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CALIFORNIA AND ALASKA CURRENTS

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Introduction

The clockwise North Pacific Subtropical Gyre and the counterclockwise Subarctic or Alaska Gyre, the two principal current gyres of the North Pacific, have dimensions similar to those of the basins, i.e., several thousand kilometers. The West Wind Drift and Subarctic Current flow approximately zonally across the Pacific basin with origins in the Kuroshio and Oyashio Currents, respectively, in the western Pacific basin (**Figure 1**). As this broad eastward flow nears the west coast of North America, it bifurcates, splitting into the northward flowing Alaska Current, the eastern limb of the Alaska Gyre, and the southward flowing California Current, the eastern limb of the North Pacific Subtropical Gyre. This bifurcation takes place several hundred kilometers offshore and depends both on the ocean currents and the wind fields over the North Pacific. The water type is primarily Subarctic, relatively cool and fresh surface water. The volume transport within each of the currents is about 10–15 Sv. Both the California Current and the Alaska Current are coupled to current systems and processes along the adjacent continental margins, where the majority of the seasonal variability occurs. On both seasonal and ENSO (El Niño) timescales, the strengths of the two current systems vary out of phase. For each boundary current system (the Alaska system and the California system) both the large-scale gyres and the coastal current systems, as well as the interactions between them, are described in the text below.

The Alaska Current System

The Alaska Current, the eastern limb of the Subarctic Gyre, flows northward along the west coast of North America beginning at about 48–50°N (**Figure 2**). A companion coastal current flows parallel to the Alaska Current but closer to the coast. This

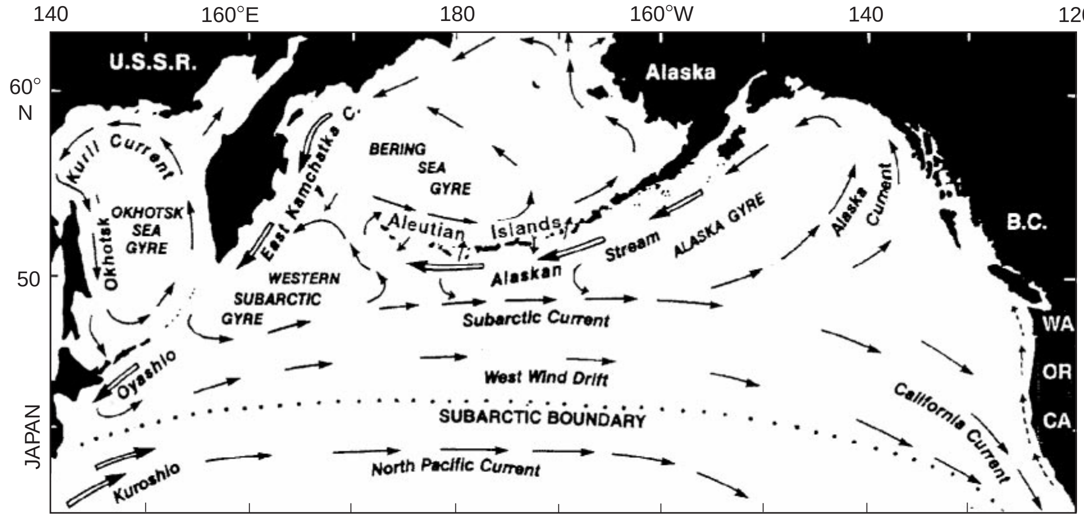

Figure 1 Schematic surface circulation of the North Pacific relative to 1000 db (i.e., assuming no flow near a depth of 1000 m) showing the Alaska and California Current systems. (Adapted with permission from Thomson, 1981.)

current has several local names – the Vancouver Island Coastal Current, the Haida Current, and the Alaska Coastal Current. These flows move in a counterclockwise sense around the Gulf of Alaska, bringing relatively warmer water northward along the eastern boundary of the Pacific Ocean. As they follow the topography in the northern gulf, they are diverted westward.

Early explorations of the Subarctic North Pacific, initiated by the Russian czar, Peter the Great, illustrate this general circulation of the northern North Pacific region. In June 1741, two ships set out from the Kamchatka Peninsula to investigate the eastern side of this unexplored basin. They sailed following the currents and winds south-eastward and then eastward across the North Pacific at about 48–50°N. Near the date line, the two vessels were separated under foggy conditions, never to see one another again. Nevertheless, explorers on both ships eventually observed North America: from the *St. Peter* commanded by Vitus Bering, land was first seen off south-east Alaska on 15 July and from the *St. Paul* commanded by Aleksei Chirikov, land was seen near Kayak Island on 16 July. Both ships

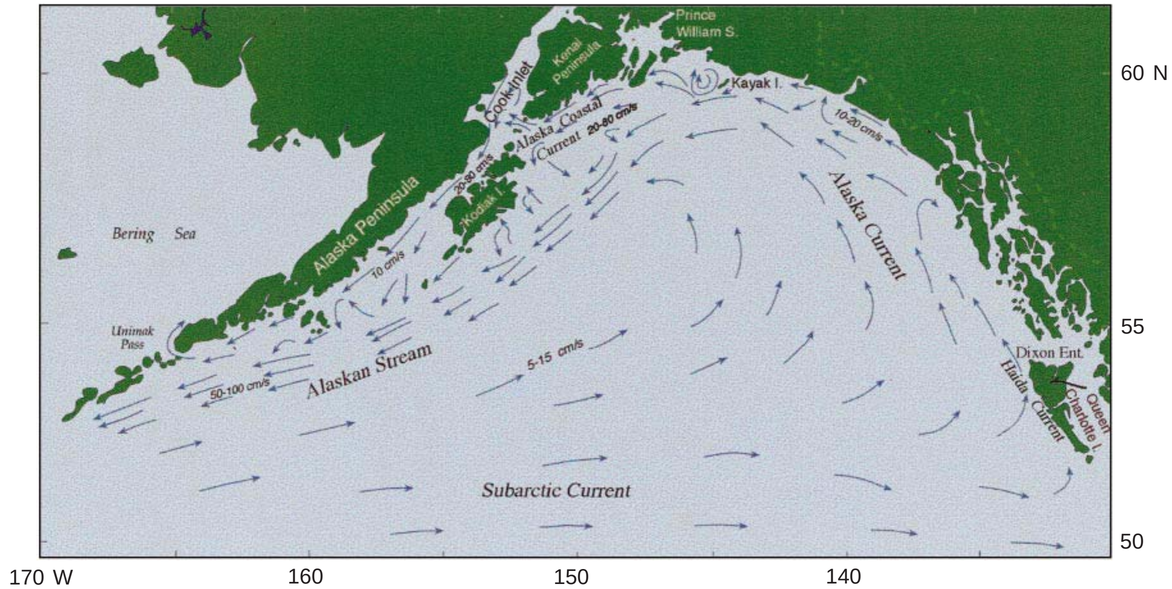

Figure 2 Schematic of North Pacific Subarctic Gyre with Alaska Current, Alaskan Stream and Alaska and Haida Coastal Currents. (Adapted with permission from Reed and Schumacher, 1986.)

