West Coast Oceanography:
Implications for Ballast Water Exchange

Draft Report

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EXECUTIVE SUMMARY

Introduction

- The purpose of this report is to inform ballast water management policy on the West Coast of North America by reviewing significant features of the nearshore water movement. Discharge of ballast water can lead to the introduction of aquatic invasive species (AIS) taken onboard during ballasting. At present, exchange of port water in ballast tanks with mid-ocean water is the only management method available for most ships. All west coast states, and some ports in British Columbia, require mid-ocean exchange for ships entering a west coast port from outside the Exclusive Economic Zone (EEZ). Oregon and Washington also require exchange of ballast water taken onboard in a west coast port outside designated areas. This coastal exchange requirement is considered to be protective of sensitive estuaries in Oregon and Washington that house port facilities.

- The fate and risk of establishment of organisms discharged in ballast water in coastal exchange is not well known. There is concern that organisms might be driven back to shore by a variety of coastal processes and therefore could inoculate the coastline and associated bays with AIS. The relative risk of establishment of AIS in coastal estuaries resulting from coastal exchange versus discharge of port water directly into estuaries is unknown. The primary goal of this report was to compile the current information on coastal processes on the West Coast to enable informed decisions on how to best manage ballast water in coastal shipping to minimize risk of AIS establishment.

Large Scale Features of the California Current System

- The West Coast of the North America from the Strait of Juan de Fuca to the tip of Baja, California is part of an eastern boundary current known as the California Current System (CCS). This region consists of three geographical regions: north of Point Conception, The Southern California Bight, and the Baja Peninsula

(Hickey, 1992).

- The CCS includes the equatorward-flowing California Current; the wintertime-poleward-flowing Davidson Current; the poleward California Undercurrent, which flows over the continental slope beneath the equatorward flowing upper layers; the Southern California Countercurrent (or Eddy); and nameless shelf and slope currents with primarily supraseasonal time scales. The CCS includes one major river plume (the Columbia), several smaller estuaries and (primarily in the north) a number of submarine canyons.

Seasonal Changes of the California Current System

- The majority of seasonal variation occurs in a relatively narrow band (~100 km) next to the coast (Strub and James, 2002).

- In late Fall and Winter, surface circulation from Point Conception in the south to Vancouver Island in the north is generally onshore and north. The transport in the surface layer is onshore due to northward winds in the winter. An organism in the surface layer could cross the continental shelf off the west coast which is about 20-50 km wide in 3-8 days. The wind-driven alongshore currents can be at least 10 times as large. The northward current (Davidson Current) in winter can be 0.5-1.0 m/s (1-2 knots) and thus transport organisms near the surface 50-100 km along the coast per day.

- In late Fall and Winter, the region nearest the coast, out to about 5 miles offshore, can become sluggish, i.e. both cross-shelf and alongshore currents can become much smaller than those noted above (Allen and Newberger, 1996; and Austin and Lentz, 2002). In effect, the fluid near the coast becomes more "viscous." As a consequence, material at the surface may not reach the shore and, if buoyant, could become trapped offshore in the strong northward jet. As a strong cautionary note on this, time-varying winds, alongshore changes in bottom depth and stirring in the coastal ocean can disrupt the cross- and alongshore circulation described here and lead to surface water parcels reaching all the way to the beach.

- In Spring and Summer, surface circulation from Point Conception in the south to Vancouver Island is generally offshore and south. The southward winds, which occur during the spring and summer, drive an offshore surface Ekman transport. As a consequence, near the coast, cold, nutrient-rich water is upwelled from depth. The core of the southward flow is often located over the mid shelf or about 80 m bottom depth and reaches speeds of 0.5-1.0 m/s. The core of the jet is associated with an upwelling front, a sharp boundary between cold, nutrient-rich water inshore and warm, low nutrient water offshore. At this speed, 50-100 km/day, a water parcel at the surface can transit the entire Oregon coast in 4-10 days. For a typical 20 knot wind, the offshore Ekman transport, when distributed over a 20 m deep surface layer, leads to about 0.10 m/s (10 km/day) offshore flow at the surface.

- In the Spring and Summer, when upwelling-favorable winds (strong southward winds) relax, flow on the shelf, especially near the bottom and nearest the coast, can reverse and flow poleward (Send et al., 1987). So water parcels on the shelf may not be simply advected to the south in the summer, but can move northward if caught in this poleward flow. One example of the influence of this circulation pattern on the coastal ecosystem is the strong correlation of crab settlement events off Bodega Bay with northward advection of warm water from south of Pt. Reyes during wind relaxation (Wing et al., 1995).

- The seasonal cycle of currents over the shelves in the Southern California Bight is generally weaker (~5 cm s^{-1} vs. 20 cm s^{-1}) and is more spatially complex. Equatorward flow is strongest in winter. Flow tends to be more equatorward higher in the water column and more poleward toward the outer shelf and at deeper depths in the water column, similar to that north of Point Conception.

- The most significant factor that distinguishes the nature of the circulation within the Bight from that farther north is likely the difference in wind forcing: local wind stress is an order of magnitude smaller within the Bight during late spring and summer, when upwelling is strongest at locations north of the Bight (Hickey, 1992). Thus, local upwelling generally occurs only in winter and early spring within the Bight. During summer, upwelled water from regions north of the Bight frequently enters the Bight and significantly alters water properties, particularly in the Santa Barbara Channel (Hickey, 1992).

- A seasonal cycle similar to that off southern California was reported in the one data set available off northern Baja California (Barton, 1985). Near-surface flow was equatorward in winter and spring but poleward in summer and fall. The seasonal cycle over the remainder of the Baja Peninsula shelf is unknown at the present time. The existence of mesoscale topographic features suggest that the circulation may be complex.

- Wind stress is somewhat higher off the peninsula of Baja California than in the Southern California Bight. The shelf is generally wider and is interrupted by several major capes. Because so few current measurements have been made in Baja California, scales of variability and forcing mechanisms are not as well understood as in regions to the north.

- 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 CCS (Huyer et al., 1979). Along much of the coast, during the transition, sea level drops at least 10 cm, currents reverse from poleward to equatorward within a period of several days (Strub et al., 1987). Within the Southern California Bight, a rapid transition between summer and fall oceanic characteristics is not observed.

- Seasonal conditions are frequently reversed for shorter periods of time in the

Pacific Northwest. Shelves are dominated by wind forced events, with typical scales of 3-10 days. Regions seaward of the shelf are dominated by jets, eddies, and, in some locations, propagating disturbances, with typical scales of 10-40 days.

Mesoscale Features

- Although many of the processes on the West Coast act over very large scales (100's of kilometers), significant mesoscale features (10's of kilometers) also occur along this coast and these mesoscale features may be of particular importance to ecosystem variability and to questions concerning exchange of ballast water.

- In regions where large coastal promontories occur such as off southern Oregon and northern and central California, Hickey (2002) suggested that plankton and larvae can be swept offshore and southward by the meandering jets and/or eddies that form where the coastal jets detach from the shelf. These plankton and larvae likely return to the coast rarely, if at all during the early upwelling season. Later in the upwelling season (July-September), it is possible for particles to be washed back to the shoreline, when the seasonal winds reverse (Barth et al., 2000a). On the other hand, in regions where banks and more complex mesoscale topography occur, such as offshore of the Strait of Juan de Fuca (the Juan de Fuca eddy) or Heceta/Stonewall bank off the central Oregon coast, retention areas are more likely.

