CHAPTER I
Scales of variation in Pacific Northwest outer-coast estuaries

This chapter provides an overview of the small, coastal-plain estuaries of the U.S. Pacific Northwest, a system of estuaries that, with the exception of the Columbia River, have received relatively little oceanographic attention, despite occupying a coherent regime of forcing very different from that on other U.S. coasts. In Section 1 the geomorphology, freshwater forcing, and tidal regime of these estuaries is described, with comparison to the more commonly studied coastal-plain estuaries of the East Coast. Sections 2 and 3 describe results from comparative studies in Willapa Bay and Grays Harbor, Washington, which suggest the range of scales of variability in these estuaries, from the coast-wide scale (~100 km) to variations over individual intertidal banks (~1 km). This is not a systematic treatment of hydrographic variability: a full climatology for Willapa Bay appears in Chapter II.

1. Physical characteristics and forcing

Four estuaries (Grays Harbor, Willapa Bay, Yaquina Bay, and Coos Bay: Fig. 1.1) were studied as part of the PNCERS program (Pacific Northwest Coastal Ecosystems Regional Study). These four are members of a chain of small estuaries that begins along the Washington coast, spans the coast of Oregon, and continues into northern California. Most of these estuaries are drowned river valleys, formed from sea level rise during the last 10,000 y. Some have also been shaped by ocean-built bars, either partially (e.g., Willapa Bay) or entirely (e.g., Netarts Bay, Oregon). Emmett et al. (2000) reviews the geography of this system in detail.

Indices of geomorphology and tide and river forcing for the PNCERS estuaries are given in Table 1.1. For comparison, the same parameters are included for the Columbia River estuary; San Francisco Bay and South San Francisco Bay alone;
Naragansett Bay; Chesapeake Bay and its tributary the James River; and Plum Island Sound, a small embayment on the Massachusetts coast. Except where otherwise marked, data are from the NOAA National Estuarine Inventory Data Atlas (NOAA 1985). Volume parameters, which are particularly difficult to define and measure (e.g., Malamud-Roam 2000), are here calculated by simple, approximate methods for the sake of uniformity, and thus only gross patterns among the area and volume parameters are significant. Volume is calculated as the product of mean depth and surface area at mean sea level (MSL), a method which gives errors up to ~20% in comparison with other published figures (NOAA/EPA 1991). Mean tidal prism volume is reported as a percentage of volume at high water, which is calculated as MSL volume plus half the tidal prism itself.

Coos Bay is only a few times larger than tiny Plum Island Sound, but is nevertheless the largest of the Oregon estuaries. Grays Harbor and Willapa Bay, the two coastal-plain estuaries north of the Columbia, are an order of magnitude larger, comparable in volume and morphology to South San Francisco Bay. Both Washington estuaries consist of multiply-connected channels 10-20 m deep surrounded by wide mud and sand flats. Half or more of the surface area of these estuaries lies in the intertidal zone. Significantly, even the smaller, narrower estuaries of Oregon have similar percentages of intertidal area (Table 1.1, Percy et al. 1974).

Tides on this coast are mixed-semdiurnal, with spring-neap amplitude variation on the order of 50% (Emmett et al. 2000). Mean tidal ranges, as shown in Table 1.1, are generally twice as large as on the outer Atlantic Coast. The combination of large tidal range with broad, open intertidal surface area yields tidal prisms that are large fractions (30-50%) of total volume. This result holds very generally for Northwest coast estuaries, and is a marked difference between these systems and all but the smallest of their counterparts on other North American coasts. These large tidal prisms suggest that flushing by tidal action is probably important in all these estuaries, even those that receive significant riverflow (see Chapter II). Tidal excursions, as estimated from current measurements in Willapa, Grays, and Coos, are
12-15 km, significant fractions (25-50%) of the length of the estuaries.