traveled back toward the west along the southern side of the Aleutian Islands, completing a counterclockwise path. This path is approximately the configuration of the mean ocean currents in the Subarctic Gyre. The *St. Paul* returned to Kamchatka in fall 1741, but the *St. Peter* ran aground on an island in the Bering Sea (now known as Bering Island) where many perished, including Bering himself.

Atmosphere–Ocean Interactions

In winter, cold, dry Siberian air masses frequently sweep out over the northern North Pacific, rapidly extracting heat and moisture from the ocean. The introduction of this heat into the atmosphere intensifies the atmospheric circulation. These storms generally move from west to east across the Pacific basin. The path of an individual storm across the North Pacific depends on the global scale atmospheric circulation which changes both seasonally and interannually. In winter, storm tracks often cross the Gulf of Alaska, resulting in a large zone of low atmospheric pressure known as the Aleutian Low. In summer, the North Pacific High strengthens and pushes northward into the gulf. Winter over the North Pacific Ocean is dominated by strong counterclockwise wind systems; in summer weak clockwise winds occur. Since the earth's rotational force ('Coriolis') tends to move near surface water to the right of the wind direction in the northern hemisphere, the counterclockwise winter winds over the Gulf of Alaska transport upper layer water shoreward, away from the central deep ocean. The subsurface waters move upward to replace these surface waters. The rising of these subsurface waters together with wind mixing brings nutrient-rich waters into the upper layers of the ocean where they can be utilized by phytoplankton. Over the continental shelf and along the coastline, the surface waters are transported shoreward in winter, leading to convergence and downwelling. The pattern of upwelling and downwelling near the coast changes seasonally from intense downwelling in winter to weak upwelling or neutral conditions in summer (**Figure** 3, upper panel). Progressing southward along the west coast of North America, the seasonal cycle of upwelling and downwelling changes from a downwelling-dominated wind system (northward winds along the coast) in the north to a more upwelling-dominated wind system (southward winds along the coast) farther south off Washington, Oregon, and California in the California Current system (see below).

The seasonal progression of storm tracks across the Gulf of Alaska also affects precipitation rates, especially along the coast. As these storms encounter the coastal mountain ranges that rim the eastern boundary of the northern North Pacific, heavy precipitation occurs. This provides vast quantities of fresh water in the coastal region and adds heat to the atmosphere. On average, about 2.4 m of rain and snow fall in a relatively narrow (~ 100 km) coastal drainage area and more than 8 m of precipitation have been reported for a single year. The majority of this precipitation runs directly into the ocean via coastal rivers when the air temperatures are above freezing. Otherwise, it is stored as snow and ice with about 20% of the region being glacial. The average annual coastal runoff is estimated to be $24\,000\,\mathrm{m^3\,s^{-1}}$, about one third greater than the outflow of the Mississippi River. However, unlike the Mississippi, the runoff here is distributed along the coast in a number of smaller rivers rather than through a single major river. Fresh water is continually added to the coastal currents as they progress around the Gulf of Alaska. The coastal discharge (**Figure 3**, upper panel) is least in winter when most of the moisture is contained in snow and ice. A small peak occurs in spring corresponding to seasonal heating at lower elevations. However, maximum discharge occurs in September–November prior to annual freeze-up, when both precipitation caused by storms and runoff from snowmelt contribute to the coastal runoff.

The Alaska Current

The Alaska Current is affected by both winds and precipitation. Winds, which are usually downwelling-favorable along the coast, maintain the density contrast between central Gulf of Alaska water and fresher, lower density water on the shelf. Precipitation and coastal runoff also diminish the water density on the shelf. In the eastern Gulf of Alaska, the Alaska Current is a relatively broad meandering flow, typically several hundred kilometers wide (**Figure 2**). Frequently it contains large mesoscale eddies that often move westward at several centimeters per second, taking years to complete their journey (**Figure 4**). These eddies serve as a mechanism for the transfer of energy and water from the ocean boundaries into the ocean's interior.

The Alaska Current follows the general shelf break topography around the Gulf of Alaska in a counterclockwise sense. It turns westward at the apex of the Gulf of Alaska, then south-westward in the western Gulf of Alaska where it behaves as a western boundary current, intensifying into an organized flow known as the Alaskan Stream (**Figures 1** and **2**). This current is highly sheared vertically due to the density field (baroclinic), with

