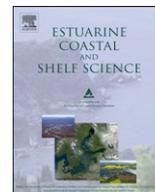




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Historic and recent patterns of dissolved oxygen in the Yaquina Estuary (Oregon, USA): Importance of anthropogenic activities and oceanic conditions

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ABSTRACT

Spatial and temporal patterns of dissolved oxygen (DO) in Yaquina Estuary, Oregon (USA) are examined using historic and recent data. There was a significant increasing trend in DO in the upstream portion of the estuary during the years 1960–1985. Historically, minimum dry season (May–October) DO levels occurred about 20 km from the estuary mouth at warm water temperatures, near both point source discharges and where extensive log rafting occurred. Presently, there is a trend of increasing dry season DO with increasing distance from the mouth of the estuary. Minimum DO levels occur at cool water temperatures (~8 deg C), suggesting that recently upwelled oceanic water from the shelf is the source of the low DO water. Recent time-series data (2001–2007) demonstrates that the water advected into the estuary from the coastal ocean has DO levels < 5 mg l⁻¹ about 13% of the time during the dry season and that water temperature is a good indicator of the oceanic source. Similarity in the flood-tide DO and water temperature relationship between recent time-series data in Yaquina and in historic data from other estuaries suggests that the hypoxic conditions observed off the Oregon coast since 2002 may have occurred previously, especially during the 1950's–1960's. It is important to characterize the natural background DO levels for estuaries in the region to be able to separate anthropogenic from natural influences on DO.

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1. Introduction

Dissolved oxygen levels within estuaries result from the interaction of numerous physical and biological factors, including stratification, water column and benthic oxygen demands, and photosynthesis. There can be significant input of oceanic nutrients and phytoplankton into estuaries bordering coastal upwelling regions, such as the west coast of the United States (De Angelis and Gordon, 1985; Roegner and Shanks, 2001; Roegner et al., 2002; Colbert and McManus, 2003; Brown and Ozretich, 2009). Recently, there have been occurrences of severe hypoxia on the inner continental shelf of Oregon (Grantham et al., 2004; Chan et al., 2008), and this low DO water may be advected into adjacent estuaries. Coastal upwelling has also been linked to recurrent hypoxia on the inner shelf in other regions (Glenn et al., 2004).

Dissolved oxygen (DO) is an important water quality metric because of its effects on the well-being of resident and transitory estuarine organisms. Hypoxia is commonly defined as occurring when the DO levels fall below 2 mg l⁻¹; however, biological stress for

organisms has been documented at DO levels between 2 and 5 mg l⁻¹ (Diaz and Rosenberg, 1995; U.S. EPA, 2000). A more recent review of oxygen thresholds for biota found that the conventional definition of hypoxia (2 mg l⁻¹) may be inadequate to conserve biodiversity in coastal ecosystems (Vaquer-Sunyer and Duarte, 2008).

This paper assesses whether there have been long-term changes in DO levels in the Yaquina Estuary, Oregon (USA) and the effect of ocean conditions on DO levels within that estuary. In addition, it compares recent DO levels in the Yaquina Estuary to historical data from other estuaries in the region and the inner Oregon shelf to evaluate whether the hypoxia recently observed on the inner shelf has previously occurred.

2. Study area

Yaquina Estuary is a small, drowned, river valley estuary located along the central Oregon coast (44.62°N, 124.02° W) of the United States (Fig. 1), with surface and watershed areas of 19 and 650 km², respectively. Tides are mixed semidiurnal, with a mean range of 1.9 m and a tidal prism volume of 2.4 × 10⁷ m³ (Shirzad et al., 1988). Approximately 70% of the volume of the estuary is exchanged with the coastal ocean during each tidal cycle (Karentz and McIntire, 1977) and approximately 48% of the estuarine area is intertidal.

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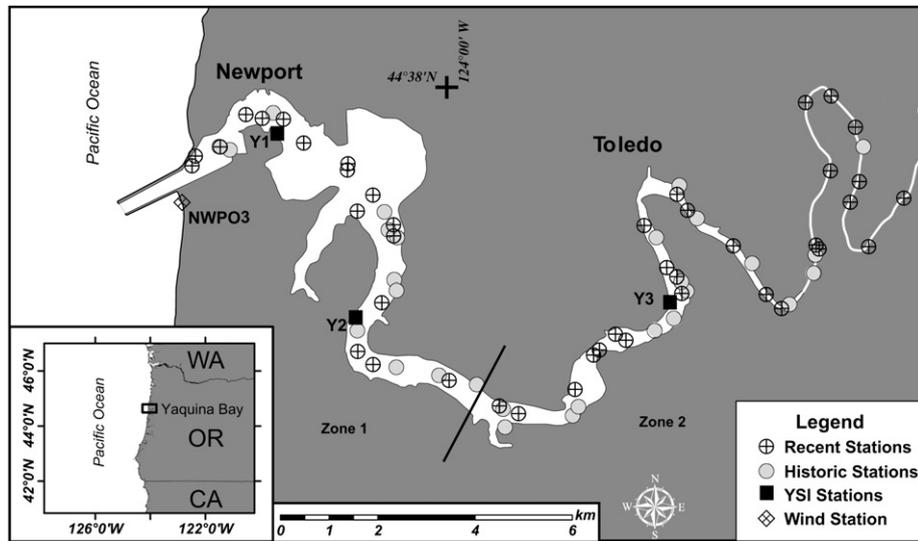


Fig. 1. Location Map showing recent and historic discrete estuarine sampling stations, locations of instruments for continuous data (Y1 - Y3) and Station NWP03 (wind data).

Rainfall is high during November to April, and the estuary is river dominated. Rainfall and riverflow decline during May to October and the estuary switches to marine dominance. The estuary is well mixed under low flow conditions, and partially- to well-mixed during high flow conditions (Burt and McAlister, 1959; Kulm and Byrne, 1966). The flushing time of the estuary during the dry season varies from 1 d near the mouth to 9 d in the upstream portions. Salt penetrates about 35 km into the estuary during periods of minimal freshwater inflow. Seasonal wind-driven upwelling advects relatively cool, nutrient rich (NO_3 and PO_4) water to the nearshore zone of the coastal ocean (Hickey and Banas, 2003) from April–September, and this water is subsequently advected into the Yaquina Estuary with the incoming tide (Brown and Ozretich, 2009).

The Yaquina watershed is approximately 70% forested, 20% grasslands and shrub/scrub, 7.0% developed, and 3% wetlands (Brown et al., 2007). The developed land is primarily developed open space with only about 1% as low-high density development. Population density is low ($12.3 \text{ persons km}^{-2}$), similar to other PNW watersheds and much lower than the national average for coastal regions (mean = $116 \text{ persons per km}^2$; Crossett et al., 2004). The Yaquina watershed and estuary has been impacted by logging practices with large scale rafting of logs occurring in the Yaquina Estuary from the 1920's to the 1980's (Sedell and Duval, 1985). Log rafts alter flow regimes, and accumulation of wood and bark debris smother benthos and result in low dissolved oxygen (Sedell et al., 1991). In the 1930's, concerns were raised regarding sawdust and timber waste pollution (The Morning Oregonian, 1930) and the discharge of untreated sewage (Fasten, 1931). Historically, untreated sewage was discharged from the towns of Newport and Toledo into the Yaquina Estuary until the 1950's. A combined sewage discharge with a pump station was constructed for Newport in the mid-1950s, which eliminated the direct discharge of sewage from Newport into Yaquina Estuary (Brown et al., 2007). By the 1960's, the water quality in the lower portion of the Yaquina basin had been negatively affected by waste discharges (Federal Water Pollution Control Administration, 1966). A municipal sewage system with primary treatment and an offshore discharge was constructed in Newport in 1964, which has since been upgraded to secondary treatment. A combined stormwater/sewage system that discharged raw sewage into the Yaquina River was constructed in Toledo in 1926, and this system was upgraded to

primary treatment in 1954, and secondary treatment in 1981 (Brown et al., 2007). This facility discharges into the Yaquina Estuary at a location about 22 km from the mouth of the estuary).

