Patterns and potential drivers of declining oxygen content along the southern California coast

J. A. T. Booth,[1] C. B. Woodson,[2,*] M. Sutula,[3] F. Micheli,[4] S. B. Weisberg,[3] S. J. Bograd,[5] A. Steele,[6] J. Schoen,[7] and L. B. Crowder [3,8]

[1] City of Los Angeles Environmental Monitoring Division, Los Angeles, California
[2] College of Engineering, University of Georgia, Athens, Georgia
[3] Southern California Coastal Water Research Project Authority, Costa Mesa, California
[4] Hopkins Marine Station, Stanford University, Pacific Grove, California
[5] Southwest Fisheries Science Center, National Marine Fisheries Service, Santa Cruz, California
[6] Los Angeles County Sanitation Districts, Whittier, California
[7] University of KwaZulu-Natal, Durban, South Africa
[8] Center for Ocean Solutions, Stanford University, Monterey, California

Abstract

Here we examine a 50+ yr data set from a regionally coordinated southern California water quality monitoring program to assess temporal trends and determine whether nearshore waters are exhibiting changes in dissolved oxygen (DO) content similar to those reported offshore. DO in sub–mixed layer nearshore waters (< 10 km from shore) have declined up to four times faster than reported for offshore waters over the last 15 yr. These trends were evident over depth, and along isopycnals. They have no precedent over the past 50 yr and do not appear to be attributable primarily to large-scale climate variability in ocean DO. Coastal biophysical processes, including increased phytoplankton biomass in surface waters, are likely contributing to the recent elevated rate of DO decline in nearshore waters, as evidenced by higher rates of increase in apparent oxygen utilization. It is unclear whether these processes result from upwelling-derived or anthropogenic nutrient inputs.

California Current waters are increasingly experiencing oxygen depletion (Chan et al. 2008), concomitant with an expanding Eastern Pacific oxygen minimum zone (Keeling and Garcia 2002; Keeling et al. 2010; Stramma et al. 2010). Some of these changes are in response to natural climate variability, such as Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) cycle influences on the California Undercurrent (Connolly et al. 2010; Nam et al. 2011). However, there also appear to be noncyclical changes associated with climate variability affecting dissolved oxygen (DO) content of ocean waters across the Eastern Pacific (Keeling and Garcia 2002; Deutsch et al. 2005; Brewer and Peltzer 2009).

Shoaling of deep, low-DO waters is particularly pertinent in the California Current because the Eastern Pacific Ocean contains the world's largest midwater oxygen minimum zone (OMZ), and the coastal region has a narrow continental shelf (Helly and Levin 2004; Fiedler and Talley 2006; Pennington et al. 2006) making the coastline susceptible to OMZ intrusion. Bograd et al. (2008) documented mean declines in DO concentration of ~ 20% below the mixed layer from 1984–2006, and an ~ 80 m shoaling of the hypoxic zone, with more intense shoaling at inshore locations of the Southern California Bight (SCB). Similarly, McClatchie et al. (2010) reported decreases in DO content of ~ 24% and shoaling of the hypoxic zone of ~ 65 m over the same period. Observed DO declines are not limited to deeper water, as oxygen-depleted offshore waters episodically intrude on the coast through seasonal upwelling, tides, and coastally trapped waves (Nam et al. 2011; Booth et al. 2012; Crawford and Peña 2013).

In other regions of the world's coastal oceans, hypoxic events are commonly attributed to stratification and eutrophication of surface waters combined with microbial respiration at depth (Diaz 2001; Rabalais et al. 2002; Diaz and Rosenberg 2008). Chesapeake Bay and the northern Gulf of Mexico are good examples of where high terrestrial runoff and long residence times combine to yield highly stratified waters with excess nutrients at the surface. The nutrient excess leads to algal blooms that eventually die, sink to the bottom, and decompose, with microbial respiration from decomposition reducing oxygen content. Strong stratification prevents mixing and ventilation of deeper, hypoxic waters with oxygen-rich surface waters. This mechanism of hypoxia development has been considered, until recently, less plausible in windy, highly advective upwelling regions such as the California Current (Chan et al. 2008). However, as large-scale processes drive DO content closer to hypoxic thresholds, and surface waters become warmer, even relatively weak contributions from nutrient-stimulated (anthropogenic or natural) productivity may lead to increased frequency, duration, and strength of hypoxia in coastal upwelling regions.

DO measurements in the nearshore environment are sparse, preventing examination of the extent to which coastal water trends reflect offshore patterns or whether they are related to land-based nutrient contributions. Here we use a data set with sampling elements dating back > 50 yr to quantify DO trends on the SCB shelf and explore alternative hypotheses regarding possible drivers of

Table 1. Data sources, time period covers, and sampling frequency and parameters for all data sets (Oxnard, Hyperion, LACSD, OCSD, CalCOFI). T, temperature; S, salinity.

Source	Time period	Frequency	Parameters
Oxnard	1998–2011	quarterly	DO, T, S, Chl *a*
Hyperion	1959–1977	weekly	DO, T
	1978–1987	yearly	DO, T
	1988–1998	weekly and monthly	DO, T, S
	1998–2011	quarterly	DO, T, S, Chl *a*
LACSD	1982–1998	monthly	DO, T, S
	1998–2011	quarterly	DO, T, S, Chl *a*
OCSD	1975–1985	quarterly	DO, T
	1985–1998	monthly	DO, T
	1998–2011	quarterly	DO, T, S, Chl *a*
CalCOFI	1987–2011	quarterly	DO, T, S, Chl *a*

observed trends. Primarily we ask: (1) Are oxygen concentrations on the continental shelf changing over time and are these trends spatially consistent throughout the SCB? (2) Are these trends consistent in magnitude and timing with those observed for deeper southern California waters as documented by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program (Bograd et al. 2008)? (3) If not, what mechanisms are most likely causing the disparity between offshore and coastal DO trajectories?

Methods

Sampling program—Oxygen data were obtained from conductivity–temperature–depth (CTD) surveys conducted by four large publically owned treatment works (POTWs) to assess the effect of treated effluent discharges on the coastal ocean (Table 1). Historically, sampling was focused around individual outfalls, but beginning in 1998 monitoring efforts were pooled into a coordinated Central Bight Water Quality (CBWQ) program in which each group samples their respective region simultaneously (Fig. 1): the southern Santa Barbara Channel by the Oxnard Wastewater Treatment Plant (Oxnard); Santa Monica Bay by the City of

Los Angeles Bureau of Sanitation (Hyperion Treatment Plant); the Palos Verdes Shelf and San Pedro Bay by the Los Angeles County Sanitation District (LACSD); and the Orange County coast by the Orange County Sanitation District (OCSD).

During each quarterly survey, each facility samples between 48 and 66 stations grouped into cross-shelf transects of about six stations each (Fig. 1). The transects begin at the 10 m isobath (usually within a few 100 m offshore) to approximately 10 km offshore, where water depths can be > 800 m, with sampling limited to the top 75–100 m. Although spacing and depths vary somewhat between agencies, transect stations generally lie on the 30 m and 60 m isobaths, the latter depth being where the four large POTW outfalls are located. Beyond the 60 m isobaths, stations are spaced about 2–3 km apart. Transects are generally 6–8 km in length and extend to the shelf break or beyond (Fig. 1).

Our analyses focused on the coordinated program since 1998, though data sets from three of the individual programs were used to examine longer-term patterns: LACSD from 1981; OCSD from 1974; and Hyperion from 1959. Prior to 1998, the sampling grids covered about one-quarter the area that each agency now samples. These historic grids included fewer stations (28 for the LACSD, and 9–17 for the OCSD), which were sampled monthly. The monthly sampling was completed in a single day, whereas the present larger coordinated sampling grid takes 2–4 d to complete.

