

Oxygen in the Southern California Bight: Multidecadal trends and implications for demersal fisheries

S. McClatchie,¹ R. Goericke,² R. Cosgrove,¹ G. Auad,^{3,4} and R. Vetter¹

Received 25 June 2010; revised 10 August 2010; accepted 24 August 2010; published 2 October 2010.

[1] Reports of hypoxic conditions (oxygen <1.5 ml L⁻¹) off the U.S. west coast over the last two decades led us to investigate hypoxia in the Southern California Bight (SCB) and its potential impacts on fisheries. The secular trend in hypoxia in the SCB over the last 57 years is not monotonic, and reversed trend in the mid-1980s, bringing oxygen concentrations back to levels measured in the late 1950s to early 1960s. Thirty-seven percent of the rockfish (*Sebastes* spp.) habitat in the Cowcod Conservation Area at 240–350 m depths suffers exposure to hypoxia in the summer of normal years. If current trends in shoaling of low oxygen water continue for another 20 years, rather than reversing as happened previously, we predict loss of 18% of the habitat with 55% of the total habitat exposed to hypoxia.
Citation: 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.

1. Introduction

[2] Over the last decades oxygen minimum zones in the tropical and subtropical North Pacific and other ocean basins have intensified [Whitney *et al.*, 2007; Stramma *et al.*, 2008]. In the equatorial [Stramma *et al.*, 2008] and eastern temperate Pacific [Bograd *et al.*, 2008] concentrations of oxygen below the euphotic zone have declined by 10 to 20% over the last 3 decades. It is probable that the observed basin-wide trends are forced by global warming and thus are expected to continue over the next decades [Stramma *et al.*, 2008]. The intensification of oxygen minimum zones is of particular concern for eastern boundary current ecosystems; not only are oxygen minimum zones in these regions found closer to the surface, but upwelling and other advective processes can carry low-oxygen water into shallow benthic habitats [Grantham *et al.*, 2004; Chan *et al.*, 2008]. It is likely that the extent of habitat of hypoxia-intolerant taxa of invertebrates and fish has been or will be impacted by these trends [Stramma *et al.*, 2008]. In general the expansion of hypoxic zones is expected to lead to a decrease in the biodiversity of the affected habitats [Levin *et al.*, 2009]. Off the west coast

of North America significant changes in ecosystem structure have been associated with previously unknown anoxic events [Grantham *et al.*, 2004].

[3] The oxygen content of water below the thermocline in some areas of the Southern California Bight (SCB) has decreased by up to 21% since 1984 [Bograd *et al.*, 2008]. The underlying causes for the decrease are unresolved. The implications for fisheries and the structure of the food web are potentially large. Declining oxygen could stress populations of commercially important rockfish (*Sebastes* spp.) on the submerged banks and islands of the SCB, which have been declining dramatically due to fishing over the last decades. The cowcod, *Sebastes levis*, is a large (up to 100 cm fork length) and highly sought after SCB rockfish with a long catch history. Numbers in 2010 are below 7% of the pre-fishing biomass, previously triggering severe management actions including the establishment of a Cowcod Conservation Area (CCA), a set-aside of 14,750 km² of prime rocky reef habitat in the SCB encompassing the 100 to 350 m depths of maximum adult abundance along the shelf-slope transition [Butler *et al.*, 2003].

[4] Recent papers documented transient changes off Oregon in the depth and intensity of hypoxic conditions and mass mortality of hypoxia-sensitive fishes and invertebrates at depths not previously thought to be impacted by hypoxia [Grantham *et al.*, 2004]. It was suggested that the frequency of hypoxic events is increasing [Chan *et al.*, 2008]. These events are driven by increased production in the euphotic zone, followed by remineralization and subsequent depletion of oxygen in the deeper water.

[5] It is less clear what may be driving the changes in oxygen in the SCB, and neither the long-term secular trend nor the effects of El Niño on hypoxia in this region are well known [Arntz *et al.*, 2006]. While the changes in oxygen concentrations since 1984 are of concern, they are not uniform over the region [Bograd *et al.*, 2008], and it is not known how dramatic they are when placed in the context of the full dataset that is available from surveys conducted by the long-term California Cooperative Oceanic Fisheries Investigation (CalCOFI). The impact of hypoxia on important fishery habitat in the SCB is also unknown.