3. Methods

3.1. Recent data

The recent data from the Yaquina Estuary consisted of discrete observations from cruises and continuous data from multiparameter datasondes. Details on the recent discrete measurements are presented in Table 1. Discrete measurements were collected using calibrated YSI 6600 multiparameter sondes (YSI, Yellow Springs, Ohio). During 2002–2007, time-series data (temperature, salinity and DO) were collected every 15-min at Stations Y1–Y3, in the Yaquina Estuary using YSI 6600 multiparameter water quality monitoring sondes (Fig. 1). Beginning in 2004, in situ fluorescence was also measured. The sondes at Y1 and Y2 were deployed at a fixed elevation at an average depth of about 2 m and 4 m, respectively, below the water surface. At Station Y3, the sonde was deployed on a float dock at a fixed depth of 1 m below the water surface. Sondes were typically deployed for 2 weeks to 1 month, after which they were exchanged for a newly calibrated sonde. The sondes were calibrated before deployment using the manufacturer's recommendations. In situ fluorescence was calibrated with a two-point calibration, using reverse osmosis water and a rhodamine WT solution with readings reported as $\mu\text{g l}^{-1}$. The DO sensor was calibrated using the saturated air-in-water method. Several techniques were used to identify time periods of significant fouling of the sensors. These techniques included post-deployment checks, comparison of adjacent stations, comparison to independent discrete measurements, and comparison of the last reading of a deployment to the first reading of a newly deployed sonde. Data were excluded from analyses if they showed evidence of biofouling or drift. If there was evidence of fouling or drift in the data from Station Y1, data from a second near-surface surface sonde were substituted, if available. To examine the variability in DO, chlorophyll *a*, and water temperature associated with ocean conditions, flood-tide values were extracted from the 15-min data. Flood-tide values were identified using the maximum salinity values that occurred close to the time of predicted high tides. We also deployed sondes near the mouths of Coos, Siletz, Tillamook, and Umpqua

Table 1
Summary of sampling details for recent discrete dissolved oxygen sampling. The location of the sampling stations is presented as distance from the mouth of the estuary.

Year	Location of stations (km)	Sampling dates	Tidal stage	Depth	Source
2004	18 and 26	April 26, 29; May 4, 7, 10, 12, 18, 21, 24, 28; June 1, 3, 7, 15, 19, 24, 28; July 2, 9, 12, 14, 19, 21, 26, 28; Aug 2, 4, 27, 20; Sept 2, 3, 14, 17, 20, 24, 30	Random	S	EPA
2006	4, 10, 13, 16, 19, 22, 26, 28, 30, 32, 34, and 35	Feb 9; March 14; Apr 11; May 25; June 8; July 10; Aug 7; Sep 26; Oct 18; Nov 30; Dec 20, 28	Sampling began at high tide near mouth, and proceeded upriver during an ebbing tide.	S, M, B	EPA
2007	2, 4, 5, 7, 8, 10, 12, 13, 15, 16, 18, 20, 21, 23, 25, 26, 28, 29, 31, and 33	June 8, 21; July 7; Aug 28 ^a ; Sept 25; Oct 23	Sampling began at high tide near mouth, and proceeded upriver during an ebbing tide.	S, M, B	EPA
2007	1, 3, 5, and 7	May 14, 23, 31; June 7, 13, 19, 26; July 2, 10, 19, 24; Aug 7, 15, 22, 28; Sep 18, 28; Oct 10, 25,	Sampling alternated between being centered on high and low tides; on each sampling date, sampled 2–4 h before slack, at low or high tide, and 2–4 h after slack	B	Oregon Department of Fish and Wildlife

^a Note due to an instrument malfunction only 6 stations sampled on 8/28/07.

estuaries during the summers of 2005 and 2008. Length of deployments at these locations varied from 2 to 7 days and the same calibration procedure described above was used for these deployments.

3.2. Historic data

Sources of historic dissolved oxygen data (1960–1985) for the Yaquina Estuary included the Oregon Department of Environmental Quality (DEQ; (<http://deq12.deq.state.or.us/lasar2/>)) and De Ben et al. (1990). De Ben et al. (1990) sampled 10 locations in the estuary every 2 weeks from March 1967 through November 1968. At each site, a water sample was collected, which was analyzed for dissolved oxygen using Winkler titration method. The locations of stations sampled within these historic data sets extended from the estuary mouth to the tidal fresh region. The estuary narrows about 25 km from the mouth, beyond which there was limited data (Fig. 1). Historic data for other Oregon estuaries were also obtained from DEQ.

3.3. Other data used in data analysis

Hourly wind speed and direction data were obtained from a nearshore station adjacent to Yaquina Bay (NWP03) as well as at a station 36 km offshore of Yaquina Bay (46050) operated by the National Data Buoy Center (NDBC; (<http://www.ndbc.noaa.gov>)). Alongshore wind stress was computed using the method of Large and Pond (1981) with a negative wind stress indicating upwelling favorable wind stress from the north. The integrated alongshore wind stress (W_k) was calculated as a weighted running mean of the wind stress which weights the past alongshore wind stress with a decaying exponential function (Austin and Barth, 2002). The integrated alongshore wind stress at time (T) is defined as

$$W_k(T) = \int_0^T \frac{\tau_y}{\rho} e^{-(t-T)/k} dt \quad (1)$$

where τ_y is the alongshore wind stress at time t , ρ is seawater density and k is an exponential decay coefficient. The exponential decay coefficient was varied over the range of 0–7 days, strongest correlations were found between W_k and DO at Y1 set to $k = 2$ days.

Inner shelf water temperature data were obtained from Station Seal Rock 15 m (SR15; Latitude 44.50° North, 124.10° West

Longitude, (<http://www.piscoweb.org>) located 12 km south of Yaquina Bay at the 15-m depth contour with sensor at 9 m depth. Historic DO, temperature and salinity data were obtained from the World Ocean Database 2005 (http://www.nodc.noaa.gov/OC5/WOD05/pr_wod05.html) for the interval of 1950–1970 inshore of the 100 m depth contour, between Latitude 42° and 48° N. Dissolved oxygen data reported in units of ml l^{-1} were converted to mg l^{-1} by multiplying by 1.4275. The minimum DO values were extracted from each shelf profile (typically occurring at the bottom) along with corresponding depth, temperature and salinity.

3.4. Analysis

To analyze Yaquina Estuary DO trends we parsed the discrete DO data into zones and seasons so as to minimize biases associated with differences in sampling (temporal or spatial). The estuary was divided into ocean- (Zone 1) and watershed-dominated (Zone 2) zones (Fig. 1, based on Brown et al., 2007). The dry season was defined as the months of May through October, and the wet season was defined as November through April. Continuous data from the sondes were excluded from the trend analysis due to large differences in sample size. The non-parametric Mann Kendall trend test was used to test whether there were significant trends within each zone. Multiple observations (either multiple stations or sampling events) on a single day were averaged for this test. We also divided the data into historic and recent groups and tested whether there were significant differences in median values using the Mann–Whitney Rank Sum test. Mann–Whitney Rank Sum (M–WRS) and correlation analyses were performed using SigmaStat software package (version 3.5, Systat Software, Inc., San Jose, CA), while trend analysis (Mann Kendall) were performed using software written by the U.S. Geological Survey (Helsel et al., 2006). Correlations between variables are presented as Pearson's product moment correlations (r).

4. Results

4.1. Seasonal patterns in dissolved oxygen within Yaquina Estuary

There are strong seasonal patterns of DO within the Yaquina Estuary. Oxygen levels are stable in the estuary during the wet season, but decline during the dry season. The wet season DO (Zone 1 and Zone 2 combined) has an overall median value of 9.8 mg l^{-1}

($n = 811$), while the dry season has a median value of 7.0 mg l^{-1} ($n = 1535$). The remainder of this paper focuses only on the dry season DO levels because of the consistently high wet season values.

