Oxygen declines and the shoaling of the hypoxic boundary in the California Current

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[1] We use hydrographic data from the California Cooperative Oceanic Fisheries Investigations program to explore the spatial and temporal variability of dissolved oxygen (DO) in the southern California Current System (CCS) over the period 1984–2006. Large declines in DO (up to 2.1 μmol/kg/y) have been observed throughout the domain, with the largest relative DO declines occurring below the thermocline (mean decrease of 21% at 300 m). Linear trends were significant ($p < 0.05$) at the majority of stations down to 500 m. The hypoxic boundary ($\sim$60 μmol/kg) has shoaled by up to 90 m within portions of the southern CCS. The observed trends are consistent with advection of low-DO waters into the region, as well as decreased vertical oxygen transport following near-surface warming and increased stratification. Expansion of the oxygen minimum layer could lead to cascading effects on benthic and pelagic ecosystems, including habitat compression and community reorganization. **Citation:** 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.

1. Introduction

[2] Dissolved oxygen (DO) concentrations in the ocean are dependent on a number of physical and biological processes, including circulation, ventilation, air-sea exchange, production and respiration. Climate-driven changes in these processes should therefore be reflected in oceanic DO observations [*Deutsch et al.*, 2005]. In particular, models driven by increasing greenhouse gases predict a decline in midwater oceanic DO as a result of enhanced stratification and reduced ventilation [*Sarmiento et al.*, 1998; *Keeling and Garcia*, 2002]. These changes will have a significant impact on the biological pump locally, while changes in large-scale circulation will act to spread and modify the oxygen signal. Spreading of low-oxygen waters could also greatly impact many higher trophic level species, depending on their oxic requirements. Although long time series of DO are relatively scarce, the few regions where they are available have seen a systematic decline [*Emerson et al.*, 2004; *Whitney et al.*, 2007]. Additional regional observations of long-term oxygen trends are critical to evaluating the causes and implications of climate-driven oxygen changes.

[3] Here we use historical hydrographic data from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program [*Bograd et al.*, 2003] to explore the spatial and temporal variability of DO in the California Current, within and offshore of the Southern California Bight (SCB). The SCB is affected by a confluence of water masses from the subarctic Pacific, via the California Current; from the northeastern tropical Pacific, via the California Undercurrent [*Lynn and Simpson*, 1987]; and from lateral shifts in the boundary of the North Pacific Subtropical Gyre. The California Current is also a highly productive region, and has undergone significant changes in lower trophic production on seasonal [*Mackas et al.*, 2006], interannual [*Bograd and Lynn*, 2001], and decadal [*McGowan et al.*, 2003] time scales related to large-scale climate forcing. The long historical time series of DO observations within this eastern boundary current provide a unique opportunity to investigate the relative role of physical and biological processes in controlling oxygen

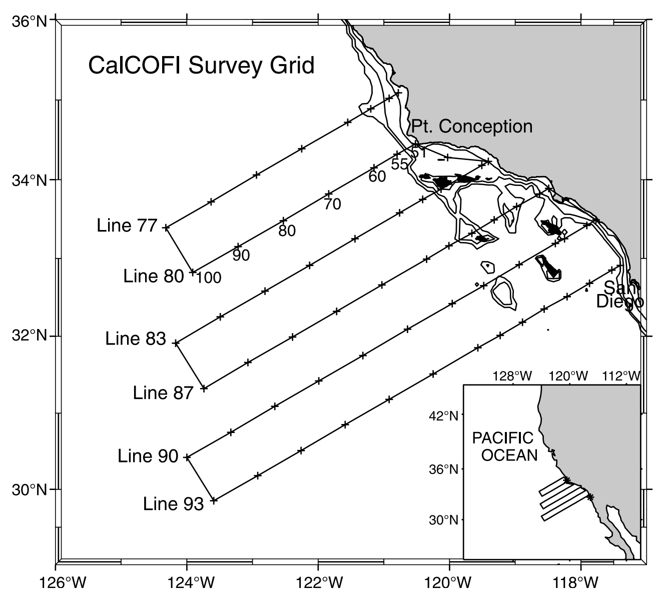

Figure 1. Map of the nominal CalCOFI survey grid. Line and station numbers are shown.