- The following regions of significance have been identified along the coast: 1) Cape Blanco (offshore flow), 2) Retention Zones (the Straight of Juan de Fuca Eddy, Heceta Bank, Pt. Reyes, Southern California Bight), and 3) estuaries (Columbia River and others).

- <u>Cape Blanco (offshore flow)</u>: The strong southward coastal upwelling jet often "separates" from the coast at or near Cape Blanco (43N) and carries coastal water far offshore (Barth et al., 2000a). The jet separation at Cape Blanco represents a major change in the circulation characteristics along the Oregon coast. It also is a biogeographic boundary with evidence for different species on either side and also for genetic differences between populations north and south of the Cape (Myers et al., 1998).

- <u>The Strait of Juan de Fuca Eddy Retention Zone (48'30"N to 47'40"N)</u>: The counterclockwise cold eddy west of the Strait of Juan de Fuca (also called the "Tully" eddy; Tully, 1942) is situated southwest of Vancouver Island and offshore of northern Washington. The eddy, which has a diameter of about 50 km, forms in spring and declines in fall (Freeland and Denman, 1982). Recent preliminary studies with drifters introduced into a diagnostic numerical model for a summer period in 1998 suggest that drifting particles can escape from the eddy to flow southeastward along the Washington shelf (Hickey, 2002).

- Heceta Bank Retention Zone (45’00”N to 43’45”N): Heceta Bank is a major submarine feature that widens the continental shelf off Oregon to about 60 km from relatively narrow (25-30 km wide) shelves to the north and south. Water parcels on the inshore side of the Bank can remain there for relatively long periods of time and surface drifter trajectories suggest that water can recirculate around the entire Bank in about 12 days (Barth et al., 2000b).

- Central California Retention Zone (36’30”N to 38’50”N): Between Point Reyes and Sur, a series of eddies or meanders occur to the west of the continental shelf. The flow along the southern edge of the eddy is offshore and is connected with the offshore flowing jet off Point Sur. While some of the onshore flow recirculates in the eddy, some flows into an upwelling center off Año Nuevo and thence southward across the entrance to Monterey Bay where it may become entrained into the cyclonic flow in Monterey Bay. Some of the onshore flow also flows to the north into the Gulf of the Farallones. The diameter of the eddy is about 30 nautical miles. This pattern of circulation has been documented during spring and summer periods of upwelling (Rosenfeld, et al., 1994; Baltz, 1997). A second feature exists to the north: a robust filament of offshore flowing upwelled waters at Point Reyes. Two well defined anticyclonic circulations features appear seaward of the continental shelf and are associated with the Point Reyes filament. The northernmost eddy is centered west of Bodega Bay and a second eddy is near the Pioneer seamount area. These eddies appear to extend deeper than the Monterey eddy and the water found at the center of these eddies is fresher than that found in the center of the Monterey eddy. This suggests either a more direct connection with the California current for these two eddies or a better connection with upwelled coastal waters for the Monterey eddy.

- The Southern California Bight Retention Zone (33’00”N to 34’30”N): The region between Point Conception and San Diego has complicated bottom topography as well as numerous coastline irregularities. Compared to areas in the north, the shelf in this region is typically much narrower (2-5 km vs. 40 km width) and shallower (~60 m vs. 200 m shelf break depth) than the area to the north. Moreover, unlike regions to the north, the shelf is highly discontinuous: at the northern end of the Bight, the shelf widens abruptly in several regions, forming half enclosed bays. Numerous islands and ridges exist offshore, separating the many deep basins that are part of this borderland. The mean circulation in the Bight during much of the year has a retentive pattern. Flow exits the Bight near Point Conception but returns to the Bight along the southern side of the Santa Barbara Channel or south of the Channel Islands (Hickey, 1992). The Santa Barbara Channel has a mean counterclockwise circulation pattern. Santa Monica Bay, offshore of Los Angeles may be particularly retentive—the mean circulation pattern consists of a double gyre (Hickey et al., 2002). Moreover, much of the velocity fluctuations also have a gyre pattern.

- The Columbia River Plume Retention Zone: The Columbia River provides over 77% of the drainage between the Strait of Juan de Fuca and San Francisco Bay.

Plumes provide retention areas: eddy like features are generated within a plume under both steady (Garcia-Berdeal et al., 2002) and unsteady (Yankovsky et al., 2001) outflow conditions. Inshore of the plume on the Washington coast, a retentive circulation pattern occurs (Hickey et al., 1998). On a seasonal basis, the plume from the Columbia flows northward over the shelf and slope in fall and winter, and southward offshore of the shelf in spring and summer except when upwelling-favorable winds relax or during northward wind events when low salinity surface water may reach the coast.

- Pacific Northwest Estuaries: Other than the Columbia, river plumes on the Pacific Northwest coast are relatively small, and their effects are likely confined to within one tidal excursion of the mouth of the river or estuary. Other river or estuarine plumes include those from Grays Harbor and Willapa Bay, Washington; and Coos Bay and Yaquina Bay (Newport), Oregon; and San Francisco Bay, California. Water presented at the mouth of the estuary (for both upwelling and downwelling events) travels up the estuary at the rate of several km per day, modifying the circulation in the estuary as it passes. Thus, water within a few tens of kilometers of the mouth of each estuary (a tidal excursion) is readily pulled in to the estuary on each tidal cycle.

Final Recommendations

- The general trends noted in this report should be carefully considered when determining "if, when, and where" coastal ballast exchange should take place. It should also be noted that strong storm events and other events can dramatically change the general trends for a short periods of time. Although many of these events/changes can be detected, it is unlikely (although not impossible) that real-time data will be used to determine when and where to exchange coastal ballast water.

- Before the recommendations are reviewed it should be noted that this report is a compilation of current data on coastal currents along the West Coast of North America provided by experts in physical oceanography for this region. This report provides a current summary of coastal currents and their implications on ballast water exchange. It is important to note that no new analysis or analysis specific to coastal ballast water exchange was conducted for this report. Although the recommendations are not based on research specific to ballast exchange, the recommendations were made by the physical oceanography experts and are based on many years of research on coastal currents along the West Coast of North America.

- Recommendation #1: The following retention zones have shown a capacity to retain organisms: Strait of Juan de Fuca Eddy (48'30"N to 47'40"N), Heceta Bank (45'00"N to 43'45"N), Central California Retention Zone (Between Point Reyes and Sur)(36'30"N to 38'50"N), the Southern California Bight (33'00"N to 34'30"N), the Columbia River Plume Retention Zone. Due to their retentive abilities, these areas should be considered as possible exclusion zones for ballast water exchange (from the shoreline to 50 nautical miles offshore). In addition, other river or estuarine plumes, including those from Grays Harbor and Willapa Bay in Washington, Coos Bay and Yaquina Bay (Newport) in Oregon, and San Francisco Bay in California have the capacity to pull water into the estuary within a few tens of kilometers of the mouth of each estuary on each tidal cycle. Therefore areas just outside estuaries (up to a 15 nautical mile radius) should be considered as possible exclusion zones for ballast water exchange.

- Recommendation #2: Along all other areas of the coast, any ballast water discharged outside of the 1000 m isobath has a relatively low probability of reaching the shoreline. This is due to the prevailing currents and the bottom topography (the 1000 m isobath is located along a steep slope). As a general trend in these locations, if the ballast water is discharged the closer to the shoreline (moving off the steep slope and onto the continental shelf around the 200 m isobath), the probability of the organisms reaching the shoreline will increase.

- Recommendation #3: Seasonal fluctuations should also be considered when determining "when and where" to exchange ballast water. In the Spring and Summer, the currents from Vancouver Island to Point Conception tend to be offshore and south. In the late Fall and Winter, currents in this region tend to be onshore and north. Disruptions in these regular trends should also be taken into consideration.