4.2. Historic and recent patterns in dissolved oxygen within Yaquina Estuary

During the interval of 1960–1985, there was a significant trend of increasing DO in Zone 2 during the dry season (Fig. 2). To examine whether differences in sampling over time (e.g., tidal stage) were responsible for the trend in DO in Zone 2, we tested whether there were significant differences in temperature or salinity (concurrent with DO measurements) in Zone 2. There were no significant trends in dry season water temperature or salinity in Zone 2 (Mann Kendall, $p > 0.05$). Recent (2002–2007) DO levels in Zone 2 are similar to DO levels during the mid 1980's, suggesting that there has not been recent change in DO levels.

In contrast to Zone 2, there were no significant trends (Mann Kendall, $p > 0.05$) in DO in Zone 1 during the dry season (Fig. 2), suggesting that the trend in historic DO levels in Zone 2 was not a result of differences in ocean conditions. Although there were no consistent trends in DO in Zone 1; recent (2001–2007) dry season DO levels (median = 6.7 mg l^{-1} , $n = 393$) are significantly lower than historic (1960–1985; median = 8.6 mg l^{-1} , $n = 525$; M-WRS, $p < 0.05$). However, the recent data had significantly higher salinity (median = 32.4 , $n = 393$) than the historic data (median = 26.7 , $n = 485$; M-WRS, $p < 0.05$), suggesting that this difference may be due to the recent data being biased for flood-tide conditions.

Since the sampling locations and frequency varied in the historic and recent dataset; we examined where there have been changes in the location or water temperature of low DO samples. There has been a temporal shift in location of minimum dry season DO levels within the estuary (Fig. 3). Historically, the minima in dry season DO occurred about 20 km from the mouth of the estuary (Fig. 3a), while recently DO minima occur near the estuary mouth and extend about 10 km into the estuary (Fig. 3b). There is a significant trend of increasing DO with distance from the mouth, suggesting that the ocean is presently the source of low DO levels. Historically, 97% of the occurrences of DO levels $< 5 \text{ mg l}^{-1}$ were associated with warm water temperatures ($\geq 15 \text{ }^\circ\text{C}$; Fig. 4a). In the historic data,

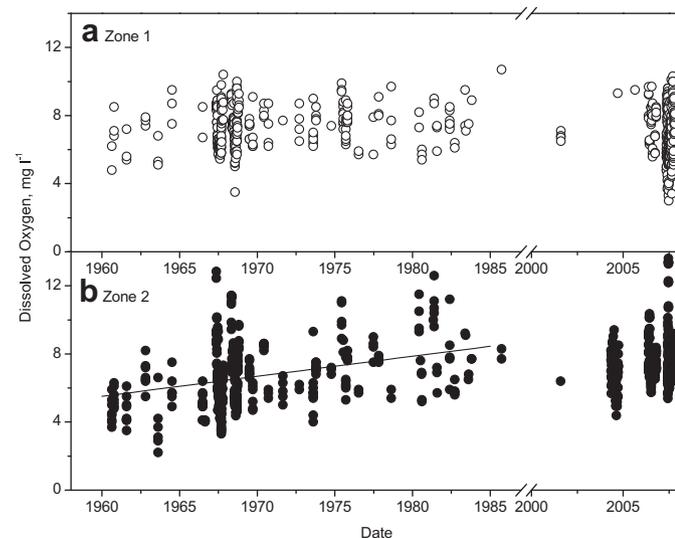


Fig. 2. Long-term trend in dry season DO in a) Zone 1 and b) Zone 2. Panel b includes the Mann Kendall trend line ($\text{DO} = -224.59 + 0.1174 \text{ Year}$, $\tau = 0.336$, $p < 0.05$).

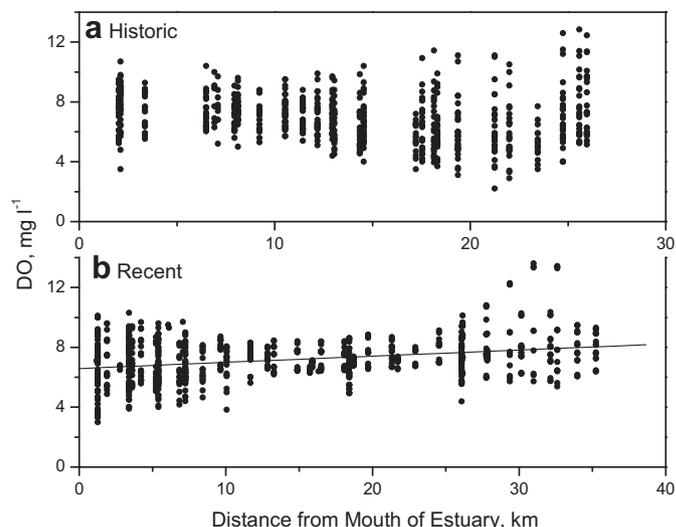


Fig. 3. Dry season dissolved oxygen (both zones) versus distance from the mouth of the estuary for a) historic (1960–1985) and b) recent discrete data (2001–2007). The line in panel b indicates the linear regression ($\text{DO} = 6.59 + 0.041 * \text{Distance from Mouth}$, $p < 0.0001$).

there are only a few observations of $\text{DO} < 5 \text{ mg l}^{-1}$ at temperatures $< 11 \text{ }^\circ\text{C}$, while in the recent data, the majority (69%) of the occurrences of $\text{DO} < 5 \text{ mg l}^{-1}$ occurred at water temperatures $< 11 \text{ }^\circ\text{C}$ (Fig. 4b). Thus, it appears that there has been a shift in location of low DO conditions.

4.3. Import of low dissolved oxygen water from the shelf

A time-series of DO measured at Stations Y1 and Y2 during July 9–27, 2002, coincided with a documented hypoxic event on the Oregon shelf off Newport, Oregon (Grantham et al., 2004) and clearly showed the import of low DO or hypoxic shelf water into the estuary during flooding tides (Fig. 5). Minimum DO levels occurred during maximum salinities (> 33) and minimum water temperatures ($\sim 9 \text{ }^\circ\text{C}$), which is indicative of recently upwelled water (data not shown). During this 18-day interval, the minimum DO concentration at Station Y1 was 0.4 mg l^{-1} , while at Station Y2 the minimum DO level was 3.2 mg l^{-1} (Fig. 5a and b). The intervals of

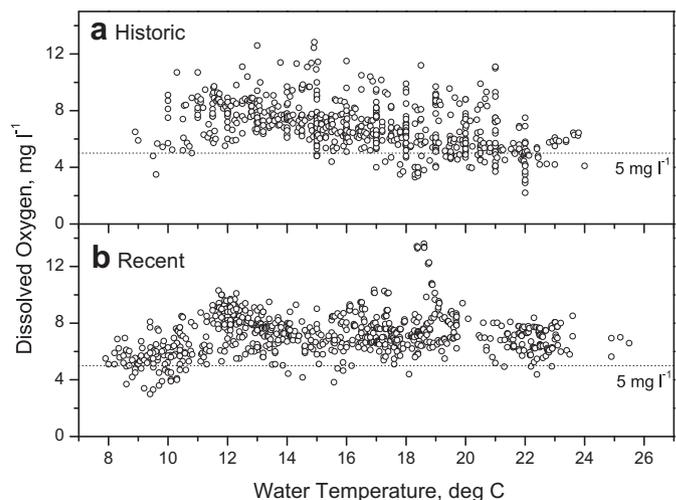


Fig. 4. Dry season dissolved oxygen (both zones) versus water temperature for a) historic and b) recent discrete data (2001–2007).