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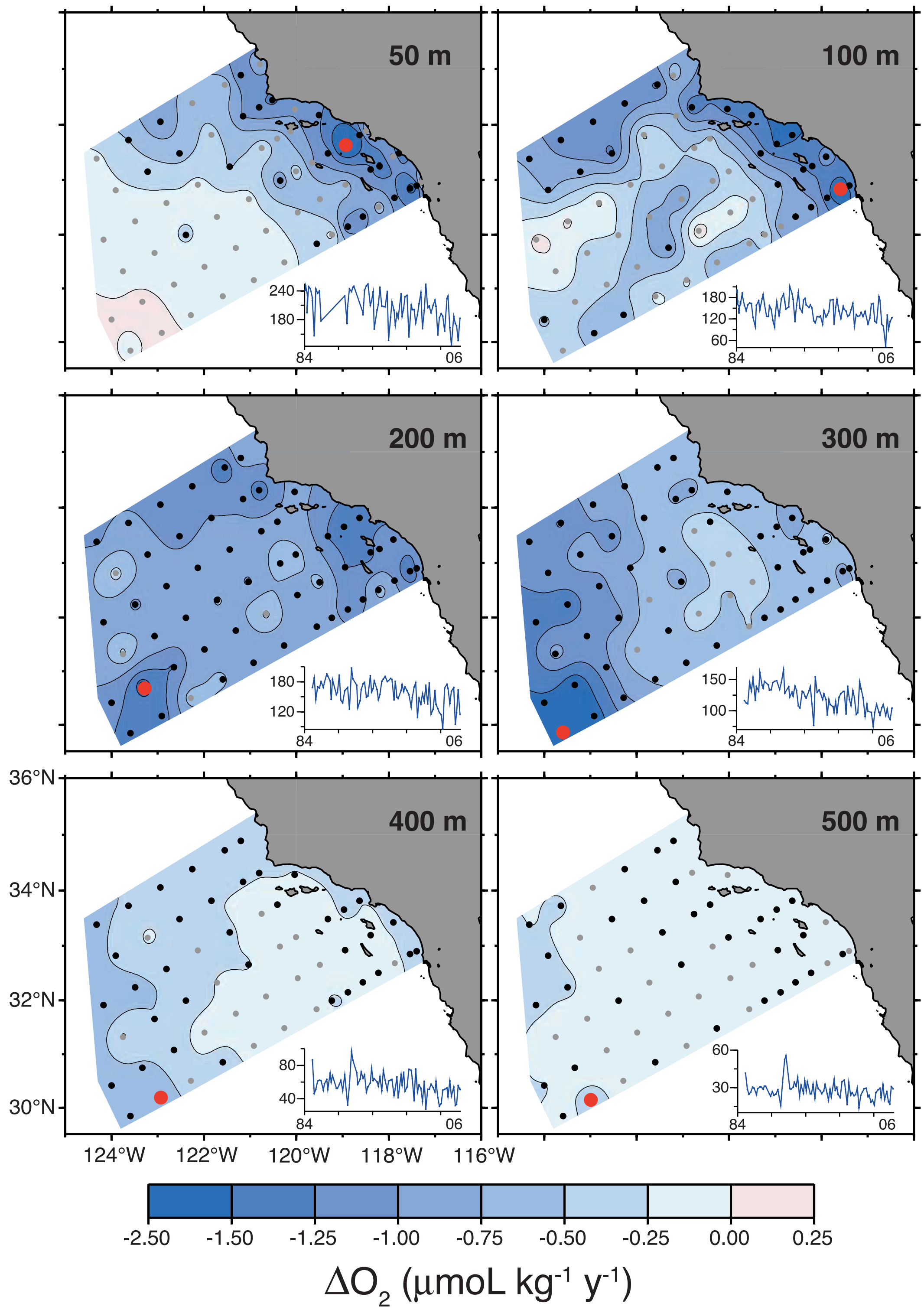

