Declining Oxygen in the Northeast Pacific*

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ABSTRACT

Climate models predict a decrease in oceanic dissolved oxygen and a thickening of the oxygen minimum zone, associated with global warming. Comprehensive observational analyses of oxygen decline are challenging, given generally sparse historical data. The Newport hydrographic (NH) line off central Oregon is one of the few locations in the northeast Pacific with long oxygen records. Good quality data are available here primarily in two time blocks: 1960–71 and 1998–present. Standard sampling extends from midshelf (bottom depth of 58 m) to 157 km offshore (bottom depth of 2880 m). Shipboard measurements have been supplemented in recent years (2006–present) with data from autonomous underwater gliders. Oxygen declines significantly over this 50-yr period across the entire NH line. In addition to decrease in the vicinity of the oxygen minimum depth (~800 m), oxygen decreases across a range of density surfaces $\sigma_\theta = 26$–27 within the thermocline, in the depth range 100–550 m. A core of decreasing oxygen (0.7 ± 0.2 μmol kg^{-1} yr^{-1} or 0.016 ± 0.005 ml l^{-1} yr^{-1}) is also found over the upper slope at 150–200-m depths, within the region of average northward flow associated with the poleward undercurrent. During the summer upwelling season, the largest decline is observed near bottom on the shelf: the dissolved oxygen of upwelled water, already low, is further reduced by shelf processes, leading to near-bottom hypoxia (<60 μmol kg^{-1}) on the Oregon shelf.

1. Introduction

The distribution of dissolved oxygen in the ocean is determined by exchange with the atmosphere, ocean circulation, and biological processes. Near-surface water tends to have high oxygen due to recent exchange with the atmosphere. Deep water masses retain oxygen if they originated as cold surface water at high latitudes and have subsequently experienced low rates of bacterial oxidation. Between these cases, a middepth oxygen minimum forms (Wyrtki 1962). The oxygen minimum zone (OMZ) refers to the layer of middepth low-oxygen water surrounding the oxygen minimum. OMZs vary in size depending on ocean basin: the North Pacific has the thickest and most extensive, due to longer circulation paths. Here, the OMZ composes about 40% of total North Pacific volume, when defined using 90 μmol kg^{-1} as the upper bound for oxygen (Karstensen et al. 2008). Long-term changes in oxygen distribution may occur if the balance between biological consumption and physical supply from oxygen-rich surface waters is altered.

Climate models under global warming scenarios predict changes in the balance of factors determining oceanic oxygen, leading to an overall decline and an expansion of the middepth OMZ (e.g., Matear et al. 2000; Bopp et al. 2002). The decline in oxygen is predicted both because oxygen is less soluble in warmer water and because increasing stratification may lead to a reduction in the supply of oxygen-rich water to the interior. Deoxygenation of the ocean will have potentially serious consequences: many organisms have a nonlinear sensitivity to drops in oxygen levels, and lower oxygen may also lead to changes in biogeochemical cycles detrimental to global productivity (Keeling et al. 2010). Changes may be detectable first in the North Pacific, with its large OMZ. The northeast Pacific is of particular interest too because, as water is brought to the continental shelf via upwelling, a small oxygen decrease in upwelled source water could cause a large increase in the area of shelf hypoxia [<60 μmol kg^{-1} $\sim$ 1.40 ml l^{-1}, a threshold suggested by Gray et al. (2002)]. Widespread hypoxia events apparently unprecedented in their severity have occurred in recent years on the

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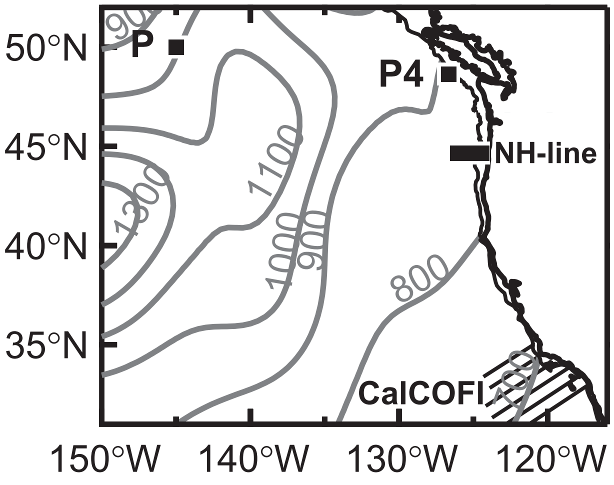

FIG. 1. Contours of oxygen minimum depth (m) in the northeast Pacific, using *World Ocean Atlas 2009* (*WOA09*) 1° × 1° gridded dissolved oxygen data. Locations with long historical records of oxygen are labeled.

