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A conceptual model of the strongly tidal Columbia River plume

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ABSTRACT

The Columbia River plume is typical of large-scale, high discharge, mid-latitude plumes. In the absence of strong upwelling winds, freshwater from the river executes a rightward turn and forms an anticyclonic bulge before moving north along the Washington coast. In addition to the above dynamics, however, the river plume outflow is subject to large tides, which modify the structure of the plume in the region near the river mouth. Observations based on data acquired during a summer 2005 cruise indicate that the plume consists of four distinct water masses; source water at the lift-off point, and the tidal, re-circulating and far-field plumes. In contrast to most plume models that describe the discharge of low-salinity estuary water into ambient high-salinity coastal water, we describe the Columbia plume as the superposition of these four plume types. We focus primarily on a conceptual summary of the dynamics and mutual interaction of the tidal and re-circulating plumes. The new tidal plume flows over top of the re-circulating plume and is typically bounded by strong fronts. Soon after the end of ebb tide, it covers roughly 50–100% of the re-circulating plume surface area. The fronts may penetrate well below the re-circulating plume water and eventually spawn internal waves that mix the re-circulating plume further. The re-circulating plume persists throughout the tidal cycle and corresponds to a freshwater volume equivalent to 3–4 days of river discharge. Finally, the plume water masses are distinguished from one another in term of surface chlorophyll concentration, suggesting that the above classification may also describe different biological growth regimes. The low-salinity re-circulating plume serves as an extension of the estuary into the coastal ocean, or an "estuary at sea", because residence times during periods of high river flow are greater than those in the estuary.

1. Introduction

The Northwest shelf of the United States is subject to moderately strong tidal forcing, with amplitudes of 2 to 4 m at the mouth of the Columbia River estuary. The tides, focused by a long estuary channel, cause reversing estuarine outflow velocities of 1 to 3 ms^{-1} and a pulsed discharge from the estuary to the shelf. While recent numerical model experiments do not report a significant change in the structure of the far-field plume when the river outflow is modulated on tidal timescales (Yankovsky et al., 2001), observations of the Columbia plume suggest that the region within approximately 50 km of the river mouth is complex, with characteristics that vary over relatively small spatial and temporal timescales as a result of this periodic forcing. Outgoing tidal pulses overrun existing plume water, generating intense fronts and extensive bands of internal waves that mix the new plume, old plume and ambient coastal water. The dynamics of this region determine the initial exchange of nutrients between the plume and ocean waters and set the stage for a highly productive coastal ecosystem.

River plume fronts have been the subject of a number of observational and analytical studies (Garvine and Monk, 1974; Garvine, 1974; O'Donnell et al., 1998; Orton and Jay, 2005). The front is defined as the narrow region on the water surface where the density changes rapidly, forming a boundary between the outward propagating lens of buoyant water and the ambient receiving water (Garvine and Monk, 1974; Garvine, 1974). Propagation perpendicular to the front leads to convergence at the front and forces ambient water and buoyant water downwards (O'Donnell et al., 1998). Pritchard and Huntley (2006) compare the interfacial mixing at a plume front with the total buoyancy input from the estuary to determine the conditions leading to plume formation and destruction. For the small-scale River plume in the English Channel, the buoyancy flux from the estuary initially exceeds frontal mixing, which is the dominant mixing mechanism in the absence of strong winds. Over the course of the tidal cycle, frontal mixing surpasses the buoyancy flux and eventually disperses the plume. In large-scale plume and oceanic fronts, the outward propagation of the front is limited by the earth's rotation (Garvine, 1979a,b). The scale of these fronts is characterized by the baroclinic Rossby radius, and they develop strong front-parallel shear.

The role of tides in the dynamics of coastal plumes has been the subject of several numerical model studies. Chao (1990) showed that

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tidal modulation contributes a subtidal vortex dipole, akin to that described by Zimmerman (1981), to the existing outflow circulation, which slightly increases the cross-shore expansion of the plume in the region near the mouth and decreases the alongshore penetration of the coastal current. In a more recent numerical model study, Yankovsky et al. (2001) reported very little difference between the structure of a plume subjected to semidiurnal tidal fluctuations and that of a non-tidal plume. Due to numerical model constraints, neither study captures changes in the small-scale dynamics or mixing of the plume that may result from tidal fluctuations. As noted above, these are likely to be important in determining how the plume affects the local coastal ecosystem.

In this work we develop a conceptual model that describes the plume water masses in the region near the river mouth. We initially ignore the effect of wind stress in order to examine the more basic plume dynamics. The effect of wind is discussed as an extension of the conceptual model and a more thorough description is presented in a companion paper Jay et al. (this volume), referred to as DJ. We outline the conceptual model in terms of scales that define the different components of the plume. We then present results from observations of the Columbia plume during a low-wind period in 2005, when the components of the plume can be differentiated. Finally, we synthesize the results to suggest the role that the tidal plume front plays as the components of the plume interact, and the ecological importance of the re-circulating plume as an extension of the estuary into the coastal ocean.