[6] Various criteria for hypoxia have been used in the literature, generally between 0.5 to 2.0 ml L⁻¹, reviewed by Vaquer-Sunyer and Duarte [2008]. These authors noted that different organisms experience hypoxia at differing oxygen concentrations, and that the definition is not precise. Lethal hypoxic concentration varies more with motility than with taxa, with fishes reported to have a median LC₅₀ at 1.75 ml L⁻¹ [Vaquer-Sunyer and Duarte, 2008]. We used 1.5 ml L⁻¹ as an operational definition of hypoxia in this study.

[7] Depth is considered a master variable in the distribution of west coast temperate rocky reef fishes [Gunderson and

¹Southwest Fisheries Science Center, La Jolla, California, USA.

²Integrative Oceanography Division, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.

³Climate Research Division, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.

⁴Now at Environmental Studies Program, Bureau of Ocean Energy Management, U.S. Department of the Interior, Herndon, Virginia, USA.

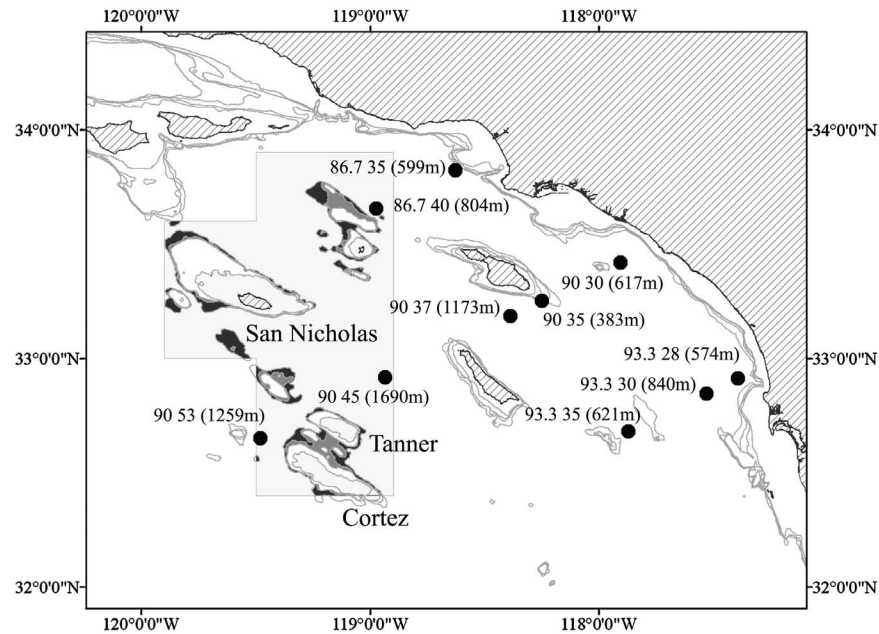


Figure 1. Map showing the potential rockfish habitat loss in the Cowcod Conservation Area (CCA highlighted as light gray) due to hypoxia (occurring where oxygen $<1.5 \text{ ml L}^{-1}$) if current trends continue for another 20 years, based on changes in the depth of the upper hypoxic zone illustrated in Figure 2. Total depth range of potential habitat is mapped as 100–350 m. Habitat in the depth range 240–350 m is affected by hypoxia in summer (July) and is marked black. Habitat potentially lost to hypoxia if a further 60 m shoaling occurs is the range 180–240 m and is marked dark gray. Habitat unaffected by hypoxia in the depth range 100–180 m is white. Land is cross-hatched. Black dots are CalCOFI stations used in the analyses labelled as CalCOFI line number CalCOFI station number (bottom depth).

Vetter, 2006]. Oxygen concentration is one of the environmental constraints that varies predictably with depth, and fishes occupying hypoxic waters often display specific adaptations that reflect the long-term persistence of this environment. High-affinity hemoglobins, low aerobic capacity, loss of a gas bladder, high water content, low productivity, and great longevity are often characteristic of fishes inhabiting hypoxic slope waters [Vetter *et al.*, 1994; Jacobson and Vetter, 1996; Vetter and Lynn, 1997]. Fishes of the shelf-slope break at 100–300 m such as the rockfish in the SCB do not generally display the hypoxia adaptations common to deeper living oxygen minimum zone specialists. Consequently, species such as the cowcod, *S. levis*, and other depleted rockfish species may suffer physiological stress or be forced out of preferred habitats by changes in oxygen in the California Current Ecosystem and throughout the Southern California Bight.