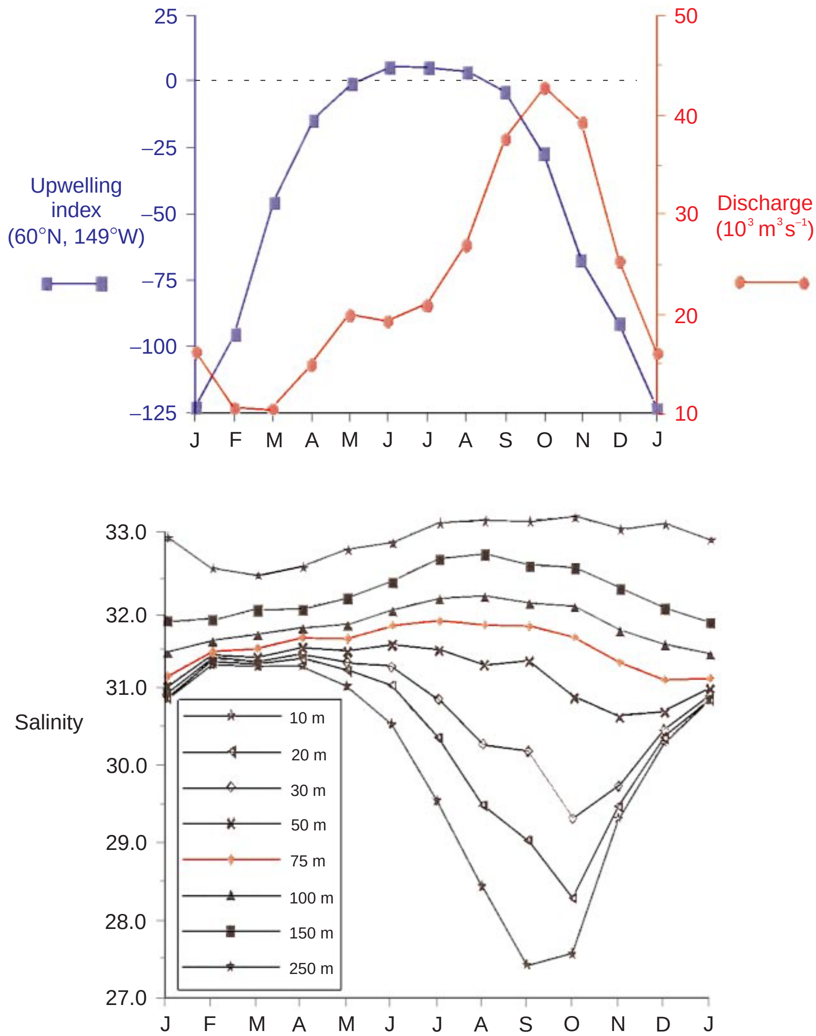

Figure 3 Seasonal changes in strength of upwelling/downwelling in the northern Gulf of Alaska and coastal freshwater discharge (upper panel). Upwelling (positive) or downwelling (negative) is indicated via the 'upwelling index', a measure of cross-shore transport by alongshelf winds (units are $m^3 s^{-1}$ per 100 m of coastline). Seasonal changes in salinity versus depth in the Alaska Coastal Current (60°N, 149°W) (lower panel).

a cross-current density gradient manifested by the offshore gradient in salinity. Surface salinities range from <30 PSU at the coast, to >31 PSU on the shelf, to >32.5 PSU over the central Gulf of Alaska. The baroclinic current transport near Kodiak Island in the western gulf (see **Figure 2**) is approximately 10 Sv in the upper 1500 m, with maximum speeds exceeding $1.0\,m\,s^{-1}$. Most of the flow ($>80\%$) is found within 60 km offshore of the shelf break. Although the seasonal variability of the atmospheric forcing is large (**Figure 3**, upper panel), the seasonal changes in transport are relatively small – less than 10%. As the topography turns more westward, some of the Alaskan Stream turns southward where it rejoins the eastward flowing Subarctic Current, completing the circuit around the Alaska Gyre. However, most of the flow continues eastward and some fraction enters the Bering Sea, subsequently returning to the North Pacific in the Kamchatka Current that becomes the Oyashio Current (**Figure 1**).

The Alaska Gyre Coastal Currents

The coastal fresh water runoff affects the nearshore salinity in the Gulf of Alaska (**Figure 3**, lower panel) and causes a strong offshore gradient in density. The winds driving downwelling confine the fresh water to the coast and also drive currents along the coast. The resulting cross-shelf density gradient, through a balance between pressure forces and the earth's rotational forces, causes the coastal current in the Gulf of Alaska to be strongly baroclinic. The

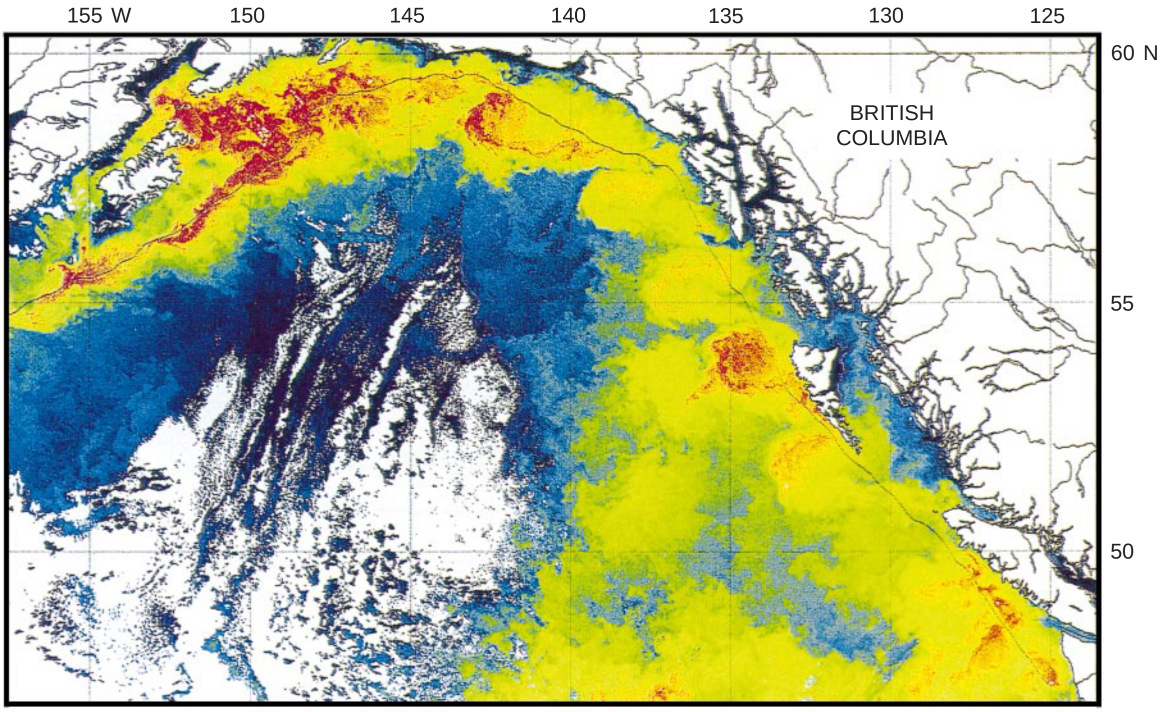

Figure 4 A composite sea surface temperature image for the Gulf of Alaska from 1, 2, 3 and 10 March 1995. The mean north–south temperature gradient has been removed to better elucidate eddy structure. Oceanic temperatures differed from the mean by -3°C (dark blue) to $+3^{\circ}$C (red). Clouds and land are white. The dotted curve is the 1000 m depth contour. (Reproduced with permission from Thompson and Gower, 1998; copyright by the American Geophysical Union.)