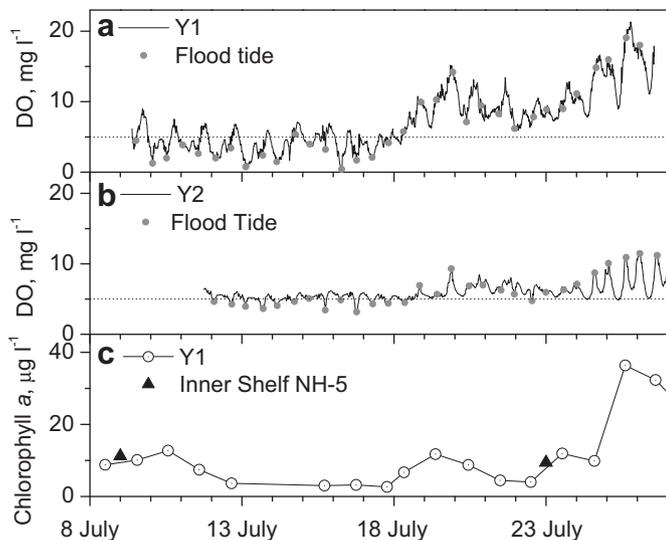


Fig. 5. Dissolved oxygen at a) Stations Y1 and b) Y2 and c) flood-tide chlorophyll *a* at Station Y1 during July 9–27, 2002. Chlorophyll *a* from an inner shelf Station NH-5 is also shown in panel c (Data Source: Pat Wheeler, Oregon State University and Bill Peterson, National Marine Fisheries Service).

low DO conditions were relatively short, with DO levels increasing to 6–8 mg l⁻¹ during ebb tides. Beginning on July 17, 2002 there was an increase in flood-tide DO levels at Stations Y1 and Y2, which coincided with an increase in chlorophyll *a* levels entering the estuary during flood tides (Fig. 5c). During the time of elevated chlorophyll *a* levels at Y1, there was a phytoplankton bloom on the inner shelf (see Station NH-5 data in Fig. 5c; Wheeler et al., 2003). Other data collected in 2002 showed that low oxygen (and occasionally hypoxic) water of oceanic origin reached Station Y2, which was consistent with the cruise data shown in Fig. 3b. During the dry season of 2002, there was a significant correlation between DO at Stations Y1 and Y2 ($r = 0.56$, $p < 0.001$, calculated using concurrent data with no evidence of fouling or sensor drift (May 23–June 10, July 11–July 26, and August 16–September 21). Data presented in this section demonstrate that hypoxic waters are advected from the inner shelf into the estuary.

4.4. Variability in ocean conditions and import of low DO water to the estuary

There was substantial interannual variability in the DO levels in oceanic water imported into the Yaquina Estuary during the dry season (Fig. 6). The import of hypoxic water (<2 mg l⁻¹) into the Yaquina Estuary was only apparent in July 2002 (Fig. 6). During the other years (2001, 2003–2007), minimum flood-tide DO levels ranged between 2.3 and 4.2 mg l⁻¹ (Fig. 6 and Table 2). During the dry seasons of 2001–2007, the highest incidence (36% of the events) of conditions with flood-tide DO < 5 mg l⁻¹ occurred during the month of July. There was no relationship between flood-tide DO levels < 5 mg l⁻¹ and time of day, demonstrating that low DO conditions were related to conditions on the inner shelf rather than diel cycles. The lowest frequency of import of DO < 5 mg l⁻¹ occurred during the dry seasons of 2004 and 2005 (Fig. 6 and Table 2). Previous studies have reported a delay in coastal upwelling on the Oregon coast during 2005 (Barth et al., 2007). This delay in upwelling resulted in the lowest frequency of flood-tide DO levels below the State of Oregon criterion (6.5 mg l⁻¹; Table 2). The highest frequency of import of DO < 5 mg l⁻¹ and the lowest median flood-tide DO levels both occurred during 2006, which coincided with the

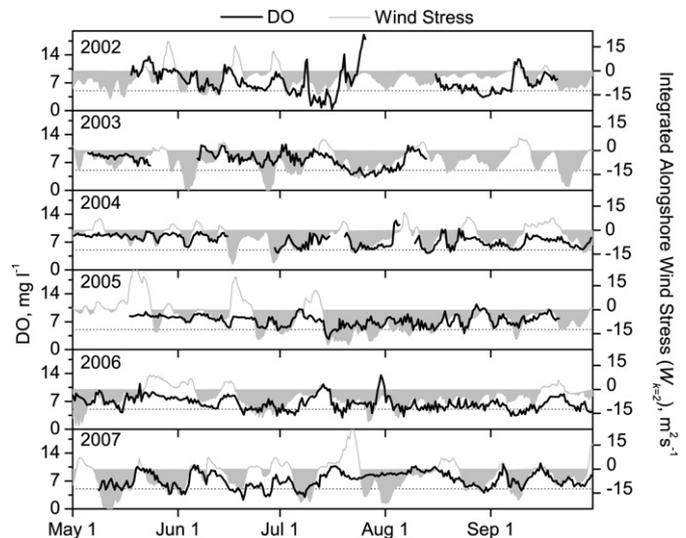


Fig. 6. Time-series of flood-tide dissolved oxygen at Y1 and integrated alongshore wind stress (calculated using Eq. (1) and a lag (k) of 2) during dry seasons of 2002–2007. The dotted line indicates DO of 5 mg l⁻¹. The shaded regions indicate upwelling favorable integrated alongshore wind stress.

occurrence of severe hypoxic conditions on the inner shelf (Chan et al., 2008). Median flood-tide DO levels are significantly correlated with median flood-tide water temperatures ($r = 0.77$, $p < 0.05$). Interannual variations in DO levels in the estuary appear to be related to conditions on the shelf.

During the dry seasons of 2002–2007, there were significant correlations between water temperature on the inner shelf (SR15) and flood-tide water temperatures at Station Y1 (Table 3), which demonstrates the coupling between the estuary and inner shelf. Flood-tide DO at Station Y1 are correlated with integrated wind stress (Fig. 6; Table 3), indicating that upwelling/downwelling conditions on the inner shelf are influencing DO levels within the estuary. Dry season flood-tide DO at Station Y1 during 2002–2007 was also significantly correlated with water temperature at Station SR15 (Table 3). The relatively weak correlation between flood-tide DO and integrated wind stress and water temperatures is expected due to the multiple factors influencing DO levels in estuaries and the non-linear relationships between variables.

Low DO conditions occur during periods of upwelling favorable winds stress and periods of low in situ fluorescence, while peak DO levels occur during periods of high in situ fluorescence which occur during relaxation conditions (integrated wind stress approximately equal to zero; Fig. 7a). During downwelling conditions, the in situ

Table 2

Minimum flood-tide DO, frequency of occurrence of DO levels less than 5 mg l⁻¹ and 6.5 mg l⁻¹, and median flood-tide DO and water temperature at Station Y1. The sample size for median values range from 141 to 287.

Year	Minimum DO, (mg l ⁻¹)	Frequency of occurrence of DO, (%)		Median flood-tide	
		< 5 (mg l ⁻¹)	< 6.5 (mg l ⁻¹)	Temperature, (°C)	DO, (mg l ⁻¹)
2001	3.17	17.0	39.7	9.7	6.87
2002	0.42	19.5	48.0	10.4	6.59
2003	3.34	12.7	27.7	11.0	8.10
2004	4.23	5.5	34.8	11.6	7.61
2005	2.63	4.7	25.1	10.9	7.71
2006	2.94	19.9	56.1	9.9	6.28
2007	2.29	12.9	38.0	10.7	7.31

Table 3

Correlation between integrated alongshore wind stress ($W_{k=2}$), flood-tide water temperature (WTP) at Station Y1, inner shelf WTP at Station SR15, and flood-tide dissolved oxygen (DO) at Station Y1. Wind data from Station 46050 were used to calculate the wind stress for all years except 2006, while for 2006 data from Station NWPO3 were used. Integrated wind stress was calculated using Eq. (1) with $k = 2$ days. All reported correlation coefficients are significant at $p < 0.05$.

