Hypoxia in Cordell Bank National Marine Sanctuary

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What is hypoxia?

In marine environments, hypoxia refers to low dissolved oxygen (DO) concentrations in the water column, low enough to pose a threat to marine life. The most commonly used threshold for hypoxia is 2 mg per liter (mg L^{-1}). Hypoxia occurs when decomposition of organic material consumes oxygen much faster than it is replenished by photosynthesis or mixed down from the water surface. DO concentrations are affected by many factors including: water temperature and salinity, light availability, stratification of water layers, tidal and wind mixing, upwelling of deep waters, abundance and decay of organic material, and runoff of high-nutrient waters from land – all phenomena that can fluctuate interannually with the Pacific Decadal Oscillation and El Niño Southern Oscillation, as well as seasonally.

Why is it a concern?

Hypoxia is the result of natural processes, but it can be influenced by human activity. The frequency of occurrence, severity and proliferation of low-oxygen zones have been increasing worldwide. Over recent decades, accelerated oxygen loss (deoxygenation) has been observed in coastal and open ocean environments (Rhein et al. 2013). Vertical expansion and intensification of hypoxic waters have been observed on the continental shelf, and in nearshore, shallow environments (Levin and Breitburg 2015; Schmidtko et al. 2017). Organisms in environments that do not typically experience low DO may not be well-adapted to survive and may experience stress or mortality under hypoxic conditions. Even DO concentrations above the hypoxic threshold of 2 mg L^{-1} can result in species avoidance and oxygen stress, see Table 1. Areas prone to hypoxic conditions tend to have lower biodiversity and reduced body sizes of organisms (Levin et al. 2009).