Future Research

- A list of research projects which could clarify and quantify some of the conclusions made in this report was created. These projects include: Modeling Study of Surface Water Parcel Trajectories in the California Current System; An Investigation of the Quantitative Relationship Between On-Offshore Motion of Surface Water in Relation to Wind Forcing in the California Current System; Drifter Studies; and Mixing of Ballast Waters in the Open Ocean. All of these proposed projects could be completed within a 2-3 year time period.

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The fate and risk of establishment of organisms discharged in ballast water in coastal exchange is not well known. There is concern that organisms might be driven back to shore by a variety of coastal processes and therefore could inoculate the coastline and associated bays with AIS. The relative risk of establishment of AIS in coastal estuaries resulting from coastal exchange versus discharge of port water directly into estuaries is unknown. The primary goal of this report was to compile the current information on coastal processes on the West Coast to enable informed decisions on how to best manage ballast water in coastal shipping to minimize risk of AIS establishment.

Context of Report/Workshop

The Pacific Ballast Water Group (PBWG), West Coast Ballast Outreach Project (WCBOP), and Pacific States Marine Fisheries Commission (PSMFC) organized a workshop on March 18, 2002, to bring together physical oceanographers to discuss the physical oceanography on the West Coast and the implications for coastal ballast exchange. At the workshop, the oceanographers were asked to consider the spread of organisms from the point of discharge for a two week period. This was also the assumption that was used in the draft ballast exchange study conducted by Beeton et al. (1998). Although some larval organisms are known to survive well past the two week period, many of the organisms will die within this time frame, and more importantly, this was thought to be a good time frame to describe the initial spread of the organisms after discharge. Following the workshop, the physical oceanographers contributed sections to this report to describe the west coast oceanography, and to detail the recommendations that were discussed at the workshop.

WEST COAST COASTAL PROCESSES

Large Scale Features of the California Current System (Hickey)

The West Coast of the North America from the Strait of Juan de Fuca to the tip of Baja, California is part of an eastern boundary current known as the California Current System. The relatively straight coastline between these two points is interrupted at several locations by substantive promontories (Figure 1). The largest bend in the coastline occurs at Point Conception to San Diego. This region (the Southern California Bight) differs dramatically from those outside this region (Hickey, 1992), creating three geographical regions: north of Point Conception, The Southern California Bight, and the Baja Peninsula.

As traditionally defined, the California Current flows equatorward year-round offshore of the U.S. West Coast from the shelf break to a distance of 1000 km from the coast (Figure 1). The current is strongest at the sea surface, and generally extends over the upper 500 m of the water column. Seasonal mean speeds are ~10 cm s^{-1}. The California Current carries colder, fresher Subarctic water equatorward along the coast. Within about 300 km of the coast, some of the fresher water in the upper 20 m of the water column is associated with a local river plume (the Columbia). South of Point Conception (the major indentation in the coastline near 35^{o} N) a portion of the California Current turns southeastward and then shoreward and poleward. This feature is known 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 Bight. This poleward flowing surface countercurrent, as well as the subsurface California Undercurrent, are the dominant features in the upper water column of the nearshore basins of the Southern California Bight (Hickey, 1979, 1992, 1993; Tsuchiya, 1980; Lynn and Simpson, 1987, 1990). The California Current, the California Undercurrent and the Southern California Eddy all have seasonal maxima in summer to early fall. The California Countercurrent has a seasonal maximum in winter, coincident with the seasonal development of the Davidson Current in regions north of Point Conception.

The California Undercurrent is a relatively narrow feature (~10-40 km) that flows poleward over the continental slope from Baja California to at least Vancouver Island. The undercurrent can be continuous over distances of at least 400 km along the slope (Collins et al., 1996a; Pierce et al., 2000). The flow in the undercurrent off central California can occasionally be interrupted by eddy-like features (Ramp et al., 1996b). Current measurements reveal a jet-like undercurrent structure, with the core of the jet located just seaward of and just below the shelf break and peak speeds observed in the Undercurrent are ~30-50 cm s^{-1}. The Undercurrent is strongest at depths of 100-300 m from the surface and transports warmer, saltier Southern water poleward along the coast (Wooster and Jones, 1970; Hickey, 1979; Chelton, 1984; Torres-Moye and Acosta-Rufz, 1986; Hickey, 1992; Rosenfeld et al., 1994; Tisch et al., 1992). The poleward flow within the Southern California Bight divides at the northwestern end of Santa Monica Basin into two components, one flowing northwestward through the Santa Barbara Channel, the other flowing westward south of the island chain that forms the southern side of the Santa Barbara Channel (Lynn and Simpson, 1990).

Poleward subsurface flow over the continental slope has a significant seasonal variation: a maximum in poleward subsurface flow occurs in summer or early fall when the equatorward California Current is also strongest. Minimum subsurface poleward flow and even equatorward flow (only within the Southern California Bight) typically occur during spring (Hickey, 1979, 1992). A second maximum in poleward flow, associated with the surface-trapped Davidson current (see below) occurs in winter, so that the seasonal signal of the subsurface flow has a semi-annual component at most locations. This is apparently not the case off central California near Point Sur (~36.5^{o} N) where the signal is annual because the fall reduction in poleward flow prior to the Davidson Current season is not observed in long term averaged geostrophic flow (Chelton, 1984).

An equatorward undercurrent occurs over the continental slope in the winter season over at least the Washington and Oregon coasts (the "Washington Undercurrent", Hickey, 1989a). This undercurrent occurs at deeper depths than the poleward undercurrent (~300-500 m). The existence of this undercurrent, like that of the poleward undercurrent, may depend on the co-occurrence of opposing wind stress and alongshore pressure gradient forces.

The Davidson Current flows poleward in fall and winter from Point Conception (~35^{o} N) to at least Vancouver Island (50^{o} N). It has been suggested that the Davidson Current is the result of "the surfacing" of the California Undercurrent during late fall (Pavlova, 1966; Huyer and Smith, 1974). This poleward flow is generally broader (~100 km in width) and sometimes stronger than the corresponding subsurface poleward flow in other seasons, and extends seaward of the slope (Hickey, 1979; Chelton, 1984). Poleward shelf flow, in the sense of a monthly mean phenomenon, is sometimes described as an expression of "The Davidson Current".

<u>Seasonal Changes in the California Current System (Hickey)</u>

The majority of the seasonal variation in the California Current System occurs in a relatively narrow band (~100 km) next to the coast, which has been described by recent work using satellite altimetry data (Strub and James, 2002). Seasonal variation in the transport or location of the West Wind drift, as was previously thought to occur, was shown to be relatively weak. Moreover, the seasonal variation in the CCS is continuously connected to similar variations in the currents of the Alaska gyre. In general, seasonal changes propagate both poleward and offshore as the seasons progress. The offshore propagation produces changes in circulation patterns in regions well offshore of the continental shelf, with alternating bands of poleward and equatorward flow.

The seasonal cycle over the mid and outer shelf is similar to that described above in the broader current systems. Mid water column shelf currents north of Point Conception are generally equatorward in the upper water column from early spring to summer and poleward the rest of the year. The duration of seasonal equatorward flow usually increases with distance offshore and with proximity to the sea surface. A poleward undercurrent is commonly observed on shelves during the summer and early fall. A strong tendency for poleward flow exists over the inner shelf throughout the water column in all but the spring season. Data from northern California (Winant et al., 1987; Largier et al., 1993) and from Washington (Hickey, 1989b) suggest that the vertical zero crossing from equatorward to poleward flow is at about 100 m over the outer shelf, 50 m over the mid-shelf, and 15 m or less on the inner shelf.