Figure 2. Linear trends in dissolved oxygen (μmol/kg/y) at six standard depths on the CalCOFI survey grid over the period 1984–2006. Stations with significant linear regressions ($p < 0.05$) are marked black. DO time series (μmol/kg) at stations with maximum linear trend (marked red on the maps) are shown in the insets for each standard depth.

changes, particularly in the context of a warming ocean [*Keeling and Garcia*, 2002].

2. Data and Methods

[4] The CalCOFI program has maintained quarterly surveys on a geographically fixed grid offshore of southern California since 1984 (Figure 1). Although CalCOFI sampling has occurred since 1949, here we only consider the post-1984 period, when implementation of a consistent sampling protocol limited systematic errors [*Scripps Institution of Oceanography (SIO)*, 2007]. Routine CalCOFI station occupations (on 66 standard stations;

Table 1. Overall Mean Change in DO in the CalCOFI Domain Between 1984 and 2006[a]

Depth (m)	ΔO_2 (μmol/kg/y)	Percent O_2 Change	ΔAOU (μmol/kg/y)	Peak Station
50	−0.62	−6.4	0.72	87.40
100	−0.74	−9.4	0.87	93.30
200	−0.99	−18.3	0.96	90.110, 93.30
300	−0.81	−21.0	0.75	93.120, 90.110
400	−0.30	−14.6	0.25	93.110
500	−0.15	−14.1	0.10	93.110, 82.47

[a]Stations with the largest changes are provided in the last column (first DO trend magnitude, then percent change when two stations are listed).

Figure 1) deploy a SeaBird CTD instrument with a 24-place rosette, which is equipped with 24 10-L plastic (PVC) Niskin bottles [*SIO*, 2007]. Epoxy-coated Nansen wire casts were done prior to August 1987; 3-L PVC bottle wire casts were done from September 1987 through April 1993. Casts were made to ~525-m depth, bottom depth permitting.

[5] DO samples were collected in calibrated 100 mL iodine flasks and analyzed at sea by the modified Winkler method [*Carpenter*, 1965], using the equipment and procedure outlined by *Anderson* [1971]. Estimated precision is 0.02 ml/l (~0.9 μmol/kg; *SIO* [2007]). Units were converted to μmol/kg based on *in situ* potential densities. Further details of the standard sampling and analysis procedures, along with data and derived variables, can be found in CalCOFI data reports or online (http://www.calcofi.org/newhome/data/data.htm).

[6] We computed linear trends of DO at six standard levels (50, 100, 200, 300, 400 and 500 m) at each station over the period 1984–2006, and determined the correlation coefficient and significance value of each fit. A linear trend was considered significant for p-values less than 0.05. Trends were computed for all 66 nominal stations, with the average number of occupations ranging from 93 (500 m) to 98 (50 m). From the linear fit, we determined the magnitude of the oxygen trend at each standard depth and station, as well as the percent change over the 23-year period. We did not consider surface oxygen trends, as these are impacted by high-frequency air-sea fluxes and can vary widely [*Garcia et al.*, 2005].

3. Dissolved Oxygen Trends

[7] Large declines in DO have been observed throughout the CalCOFI domain and to at least 500 m depth (Figure 2, Table 1). In the upper 100 m, the largest declines occurred along the shelf and slope region, within the SCB, and at the center of Line 77, where the core of the California Current typically enters the domain [*Bograd and Lynn*, 2003]. Significant linear declines ($p < 0.05$) in DO were observed at 27 (24) stations at 100 m (50 m), with the largest decline at 50 m at Station 87.40 of −2.13 μmol/kg/y. The largest DO declines occurred during summer (July–September) on the shelf and within the SCB, and during autumn (October–November) within the California Current core (not shown). A higher number of stations had significant DO declines at mid-depths (52 stations at 200 m, 47 at 300 m), with the largest declines (−1.8 μmol/kg/y) on the offshore end of Lines 90 and 93. DO trends at 400–500 m were smaller (−0.1–0.7 μmol/kg/y), but nonetheless significant (38 stations at 400 m, 33 at 500 m). These deep declines occurred primarily in winter (January–March; not shown). The DO trends are also reflected in apparent oxygen utilization (AOU; *Emerson et al.* [2004]), which increased by nearly 1 μmol/kg/y at 200 m (Table 1).