At each station, vertical profiles of temperature, salinity, density, DO, pH, turbidity, chlorophyll *a* (Chl *a*), and colored dissolved organic matter are obtained using either an SBE911 (Seabird Inc.; Oxnard, Hyperion) or SBE25 (Seabird Inc.; LACSD, OCSD). CTDs recorded at 24 scans s^{-1} and a descent rate of ~ 1 m s^{-1}. CTDs are deployed to within 2 m of the bottom or to a maximum of 75 or 100 m if the station is deeper than 100 m. All data are post-processed as described in Nezlin et al. (2007). Turbidity and Chl *a* are measured using WetLab instruments. DO data have been collected using membrane diffusion sensors attached to CTDs since 1985. The first sensors were manufactured by Beckman and Yellow Springs Instruments, which were linearly calibrated prior to each survey using end point readings of zero DO and
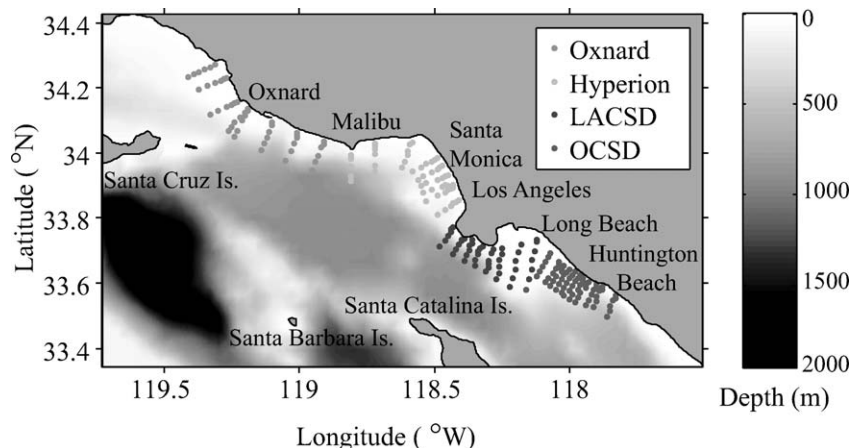

Fig. 1. Map of the Southern California Bight showing locations of coastal water quality monitoring data (CTD casts) by the four regional water quality control boards (Oxnard, Hyperion, LACSD, OCSD).

temperature-adjusted DO saturation. Since the early 2000s, all agencies have used SBE43 sensors (SeaBird), which are supplier-calibrated annually. Prior to the mid-1980s, DO data were obtained by Winkler titrations of discrete samples taken at ~ 10 m depth intervals, though the depth intervals for the earliest Hyperion data were inconsistent between surveys. Apparent oxygen utilization (AOU) was calculated as the difference between the oxygen concentration at saturation and the measured oxygen concentration, and is used as a measure of oxygen consumption through biological processes (Deutsch et al. 2005).

Analyses—Water profiles from CTD casts were binned at 1 m from the surface down to 75 m due to inconsistent sampling below 75 m. All regressions for DO, AOU, temperature, Chl *a*, and salinity were calculated using a robust locally weighted regression (rloess) with a 2 or 4 yr window with an iteratively reweighted least squares algorithm and a bisquare weighting function. We computed the rate of change of the above variables both over depth, and by isopycnal to account for changes in hydrographic structure over the quarterly time series at each location. The rate of change was calculated as the difference between the initial and final values of the regression over the period of analysis, and dividing by the number of years. We also divided these analyses into seasons to account for seasonal wind-driven uplifting of isopycnals (upwelling).

Comparison to offshore trends—We performed similar analyses with CalCOFI data from stations on lines 83, 87, and 90, which we used to compare coastal and offshore water quality time series. Sampling and laboratory analysis procedures for the CalCOFI data are available online (http://www.calcofi.org/references/ccmethods/283-art-ctdatsea.html). The offshore threshold of 175 km was chosen because this appeared to be the boundary between the nearshore upwelling regime and offshore based on maps of time-mean DO along isopycnals.

Individual CalCOFI stations were also matched with the closest CBWQ monitoring station and compared over time at 10, 20, 30, and 40 m depths. The most inshore CalCOFI station on line 83 was compared to the most northern offshore Oxnard station. The most inshore CalCOFI station on line 87 was compared to several stations in Santa Monica Bay. The most inshore CalCOFI station on line 90 was compared to several stations off Orange County. Comparisons of DO over time were made along both isobaric (depth) and isopycnal (density) surfaces using data from all coastal water quality monitoring stations and CalCOFI stations on lines 83, 87, and 90 inshore of ~ 175 km. This is a subset of the data set used in Bograd et al. (2008) for comparison to coastal data. Extensive comparison of nearby (and closely sampled in time) CalCOFI and POTW stations did not yield any systematic errors that may arise between different instruments and calibrations in any of the variables analyzed here.

Results

Spatiotemporal patterns of DO—There were three distinct periods for DO content trends on the southern California shelf: 1959 to the early 1980s (data mostly from Hyperion), when there was no apparent trend or evidence of a strong decadal variability; 1982–1998, when DO increased; and then a radical decline in DO since 1998 (Fig. 2). From 1982 until 1998, DO increased at a rate of 1.65 μmol kg^{-1} yr^{-1} for LACSD (Fig. 3), a trend that was strongest at depth on the shelf and just below the mixed layer during spring and summer (Fig. 4). During this period, temperature also increased at moderate rates throughout the water column, except in summer, which had cooler surface temperatures. The rate of DO decline increased after 1998 (Fig. 3; -4.41 μmol kg^{-1} yr^{-1} for 1998–2011) similar to observations documented by McClatchie et al. (2010) and Bograd et al. (2008). Similar rates for offshore waters were observed by Pierce et al. (2012) for the Northeast Pacific off of Oregon of 0.7 μmol kg^{-1} yr^{-1} where recent hypoxic events on the shelf have had serious ecological and economic effects (Chan et al. 2008). During the spring–summer periods of this later period, isopycnals at depth were raised by about 50–100 m relative to winter and fall conditions (Fig. 5). On the shelf, there was also strong stratification in the upper 25 m and high O_2 production in the mixed layer, with the highest AOU on the shelf from 40–80 m depth (Fig. 5).

For the period from 1998 to 2011, negative trends in DO were observed at every depth for each of the four monitoring programs (Fig. 6), with the strongest rates ($>$ 8 μmol kg^{-1} yr^{-1}) observed just below the mixed layer during spring and summer in all regions. These high rates of decline occurred between 15 and 20 m depth in the spring, but progressed to deeper depths in the summer (25–40 m), consistent with seasonal mixed-layer deepening. However, there were no obvious trends in surface waters ($<$ 10 m depth) during any season, due to saturation associated with atmospheric exchange and a well-mixed surface layer. Rates of oxygen decline in the fall and winter were also significant, but less than observed in spring and summer, and more uniform throughout the water column (Fig. 6). Patterns in oxygen decline by depth did not vary regionally in the spring, fall, or winter. However, in the summer, negative trends were weaker in the southern regions sampled by LACSD and OCSD. While the midwater column (~ 10–50 m) had regional differences in summer, the deepest depths (~ 75 m) were regionally similar (Fig. 6).