Table 1.1 includes long-term mean flows for the lowest- and highest-flow months of the year, and, as a measure of the strength of river forcing relative to estuary size, the "river-filling time," volume divided by flow rate. The outflow from the Columbia River is two orders of magnitude larger than riverflow into the other coastal estuaries. With the exception of the Columbia, these estuaries receive freshwater input from local rainfall only, not from snowmelt. Thus, local riverflow, like local rainfall, is high during winter, when storms are frequent, intermittent during spring and early summer, and negligible during late summer (Emmett et al. 2000). This seasonality in riverflow is generally several times greater than in East Coast estuaries (NOAA 1985), though flood and drought events beyond the mean seasonal cycle have not been considered here. As a result we might expect the hydrodynamic classification of Northwest estuaries to change dramatically between seasons, or even—who flushing and adjustment times are short—between individual wind events.

This riverflow pattern yields a seasonal hydrographic cycle that contrasts strongly with traditional models of temperate partially mixed estuaries, with possibly important ecological implications. Tyler and Seliger (1980), for example, show that primary production in Chesapeake Bay is controlled by "stratification dependent pathways" reminiscent of the seasonal dynamics of the open-ocean mixed layer. In that estuary, in winter, mixing by wind and tide erases stratification and resuspends nutrients, while in spring and summer increased riverflow and solar heating produce strong stratification and reduced vertical exchange. In such a system, stratification controls on vertical mixing are crucial to determining plankton growth rates and the potential for phytoplankton blooms, as in San Francisco Bay (Lucas et al. 1999a,b). In sharp contrast, in Willapa Bay stratification is in general very low during summer, when riverflows are low, and high during the winter, when riverflow peaks (see Chapter II). Vertical, one-dimensional, stratification-centered models of primary productivity thus would not apply here even at the coarsest level. Rather, during the
growing season in Pacific Northwest estuaries, hydrography, nutrient levels, and biomass all appear to be controlled less by in situ processes than by mesoscale processes in the coastal ocean.

2. Upwelling, downwelling, and Columbia River plume intrusions

Both river and ocean forcing in this region are controlled by 500-km-scale atmospheric patterns (Halliwell and Allen 1989, Hickey and Banas 2003). During summer and breaks of fair weather in winter, southward large-scale winds drive coastal upwelling, in which surface waters move offshore, and colder, saltier, nutrient-rich water is brought to the surface at the coastal wall. (This process is the primary nutrient source for Willapa Bay: see Chapter IV.) During winter and breaks of foul weather in other seasons, the northward large-scale winds that accompany local rainfall drive coastal downwelling, in which warmer, fresher, nutrient-depleted surface waters move inshore and fill the water column at the coastal wall down to the depth of the estuary mouths (15-25 m).

Hickey and Banas (2003) show that the estuaries of Washington and Oregon generally respond to coastal upwelling and downwelling cycles coherently, even on the event (2-10 d) scale, because the atmospheric patterns that drive them span the entire coast. Nevertheless, the Columbia River plume can cause major asymmetries between the Washington and Oregon estuaries. Since the plume moves offshore when it flows southward past Oregon during periods of upwelling-favorable winds, it does not impinge upon most Oregon estuaries directly under those conditions. When the plume flows north under downwelling winds, however, it fills the nearshore water column north of the river mouth past the depth of the estuary mouths (Garcia-Berdeal et al. 2002, Roegner et al. 2002). Hickey et al. (2005) have found that the Columbia plume is generally bi-directional in upwelling conditions: for most of spring and summer, even when the main plume is tending south over the Oregon shelf, older plume water is still present offshore on the Washington shelf, and thus can quickly
return to the inner shelf and the estuary mouths during brief wind relaxations and reversals. In general, the effect of the plume on the Washington estuaries is most dramatic and sustained in late spring and early summer, when local riverflow has slackened but the Columbia is still running high with snowmelt.