Hypoxia Category	***Oxygen Concentration mg O_2 L^{-1}***	***Biological Response***
Mild	*3.5*	*Species exhibit avoidance reactions.*
Intermediate/ 'Coastal'	*2.0*	*Species require adaptive features to exist.*
Severe	*0.71*	*Mass mortality for most organisms; only highly specialized species can survive.*

Table 1: Hypoxia categories and associated oxygen concentrations and species reaction. Content modified from Moffitt et al. 2013.

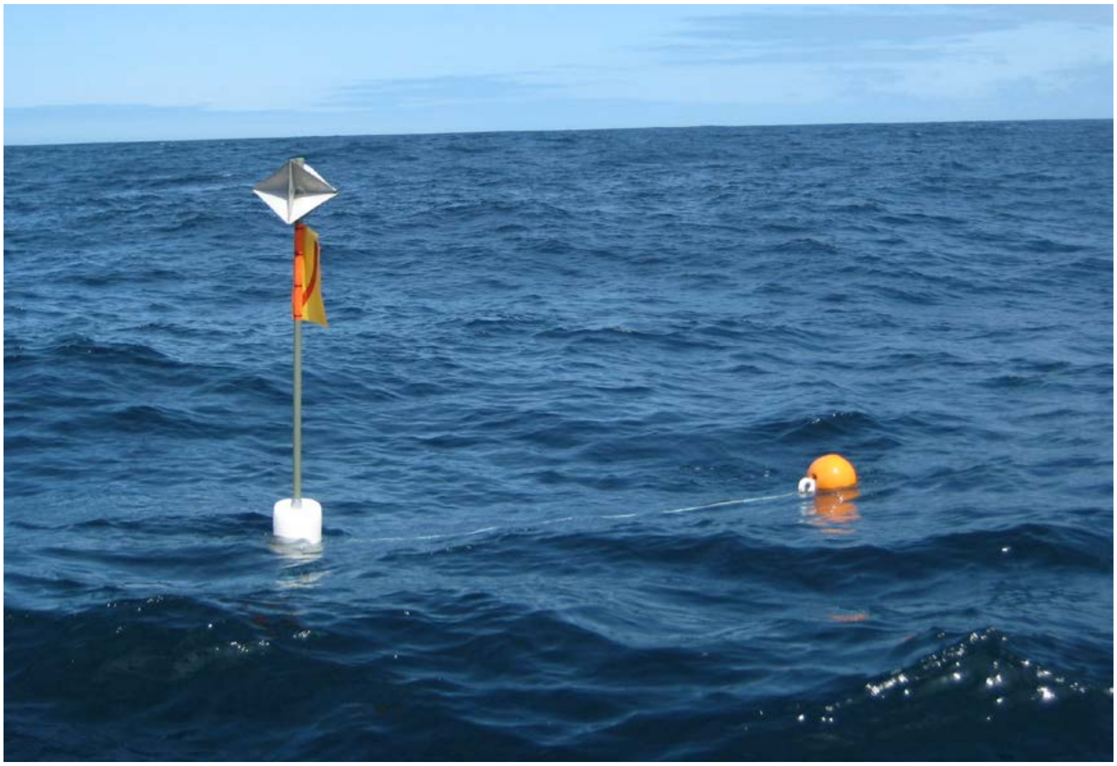
How is hypoxia related to climate change?
The extent and severity of both coastal and open ocean hypoxia are on a rise, with seasonal or episodic hypoxia now observed on continental margins, shelves, and estuarine environments that were previously well-oxygenated (Levin and Breitburg 2015). Deoxygenation, ocean acidification, and ocean warming are three primary effects to the marine environment of increased atmospheric carbon dioxide (CO_2; Matear and Hirst 2003; Keeling et al. 2010). As ocean surface temperatures increase, the amount of oxygen the water can hold decreases. At the same time, changes in stratification of ocean waters modulate DO concentrations: oxygen enters the ocean at the surface, from exchange with the atmosphere and from photosynthetic activity in the photic zone. As the ocean warms, stratification increases and reduces the ability to mix oxygenated waters down to deeper layers. Additionally, climate induced atmospheric changes are expected to result in changes in upwelling. Upwelling breaks stratification in the nearshore and brings cold, nutrient-rich, oxygen-poor waters on to the shelf and up to the surface. Climate-change affects the composition of deep waters (upwelling source waters), wind-driven currents, and the rate of upwelling of waters from depth. Both have the potential to enhance hypoxic conditions in nearshore environments.