Percent change in oxygen since 1998 showed similar patterns to the absolute values, but greater relative loss at depth, consistent with observations of Bograd et al. (2008). Again, no trends were seen at depths $<$ 10 m. In the spring, the largest total percent losses of 40–60% were seen between 15–25 m and decreasing slightly to 30–50% at depth. Summer showed larger relative losses (~ 50%) below 30 m. Unlike the differences in the absolute changes seen between sampling regions, Oxnard, Hyperion, and LACSD clustered together while OCSD showed less relative reduction in DO concentration. The lowest relative losses occurred in fall, with between 10–20% changes consistent throughout the water column, while the winter had minor negative trends at the surface but slightly higher (30–40%) negative trends below ~ 30 m.
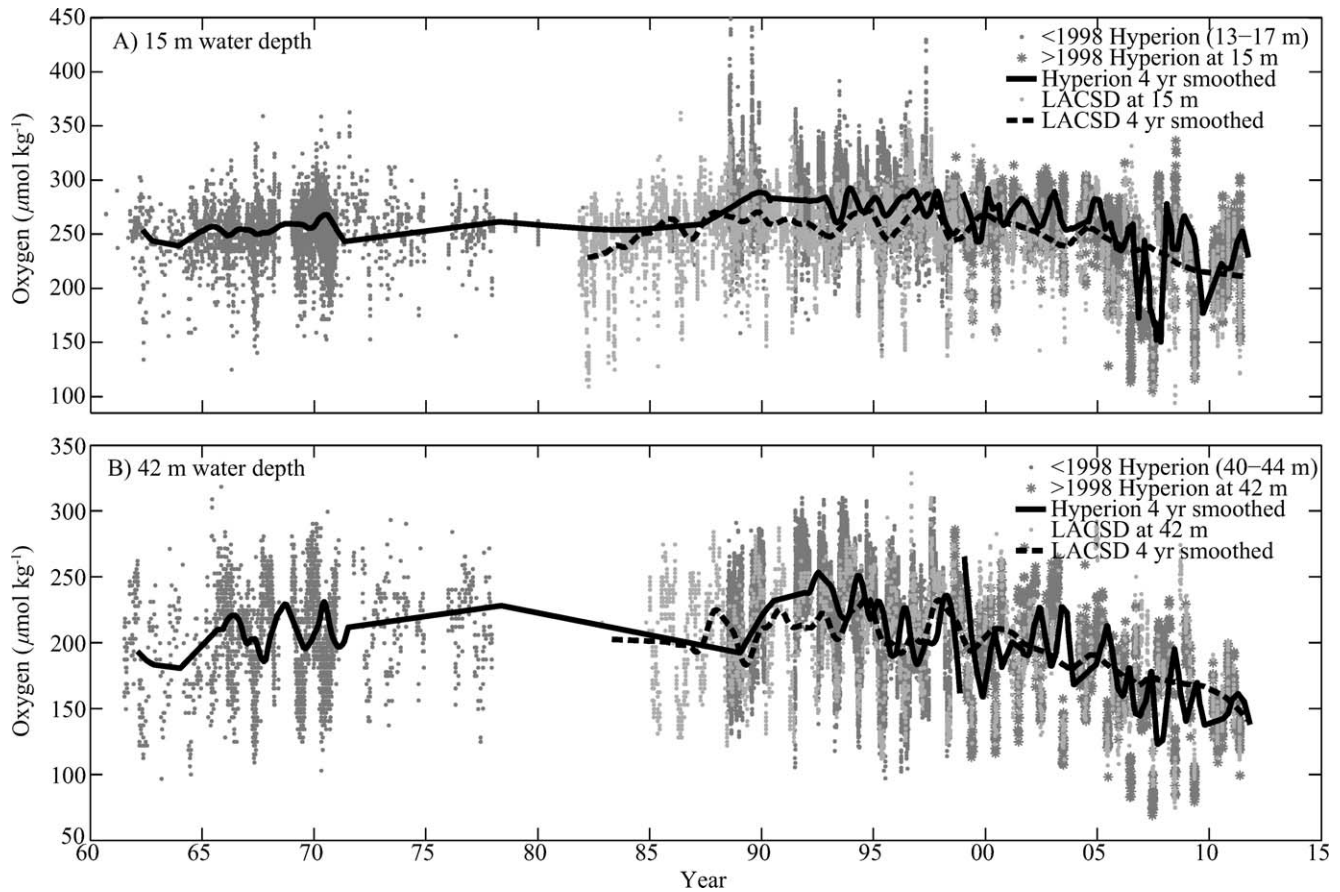
Fig. 2.   Extended dissolved oxygen time series at Hyperion (back to 1959) shown with LACSD and more recent Hyperion data at (A) 15 m and (B) 42 m water depth. Solid and dashed lines are the 4 yr rloess fit to the data.
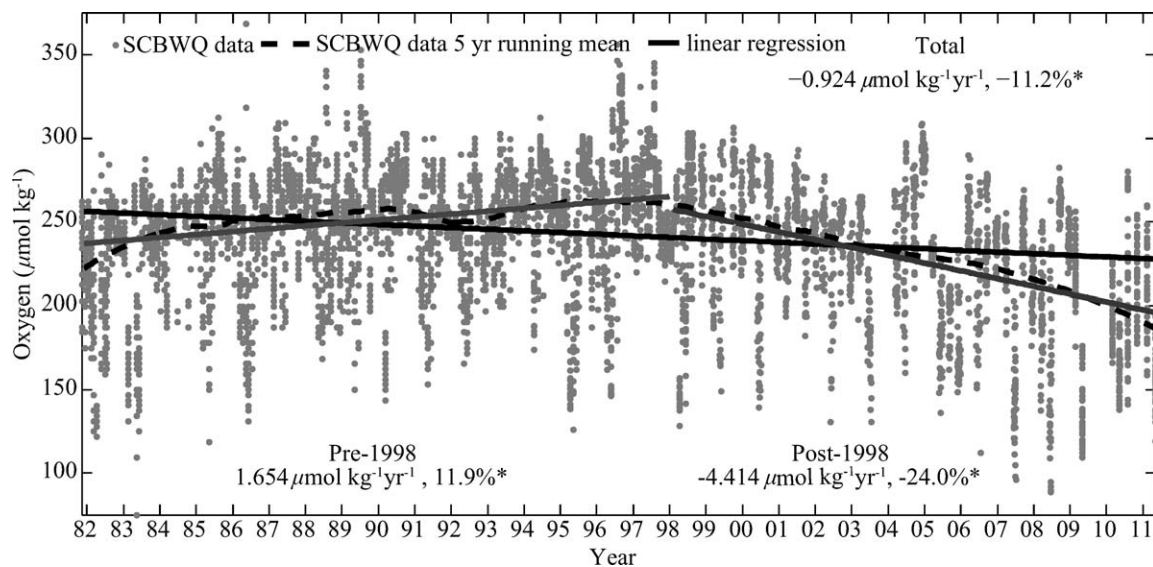

Fig. 3.   DO time series of all samples collected by LACSD at 20 m depth November 1981 to May 2011. Linear regression from 1981 to 2011 is shown as a solid black line and the rate of change per year ($\mu mol\ kg^{-1}\ yr^{-1}$). Regressions for 1981–1997 are shown in light gray and for 1998–2011 in dark gray. Significant trends ($p < 0.05$) are indicated with an asterisk. Black dashed line is the 4 yr rloess fit to the data.
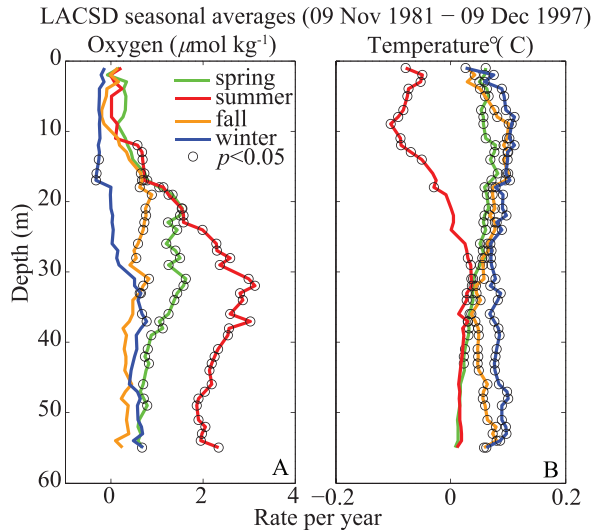
LACSD seasonal averages (09 Nov 1981 − 09 Dec 1997)

Fig. 4. (A) Average annual change in oxygen (μmol kg^{-1} yr^{-1}) and (B) temperature ($^\circ$C yr^{-1}) by depth for every 1 m bin, averaged over each season within the LACSD sampling district (November 1981 to December 1997). Color for each season: spring in green, summer in red, fall in orange, and winter in blue. Black circles indicate significant trend at $p < 0.05$.

There were significant negative trends in DO along isopycnals as well, with peak declines between 25 and 25.5 σ_θ irrespective of season (Fig. 7). Winter, spring, and summer showed the most extreme negative trends in DO (approximately -8 μmol kg^{-1} yr^{-1}) between 25.25 and 25.5 σ_θ, with the largest trends occurring in the LACSD and Hyperion sampling regions. Trends during fall, changes in DO above 26 σ_θ, and the net observed decreases in DO are consistent across all regions (Figs. 6, 7).