Lower water column salinities from moorings inside the mouths of Willapa Bay and Grays Harbor during April and May 2000 are shown in Fig. 1.2. For each station, the along-channel salinity gradient has also been calculated as a subtidal time series, by dividing the difference between high- and low-water salinities by the tidal excursion for each semidiurnal tidal cycle, and then filtering the resulting discrete series. This method takes advantage of the fact that each station effectively samples ~15 km of the channel through tidal advection. This allows us to calculate along-channel gradients without requiring pairs of stations to obtain differences. An upwelling event, which brings ~32 psu water into the estuaries and produces strong along-channel gradients (on April 19, ~5 psu over one tidal excursion), is followed by a plume intrusion, indicated by a dramatic decrease in salinity and weak along-channel salinity gradients. When downwelling-favorable winds slacken after ~April 27, salinity and the along-channel salinity gradient increase again. The five-month wind time series shown in Fig. 1.2a suggests that this intermittent alternation of upwelling and plume intrusion continues from late winter through early summer.

During the onset of plume intrusions the along-channel salinity gradient in the estuary can reverse for sustained periods. In Fig.1.2b, for example, as the plume intrusion intensifies during the period April 20-28, salinity at the Willapa Bay mooring at high slack water (indicated by dots) is generally lower than the subtidal average, indicating that each flood tide is bringing somewhat fresher water into the estuary. This reversal of the expected gradient between mid-estuary and ocean water is illustrated in a CTD transect along the main channel of Willapa Bay on May 3, 2000, during the recovery from the plume intrusion (Fig. 1.3a). Salinity increases downstream from the head to > 21.8 psu, drops to < 21.4 psu, and then increases again within one tidal excursion of the mouth.
Vertical gradients weaken during plume intrusions along with the longitudinal gradients. The vertical salinity difference in the interior of the estuary in the May 3 transect is on the order of 0.1 psu. In comparison, a transect on May 30 during the onset of an upwelling event after a period of intermittent winds (Fig. 1.3b) shows vertical salinity differences ~2-4 psu within a tidal excursion of the mouth. During a plume intrusion, the reduced salinity contrast between the river and ocean end-members of the estuary presumably weakens baroclinic pressure gradients and thus stratification to the point where vertical mixing can completely homogenize the water column. Thus in contrast to input of freshwater from the local rivers, which tends to increase stratification and gravitational exchange (see Chapter II), input of freshwater from the Columbia River via the coastal ocean tends to produce near-complete mixing in Washington estuaries.

As described in the preceding section, downwelling conditions tend to reduce estuarine salinity gradients even in the absence of plume intrusions (Hickey et al. 2002), though to a much lesser extent. The effect of the Columbia River plume, then, is to greatly intensify the contrast between spring and summer upwelling and downwelling conditions in the Washington estuaries in comparison with Oregon estuaries. This asymmetry between the two coasts would likely be observed not just on the event scale, but on interannual scales as well. Following wet (La-Niña-like) winters like 1998-1999, but not following dry (El-Niño-like) winters like 1997-1998, sustained plume intrusions would be expected in the Washington estuaries during May and June.

3. Spatial variability in the intertidal zone

Pervasive, significant variation in currents and hydrography is possible on scales as short as ~ 100 m in estuaries with complex bathymetry, particularly in very shallow regions, which often are most important biologically. These small-scale variations, which can be thought of as creating estuarine microenvironments, easily
confound attempts to generalize from measurements that do not integrate over larger scales.