Time-series compared	Correlation coefficient (r)	Sample size (n)
2002		
Y1 WTP and SR15 WTP	0.88	169
Y1 DO and SR15 WTP	0.46	169
Y1 WTP and $W_{k=2}$	0.49	200
Y1 DO and $W_{k=2}$	0.40	200
2003		
Y1 WTP and SR15 WTP	0.91	91
Y1 DO and SR15 WTP	0.73	91
Y1 WTP and $W_{k=2}$	0.74	166
Y1 DO and $W_{k=2}$	0.46	166
2004		
Y1 WTP and SR15 WTP	0.92	102
Y1 DO and SR15 WTP	0.71	102
Y1 WTP and $W_{k=2}$	0.76	253
Y1 DO and $W_{k=2}$	0.66	253
2005		
Y1 WTP and SR15 WTP	0.97	227
Y1 DO and SR15 WTP	0.48	227
Y1 WTP and $W_{k=2}$	0.74	275
Y1 DO and $W_{k=2}$	0.57	275
2006		
Y1 WTP and SR15 WTP	0.94	261
Y1 DO and SR15 WTP	0.48	261
Y1 WTP and $W_{k=2}$	0.72	287
Y1 DO and $W_{k=2}$	0.41	287
2007		
Y1 WTP and SR15 WTP	0.97	254
Y1 DO and SR15 WTP	0.40	254
Y1 WTP and $W_{k=2}$	0.75	279
Y1 DO and $W_{k=2}$	0.43	279

fluorescence is low and DO levels average about 8 mg l^{-1} (Fig. 7a). Time periods of $\text{DO} < 5 \text{ mg l}^{-1}$ (threshold for biological stress) had average water temperature of $9.5 \text{ }^\circ\text{C}$ and salinity of 33.6 ($n = 204$; Fig. 7b). Water temperature appears to be a better indicator of the import of low DO water from the ocean than salinity. There is more variability in DO levels for a given salinity threshold as compared to a water temperature threshold (Fig. 7b).

4.5. Comparison with historical data from the inner shelf and other estuaries

To assess whether hypoxic conditions on the inner shelf are a new occurrence, we examined historic inner shelf data (inside the 100-m depth contour between latitudes 42° N and 48° N) from the World Ocean database from 1950–1970. There was at least one recorded occurrence of hypoxic conditions ($\text{DO} < 2 \text{ mg l}^{-1}$) on the inner shelf during the years of 1950, 1953, 1956, 1957, 1961–1968 and 1970. Hypoxic conditions typically occurred during June through early October (Fig. 8a). Twelve percent of the historic inner shelf observations during the months of the June–September indicated hypoxic conditions (Fig. 8b), and there were several occurrences of severe hypoxia ($< 0.7 \text{ mg l}^{-1}$), all occurring inshore of the 60-m depth contour. During the months of June–September, the median bottom DO on the inner shelf was 3 mg l^{-1} ($n = 775$).

The relationship between flood-tide DO and water temperature from the Yaquina Estuary was consistent with data from other PNW estuaries (Fig. 9a–c) and the inner shelf (Fig. 9d). The 2002 data from Station Y1 appeared to be anomalously low compared to the data from other estuaries; however, they were consistent with historical

data from the inner shelf. One observation from 1975 near the entrance of Coos Bay ($\text{DO} = 0.3 \text{ mg l}^{-1}$) was similar to the 2002 data (Fig. 9a). The data from Grays Harbor, WA (Pearson and Holt, 1960) were similar to that observed in the majority of the recent data collected at Station Y1 (Fig. 9b). Recent data collected near the mouth of Coos, Siletz, Tillamook, and Umpqua estuaries exhibited low DO at cool water temperatures (Fig. 9c). Years which had observations of low DO at relatively cool water temperatures in PNW estuaries are 1951–1957 (Grays Harbor; Pearson and Holt, 1960), 1960 (Yaquina), 1964 (Columbia; Haertel and Osterberg, 1967), 1968 (Alsea, Siuslaw, Yaquina), 1975 (Coos, Netarts), 2001–2007 (Yaquina), 2005 (Columbia, Coos, Tillamook, Umpqua), and 2008 (Siletz).

5. Discussion

The trend analyses revealed a significant increasing trend in dry season DO levels in Zone 2 during the interval of 1960–1985. In other estuaries, improvements in sewage treatment systems have led to increases in DO levels (e.g., Mallin et al., 2005). Review of Yaquina watershed history suggests that current anthropogenic impacts are probably less than they were historically (particularly during 1960's–1980's). Improvements in DO levels in Zone 2 are probably related to the concurrent reductions in point source inputs and log rafting during that period. The historical record of DO in the Zone 2 demonstrates that this portion of the estuary may be susceptible to DO degradation.

The absence of a significant long-term trend in Zone 1 suggests that the trend in historic DO levels in Zone 2 was not a result of differences in ocean conditions. Historically, minimum dry season DO levels occurred about 20 km from the mouth of the estuary, which coincided with the location of the point source discharges and the region of extensive log rafting (determined from historical photographs). In recent dry season data, there is a trend of increasing DO with distance from the mouth of the estuary, suggesting that the ocean is presently the primary source of low DO conditions in lower portion of the estuary. This is in contrast to many other estuaries which typically have low DO conditions in the riverine or mesohaline portion of the estuary (Melrose et al., 2007; and Lee and Lwiza, 2008), not near the mouth of the estuary. The import of low DO water from the shelf into estuaries has been documented in other regions (Epifanio et al., 1983; Conley et al., 2000), and is believed to be facilitated by a narrow shelf (Epifanio et al., 1983), such as that which occurs off of the Yaquina Estuary.

DO levels in the lower estuary are clearly related to ocean conditions on the inner shelf; however, flood-tide DO levels in the estuary are not as low as those being experienced near the bottom ($< 0.5 \text{ mg l}^{-1}$) on the inner shelf (Grantham et al., 2004; Chan et al., 2008). This is not surprising, since the estuary receives flood-tide waters from multiple depths (due to mixing) and not just the bottom waters. Oxygen supersaturation has been observed near the surface when hypoxic conditions are present near the bottom on the inner Oregon Shelf (Wheeler et al., 2003; Grantham et al., 2004). Although water temperature is not a conservative property, it appears to be a better indicator of the oceanic source of low DO water masses than salinity. Periods of low flood-tide DO in the lower Yaquina Estuary typically have cool water temperatures and low in situ fluorescence, suggesting the source is recently upwelled shelf water. Conversely, intervals of high flood-tide DO ($> 8 \text{ mg l}^{-1}$) are characterized by warmer temperatures and high in situ fluorescence. Recently upwelled water is exposed to sunlight in the surface waters, warming it and exposing it to atmospheric oxygen that enters the water column through diffusion and surface mixing. Recently upwelled water also has high nutrients, and exposure to sunlight induces phytoplankton blooms, leading to increased DO from photosynthesis. In comparison, recently upwelled water has