Comparison to hydrographic properties—Oxygen declines in nearshore waters were coincident with changes in dominant hydrographic parameters from 1998–2011 (Table 2; Fig. 8 [red stars show CalCOFI stations used for direct comparisons]). Surface temperatures cooled slightly during this period by up to 1.08°C. Surface salinity also dropped during this period by 0.08. There was no significant trend in depth of the mixed layer over this period (Table 2). Stratification, estimated as the maximum buoyancy frequency at the base of the mixed layer, also increased over the region during this period at moderate rates of 0.2–1.4 $\times$ 10^{-2} s^{-1} as the overall cooling trends in surface waters were offset by a weak freshening. Surface waters experienced a cooling and freshening from 1998 to 2011 (Table 2) coincident with the
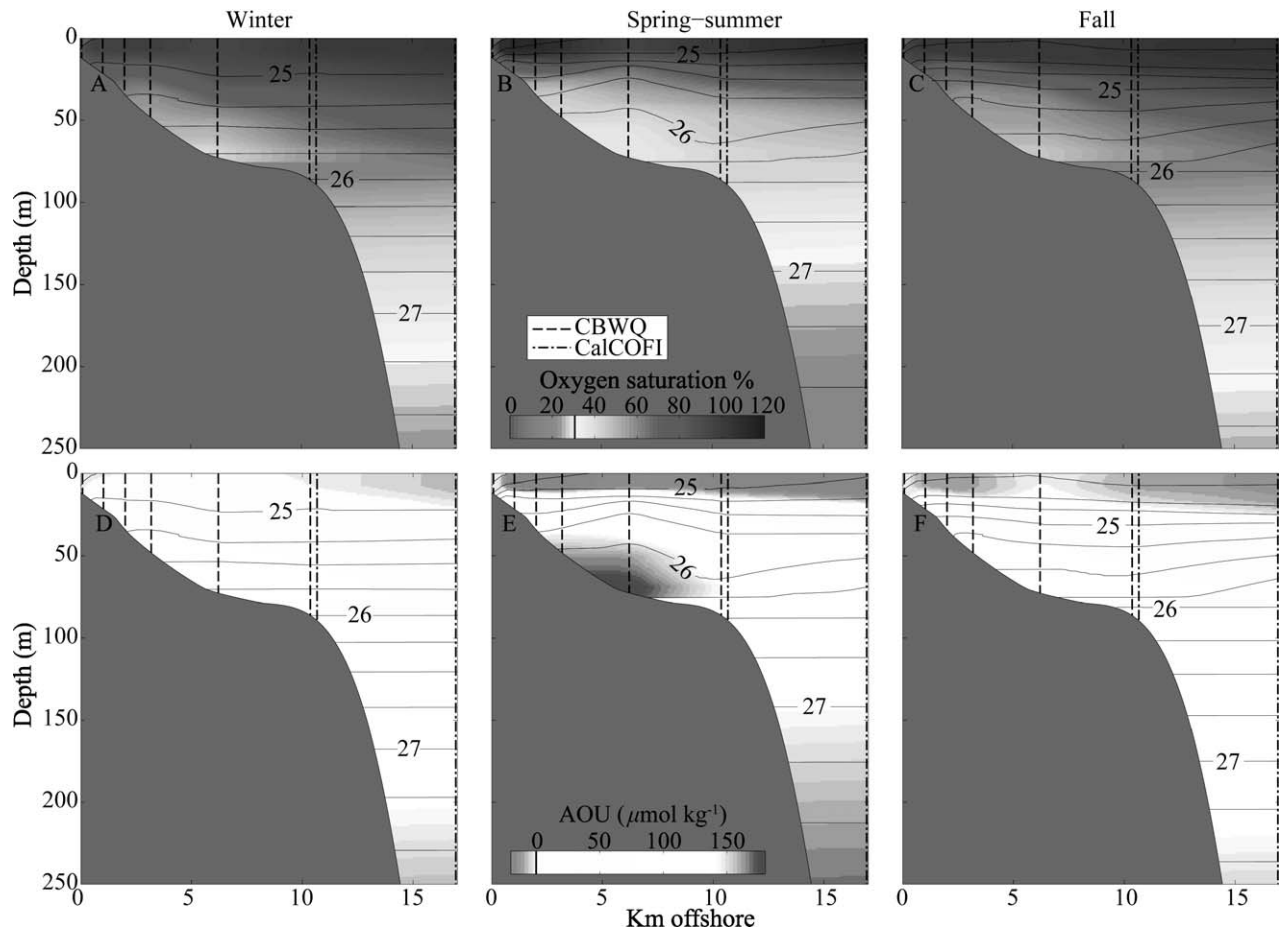

Fig. 5. Mean cross-shelf oxygen and AOU shown with density distributions during major seasons in the SCB (winter, spring–summer, fall) for LACSD. (A–C) Dissolved oxygen saturation with red–blue transition at 30% saturation (hypoxia); (D–F) AOU with contours set to white between zero and the wintertime 200 m depth value. Contour intervals are 0.25 σ_θ.
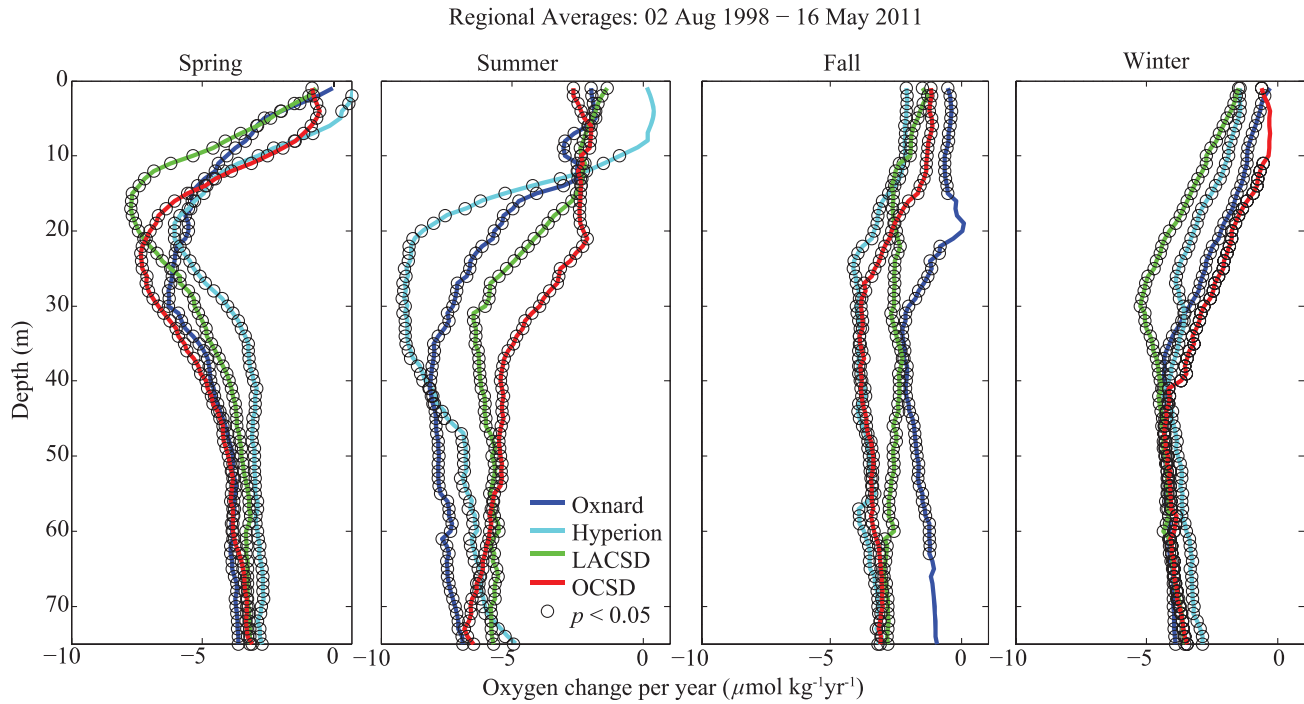
Regional Averages: 02 Aug 1998 − 16 May 2011

Fig. 6. Change in oxygen per year (μmol kg^{-1} yr^{-1}) by depth for every 1 m bin over each season, averaged across all stations within a regional sampling district (August 1998 to May 2011). Black circles indicate significance of the trend at $p < 0.05$.
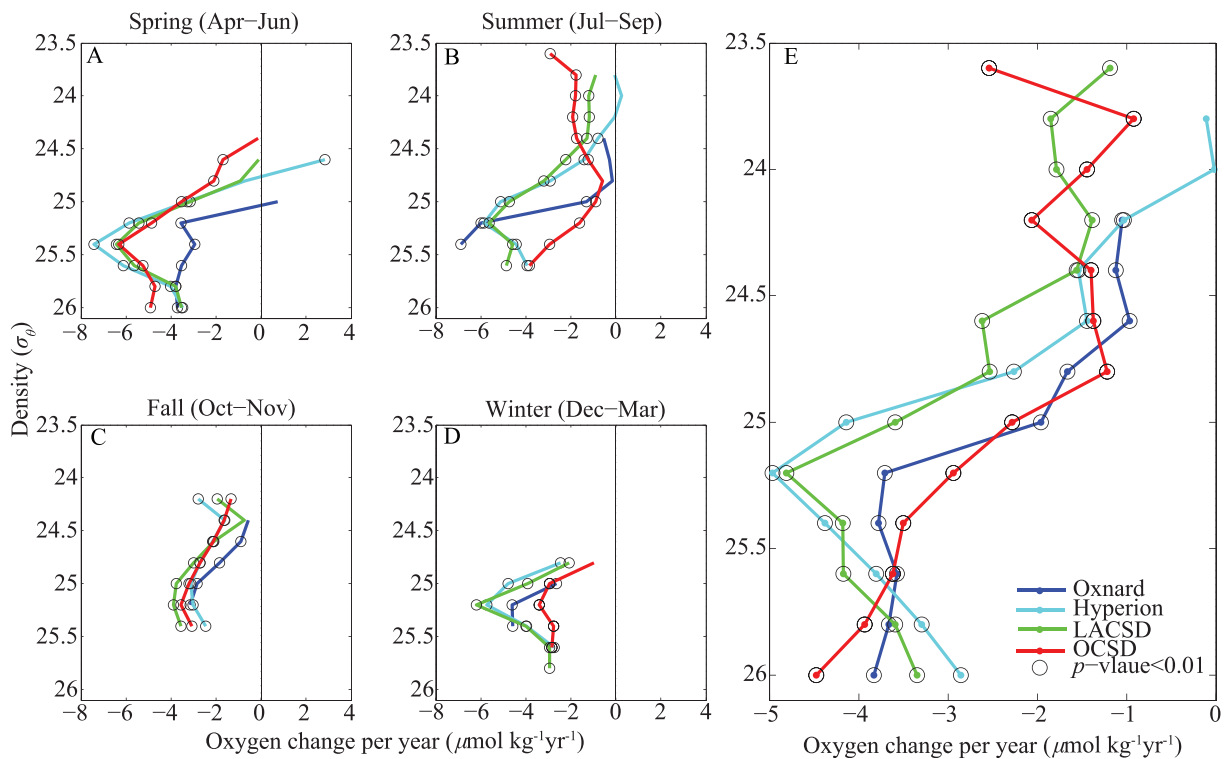

Fig. 7. Change in oxygen per year (μmol kg^{-1} yr^{-1}) from August 1998 to May 2011 by density (σ_θ) and season, (A–D) averaged across all stations within a regional sampling district and (E) all seasons combined. Oxnard stations in blue, Hyperion in teal, LACSD in green, and OCSD in red. Black circles indicate significance of the trend at $p < 0.05$.

