

## Causes of Upwelling

It is well known that the ocean surface becomes increasingly warmer toward the equator. If it didn't, tourist havens like Hawaii and Fiji would have little appeal. However, there are important exceptions to this general rule. For example, in summer the surface water temperatures along the coast between California and Oregon are often lower than those off the west coast of British Columbia. It is sometimes not until the latitude of Baja California that coastal water temperatures become as high as their more offshore counterparts (Fig. 5.1).

The reason for these regions of anomalously cold sea water is upwelling, the process by which subsurface water moves upward to the surface. It is an extremely important phenomenon that affects the fisheries, weather, and current patterns in many parts of the world. It also can be a very localized process confined to bays or tidal channels. To understand this, the two fundamental reasons for upwelling will be explained.

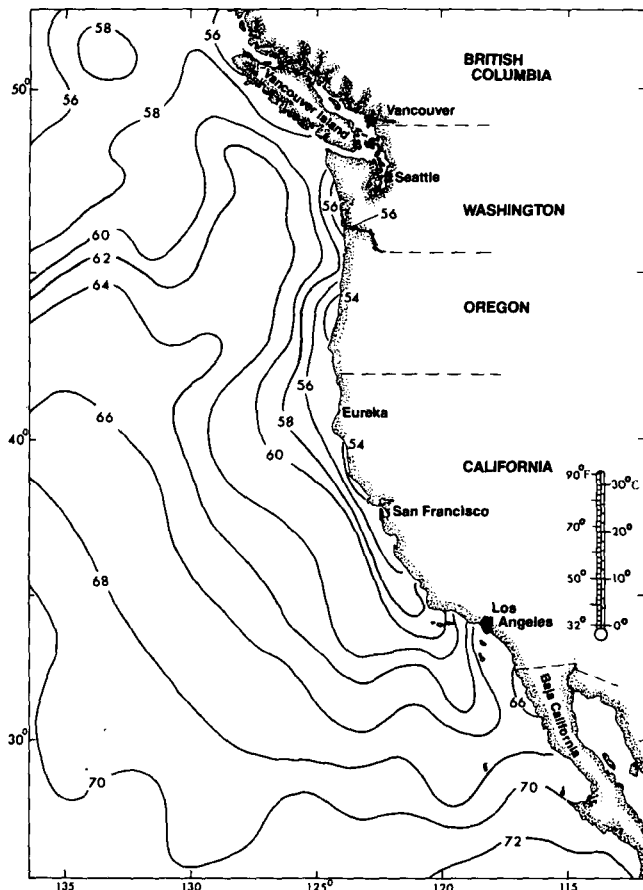


FIG. 5.1. Average sea surface temperatures off west coast North America, Aug. 1-15, 1977. Temperatures in °F. (From Natl. Mar. Fish. Serv. Bull. 1977)

First, it will occur whenever colder water from below forces its way upward and pushes away the warmer surface water (Fig. 5.2). Extremely vigorous examples of this process take place in many B.C. passes where tidal currents are deflected upward by underwater ridges, shoals, and other bumps on the channel bottom. The smooth, dome-shaped upwellings in strong tidal channels like Active Pass and Seymour Narrows are formed in this manner. (Any boater who has been at the helm as his boat

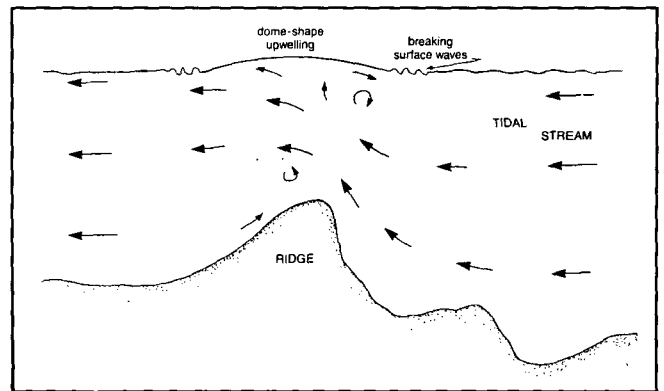


FIG. 5.2. Upwelling of cooler water produced by deflection of tidal currents over underwater ridge. Extent and location of upwellings may fluctuate over periods of a few minutes due to variations in current velocity.