2. Methods

[8] We used data from the CalCOFI surveys (available at <http://www.calcofi.org/>) to examine the changes in oxygen concentration in the Southern California Bight from 1950 to 2007. We produced one time series from CalCOFI line 90, stations 45 and 53 in a central basin of the Cowcod Conservation Area, or CCA (Figure 1) and a second from a coastal band within 70 km of the shore between San Diego (117.3°W , 32.9°N) and Ventura, California (119.3°W , 34.2°N). Only data from CalCOFI lines 86.7, 90 and 93.3 were included in the coastal band because other lines have very spotty coverage. Line 86.7 lacked data for the critical 1960 to 1965 time

period when the low oxygen concentrations were observed. This lack of data will bias simple averages across this time period when compared to other time periods. Consequently we stratified the averaging. For any one cruise and line the average value of the property was calculated from all stations which were sampled and satisfied the geographic criteria. The line averages were averaged to derive one cruise average. There is a significant seasonal variability in the data so anomalies were calculated to remove it. The seasonally adjusted depth of the 1.5 ml L^{-1} oxygen concentration was calculated by adding the average depth of the 1.5 ml L^{-1} oxygen concentration for all data to all anomalies.

[9] Detailed standard sampling methods for CalCOFI surveys are reported on the website www.calcofi.org. The precision of the oxygen measurements is discussed in the auxiliary material for this article.¹ The anomalies in the time series that we describe in this paper are on the order of 20%, which is at worst one order of magnitude, and at best two orders larger than any differences in precision between the early and late years of the CalCOFI time series.

[10] Habitat area for the CCA was calculated from contoured bathymetry data using the ArcGIS Desktop, version 9.2, software package. A bathymetric digital elevation model, of 90 m spatial resolution, from the NOAA/NGDC Coastal Relief Model (version 4.1) was used to contour the 100, 180, 240 and 350 m isobaths. The contour lines were assembled into polygons. Subsequently, the areas were calculated for each polygon and classified by depth range. All of the GIS

¹Auxiliary materials are available in the HTML. doi:10.1029/2010GL044497.

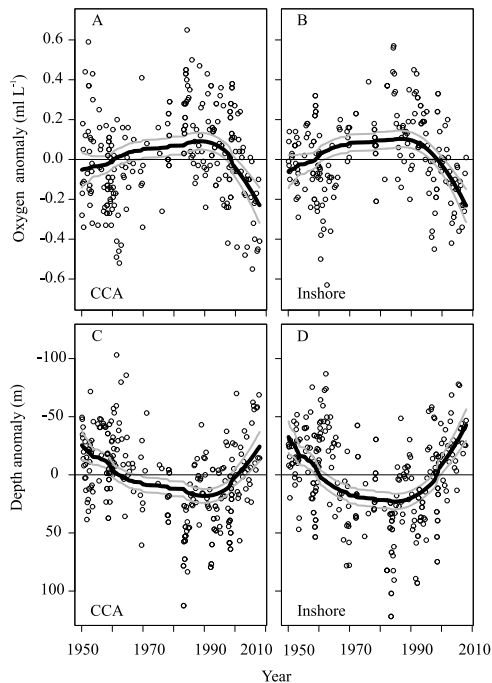


Figure 2. Time series of oxygen concentration anomalies at $\sigma_{\theta} = 26.6$ between 1950 and 2007 for (a) the Cowcod Conservation Area and (b) the Inshore Area. Time series of the depth anomaly for oxygen concentrations of 1.5 ml L^{-1} during the same time period for (c) the Cowcod Conservation Area and (d) the Inshore Area. The horizontal line represents the long-term average, which in the case of anomalies, is zero. Fitted lines are lowest smooths ± 2 CI.

data processing was completed within the California Teale Albers Conical Equal Area map projection using the NAD 1983 datum.

3. Results and Discussion

3.1. Secular Trends

[11] We examined the 57-year time series of oxygen concentrations at $\sigma_{\theta} = 26.6$ for both an inshore area and the offshore CCA. There is considerable variability and we discuss temporal differences in the smoothed data. The oxygen anomalies increased by 0.15 ml L^{-1} in both the CCA and inshore between 1950 and 1990 (Figures 2a and 2b). From 1990 to 2007 the oxygen anomaly decreased by 0.3 ml L^{-1} in both areas (Figures 2a and 2b).

