

Seasonal and interannual variation in the extent of hypoxia in the northern California Current from 1998–2012

Jay O. Peterson,^{1,*} Cheryl A. Morgan,¹ William T. Peterson,² and Emanuele Di Lorenzo³

¹Cooperative Institute for Marine Resources Studies, Oregon State University, Hatfield Marine Science Center, Newport, Oregon

²National Oceanic and Atmospheric Administration, Northwest Fisheries Science Center, Hatfield Marine Science Center, Newport, Oregon

³School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia

Abstract

This study addresses the occurrence, severity, and extent of hypoxia over the continental shelf of the northern California Current (40–48.5°N latitude) from 1998 to 2012. Clear seasonal trends exist in the timing and duration of hypoxia. The highest bottom-water dissolved oxygen concentrations occurred from November to March, and levels below the 1.4 mL L⁻¹ hypoxia threshold were detected during the upwelling season (May through October). Regions of hypoxia tended to occur north of 42°N latitude and were most severe over the widest areas of the continental shelf. Hypoxic waters covered up to 62% (15,600 km²) of the continental shelf during some years (2002, 2007, 2008), and < 10% in others (2003, 2010–2011). There are seasonal and interannual shifts in both the depth and oxygen content of upwelled waters. Years with the greatest extent and severity of hypoxia had the lowest concentration of dissolved oxygen in upwelling source waters. The dissolved oxygen concentration of source waters showed a gradual decline from 1998 through 2007, with a subsequent increase from 2008–2010 before leveling off in 2011 and 2012. The variability in oxygen content of source waters correlates well with the North Pacific Gyre Oscillation and may indicate the importance of large-scale climate dynamics in determining the extent and severity of hypoxia in the northern California Current.

Hypoxic bottom waters (< 1.4 mL L⁻¹ dissolved oxygen) are common throughout the world in both marine and freshwater systems. Depending on the rate of mixing, the hypoxic waters occur persistently, seasonally, or at much less predictable intervals (Diaz 2001).

Persistent hypoxia primarily occurs in regions such as fjords (Spicer et al. 1999) and enclosed seas (Diaz and Rosenberg 1995, 2008), where water masses are trapped for extended periods of time. Seasonal hypoxia is common in estuaries and bays, especially during the summer months when waters are often more stratified and increased production leads to a greater flux of organic matter to bottom waters where degradation processes consume available oxygen.

Much attention has been given to hypoxic regions recently due to evidence that such regions are becoming more numerous, more severe, and increasing in area and volume (Diaz and Rosenberg 2008). They are often linked to increases in nutrient loading directly tied to human activity, particularly in freshwater systems (Carpenter et al. 1998) and regions such as the Gulf of Mexico (Rabalais and Turner 2001) and Long Island Sound (Anderson and Taylor 2001). Regions of hypoxia are attributed to increased biological oxygen demand linked to high primary production in surface waters, combined with reduced circulation (venting) and oxygen-poor source waters (Helly and Levin 2004).

In the northern section of the California Current (NCC), running along the west coast of the U.S.A., seasonal hypoxia events are driven by a combination of relatively low oxygen waters upwelling onto the shelf with further

oxygen drawdown stemming from the decomposition of organic matter settling to the seafloor (Chan et al. 2008; Connolly et al. 2010). During the upwelling season (typically mid-April to mid-October), water from ~ 100–150 m depth is transported up onto the shelf and replaces surface waters that move offshore via wind-driven Ekman transport. The upwelled waters are relatively old and tend to be low in oxygen due to extended exposure to water column respiration and isolation from the atmosphere.

Deeper in the water column, an oxygen minimum zone (OMZ) develops (Wyrski 1962) and is common in large areas of the eastern Pacific, southeast Atlantic, and northern Indian Ocean (Reid et al. 1978; Helly and Levin 2004). In some regions, e.g., southeast Pacific (Reid et al. 1978), the OMZ is shallow enough that it can intrude onto the continental shelf and result in hypoxic bottom waters. In the northeast Pacific, the OMZ is too deep (400–800 m) to directly influence the continental shelf (Helly and Levin 2004).

Recent research has found a drop in dissolved oxygen values in NCC shelf waters over the last several decades (Chan et al. 2008), and it is part of a global trend of decreasing oxygen concentrations in coastal environments (Diaz and Rosenberg 2008) as well as in the deeper pelagic areas (Stramma et al. 2010).

The presence of hypoxia is ecologically important due to the ability to drastically change the behavior and condition of a range of species and alter the community composition of a region for extended periods of time (Diaz and Rosenberg 1995; Wu 2002). Effects on zooplankton include a reduction in recruitment of meroplanktonic species, changes in vertical distribution, with plankton often being compressed into shallower depth strata, and a reduction in

* Corresponding author: jay.peterson@oregonstate.edu

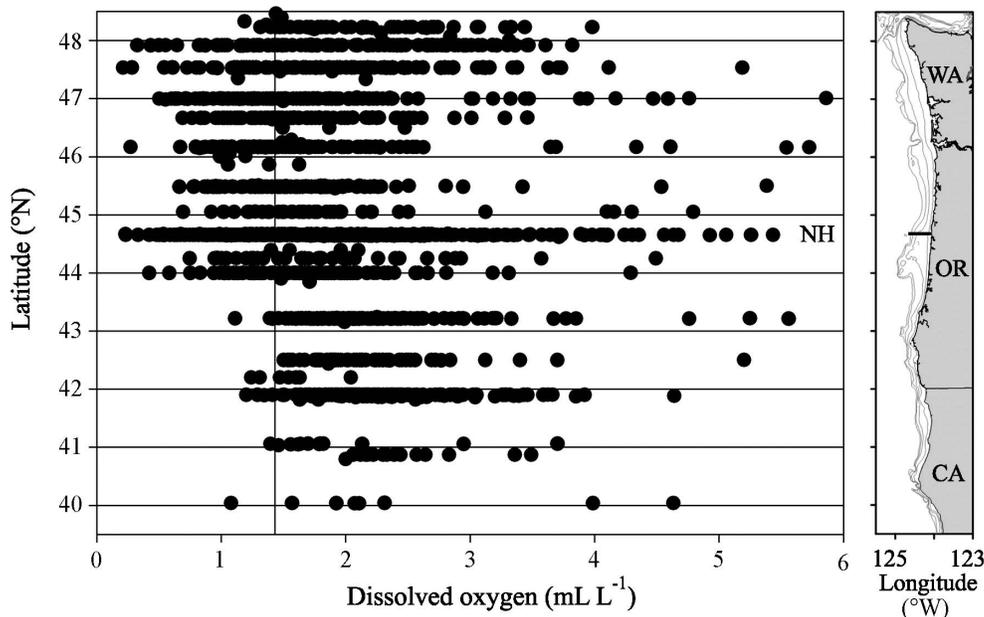


Fig. 1. Latitudinal distribution of minimum dissolved oxygen values within 10 m of the bottom or 200 m maximum. Data are from May to September of 1998–2012. The map on the right shows the general survey area. Contours are every 50 m out to 200 m depth. The solid line at 44°39.1'N latitude represents the Newport Hydrographic (NH) Line.

abundance of early life stages (Keister et al. 2000; Qureshi and Rabalais 2001). Benthic macrofauna exhibit behavioral changes and a reduction in biomass and community composition (Diaz and Rosenberg 1995; Montagna and Ritter 2006). Demersal fish and invertebrate species in continental shelf waters can sustain high mortality within hypoxic regions or may be forced from their preferred habitat to shallower, less suitable habitats where they may experience high mortality rates through predation or being washed ashore (Breitburg et al. 2001; Grantham et al. 2004).

This paper uses a 15 yr data set of hydrographic measurements to investigate the seasonal and interannual variability in the distribution and severity of NCC continental shelf hypoxia from 40–48.5°N latitude. We describe seasonal variability from a time series of biweekly sampling along the Newport Hydrographic Line (NH Line), which spans the continental shelf, and spatial variations from historical data and more recent surveys.

Methods

Data collection (NH Line)—Data were collected along a 46 km transect, called the Newport Hydrographic Line, extending across the shelf from Newport, Oregon, along latitude 44°39.1'N (Fig. 1). There were a total of seven stations sampled along the line, spaced every 3.6 km inshore and every 9.3 km at water depths exceeding 60 m. Stations are identified by their historical names based on distance (nautical miles) from shore and are referred to as NH01, NH03, NH05, NH10, NH15, NH20, and NH25. Water depths ranged from 28 m (NH01) to 300 m (NH25).

Surveys of the NH Line occurred approximately every 2 weeks throughout the year aboard the R/V *Elakha*, with

the ability to sample the entire line dependent upon sea conditions. At each station, an SBE19 or SBE25 conductivity–temperature–depth sensor (CTD; SeaBird Electronics) equipped with an SBE43 dissolved oxygen sensor and pump (SeaBird Electronics) was deployed from the surface to ~ 5 m from the bottom at a rate of 30 m min⁻¹. The data were internally logged and downloaded and processed at the end of each cruise. Only data from the downcast of the CTD were used. Sensors were factory calibrated annually. No corrections were made to the data after the annual calibration as the oxygen sensor “drift” over the course of the year was consistently < 0.05 mL L⁻¹.