passed over an upwelling can testify to the strength of the water motions.) This type of upwelling helps keep the water in Juan de Fuca Strait and the southern Strait of Georgia cold throughout the year. Although much less vigorous, a similar process takes place in mid-ocean, where slowly moving currents are deflected upward by submarine mountain peaks or ridges. Cobb Seamount, for instance, about 500 km southwest of Vancouver Island, rises abruptly from 2400 m to a depth of only 30 m in less than 35 km, and has a profound effect on the currents in its vicinity.

The second cause of upwellings is slightly more subtle and has more widespread importance. The deeper water doesn't force its way upward. Rather, the classical explanation is that winds push the surface water away from a particular area so the deeper water must rise to replace it. The subsurface water is responding, therefore, to what takes place near the surface, whereas, in the first case, the surface water is responding to what takes place below. It is this second type of upwelling that regularly produces the very cold summer water along the west coast of the United States. (A change in the coastal circulation by other means can produce the same effect.) Other major west coast regions similarly affected are Peru, Southwest Africa, Portugal, and Morocco (Fig. 5.3). Upwelling also occurs off the west coast of Vancouver Island during summer but tends to be more intermittent and less well developed. The only major upwelling region on an eastern

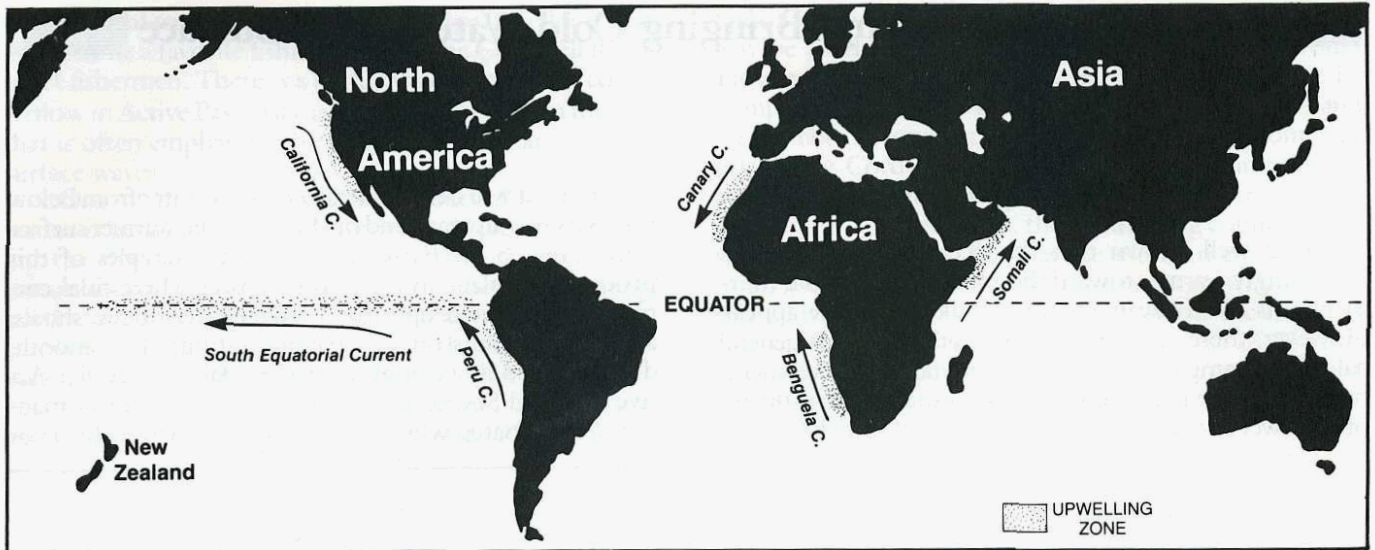


FIG. 5.3. Major oceanic upwelling zones and regional coastal currents.

shore is along the Arabian coast during the southwest monsoon. Finally, a very important belt of upwelled water is stretched out along the equator between the International Dateline and the Galapagos Islands in the Pacific Ocean.