Table 2. Mean trends in oxygen and important hydrographic parameters over the period 1998–2011 for all districts by season. Negative rate for mixed-layer depth indicates shoaling.

Parameter	Winter		Spring		Summer		Fall	
	Rate (yr^{-1})	Total	Rate (yr^{-1})	Total	Rate (yr^{-1})	Total	Rate (yr^{-1})	Total
Surface (<20 m) temperature (°C)	0.01*	0.14	−0.02*	−0.24	−0.08*	−1.17	−0.05*	−0.63
Surface (<20 m) salinity	−0.01*	−0.20	−0.006*	−0.09	−0.003*	−0.05	−0.006*	−0.08
Mixed-layer depth (m)	—	—	−0.22*	3.1	−0.18*	2.6	−0.23*	3.2
Stratification ($\times 10^2$ s^{-1})	0.093*	1.3	0.075	1.1	0.059	0.83	0.019	0.26
AOU (μmol kg^{-1})	3.0*	41.7	6.0*	83.8	4.3*	60.0	2.5*	34.6

* Indicates a rate significantly different than zero ($p < 0.05$).

rapid decrease in DO content. The freshening trend was greater at the surface, resulting in increased stratification on the shelf.

Comparison to offshore trends—Declining trends in DO at individual CalCOFI stations were much less than those seen in the monitoring time series from nearshore stations within the same region (Table 3), which is surprising given the spatial proximity of the sampling stations ($\sim$ 5 km). All coastal water quality monitoring stations combined showed a mild, but significant, decrease (-1.56 μmol kg^{-1} yr^{-1}) in DO along isopycnals < 25 σ_θ (Figs. 8, 9). The rate increases between 25 and 26 σ_θ, with a peak at 25.25 σ_θ of -4.06 mg L^{-1} yr^{-1}. Offshore trends measured by CalCOFI were approximately four times weaker than the trends seen in the shelf-based monitoring time series, with a peak at 25.75 σ_θ of -1.18 μmol kg^{-1} yr^{-1} and at 26.5 σ_θ of -1.28 μmol kg^{-1} yr^{-1} (Figs. 8, 9). The CalCOFI stations

offshore of 175 km showed a similar peak at 26.5 σ_θ but no peak at 25.75 σ_θ. When available, changes in DO (approximately -1.63 μmol kg^{-1} yr^{-1}) along isopycnals > 26.5 σ_θ in the POTW data were comparable to CalCOFI data sets.

Apparent oxygen utilization—AOU showed similar patterns to those of measured oxygen, but positive trends indicated that lower DO solubility induced by increasing temperatures was not the dominant cause of DO loss in nearshore waters at depth (Table 2; Figs. 5, 10). Again, changes in the upper 10 m of the water column were small. In the spring, the highest rate per year was between 15–25 m at -6.2 to 7.8 μmol kg^{-1} yr^{-1} and decreased to -3.12 μmol kg^{-1} yr^{-1} at 75 m depth. The largest positive trends in AOU of $\sim$ 9.36 μmol kg^{-1} yr^{-1} occurred between 25–35 m during summer in the Oxnard and Hyperion data sets (Fig. 10; Table 2). AOU for LACSD and OCSD had
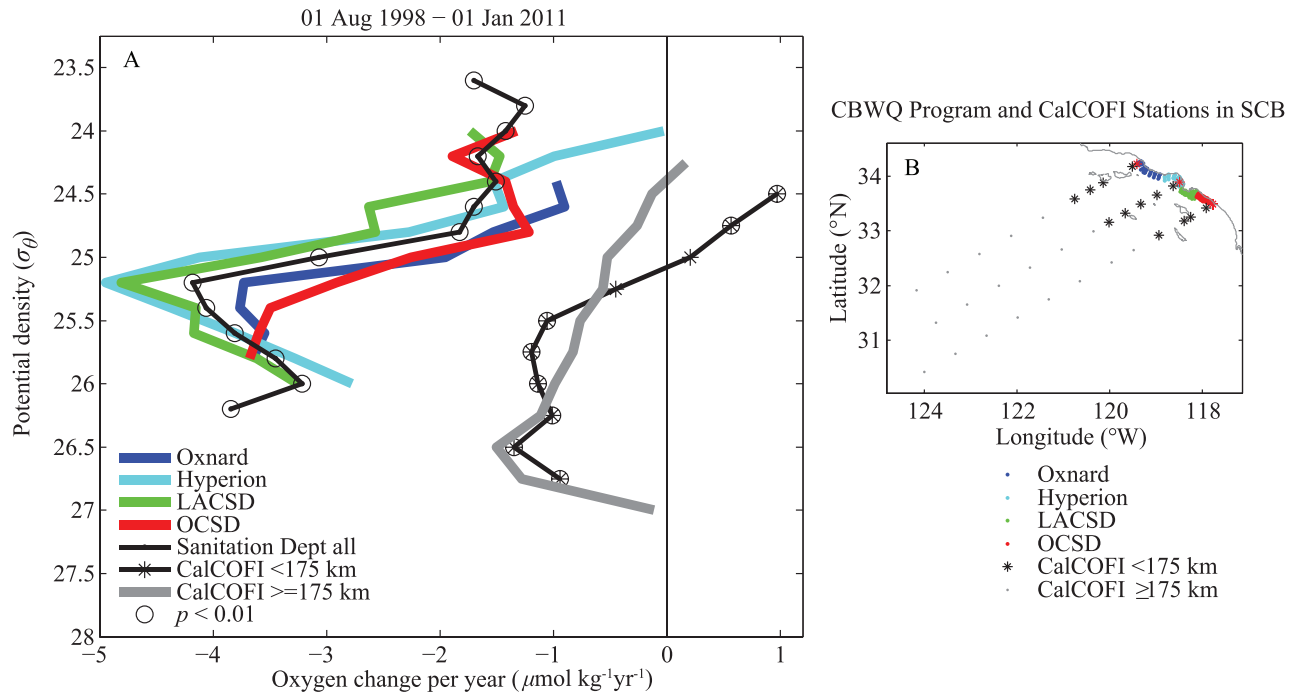

Fig. 8. Change in oxygen per year (μmol kg^{-1} yr^{-1}) from August 1998 to May 2011 by density (σ_θ) averaged across all stations within a regional sampling district (colored lines) and across all sampling districts (black dots). Oxnard stations in blue, Hyperion in teal, LACSD in green, and OCSD in red. Nearshore (< 175 km) CalCOFI change in oxygen is illustrated with black asterisks and offshore (> 175 km) rates in gray. Black circles indicate significance of the trend at $p < 0.01$. Red stars show CalCOFI stations used for intercomparison in Table 3.

Table 3. Trends in dissolved oxygen at 20 m depth in CalCOFI (near shelf) and POTW time series (1998–2011) for each of the four POTW regions. All units are μmol kg^{-1}. nc indicates no significant change.

Region	CalCOFI	POTW district
Oxnard	−0.18	−3.45
Hyperion	−1.30	−4.68
LACSD	nc	−4.41
OCSD	−1.69	−3.47

smaller positive trends, but peak rates for both were around the same depth as in the northern regions. During fall and winter the rate of change in AOU was similar across regions and depths.

Total integrated Chl *a* increased significantly from 1998–2011 (Fig. 11A). In addition, the depth of the Chl *a* center of mass has shoaled at a faster rate than the depth of the mixed layer (Fig. 11B). Although stratification has not changed significantly over this period (Fig. 11C), shallower Chl *a* biomass and therefore oxygen production favors escape of excess oxygen to the atmosphere as opposed to being mixed downward. Changes in stratification, estimated as the difference in temperature between 5 and 50 m

depth from 1985–2011 (Fig. 12), reflect large-scale climate variability with little change prior to the mid-1990s, decreasing stratification during the upwelling season since the mid-1990s, and increasing stratification in the fall since this period. Prior to the mid-1990s, significant changes in stratification only occurred in the winter.