Data collection (coast-wide)—A long-term data set has been acquired from various research projects over the period 1998–2012. From August 1998–September 2003 multiple regional surveys were done as part of the Global Ocean Ecosystems Dynamics–Long Term Observations Program. Details of the sampling protocol, station locations, and vessels are available online (<http://ltop.coas.oregonstate.edu/~ctd/>) as data reports. In brief, samples were collected at stations along fixed, latitudinal transects: Crescent City (CC; 41°54'N), Rogue River (RR; 42°30'N), Five Mile Point (FM; 43°13'N), Heceta Head (HH; 44°N), and NH. Oxygen data come from a SeaBird Model 13 Beckman-type dissolved oxygen sensor (1998–2002) and Model 43 polarographic (2003) mounted to a SeaBird 9/11 CTD and rosette. The dissolved oxygen sensor was calibrated, during each cruise from 1999–2004, against periodic water samples analyzed by Winkler titration.

From 2004–2006, annual surveys were conducted as part of the National Science Foundation funded River

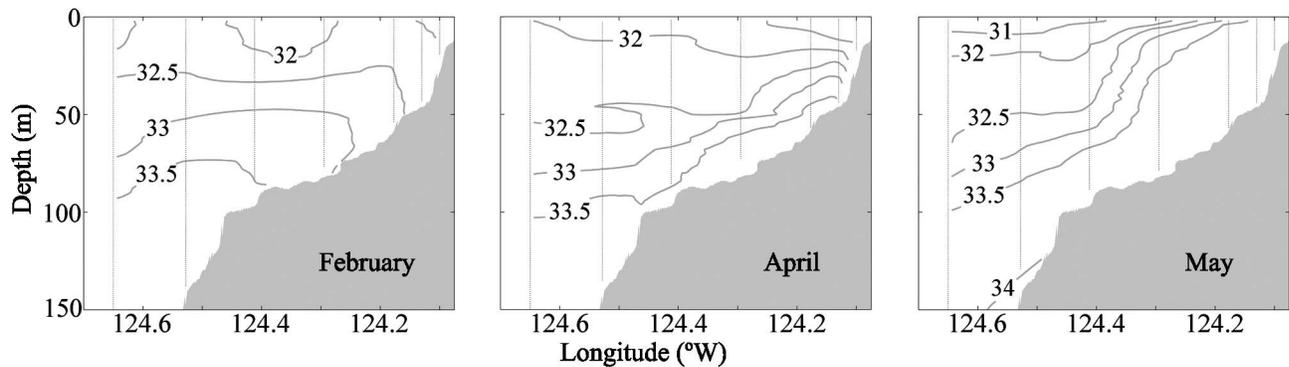


Fig. 2. Vertical distribution of salinity isopleths along the NH Line before (February), during (April), and after (May) the spring transition in 2007. Upwelling draws deep, high-salinity water onto the shelf. The vertical dashed lines are the positions of the seven sampling stations.

Influences on Shelf Ecosystems (RISE; <http://www.ocean.washington.edu/rise/>) program. Oxygen samples were collected with a SeaBird 43 dissolved oxygen sensor attached to a 9/11 CTD (SeaBird) and water sampling rosette (Connolly et al. 2010).

Several cruises in 2004 (September), 2006 (May), 2008 (July), 2009 (August), and 2010 (May, August) were part of the Pacific Coast Ocean Observing System (<http://www.pacoos.org>) program. Oxygen data were collected in a manner similar to the RISE program, with instrument accuracy determined through annual factory calibrations and comparisons to periodic samples analyzed by Winkler titration.

The 2006 (September) and 2007–2012 (May, June, and September) surveys, with the exception of May 2010, were part of a project funded by the Bonneville Power Administration. Data collection during these regular surveys of the distribution and abundance of juvenile salmon (*Oncorhynchus* spp.) used a SeaBird Model 43 dissolved oxygen sensor attached to a CTD (SeaBird). The instrument package was deployed at a rate of 30 m min⁻¹ from the vessel (Fishing Vessel [F/V] *Frosti*, F/V *Snow Drift*, or F/V *Miss Sue*) at fixed station locations along the following cross-shelf transect lines: NH, Cascade Head (CH; 45°03'N), Cape Meares (CM; 45°29'N), Columbia River (CR; 46°10'N), Willapa Bay (WB; 46°40'N), Grays Harbor (GH; 47°N), Queets River (QR; 47°32'N), La Push (LP; 47°55'N), and Father and Son (FS; 48°14'N; Peterson et al. 2010).

Area of hypoxia—Dissolved oxygen data from the vertical profiles taken at each station sampled were binned into 1 m depth bins. The minimum value in the upper 200 m of the water column was extracted from each vertical profile and used to generate horizontal distribution maps using mapping software (Surfer 10; Golden Software). Stations where no samples were collected within 10 m of the bottom, or to a depth of at least 190 m, were excluded. The data were gridded, using the Kriging routine in the software package with x and y resolutions of 0.03 degrees, and contoured.

The area of hypoxia was calculated from regions over the continental shelf bounded by the 1.4 mL L⁻¹ dissolved oxygen contour using Grapher 9 (Golden Software). The area of the continental shelf between the 0 and 200 m depth

contour was also calculated within each survey region for estimations of the percentage of the shelf covered by hypoxic waters.

Source of upwelled water—We used a comparison of salinity values between the shelf slope station (NH25) and a mid-shelf station (NH10) to estimate the depth from which upwelled water originates. Deep water from the shelf slope is drawn onto the shelf through Ekman transport during the upwelling season, causing a tilting of isopycnals (see fig. 11 in Huyer 1983). To eliminate any potential influence of temperature change as the water moves to shallower depths across the shelf, salinity is used in this study instead of density, and shows a similar pattern to what Huyer (1983) illustrated (Fig. 2). Nutrient and other chemical composition data are sometimes used as water-mass tracers, but were not available for this study.

The depth of upwelling was calculated as the minimum depth at Sta. NH25 that had a salinity value within 0.01 of the value measured at 72 m at the mid-shelf station (NH10; bottom depth of 80 m). The tilt of the isopycnals (Fig. 2) means that upwelled water found at 72 m at the mid-shelf station originated from a deeper depth off the shelf before it was moved onto the shelf via Ekman transport. As an example, if the salinity at 72 m at NH10 was 33.53, and that same salinity value was found at 131 m at NH25, then the depth of upwelling source waters would be recorded as 131 m.

For analysis of the oxygen concentration of upwelling source waters, we compared dissolved oxygen values measured at the salinity-derived depths, a constant density ($\sigma_\theta = 26.44$), and a constant depth (150 m). The 26.44 isopycnal was chosen from the average density (26.44 ± 0.12) of the salinity-based upwelling depths. The 150 m depth stratum was chosen to coincide with historic estimates of the deepest depth for upwelled water (Huyer 1983) and to maintain consistency with similar studies conducted in other regions of the California Current (McClatchie et al. 2010).

Results

Seasonal occurrence—The dissolved oxygen concentration of bottom waters on the continental shelf varies

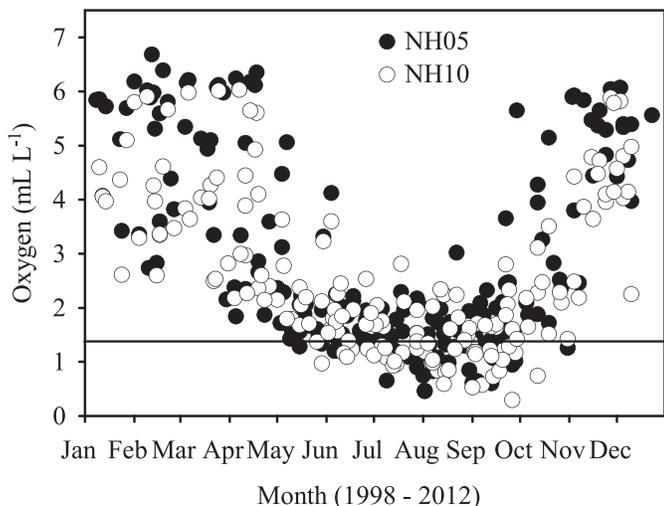


Fig. 3. Seasonal pattern in hypoxia along the NH Line. Data are from 1998–2012 and were collected 8 m off the bottom at Sta. NH05 and NH10, located 9 and 18 km from shore, respectively. Water depths of the stations are 60 m (NH05) and 80 m (NH10). The horizontal line (1.4 mL L^{-1}) depicts the threshold for hypoxia.

seasonally. The highest concentrations at Sta. NH05 and NH10 occur from November to March and decline to an annual low during the months of July through September (Fig. 3). The period of time when bottom waters fall below the 1.4 mL L^{-1} threshold for hypoxia extends from May to late October, based on data collected from 1998–2012. From mid-May through mid-September the dissolved oxygen concentration is nearly always $< 3.0 \text{ mL L}^{-1}$. The exceptions were during late May and early June 2010 and August 2008, following strong downwelling events, when values were between 3.1 and 4.1 mL L^{-1} . At the lower end of the scale, values $< 0.7 \text{ mL L}^{-1}$ occurred in July 2002, August 2004 and 2009, and September 2000, 2001, 2006, and 2011. The lowest value shown is 0.29 mL L^{-1} on 26 September 2006.