This section describes the two mechanisms of lateral variability best resolved by tidal scale observations in the Washington estuaries: 1) direct solar heating of bank water, and 2) the creation of persistent lateral gradients by tidal advection. A full account of the transverse structure of these estuaries—which must consider competition and interaction between tidal currents, density-driven flows, rotational effects, and wind-driven circulations, all of which are shaped by bathymetry (e.g., Friedrichs et al. 1992, Valle-Levinson and O'Donnell 1996)—is beyond the scope of available data.

a. Solar heating

Coordinated longitudinal (along-channel) and transverse (bank-to-channel-to-bank) CTD transects were obtained in Willapa Bay and Grays Harbor during the summers of 1999 and 2000. These observations frequently suggest solar heating of water on shallow intertidal flats: either direct heating of the water at high tide, or transfer to the water of heat stored in the mud flats themselves from insolation at low tide. Consider, for example, a late-afternoon, early-flood transect along the main channel of Grays Harbor during a period of fair weather in June 1999 (Fig. 1.4). The warmest water in the channel is associated with neither the ocean nor the river end-member, but rather appears near the surface over a broad middle reach of the channel. CTD casts along this transect were separated by ~4 km, and therefore the spatial structure of this warm water may be patchier than contouring between casts allows. We interpret this signal as evidence of water warmed during the midday high tide that has circulated back into the main channel on the following ebb. A temperature-salinity (T-S) diagram of this transect (Fig. 1.4c) shows clearly that this signal represents warming of water at intermediate salinity, and effectively constitutes a third mixing endmember, toward which the T-S profile of the channel is inflected. Furthermore,
transverse, channel-to-shoal surveys on the day of the along-channel transect and over the next four days locate a similar warm water mass in depths < 5 m at higher stages of the tide (dots in Fig. 1.4c).

Surveys in Willapa Bay from June and July 2000 (Fig. 1.5) show similar results: warmest temperatures on banks in the interior of the estuary, inflection of the main-channel T-S profile that lifts intermediate water above the mixing line between the ocean and river end-members. The warmest points in the June 2000 survey, more than 4°C warmer than main-channel water of the same salinity, represent the shallowest water sampled, water < 0.5 m deep sampled by foot with a hand-held meter.

b. Differential tidal advection

Not all bank-to-channel hydrographic variations result from solar heating or other transformation of water properties. Consider the along- and cross-channel flood-tide transects from July 1999 in Willapa Bay shown in Fig. 1.6. The along-channel salinity gradient is ~5 psu over one tidal excursion (15 km); across a shallow, narrow bank adjacent to the main channel during late flood, the salinity gradient is ~ 4 psu over only 1.3 km. Huzzey (1988) likewise found that in the York River, which like Willapa consists of a deep central channel flanked by shoals, the freshest water in a cross-section at high slack water was located on the banks. A T-S diagram of the July 1999 transects (Fig. 1.6c) shows that the bank and channel water masses, unlike those shown in Figs. 1.4 and 1.5, are indistinguishable. The lateral variation in salinity and temperature thus must have arisen from advective rearrangement, not transformation, of main-channel water in the intertidal zone.

Since these strong gradients appear on intertidal banks that are submerged for only a few hours each tidal cycle, they must be the result of tidal-timescale processes and not tidal-residual ones. Indeed, large lateral gradients can arise solely from differential advection by tidal currents (Huzzey and Brubaker 1988, O'Donnell 1993);
i.e., the fact that on a shallow bank tidal motion is slowed by friction so that a given flood or ebb moves water parcels farther longitudinally in a channel than on an adjacent shoal. This shearing of the flow effectively transfers the along-channel gradient over one tidal excursion, or some fraction thereof, into a cross-channel gradient. In support of this explanation for the lateral variation seen in Willapa in July 1999, repeated channel-to-bank surveys in the same location have shown that the transverse gradient there at high water follows the along-channel variation. On November 1-2, 1999, for example, the along-channel salinity gradient in the central reach of the estuary was much weaker than that shown in Fig. 1.6, only ~ 0.5 psu over one tidal excursion (see Chapter II), and the salinity variation over the bank was likewise ~ 0.5 psu (not shown).