Seasonal Surface Circulation: Fall and Winter Circulation (Barth)

In late Fall and Winter, flow from Point Conception in the south to Vancouver Island in the north is generally onshore and north. During this time of year the Davidson current flows north along the U.S. and Canadian west coasts from as far as Point Conception in the south to Vancouver Island in the north (Hickey, 1979, 1998). This strong current (sometimes up to 1 m/s or 2 knots) is driven by both a large-scale north-south pressure gradient, but also by the strong winds from the south ("southerlies" in meteorological terms or "northward" in oceanographic context) accompanying storms which frequent the Pacific Northwest coast during winter. On the rotating earth, surface wind stress combines with the Coriolis force to drive surface currents to the right of the wind in the northern hemisphere. This "Ekman transport" extends down to about 30 m and when the entire transport is integrated over this 30-m deep layer it is exactly 90 degrees to the right of the wind. Hence transport in the surface layer is onshore due to northward winds in the winter.

The Ekman transport can be estimated very simply from the wind stress (tau) as M=tau/(rho*f) where rho is the density of water (1024 kg/m**3) and f is the Coriolis parameter equal to twice the rotation rate of the earth times the sine of the latitude. For mid-latitudes, the Coriolis parameter is about 0.0001 1/s. Wind stress (in N/m**2) is equal to the density of air (1.3 kg/m**3) times a drag coefficient, dependent on wind speed and details of the atmospheric boundary layer structure but about equal to 0.0014, times the wind speed (in m/s) squared. As an aside, this formula is used to compute the "Bakun Upwelling Index" (see more complete description below), a value commonly used to describe wind-driven surface transport off the west coast. As an example, a 20 knot -- a knot is approximately 0.5 m/s -- wind from the south in a winter storm yields an onshore Ekman transport of 1.9 m**2/s. If this is distributed over a 30-m deep layer, the onshore velocity is 0.06 m/s or about 6 km/day. Therefore, an organism in the surface layer could cross the continental shelf off the west coast which is about 20-50 km wide in 3-8 days.

While the surface currents can move material to the right of the wind at about 5-10 km/day, it must be remembered that the wind-driven alongshore currents can be at least 10 times as large. The northward current in winter can be 0.5-1.0 m/s (1-2 knots) and thus transport organisms near the surface 50-100 km along the coast per day.

Recently, more details of the winter circulation within five miles of the shoreline have emerged. By using numerical circulation models, Allen and Newberger (1996) and Austin and Lentz (2002) have shown how the region nearest the coast, out to about 5 miles offshore, can become sluggish, i.e. both cross-shelf and alongshore currents can become much smaller than those noted above. This essentially happens because the entire water column is mixed by the strong surface winds so that the surface wind stress is efficiently countered by bottom stress. In effect, the fluid near the coast becomes more "viscous." As a consequence, the onshore Ekman transport may not reach the coast and instead feeds a downward current some distance offshore, again roughly about 5 miles. The alongshore currents nearest the coast are reduced too, so that the strongest northward flow is found farther offshore. This forms a jet-like structure, i.e. weaker northward flow both onshore and offshore of a central strong jet at about the mid-shelf around 75-100 m bottom depth. As a consequence, material at the surface may not reach the shore and, if buoyant, could become trapped offshore in the strong northward jet. Evidence for this scenario has been documented by Austin and Barth (2002) who examined the trajectories of a large number of satellite-tracked surface drifters and found that they did get trapped in a strong northward current rather than immediately reaching the coast as predicted by simple Ekman theory. As a strong cautionary note on this, time-varying winds, alongshore changes in bottom depth and stirring in the coastal ocean, for example by eddies, can disrupt the cross- and alongshore circulation described here and lead to surface water parcels reaching all the way to the beach. Many of the drifters used in the Austin and Barth (2002) study do eventually beach.

The surface ocean off the Pacific Northwest is influenced by the presence of the Columbia River. While the input of the river to the ocean is substantial, in excess of 10,000 meters cubed per second during peak runoff periods in spring, this flow is not sufficient to overcome the prevailing coastal ocean currents. Consequently, in winter the Columbia River outflow is carried to the north along the Washington coast and is trapped near the coast by the onshore surface Ekman transport forced by southerly winds (Huyer, 1983).

Spring and Summer Surface Circulation (Barth)

In Spring and Summer, flow from Point Conception in the south to Vancouver Island in the north is generally offshore and south. During this time of year, the winds off the Pacific Northwest are generally from the north ("northerlies" in meteorological terms or "southward" in oceanographic context) as a result of the strong North Pacific High pressure system (Huyer, 1983). The southward winds drive an offshore surface Ekman transport. As a consequence, near the coast, cold, nutrient-rich water is upwelled from depth. When the nutrient-rich water reaches the euphotic zone, phytoplankton growth occurs and fuels the coastal ocean food web. The presence of cold water next to the coast also creates a density gradient across the shelf since it is denser than warm water found offshore. This density gradient forms a cross-shelf pressure force which is balanced with the Coriolis force associated with a strong southward flow. The southward flow is concentrated over the shelf and is surface intensified, the so-called upwelling jet (Huyer, 1990). The core of the southward flow is often located over the mid shelf or about 80 m bottom depth and reaches speeds of 0.5-1.0 m/s. The core of the jet is associated with an upwelling front, a sharp boundary between cold, nutrient-rich water inshore and warm, low nutrient water offshore. At this speed, 50-100 km/day, a water parcel at the surface can transit the entire Oregon coast in 4-10 days. For a typical 20 knot wind, the offshore Ekman transport, when distributed over a 20 m deep surface layer, leads to about 0.10 m/s (10 km/day) offshore flow at the surface.

The Spring and Summer currents can shift when the direction and/or the speed of the wind changes. The winds vary on a 2-10 day time scale, the so-called "weather band" so that periods of strong, upwelling-favorable (southward) winds are separated by low winds (relaxation) or even northward winds. During relaxation and northward wind events the upwelling jet can weaken and change its location over the shelf. When upwelling-favorable winds relax, flow on the shelf, especially near the bottom and nearest the coast, can reverse and flow poleward (Send et al., 1987). So water parcels on the shelf may not be simply advected to the south in the summer, but can move northward if caught in this poleward flow. One example of the influence of this circulation pattern on the coastal ecosystem is the strong correlation of crab settlement events off Bodega Bay with northward advection of warm water from south of Pt. Reyes during wind relaxation (Wing et al., 1995). A recent modeling study suggests that short alongshore-scale northward pressure gradients established by variations in upwelling intensity along the coast can drive these poleward flows during wind relaxations (Gan and Allen, 2002).

In the presence of the summertime wind-driven upwelling circulation, the Columbia River outflow is swept offshore and to the south (Huyer, 1983). Low salinity water from the Columbia River plume can be traced as far south as the Oregon-California border (42N). The low salinity water is held offshore along most of the Oregon coast by the offshore surface Ekman transport accompanying the northerly winds. However, during wind relaxations and reversals, Columbia River-influenced water does reach the coast. When the low salinity water is held offshore by the upwelling circulation, it augments the cross-shelf density gradient and hence helps accelerate the surface currents in the upwelling jet.