Latitudinal gradient—Hypoxic waters overlying the continental shelf occurred primarily north of 43°N latitude (Fig. 1). Minimum dissolved oxygen concentrations ranged from 0.21 – 6.38 mL L^{-1} during the May to September time period, although only values $< 6 \text{ mL L}^{-1}$ are plotted (Fig. 1). Generally, the higher values were from shallower water depths ($< 40 \text{ m}$) which are typically inshore of the upwelling circulation cell and where vertical, wind-driven, and tidal mixing creates a more homogenous water column. Geographically, the areas with the widest continental shelf, such as Heceta Bank (44°N) and along the coast of the state of Washington (north of $46^\circ 15'\text{N}$), had the lowest recorded dissolved oxygen values ($< 0.5 \text{ mL L}^{-1}$).

Vertical extent—Oxygen concentrations decrease with depth, with the minimum values in shelf waters typically measured near the seafloor. An example of this is illustrated using data from 2007 (Fig. 4). During the upwelling season, from April to October, the oxygen isopleths (lines of equal oxygen concentration) typically

run parallel to the bathymetry as Ekman transport moves water up onto the shelf (Fig. 4). From the biweekly sampling along the NH Line, the hypoxic region of the water column over the shelf is primarily in the bottom 10–30 m of the water column. Along the shelf slope, where bottom depths exceed 200 m depth, the hypoxic waters form a much deeper layer, often extending from 150 m to the bottom (data not shown). By November, the oxygen isopleths recede downward and off the shelf as seasonal downwelling conditions are established and bottom waters are ventilated by more oxygenated surface waters.

Horizontal distribution—The horizontal distribution of hypoxia varies seasonally and interannually (Fig. 5). Surveys along the southern portion of the Oregon shelf found little evidence of hypoxic bottom waters in 1998 and 1999. From 2000 through 2002 there was a recurring pool of hypoxic bottom waters during the summer months over Heceta Bank (44°N) that was not evident in samples collected in the same region in 2003 and 2004. From 2006 to 2009, large regions of hypoxia occurred during the summer months throughout the northern section of the NCC, particularly over the wide shelf regions off Washington. Little to no hypoxia was observed in early 2010 (May and June) and 2011–2012 (May). Coverage ranged from 0–62% of the shelf area surveyed (Table 1), with the greatest coverage occurring in September 2007 (62%) and June 2008 (60%).

Change in oxygen of upwelled water—The source depth of upwelled waters, based on salinity, varied seasonally and interannually. The mean depth across all years and months (limited to the May to September upwelling season) is 127 m. However, there is an apparent shoaling of the upwelling depth from July through September (Fig. 6), with a monthly average depth of 135 m from May through July and a decrease to 126 m in August and 110 m in September.

On an interannual basis, the mean upwelling depth based on salinity has remained relatively constant at 127 m (Fig. 7). There is no statistically significant linear increase or decrease in the depth of upwelling for any of the months, or for all data as an aggregate over the 16 yr of measurements.

The oxygen concentration of source waters for upwelling is typically between 1.4 and 2.5 mL L^{-1} (Fig. 8A–C). Instances of source waters having an oxygen concentration below the 1.4 mL L^{-1} threshold for hypoxia occurred in 2002 (July), 2007 (July, August), and 2011 (September). The interannual trend in dissolved oxygen concentration of source waters has a gradual decline from 1998 through 2007, with a subsequent increase from 2008–2010 before leveling off for the last 2 yr. This pattern is similar across the three metrics used to determine the depth of upwelled water (i.e., salinity-based, constant isopycnal, and constant depth), and is more evident in the annual oxygen anomalies (Fig. 8D–F). There are some differences between the three methods used to portray the upwelling depth, but the most negative anomaly values were consistently found in years 2002, and 2005 through 2007.

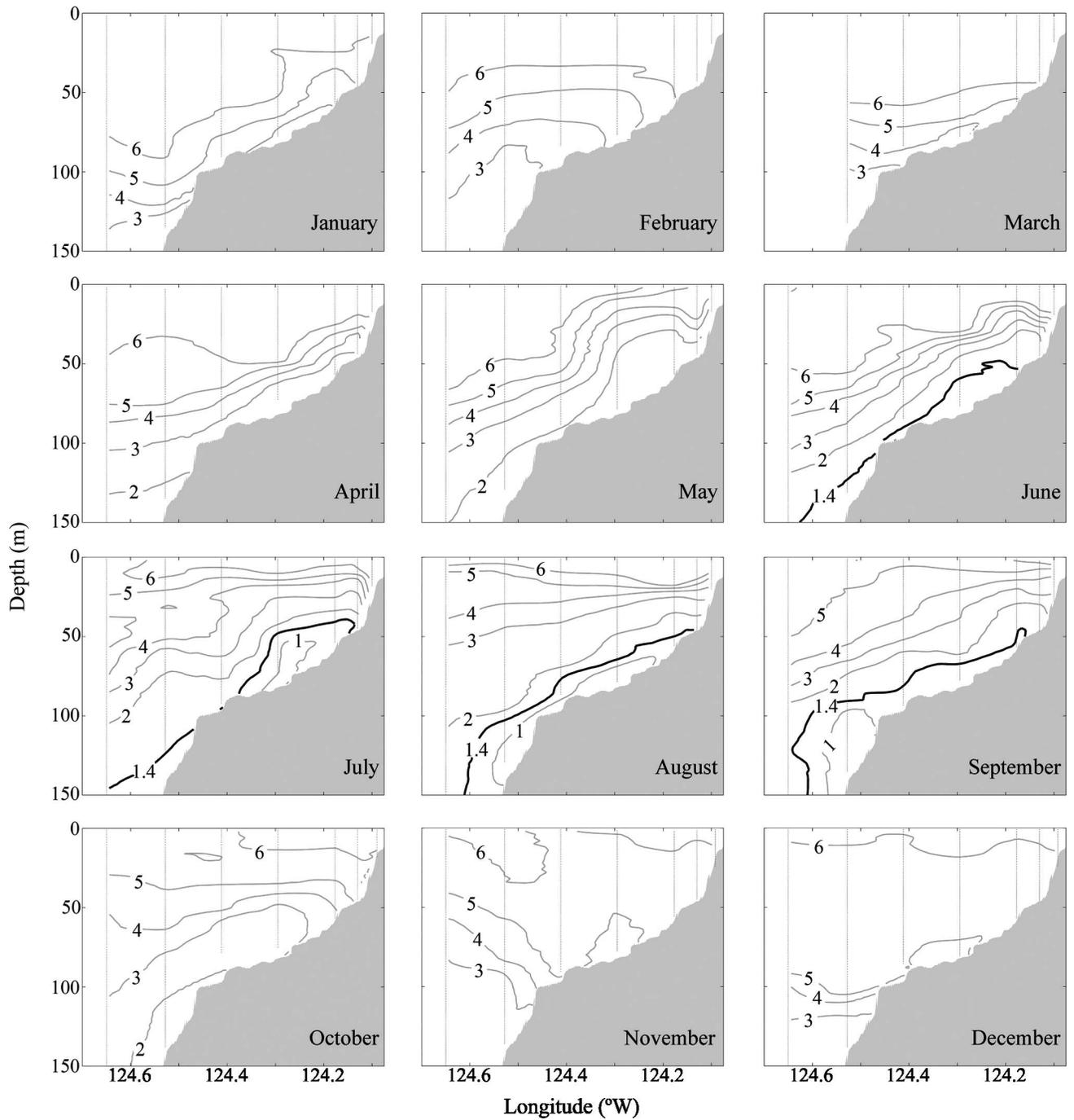
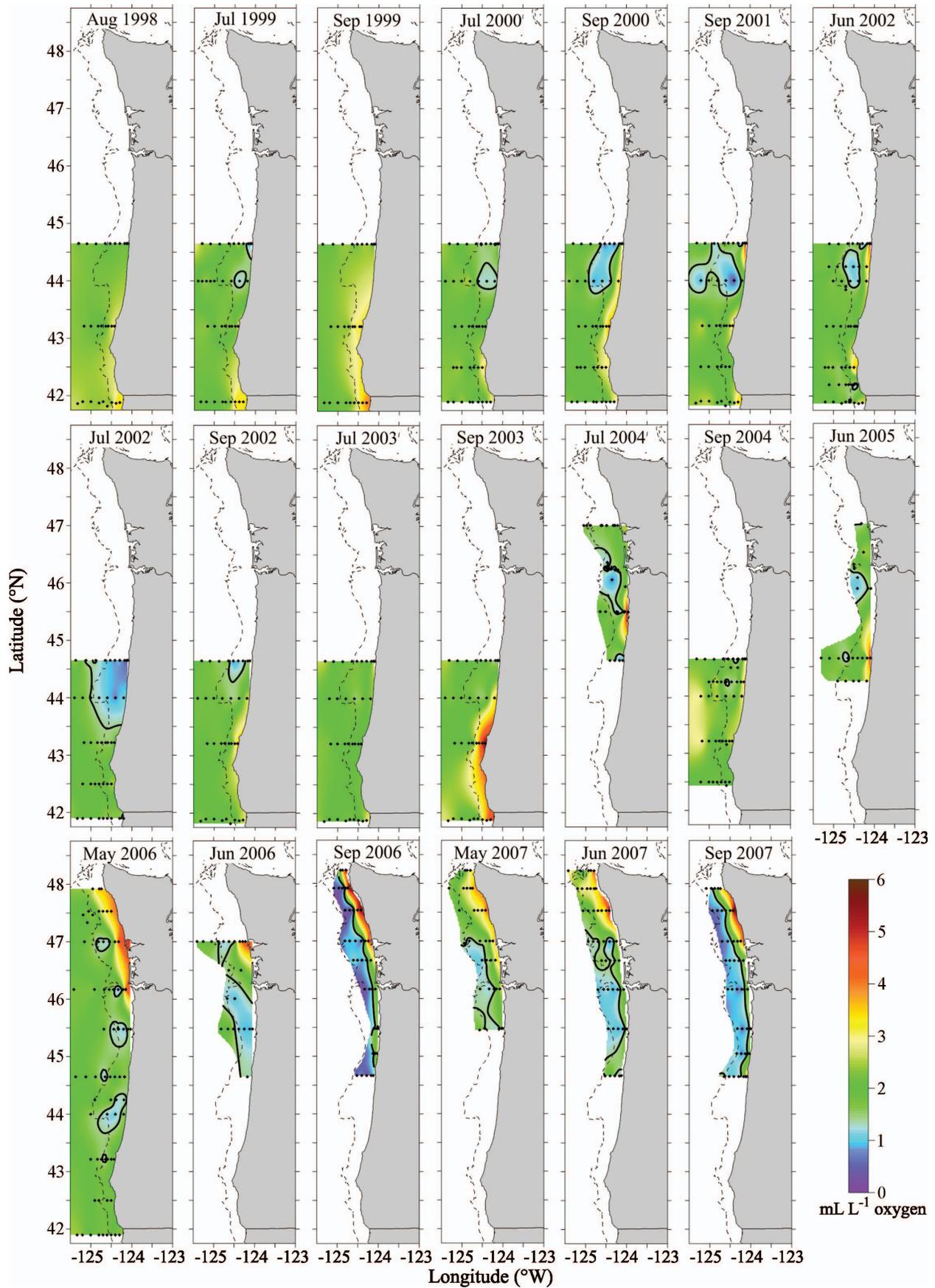