In other coastal regions, outside of strong upwelling regions such as the California Current System, hypoxic events are commonly attributed to nutrient enrichment and organic loading (eutrophication) and stratification. Areas that experience eutrophication from land runoff (e.g., Chesapeake Bay, Gulf of Mexico) have proliferated in recent decades and received attention as “dead zones” (Diaz and Rosenberg 2008). Although this is not the primary cause of hypoxia off California, as the oxygen content of the world’s ocean decrease, and surface waters become warmer, even relatively weak anthropogenic nutrient contributions may lead to increased frequency, duration, and strength of coastal hypoxia (Booth et al. 2014).

What do we know about hypoxia on the west coast?
Hypoxia has been observed on the Oregon shelf since 2002 (Grantham et al 2004; Chan et al., 2008). These hypoxic events have been harmful to wildlife, particularly crabs and fish. Oxygen decline has also occurred in Southern California (Bograd et al. 2008 & 2015) and the eastern subartic Pacific (Whitney et al. 2007; Crawford and Pena 2013; Pierce et al. 2012). Hypoxic conditions have been observed locally, along the north central California coast, but have not been as severe as the events offshore the Pacific Northwest. Since 2013, researchers in the Coastal Oceanography Group at UC Davis Bodega Marine Laboratory (BML) have recorded hypoxic conditions at moorings off Bodega Head, in the Gulf of Farallones, and on Cordell Bank.

How are we addressing hypoxia in Cordell Bank National Marine Sanctuary?
If long-term, large-scale hypoxic conditions were to occur in Cordell Bank National Marine Sanctuary (CBNMS), it could be devastating to its abundant marine life. We are working to better understand DO conditions at Cordell Bank, the timing and persistence of hypoxia, and potential effects to biological communities. In 2014, following observation of low-DO conditions in the nearshore environment, CBNMS and BML staff worked together to deploy instruments on two moorings on Cordell Bank to record DO and temperature levels. One mooring location is at 83 meters (shallow mooring) and one is at 114 meters (deep mooring). Funding was provided by the Cordell Marine Sanctuary Foundation, CBNMS, and BML. The

instruments have been deployed for several months at a time, during the upwelling season from spring through fall. A salinity sensor was added to the deep mooring on Cordell Bank in 2016. CBNMS also conducts research cruises in the sanctuary, in partnership with Greater Farallones National Marine Sanctuary (GFNMS) and Point Blue Conservation Science, three times a year during which DO and other variables are measured throughout the water column. The Coastal Oceanography Group at BML is working to better understand temperature, salinity and DO variability and forcing mechanisms in the larger region, including CBNMS and GFNMS. These analyses are being performed to identify the importance of physical and biological drivers of DO, which is an important step in understanding past and predicting future low-DO events in the region. A publication summarizing these analyses and results is in preparation as part of Kate Hewett's PhD thesis.