Discussion

We found a substantial decline in sub–mixed-layer DO content over the past 15 yr that occurred consistently across the SCB. Similar declines were not observed in the previous four decades of observations. Extreme hypoxic events observed off Oregon starting in 2002–2003 were also found to have no precedent over the past 50 yr (Chan et al. 2008). Moreover, frequent hypoxic conditions on shelf and nearshore ecosystems have now been reported for multiple locations within the California Current (Chan et al. 2008; Booth et al. 2012; Micheli et al. 2012), indicating that the recent declining DO trends are a regional phenomenon. Some of the recent decline off southern California is undoubtedly attributable to low-frequency climate oscillations (Bograd et al. 2008; McClatchie et al. 2010; Pierce et al. 2012), as we also saw DO increases during the early
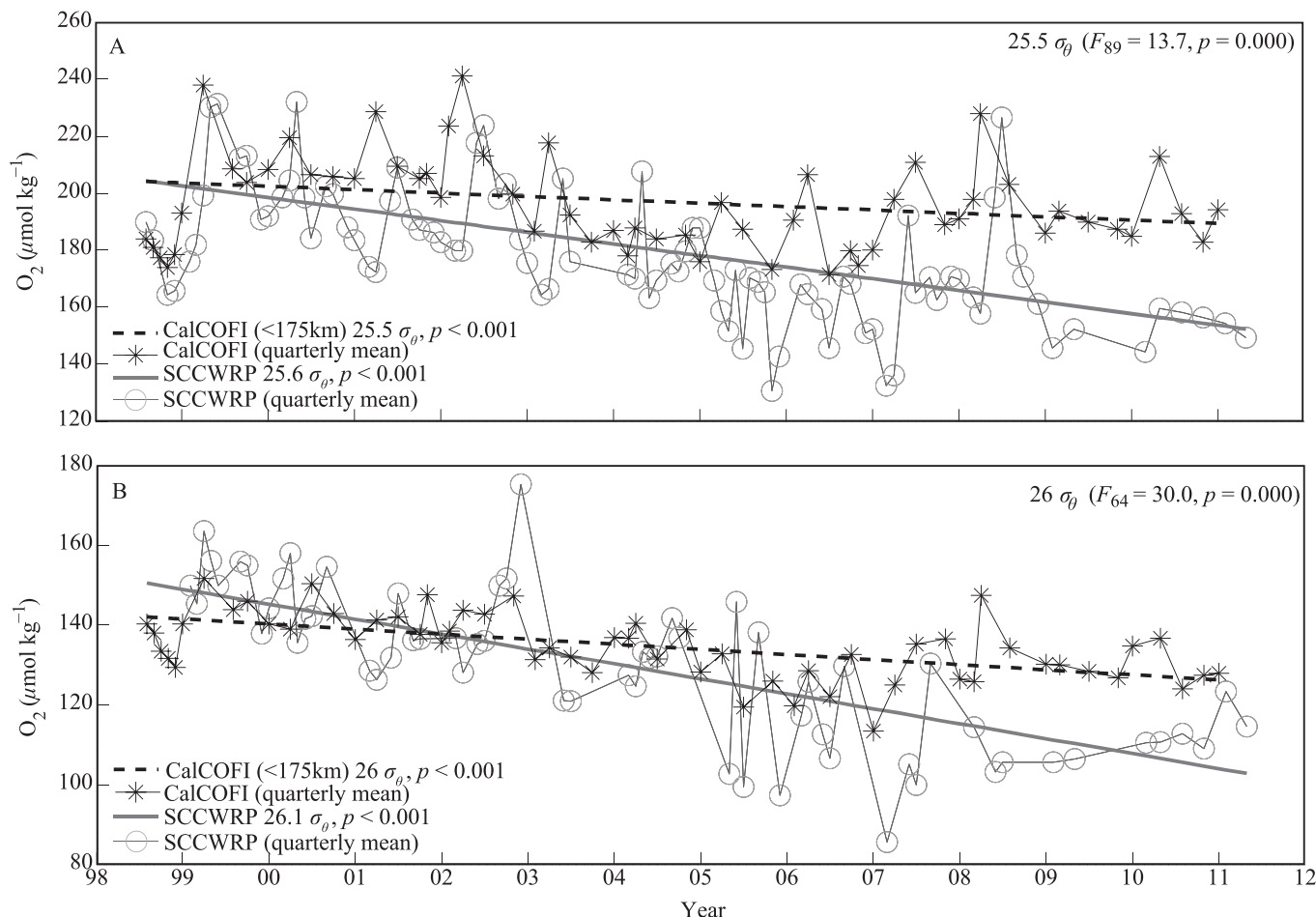

Fig. 9. Time series of quarterly averaged DO at (A) 25.5 and (B) 26 σ_θ isopycnals and linear regressions for both POTW and CalCOFI data sets.

Regional Averages: 02 Aug 1998 − 16 May 2011
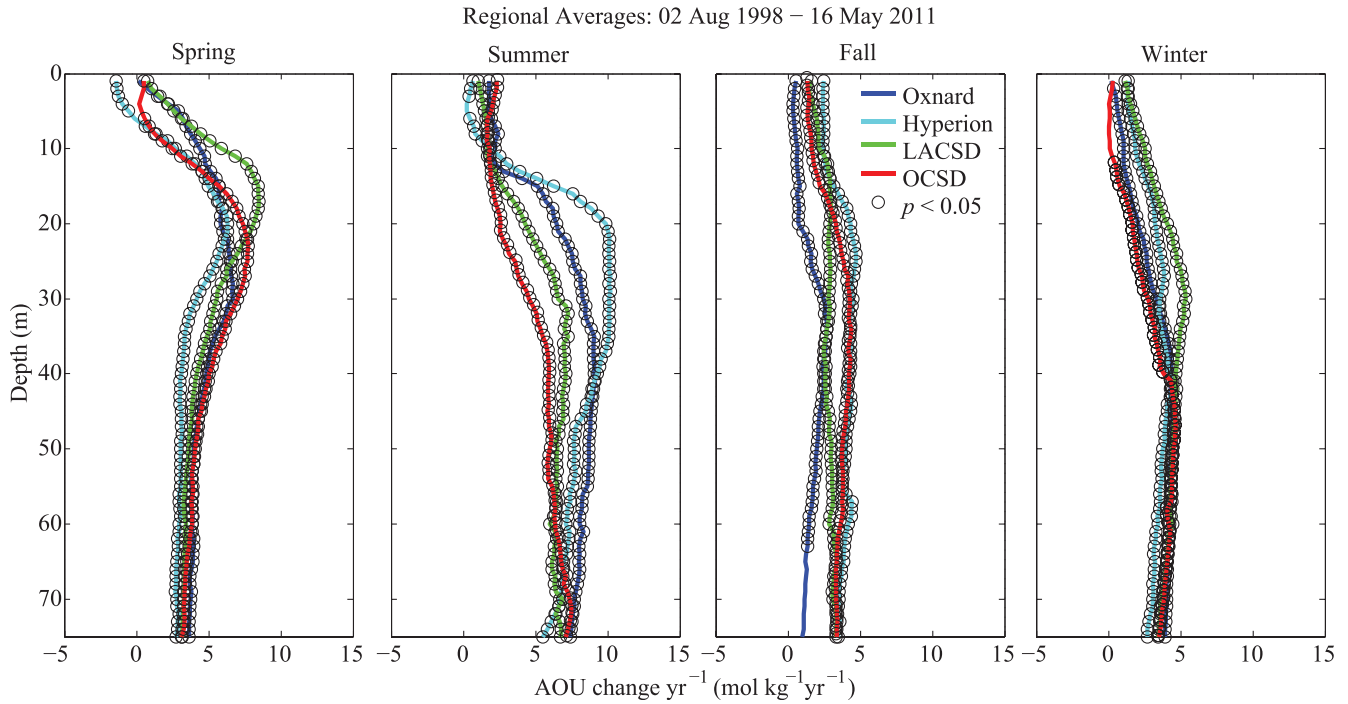

Fig. 10. Change in apparent oxygen utilization per year (μmol kg^{-1} yr^{-1}) from August 1998 to May 2011 by depth and season, averaged across all stations within a regional sampling district. Oxnard stations in blue, Hyperion in teal, LACSD in green, and OCSD in red. Black circles indicate significance of the trend at $p < 0.01$.