Seasonal Cycles in the Southern California Bight (Hickey)

The seasonal cycle of currents over the shelves in the Southern California Bight is generally weaker (~5 cm s^{-1} vs. 20 cm s^{-1}) and is more spatially complex. Equatorward flow is strongest in winter. Flow tends to be more equatorward higher in the water column and more poleward toward the outer shelf and at deeper depths in the water column, similar to that north of Point Conception. However, deviations from this pattern are relatively common even in regions of straight coastline. On wider shelves that are partially enclosed, mean circulation patterns can be strongly affected by the local topography. For example, during some seasons, the Santa Monica Bay shelf has a double gyre circulation pattern (Hickey et al., 2002).

Seasonal Cycles off northern Baja California (Hickey)

A seasonal cycle similar to that off southern California was reported in the one data set available off northern Baja California (Barton, 1985). Near-surface flow was equatorward in winter and spring but poleward in summer and fall. The seasonal cycle over the remainder of the Baja Peninsula shelf is unknown at the present time. The existence of mesoscale topographic features suggests that the circulation may be complex.

Spring Transition (Hickey)

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 CCS (Huyer et al., 1979). Along much of the coast, during the transition, sea level drops at least 10 cm, currents reverse from poleward to equatorward within a period of several days and isopycnals slope upward toward the coast (Strub et al., 1987). 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 CCS. The alongshore scale of the sea level response is typically ~800 km, but considerable interannual variability in both the atmospheric forcing and the coastal response is observed (Strub and James, 1988). Within the Southern California Bight, the response to the transitional wind event, if present, is much weaker than at more northern latitudes. A similar rapid transition between summer and fall oceanic characteristics is not observed. Rather, sea level data suggest synoptic variability superimposed on a gradual seasonal increase of the up-to-the-north alongshore slope (Strub and James, 1988).

Several Day Disturbances to Seasonal Patterns (Hickey)

Seasonal conditions are frequently reversed for shorter periods of time in the Pacific Northwest. Although processes that occur on the shelf and the resulting flows and water properties can be intimately connected with those farther seaward, dominant scales and patterns of variability differ significantly in the two regions. Shelves are dominated by wind forced events, with typical scales of 3-10 days. Regions seaward of the shelf are dominated by jets, eddies, and, in some locations, propagating disturbances, with typical scales of 10-40 days.

Several Day Disturbances to Seasonal Patterns: Continental Shelf (Hickey)

Fluctuations in currents, water properties and sea level over the shelf at most locations are dominated by wind forcing, with typical scales of 3-10 days. During periods of fair weather the stress of the southward winds at the sea surface accelerates the coastal currents, producing offshore and alongshore directed currents in the surface Ekman layer (~5-30 m thick) (45 degrees to the right of the wind), alongshore currents in the central water column (geostrophically balanced with the cross-shelf sea surface height) and onshore and alongshore currents in the bottom boundary layer (~5-20 m thick). Plumes of fresher water originating at coastal estuaries tend to spread offshore and to the south. Upwelling occurs within a few kilometers of the coast (typically, within on Rossby radius). During periods of poor weather the patterns reverse and freshwater plumes move back onshore.

The alongshelf currents include a response to both local and remote wind forcing; that is, as a result of the narrow, relatively straight shelf and alongshore structure in the wind field, much of the mid water column variability can be described with the dynamics of coastally trapped waves (Hickey, 1989b). With these dynamics, currents occur as a result of alongshelf wind stress not only at the given location but also up to a few hundred kilometers south of the location. At any given time and location, the ratio of remote and local forcing varies. In winter, local wind forcing dominates, especially in regions such as the Washington coast where winter storms are accompanied by strong northward winds whose magnitude increases in the direction of propagating waves. In summer, when wind stress decreases in the direction of the wave propagation, free waves are more dominant, particularly in regions north of northern California to the British Columbia coast (Hickey et al., 1991).

In contrast to most East Coast environments, the West Coast shelf is relatively narrow, so that nutrient-rich deeper water can be effectively brought to the surface by the wind-driven upwelling that occurs in the growing season along the entire coastal boundary. Also in contrast to most East Coast coastal areas, nutrient input from coastal rivers is negligible except in the associated estuary and right at the river mouth. Both seasonal and event-scale patterns of all nutrients on the continental shelf are dominated by seasonal and event-scale patterns in the upwelling processes (Landry et al., 1989; Hickey, 1989a). Wind-driven upwelling of nutrients from deeper layers fuels coastal productivity, resulting in both a strong seasonal cycle and several day fluctuations that mimic changes in the wind direction and, hence, upwelling. During an upwelling event, phytoplankton respond to the infusion of nutrients near the coast and this "bloom" is moved offshore, continuing to grow while depleting the nutrient supply. When winds reverse (as occurs during storms), the bloom moves back toward shore where it can contact the coast or enter coastal estuaries.

Within the Southern California Bight, current fluctuations at shorter than seasonal scales are significantly different than those north of Point Conception (Winant, 1983; Lentz and Winant, 1986; Hickey, 1992). For example, current fluctuations in the Southern California Bight have much smaller alongshelf scales than in the region north of the Bight (20 km vs. 500 km) (Winant, 1983). Topography within the Bight is extremely complex. In particular, the shelf is typically much narrower (2-5 km vs. 40 km width) and shallower (~60 m vs. 200 m shelf break depth). Moreover, unlike regions to the north, the shelf is highly discontinuous: at the northern end of the Bight, the shelf widens abruptly in several regions, forming half enclosed bays. The abrupt changes in shelf width are likely to give rise to scattering of CTWs traveling through the region (Wilkin and Chapman, 1990). However, the most significant factor that distinguishes the nature of the circulation within the Bight from that farther north is likely the difference in wind forcing: local wind stress is an order of magnitude smaller within the Bight during late spring and summer, when upwelling is strongest at locations north of the Bight (Hickey, 1992). In winter, winds within the Bight are correlated with those outside the Bight, although still reduced significantly in magnitude. Thus, local upwelling generally occurs only in winter and early spring within the Bight. During summer, upwelled water from regions north of the Bight frequently enters the Bight and significantly alters water properties, particularly in the Santa Barbara Channel (Hickey, 1992).

Wind stress is somewhat higher off the peninsula of Baja California than in the Southern California Bight. The shelf is generally wider and is interrupted by several major capes. A clear example of wind-forced upwelling was reported by Barton and Argote (1980). Their data show equatorward shelf currents and upwelling of isopycnals in response to winds of about 10 m s^{-1}. The hydrographic structure and the response appear to be similar to that in regions north of Point Conception during that event. Because so few current measurements have been made in Baja California, scales of variability and forcing mechanisms are not as well understood as in regions to the north.

Several Day Disturbances to Seasonal Patterns: Continental Slope (Hickey)

Currents over the slope all along the West Coast are dominated by fluctuations with periods much longer than those on the shelf. Off northern and central California these fluctuations have generally been associated with the offshore eddy and meander field (Largier et al., 1993; Ramp et al., 1996b); whereas, off southern California they have been associated with propagating disturbances (Hickey, 1992; Hickey et el., 2002). Satellite imagery consistently show filaments jets and eddies emanating from near coastal promontories to regions well seaward of the coast from Cape Blanco south to Point Conception (Kelly, 1985; Kosro and Huyer, 1986). Shipboard surveys demonstrate that the filaments extend from the surface to depths of over 200 m and that they separate fresher, warmer, chlorophyll-depleted water from colder, saltier, chlorophyll-rich recently upwelled water (e.g., Huyer et al., 1991; Strub et al, 1991; Hood et al., 1990). Jets are characterized by core speeds exceeding 50 cm s^{-1} at the surface, widths of 50-75 km and total baroclinic transports of about 4 Sv (Huyer et al., 1991). The large scale surveys confirm that filaments are much more common in spring and summer than in other seasons (Kosro et al., 1991). Both water mass analyses and studies of phytoplankton suggest that subduction as well as lateral advection occurs within the mesoscale filaments (Washburn et al., 1991). The association with promontories explains why fewer filaments are observed north of about 43^{o} N where the coastline is straighter. Filaments are the result of separation from the shelf of the coastal jet formed over the shelf during upwelling events (Strub et al., 1991). Individual jets can be followed from the Oregon coast near Cape Blanco south past the entire California coast (Barth et al., 2000a). These meandering jets carry much of the water volume of the California Current at these latitudes and are responsible for much of its seasonal transport variation.