currents driven by these processes have been given specific names locally (the Vancouver Island Coastal Current off Vancouver Island, the Haida Current off central British Columbia, and the Alaska Coastal Current off the Alaskan coast). It is presently unknown whether the coastal current is continuous throughout the Gulf of Alaska at a given time. The coastal current likely begins with the Davidson Current, a wintertime current in the California Current system (see below) that links the two major current systems, at least in winter. The northward tending Alaska Coastal Current is strongest in winter and weakest in summer, exactly out of phase with the southward tending coastal currents in the California Current (see later sections).

The buoyancy and wind-driven coastal current flows along the coast with the coast on its right around the Gulf of Alaska, eventually flowing through Unimak Pass into the Bering Sea (see **Figure 2**). The flow has a typical width of about 30 km, a depth of 100–200 m and speeds $> 1.0\,\mathrm{m\,s^{-1}}$ have been reported. The mean transport is about 0.6 Sv with a seasonal variation of about 0.2 Sv. Transports of more than 2 Sv have been reported.

The coastal current is usually constrained along the coast by the downwelling winds. As it passes coastal openings at the entrance to Prince William Sound and Cook Inlet, some of the current enters these enclosures. Near Kayak Island (about 144°W) the coastal current is diverted across the shelf and some of it merges with the Alaska Current. In the western Gulf of Alaska, downwelling winds are less dominant and precipitation rates are lower. Here the current tends to diverge from the coast and spread across the shelf.

The coastal current is believed to be important for marine mammals and fish including salmon. Salmon might use chemical tracers carried by this current to navigate back to their original spawning streams. Similarly, the current is capable of carrying pollutants alongshore. In March 1989, more than 242 000 barrels of crude oil were spilled into Prince William Sound from T/V *Exxon Valdez*. The oil was carried westward in the Alaska Coastal Current more than 800 km in the span of about 2 months (about $0.15\,\mathrm{m\,s^{-1}}$).

The reduction in North Pacific sea surface salinity by precipitation and runoff (**Figure 3**, lower panel) creates a surface low-density lens that restricts vertical mixing in the Alaska Gyre and tends to prevent deep water formation. This is in sharp contrast to the deep circulation of other high latitude regions of the world's oceans such as the North Atlantic or Weddell Sea.

The California Current System

The California Current system (**Figure 5**) includes the southward California Current, the wintertime northward Davidson Current, the northward California Undercurrent (which flows over the continental slope beneath the southward flowing upper layers), the Southern California Countercurrent (or Eddy) as well as 'nameless' shelf and slope currents with primarily shorter-than-seasonal time scales. The California Current system includes one major river plume (the Columbia), several smaller estuaries, and (primarily in the north) numerous submarine canyons. The dominant scales and dynamics of the circulation over much of the California Current system are set by several characteristics of the physical environment; namely, strong winds, large alongshore scales for both the winds and the bottom topography, and a relatively narrow and deep continental shelf. Because of these characteristics,