[8] Although the largest absolute DO declines occurred in the upper water column, the largest *relative* declines occurred at the deeper levels (Figure 3, Table 1). The decrease in DO over the 23-year period was generally <10% at 50–100 m, but ranged from 10–30% at 200–300 m. The largest relative decline in mean DO at specific depth was −21%, observed at 300 m (Table 1). Several stations had DO declines greater than 30% (80.55, 87.35, 87.40, 87.45, 93.30 at 200 m; 87.35, 90.110, 93.30 at 300 m). At these deeper levels, the highest percent change in DO occurred at the southwest corner of the domain (−26% at 93.110), and at 500 m within the Santa Barbara Basin (−25% at 82.47), where a recent decline in flushing rate has resulted in anoxic bottom conditions (S. J. Bograd et al., manuscript in preparation). Non-significant DO increases were observed at a few offshore stations at 50–100 m.

[9] CalCOFI samples the upper portion of the oxygen minimum layer (OML) in the southern California Current [*Kamykowski and Zentara*, 1990], thus the observed water column DO declines can be interpreted as a shoaling of the OML. In particular, the level of the OML representing an accepted threshold for hypoxia (~ 60 μmol/kg; *Diaz and Rosenberg* [1995]) has shoaled by an average of 41 m since 1984 (Figure 4). Within the inner SCB and near Point Conception, the hypoxic boundary has shoaled by up to 90 m (at station 93.30). The shoaling of this layer is significant at 37 of 46 stations (Figure 4).

[10] The DO declines observed off southern California are of similar amplitude to the mid-depth DO declines observed in several regions of the western [*Ono et al.*, 2001; *Andreev and Watanabe*, 2002; *Watanabe et al.*, 2003; *Nakanowatari et al.*, 2007] and eastern [*Emerson et al.*, 2004; *Whitney et al.*, 2007] subarctic North Pacific. In shelf regions of the northern CCS, a higher frequency of upwelling-driven nearshore hypoxia has also been observed in recent years [*Grantham et al.*, 2004; *Chan et al.*, 2008]. Taken together, these observations point to a basin-wide reduction in DO.

4. Causes of the Oxygen Decline

[11] Ocean general circulation models predict a global reduction in mid-depth DO under global warming scenarios, with most of this reduction attributed to enhanced near-surface stratification [*Sarmiento et al.*, 1998; *Keeling and Garcia*, 2002]. While stratification can increase subsurface oxygen by slowing the rate of the biological pump (i.e., reducing the upwelling of nutrients and subsequent photosynthesis and sinking of detritus), the models found that the greater impact is a reduction in downward transport of oxygen from well-oxygenated surface waters into the ocean interior [*Keeling and Garcia*, 2002]. Thus, in this scenario, the net impact of surface ocean warming and enhanced stratification is a reduction in the efficiency, rather than the rate, of the biological pump [*Keeling and Garcia*, 2002]. Recent studies have found a significant surface-intensified