One of the moorings deployed at Cordell Bank. Photo credit: CBNMS

What are the results from the CBNMS moorings?

Results from the past three years indicate variability of DO conditions on the bank on synoptic (weather time scale), seasonal and annual timescales, with hypoxic conditions observed for weeks at a time. Although the drivers and mechanisms are still being studied, the DO dynamics at Cordell Bank appear to be influenced by both local conditions (e.g., upwelling) as well as larger basin-wide phenomena (e.g., marine heat waves, "the blob"). Figures 1 – 3 show annual results.

<u>2014 Deployment (Figure 1):</u> Early upwelling conditions were not captured as the moorings were deployed in mid-June. Variable DO conditions were observed later during the summer. In late June, oxygen-rich water was measured at the moorings on the bank during a strong windy period. However, after the winds relaxed during the first two weeks in July, DO concentrations dropped to 2 mg L^{-1} (hypoxic conditions) before slowly increasing over next several months. Slightly lower DO concentrations and colder water were observed at the deep mooring compared with the shallow mooring, but the patterns of variability at both moorings were similar.

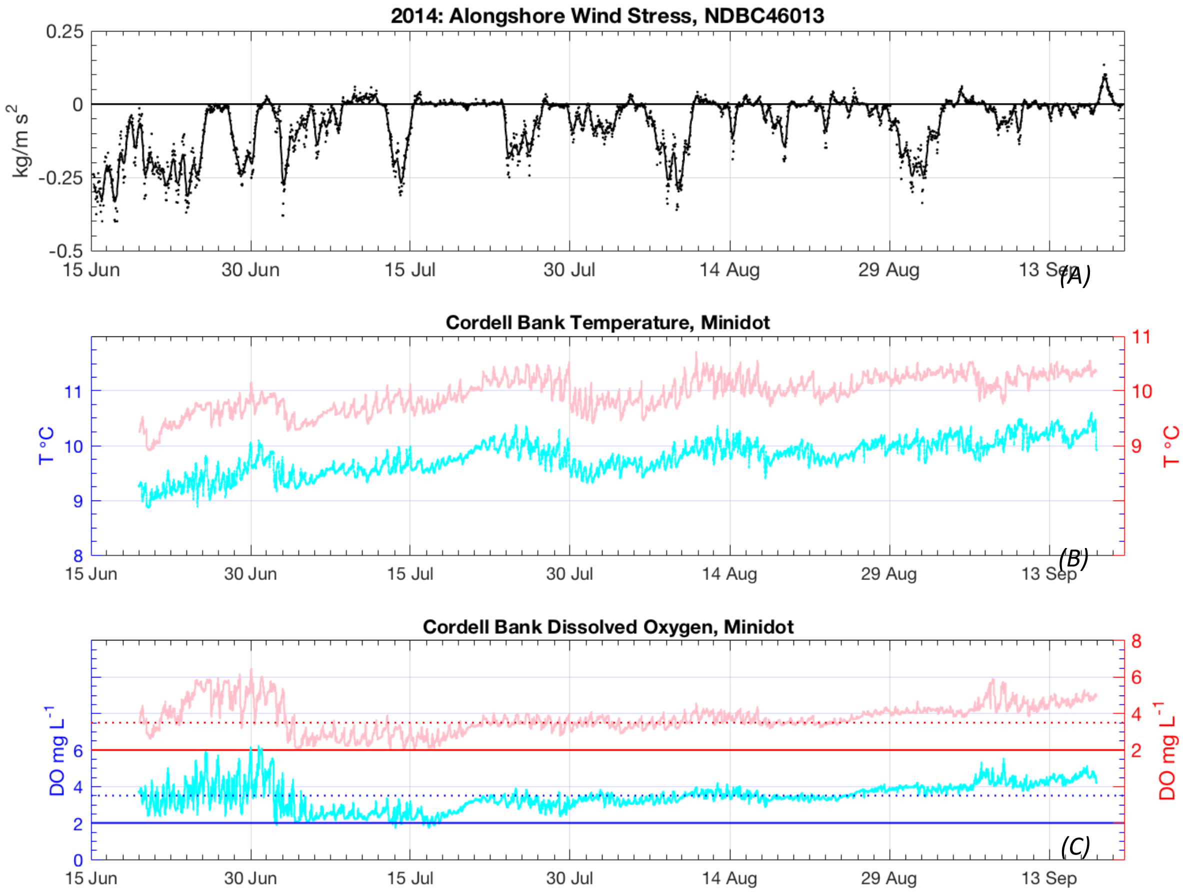


***Figure 1: 2014 Cordell Bank wind, temperature, and dissolved oxygen**: A) Top panel: alongshore wind stress calculated using wind speed and direction data from NDBC 46013. Negative values indicate upwelling favorable (northwesterly) winds. Black points indicate hourly data and the solid black line represents a 24-hour wind stress average. B) Middle panel: Temperature data obtained during 2014 from deep (blue; primary y-axis) and shallow (red; secondary y-axis) moorings. C) Bottom panel: DO data obtained during 2014 from deep (blue; primary y-axis) and shallow (red; secondary y-axis) moorings on Cordell Bank. Solid lines (dark blue or dark red) indicate hypoxic threshold (2 mg L^{-1}) and dashed lines indicate oxygen stressed conditions (3.5 mg L^{-1}).*

<u>2015 Deployment (Figure 2):</u> The moorings were deployed in May 2015 a month earlier than in 2014. Low DO conditions were present for the first two months of deployment, corresponding to upwelling conditions, but overall DO levels were higher than in the previous year. DO levels rose in August before briefly dropping in September and then increased for the remainder of the year. In 2015 the west coast of the US experienced a marine heatwave, which received attention as "the blob", an anomalous, persistent patch of warm water extending from the Gulf of Alaska to Baja California, which increased stratification of the ocean and reduced vertical mixing. Similar to 2014, slightly lower DO concentrations were observed at the deep mooring compared to the shallow mooring.