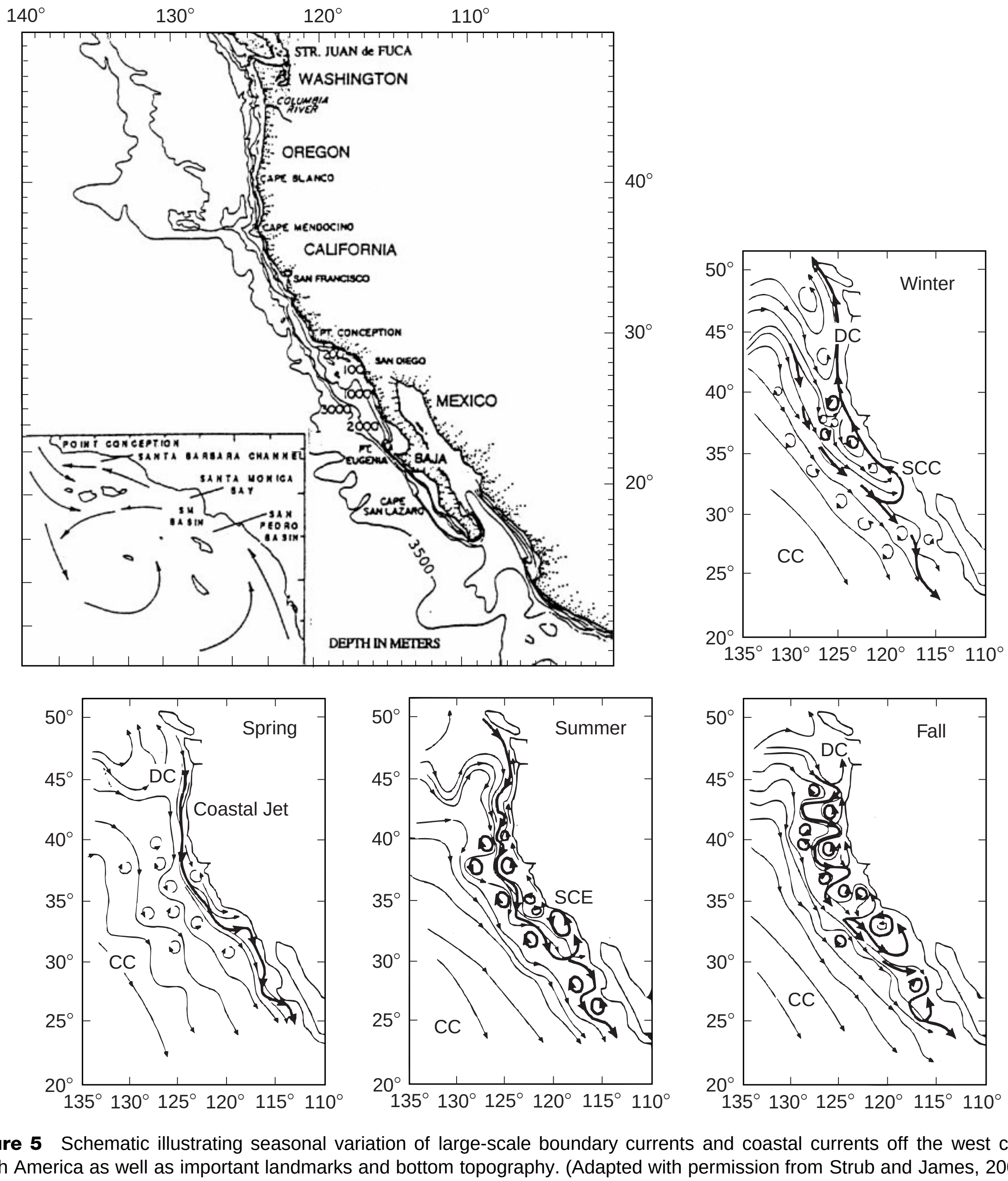

Figure 5 Schematic illustrating seasonal variation of large-scale boundary currents and coastal currents off the west coast of North America as well as important landmarks and bottom topography. (Adapted with permission from Strub and James, 2000.) An enlargement of the Southern California Bight, including the offshore islands, is given in the upper left panel. CC, California Current; DC, Davidson Current; SCC, Southern California Countercurrent; SCE, Southern California Eddy.

coastal-trapped waves (disturbances that travel northward along the shelf and slope) are efficiently generated and travel long distances toward the North Pole along the continental margins of much of western North America. Typical speeds are about $300–500\,\mathrm{km\,d^{-1}}$. These waves are integral to the current patterns observed in the California Current system and to their variability.

The California Current flows southward year-round offshore of the US and Mexican west coast from the shelf break to a distance of several hundred kilometers from the coast (**Figure 5**). The current is strongest at the sea surface, and generally extends over the upper 500 m of the water column. Seasonal mean speeds are $\sim 0.1\,\mathrm{m\,s^{-1}}$. The California Current in summer carries relatively colder, fresher water southward along the coast. South of Point Conception (the major indentation in the coastline near 35°N), a portion of the California Current turns southeastward and then shoreward and northward. This feature is known either as the 'Southern California Countercurrent' during periods when the flow successfully rounds Point Conception or the 'Southern California Eddy' when the flow recirculates within the southern California Bight (the indented region south of Point Conception; see inset map in **Figure 5**). The California Undercurrent is a relatively narrow feature ($\sim$10–40 km) flowing northward over the continental slope of the California Current system at depths of about 100–400 m as a nearly continuous feature, transporting warmer, saltier water of more southern origin northward along the coast. The Undercurrent has a jet-like structure, with the core of the jet usually located just seaward of the shelf break and peak speeds $\sim 0.3–0.5\,\mathrm{m\,s^{-1}}$. The Undercurrent divides into two components within the Southern California Bight, one flowing north-westward through the Santa Barbara Channel, the other flowing westward south of the island chain that forms the southern side of the Santa Barbara Channel. A southward undercurrent occurs over the continental slope in winter at some latitudes. This undercurrent occurs at deeper depths than the northward undercurrent ($\sim$300–500 m). The existence of this southward undercurrent, like that of the northward undercurrent, likely depends on the co-occurrence of opposing local alongshore winds and alongshore sea level slope. The Davidson Current flows northward in fall and winter from Point Conception ($\sim$35°N) to at least Vancouver Island ($\sim$50°N) and may connect with the coastal currents that flow around the Alaska Gyre. This northward flow is generally broader ($\sim$100 km in width) and sometimes stronger than the corresponding subsurface northward flow in other seasons (the 'Undercurrent') and extends seaward of the slope. Poleward shelf flow, in the sense of a monthly mean phenomenon, is sometimes described as an expression of 'the Davidson Current'.

Winds in the California Current system are governed by atmospheric pressure systems – on average a low pressure system in winter and a high pressure system in summer, producing northward winds in winter and southward winds in summer over much of the California Current system. Because of the dramatic seasonal reversal in winds along much of the coast, currents and water properties of the California Current system also undergo large seasonal fluctuations. The southward flowing California Current and the northward flowing California Undercurrent are strongest in summer to early fall and weakest in winter. The majority of the seasonal variability occurs along the coastal boundaries rather than in the central basin. The seasonal signal in transport near the coast migrates northward and offshore in both the California and Alaska Current systems. The North Pacific Current, which feeds both the California Current and the Alaska Current (see **Figure 1**) has little seasonal variability in either strength or position. Much of the variability in the California Current is related to coastal wind variability. However, remote forcing (disturbances that are caused farther south and travel along the coastal margins as waves) is also likely important, particularly off California. The northward flowing Davidson Current is strongest in winter, as is the Southern California Countercurrent. Shelf currents along the coast from Point Conception to the Strait of Juan de Fuca are generally southward in the upper water column from early spring to summer and northward the rest of the year. The seasonal duration of southward flow usually increases with distance offshore and with proximity to the sea surface. A northward undercurrent is commonly observed on shelves during the summer and early fall. A strong tendency for northward flow throughout the water column exists over the inner shelf in all but the spring season.

The transition of currents and water properties over the shelf and slope between winter and spring, the 'spring transition', is a sudden and dramatic event in the California Current system. Along much of the coast sea level drops at least 10 cm during the transition, currents reverse from predominantly northward to predominantly southward within a period of several days and isopycnals tilt upward towards the coast. The transition is driven by changes in the large-scale wind field and these changes are a result of changes in the large-scale atmospheric pressure field over the Northeast Pacific and the California Current system. The transition includes both a local and a remotely forced response to the change in wind conditions. The fall transition is not as rapid or as dramatic as the spring transition.