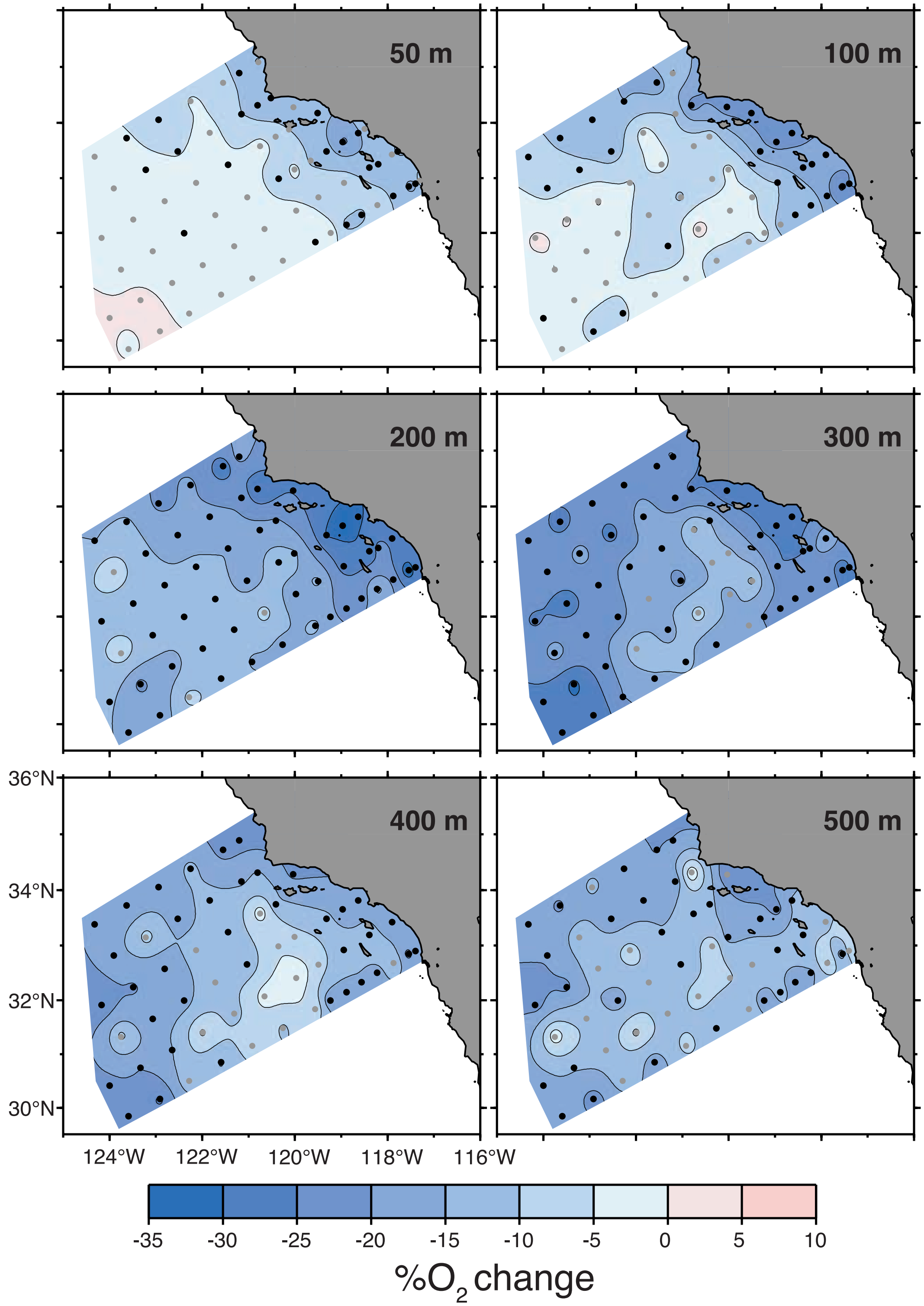

Figure 3. Same as Figure 2, but percent change in DO over the period 1984–2006.

warming in the southern CCS, with a subsequent increase in thermal stratification [*Bograd and Lynn*, 2003; *Palacios et al.*, 2004; *Di Lorenzo et al.*, 2005]. The large DO declines observed throughout the southern CCS, with the largest relative changes occurring below the seasonal thermocline, are consistent with a hypothesized reduction in vertical oxygen transport.