2. Conceptual model

2.1. Physical setting

The Columbia River flows into the Pacific Ocean near Astoria, Oregon on the border between Oregon and Washington states (Figs. 1 and 2). It is among the four largest rivers entering the ocean in the United States with an annual mean discharge of approximately 7300 m^3s^{-1} (Barnes et al., 1972; Hickey et al., 1998). The tidal range in the vicinity of the mouth is large and the main estuary channels are relatively narrow (1–2 km), resulting in a salinity intrusion that propagates 5 to 50 km upstream from the mouth. The river mouth is 3 km wide and oriented towards the south west. As a result of complex bathymetry in the estuary channel near the mouth, the estuarine outflow discharges approximately due west during maximum ebb. The shelf off of Oregon and Washington slopes steeply away from the coast, resulting in a plume that detaches from the bottom close to the river mouth. Garvine (1995) developed a classification for river plumes based on the observed plume scales. Plumes with high Kelvin number, defined as $K=fW_p(g_p'H_p)^{-1/2}$, are considered to be large scale plumes and are characterized by linear dynamics and a cross-shore geostrophic balance. Here W_p, g_p', and H_p are representative scales for the plume width, reduced gravity and depth. For the Columbia, $W_p=20$ km, $H_p=10$ m and $g_p'=0.1$ m s^{-1}, and thus K = 2. This is a relatively large value of K, according to the Garvine (1995) classification, and suggests that the Columbia be considered a large-scale plume. Such a classification is consistent with regional scale field studies of the plume (Hickey et al., 1998).

In a relatively large region near the mouth, however, high river discharge and large tidal amplitude result in strongly non-linear dynamics. Based on the average annual flow, river width W = 3 km, an approximate layer depth of H = 5 m and reduced gravity $g'=\Delta\rho\rho_o^{-1}=0.21$ m s^{-2}, the internal Froude number of the outflow is $Fr=U(g'H)^{-1/2}=0.5$, where $U=0.5$ m s^{-1} is the mean outflow velocity, $\Delta\rho$ is the density anomaly and ρ_o is the reference density. The inflow Rossby number for the same parameters is $Ro=U(fW)^{-1}=1.6$, where f is the Coriolis frequency. During peak ebb, the estuary discharge may be more than four times the river discharge and the outflow velocity exceeds 3 m s^{-1}. Under these conditions, Fr = 2.0 and Ro = 6.4. These values suggest a jet-like outflow that is dominated by the momentum of the river close to the mouth; the Coriolis force only becomes important once the plume has expanded and slowed away from the mouth. The supercritical Fr implies that the outflow will develop strong, convergent density fronts in the region offshore from the river mouth. These dynamics are more commonly associated with small-scale river plumes such as the Connecticut or Teign rivers (Garvine, 1995; O'Donnell et al., 1998; Pritchard and Huntley, 2006). In small-scale plumes, however, the river discharge is much smaller than that of the Columbia and their impact on the coastal hydrography is correspondingly smaller. In addition, the new plume that is discharged with each ebb generally propagates into high salinity coastal water and is significantly dissipated by the time of the following ebb. As demonstrated in the current work, this is often not the case for the Columbia plume. The combination of a high-discharge, large-scale plume with a supercritical tidal plume leads to complex dynamics. The aim of the present conceptual model is to describe the plume in terms of its components so that the dynamics can be better understood.

2.2. Plume anatomy

We propose a conceptual model, in which the Columbia plume is described in terms of four water masses: source water, the tidal plume, the re-circulating plume and the far-field plume. A cartoon of the four water masses for the low-wind case is shown in Fig. 3a. Water originating in the river moves sequentially through the source zone, which is close to the river mouth, and then into the tidal plume as it is discharged onto the shelf. Depending on wind conditions, it may be retained in the re-circulating plume before it becomes far-field plume water and is subsequently mixed into the ambient shelf water. Although these water masses are associated with different physical regions of the plume (Fig. 3a), they are also differentiated in terms of their respective time scales and salinity due to the large variability in the plume structure. It is natural to define the plume components based on salinity bounds since they correspond roughly to progressive stages in the mixing of river water into the ocean. However, the salinity thresholds that differentiate between different plume components will vary depending on the intensity of mixing processes, which are modified by tides, winds and river discharge. For example, the salinities that characterize the tidal plume will likely be lower during a neap tide in high discharge conditions than during a spring tide in low discharge conditions due to the high vertical density stratification and relatively lower energy available for mixing in the former case. In the following description of the plume components a salinity range is proposed for each that corresponds to the conditions observed during surveys in the first week of June 2005. They are representative of moderately high discharge conditions close to the spring tide and are justified in more detail in Section 4.1. Analysis of how different conditions modify the salinity range is left for future work.

The two remote sensing images of the plume shown in Fig. 2a and b illustrate different components of the plume structure in low-wind conditions. In the SAR image (Fig. 2a) lighter shading corresponds to high backscatter, indicating regions of enhanced surface roughness (Hessner et al., 2001). In the Columbia plume, bands of high SAR backscatter occur in association with strong fronts and internal waves. The image is taken 10.5 h after high tide on June 3, 2005 and shows the semi-circular tidal plume front, which is roughly symmetric about the river mouth. At the time of the image, the front extends approximately 36 km from the river mouth. It is strong to the north of the mouth and has dissipated south of the mouth. A series of solitons have been released from the western edge of the front; these are released earlier on the south than the north based on the spacing between the waves (DJ).

In the MODIS image from May 16, 2006 (Fig. 2b), lighter colored pixels correspond to greater concentrations of suspended matter near the water surface. This image shows the rough delineation of the complete plume. Near the river mouth, water discharged from the