[12] The time-series from 1950 to 2007 in both inshore and CCA clearly show first deepening and shoaling of the hypoxic zone (Figures 2c and 2d). Lower oxygen values are found when the oxycline is shallower (Figure 2, note reversed axes). The depth of the hypoxic zone deepened by 40–45 m from 1950 to 1985–90 (Figures 2c and 2d). Since 1990, the depth of the hypoxic zone has shoaled by 45 m in the CCA and by 65 m inshore. The shoaling appears to have begun 5 years earlier (1985) inshore.

[13] Trends in the last 23 years are toward lower oxygen and a shallower hypoxic zone, in accord with *Bograd et al.* [2008]. The whole 57 year record shows that while the decline in oxygen concentrations described by *Bograd et al.*

[2008] is the longest and largest negative trend in the time series, conditions similar to those that exist today existed in the late 1950s to early 1960s. *Bograd et al.* [2008] noted up to 80 m shoaling of the hypoxic zone in the more recent period, particularly inshore. We found shoaling of 65 m inshore.

[14] Averaged vertical oxygen profiles show no difference between 1950–1957 and 2000–2007 in either the inshore area or the offshore CCA (Figures 3a and 3b). In contrast, during the intervening years (1980–1987), the upper hypoxic zone was 50 m deeper than in the 1950s or in recent years (Figures 3a and 3b). The depth profiles of oxygen anomalies also showed little difference between 1950–1957 and 2000–2007. Both early and recent years show negative anomalies at most depths in both the inshore area and the CCA (Figures 3c and 3d). In contrast to early and recent years, the depth anomalies during 1980–1987 were positive at all depths (Figures 3c and 3d).

[15] The data presented here show that recent trends in oxygen at depth in the Southern California Bight are driven by a shoaling of isopycnals and declining concentrations of oxygen on isopycnals. Changes in the case of the $\sigma_{\theta} = 26.6$ isopycnal since the early 1980's are a shoaling of about 65 m and a decline of oxygen concentrations of about 0.5 to 0.6 ml L^{-1} oxygen. These two processes, shoaling isopycnals and declining concentrations of oxygen, combined lead to a 24 and 28% decline in oxygen concentrations at a depth of 250 m, the approximate depth of the 26.6 isopycnal, in the Cowcod and Nearshore areas, respectively (data not shown, but see figure below), results virtually identical to those of *Bograd et al.* [2008], who analyzed trends at depths of 200 and 300 m.

[16] However, concentrations of oxygen in the Cowcod and Nearshore areas at 250 m during the 1950's and early 60's were as low or lower than values observed recently, i.e., 1.38 and 1.42 ml L^{-1} , respectively. *Bograd et al.* [2008] suggested that declining concentrations of oxygen in the CCS are driven by rates of isopycnal ventilation, which is affected by stratification in general, and by changing rates of advection of low-oxygen waters into the region and changing properties of waters advected into the region, primarily those of the California Undercurrent. The latter changes are possibly linked to changing stratification of the subtropical and equatorial ocean [*Stramma et al.*, 2008, 2010] and thus to global warming. Indeed, changing concentrations of oxygen at isopycnals in the CalCOFI study area have covaried tightly with global land-ocean temperatures since the early 1980's (data not shown), suggesting that current trends in declining oxygen at depth in the SCB will hold if global warming continues [cf. *Stramma et al.*, 2010]. The effect of changing concentrations of oxygen in the SCB is of significant concern to the management of its living resources.