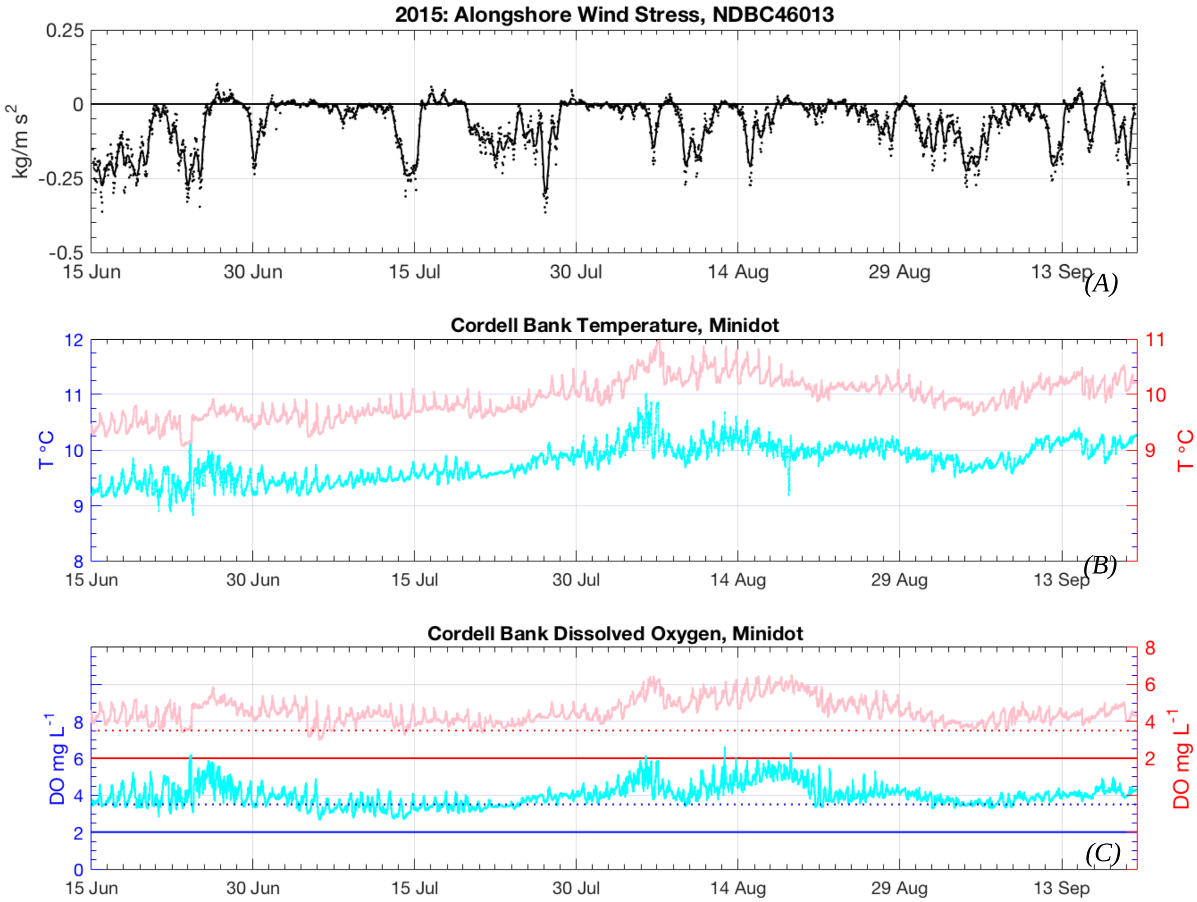


***Figure 2: 2015 Cordell Bank wind, temperature, and dissolved oxygen**: A) Top panel: alongshore wind stress calculated using wind speed and direction data from NDBC 46013. Negative values indicate upwelling favorable (northwesterly) winds. Black points indicate hourly data and the solid black line represents a 24-hour wind stress average. B) Middle panel: Temperature data obtained during 2015 from deep (blue; primary y-axis) and shallow (red; secondary y-axis) moorings. C) Bottom panel: DO data obtained during 2015 from deep (blue; primary y-axis) and shallow (red; secondary y-axis) moorings on Cordell Bank. Solid lines (dark blue or dark red) indicate hypoxic threshold (2 mg L^{-1}) and dashed lines indicate oxygen stressed conditions (3.5 mg L^{-1}).*

<u>2016 Deployment (Figure 3):</u> In 2016 the moorings were deployed on April 1. The deep mooring was recovered on June 16. In addition, the deep mooring that had been deployed in 2015 was also recovered in June 2016, providing a continuous record for that location through fall, winter and spring. The shallow mooring was recovered on September 27. To better track water masses, a salinity probe was added to the deep mooring on Cordell Bank in April 2016; however, logistical complications prevented redeployment in late June 2016. Because salinity does not change through chemical or biological reactions (it is a "conservative" property), it is used to label and track deep upwelled water masses. Low DO was observed during late March and again from March through September 2016, with periodic intervals of increased DO. Hypoxic conditions were not observed during the 2016 deployment.