For the most part, extensive wind systems, in conjunction with the Coriolis effect associated with the earth's rotation, create these upwelling regions. Off the west coast of North America, for instance, the summer northwesterlies initiate the whole process (Fig. 5.4). When these winds blow down the coast, the stress they exert on the water produces slow drift currents to depths of about 100 m. As discussed in Chapter 4, the earth's rotation then causes the drift currents to deflect to the right of the wind. As the water is pushed offshore, cold, nutrient-rich water from depths of 100–300 m wells up to replace it. Unlike the situation in B.C. tidal channels, such wind-induced upwelling is extremely slow, with upward speeds between 1 and 10 m/day. But, because thousands of square kilometres may be influenced at one time, the overall effect is of great consequence.

As fishermen in offshore coastal regions discovered long ago, the cold, upwelled water appears in the form of patches, tongues, and plumes that continually change their shapes. The extent of any particular cold spot may be less than 1 km or as much as 30 km across, and 20 m or so thick. Moreover, the lateral fronts or boundaries between the colder upwelled water and the warmer water it is replacing may be very distinct. Even without a thermometer, an observant fisherman can distinguish between the deeper blue color of the newly upwelled water and the murky green of the older warmer water. (Figure 5.5 shows a more modern way to observe upwelling.)

In the equatorial Pacific, upwelling occurs almost the entire year, but is most intense from June to October when the southeast trade winds blow across the equator. Equatorial uprising arises because the earth's rotation deflects the trade wind-produced currents northward on the north side of the equator and southward on the south side of the equator. This diverging of currents induces the belt of upwelling along the equator.

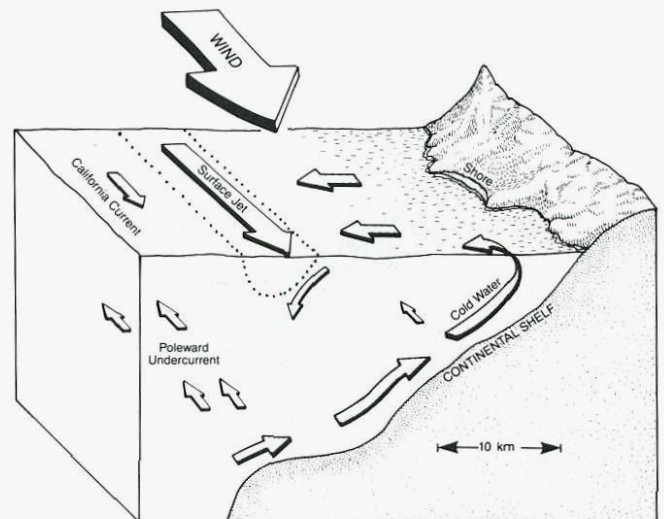


FIG. 5.4. Main features of classical wind-induced upwelling in northern hemisphere. Equatorward winds combined with Coriolis force move nearshore surface water offshore; colder subsurface water rises to replace it. Temperature fronts form at confluence of upwelling region (seaward edge of dashed area). Secondary currents associated with upwelling are strong, narrow equatorward surface jet and weak poleward undercurrent. Dotted line delineates core of surface jet.

At a more local level, winds that push water directly away from a lee shore will induce upwelling (Fig. 5.6). The Coriolis effect is unimportant because of the limited area of water affected. In the Strait of Georgia, westerlies will produce weak upward motion along the eastern shores of Vancouver Island and some of the larger islands. Similarly, the prevailing northwest winds in summer over the northern Strait of Georgia will induce upwelling on the leeward sides of Texada, Lasqueti, and Denman islands. The same winds push the sun-warmed surface waters out of partially enclosed regions like Departure Bay and make swimming much less pleasant. Lastly, limited areas of upwelling can form on the down-current side of prominences that project into a current. As a current flows past a point of land, for example, it will draw some surface