Variability on Shorter-than-Seasonal Timescales

Seasonal conditions are often reversed for shorter periods of time in the California Current system. Changes in currents, water properties, and sea level over the shelf at most locations are dominated by wind forcing, with typical timescales of 3–10 days. Regions seaward of the shelf are dominated by jets, eddies, and in some locations, wave-like propagating disturbances, with typical timescales of 10–40 days. Along-shelf flow on the inner to mid shelf is primarily wind-driven and can be predicted with numerical models. However, the amplitude of current fluctuations is generally underpredicted, and the amount of variability predicted decreases offshore toward the shelf break (to $< 20\%$ over the upper slope off northern California). Predictive capability for both temperature fluctuations and cross-shelf flow is very poor at the present time. The alongshelf currents include a response to both local wind forcing and wind forcing all along the coast south of a particular latitude ('remote' forcing). At any given time and location, the ratio of remote and local forcing varies. In winter, local wind forcing of currents dominates in regions where winter storms are accompanied by strong northward winds that increase northward (in the direction of propagating coastal-trapped waves). In summer, when winds increase southward, freely propagating coastal-trapped waves often contribute to current variability in the coastal regions of the Pacific Northwest. Off northern California, where wind stress is generally strongest in summer, both local and remote forcing are almost always important. Wind-driven currents in the Southern California Bight typically have much smaller alongshelf scales than in the region north of the Bight (20 km versus 500 km), weaker amplitudes, and weaker seasonal variation; likely a result of the much reduced winds and the narrow, more irregular shelves in this region.

The eddy/meander field in the regions seaward of the shelves in the California Current system has a seasonal variation, with maximum energy in summer, when upwelling is also at a maximum (**Figure 6**). Meandering jets extend from the sea surface to depths of over 200 m and separate fresher, warmer, chlorophyll-depleted water from colder, saltier, chlorophyll-rich, recently upwelled water. Jets are characterized by core speeds exceeding $0.5\,\mathrm{m\,s^{-1}}$ at the surface, widths of 50–75 km and total baroclinic transports of about 4 Sv. These filaments are particularly evident in regions which contain coastline irregularities, such as southern Oregon, northern California, and the Baja peninsula, and appear to be tied to these irregularities. One meandering jet can be traced continuously from southern Oregon, where it separates from the shelf, to southern California. Such separated coastal jets account for much of the energy, as well as seasonal and interannual variability in the California Current system. The jets and meanders are a dominant feature in satellite-derived images of sea surface temperature in the summer season (**Figure 6**).

Changes in currents with timescales similar to those of the eddy/meander field (15–40 days) dominate current variance over the slope within the southern California Bight. The majority of this variability is the signature of freely propagating coastal-trapped waves or disturbances, with an as yet unknown source along the coast of Baja California or even farther south. Such waves are likely to be important in other slope regions, but to date have not been separated from other sources of variability.

Water Properties and Upwelling

The California Current system contains waters of three primary types: Pacific Subarctic, North Pacific Central and Southern (sometimes termed 'Equatorial'). Pacific Subarctic water, characterized by relatively low salinity and temperature and high oxygen and nutrients, is advected southward in the outer edges of the California Current system and into the southern California Bight. Colder, fresher water from British Columbia and the US Pacific Northwest coastal region is also advected southward near the boundaries. North Pacific Central water, characterized by high salinity and temperature and low oxygen and nutrients, enters the California Current system from the west. Southern water, characterized by high salinity, temperature and nutrients, and low oxygen, enters the California Current system from the south with the northward flowing California Undercurrent. In general, salinity and temperature increase southward in the California Current system and also with depth.

Upwelling along the coast brings colder, saltier and more nutrient-rich water to the surface adjacent to the coast. In general, maximum upwelling (as seen at the sea surface) occurs off northern California, consistent with the alongshore maximum in alongshelf wind stress and hence mass transport away from the coast that causes deeper water to 'upwell' to fill the void (Ekman transport) (**Figure 7**). Maximum upwelling occurs in spring or summer in the California Current system. Stratification in the