Fig. 4. Distribution of hypoxic waters across the Oregon shelf along the NH Line during 2007. Isoleths are for dissolved oxygen (mL L^{-1}), with the bold isopleth marking the hypoxia threshold (1.4 mL L^{-1}). Vertical dashed lines show the position of the seven sampling stations.

→

Fig. 5. Maps of the minimum dissolved oxygen concentration in the upper 200 m of the water column. Colors are dissolved oxygen (mL L^{-1}). The solid contour represents the 1.4 mL L^{-1} hypoxia threshold. The dashed contour line is the 200 m isobath (shelf break). Station locations for data collection are represented by solid dots.



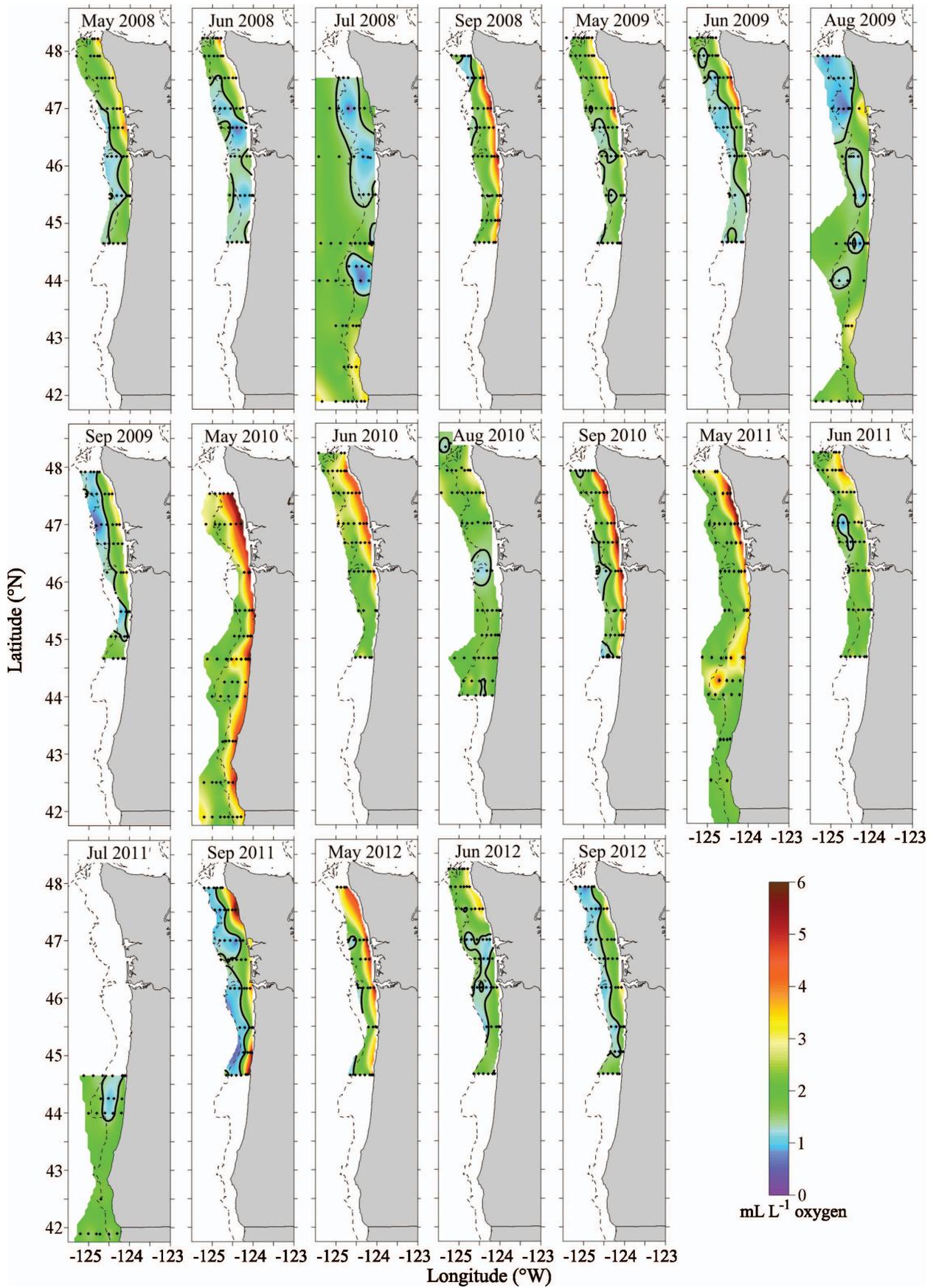


Figure 5. Continued.

Table 1. Proportion of the continental shelf covered by hypoxic waters during each of the broad-scale surveys (Fig. 5). The area of the continental shelf is 10,226 km² to the south of the NH Line (41°54' to 44°39.1'N) and 15,750 km² to the north (44°39.1' to 47°55'N).

Date	Hypoxia area (km ²)	% of shelf
South of NH Line		
Aug 98	0	0
Jul 99	713	7
Sep 99	0	0
Jul 00	1391	14
Sep 00	3146	31
Sep 01	2987	29
Jun 02	1913	19
Jul 02	6089	60
Sep 02	941	9
Jul 03	0	0
Sep 03	0	0
May 06	1730	17
Jul 08	2851	28
Aug 09	1445	14
May 10	0	0
May 11	0	0
July 11	2438	24
North of NH Line		
May 06	1837	12
Sep 06	8264	52
May 07	3724	24
Jun 07	5408	34
Sep 07	9758	62
May 08	3176	20
Jun 08	9488	60
Sep 08	1924	12
May 09	1453	9
Jun 09	6305	40
Aug 09	7714	49
Sep 09	5292	34
Jun 10	0	0
Aug 10	1576	10
Sep 10	972	6
May 11	0	0
Jun 11	871	6
Sep 11	7456	47
May 12	180	1
Jun 12	4406	28
Sep 12	6503	41

Discussion

The data presented here, collected over the last 15 yr, illustrate that hypoxia in the NCC is highly seasonal, patchily distributed in both time and space, and can potentially affect over 60% of the shelf. Several regions, particularly the wider shelf areas such as Heceta Bank off Oregon (44°N) and much of the Washington shelf (north of 46°15'N), are the most prone to early development and persistence of hypoxic bottom waters.