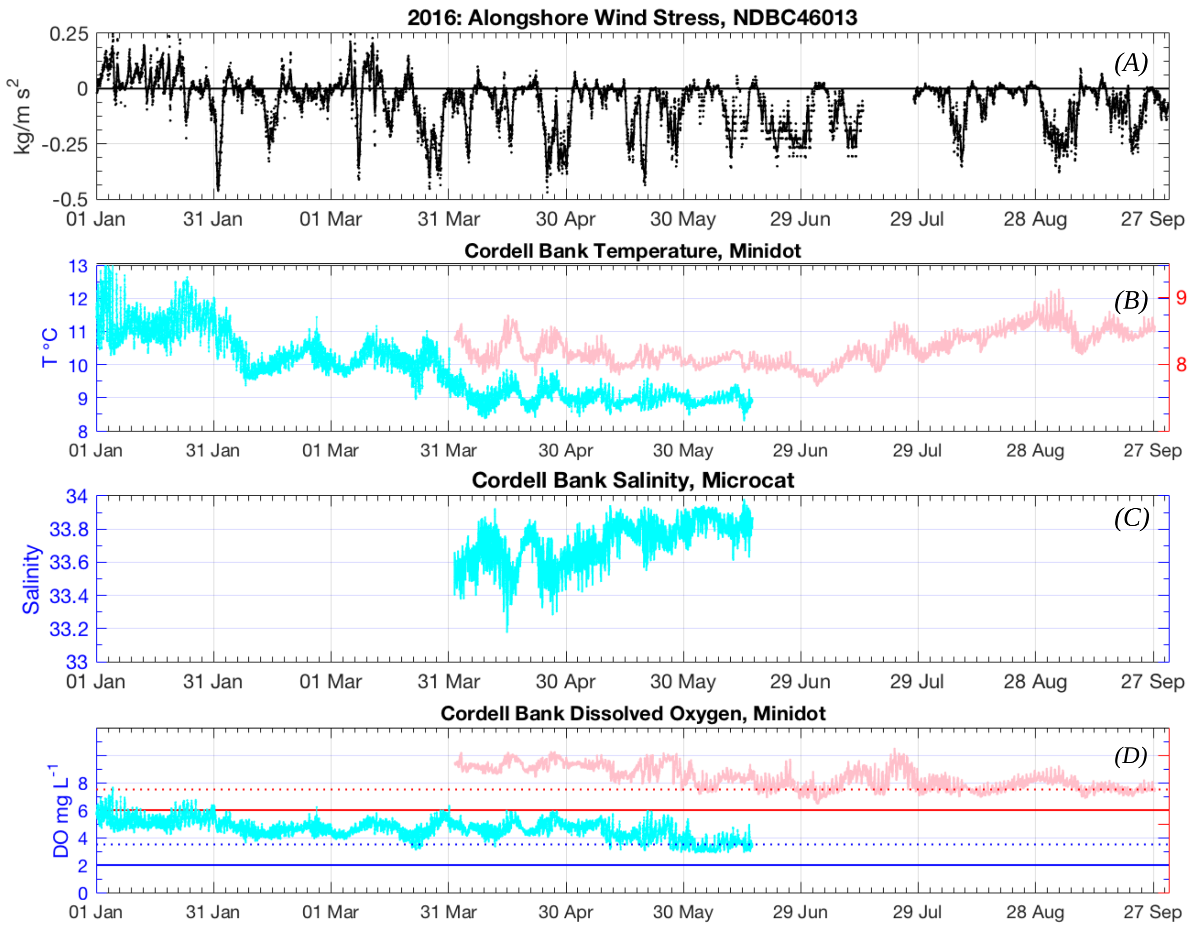


Figure 3: 2016 Cordell Bank wind, temperature, salinity, and dissolved oxygen: *A) Top panel: alongshore wind stress calculated using wind speed and direction data from NDBC 46013. Negative values indicate upwelling favorable (northwesterly) winds. Black points indicate hourly data and the solid black line represents a 24-hour wind stress average. B) second panel: Temperature data obtained during 2016 from deep (blue; primary y-axis) and shallow (red; secondary y-axis) moorings. C) third panel: Salinity data obtained during 2016 from deep mooring (blue). D) bottom panel: DO data obtained during 2016 from deep (blue; primary y-axis) and shallow (red; secondary y-axis) moorings on Cordell Bank. Solid lines (dark blue or dark red) indicate hypoxic threshold (2 mg L-1) and dashed lines indicate oxygen stressed conditions (3.5 mg L-1).*

<u>2017 Deployment</u>: In 2017 the moorings were deployed on March 16. Results are not yet available.

What can we do about hypoxia?

Our first step is to understand better the conditions the sanctuary experiences and the mechanisms that can account for changes in DO concentrations. Given that deoxygenation is a global phenomenon associated with climate change, our best approach as stewards of CBNMS is to protect the sanctuary from other stressors which can be managed locally. This includes protecting habitat, water quality, and biological communities. By ensuring healthy ocean ecosystems, we maintain their resilience and give them the best chance to thrive in the face of changing global conditions.

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