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Natural intrusions of hypoxic, low pH water into nearshore marine environments on the California coast

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ABSTRACT

A decade-long time series recorded in Central California demonstrates that a shallow, near-shore environment (17 m depth) is regularly inundated with pulses of cold, hypoxic and low-pH water. During these episodes, oxygen can drop to physiologically stressful levels, and pH can reach values that potentially result in dissolution of calcium carbonate. Pulses of the greatest intensity arose at the onset of the spring upwelling season, and fluctuations were strongly semidiurnal and diurnal. Arrival of cold, hypoxic water on the inner shelf appears to be driven by tidal-frequency internal waves pushing deep, upwelled water into nearshore habitats. We found no relationship between the timing of low-oxygen events and the diel solar cycle. These observations are consistent with the interpretation that hypoxic water is advected shoreward from the deep, offshore environment where water masses experience a general decline of temperature, oxygen and pH with depth. Analysis of the durations of exposure to low oxygen concentrations establishes a framework for assessing the ecological relevance of these events, but physiological tolerance limits to such hypoxic events are not well documented for most near-shore organisms expected to be impacted.

1. Introduction

Continental shelves off the west coast of North America do not experience the eutrophication and severe hypoxia from terrestrial-nutrient-driven algal production experienced by regions such as the Gulf of Mexico (Rabalais and Turner, 2002). However, observations of dissolved oxygen (DO) over the past decade demonstrate the prevalence of seasonal hypoxic conditions on the shelves of Washington, Oregon, and California (Diaz and Rosenberg, 2008; Whitney et al., 2007; Chan et al., 2008). Seasonal upwelling and its shoreward transport of previously deep, low-DO water, is a known contributor to these events, and this factor, along with interannual variations in the oxygen concentrations of source water plays a strong role in determining the oxygen climate over mid- and outer shelves in this system (Grantham et al., 2004). However, upwelling draws from depths shallower than the 600- to 1300-m depth of the oxygen minimum zone (OMZ), and onshore advection of deep water cannot alone explain hypoxic events.

Studies over Washington and Oregon shelves demonstrate the importance of upwelling of low-oxygen water, but also show that benthic and water-column biogeochemical processes are additional factors necessary to explain reduced oxygen concentrations in these regions (Connolly et al., 2010). Low DO has been found on Oregon shelves both over mid- and shallow-shelf depths, and some of the shallower observations were documented during an extreme hypoxia/anoxia event that were biologically driven (Grantham et al., 2004). Less is known about variability and short-term advection of low oxygen over shallow and mid-depth shelves. Surface mixing and atmospheric equilibration maintain high DO concentrations in near-surface waters, but below the thermocline DO decreases with depth, and fluctuations in thermocline depth, surface mixed-layer thickness, and onshore/offshore advection can all affect oxygen concentrations on the inner shelf. Oxygen at depths of <40 m on the Oregon and Washington shelves shows variability at shorter time scales than does oxygen on the middle and outer shelf depths (Connolly et al., 2010; Grantham et al., 2004). However, little is known about how onshore transport of deep waters affects oxygen concentrations in the shallow,

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inner shelf (depth <20 m, roughly within 1-km of the coast). We also know less about oxygen on shelves of Central California than we do about shelves in the northern part of the California Current System off Oregon.

Here we take advantage of a decade-long data set to examine oxygen variability on the inner shelf off of Central California. The Monterey Bay Aquarium in Monterey, California, has been monitoring oxygen concentrations in the seawater pumped into their facility in order to ensure proper oxygenation for aquarium fauna. Records of oxygen, along with temperature and sometimes pH, were collected regularly at a site close to shore ($\sim$340 m) with a water depth of $\sim$19 m. These data provide an extremely valuable glimpse of coastal oxygen variability in an area of great ecological importance. Our objectives were to document the range and temporal variability of oxygen concentrations in near-bottom inner-shelf waters in order to better understand oxygen stress on the subtidal communities of this productive rocky environment. We found intense temporal variation in near-coast oxygen and pH, and surprisingly low oxygen concentrations for such shallow waters. Variability occurred on both short (semidiurnal and diurnal) and much longer (seasonal) time-scales, with the seasonal pattern being dominated by variation in wind-driven in offshore areas. A tight relationship between temperature, DO and pH, combined with a lack of evidence for daily-scale local consumption of oxygen, suggest that most variability at the monitoring site was due to advection onshore of previously deeper, low-DO water, by seasonal upwelling modulated by semidiurnal baroclinic motions.