3.2. Predicted Effect on Fish Habitat

[17] Fish species with latitudinal distributions from Alaska to Mexico segregate over vertical distances of a few hundred meters [*Jacobson and Vetter*, 1996; *Vetter and Lynn*, 1997; *Hyde et al.*, 2008]. Continued shoaling of the upper hypoxic zone over the CCA would be expected to impact the 100–350 m rockfish habitat around Tanner Bank and San Nicolas Island (Figure 1). Unlike typical continental shelf systems, the availability of specific depth habitats is extremely limited in the SCB due to steep vertical contours. Fish appear to be habitat limited [*Gunderson and Vetter*, 2006], and loss of

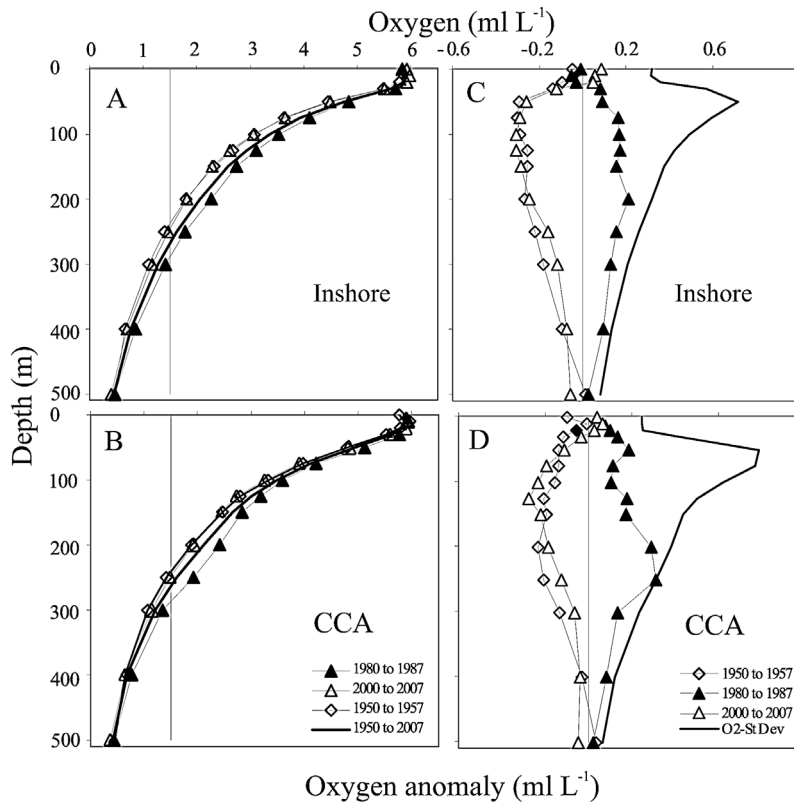


Figure 3. Depth profiles of oxygen concentrations at standard CalCOFI depths for (a) the Inshore area and (b) the Cowcod Conservation Area (CCA). Corresponding depth profiles of oxygen concentration anomalies for the data for (c) the Inshore area and (d) the CCA. Anomalies are defined as deviations from the average concentrations at that depth using the time periods 1950–2007 as a base. Data from individual stations and cruises were first averaged for individual lines and years, then for individual years, and last for the indicated time periods to avoid bias due to uneven sampling in space and time.

habitat may be critical for recovery of over-fished species. While continental margin habitats may provide the option of vertical movement to shallower, better oxygenated habitats to escape the effects of low oxygen, submerged offshore banks such as those of the SCB may limit responses to hypoxia in benthic fishes. The fish on these banks may ultimately be at risk from intrusions of low-oxygen water into the SCB.

[18] We estimate how much habitat in the CCA might be affected by hypoxia if current trends of declining oxygen continue. We define the cowcod rockfish habitat as the 100–350 m depth range [Butler *et al.*, 2003]. In summer months about 37% of the CCA at depths of 240–350 m is affected by hypoxia (Figure 1). If current trends continue for 20 years, the top of the hypoxic zone would shoal by 60 m to a depth of 180 m, and the area affected by hypoxia would increase to 55% of the total habitat, placing an additional 18% of habitat under oxygen stress in the 180–240 m depth range (Figure 1). About 45% of the habitat is never impacted by hypoxia based on our analyses, and this habitat in the 100–180 m depth range constitutes a refuge from oxygen stress.

[19] In conclusion, the current state of oxygen in the SCB is similar to that in the late 1950s and early 1960s, and trends in oxygen levels show evidence of reversing on decadal time scales. The highly diverse rockfishes (*Sebastes*) are the dominant benthic fishes of the SCB. The tissue oxygen demands and downward oxygen cascade from water to hemoglobin to ovary may put brooding females at particular risk of hypoxia. Consideration of habitat quality in the

Southern California Bight should take potential exposure to hypoxia into consideration. Consequently it is important to monitor future levels of oxygen in the Southern California Bight to determine whether trends will continue in the current direction as climate continues to change. While our results show that present trends could reverse, as they have done in the past, the continuation of current trends would have detrimental impacts on rockfish fisheries.