Seasonal occurrence and variability—The observation that hypoxic conditions develop in bottom waters of the shelf solely during the upwelling season makes it clear that

upwelled waters play a strong role in the development of hypoxia. It is also clear that upwelled waters are not typically hypoxic before they are drawn onto the shelf via Ekman transport. The upwelling source waters typically contain 1.5–3 mL L⁻¹ dissolved oxygen, whereas bottom waters over the shelf have 0.5–2 mL L⁻¹. Biochemical drawdown of dissolved oxygen within the water column and sediments are an obvious contributing factor to this mismatch. Within the water column, respiration rates in the NCC are estimated to be 0.02 mL L⁻¹ d⁻¹ (Connolly et al. 2010; Reimers et al. 2012) with a similar additional amount of drawdown in the bottom 5 to 10 m attributed to benthic respiration (Reimers et al. 2012).

Assuming cross-shelf transport of bottom water on the order of 2–5 cm s⁻¹ (Huyer 1983), and an average shelf width of 35 km, it would take 8–20 d for water to move to the inner shelf. With a drawdown rate of 0.04 mL L⁻¹ d⁻¹ due to water column and benthic respiration, dissolved oxygen concentrations would drop by 0.3–0.8 mL L⁻¹ over the 8–20 d cross-shelf transit time. This would be barely enough to account for the 0.77 mL L⁻¹ difference between the hypoxia threshold (1.4 mL L⁻¹) and the average concentration of dissolved oxygen in upwelling waters (2.17 mL L⁻¹). Average relaxation events during the upwelling season are on the order of 7 d, adding to the residence time of near-bottom waters and an additional 0.3 mL L⁻¹ reduction in oxygen concentration. Note that this is most applicable to a two-dimensional assumption for the movement of upwelled waters onto the shelf. Horizontal advection and retention increases residence times in some areas, particularly over shallow banks. This is discussed further in regards to spatial variability, below.

In several years (2001, 2002, 2004, 2006, 2011), oxygen concentrations below 0.65 mL L⁻¹ were detected mid-shelf along the NH Line, with the lowest value of 0.29 mL L⁻¹ measured in 2006. Both 2002 and 2006 were years in which severe hypoxia and anoxia were detected north and south of the NH Line (Grantham et al. 2004; Chan et al. 2008; Connolly et al. 2010). During these years, the dissolved oxygen concentration in upwelled waters was measured to be in the range of 1.4–2.5 mL L⁻¹. Using a 0.65 mL L⁻¹ threshold, the 0.75–1.85 mL L⁻¹ difference between the concentration of freshly upwelling water and the mid-shelf measurements is outside the range accounted for by water column and benthic respiration referenced above. Reimers et al. (2012) pointed out that their measured respiration values may be slightly underestimated, as these average benthic respiration values (3 to 10 mmol m⁻² d⁻¹) were below the predicted average of 11 mmol m⁻² d⁻¹. Clearly, more work is needed before accurate oxygen budgets can be developed. Accounting for seasonal variability in the supply and degradation of organic matter at the base of the water column is of particular importance.

Spatial variability—Areas of hypoxia tend to occur north of 43.5°N latitude, coincident with the wider shelf regions along the Oregon and Washington coast (Fig. 1). The few instances of hypoxia detected between 40.9° and 44°N came from samples collected in 2002 and 2006 when extremely low dissolved oxygen values were detected in other parts of the NCC (Grantham et al. 2004; Chan et al. 2008).

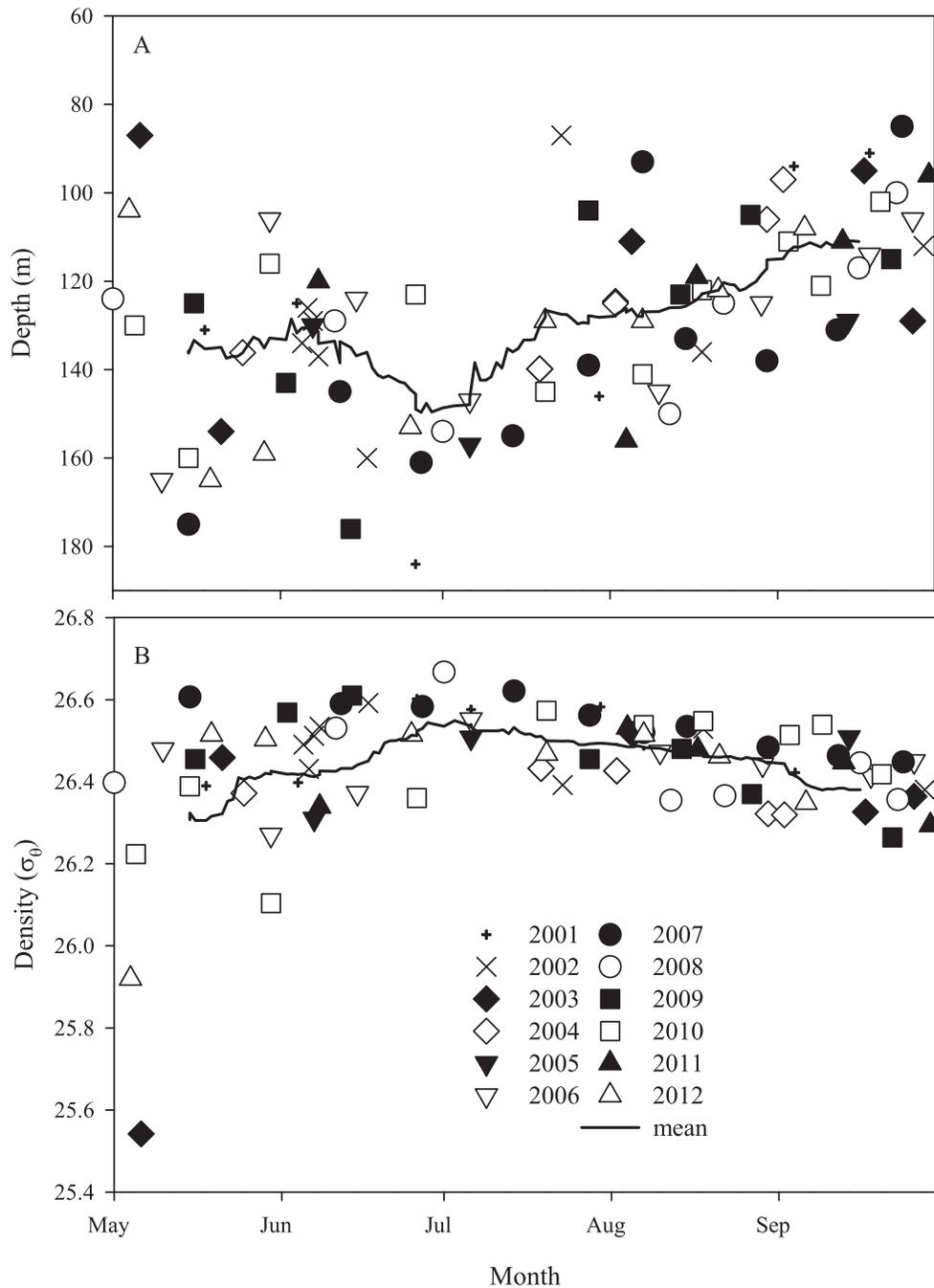


Fig. 6. Seasonal change in the (A) depth and (B) density of upwelling source water based on a salinity comparison between a shelf-slope (NH25) and mid-shelf (NH10) station.

The occurrence of low-oxygen bottom waters over the wider shelf areas is not surprising given the reduced current velocities and reversals in current direction indicative of retention of water masses over banks and within canyons in the NCC (Checkley and Barth 2009). Barth et al. (2005), and references therein, provide a nice explanation of how elevated levels of primary production and zooplankton lead to an increased flux of organic matter and a reduction in dissolved oxygen in bottom waters over Heceta Bank off central Oregon (Barth et al. 2005). A similar mechanism is

described for the Washington shelf (Hickey and Banas 2003; Banas et al. 2009) in which its wider shelf combined with reduced wind stress is conducive to longer water and particulate matter retention times, thereby allowing for additional drawdown of dissolved oxygen.