2. Data collection and study site

During the past decade the Monterey Bay Aquarium (MBA) has monitored seawater temperature, DO and pH from the inner shelf of southern Monterey Bay (36.621°N, 121.899°W; Fig. 1). The site is in the southeastern corner of the Bay where the coast is generally protected from surface swell and strong surf. Seawater is sampled from intake pipes that draw in water from 17-m depth, 2 m above the bottom, and routinely monitored as part of the animal husbandry division's water quality program. Measurements are made every 5 min and automatically logged. Recording started for temperature in June 1995 (only data after April 2000 are analyzed here), DO in April 2000 and pH in September 2009, and monitoring continues to the present. Typical flow rate was $\sim$110 L s^{-1} and sensors were cleaned weekly and calibrated monthly. Oxygen was measured with a Point Four OxyGuard Type 1 Stationary Probe (OxyGuard International, Birkerød, Denmark), and temperature was measured with an AGM single element type "J" thermocouple (AGM Electronics, Tucson, AZ). On 24 September 2009 a GLI Encapsulated LCP (Liquid Crystal Polymer) differential pH sensor with internal preamplifier and glass electrode (Hach, Loveland. CO) was installed and has since been calibrated monthly using NBS-certified standards (Fisher Scientific, Pittsburgh, PA). In addition, manual 'spot checks' of pH have been taken once or twice per week since 18 June 1996 using initially a Corning then a Hach IntelliCAL liquid-filled pH electrode (results discussed in Ref. Woodson et al. (2007)). The pH probes was calibrated approximately every one to three months during this period using NBS-certified standards. Although use of NBS low-salinity standards does not achieve the accuracy possible with buffers of seawater salinity (Millero et al., 1993), any error is much smaller than the natural variations described and does not affect the conclusions of this study.

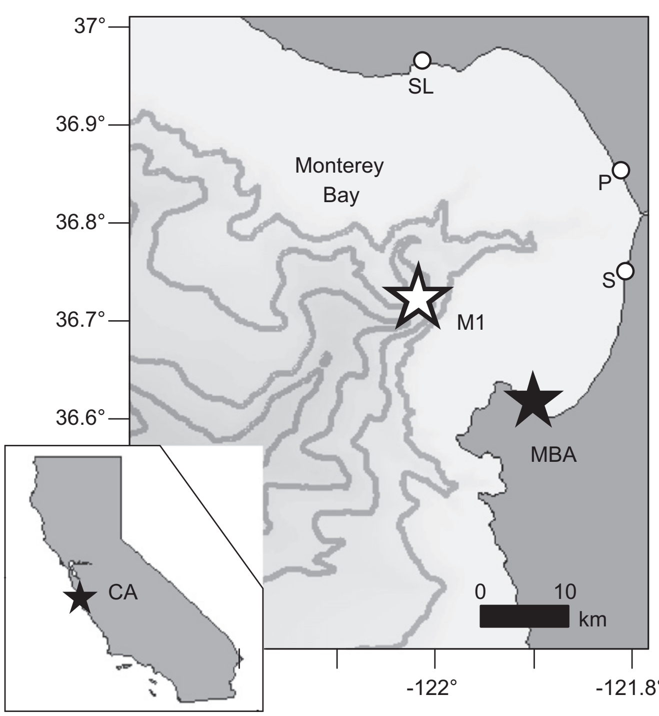

Fig. 1. Map of study area showing locations of MBA and shallow cast (black star) and deep-water cast (white star). Bathymetric contours are at 500 m intervals. Locations of river mouths are also noted—Salinas (S), Pajarro (P) and San Lorenzo (SL).

3. Consideration of errors

Raw DO measurements were taken in units of mg L^{-1} from 1 April 2000 to 15 December 2003, but the unit recorded was changed to percent saturation from 2004 to present. To achieve consistency over the record, we converted percent saturation readings to mg L^{-1} using the recorded temperature, an assumed salinity of 34 and published oxygen-solubility equations (Colt, 1984). Based on several conductivity-temperature-depth (CTD) profiles obtained with a Seabird SBE19plus profiler (Seabrid Electronics, Bellevue, Washington) at the study site in March and April of 2009, salinity was found to fluctuate between 33.5 and 34.0. Such variation could lead to a maximum predicted error of 0.01% for the DO conversion, and thus would has negligible effect on our results. Between April 1, 2000 and August 15, 2001, the oxygen monitoring system was programmed to record measurements only up to 10 mg L^{-1}, but after that period the range was extended to 20 mg L^{-1} because DO concentrations often exceeded the original limit. For the entire study period, 19.6% of DO and 2.7% of temperature readings were unusable or missing, generally due to system maintenance issues.

Salinity, temperature and DO were also recorded for three short time-series from a moored CTD stationed at two locations within 150 m of the intake pipe site (36.6214°N, 121.8996°W and 36.6212°N, 121.9005°W) (1 October–17 November 2009; 16 July–3 August 2010; 17 August–30 September 2010). Instrumentation included a Seabird SBE16plus CTD equipped with an optode DO sensor (Aanderra Data Instruments, Bergen, Norway). The CTD was moored between 14–16-m depth in 17 m of water. A comparison between the moored CTD and MBA temperature and DO time series showed that MBA measurements lagged the environment by approximately 10 min and that some high-frequency variation was reduced in the MBA record, presumably by mixing in the input plumbing system. Temperatures at the three sites were significantly correlated (mean cross-covariance coefficient=0.96, p-values <0.001). DO measurements showed a mean cross-correlation value of 0.84 (p-values <0.001) and MBA DO values were on average 0.86 mg L^{-1} higher in the seawater