1980s. However, the decline does not appear attributable to decadal climate variability alone as the DO values observed during the last decade are considerably lower than anything seen in the historical data sets, which date back to the 1950s. Moreover, declines on the shelf were much greater than reported for offshore stations even along similar
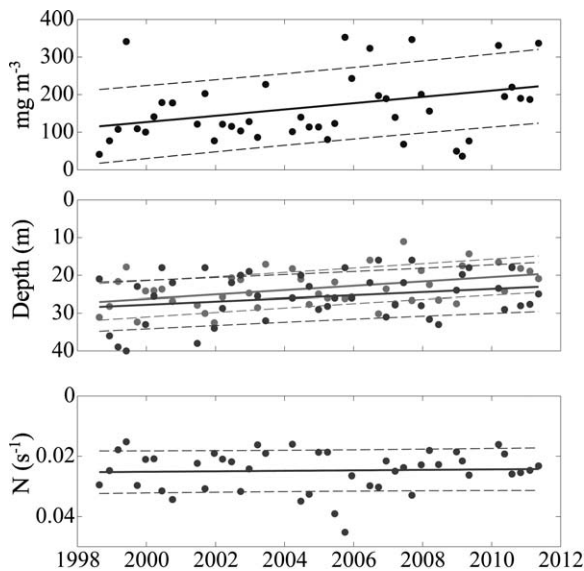

Fig. 11. (A) Integrated Chl *a*, (B) depth of mixed layer and Chl *a* center of mass, and (C) mean stratification at base of mixed layer from 1998–2012. Solid lines represent linear least-squares best fit regression. Dashed lines show 95% confidence intervals of the fits.

isopycnals. Based on declines reported in other studies (Bograd et al. 2008; McClatchie et al. 2010), decadal variability in source water oxygen content contributes $\sim 29\%$ of the total observed declines in DO on the shelf between 1998–2012. In 1998 the warm phase of the PDO (1973–1998) was replaced by cold phase (1998–present), although how the transition from warm to cold PDO resulted in the start of DO decline is presently unclear. ENSO events can also lead to dramatic changes in DO content on the shelf (Nam et al. 2011), but we saw no evidence of increased frequency or ENSO strength that could account for the trends in DO. It is also unlikely that the greater DO decline on the shelf can be attributed to methodological differences, as CalCOFI surveys have used a SBE43 DO sensor since 2003 and a Beckman DO sensor prior to that, similar to that used by the POTW monitoring agencies. The lack of change in the mixed-layer values also suggests that calibration through the monitoring period has been consistent. The POTW monitoring agencies factory-calibrate their DO sensors annually and perform pre-survey checks in DO-saturated water. Moreover, a similar rate of decline was observed independently by all four POTW monitoring agencies.

We therefore suspect two potential mechanisms for the dramatic declines in DO content in coastal waters of the SCB. Changes in stratification are outpacing any changes in the wind stress associated with climate change (Bakun 1990). Based on temperature differences between 5 and 50 m depths, stratification did not change significantly in the upwelling season (spring, summer) prior to the mid-1990s, and has decreased since this period, although recent data suggest a modest increase in the spring (Fig. 12). Interestingly,
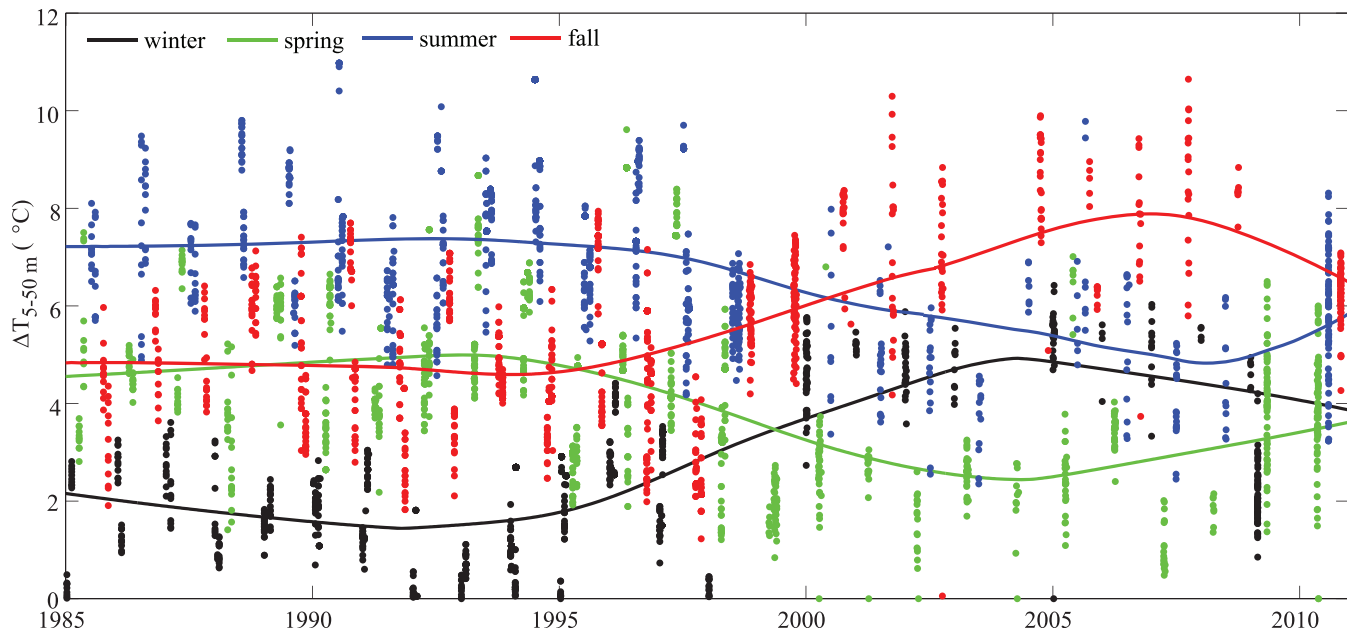
Fig. 12.   Change in stratification for shelf of the SCB by season using the difference in temperature between 5 m and 50 m depth as a proxy since salinity measurements are not consistently available pre-1998. Solid lines are smoothed using rloess with a 2 yr window. Winter (black), spring (green), summer (blue), and fall (red).

the declines in DO content are strongest in spring and summer when stratification was decreasing until recently, but DO declines continued as stratification began to increase in the latter part of the record (Fig. 12). Changes in temperature and salinity that are leading to changes in coastal stratification are likely linked to PDO variability, which can also have relatively large effects on salinity in coastal waters (Nam and Send 2011; Fig. 12). As sub–mixed-layer temperatures decrease in coastal waters, stratification becomes more intense and therefore prevents mixing and reoxygenation of waters at depth. However, while there is a clear signal of stratification change (decreasing in spring and summer), it is not wholly consistent with observed DO declines.

Increased phytoplankton abundance and shoaling of the deep Chl *a* maximum during spring and summer along with increased residence time of waters on the shelf allow for an eutrophication-like process in the nearshore regions of the SCB. Increased Chl *a* suggests a strong effect of increased nutrients in the photic zone; however, the source of the nutrients is not clear. As the depth of the Chl *a* center of mass shoals, oxygen preferentially escapes to the atmosphere. In

addition, higher biomass leads to stimulated microbial respiration at depth reflected in the highest AOU values being observed on the shelf (Fig. 5). Combined with the large-scale climate variability in DO and stratification, even a weak eutrophication signal might be sufficient to allow hypoxia development (Connolly et al. 2010).

Evidence for oxygen drawdown through biological processes exists in the distribution of observed rates of DO decline over depth (Figs. 5, 6), changes in AOU (Fig. 5), and changes in integrated Chl *a* (Fig. 11). At depths greater than about 40 m, declines in DO are consistent around -3.11 μmol kg^{-1} yr^{-1}. However, during spring and summer months, rates of DO decline increase up to -9.36 μmol kg^{-1} yr^{-1} over intermediate depths of $\sim$ 20–40 m depth. These values are 10 times greater than those observed in offshore data from CalCOFI. Trends in Chl *a* concentration suggest a large increase in algal blooms in surface waters of the SCB ($\sim$ 13.46 mg m^{-3} yr^{-1}) during spring and summer (Fig. 11). These values are greater than, but consistent with satellite-observed Chl *a* patterns (Kahru et al. 2012; Nezlin et al. 2012), and coincide with the largest declines in DO at depth. In spring and summer months,

Table 4.   Characteristics of POTW effluent discharged to ocean outfalls in the Southern California Bight during 1971, 2000, 2005, and 2009, given as annual total flow, load, and flow-weighted mean concentration of dissolved inorganic nitrogen (DIN; ammonia + nitrate). Data from Lyon and Stein (2009), Lyon and Sutula (2011), and Howard et al. (2014).

	Year			
Characteristics of POTW effluent discharged	1971	2000	2005	2009
Flow (10^9 liters)	1384	1683	1742	1429
Ammonia load ($\times 10^7$ moles N)	397	328	372	317
Nitrate load ($\times 10^7$ moles N)	2.21	3.06	3.49	24.5
Total DIN load ($\times 10^7$ moles N)	399	331	375	342
Flow-weighted mean DIN concentration (mmol L^{-1} N)	2.89	1.97	2.15	2.37

trends in declining temperature also peak between 10–20 m depth (Table 2) with declines in salinity stronger near the surface, suggesting an increase in stratification from 1998–2012. Increases in the AOU also suggest increased biological activity that may be associated with aerobic decay of phytoplankton and lack of reoxygenation through wind-driven mixing (Fig. 5).