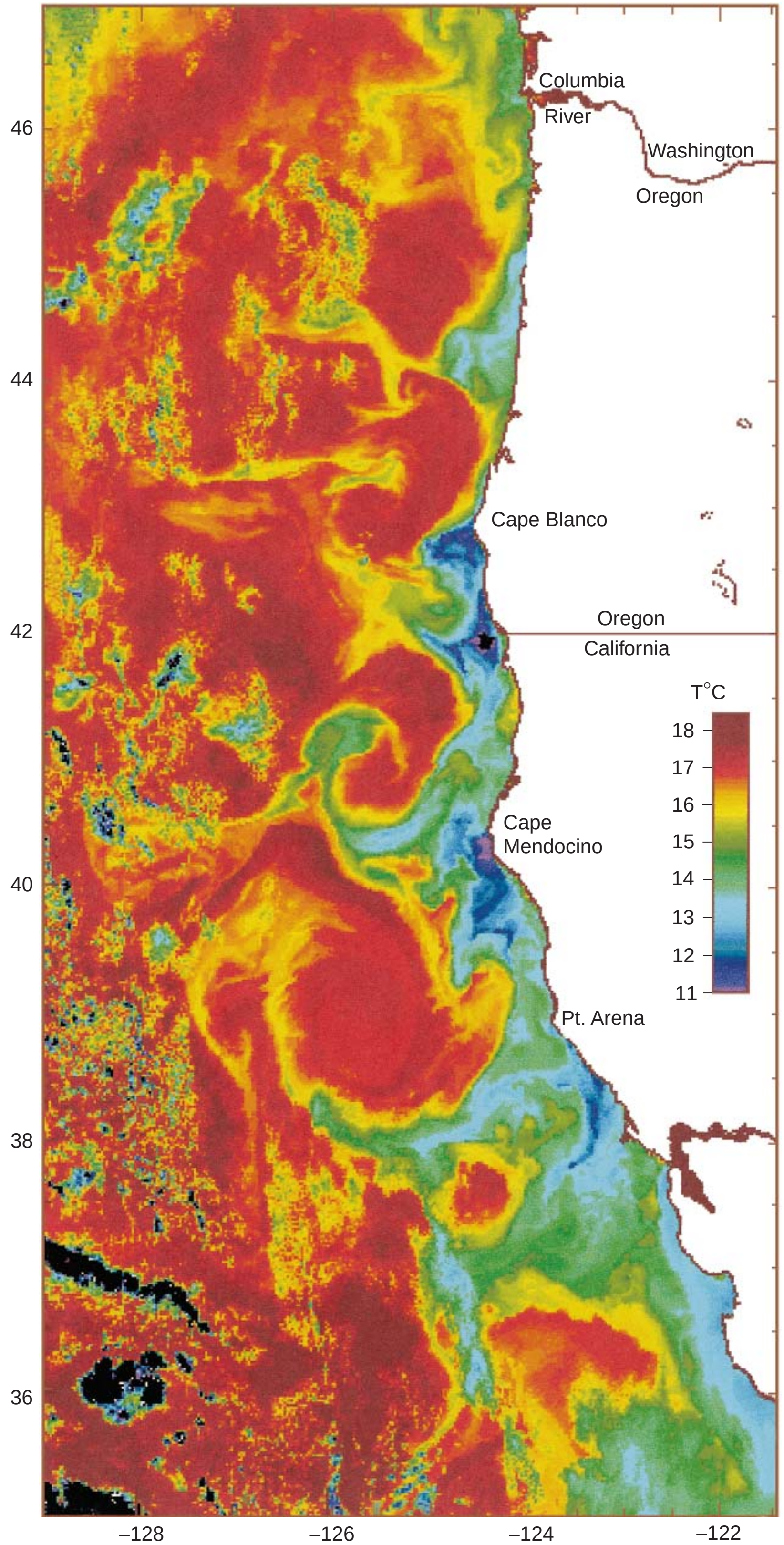

Figure 6 Satellite-derived image of sea surface temperature in the California Current System. The figure illustrates the jets, eddies, and meanders, many of which originate near coastal promontories. (AVHRR data collected and processed at Ocean Imaging, Inc., archived and made available at COAS/Oregon State University with funding from NSF and NASA in the US GLOBEC Northeast Pacific program.)

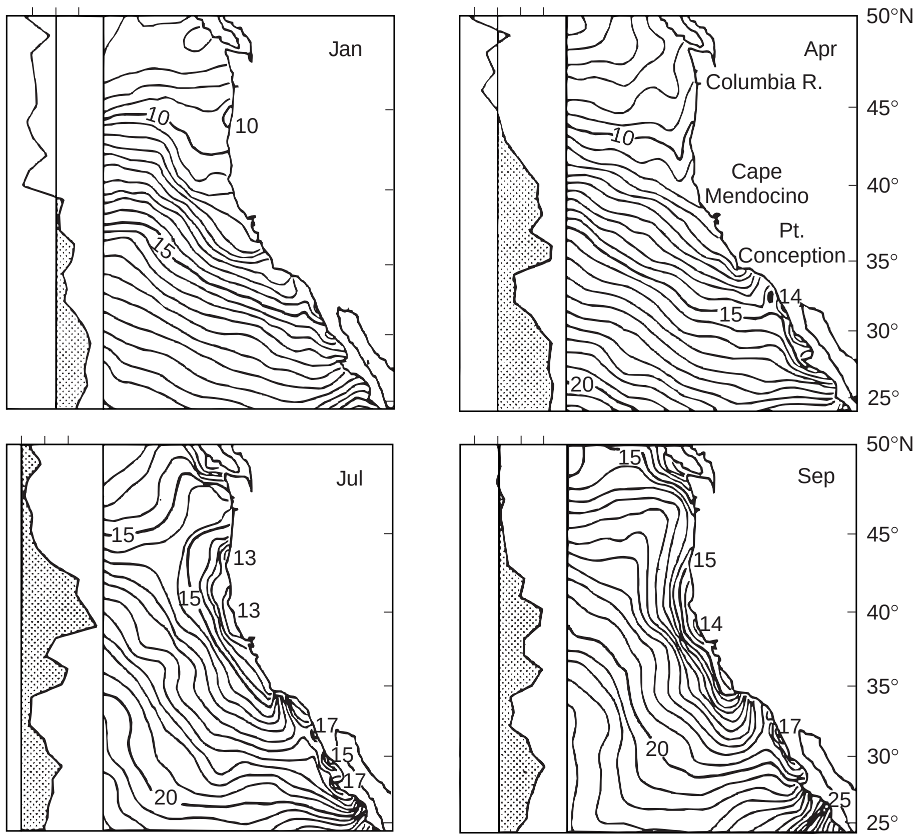

Figure 7 Maps of monthly mean sea surface temperature in the California Current system. The corresponding profile of cross-shore transport due to local winds is shown next to each map. Each tick represents a mass transport of $50 \times 10^3\,\mathrm{kg\,s^{-1}}$ per 100 m of coastline. Offshore transport, indicative of upwelling conditions, is shaded. (Adapted with permission from Huyer, 1983.)

California Current system is remarkably similar at most locations and is largely controlled by the large-scale advection and upwelling of the water masses as described above.

With the possible exception of catastrophic storms (a '10-year storm') most river plumes on the coast between the tip of Baja California and the Strait of Juan de Fuca are relatively small, and their effects are likely confined to within one tidal excursion of the mouth of the river or estuary. The only large river plume in the California Current system is that from the Columbia River. The Columbia provides over 77% of the drainage between the Strait of Juan de Fuca and San Francisco Bay. As mentioned above, water from the Strait of Juan de Fuca, with origins in the Fraser River, also contributes to fresh water in the nearshore California Current in spring and summer.

The plume from the Columbia River is a dominant feature in near surface salinity (and, in some seasons, temperature) off the US west coast. On a seasonal basis, the plume flows northward over the shelf and slope in fall and winter, and southward well offshore of the shelf in spring and summer. In winter the Columbia plume provides a substantial fraction of fresh water to the Davidson Current, and, ultimately, the coastal currents of the Alaska Gyre. In summer, the Columbia provides fresh water to the California Current, giving rise to the low salinity signal and associated front used to trace the meandering coastal jet that separates from the shelf at Cape Blanco. Most other smaller rivers on the Pacific coast have significant river plumes only during major floods. In winter and spring, the Columbia plume has a dramatic effect on the Washington coast, producing time-variable currents as large as the wind-driven currents and flooding local estuaries with fresh water (fresher than that in much of the estuary). Short-term variability in both fresh water volume and plume location can have significant effects on shelf and slope currents as well as water properties.

Topographic Effects in the Alaska/California Current Systems

The outer edge of the continental shelf along the US west coast from California to the Aleutian Islands is intersected at many locations by submarine canyons.