In the Southern California Bight, long period (15-25 day) fluctuations dominate the variance along the continental slope. These fluctuations are the signature of coastally trapped waves generated several hundred kilometers south off the Baja peninsula (Hickey et al., 2002). The amplitude of these waves is reduced by scattering within the southern California Bight. These waves are also responsible for much of the variability on the semi-enclosed Santa Monica shelf-- currents on the inner shelf appear to be driven by the pressure field associated with the currents on the upper slope (Hickey, 1992; Hickey et al., 2002). Currents on the inner and outer shelf are in opposite directions during these events.

Important Mesoscale Features (Hickey)

Although many of the processes on the West Coast act over very large scales (100's of kilometers), significant mesoscale features (10's of kilometers) also occur along this coast and these mesoscale features may be of particular importance to ecosystem variability and to questions concerning exchange of ballast water.

For example, on a coast-wide survey of domoic acid in surface waters in 1998, high values of this toxin were measured only in the vicinity of known topographic features such as banks or offshore islands (Hickey, 2002; Trainer et al., 2000). The domoic acid is associated with the diatom *Pseudo-nietzsche* spp. Hickey (2002) suggested that in regions where large coastal promontories occur such as off southern Oregon and northern and central California, plankton and larvae can be swept offshore and southward by the meandering jets and/or eddies that form where the coastal jets detach from the shelf. These plankton and larvae likely return to the coast rarely, if at all during the early upwelling season. Later in the upwelling season (July-September), it is possible for particles to be washed back to the shoreline, when the seasonal winds reverse (Barth et al., 2000a). On the other hand, in regions where banks and more complex mesoscale topography occur, such as offshore of the Strait of Juan de Fuca (the Juan de Fuca Eddy) or Haceta/Stonewall bank off the central Oregon coast, retention areas are more likely. Maps of ocean pigment clearly show that chlorophyll is greater and located father offshore in the vicinity of both of these features (Strub and James 2002). Under weak wind southward conditions or during northward winds associated with storms, plankton and larvae in these retention areas can return to the coast to settle on the coast or enter coastal estuaries. For example, a relationship between toxic events in coastal razor clam populations due to toxic *Pseudo-nitzschia* and the Juan de Fuca eddy has been documented (Trainer et al., 2000). The toxin (domoic acid) reached the coast during the first significant storm of the year. Retention areas may also provide particularly favorable growth conditions for larval fish.

The sections below describe several features and regions along the coast that have particular significance. Cape Blanco represents an area were currents are generally more offshore and southward by the meandering jets and/or eddies. Organisms in these waters are return to the coast rarely, if at all during the early upwelling season. Other regions tend to retain organisms (retention zones) or “suck” them in (estuaries). The following regions of significance are detailed below: 1) Cape Blanco, 2) Retention Zones (the Straight of Juan de Fuca Eddy, Heceta Bank, Pt. Reyes, Southern California Bight), and 3) estuaries (Columbia River and others).

Cape Blanco (Barth)

Cape Blanco (43N) is a major coastal promontory and has a strong influence on the circulation off Oregon. The strong southward coastal upwelling jet often "separates" from the coast at or near Cape Blanco and carries coastal water far offshore (Barth et al., 2000a). The separated jet forms the top of the region of the California Current with enhanced mesoscale, i.e. eddies and meanders, activity (Barth et al., 2000a). This region widens to around 500 km farther south off central California. The jet separation at Cape Blanco represents a major change in the circulation characteristics along the Oregon coast. It also is a biogeographic boundary with evidence for different species on either side and also for genetic differences between populations north and south of the Cape (Myers et al., 1998). Colder water is often found to the south of the Cape and because of the strength of the upwelling circulation, the water may be low in chlorophyll because phytoplankton do not have sufficient time to respond to freshly upwelled nutrients before they are swept downstream and offshore (van Geen, et al., 2000). Cape Blanco is also where significant increases in the alongshore wind stress are observed (Samelson et al., 2002) and hence stronger upwelling and southward currents should exist in that region.

The Strait of Juan de Fuca Eddy Retention Zone (47’40”N to 48’30”N) (Hickey)

The counterclockwise cold eddy west of the Strait of Juan de Fuca (also called the

"Tully" eddy; Tully, 1942) is situated southwest of Vancouver Island and offshore of northern Washington. The eddy, which has a diameter of about 50 km, forms in spring and declines in fall (Freeland and Denman, 1982). The eddy is a dominant feature of circulation patterns off the northern Washington coast and is visible in summertime satellite imagery as a relative minimum low in sea surface temperature and, generally, a relative maximum in chlorophyll *a*. The seasonal eddy is a result of the interaction between effluent from the Strait, southward wind-driven currents along the continental slope and the underlying topography—a spur of the Juan de Fuca submarine canyon. Recent preliminary studies with drifters introduced into a diagnostic numerical model for a summer period in 1998 suggest that drifting particles can escape from the eddy to flow southeastward along the Washington shelf (Hickey, 2002). During storms, onshore flow in the surface Ekman layer moves drifter pathways closer to the coast and even reverses the path to a northward direction. Pathways of drifters deployed this year in the field were consistent with these pathways; during a storm the drifter track reversed and the drifter moved backup the coast. Thus marine organisms residing in the Juan de Fuca eddy can, under certain ocean conditions, impact the Washington coast.

Haceta Bank Retention Zone (43'45"N to 45'00"N) (Barth)

Heceta Bank (44-44.5N) is a major submarine feature that widens the continental shelf off Oregon to about 60 km from relatively narrow (25-30 km wide) shelves to the north and south. Stonewall Bank forms the northern end of the Heceta Bank complex and rises to within 10 m of the surface from its mid-shelf (80 m water depth) location. Thus, Stonewall and Heceta Banks are major topographic features to which the southward coastal upwelling jet must adjust. The upwelling jet is swept offshore off Newport and Waldport as the flow follows bottom contours around the Bank (Barth, et al., 2000b). When it reaches the southward edge of the Bank where the continental shelf break (about the 200 m isobath) turns sharply back toward the coast, the flow cannot turn as swiftly and transports coastal water out into the deep ocean. Flow does turn back toward the coast, narrowing the area of coastal influence downstream of the Bank, but depending on the strength of the wind-driven currents more or less material may be fluxed offshore. This coastal material can sometimes take the form of cold-core, counter-clockwise eddies (see more about offshore eddies below). Because the equatorward upwelling jet flows southwestward around the outside of the Bank, a region of weaker flow is formed inshore of the Bank. This "lee" region is sheltered from the strong southward flow and has been observed to contain large amounts of phytoplankton (Barth et al., 2000b). The Bank region is a highly productive fishery off the Oregon coast. Water parcels on the inshore side of the Bank can remain there for relatively long periods of time and surface drifter trajectories suggest that water can recirculate around the entire Bank in about 12 days (Barth et al., 2000b). In summary, the Bank acts like a rock disrupting a stream which creates a lee region with weaker flow on its downstream side.