The differential-advective effect would be expected to be strongest on or at the edge of the shallowest banks (like that shown in Figure 1.6b) where the effect of friction is presumably greatest, and less important on deeper, subtidal shoals. Such lateral structure in tidal advection may have important local, biological consequences. For example, sessile organisms in a shallow region with strong lateral gradients may experience mean temperatures or rates of nutrient or food supply appreciably different—more like conditions a large fraction of a tidal excursion up-estuary—than organisms in deeper water a short distance away. At the same time, differential tidal advection may contribute to overall estuarine flushing if these lateral shears are a lateral-dispersion mechanism similar to the models of tidal trapping reviewed by Fischer (1976).

4. Summary

Comparative studies in Willapa Bay and Grays Harbor, in the context of the broader PNCERS dataset described by Hickey and Banas (2003), show that a broad range of scales of variation must be considered in any full oceanographic analysis of the estuaries on this coast. On the one hand, synoptic-scale atmospheric forcing and the
crucial role of a single mesoscale oceanic feature, the Columbia River plume, establish coherent patterns of variability on the scale of 100-500 km. At the same time, variations in morphology and circulation over ~100 km play an important role in shaping water properties and microenvironments within these estuaries. Against this background, in Chapters II-IV we turn our attention more systematically to a single case study, Willapa Bay.
Table 1.1. Indices of morphology, tidal forcing, and river input for the four PNCERS estuaries and seven others on the U.S. East and West Coasts.