[20] **Acknowledgments.** Ron Lynn, Steven Bograd, Lou Zeidberg, Lisa Levin, Paul Fiedler, Tim Baumgartner and John Field provided helpful comment on the manuscript. This research was funded by the Fisheries And The Environment program (FATE) of the NOAA Fisheries Service of the National Oceanic Atmospheric Administration.

References

- Arntz, W., et al. (2006), El Niño and similar perturbation effects on the benthos of the Humboldt, California, and Benguela current upwelling systems, *Adv. Geosci.*, 6, 243–265.
- 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.
- Butler, J., L. Jacobson, J. Barnes, and H. Moser (2003), Biology and population dynamics of cowcod (*Sebastes levis*) in the Southern California Bight, *Fish. Bull.*, 101, 260–280.
- Chan, F., J. Barth, J. Lubchenko, A. Kirincich, H. Weeks, W. Peterson, and B. Menge (2008), Emergence of anoxia in the California Current large marine ecosystem, *Science*, 319, 920.
- Grantham, B., F. Chan, K. Nielsen, D. Fox, J. Barth, A. Huyer, J. Lubchenko, and B. Menge (2004), Upwelling-driven nearshore hypoxia signals

- ecosystem and oceanographic changes in the northeast Pacific, *Nature*, 429, 749.
- Gunderson, D., and R. Vetter (2006), Temperate rocky reef fishes, in *Marine Metapopulations*, edited by P. Sale and J. Kritzer, pp. 69–117, Elsevier, Amsterdam.
- Hyde, J., C. Kimbrell, J. Budrick, E. Lynn, and R. Vetter (2008), Cryptic speciation in the vermilion rockfish (*Sebastes miniatus*) and the role of bathymetry in the speciation process, *Mol. Ecol.*, 17, 1122–1136.
- Jacobson, L., and R. Vetter (1996), Bathymetric demography and niche separation of thornyhead rockfish: *Sebastolobus alascanus* and *Sebastolobus altivelis*, *Can. J. Fish. Aquat. Sci.*, 53, 600–609.
- Levin, L., W. Ekau, A. Gooday, F. Jorissen, J. Middelburg, S. Naqvi, C. Neira, N. Rabalais, and J. Zhang (2009), Effects of natural and human-induced hypoxia on coastal benthos, *Biogeosciences*, 6, 2063–2098.
- Stramma, L., G. Johnson, J. Sprintall, and V. Mohrholz (2008), Expanding oxygen minimum zones in the tropical oceans, *Science*, 320, 655–658.
- Stramma, L., S. Schmidt, L. Levin, and G. Johnson (2010), Ocean oxygen minima expansions and their biological impacts, *Deep Sea Res., Part I*, 57(4), 587–595.
- Vaquier-Sunyer, R., and C. Duarte (2008), Thresholds of hypoxia for marine biodiversity, *Proc. Natl. Acad. Sci. U. S. A.*, 105(40), 15,452–15,457.
- Vetter, R., and E. Lynn (1997), Bathymetric demography, enzyme activity patterns, and bioenergetics of deep-living scorpaenid fishes (genera *Sebastes* and *Sebastolobus*): Paradigms revisited, *Mar. Ecol. Prog. Ser.*, 155, 173–188.
- Vetter, R., E. Lynn, M. Garza, and A. Costa (1994), Depth zonation and metabolic adaptation in dover sole, *Microstomus pacificus*, and other deep-living flatfishes: Factors that affect the sole, *Mar. Biol.*, 120, 145–159.
- Whitney, F., H. Freeland, and M. Robert (2007), Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific, *Prog. Oceanogr.*, 75, 179–199.
-
- G. Auaad, Environmental Studies Program, Bureau of Ocean Energy Management, U.S. Department of the Interior, MS 4041, 381 Elden St., Herndon, VA 20170, USA.
- R. Cosgrove, S. McClatchie, and R. Vetter, Southwest Fisheries Science Center, 8604 La Jolla Shores Dr., La Jolla, CA 92037-1508, USA. (sam.mcclatchie@noaa.gov)
- R. Goericke, Integrative Oceanography Division, Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Dr., La Jolla, CA 92093, USA.