Central California Retention Zone (36’30”N to 38’50”N) (Collins)

Along the Pacific Coast, the shape of the coastline and subsurface bathymetry interact with alongshore flowing currents to create a series offshore flowing jets and squirts as well as a number of semi-permanent eddies. The offshore flowing jets are usually anchored at coastal promontories where the coastline changes shape: Points Conception, Sur and Reyes and Cape Mendocino. Between Point Sur and Reyes, a series of eddies or meanders occur to the west of the continental shelf. The surface circulation that is associated with the eddy that occurs off Monterey Bay is shown in Figure 2. The flow along the southern edge of the eddy is offshore and is connected with the offshore flowing jet off Point Sur (not shown). Onshore flow occurs along the northern edge of the eddy. While some of the onshore flow recirculates in the eddy, some flows into an upwelling center off Año Nuevo and thence southward across the entrance to Monterey Bay where it may become entrained into the cyclonic flow in Monterey Bay. Some of the onshore flow also flows to the north into the Gulf of the Farallones. The maximum speed of the flows shown in Figure 2 is about half a knot but currents as strong as a knot have been measured in this region. The diameter of the eddy is about 30 nautical miles. This pattern of circulation has been documented during spring and summer periods of upwelling (Rosenfeld, et al., 1994; Baltz, 1997). When the winds which cause the upwelling relax during these seasons, the offshore waters translate shoreward, often penetrating into Monterey Bay.

To the north, a robust filament of offshore flowing upwelled waters exists at Point Reyes. Two well defined anticyclonic circulations features appear seaward of the continental shelf and are associated with the Point Reyes filament. The northernmost eddy is centered west of Bodega Bay and a second eddy is near the Pioneer seamount area. Offshore moving waters from the Pt. Reyes filament create a wedge of dense water which separates the Pioneer and Bodega eddies. The filament remains persistent during the upwelling season over a wide range of wind conditions, even during prolonged wind relaxation events so that its dynamics cannot be ascribed to variations in Ekman transport alone. The Bodega and Pioneer eddies appear to extend deeper than the Monterey eddy and the water found at the center of these eddies is fresher than that found in the center of the Monterey eddy. This suggests either a more direct connection with the California current for these two eddies or a better connection with upwelled coastal waters for the Monterey eddy.

The Southern California Bight Retention Zone (33’00”N to 34’30”N) (Hickey)

The region between Point Conception and San Diego (the Southern California Bight) has complicated bottom topography as well as numerous coastline irregularities. The continental shelf is relatively wide (~20 km) in several areas such as Santa Monica Bay and the San Pedro shelf and very narrow in other areas. Numerous islands and ridges exist offshore, separating the many deep basins that are part of this borderland. The mean circulation in the Bight during much of the year has a retentive pattern. Flow exits the Bight near Point Conception but returns to the Bight along the southern side of the Santa Barbara Channel or south of the Channel Islands (Hickey, 1992). The Santa Barbara Channel has a mean counterclockwise circulation pattern.

Santa Monica Bay, offshore of Los Angeles may be particularly retentive—the mean circulation pattern consists of a double gyre (Hickey et al., 2002). Moreover, much of the velocity fluctuations also have a gyre pattern.

The Columbia River Plume Retention Zone (Hickey)

The Columbia River provides over 77% of the drainage between the Strait of Juan de Fuca and San Francisco Bay. The plume from the Columbia River likely has major ecological effects on the Washington-Oregon coast. River plumes are generally turbid, thereby providing less light for plankton growth, while at the same time providing better cover from grazing for higher trophic levels. Plumes provide retention areas: eddy like features are generated within a plume under both steady (Garcia-Berdeal et al., 2002) and unsteady (Yankovsky et al., 2001) outflow conditions. Plumes provide a more stable upper layer overlying higher stratification: Plumes alter regional current patterns in the upper layers, providing along plume jets for rapid transport and convergences and trapping at frontal boundaries on the edges. Recent studies suggest that plume edges are preferred feeding sites for zooplankton. Inshore of the plume on the Washington coast, a retentive circulation pattern occurs (Hickey, 1998). The fact that juvenile salmonids are frequently found in this location may be due to this local retention pattern which might enhance food availability in this region.

On a seasonal basis, the plume from the Columbia flows northward over the shelf and slope in fall and winter, and southward offshore of the shelf in spring and summer except when upwelling-favorable winds relax or during northward wind events when low salinity surface water may reach the coast. Most other smaller rivers on the Pacific coast have significant river plumes only during major floods. In winter, the plume has a dramatic effect on the Washington coast, producing time-variable currents as large as the wind-driven currents. In summer, fresh water from the Columbia gives rise to the low salinity signal and associated front used to trace the meandering jet that separates from the shelf at Cape Blanco. Both observational and modeling studies show that the plume is a “moving target”, changing direction, thickness and width with every change of local wind strength or direction (Hickey, 1998; Garcia-Berdeal et al., 2002). Thus the interaction of the plume with the local ecosystem is likely to be complex and is not well understood at the present time.

Pacific Northwest Estuaries (Hickey)

Other than the Columbia, river plumes on the PNW coast are relatively small, and their effects are likely confined to within one tidal excursion of the mouth of the river or estuary. Other river or estuarine plumes include those from Grays Harbor and Willapa Bay, Washington; and Coos Bay and Yaquina Bay (Newport), Oregon; and San Francisco Bay, California.

Recent studies show that water properties in Pacific Northwest coastal estuaries during the spring to fall growing season are controlled largely by processes occurring in the adjacent ocean rather than in situ estuarine processes (Hickey et al., 2002; Roegner et al. 2002). The type of water presented at the mouth of the estuary on flooding tides is governed by the water available near the coast at that time. The properties of that water (temperature, salinity, nutrient levels and phytoplankton content are governed by whether upwelling or downwelling is occurring along the coast at that time. During upwelling, surface waters move offshore and cold, saltier, nutrient rich water is moved upward within a few kilometers of the coast; during downwelling, surface waters move onshore and warmer, fresher, nutrient-poorer water moves inshore and downward within a few kilometers of the coast. In the Pacific Northwest, transitions between these two states occur at 2-10 day intervals. Water presented at the mouth of the estuary (for both upwelling and downwelling events) travels up the estuary at the rate of several km per day, modifying the circulation in the estuary as it passes. The modulations in estuarine circulation and water properties lag local wind stress fluctuations (hence, upwelling or downwelling) by more than a day. Thus, water within a few tens of kilometers of the mouth of each estuary (a tidal excursion) is readily pulled in to the estuary on each tidal cycle.

Final Recommendations:

As can be determined from the above descriptions of the coastal currents involved with the West Coast of North America, the problem of ballast water management practices for coastal vessels involves many complex oceanographic processes. The general trends noted in this report should be carefully considered when determining "if, when, and where" coastal ballast exchange should take place. When the decisions are being made, it should also be noted that strong storm events and other events can dramatically change the general trends for a short periods of time. Although many of these events/changes can be detected, it is unlikely (although not impossible) that real-time data will be used to determine when and where to exchange ballast water.

Before the recommendations are reviewed it should be noted that this report is a compilation of current data on coastal currents along the West Coast of North America provided by experts in physical oceanography for this region. This report provides a current summary of coastal currents and their implications on ballast water exchange. It is important to note that no new analysis or analysis specific to coastal ballast water exchange was conducted for this report. Although the recommendations are not based on research specific to ballast exchange, the recommendations were made by the physical oceanography experts and are based on many years of research on coastal currents along the West Coast of North America.