[12] Advection of low-DO waters into the region may also have contributed to the observed DO decline. The spatial patterns of the DO trends off California suggest that the region's source waters are lower in DO content. At 50–100 m, stations within the core of the California Current (middle of Line 77) had among the largest absolute DO declines (Figure 2). At 200–300 m, large declines were

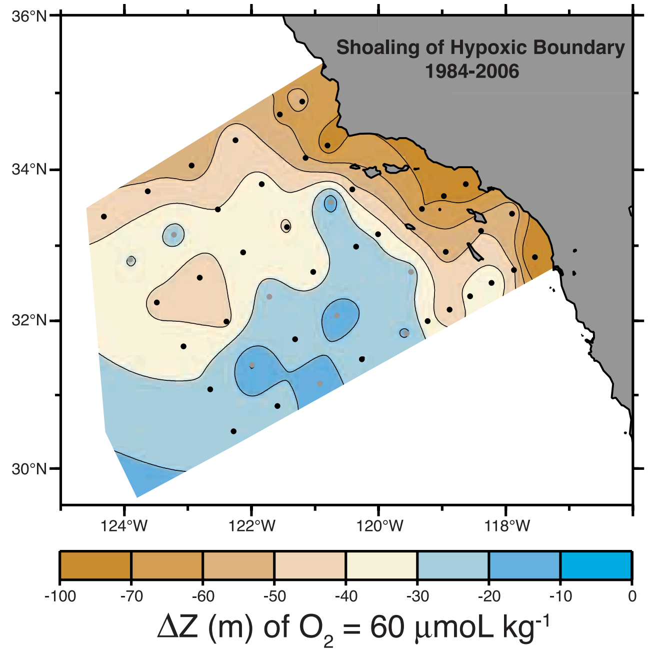

Figure 4. Total change in the depth (m) of the O_2 = 60 μmol/kg surface on the CalCOFI survey grid over the period 1984–2006. Stations with significant linear regressions ($p < 0.05$) are marked black.

seen within the Bight (Station 93.30; Figure 2, Table 1), where source waters within the California Undercurrent have seen a significant DO decline (Bograd et al., manuscript in preparation). Recent observations have shown a thickening of the OML in the equatorial Pacific, which could lead to reduced oxygen supply to the CCS [*Stramma et al.*, 2008]. And at all depths below 200 m, offshore areas affected by intrusions of Subtropical Gyre waters have seen the largest absolute and relative DO declines (Figure 2, Table 1). Experiments with ROMS model hindcasts for the period 1950–2004 have been shown to capture the physical-biological dynamics in the California Current [*Di Lorenzo et al.*, 2008]. Further analysis of these experiments (not shown) suggest that there has been increased advection of Subtropical Waters (characterized by high temperature, low DO) into the SCB since 1984.

[13] It is important to note that the observed DO declines off California could have been forced locally, through thermodynamic or biological processes, or remotely (e.g., a large-scale shoaling of the pycnocline and OML), and subsequently advected to the region. We cannot distinguish between locally-induced DO changes and the advection of remotely-altered water masses, although both processes are probably important. Quantification of the relative impact of advection, stratification, and local changes in production/respiration on the DO trends will require carefully planned measurements as well as dedicated coupled physical-biological modeling experiments.

5. Ecological Implications of the Oxygen Decline

[14] Shoaling of the OML is expected to lead to significant and complex ecological changes in the CCS. These include direct hypoxia-related effects on benthic organisms where the OML contacts the continental margin [*Levin*, 2003] as well as on hypoxia-tolerant mesopelagic organisms, including myctophid fishes and crustaceans, that reside in its upper boundary region [*Childress and Seibel*, 1998]. These latter organisms impact epipelagic planktonic communities, because they migrate to near-surface waters at night to feed. A shoaling OML could also lead to a compression of favorable habitat for pelagic or benthic fishes and invertebrates [*Prince and Goodyear*, 2006], but could represent an expansion of favorable habitat for mesopelagic predators such as Humboldt squid (*Dosidicus gigas*). During the last decade *D. gigas* has expanded its range northward from Baja California to southeast Alaska [*Cosgrove*, 2005; *Gilly*, 2005; *Wing*, 2006], and shoaling of the OML in the northeastern Pacific during this period may have been a relevant factor in this major ecological shift [*Gilly and Markaida*, 2007].