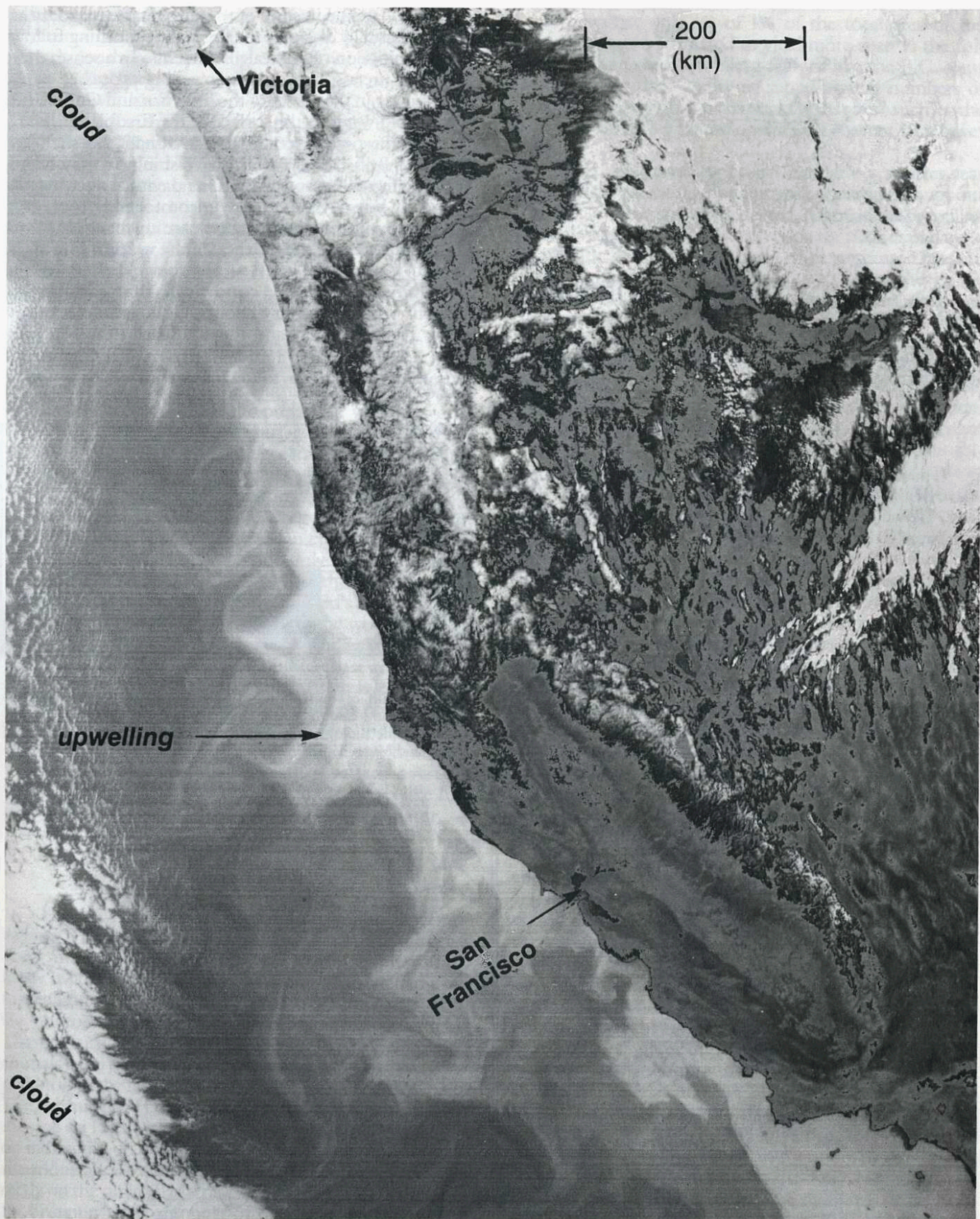


FIG. 5.5. NOAA satellite infrared scan of Pacific coast from Vancouver Island to southern California (Sept. 11, 1974, from 1500 km). Warmer areas darker. Relatively cold upwelled water adjacent to Oregon–California coast whitish compared to warmer water of midocean (See Fig. 5.1). Clouds and snow appear white, forests and land dark. (Courtesy S. Tabata)