The horizontal extent of hypoxia in the NCC reached as high as 62% of the shelf area surveyed north of the NH Line and 60% to the south (Table 1). The entire shelf north and south of the NH Line was not surveyed during these periods of greatest coverage by hypoxic waters (e.g.,

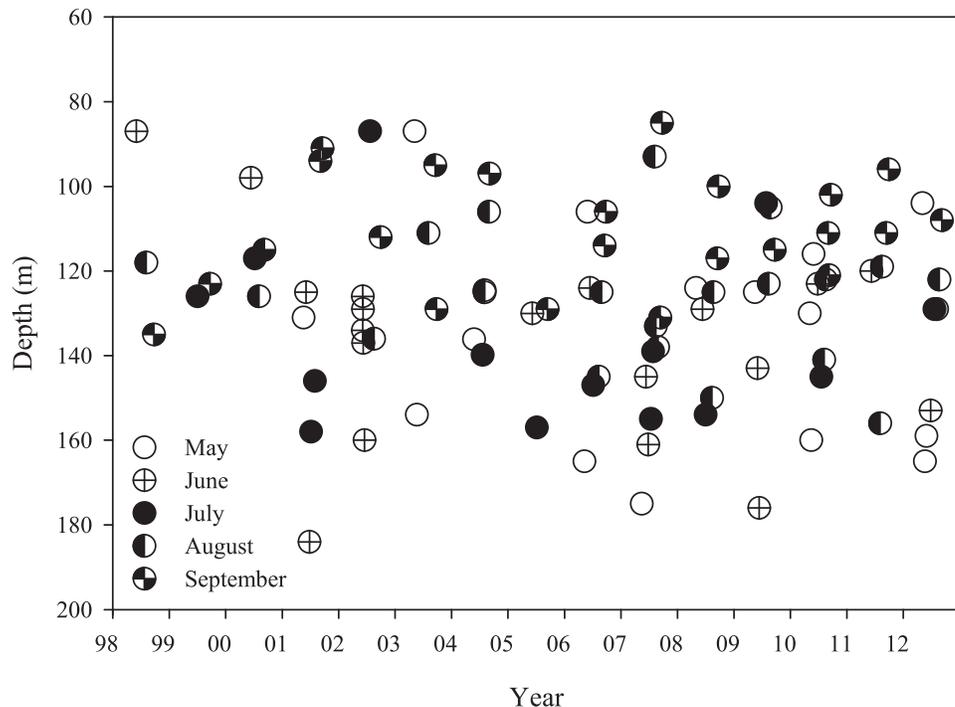


Fig. 7. Interannual variability in the depth of upwelling source water. Data are from May–September of each year (1998–2012) and the depths were determined from a salinity-based comparison between Sta. NH10 and NH25.

2002, September 2006, 2007). However, assuming equal proportions of the shelf could be affected, total coverage of the $\sim 26,000$ km² of shelf in the NCC is likely on the order of 15,600 km². In comparison, the hypoxic area in the Gulf of Mexico during midsummer averages about 15,900 km² with a maximum extent of 22,000 km² (Rabalais et al. 2007).

The occurrence of hypoxia in the Gulf of Mexico is a result of anthropogenic nutrient loading via runoff into the Mississippi River. In the NCC, the primary supply of nutrients is from upwelled waters. There is significant riverine input to the NCC from the Columbia River and Fraser River via the Strait of Juan de Fuca. These freshwater inputs provide nutrients, particularly silica and iron, but the amounts are relatively minor compared to what is being upwelled onto the shelf (Lohan and Bruland 2006). The Columbia River, however, acts as a mechanism for nutrient distribution. The river plume is bidirectional, flowing offshore and to the south during the summer months (due to southward upwelling winds) as well as close to shore and northwards (due to the Coriolis effect; Hickey et al. 2005). Upwelled waters are mixed into the plume and carried across the shelf (Lohan and Bruland 2006). Interestingly, the seasonal development of hypoxia in the NCC is often characterized by early presence of hypoxic bottom waters near the mouth of the Columbia River (e.g., see the series of maps for 2007 and 2008 in Fig. 5). The area around the river mouth, however, does not have particularly low summertime dissolved oxygen values relative to the shelf regions to the north, or Heceta Bank (44°N) and the NH Line (44°39'N) to the south

(Fig. 1). It is likely that the early onset of hypoxia in the Columbia River area is a function of deeper waters being upwelled through the nearby canyons, including Astoria Canyon located just offshore of the mouth of the river (Hickey and Banas 2008).

Source waters—There is distinct interannual variability in the amount of dissolved oxygen in upwelled waters over the last 15 yr. The data from this study show a general decline from 1998–2007, an increase from 2007–2010, and then a plateau or potential decline again in 2011–2012 (Fig. 8). The oxygen anomaly plots (Fig. 8D–F) depict the trend. It must be noted that some years, in particular 2005, contain data from only 1 month and may not represent the actual mean oxygen concentration for that season. Over a longer timescale of 50 yr there is evidence that waters in the poleward undercurrent, at depths between 150–200 m along the shelf slope, have decreased in oxygen concentration by 25% to around $100 \mu\text{mol kg}^{-1}$ (Pierce et al. 2012), equivalent to 2.24 mL L^{-1} dissolved oxygen. This decline is based on data from two time periods: 1960–1972 and 1998–2010, with very few data available between 1973–1998 (see fig. 4a in Pierce et al. 2012), so it is not possible to discern if the oscillation we see in the most recent 15 yr extends beyond this time frame, possibly correlating with factors that influence mixing in the North Pacific, such as the 18.6 yr lunar-nodal cycle (Yasuda et al. 2006), El Niño Southern Oscillation (PDO; Mantua et al. 1997; Chhak and Di Lorenzo 2007) and North Pacific Gyre Oscillation (NPGO; Di Lorenzo et al. 2008), and subsequent variability in the California

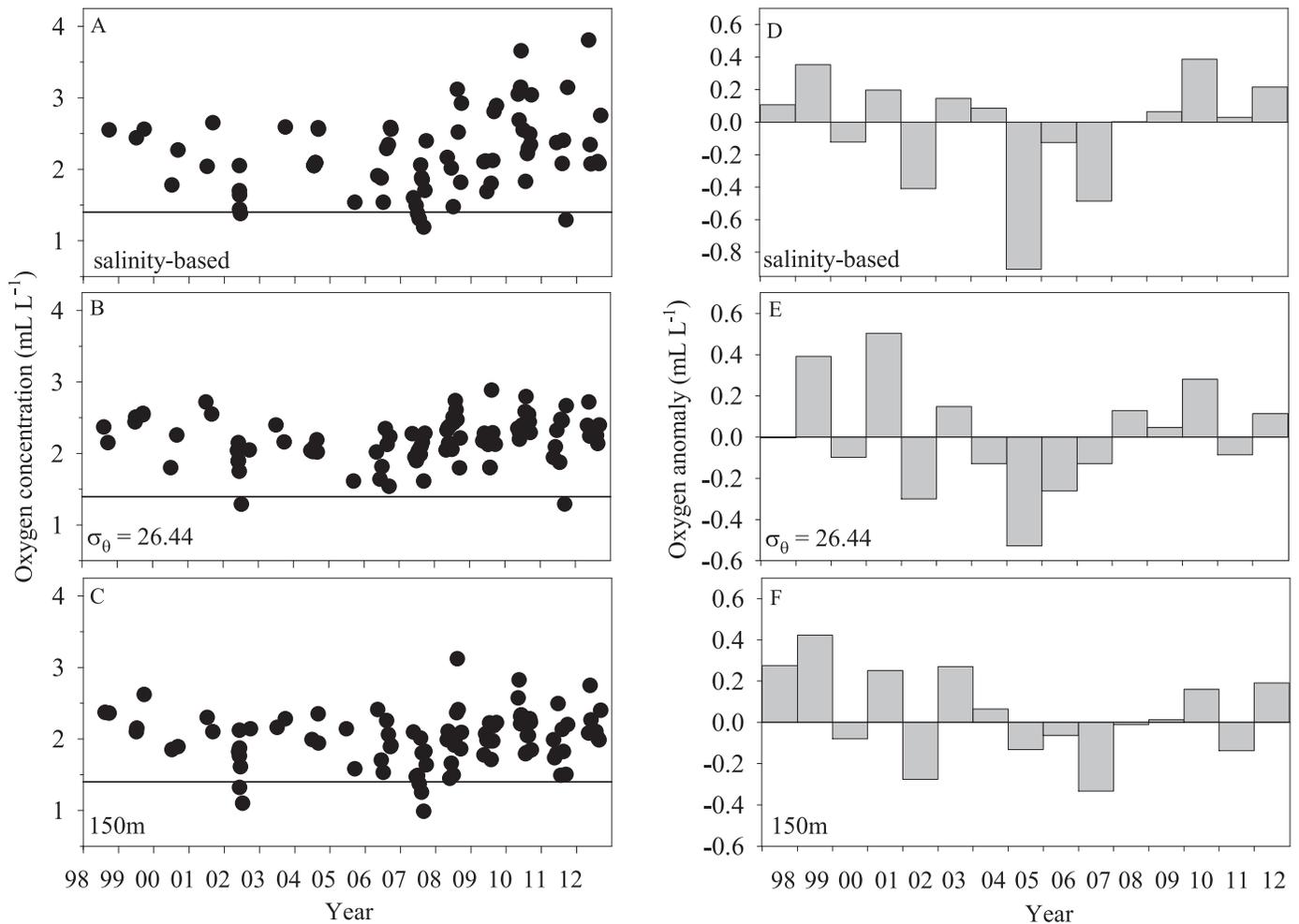


Fig. 8. Dissolved oxygen concentration and average annual oxygen anomaly of upwelling source waters based on three metrics: (A, D) salinity difference, (B, E) constant isopycnal ($\sigma_{\theta} = 26.44$), and (C, F) constant depth (150 m). The data are from the upwelling months (May–September). The horizontal line in each plot (A–C) is the 1.4 mL L^{-1} hypoxia threshold.