<table>
<thead>
<tr>
<th></th>
<th>Grays Harbora</th>
<th>Willapa Baya</th>
<th>Yaquina Baya</th>
<th>Coos Baya</th>
<th>Columbia Rivera</th>
<th>San Francisco Baya</th>
<th>South S.F. Bayb</th>
<th>Plum I. Soundc</th>
<th>Naragansett Baya</th>
<th>Chesapeake Baya</th>
<th>James Rivera</th>
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<tbody>
<tr>
<td>area at MSL ( A_{MSL} ) (km²)</td>
<td>150</td>
<td>240</td>
<td>13</td>
<td>34</td>
<td>550</td>
<td>1170</td>
<td>480</td>
<td>7.2–15</td>
<td>430</td>
<td>9900</td>
<td>610</td>
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<tr>
<td>mean depth ( H ) (m)</td>
<td>4.3</td>
<td>3.2</td>
<td>2.6</td>
<td>4.0</td>
<td>7.3</td>
<td>6.8</td>
<td>4.4</td>
<td>2.3</td>
<td>10</td>
<td>8.5</td>
<td>5.2</td>
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<tr>
<td>volume below MSL ( V = H \cdot A_{MSL} ) (km³)</td>
<td>0.64</td>
<td>0.76</td>
<td>0.034</td>
<td>0.14</td>
<td>4.0</td>
<td>8.0</td>
<td>2.1</td>
<td>~0.016</td>
<td>4.3</td>
<td>84</td>
<td>3.2</td>
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<tr>
<td>mean tidal range at mouth (m)</td>
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<td>1.9</td>
<td>1.8</td>
<td>1.7</td>
<td>1.7</td>
<td>1.3</td>
<td>1.4</td>
<td>2.6</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
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<tr>
<td>intertidal area (% area at MHW)</td>
<td>—</td>
<td>55d</td>
<td>47e</td>
<td>47e</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>tidal prism volume (% volume at MHW)</td>
<td>46</td>
<td>50</td>
<td>52</td>
<td>31</td>
<td>14</td>
<td>16a–27b</td>
<td>37</td>
<td>~50</td>
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<td>8.6</td>
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<tr>
<td>drainage area (1000 km²)</td>
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<td>2.9</td>
<td>0.66</td>
<td>1.5</td>
<td>670</td>
<td>120</td>
<td>—</td>
<td>0.58</td>
<td>4.6</td>
<td>180</td>
<td>26</td>
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<tr>
<td>monthly-mean riverflow ( R ) (m³ s⁻¹)</td>
<td>56</td>
<td>17</td>
<td>~0</td>
<td>2.8</td>
<td>4200</td>
<td>330</td>
<td>—</td>
<td>~0</td>
<td>34</td>
<td>950</td>
<td>150</td>
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<td>lowest mo. flow</td>
<td>880</td>
<td>390</td>
<td>68</td>
<td>190</td>
<td>10000</td>
<td>1800</td>
<td>—</td>
<td>10</td>
<td>170</td>
<td>4200</td>
<td>600</td>
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<tr>
<td>highest mo. flow</td>
<td>100</td>
<td>500</td>
<td>long</td>
<td>600</td>
<td>300</td>
<td>—</td>
<td>long</td>
<td>2000</td>
<td>1000</td>
<td>2000</td>
<td>200</td>
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<tr>
<td>river-filling time ( V/R ) (d)</td>
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<td>20</td>
<td>6</td>
<td>8</td>
<td>50</td>
<td>—</td>
<td>20</td>
<td>300</td>
<td>200</td>
<td>60</td>
<td>—</td>
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\( ^a \)NOAA 1985; \( ^b \)Malamud-Roam 2000; \( ^c \)Jay et al. 1997; \( ^d \)Andrews 1965; \( ^e \)Percy et al. 1974.
Figure 1.1. (a) Map of the Pacific Northwest coast from Washington to Northern California, showing the location of the four PNCERS estuaries and other major estuaries in the region. (b,c) Maps of Grays Harbor, Willapa Bay, and Coos Bay, with the locations of estuarine and offshore moorings marked.
Figure 1.2. (a) Time series of the north-south component of nearshore wind from late winter to early summer 2000. Data are from the National Data Buoy Center, Columbia Bar buoy B46029; gaps have been filled with a regression to the Newport buoy. The times of the two CTD transects of Willapa Bay shown in Fig. 1.3 are indicated. (b) Salinity and (c) the local along-channel salinity gradient near the mouths of Willapa Bay and Grays Harbor during a three-week period Apr-May 2000, showing a brief upwelling event, an intrusion of the Columbia River plume, and a recovery from that intrusion. In (b), both 30-min and subtidal (48-hr-Butterworth-filtered) data are shown. Dots mark times of high slack water in Willapa Bay. In (c), the difference between high-slag and low-slag salinity divided by the tidal excursion for each semidiurnal tidal cycle has been filtered as above to provide a subtidal, single-station time series of the along-channel salinity gradient.
Figure 1.3. Salinity from CTD transects along the main channel of Willapa Bay on (a) May 3, 2000, near the end of a Columbia River plume intrusion, and (b) May 30, 2000, during the early part of a strong upwelling event that replaces plume water (~21.5 psu) with much saltier water (≥ 29 psu). A reversal of the along-channel salinity gradient is marked in (a). Triangles at the top of the salinity sections give the location of CTD casts. Tidal stage and transect route are also given for each section. These surveys are situated within a five-month wind time series in Fig. 1.2.
Figure 1.4. (a,b) Temperature and salinity from a CTD transect along the main channel of Grays Harbor Jun 11, 1999 during a time of strong solar heating. Triangles at the top of the sections give the location of CTD casts. (c) Temperature-salinity profile of the along-channel transect (lines) and CTD casts on shoals adjacent to the channel June 11-15 (dots). Location and tidal stage of bank and channel surveys are also shown.
Figure 1.5. Temperature-salinity diagrams for surveys of Willapa Bay during (a) June and (b) July 2000, showing the hydrographic signature of direct solar heating. Line segments represent CTD casts within the main channels of the estuary; dots represent water on banks in depths < 5 m.
Figure 1.6. Salinity from CTD transects on Jul 14, 1999 (a) along the main channel of Willapa Bay and (b) from the channel to shore across a shallow, narrow bank. Location and tidal stage are shown; triangles at the top of the sections give the location of CTD casts. The nearly identical temperature-salinity profiles of the two transects are shown in (c).