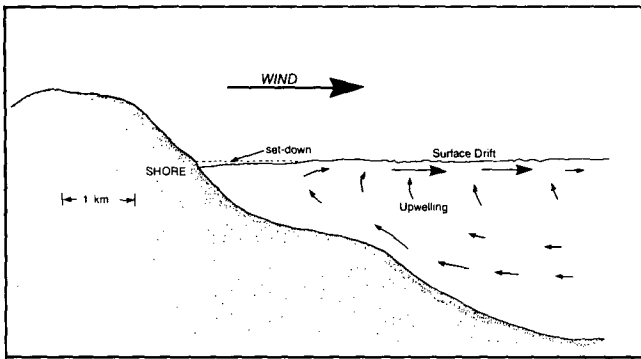


FIG. 5.6. Localized upwelling generated along a leeward shore. Set-down is small drop in mean sea level, result of net offshore transport of water.

water behind the point along with it, which in turn causes subsurface water to upwell.

### Localized Effects

The most obvious feature of upwelling is the presence of colder than normal temperatures at the sea surface. Upwelled water along an open coast may have originated from as deep as 300 m so these temperatures may, in fact, be lower in summer, when upwelling is most intense, than in winter, when it is weaker or nonexistent (Fig. 5.7). One effect of this cold water is to produce sea fog where it comes into contact with moist warm air. Dense fogs along the Pacific coast of North America during summer are generally created this way and may persist for many days, regardless of wind strength. The comparatively cold surface water of Juan de Fuca Strait is also a cause of frequent sea fog, particularly during atmospheric inversions when stable air conditions exist near

sea level. Daytime heating of the surrounding land, however, will usually dissipate the fog by late morning following the initiation of vertical air currents. In a sense, these fogs, too, are associated with upwelling processes — the tidal mixing in the passes of the San Juan and Gulf islands brings cold water to the surface in the first place.

Summertime recreational activity in the sheltered waters of British Columbia and Washington may be adversely affected by upwelling. One day the water may be pleasantly warm, the next day uncomfortably cool, even though daytime air temperatures are unchanged. Water temperatures along the beaches on the western side of the Strait of Georgia are often subject to rapid alterations in swimming conditions; conditions that can change abruptly within a matter of hours. Good examples of this are at Departure Bay and Piper's Beach near Nanaimo (Fig. 5.8) where the author noticed a deterioration of swimming conditions following a shift of local winds.

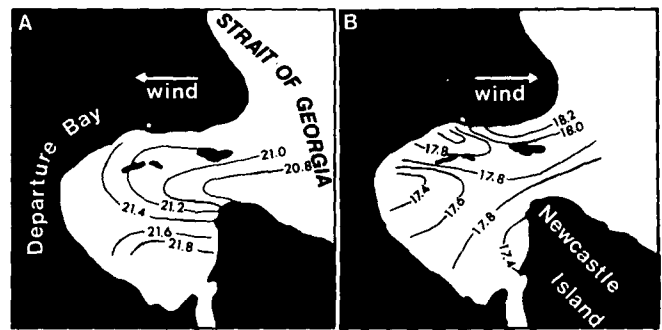


FIG. 5.8. Surface temperatures ( $^{\circ}\text{C}$ ) Departure Bay, Nanaimo. (A) July 4, 1968 during easterly winds; and (B) July 5, 1968 during westerly winds. Pacific Biological Station marked on north side of bay. (From Henry and Murty 1972)