[15] Perhaps the most severe potential ecological impact of a shoaling OML would be the upwelling of hypoxic water in such areas as off Point Conception. An exceptionally large decrease in oxygen over the 50–100 m depth range has occurred in this area (Figure 2) along with the largest degree of shoaling (Figure 4). These trends could lead to cascading effects on benthic and pelagic ecosystems, including habitat compression [*Chan et al.*, 2008], community reorganization, and alterations in ocean acidification. Further warming and increased stratification could lead to substantially larger declines in oceanic DO in the CCS and other coastal ecosystems.

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References

Anderson, G. C. (1971), Oxygen analysis, in *Marine Technicians Handbook*, *SIO Ref. 71–8*, Scripps Inst. of Oceanogr., La Jolla, Calif.

Andreev, A., and S. Watanabe (2002), Temporal changes in dissolved oxygen of the intermediate water in the subarctic North Pacific, *Geophys. Res. Lett.*, *29*(14), 1680, doi:10.1029/2002GL015021.

Bograd, S. J., and R. J. Lynn (2001), Physical-biological coupling in the California Current during the 1997–99 El Niño-La Niña cycle, *Geophys. Res. Lett.*, *28*, 275–278.

Bograd, S. J., and R. J. Lynn (2003a), Long-term variability in the southern California Current System, *Deep Sea Res., Part II*, *50*, 2355–2370.

Bograd, S. J., D. M. Checkley, and W. S. Wooster (2003b), CalCOFI: A half century of physical, chemical, and biological research in the California Current System, *Deep Sea Res., Part II*, *50*, 2349–2354.

Carpenter, J. H. (1965), The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method, *Limnol. Oceanogr.*, *10*, 141–143.

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.

Childress, J. J., and B. A. Seibel (1998), Life at stable low oxygen levels: Adaptations of animals to oceanic oxygen minimum layers, *J. Exp. Biol.*, *201*, 1223–1232.

Cosgrove, J. A. (2005), The first specimens of Humboldt squid in British Columbia, *PICES Press*, *13*(2), 30–31.

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., and R. Rosenberg (1995), Marine benthic hypoxia: A review of its ecological effects and the behavioral responses of benthic macrofauna, *Oceanogr. Mar. Biol.*, *33*, 245–303.

Di Lorenzo, E., A. J. Miller, N. Schneider, and J. C. McWilliams (2005), The warming of the California Current System: Dynamics and ecosystem implications, *J. Phys. Oceanogr.*, *35*, 336–362.

Di Lorenzo, E., et al. (2008), North Pacific Gyre Oscillation links ocean climate and ecosystem change, *Geophys. Res. Lett.*, *35*, L08607, doi:10.1029/2007GL032838.

Emerson, S., Y. W. Watanabe, T. Ono, and S. Mecking (2004), Temporal trends in apparent oxygen utilization in the upper pycnocline of the North Pacific: 1980–2000, *J. Oceanogr.*, *60*, 139–147.

Garcia, H. E., T. P. Boyer, S. Levitus, R. A. Locarnini, and J. Antonov (2005), On the variability of dissolved oxygen and apparent oxygen utilization content for the upper world ocean: 1955 to 1998, *Geophys. Res. Lett.*, *32*, L09604, doi:10.1029/2004GL022286.

Gilly, W. F. (2005), Spreading and stranding of Humboldt squid, in *Ecosystem Observations for the Monterey Bay National Marine Sanctuary*, report, pp. 20–22, Monterey Bay Natl. Mar. Sanctuary, Monterey, Calif.

