

Emergence of Anoxia in the California Current Large Marine Ecosystem

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Eastern boundary current systems are among the most productive large marine ecosystems in the world. Their productivity arises from wind-driven upwelling of nutrient-rich water into the photic zones of coastal oceans and supports 20% of global fishery yield (1). Upwelling also transports oxygen-poor waters onto productive continental shelves, where respiration can further reduce water-column dissolved oxygen (DO) content and thus subject coastal ecosystems to the risk of hypoxia or anoxia.

Of the world's four major eastern boundary current systems, water-column shelf anoxia is previously known for only the Humboldt and Benguela Current systems (2). Because oxygen deficit can be a critical determinant of fishery, ecological, and biogeochemical processes (3, 4), the rise or expansion of hypoxia and anoxia represent major perturbations to the structure and functioning of coastal marine ecosystems. Here, we report the intensification of severe inner-shelf hypoxia (defined here as $\leq 0.5 \text{ ml l}^{-1}$) and the novel rise of water-column anoxia in the California Current large marine ecosystem (CCLME) along the U.S. West Coast.

Following changes in upwelling-favorable winds in 2006, we measured the emergence of anoxia along the central Oregon coast. Anoxia was evident in inner-shelf ($< 50 \text{ m}$) stations situated within 2 km of the surf zone (Fig. 1C). The onset of anoxia was accompanied by the expansion of severe hypoxia across broad sections of the central Oregon shelf. At its largest, hypoxia prevailed across all cross-shelf transect lines between 44.25°N and 45.00°N, extending from the shelf break to the inner shelf and encompassing at least 3000 km². Hypoxia was

also exceptional in its vertical and temporal extents, occupying up to 80% of the water column in shallow (60 m) shelf waters and persisting over mid- and inner-shelf waters from June to October.

Although severe hypoxia is a permanent feature of the oxygen minimum zone (OMZ) that intersects the continental slope ($> 600 \text{ m}$ in this system), there are no prior records of anoxia over the continental shelf or within the OMZ (Fig. 1A). In contrast to OMZ marine life that possess adaptations to severe oxygen stress (3), demersal fish and benthic invertebrate communities in these shallow shelf waters were acutely affected by seasonally persistent anoxia and severe hypoxia. In August 2006, submersible-based surveys along the same previously monitored (2000 to 2004) transect lines revealed the complete absence of all fish from rocky reefs that normally serve as habitats for diverse rockfish (*Sebastes* species) communities that are of current fishery management concern. Our surveys also revealed near-complete mortality of macroscopic benthic invertebrates and an accompanying rise of putative sulfide-oxidizing bacterial mats in shallow (50 m) waters (movie S1).

The rise of anoxia has occurred against a backdrop of recent increases in the frequency and severity of shelf hypoxic events in this system (Fig. 1B). Five decades of available records show little evidence of shelf hypoxia and no evidence of severe inner-shelf hypoxia before 2000 (Fig. 1A). Recent studies indicate that the onset of shelf hypoxia can reflect basin-scale fluctuations in atmosphere-ocean processes that alter the oxygen content of upwelled water, the intensity of upwelling wind stress, and productivity-driven increases in coastal respi-

ration (5, 6). Strongly coupled atmospheric and oceanic circulation underpins ecosystem dynamics in wind-driven upwelling shelves and ecosystem susceptibility to modulations of upwelling wind stress from climate warming (7, 8). The present-day global distribution of shelf anoxia reflects broad cross-system differences in vertical proximity to OMZs, shelf productivity, and circulation. The novel rise of shelf anoxia in the CCLME highlights the potential for rapid reorganization in the distribution of anoxia and the sensitivity of productive upwelling shelves to discontinuous ecosystem change.

References and Notes

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Supporting Online Material

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Movie S1

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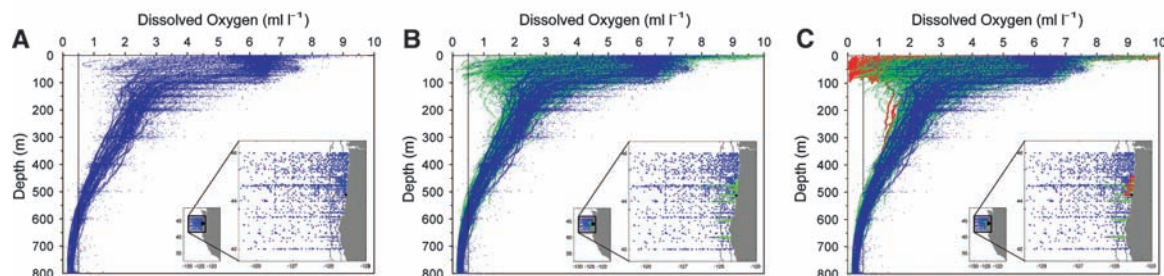


Fig. 1. Dissolved oxygen profiles during the upwelling season (mid-April to mid-October) in the upper 800 m of the continental shelf and slope of Oregon (42.00°N to 46.00°N). (A) 1950 to 1999 from the World Ocean Database and Oregon State University archives ($n = 3101$ hydrocasts, blue). (B) (A) with additional data for 2000 to 2005 ($n = 834$

hydrocasts, green). (C) (A) and (B) plus data for 2006 ($n = 220$ hydrocasts, red). The black vertical line denotes the 0.5 ml l^{-1} threshold. (Insets) Overlapping locations of hydrographic (blue, green, and red) and remotely operated vehicle (black) stations through time and the 100-m and 1000-m isobaths.