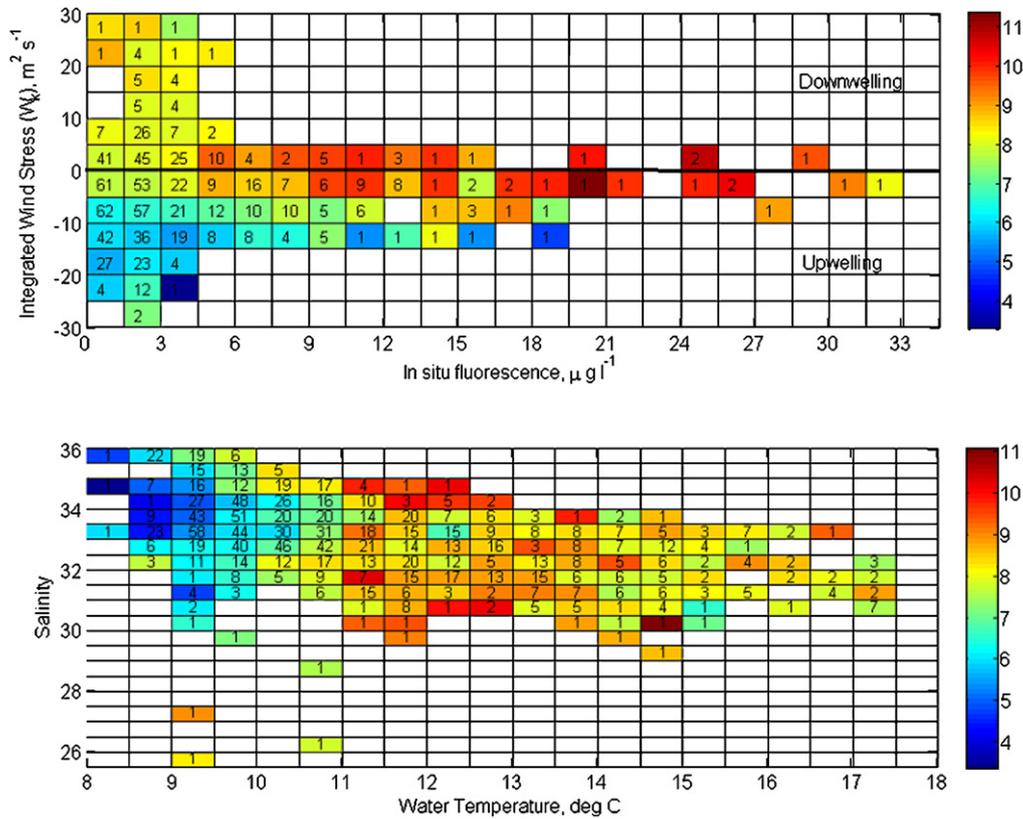


Fig. 7. Relationship between integrated alongshore wind stress, flood-tide in situ fluorescence at Y1 and flood-tide dissolved oxygen at Y1 (top panel) and flood-tide salinity, temperature and dissolved oxygen at Y1 (bottom panel). The shading of each cell represents the average flood-tide dissolved oxygen at Y1 for a given wind stress and fluorescence (top panel) and salinity and temperature (bottom panel). The number in each cell is the number of observations included in each mean value. The upper panel is generated using Y1 data during the months of May–September from 2004, 2005, and 2007, while the lower panel is generated using Y1 data from 2002–2007.

a high salinity and the salinity remains relatively constant as DO levels increase due to diffusion, mixing, and phytoplankton production.

Previous studies have documented the advection of high chlorophyll *a* levels into the Oregon estuaries (Roegner and Shanks, 2001; Brown and Ozretich, 2009). Brown and Ozretich (2009) found that the maximum correlation between wind stress and chlorophyll *a* occurred at a lag of 6 days and the maximum correlation between water temperature and chlorophyll *a* occurred at 4 days lag. This suggests that it takes approximately 5–6 days for phytoplankton to utilize the newly upwelled nitrogen and be transported across the shelf into the Yaquina Estuary. We show that when high concentrations of chlorophyll *a* are advected into the estuary, there are increases in flood-tide dissolved oxygen levels. The factors that determine DO levels in water imported into the estuary appear to switch between physical (minimum values associated with upwelling wind stress and having a cool water temperature signature) and biological controls (maximum values associated with high chlorophyll *a*). The influence of ocean conditions on DO levels extends about 10 km into the estuary, which is similar to how far variations in chlorophyll *a* and nutrient propagate into the estuary (Brown and Ozretich, 2009).

A recent review has suggested the conventional definition of hypoxia of 2 mg l⁻¹ falls below the oxygen thresholds for more sensitive taxa (Vaquer-Sunyer and Duarte, 2008). In addition, sublethal oxygen thresholds varied by taxa with fish and crustaceans exhibiting higher oxygen thresholds than other taxa (Vaquer-Sunyer and Duarte, 2008). Vaquer-Sunyer and Duarte (2008) suggested that a more conservative threshold of 4.6 mg l⁻¹ would maintain most populations except for the 10% most sensitive species. In the Yaquina

Estuary during the dry season, flood-tide DO levels would fall below this threshold approximately 10% of the time.

The existing State of Oregon dissolved oxygen criterion for estuaries (6.5 mg l⁻¹) is based on a review of physiological

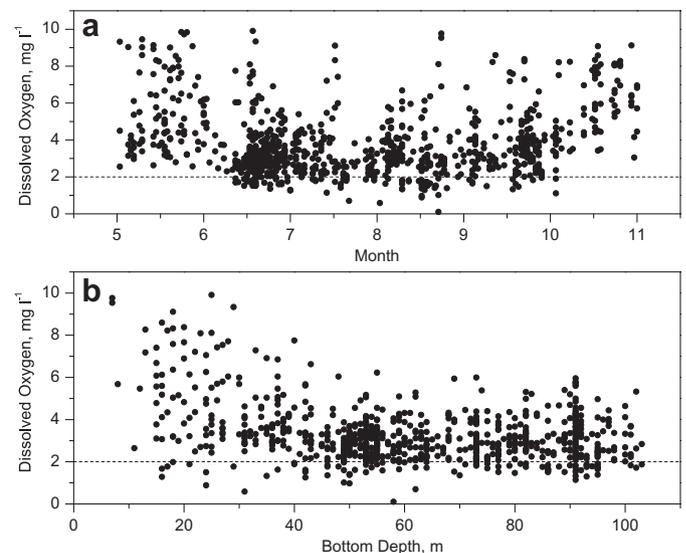


Fig. 8. a) Historic (1950–1970) minimum dissolved oxygen (typically the bottom value of each profile) inside the 100-m depth contour of the region between latitudes 42° and 48° North, and b) dissolved oxygen versus bottom depth during the months of June–September. The dashed line indicates dissolved oxygen of 2 mg l⁻¹.

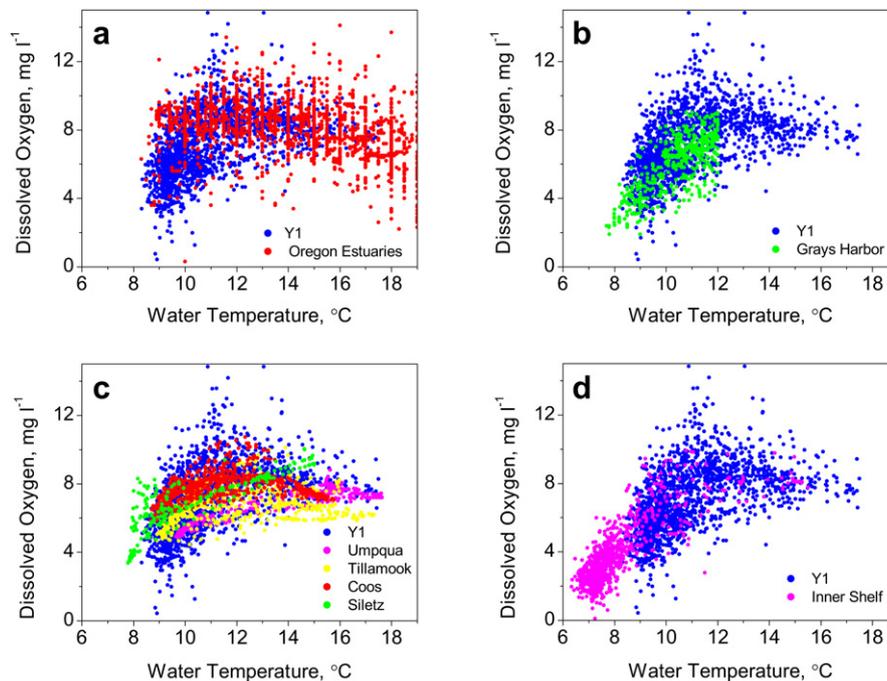


Fig. 9. Comparison of DO versus water temperature from Station Y1, (a) other Oregon estuaries, (Data Source: DEQ) (b) historic data from Grays Harbor, WA (Pearson and Holt, 1960), (c) recent data from Umpqua, Tillamook, Coos, and Siletz estuaries, and (d) historic data from the inner Washington and Oregon shelf (Source: World Ocean Database, data from 1950–1970, minimum dissolved oxygen inside the 100-m depth contour between latitudes 42° and 48° North).

