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Hydrographic and dissolved oxygen variability in a seasonal Pacific Northwest estuary

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A R T I C L E I N F O

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A B S T R A C T

Hypoxia is an issue of growing concern for coastal communities. In the California Current System, a prototypical eastern boundary current, attention has been focused on explaining the trend of increasing shelf hypoxia. Despite the regional focus on hypoxia in eastern boundary regions, relatively few studies have examined smaller estuarine systems. Here, we present results from an observational study in Coos Bay, a small estuary on the southern Oregon coast, subject to seasonal upwelling/downwelling winds, strong tides, and wide fluctuations in freshwater input. Coos Bay exhibits characteristics of a salt-wedge type estuary under high river discharge conditions (>150 $m^3 s^{-1}$), a well-mixed estuary under low discharge conditions (0–30 $m^3 s^{-1}$), and partially-mixed estuary during times of moderate discharge (30–150 $m^3 s^{-1}$). The observed vertical stratification and along-estuary salinity gradients correlate significantly with river discharge and tidal forcing. Despite a strong coupling with coastal waters where hypoxia has been present, we do not find evidence for pervasive hypoxia in Coos Bay. We find that upwelling on the shelf advects low dissolved oxygen water into the estuary on synoptic timescales. Early in the upwelling season (April and May), dissolved oxygen minima are found at the estuary mouth, while later in the summer (September), dissolved oxygen minima are found at the riverine end, presumably due to decreased discharge and increased productivity. However, in a given year, the overall strength of the upwelling season is not a good predictor of low dissolved oxygen levels in the estuary.

1. Introduction

In the past decade, there has been growing concern about the increase in hypoxia on the mid- and inner continental shelf of the California Current System (CCS) (Grantham et al., 2004; Bograd et al., 2008; Chan et al., 2008; Connolly et al., 2010). Hypoxia occurs when waters become undersaturated in dissolved oxygen (DO), causing organisms to suffer adverse and potentially lethal effects (Rabalais et al., 2010). Depending on the effects and the organisms being assessed, thresholds for hypoxia vary widely in the literature (Vaquer-Sunyer and Duarte, 2008; Rabalais et al., 2010). For example, 6.5 mg O_2 L^{-1} is a threshold for oxygen stress in cool water fish (e.g., salmonids) commonly used by regulatory agencies (Brown and Nelson, 2015). For hypoxia, a threshold of 2 mg O_2 L^{-1} is frequently cited, which is what we will use here in defining hypoxic waters.

In the CCS during the summer, equatorward winds drive upwelling of deep, nutrient-rich and oxygen-poor waters onto the outer shelf (Huyer, 1983). Coupled physical and biological processes regulate the DO concentrations of these waters (Monteiro et al., 2006; Bograd et al., 2008; Adams et al., 2013). While outer shelf hypoxia is natural, the recent development of mid- and inner shelf hypoxia is linked to changes in basin-scale atmospheric and oceanic processes that have led to decreases in the oxygen content of upwelled water (Bograd et al., 2008; Chan et al., 2008; Pierce et al., 2012; Peterson et al., 2013), an increase in upwelling-favorable wind stress (Bakun, 1990; Snyder et al., 2003), and productivity-driven increases in respiration (Thomas et al., 2003; Grantham et al., 2004). Understanding changes in the conditions of CCS waters has wide implications for other eastern boundary current systems around the world that experience similar dynamics (Epifanio et al., 1983; Chavez and Messié, 2009).

Despite the overall increase in hypoxic area in the CCS, there is significant along-coast variability in the observed incidence of hypoxia (Peterson et al., 2013). On a regional scale, this spatial variability is attributed to wider shelf regions facilitating longer residence times and more organic matter input, thus elevating the

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potential for the development of hypoxia (Barth et al., 2007; Peterson et al., 2013). Distinct from this regional shelf-scale variability, a latitudinal gradient exists along the CCS, with O'Higgins and Rumrill (2008) reporting that warmer water estuaries in the southern portion of the CCS (e.g., Elkhorn Slough or the Tijuana River) experience lower DO levels, i.e. more oxygen stress, a higher percentage of the time compared to their northerly counterparts (e.g., South Slough or Padilla Bay).

Considerable attention has been directed towards understanding the drivers of spatiotemporal variability in hypoxia on the shelf (Connolly et al., 2010; Pierce et al., 2012; Adams et al., 2013; Peterson et al., 2013) and in larger estuarine environments like the Columbia River (Roegner et al., 2011) and Hood Canal (Newton et al., 2007) on the US West Coast or the Gulf of Mexico (Rabalais et al., 2002) and Chesapeake Bay (Hagy et al., 2004; Scully, 2013) on the US East Coast. In the Columbia River estuary, low-DO waters entered the estuary on flood tides after upwelling wind events, associated with the advection of higher salinity, nutrient rich oceanic water into the estuary (Roegner et al., 2011). A similar correlation of upwelling winds and low-DO was found in the South Slough, a small arm of the Coos Bay estuary in southern Oregon, although in that case, the evidence suggested that it was high respiration following increased productivity fueled by the nutrient input that caused the DO decrease (O'Higgins and Rumrill, 2008). In general, though, much less attention has been given to the vulnerability of smaller coastal estuarine environments in the CCS (Roegner et al., 2002; O'Higgins and Rumrill, 2008; Brown and Power, 2011).