Increased Chl *a* in surface waters likely results from either natural changes in nutrient supply through upwelling, or from anthropogenic sources of nutrients and oxygen-consuming organic matter in river runoff and wastewater effluent driving biological activity on the shelf, similar to the eutrophication-driven hypoxia in the Gulf of Mexico and Chesapeake Bay (Rabalais et al. 2002; Diaz and Rosenberg 2008). Biochemical oxygen demand of wastewater effluent is unlikely to be a big contributor as the LACSD, OCSD, and Los Angeles City have all enhanced their treatment levels during the period of DO decline and the monitoring programs do not indicate local oxygen depletion near the outfalls. Major point source loading of ammonia and nitrate decreased 18% from 1971 through 2000, then over the last decade stayed largely flat (Table 4; Lyon and Sutula 2011). Non–point source nutrient loadings have been shown to be 2–3 orders of magnitude less than point sources or upwelling (Howard et al. 2014). If increased biomass and lower DO was solely due to human-derived nutrient enhancement, we would expect large declines from the 1960s to 1970s, then a leveling off as well from 1971 through 2010, which are not evident in the data available. This suggests that the major driver of trends may be variation in natural inputs.

Trends in DO content documented in this study through the CalCOFI and CBWQ monitoring program illustrate the power of long-term continued monitoring to understand trends in DO content. However, there is a need to better connect these two programs in the SCB. Additional observational and modeling efforts are needed to address the relative effects of nutrient inputs advected from offshore through upwelling relative to those due to anthropogenic sources. Moored and ship-based sampling using CTDs should also be complemented with additional types of monitoring that can better characterize the episodic nature of hypoxic events in upwelling-dominated coastal zones such as autonomous gliders (Pierce et al. 2012). In southern California, an operational Regional Ocean Modeling System (ROMS) model (Shchepetkin and McWilliams 2005; Gruber et al. 2006) also provides an excellent framework to begin addressing these questions. However, such regional models need to be adapted for the nearshore region in order to tease apart anthropogenic vs. natural influences on DO content.

Over the past 15 years, DO concentrations within the coastal region of the SCB have decreased dramatically and faster than observed in offshore data sets. The cause of the observed declines in DO appear to be a complex integration of large-scale trends caused by natural climate variability combined with local increases in primary productivity due to enhanced nutrient supply from both natural and anthropogenic sources. Further analyses are needed to constrain estimates of the contribution of anthropogenic nutrient inputs to declining oxygen trends in the SCB.

References

BAKUN, A. 1990. Global climate change and the intensification of coastal upwelling. Science **247:** 198–201, doi:10.1126/science.247.4939.198

BOGRAD, S. J., C. G. CASTRO, E. DI LORENZO, D. M. PALACIOS, H. BAILEY, W. GILLY, AND F. P. CHAVEZ. 2008. Oxygen declines and the shoaling of the hypoxic boundary in the California Current. Geophys. Res. Lett. **35:** L12607, doi:10.1029/2008GL034185

BOOTH, J. A. T., AND OTHERS. 2012. Natural intrusions of hypoxic, low pH water into nearshore marine environments on the California coast. Cont. Shelf Res. **45:** 108–115, doi:10.1016/j.csr.2012.06.009

BREWER, P. G., AND E. T. PELTZER. 2009. Oceans: Limits to marine life. Science **324:** 347–348, doi:10.1126/science.1170756

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:** 920–920, doi:10.1126/science.1149016

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

CRAWFORD, W. R., AND M. A. PEÑA. 2013. Declining oxygen on the British Columbia continental shelf. Atmos.-Ocean **51:** 88–103, doi:10.1080/07055900.2012.753028

DEUTSCH, C., S. EMERSON, AND L. THOMPSON. 2005. Fingerprints of climate change in North Pacific oxygen. Geophys. Res. Lett. **32:** L16604, doi:10.1029/2005GL023190

DIAZ, R. J. 2001. Overview of hypoxia around the world. J. Environ. Qual. **30:** 275–281, doi:10.2134/jeq2001.302275x

———, AND R. ROSENBERG. 2008. Spreading dead zones and consequences for marine ecosystems. Science **321:** 926–929, doi:10.1126/science.1156401

FIEDLER, P. C., AND L. D. TALLEY. 2006. Hydrography of the eastern tropical Pacific: A review. Prog. Oceanogr. **69:** 143–180, doi:10.1016/j.pocean.2006.03.008

GRUBER, N., AND OTHERS. 2006. Eddy-resolving simulations of plankton ecosystem dynamics in the California Current System: Part I: Model description, evaluation, and ecosystem structure. Deep-Sea Res. I **53:** 1483–1516, doi:10.1016/j.dsr.2006.06.005

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

HOWARD, M. D. A., AND OTHERS. 2014. Anthropogenic nutrient sources rival natural sources on small scales in the coastal waters of the Southern California Bight. Limnol. Oceanogr. **59:** 285–297, doi:10.4319/lo.2014.59.1.0285

KAHRU, M., R. M. KUDELA, M. MANZANO-SARABIA, AND B. G. MITCHELL. 2012. Trends in the surface Chl a of the California Current: Merging data from multiple ocean color satellites. Deep-Sea Res. II **77:** 89–98, doi:10.1016/j.dsr2.2012.04.007

KEELING, R. F., AND H. E. GARCIA. 2002. The change in oceanic O_2 inventory associated with recent global warming. Proc. Natl. Acad. Sci. USA **99:** 7848–7853, doi:10.1073/pnas.122154899

———, A. KÖRTZINGER, AND N. GRUBER. 2010. Ocean deoxygenation in a warming world. Annu. Rev. Mar. Sci. **2:** 199–229, doi:10.1146/annurev.marine.010908.163855

LYON, G. S., AND E. D. STEIN. 2009. How effective has the Clean Water Act been at reducing pollutant mass emissions to the Southern California Bight over the past 35 years? Environ. Monit. Assess. **154:** 413–426, doi:10.1007/s10661-008-0408-1

———, AND M. A. SUTULA. 2011. Effluent discharges to the Southern California Bight from large municipal wastewater treatment facilities from 2005 to 2009 [Internet]. SCCWRP Annual Report 2011. Costa Mesa (CA): Southern California Coastal Water Research Project [accessed 11 Nov 2013]. Available from http://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/2011AnnualReport/ar11_223_236.pdf

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

MICHELI, F., A. SAENZ-ARROYO, A. GREENLEY, L. VAZQUEZ, J. A. ESPINOZA MONTES, M. ROSSETTO, AND G. A. DE LEO. 2012. Evidence that marine reserves enhance resilience to climatic impacts. PLoS ONE 7: e40832, doi:10.1371/journal.pone.0040832

NAM, S., AND U. SEND. 2011. Direct evidence of deep water intrusions onto the continental shelf via surging internal tides. J. Geophys. Res.: Oceans **116:** C05004, doi:10.1029/2010JC006692

NAM, S.-H., H.-J. KIM, AND U. SEND. 2011. Amplification of hypoxic and acidic events by La Niña conditions on the continental shelf off California. Geophys. Res. Lett. **38:** L22602, doi:10.1029/2011GL049549

NEZLIN, N. P., AND OTHERS. 2007. Southern California Bight 2003 monitoring program: V. Water quality [Internet]. Costa Mesa (CA): Southern California Coastal Water Research Project [accessed 12 Nov 2013]. http://www.sccwrp.org/Documents/BightDocuments/Bight03Documents/Bight03AssessmentReports.aspx

———, M. A. SUTULA, R. P. STUMPF, AND A. SENGUPTA. 2012. Phytoplankton blooms detected by SeaWiFS along the central and southern California coast. J. Geophys. Res. **117:** C07004, doi:10.1029/2011JC007773

PENNINGTON, J. T., K. L. MAHONEY, V. S. KUWAHARA, D. D. KOLBER, R. CALIENES, AND F. P. CHAVEZ. 2006. Primary production in the eastern tropical Pacific: A review. Prog. Oceanogr. **69:** 285–317, doi:10.1016/j.pocean.2006.03.012

PIERCE, S. D., J. A. BARTH, R. K. SHEARMAN, AND A. Y. EROFEV. 2012. Declining oxygen in the Northeast Pacific. J. Phys. Oceanogr. **42:** 495–501, doi:10.1175/JPO-D-11-0170.1

RABALAIS, N. N., R. E. TURNER, AND W. J. WISEMAN, JR. 2002. Gulf of Mexico hypoxia, a.k.a. "The Dead Zone." Annu. Rev. Ecol. Syst. **33:** 235–263, doi:10.1146/annurev.ecolsys.33.010802.150513

SHCHEPETKIN, A. F., AND J. C. MCWILLIAMS. 2005. The regional oceanic modeling system (ROMS): A split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Modell. **9:** 347–404, doi:10.1016/j.ocemod.2004.08.002

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