Canyons enhance the transfer of particles and water between the shelf and the deeper ocean. Upwelling of colder, nutrient-rich water can be enhanced by more than a factor of 10 over regions with a straight slope rather than a canyon indentation. For example, upwelling from a spur of Juan de Fuca canyon is responsible for enhanced seasonal productivity in that region. In the Alaska Current system, Hinchinbrook Canyon, which crosses the shelf adjacent to Prince William Sound, is a potential conduit for the exchange of deep waters with this coastal feature. Moreover, counterclockwise circulation patterns are generally observed both within and over submarine canyons (although not necessarily extending to the sea surface). Such eddies provide an effective mechanism for trapping particles such as suspended sediment or food for the biomass. Several major promontories and one major ridge (near Cape Mendocino) also occur along the coast adjacent to the California Current system (see **Figure 5**). Flow in the vicinity of such features is highly three-dimensional, generally producing offshore tending jets as well as counterclockwise eddies in their lee.

Interannual and Interdecadal Variability in the Alaska/California Current Systems

Year-to-year variability in the California and Alaska Current systems is significant in both physical and biological parameters. Surface transport in the two systems varies out of phase on El Niño timescales: when the Alaska Gyre strengthens, as during an El Niño, the California Current system weakens. As with seasonal changes, the majority of the changes in transport occur along the ocean boundaries in both systems. On interannual scales, some change in the North Pacific Current also occurs, but these changes follow those along the boundary. For the California Current system property anomalies of ~ 2–$4°C$ and ~ 0.3 PSU have been observed at depths of 50–200 m from the sea surface, and these anomalies extend several hundred kilometers from the coast. Much of this variability is related to the El Niño (ENSO) phenomenon, occurring at periods of 3–7 years (**Figure 8**, right panels). In the Alaska Current system, subsurface temperature anomalies of $>1.5°C$ have been observed at the coast 7–8 months after an El Niño has occurred at the equator. El Niño has been shown to affect the west coast both via an atmospheric route (i.e., by changes in the local winds which then cause changes in the local ocean currents and water properties) and by an oceanic route (i.e., by transmission of signals from the equator along the continental margin as propagating coastal-trapped waves). Local wind effects are more dominant in the Pacific Northwest and Alaska; remote forcing via waves is more dominant from central America to California. There is also evidence of increased formation of eddies along

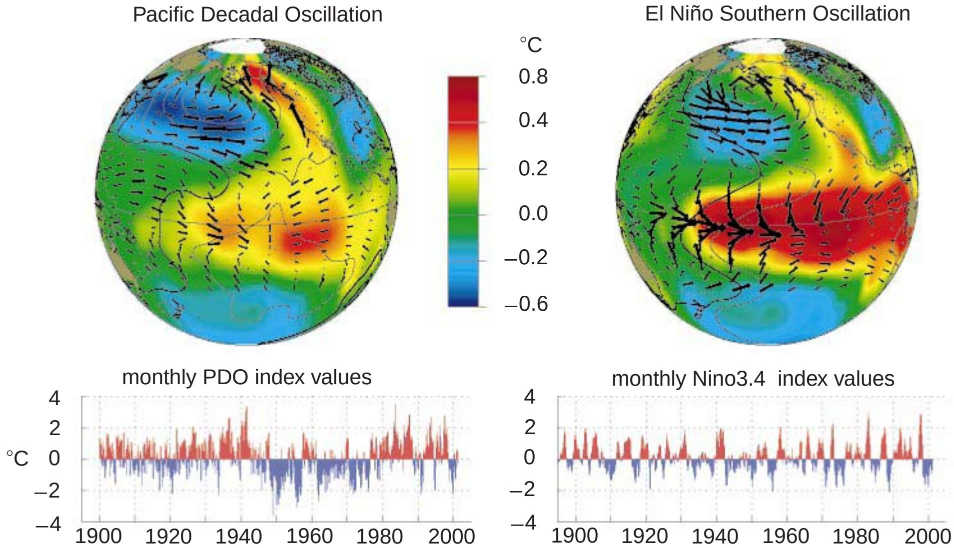

Figure 8 October-to-March average surface climate anomalies associated with a $+1$ standard deviation value in the Pacific Decadal Oscillation (PDO) index (left panel) and El Niño (cold-tongue) Index (right panel). Sea surface temperature anomalies are depicted by the color shading in degrees Celsius; surface wind stress anomalies are shown with vectors, with the largest vectors representing $10\,m^2\,s^{-2}$ anomalies. Thin solid contours depict positive sea level pressure (SLP) anomalies; dashed contour lines depict negative SLP anomalies, with contour intervals at $\pm$ 0.5, 1, 2 and 3 mb. The heavy solid contour depicts the SLP anomaly zero-line. (Courtesy of Steven Hare at the International Pacific Halibut Commission and Nathan Mantua at the Joint Institute for the Study of the Atmosphere and Oceans, University of Washington.)

the shelf break in the eastern Gulf of Alaska during El Niño conditions.

The Northeast Pacific also has lower frequency fluctuations – periods of about 22 and 52 years, associated with the Pacific Decadal Oscillation (PDO) (**Figure 8**, left panels). PDO has oceanic and atmospheric patterns similar to those of El Niño, but has much longer duration. PDO is a pattern of low sea surface temperatures in the central North Pacific and high sea surface temperatures along the eastern Pacific boundary. The major pattern reverses at 25–30 year intervals. PDO was mostly positive from 1922 to 1942 and mostly negative (warm in the central gulf, cold nearshore) from 1942 to 1976 and has been mostly positive again through 1998. From fall 1998 until summer 2001 the PDO has been negative. The coastal precipitation follows a similar pattern and could reinforce the PDO locally. High rates of coastal precipitation would increase cross-shelf pressure differences, enhancing northward flow in the coastal currents as well as the Alaska Current through the balance between pressure and rotational forces. Relatively warm water from more southern latitudes would thus be advected northward, reinforcing the positive PDO sea surface temperature pattern. The ecosystem seems to respond to the PDO – salmon production in the northern Gulf of Alaska is positively correlated with PDO; Washington/Oregon salmon production is negatively correlated with PDO.

See also

Arctic Basin Circulation. Coastal Trapped Waves. Ocean Circulation. River Inputs. Salmon Fisheries: Pacific. Wave Generation by Wind.

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