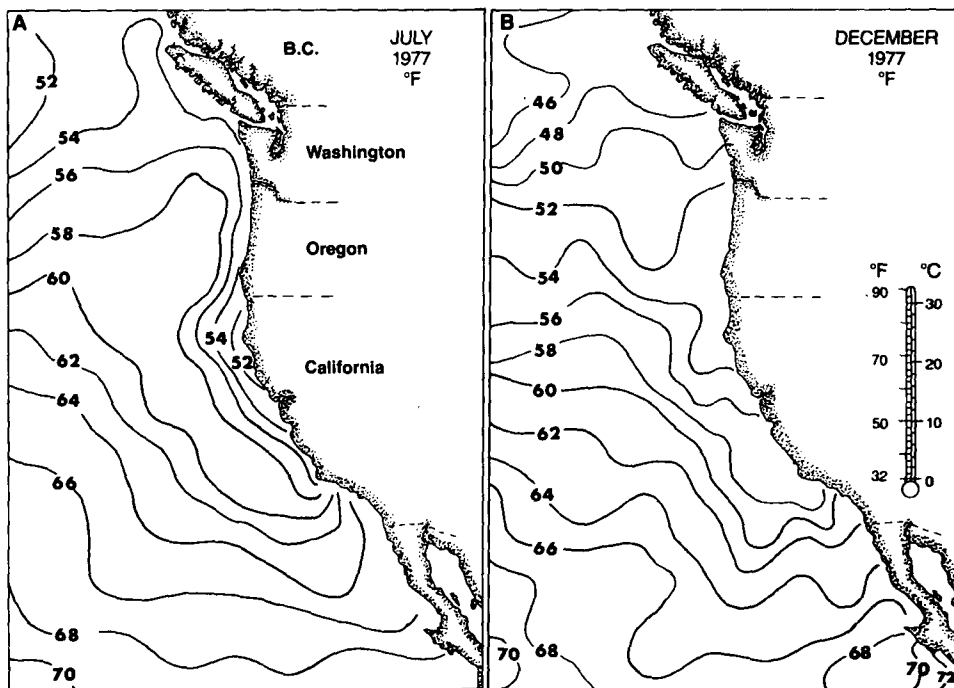


FIG. 5.7. Average sea surface temperatures ( $^{\circ}\text{F}$ ) off west coast North America, (A) July–15, and (B) Dec. 16–31, 1977. (From Natl. Mar. Fish. Serv. Bull. 1977)

More scientifically, Fig. 5.8a shows surface water temperatures for Departure Bay on July 4, 1968, during easterly (onshore) winds; Fig. 5.8b shows water temperatures a day later after the winds shifted to westerlies (offshore winds). The drop of almost 4C° in water temperatures in less than 24 h was caused by the upwelling of colder water from a depth of about 5 m to replace the warmer surface layer that was moved out of the bay by the westerly winds. The onset of afternoon westerly winds via the sea-breeze effect is a common occurrence over the Strait of Georgia region during summer and, consequently, a bather should not be surprised to find a drop in the water temperature at his or her favorite beach by late afternoon.

## Climate

Another aspect of upwelling is its effect on coastal climates. In regions where the prevailing winds have an onshore component, the cold surface water will cool the air, and thereby moderate the coastal temperatures and humidity. Tofino, for example, has much lower summer temperatures and higher humidities than Kamloops. The contrast is even more striking in Oregon where the rather cool, moist, seaboard conditions can change to the sweltering dry heat of the countryside only a few kilometres inland. However, the reverse is true of the coastal area of Peru, which is flanked by one of the world's major upwelling regions on one side and by one of the world's highest mountain chains (the Andes) on the other. In this case, the plantless sand desert at the hot, humid coast gives way to the pleasant warmth of the foothill grasslands less than 30 km inland. But the influence of upwelling is not confined to local climatic regimes. Recent studies indicate that changes in the intensity of the upwelling along the equator lead to alterations of the weather pattern over the whole northern hemisphere. Even remote places like Iceland and Siberia are affected by events at the equator.

## Fishing Grounds

Probably the most directly important aspect of upwelling is that it acts like a "biological bump" that brings deep, nutrient-rich water upward to the sunlit surface layer. It is here that one-celled marine plants called phytoplankton use these nutrients, together with solar energy for photosynthesis, to grow into vast oceanic "crops." These in turn provide the basic food source for all marine animals from the simplest microscopic animals called zooplankton to the largest of living creatures, the blue whale. The oceanic food chain is of course, exactly analogous to the one on land where all animals depend, either directly or indirectly, on plants for their existence. In fact, the situations are so alike that aquatic animals that feed directly on the phytoplankton crop are said to be "grazing." By bringing large amounts of nutrients to the surface, upwelling encourages the growth of lush oceanic pastures where marine life can thrive in abundance. Fishing yields in these regions are at least a thousand times greater than in other oceanic regions. Although coastal upwelling

areas comprise only 1/10 of 1% of the total area of the oceans, they are estimated to yield more than 1/2 the fish harvest. Even weak upwelling regions like the B.C. coast are noted for their ability to support great numbers of fish, especially within biological "hot spots" such as the entrance to Barkley Sound on the west coast of Vancouver Island.