The following recommendations have been made:

- Recommendation #1: The following retention zones have shown a capacity to retain organisms: Strait of Juan de Fuca Eddy (48'30"N to 47'40"N), Heceta Bank (45'00"N to 43'45"N), Central California Retention Zone (Between Point Reyes and Sur)(36'30"N to 38'50"N), the Southern California Bight (33'00"N to 34'30"N), and the Columbia River Plume Retention Zone (Figure 3). Due to their retentive abilities, these areas should be considered as possible exclusion zones for ballast water exchange (from the shoreline to 50 nautical miles offshore). In addition, other river or estuarine plumes, including those from Grays Harbor and Willapa Bay, Washington and Coos Bay, Oregon have the capacity to pull water into the estuary within a few tens of kilometers of the mouth of each estuary on each tidal cycle. Therefore areas just outside estuaries (up to a 15 nautical mile radius) should be considered as possible exclusion zones for ballast water exchange.

- Recommendation #2: Along all other areas of the coast, any ballast water discharged outside of the 1000 m isobath has a relatively low probability of reaching the shoreline. This is due to the prevailing currents and the bottom topopgraphy (the 1000 m isobath is located along a steep slope). As a general rule, if the ballast water is discharged to the closer to the shoreline (moving off the steep slope and onto the continental shelf at the 200 m isobath), the probability of the organisms reaching the shoreline will increase. Figures 4 & 5 show the distance offshore of the 1000 m isobath and the 200 m isobath, along the West Coast of North America.

- Recommendation #3: Seasonal fluctuations should also be considered when determining "when and where" to exchange ballast water. In the Spring and Summer, the currents from Vancouver Island to Point Conception tend to be offshore and south. In the late Fall and Winter, currents in this region tend to be onshore and north. Disruptions in these regular trends should also be taken into consideration.

Research Recommendations:

Due to the need to make management decisions quickly, based on the best scientific knowledge, the oceanographers complied this report based on their most current data. As noted earlier no new analysis or analysis specific to coastal ballast water exchange was conducted for this report. The oceanographers were asked to detail research projects that could clarify and quantify some of the conclusions made in this report. They developed the following list of research project that could be completed within a 2-3 year time period.

Modeling Study of Surface Water Parcel Trajectories in the California Current System (Jack Barth)

A study of water parcel trajectories within the California Current System off the US west coast to determine the likely fate of exchanged ballast water. A number of increasingly credible regional-scale circulation models of the California Current system have recently been developed (e.g., Marchesiello et al., 2002; Clancy et al., 1996) and are ready to be used for tracking water parcel trajectories (e.g., Righi and Strub, 2001). Water parcels should be tracked from locations all along the US West coast during different seasons of the year. Ensemble averaging should be used to predict the likelihood that ballast water released offshore will reach shore within two weeks or shorter. Areas where currents preferentially carry water parcels onshore or offshore should be identified. These should be characterized seasonally. An assessment of the effectiveness of existing ballast water exchange requirement should also be pursued. An effort should be made to compare the model trajectories with those available from existing surface drifter trajectories (e.g., Swenson and Niiler, 1996; Brink et al., 2000; Austin and Barth, 2002).

This study could be carried out by a Masters level graduate student under the supervision of a coastal physical oceanographer(s). A useful study could be designed and completed in about 2-3 years.

An Investigation of the Quantitative Relationship Between On-Offshore Motion of Surface Water in Relation to Wind Forcing in the California Current System (Barth):

Existing surface drifter trajectories near the coast in the California Current System should be analyzed in an effort to quantify their on-offshore motion in relation to the local wind forcing. This will help to make reasonable estimates of the fate of ballast water released offshore during different times of the year under various wind forcing regimes. There exists a number of near-coast surface drifter data sets along the US West Coast that could be used (e.g., Southern California Bight: Winant et al., 1999; central California coast:

Brink et al., 2000; Oregon and northern California: Austin and Barth, 2002 and Barth et al., 2000a; Washington and British Columbia: B. Hickey, unpublished data). Wind-forcing along the US West coast differs by latitude, both in strength and in the amount of variability (Halliwell and Allen, 1987; Strub et al., 1987). These differences will be important to the fate of near-coast surface water parcels as they respond to wind-driven surface flows. The basic response of the near-surface layer of the coastal ocean is for Ekman transport to the right of the wind stress: offshore during northerly winds and onshore during southerly. Recent work has shown that in the winter the Ekman transport may cease closest to the coast in response to the underlying coastal ocean response to downwelling (Austin and Barth, 2002). A useful study could be designed and completed in a two-year period.

Drifter Studies (Hickey):

Residence times for dissolved and particulate matter in some portions of the California Current System or under some environmental conditions are not well understood. To help determine possible particle pathways for ballast waters, additional studies should be done tracking (via satellite) drifters at the sea surface for extended periods of time. Areas of interest include the California Coast in winter conditions and each of the mesoscale regions described in the introduction. Drifters should be deployed at several distances from the coast in each situation.

Mixing of Ballast Waters in the Open Ocean (Collins)

Ballast water is replaced while a vessel is underway at sea by flushing with a volume of ambient sea water about three times the volume of the tank. The concentration of the "old" ballast water entering the ocean will be determined by (1) when, during this flushing process, the water enters the sea, (2) how much mixing takes place within the ballast tank, (3) the rate at which the water is discharged, and (4) the speed of the vessel. The subsequent mixing of the "old" ballast water with the surrounding sea water will depend upon its buoyancy relative to the ambient seawater, the type of nozzle or method used to inject the ballast water into the sea, and subsequent dispersion by ocean mixing processes. Oscillating broad-scale flow will move the plume of old ballast water away from the injection point but without significantly stirring or mixing. Lateral dispersion will largely determine the mean concentration and can be measured with current-following drifters and floats. As the “old” ballast waters spread, they are stretched into streaks of high concentration with regions of very low concentration between. Those ballast waters which remain at or near the ocean surface, will be acted upon by winds and waves which will accelerate their mixing with ambient ocean waters.

The processes that determine how well mixed a plume of ballast water will become can be measured by using a tracer that serves to tag the injection plume. The same tracer can determine the diapycnal spread of the plume. Recent technical advances in detecting extremely small quantities of the tracer SF_6, in deploying and sampling tracers, and in current-following neutrally buoyant floats and drifters make it feasible to gather the information needed to understand the ocean dispersal of ballast waters. To do this a combination of an easily measured dye (fluoroscene or rhodomine-B) is needed for the near field (within 10 km of the ballast water injection site) and SF_6 for the far field spanning distances of 1000 km.

Dyes are easily measured from ships, aircraft, and autonomous underwater vehicles. This makes it feasible to sample the early spread of a locally injected dye for a few days as it disperses and is strained over tens of kilometers. After this point, dye concentrations decrease to the limit of detectability. For the longer time scales and larger space scales needed to fully assess dispersion, it is necessary to use a tracer like SF_6 that can be detected at dilutions of as great as 10^{10}. Sampling SF_6 is now done only from ships but it should be possible to develop techniques to allow sampling for later analysis from platforms with lower operating costs. Even without these advances, it is possible to map out the extent and degree of mixing of SF_6 plumes as they disperse over times of years and 1000's of kilometers.

To more fully interpret the evolution of the dye and tracer fields (and to speed sampling of SF_6 plumes) it is very helpful to also deploy surface drifters or neutrally buoyant floats as a third "tracer" that disperses along with the dye and SF_6. Because they are much more easily tracked than tracers, floats are particularly useful in extending the area sampled and filling in between filaments of the tracer plume.

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