Given the observed along coast variability in DO levels, one might ask which estuaries are most susceptible to direct intrusions of low-DO water from the shelf versus local drawdown of DO driven by nutrient input and the increased productivity and respiration that follows. At a specific location inside an estuary, both processes are likely to occur at different temporal and spatial scales, depending on the time of year, tidal stage, variations in wind and river forcing, and water depth.

Here, we focus on understanding what drives DO variability in Coos Bay, a relatively small estuary on the southern Oregon coast, which is subject to the highly seasonal conditions common throughout the coastal Pacific Northwest. Since no seasonal description of the water properties along the Coos Bay estuary exists, we first focus on identifying the dominant dynamics through a monthly along-estuary hydrographic surveying program coupled with several longer-term time series of water properties. We next investigate variations in DO levels and compare them with the observed hydrography over various timescales, including the seasonal, interannual, tidal, and synoptic (weather-driven) range. Finally, we compare our dataset to a historic DO dataset that extends back to the late 1950s in Coos Bay.

2. Study location

The Coos Bay estuary is mesotidal with mixed semidiurnal tides ranging from 2.3 m at the mouth to 2.2 m at the city of Coos Bay (Rumrill, 2006). It is located south of Heceta Bank, adjacent to a relatively narrow continental shelf (Fig. 1). High sedimentation rates and tidal fluctuations result in large intertidal areas that make up approximately half of the estuary's 54 km^2 surface area (Hickey and Banas, 2003; Rumrill, 2006). These extensive flats, in conjunction with a deep, dredged navigation channel, produce an ebb-dominant system where flood tides are dampened by friction with the flats and ebb tides rush out the channel (Hyde, 2007). Tidal currents average 1 m s^{-1} with maximum-recorded currents at 1.7 m s^{-1} (Baptista, 1989). Based on these tidal speeds, a mean tidal excursion is 14 km, about half the distance from the mouth to the Coos River opening (Fig. 1). However, compared to other small PNW estuaries, such as Yaquina Bay, Willapa Bay, and Grays Harbor, where the tidal prism is ~50% of the estuarine volume, the tidal prism in Coos Bay is only ~30%, suggesting that both tidal and exchange processes might be important to estuarine circulation (Hickey and Banas, 2003).

The estuary has one opening to the Pacific Ocean at its southern end, near the town of Charleston (Fig. 1). The Coos River is the primary source of freshwater input to the system. The majority of previous work has focused on the South Slough, the smaller southern arm (Rumrill, 2006; O'Higgins and Rumrill, 2008) and the site of the South Slough National Estuarine Research Reserve (SSNERR).

3. Data and methods

3.1. Monthly CTD transects

To describe the seasonal changes in hydrography and DO levels along the estuary, we conducted monthly sampling over a roughly two-year period. During each sampling cruise we obtained along-channel hydrographic sections of salinity and temperature using a conductivity/temperature/depth (CTD) sensor. CTD profiles were collected from a 20-foot aluminum boat, the *R/V Pugettia*, of the Oregon Institute of Marine Biology (OIMB). Data used in this study span sampling cruises starting in Nov-2012 and continuing though Jul-2014 (Table 1). We targeted flood tide and high water times in order to sample the expected maximum extent of the salt intrusion into the estuary. Only 2 of the 25 sections were taken on ebb tides (Fig. S1). On three cruise dates, we occupied an along-estuary transect from the mouth to the up-estuary end and then back to the mouth (Table 1), allowing us to examine the influence of tidal stage on the observed hydrographic and DO transects. A single transect took on average 1.5 h to sample with a mean station spacing of 1.5 km (Table 1).

For the majority of the fieldwork we used a RBR Titanium XR-620 profiling CTD with three cable-mounted sensors (Rinko DO, Seapoint Turbidity and Seapoint Fluorometer). The instrument was factory calibrated each year. We sampled at 6 Hz and use downcast data pressure averaged into 1 dbar bins. On a few occasions, a different sensor set up was used (Table 1), including a SeaBird 19plus CTD, and a RBR Concerto CTD with DO (bulkhead-mounted Oxyguard). The SeaBird lacked a DO sensor, so for these cruises no DO data were collected along estuary. For gridding and visualization purposes, we created distance versus depth sections of T, salinity (S), and DO, by linearly interpolating between stations and in depth.

3.2. Water quality loggers

The monthly sampling cruises are adequate to resolve large seasonal differences in water properties, but do not give sufficient temporal resolution to resolve tidally-driven variability or synoptic, weather-driven variability. To put our monthly cruises in context, we obtained records from three YSI model 6600 data loggers that measured temperature, salinity, DO, turbidity, and pH. These loggers were deployed 0.5 m off the bottom at 3.1, 6.9, and 8.4 km from the mouth and provide time-series of water quality along the estuary (Fig. 1). Two of the loggers are maintained by the Confederated Tribes of the Coos, Lower Umpqua, and Siuslaw (CTCLUSI) water quality-monitoring program, which has been sampling continuously since Oct-2011. One is located at the Empire Docks at 43.3942°N, 124.2804°W (EMP; $x = 6.9$ km) in water depth of 6 m, while the other is at the Bureau of Land Management boat ramp at 43.4139°N, 124.2789°W (BLM; $x = 8.1$ km) on the North Spit of Coos