Although upwelling occurs regularly year after year in specific areas, it does not continue nonstop throughout the whole of the upwelling period. After all, the prevailing coastal winds often reverse direction for periods of days or weeks due to changes in the weather patterns. Thus, despite the fact that the summer winds along the Pacific shores of North America are usually from the northwest, they can often shift and blow from the south. When this happens, the winds no longer move the surface water offshore and upwelling comes to a halt. So does the unfettered growth of phytoplankton. As a consequence, fish that were feeding in the rich upwelling ecosystem disperse elsewhere in search of food or, if the stoppage of upwelling occurs suddenly, die of starvation. This is followed by a sharp drop in fish catches. Although fishing fleets along the Pacific coast from California to Alaska are often affected by such events, their losses are nowhere as drastic as those that befall the Peruvian fishing industry.

## El Niño

Although seasonal off the B.C. coast, along the Peruvian coast upwelling essentially occurs throughout the year. The exception is during February and March when upwelling ceases off northern Peru and a tongue of the warm eastward-flowing equatorial and countercurrent pushes southward to about 6°S. Called El Niño, the Christ Child, because it occurs in the Christmas season, this event is not usually of dire consequence to the rest of the Peruvian coast. On the average of every 7 yr, however, there is a general break-down of the trade winds system over the equatorial Pacific Ocean, which leads to a weakening of the westward flowing South Equatorial Current and northward flowing Peru Current (Fig. 5.3). Within a period of a few months, this in turn results in a cessation of upwelling along the entire coast of Peru, and to a southward penetration of warm, low-nutrient equatorial water as far as 12°S. This extreme form of El Niño can lead to the catastrophic mortality of phytoplankton and fish or, at best, forces the fish to scatter offshore or into deeper water in search of food, with disastrous consequences for fishermen and sea birds alike. Recorded by fishermen for 180 yr, the most recent major El Niño events were in 1965, 1972-73, and 1976. It appears that an El Niño type event also occurred in 1982-83 and influenced the weather and oceanography of the Equatorial region of the Pacific Ocean. In 1970 when this effect did not take place, the Peruvian waters yielded 22% (12.3 million t) of the total world fish catch, mostly anchovies. In 1972-73, the catch plummeted to only 4.7 million t, a catastrophe for Peru. To add to the problems, the scarcity of accessible fish concentrations near the coast also leads to the mass starvation of sea birds and, therefore, to depletion of the Peru-

vian foreign monetary reserve, which depends heavily on the export of fertilizer produced from the excreta (guano) from these birds. Moreover, the rotting phytoplankton on the beaches produce hydrogen sulphide gas, which combines with the moist sea breezes to blacken the paint on ships. Dubbed the "Callao Painter," this occurs each year but is most intense during a catastrophic El Niño. Lastly, there are often torrential rains associated with the cessation of upwelling that produce severe flooding and crop damage. Considering all these disasters, it is easy to sympathize with Peru's 200-mile limit and the government's tenacious desire to protect the fish stocks from foreign fishermen.

## Coastal Currents

A recent investigation off Oregon and Washington by American oceanographers has shown that upwelling

leads to an intensification of the southward coastal current. Known as the California Current, this southward flow is usually broad and slow, but during sustained upwelling the portion of the current within 20–40 km of the coast accelerates into a narrow "jet," which can attain speeds in the neighborhood of 100 cm/s (Fig. 5.4). Off the coasts of British Columbia and Washington, upwelling is much less intense than off Oregon so the coastal "jet" should be proportionally weaker. From this discussion, it is obvious that sail boats journeying southward off these coasts in summer will generally have the best of conditions — winds from the northwest and southward setting currents — while northbound boats will be tacking against opposing ocean currents. Just to complete the picture, the investigation off Oregon further showed that the upwelling also induces a slow northward flow at depth, to compensate for the southward flow near the surface. Similar conditions are generated in other upwelling regions in the world although not all have been investigated in great detail.