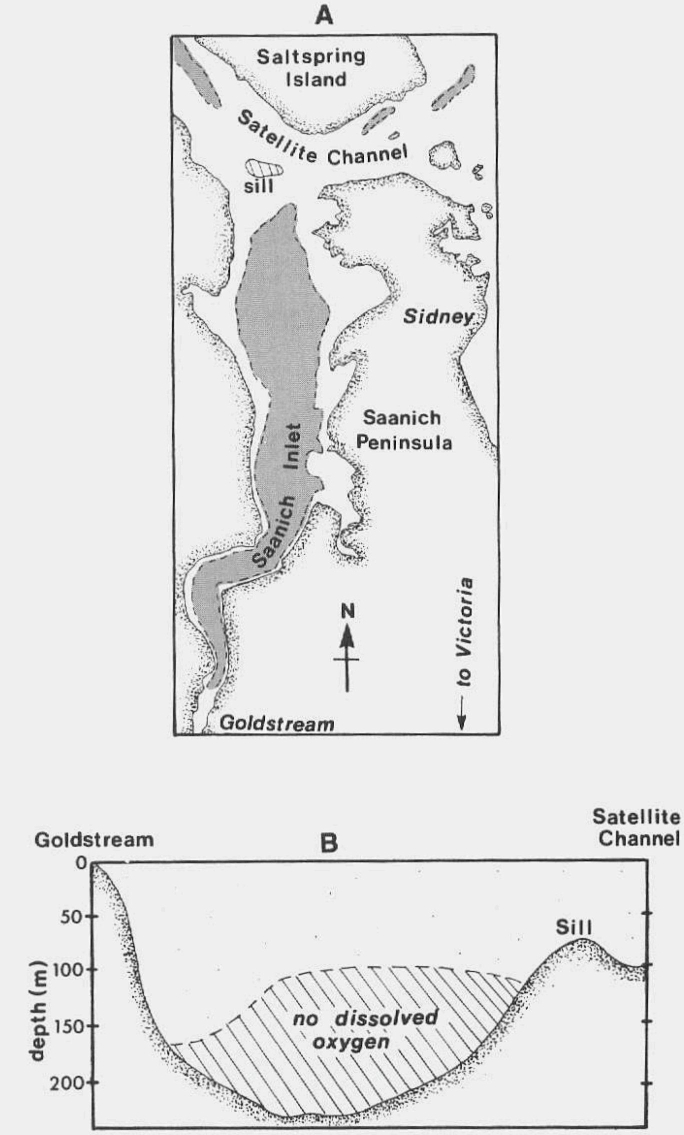

FIG. 10.25. Saanich Inlet. (A) Location of sill and regions with depths exceeding 100 m (shaded area). (B) Hatched area in north–south profile illustrates the extent of oxygen-depleted waters at certain times of year. (From Herlinveaux 1962)