requirements of salmonids, and is high compared to DO criteria for other estuaries (U.S. EPA, 2003). A review of the DO criterion (DEQ, 1995) found that 6.5 mg l^{-1} may be difficult to achieve in Oregon estuaries during the summer due to natural conditions, in which case, the background conditions become the criterion per the State of Oregon's narrative criterion. The incidence of flood-tide DO levels $< 6.5 \text{ mg l}^{-1}$ averaged about 38% during the dry seasons of 2001–2007 (Table 2). DO levels $< 6.5 \text{ mg l}^{-1}$ occurred 44% and 17% of the time in Zones 1 and 2, respectively (Brown et al., 2007). These below-criterion observations are related to the import of low oxygen water from the coastal ocean into the estuary, rather than oxygen depletion within the estuary. In a review of DO conditions in Oregon estuaries (DEQ, 1995), the opposite spatial pattern was found, with minimum DO levels occurring near the upper end of salt water intrusion and higher DO levels associated with inflow of ocean water. DEQ (1995) suggested that greater frequency of low DO would be expected if sampling occurred near the upper extent of salt water intrusion, but our results suggest this may not be the case.

DO levels typically decrease with increasing temperature due to both reduced solubility of oxygen and increased respiration and decomposition (e.g., Verity et al., 2006; Lee and Lwiza, 2008). In the upper estuary (Station Y3), DO levels decreased with increasing water temperature. However the opposite pattern was found in the lower portion of the Yaquina Estuary, with lower DO levels occurring at cool water temperatures during the dry season. Recent DO levels in Zone 1 are consistent with historical data for the Yaquina Estuary, as well as other Oregon and Washington estuaries. The import of hypoxic water into the Yaquina Estuary during 2002, suggests that DO levels on the inner shelf were lower during this year. Hales et al. (2006) suggested that the anomalous hypoxic conditions during 2002 may have resulted from unusually long-period of uninterrupted upwelling favorable winds.

Chan et al. (2008) found there was “little evidence of shelf hypoxia and no evidence of severe inner shelf hypoxia before 2000.” The similarity in the flood-tide DO and water temperature

relationship between recent continuous data in Yaquina and historic data from other estuaries (particularly the data from Grays Harbor, from Pearson and Holt, 1960) and historic data from the inner shelf indicates that the hypoxic conditions observed since 2002 off the Oregon coast may have occurred previously, especially in the 1950's–1960's. Our analyses of inner shelf data suggest that hypoxic conditions historically occurred near bottom about 12% of the time during June to September, and there was some evidence of severe hypoxic conditions. Pearson and Holt (1960) observed hypoxic water off of Grays harbor (~ 1 mile from tip of jetties) with minimum DO levels of $\sim 0.7 \text{ mg l}^{-1}$, with concurrent DO levels at the mouth of the estuary of about 3 mg l^{-1} . Haertel and Osterberg (1967) also found lowest dissolved oxygen levels (3.6 mg l^{-1}) in the Columbia River Estuary in the salt wedge near the mouth during the summer. Collias (1985) stated that “low dissolved has also been observed near the entrance” of the Yaquina Estuary and is “attributable to coastal upwelling”; however, data demonstrating this were not included in this report. The recent and historical data from Oregon and Washington estuaries demonstrate that the advection of low DO water into estuaries occurs at a regional scale.

Population densities are relatively low in the watersheds of most Oregon and Washington estuaries, when compared to other regions of the United States (Crossett et al., 2004). However, the population densities of these watersheds are expected to increase in the next few decades. Eutrophication pressure is expected to increase as watersheds shift from forested to greater development. The advection of relatively low DO water to PNW estuaries may increase their susceptibility to eutrophication in the future. Typically, for estuaries the seaward exchange is a source of oxygen to the estuarine system (Kemp et al., 1992).

We conclude that it is important to characterize the natural background conditions for PNW estuaries when evaluating non-attainment of present DO criterion. In addition, the advection of oceanic low oxygen water into PNW estuaries makes it difficult to use DO as an indicator of eutrophication status. Continuous

monitoring of water temperature, salinity, and DO may aid in identifying whether low oxygen water in these estuaries is imported from the coastal ocean or a result of processes occurring within the estuaries. In addition, it has been suggested that global climate change may result in increases in the frequency or severity of hypoxia in coastal and estuarine waters (Rabalais et al., 2009) as well as in the ocean interior (Keeling et al., 2010). Some studies have suggested that future climate change may lead to changes in the seasonality or intensity of wind-driven upwelling (Snyder et al., 2003). The elevation of sea level may result in increased intrusion of low oxygen water into estuaries adjacent to upwelling regions. These three factors (changes in oxygen levels in coastal ocean, changes in upwelling, and rising sea level) have the potential to influence dissolved oxygen levels in estuaries. The dataset presented in this paper provides a baseline on advection of oceanic water into the Yaquina Estuary, which will be useful for assessing changes in oxygen levels resulting from global climate change.