Undercurrent (CU; Hickey 1979). The CU originates in the subtropics and this region has seen a recent trend of decreasing oxygen content (Bograd et al. 2008; McClatchie et al. 2010). Bograd et al. (2008) identify and reference some possible mechanisms contributing to a change in the oxygen content of CU water, including the shoaling of the OMZ and reduced ventilation of subsurface waters due to increased stratification (Keeling and Garcia 2002), both of which may be acting locally as well as influencing waters that are being advected into the area. Within the time frame of this study, there is a significant, linear relationship between the oxygen anomalies of upwelling source waters and both the NPGO (data from <http://www.o3d.org/npgo>) and PDO (data from <http://jisao.washington.edu/pdo/PDO.latest>; Fig. 9). The correlation is over a relatively short time span (15 yr) relative to the typically decadal scale oscillation of the PDO and NPGO. However, the correlation between the oxygen anomaly of upwelling source waters and the NPGO provides additional support for the importance of subsurface transport. In this region the NPGO tracks changes in the intensity of the North Pacific Current (NPC; Di Lorenzo et al. 2009). Anomalies in the geostrophic transport of the

NPC likely play an important role in modulating the subsurface advection of water masses into the coastal upwelling system and onto the Oregon shelf.

Our analysis shows that upwelled waters are drawn from 90–170 m depth, with the depth decreasing by 45 m through the season from an average depth (30 d running mean) of 155 m at the beginning of July to 110 m by mid-September (Fig. 6). This seasonal pattern of the depth of upwelled water is consistent with what would be expected by average wind velocities, in that the peak in upwelling winds and the magnitude of upwelling typically occurs from late June to late September (mean = August 17; Bograd et al. 2009). Assuming that stronger winds would translate to water upwelling from deeper depths (Huyer 1983), one would expect to see an increase in upwelling from the start of the season until July or August and then a decrease until the end of the season. For the data presented in this study, the deepest average upwelling depth occurs in early July, though there are also data from the upwelling of deep water in May. This high variability in May is potentially due to a combination of weaker water column stratification early in the season as well as storm events. The spring

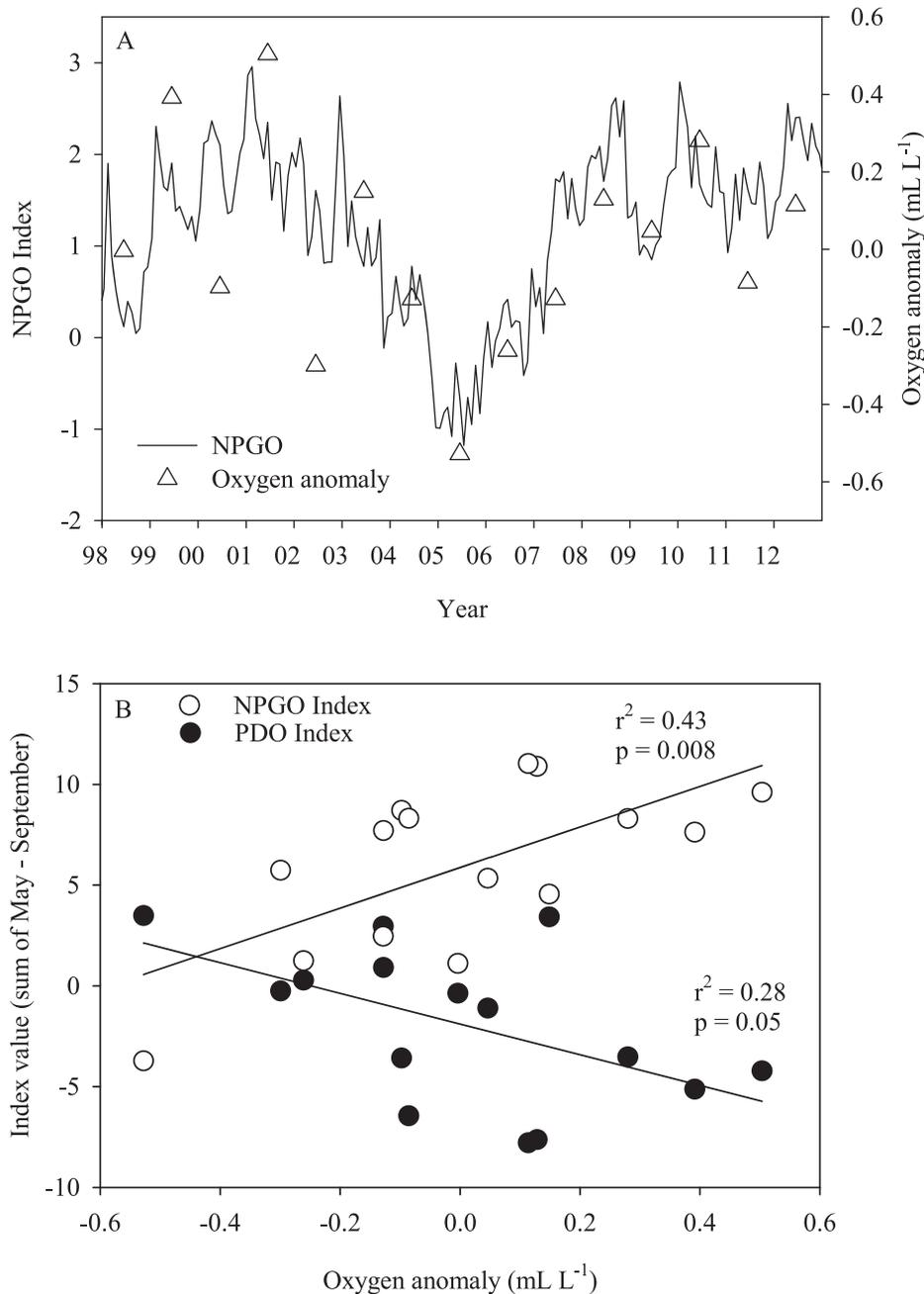


Fig. 9. (A) Interannual variability of the NPGO and the average oxygen anomaly of upwelling source waters. (B) Relationship between the average annual oxygen anomaly of upwelling source waters and the PDO and NPGO indices. For both plots, the oxygen anomaly data are from a constant isopycnal (Fig. 8E).

transition to primarily equatorward, upwelling-favorable winds occurs in April, but there are often occurrences of wind reversals in May as the system is transitioning. The shallow (< 110 m) upwelling depths in early May (Fig. 6) were recorded after periods of strong poleward winds (data not shown) that drive water towards shore (downwelling). These storm events are potentially important to the ecosystem as they can reduce the beneficial effects of upwelling (e.g., nutrient input to surface waters) for extended periods of time, especially during the spring season when many species rely on abundant food

resources for successful feeding and reproduction. It would be interesting to further investigate the effect of these storm events on the ecosystem, including early development of hypoxia, but it is beyond the scope of this paper.

The average depth range (110–155 m) for upwelled water is nearly identical to the 80–200 m depth of the CU and highlights the fact that processes in the subtropical regions influence the shelf in the NCC and farther north to British Columbia and Alaska (Thomson and Krassovski 2010; Pierce et al. 2012). Occurrences of hypoxia have been noted to varying degrees

throughout the entire California Current and north to British Columbia. The spatial and temporal resolution of dissolved oxygen data through this area is historically sparse, but becoming increasingly available. Cooperative efforts to compile and analyze these data for a larger geographic region than what was presented here should prove to be a valuable contribution to our understanding of the dynamics of hypoxia along the west coast of North America.

Acknowledgments

We thank C. Tracy Shaw, Leah Feinberg, Jennifer Menkel, Jennifer Fisher, Aaron Chappelle, Alyssa Hopkins, Bobby Ireland, and the crew of the R/V *Elakha* for Newport Hydrographic Line data collection and the National Oceanic and Atmospheric Administration (NOAA) Fish Ecology Plume group and the crew of the F/V *Frosti* for spatial data collection. We thank the anonymous reviewers for their significant improvements to the manuscript. This work was possible because of the people who collected and processed data as part of, and the funding provided by, the following agencies and programs: National Science Foundation (Global Ocean Ecosystem Dynamics [GLOBEC], River Influence on Shelf Ecosystems [RISE]), NOAA (Stock Assessment Improvement Program [SAIP]), and the Bonneville Power Administration (BPA; Ocean Survival of Salmon Project). This is GLOBEC contribution 732 and RISE contribution 54.