Gilly, W. F., and U. Markaida (2007), Perspectives on *Dosidicus gigas* in a changing world, in *The Role of Squid in Open Ocean Ecosystems*, edited by R. J. Olson and J. W. Young, *Rep. 24*, pp. 81–90, Global Ocean Ecosyst. Dyn., Honolulu, Hawaii.

Grantham, B. A., F. Chan, K. J. Mielsen, D. S. Fox, J. A. Barth, A. Huyer, J. Lubchenco, and B. A. Menge (2004), Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific, *Nature*, *429*, 749–754.

Kamykowski, D. Z., and S. J. Zentara (1990), Hypoxia in the world ocean as recorded in the historical data set, *Deep Sea Res., Part A*, *37*, 1861–1874.

Keeling, R. F., and H. E. Garcia (2002), The change in oceanic O_2 inventory associated with recent global warming, *Proc. Natl. Acad. Sci. U. S. A.*, *99*, 7848–7853.

Levin, L. A. (2003), Oxygen minimum zone benthos: Adaptation and community response to hypoxia, *Oceanogr. Mar. Biol.*, *41*, 1–45.

Lynn, R. J., and J. J. Simpson (1987), The California Current System: The seasonal variability of its physical characteristics, *J. Geophys. Res.*, *92*(C12), 12,947–12,966.

Mackas, D. L., W. T. Peterson, M. D. Ohman, and B. E. Lavaniegos (2006), Zooplankton anomalies in the California Current System before and during the warm ocean conditions of 2005, *Geophys. Res. Lett.*, *33*, L22S07, doi:10.1029/2006GL027930.

McGowan, J. A., S. J. Bograd, R. J. Lynn, and A. J. Miller (2003), The biological response to the 1977 regime shift in the California Current, *Deep Sea Res., Part II*, *50*, 2582–3567.

Nakanowatari, T., K. I. Ohshima, and M. Wakatsuchi (2007), Warming and oxygen decrease of intermediate water in the northwestern North Pacific, originating from the Sea of Okhotsk, 1955–2004, *Geophys. Res. Lett.*, *34*, L04602, doi:10.1029/2006GL028243.

Ono, T., T. Midorikawa, Y. W. Watanabe, K. Tadokoro, and T. Saino (2001), Temporal increases of phosphate and apparent oxygen utilization in the subsurface waters of the western subarctic Pacific from 1968 to 1998, *Geophys. Res. Lett.*, *28*, 3285–3288.

Palacios, D. M., S. J. Bograd, R. Mendelssohn, and F. B. Schwing (2004), Long-term and seasonal trends in stratification in the California Current, 1950–1993, *J. Geophys. Res.*, *109*, C10016, doi:10.1029/2004JC002380.

Prince, E. D., and C. P. Goodyear (2006), Hypoxia-based habitat compression of tropical pelagic fishes, *Fish. Oceanogr.*, *15*, 451–464.

Sarmiento, J. L., T. M. C. Hughes, R. J. Stouffer, and S. Manabe (1998), Simulated response of the ocean carbon cycle to the anthropogenic climate warming, *Nature*, *393*, 245–248.

Scripps Institution of Oceanography (SIO) (2007), Data report, CalCOFI cruise 0501, *CC Ref. 07-03*, La Jolla, Calif.

Stramma, L., G. C. Johnson, J. Sprintall, and V. Mohrholz (2008), Expanding oxygen-minimum zones in the tropical oceans, *Science*, *320*, 655–658.

Watanabe, Y. W., M. Wakita, N. Maeda, T. Ono, and T. Gamo (2003), Synchronous bidecadal periodic changes of oxygen, phosphate and temperature between the Japan Sea deep water and the North Pacific intermediate water, *Geophys. Res. Lett.*, *30*(24), 2273, doi:10.1029/2003GL018338.

Whitney, F. A., H. J. Freeland, and M. Robert (2007), Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific, *Prog. Oceanogr.*, *75*, 179–199.

Wing, B. (2006), Unusual observations of fish and invertebrates from the Gulf of Alaska, 2004–05, *PICES Press*, *14*(2), 26–28.

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