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References

- Austin, J.A., Barth, J.A., 2002. Variation in the position of the upwelling front on the Oregon shelf. *Journal of Geophysical Research* 107 (C11): Art. No. 3180.
- Barth, J.A., Menge, B.A., Lubchenco, J., Chan, F., Bane, J.M., Kirincich, A.R., McManus, M.A., Nielsen, K.J., Pierce, S.D., Washburn, L., 2007. Delayed upwelling alters nearshore coastal ocean ecosystem in the northern California current. *Proceedings of National Academy of Sciences of the United States of America* 104 (10), 3719–3724.
- Brown, C.A., Nelson, W.G., Boese, B.L., DeWitt, T.H., Eldridge, P.M., Kaldy, J.E., Lee, H., Power, J.H., Young, D.R., 2007. An Approach to Developing Nutrient Criteria for Pacific Northwest Estuaries: a Case Study of Yaquina Estuary, Oregon. USEPA Office of Research and Development, National Health and Environmental Effects Laboratory. Western Ecology Division. EPA/600/R-07/046.
- Brown, C.A., Ozretich, R.J., 2009. Coupling between the coastal ocean and Yaquina Bay, Oregon: importance of oceanic inputs relative to other nitrogen sources. *Estuaries and Coasts* 32, 219–237. doi: 10.1007/s12237-008-9128-6.
- Burt, W.V., McAlister, W.B., 1959. Recent Studies in the Hydrography of Oregon Estuaries. In: *Research Briefs*, 7. Fish Commission of Oregon. 14–27.
- Chan, F., Barth, J.A., Lubchenco, J., Kirincich, A., Weeks, A., Peterson, W.T., Menge, B.A., 2008. Emergence of anoxia in the California Current large marine ecosystem. *Science* 319, 920.
- Colbert, D., McManus, J., 2003. Nutrient biogeochemistry in an upwelling-influenced estuary in the Pacific Northwest (Tillamook bay, Oregon, USA). *Estuaries* 26 (5), 1205–1219. doi: 10.1007/BF02803625.
- Collias, E.E., 1985. Nationwide review of oxygen depletion and eutrophication in estuarine and coastal waters, West coast Region. Report to U.S. Dept. of Commerce. NOAA, National Ocean Service, Rockville, MD.
- Conley, D.J., Kaas, H., Møhlenberg, F., Rasmussen, B., Windolf, J., 2000. Characteristics of Danish estuaries. *Estuaries* 23 (6), 820–837.
- Crossett, K.M., Culliton, T.J., Wiley, P.C., Goodspeed, T.R., 2004. Population Trends along the Coastal United States: 1980–2008. In: *Coastal Trends Report Series*. National Oceanic and Atmospheric Administration, p. 47.
- De Angelis, M.A., Gordon, L.I., 1985. Upwelling and river runoff as sources of dissolved nitrous oxide to the Alsea estuary, Oregon. *Estuarine, Coastal and Shelf Science* 20, 375–386. doi:10.1016/0272-7714(85)90082-4.
- De Ben, W.A., Clothier, W.D., Ditsworth, G.R., Baumgartner, D.J., 1990. Spatio-temporal fluctuation in the distribution and abundance of demersal fish and epibenthic crustaceans in Yaquina Bay, Oregon. *Estuaries* 13, 469–478.
- Diaz, R.J., Rosenberg, R., 1995. Marine benthic hypoxia: a review of its ecological effects and the behavioral responses of benthic macrofauna. *Oceanography and Marine Biology, Annual Review* 33, 245–303.
- Epifanio, C.E., Maurer, D., Dittel, A.I., 1983. Seasonal changes in nutrients and dissolved oxygen in the Gulf of Nicoya, a tropical estuary on the Pacific coast of Central America. *Hydrobiologia* 101, 231–238.
- Fasten, N., 1931. The Yaquina oyster beds of Oregon. *American Naturalist* 65, 434–468.
- Federal Water Pollution Control Administration, 1966. Reconnaissance Investigation Water Supply and Water Quality Control Study Yaquina River Basin, Oregon. United States Department of the Interior, p. 10.
- Glenn, S., Arnone, R., Bergmann, T., Bissett, W.P., Crowley, M., Cullen, J., Gryzmski, J., Haidvogel, D., Kohut, J., Moline, M., Oliver, M., Orrico, C., Sherrell, R., Song, T., Weidemann, A., Chant, R., Schofield, O., 2004. Biogeochemical impact of summertime coastal upwelling on the New Jersey Shelf. *Journal of Geophysical Research* 109, C12S02. doi:10.1029/2003JC002265.
- Grantham, B.A., Chan, F., Nielsen, K.J., Fox, D.S., Barth, J.A., Huyer, A., Lubchenco, J., Menge, B.A., 2004. Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature* 429, 749–754.
- Haertel, L., Osterberg, C., 1967. Ecology of zooplankton, benthos, and fishes in the Columbia River Estuary. *Ecology* 48 (3), 459–472.
- Hales, B., Karp-Boss, L., Perlin, A., Wheeler, P.A., 2006. Oxygen production and carbon sequestration in an upwelling coastal margin. *Global Biogeochemical Cycles* 20, GB3001. doi:10.1029/2005GB002517.
- Helsel, D.R., Mueller, D.K., Slack, J.R., 2006. Computer Program for the Kendall Family of Trend Tests, U.S. Geological Survey Scientific Investigations Report 2005-5275, 4 pp.
- Hickey, B.M., Banas, N., 2003. Oceanography of the U.S. Pacific Northwest coastal ocean and estuaries with application to coastal ecology. *Estuaries* 26, 1010–1031.
- Karentz, D., McIntire, C.D., 1977. Distribution of diatoms in the plankton of Yaquina estuary, Oregon. *Journal of Phycology* 13, 379–388.
- Kemp, W.M., Sampou, P.A., Garber, J., Tuttle, J., Boynton, W.R., 1992. Seasonal depletion of oxygen from bottom-water of Chesapeake Bay: roles of benthic and planktonic respiration and physical exchange processes. *Marine Ecology Progress Series* 85, 137–152.
- Keeling, R.F., Körtzinger, A., Gruber, N., 2010. Ocean deoxygenation in a warming world. *Annual Review of Marine Science* 2, 199–229.
- Kulm, L.D., Byrne, J.V., 1966. Sedimentary response to hydrography in an Oregon estuary. *Marine Geology* 4, 85–109.
- Large, W.G., Pond, S., 1981. Open ocean momentum flux measurements in moderate to strong winds. *Journal of Physical Oceanography* 11, 324–336.
- Lee, Y.J., Lwiza, K.M.M., 2008. Characteristics of bottom dissolved oxygen in long Island Sound, New York. *Estuarine, Coastal and Shelf Science* 76 (2), 187–200.
- Mallin, M.A., McIver, M.R., Wells, H.A., Parsons, D.C., Johnson, V.L., 2005. Reversals of eutrophication following sewage treatment upgrades in the New River Estuary, North Carolina. *Estuaries* 28 (5), 750–760.
- Melrose, D.C., Oviatt, C.A., Berman, M.S., 2007. Hypoxic events in Narragansett Bay, Rhode Island, during the summer of 2001. *Estuaries and Coasts* 30 (1), 47–53.
- Oregon Department of Environmental Quality, 1995. Dissolved Oxygen, 1992–1994 Water Quality Standards Review. Department of Environmental Quality Standards and Assessment Section, Portland, Oregon.
- Pearson, E.A., Holt, G.A., 1960. Water quality and upwelling at Grays Harbor entrance. *Limnology and Oceanography* 5 (1), 48–56.
- Rabalais, N.N., Turner, R.E., Diaz, R.J., Justic, D., 2009. Global change and eutrophication of coastal waters. *ICES Journal of Marine Science* 66, 1528–1537.
- Roegner, G., Shanks, A., 2001. Import of coastally-derived chlorophyll *a* to South Slough, Oregon. *Estuaries* 24, 224–256. doi: 10.2307/1352948.
- Roegner, G.C., Hickey, B.M., Newton, J.A., Shanks, A.L., Armstrong, D.A., 2002. Wind-induced plume and bloom intrusions into Willapa Bay, Washington. *Limnology and Oceanography* 47 (4), 1033–1042.
- Sedell, J.R., Duval, W.S., 1985. Influence of Forest and Rangeland Management on Anadromous Fish Habitat in Western North America, Water Transportation and Storage of Logs. United States Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. General Tech. Report PNW-186.
- Sedell, J.R., Leone, N., Duval, W.S., 1991. In: *Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats*. Water Transportation and Storage of Logs, 19. American Fisheries Society Special Publication, pp. 325–368.
- Shirzad, F.F., Orlando, S.P., Klein, C.J., Holliday, S.E., Warren, M.A., Monaco, M.E., 1988. National Estuarine Inventory: Supplement 1, Physical and Hydrologic Characteristics, the Oregon Estuaries. United States Department of Commerce, National Oceanic and Atmospheric Administration, Rockville, MD.
- Snyder, M.A., Sloan, L.C., Diffenbaugh, N.S., Bell, J.S., 2003. Future climate change and upwelling in the California Current. *Geophysical Research Letters* 30 (15), 1823. doi:10.1029/2003GL017647.
- The Morning Oregonian, January 17, 1930. Sawdusts or Oysters in Yaquina Bay.

- U.S. Environmental Protection Agency, 2000. Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras. Office of Water & Office of Research and Development. EPA-822-R-00-012.
- U.S. Environmental Protection Agency, 2003. Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries. Region III Chesapeake Program Office & Region III. Water Protection Division. EPA-903-R-03-002.
- Vaquier-Sunyer, R., Duarte, C.M., 2008. Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Sciences* 105 (40), 15452–15457.
- Verity, P.G., Alber, M., Bricker, S.B., 2006. Development of hypoxia in well-mixed subtropical estuaries in the Southeastern USA. *Estuaries and Coasts* 29 (4), 665–673.
- Wheeler, P.A., Huyer, A., Fleischbein, J., 2003. Cold halocline, increased nutrients and higher chlorophyll off Oregon in 2002. *Geophysical Research Letters* 30 (15), 8021. doi:10.1029/2003GL017395.