References

- ANDERSON, T., AND G. TAYLOR. 2001. Nutrient pulses, plankton blooms, and seasonal hypoxia in Western Long Island Sound. *Estuaries* **24**: 228–243, doi:10.2307/1352947
- BANAS, N. S., P. MACCREADY, AND B. M. HICKEY. 2009. The Columbia River plume as cross-shelf exporter and along-coast barrier. *Cont. Shelf Res.* **29**: 292–301, doi:10.1016/j.csr.2008.03.011
- BARTH, J. A., S. D. PIERCE, AND R. M. CASTELAO. 2005. Time-dependent, wind-driven flow over a shallow midshelf submarine bank. *J. Geophys. Res.* **110**: C10S05, doi:10.1029/2004JC002761
- BOGRAD, S., C. G. CASTRO, E. DI LORENZO, D. M. PALACIOS, H. BAILEY, W. GILLY, AND F. CHAVEZ. 2008. Oxygen declines and the shoaling of the hypoxic boundary in the California Current. *Geophys. Res. Lett.* **35**: L12607, doi:10.1029/2008GL034185
- , I. SCHROEDER, N. SARKAR, X. QIU, W. J. SYDEMAN, AND F. B. SCHWING. 2009. Phenology of coastal upwelling in the California Current. *Geophys. Res. Lett.* **36**: L01602, doi:10.1029/2008GL035933
- BREITBURG, D. L., L. PIHL, AND S. E. KOLESAR. 2001. Effects of low dissolved oxygen on the behavior, ecology and harvest of fishes: A comparison of the Chesapeake Bay and Baltic-Kattegat systems, p. 241–267. *In* N. Rabalais and R. E. Turner [eds.], *Coastal and estuarine studies: Coastal hypoxia*. American Geophysical Union.
- CARPENTER, S. R., N. F. CARACO, D. L. CORRELL, R. W. HOWARTH, A. N. SHARPLEY, AND V. H. SMITH. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Appl.* **8**: 559–568, doi:10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2
- CHAN, F., J. A. BARTH, J. LUBCHENCO, A. KIRINCICH, H. WEEKS, W. T. PETERSON, AND B. A. MENGE. 2008. Emergence of anoxia in the California Current large marine ecosystem. *Science* **319**: 920, doi:10.1126/science.1149016
- CHECKLEY, D. M., AND J. A. BARTH. 2009. Patterns and processes in the California Current System. *Prog. Oceanogr.* **83**: 49–64, doi:10.1016/j.pocan.2009.07.028
- CHHAK, K., AND E. DI LORENZO. 2007. Decadal variations in the California Current upwelling cells. *Geophys. Res. Lett.* **34**: L14604, doi:10.1029/2007GL030203
- CONNOLLY, T. P., B. M. HICKEY, S. L. GEIER, AND W. P. COCHLAN. 2010. Processes influencing seasonal hypoxia in the northern California Current System. *J. Geophys. Res.* **115**: C03021, doi:10.1029/2009JC005283
- DI LORENZO, E., AND OTHERS. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophys. Res. Lett.* **35**: L08607, doi:10.1029/2007GL032838
- , AND OTHERS. 2009. Nutrient and salinity decadal variations in the central and eastern North Pacific. *Geophys. Res. Lett.* **36**: L14601, doi:10.1029/2009gl038261
- DIAZ, R. 2001. Overview of hypoxia around the world. *J. Environ. Qual.* **30**: 275–281, doi:10.2134/jeq2001.302275x
- DIAZ, R. J., AND R. ROSENBERG. 1995. Marine benthic hypoxia: A review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanogr. Mar. Biol. Annu. Rev.* **33**: 245–303.
- , AND ———. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* **321**: 926–929, doi:10.1126/science.1156401
- GRANTHAM, B. A., AND OTHERS. 2004. Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature* **429**: 749–754, doi:10.1038/nature02605
- HELLY, J. J., AND L. A. LEVIN. 2004. Global distribution of naturally occurring marine hypoxia on continental margins. *Deep-Sea Res. I* **51**: 1159–1168, doi:10.1016/j.dsr.2004.03.009
- HICKEY, B., AND N. S. BANAS. 2008. Why is the northern end of the California Current System so productive? *Oceanography* **21**: 90–107, doi:10.5670/oceanog.2008.07
- HICKEY, B. M. 1979. The California current system—hypotheses and facts. *Prog. Oceanogr.* **8**: 191–279, doi:10.1016/0079-6611(79)90002-8
- , AND N. S. BANAS. 2003. Oceanography of the U.S. Pacific Northwest coastal ocean and estuaries with application to coastal ecology. *Estuaries* **26**: 1010–1031, doi:10.1007/BF02803360
- , S. GEIER, N. KACHEL, AND A. MACFADYEN. 2005. A bidirectional river plume: The Columbia in summer. *Cont. Shelf Res.* **25**: 1631–1656, doi:10.1016/j.csr.2005.04.010
- HUYER, A. 1983. Coastal upwelling in the California Current system. *Prog. Oceanogr.* **12**: 259–284, doi:10.1016/0079-6611(83)90010-1
- KEELING, R. F., AND H. E. GARCIA. 2002. The change in oceanic O₂ inventory associated with recent global warming. *Proc. Natl. Acad. Sci. USA* **99**: 7848–7853, doi:10.1073/pnas.122154899
- KEISTER, J. E., E. D. HOUE, AND D. L. BREITBURG. 2000. Effects of bottom-layer hypoxia on abundances and depth distributions of organisms in Patuxent River, Chesapeake Bay. *Mar. Ecol. Prog. Ser.* **205**: 43–59, doi:10.3354/meps205043
- LOHAN, M. C., AND K. W. BRULAND. 2006. Importance of vertical mixing for additional sources of nitrate and iron to surface waters of the Columbia River plume: Implications for biology. *Mar. Chem.* **98**: 260–273, doi:10.1016/j.marchem.2005.10.003
- MANTUA, N. J., S. HARE, Y. ZHANG, J. WALLACE, AND R. FRANCIS. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Am. Meteor. Soc.* **78**: 1069–1079, doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2
- MCCLATCHIE, S., R. GOERICKE, R. COSGROVE, G. AUAD, AND R. VETTER. 2010. Oxygen in the Southern California Bight: Multidecadal trends and implications for demersal fisheries. *Geophys. Res. Lett.* **37**: L19602, doi:10.1029/2010GL044497
- MONTAGNA, P. A., AND C. RITTER. 2006. Direct and indirect effects of hypoxia on benthos in Corpus Christi Bay, Texas, U.S.A. *J. Exp. Mar. Biol. Ecol.* **330**: 119–131, doi:10.1016/j.jembe.2005.12.021

- PETERSON, W. T., C. A. MORGAN, J. P. FISHER, AND E. CASILLAS. 2010. Ocean distribution and habitat associations of yearling coho (*Oncorhynchus kisutch*) and Chinook (*O. tshawytscha*) salmon in the northern California Current. *Fish. Oceanogr.* **19**: 508–525, doi:10.1111/j.1365-2419.2010.00560.x
- PIERCE, S. D., J. A. BARTH, R. KIPP SHEARMAN, AND A. Y. EROFEEV. 2012. Declining oxygen in the Northeast Pacific. *J. Phys. Oceanogr.* **42**: 495–501, doi:10.1175/JPO-D-11-0170.1
- QURESHI, N. A., AND N. N. RABALAIS [Eds.]. 2001. Distribution of zooplankton on a seasonally hypoxic continental shelf. American Geophysical Union.
- RABALAIS, N., R. TURNER, B. SEN GUPTA, D. BOESCH, P. CHAPMAN, AND M. MURRELL. 2007. Hypoxia in the northern Gulf of Mexico: Does the science support the Plan to Reduce, Mitigate, and Control Hypoxia? *Estuaries Coasts* **30**: 753–772, doi:10.1007/BF02841332
- , AND R. E. TURNER [Eds.]. 2001. Coastal hypoxia: Consequences for living resources and ecosystems. American Geophysical Union.
- REID, J. L., E. R. BRINTON, A. FLEMINGER, E. L. VENRICK, AND J. A. MCGOWAN. 1978. Ocean circulation and marine life, p. 65–130. *In* H. Charnock and G. Deacon [eds.], *Advances in oceanography*. Plenum.
- REIMERS, C. E., H. T. OZKAN-HALLER, P. BERG, A. DEVOL, K. MCCANN-GROSVENOR, AND R. D. SANDERS. 2012. Benthic oxygen consumption rates during hypoxic conditions on the Oregon continental shelf: Evaluation of the eddy correlation method. *J. Geophys. Res.* **117**: C02021, doi:10.1029/2011JC007564
- SPICER, J. I., M. A. THOMASSON, AND J.-O. STROMBERG. 1999. Possessing a poor anaerobic capacity does not prevent the diel vertical migration of Nordic krill *Meganyctiphanes norvegica* into hypoxic waters. *Mar. Ecol. Prog. Ser.* **185**: 181–187, doi:10.3354/meps185181
- STRAMMA, L., S. SCHMIDTKO, L. A. LEVIN, AND G. C. JOHNSON. 2010. Ocean oxygen minima expansions and their biological impacts. *Deep-Sea Res. I* **57**: 587–595, doi:10.1016/j.dsr.2010.01.005
- THOMSON, R. E., AND M. V. KRASSOVSKI. 2010. Poleward reach of the California Undercurrent extension. *J. Geophys. Res.* **115**: C09027, doi:10.1029/2010JC006280
- WU, R. S. S. 2002. Hypoxia: From molecular responses to ecosystem responses. *Mar. Pollut. Bull.* **45**: 35–45, doi:10.1016/S0025-326X(02)00061-9
- WYRTKI, K. 1962. The oxygen minima in relation to ocean circulation. *Deep-Sea Res.* **9**: 11–23.
- YASUDA, I., S. OSAFUNE, AND H. TATEBE. 2006. Possible explanation linking 18.6-year period nodal tidal cycle with bi-decadal variations of ocean and climate in the North Pacific. *Geophys. Res. Lett.* **33**: L08606, doi:10.1029/2005gl025237

Associate editor: Ronnie Nohr Glud

Received: 04 December 2012

Amended: 07 September 2013

Accepted: 11 September 2013