Oregon shelf (Grantham et al. 2004; Chan et al. 2008). On the Washington shelf, the lowest oxygen ever observed at that particular location was in 2006 (22 μmol kg^{-1}), although years 2003–05 of the study had levels similar to historical data during 1950–86 (Connolly et al. 2010).

Additional observational studies of oxygen over time are needed to help determine the extent of decline and to confirm climate model predictions. Historical oxygen data are relatively sparse and were collected for various purposes by different programs over the years. A global historical data mapping study extending from 40°S to 40°N compared the time periods 1960–74 and 1990–2008 and found a large region of the tropical Pacific where oxygen at 200 dbar had decreased by at least 8 μmol kg^{-1}, or 0.3 μmol kg^{-1} yr^{-1} (Stramma et al. 2010). A few hydrographic lines from the 1980s have been repeated in recent years (2004–06), allowing for direct comparison: along 152°W in the North Pacific, for example, differences on density surfaces show 0.5–1.1 μmol kg^{-1} yr^{-1} declines in oxygen in the vicinity of $\sigma_\theta = 26.6$ and present in both the subtropical and subpolar gyres (Mecking et al. 2008). Keeling et al. (2010) provide a good review of additional recent studies documenting oxygen changes.

Analysis of regional individual oxygen time series provides a useful complement to broader-based studies. Station P in the subpolar North Pacific (Fig. 1) has data extending back to 1956: over 50 yr, oxygen on σ_θ surfaces 26.3–27.0 has declined 0.4–0.7 μmol kg^{-1} yr^{-1}, with significant quasi-decadal variability as well (Whitney et al. 2007). At station P4 over the slope off British Columbia (Fig. 1), a shorter 20-yr series from 1987 to 2006 shows a decreasing trend on $\sigma_\theta = 26.7$ of 1.2 μmol kg^{-1} yr^{-1}, nearly twice the rate seen at station P over 50 yr (Whitney et al. 2007). It is not yet clear whether this is an acceleration of the long-term trend or part of the decadal variability. Similar declines from 1984 to 2006 are seen in the California Cooperative Oceanic Fisheries Investigations (CalCOFI) data off California (Bograd et al. 2008).

One of the longer oxygen records along the eastern Pacific margin is available at the Newport hydrographic (NH) line off central Oregon (Fig. 1), the focus of the present study. This was particularly well sampled by ship during the Ten Years of Oceanography (TENOC; 1960–71) and U.S. Global Ocean Ecosystems Dynamics (GLOBEC) Northeast Pacific Long-Term Observation Program (LTOP; 1998–2005) studies. In recent years (2006–present), it has been occupied by underwater gliders. The standard sampling extends from midshelf (NH-5, bottom depth of 58 m) to offshore (NH-85, bottom depth of 2880 m). Here, we primarily compare the two 12-yr periods, 1960–71 and 1998–2009. Chan et al. (2008) briefly noted the increasing frequency of hypoxia in recent Oregon data compared with historical data in the upper 800 m in the region 42°–46°N. The present study uses the well-sampled NH line at 44.66°N, within the Chan et al. (2008) region, to document oxygen decrease.

2. Data and methods

We assembled NH-line shipboard hydrographic data at standard depths, from Oregon State University archives (http://ltop.coas.oregonstate.edu) and the World Ocean Database 2009 (WOD09), with exclusion using all National Oceanographic Data Center (NODC) quality control flags. The TENOC program (1960–71) sampled the NH line almost bimonthly, and the LTOP (1997–2005) averaged three cruises per year. More details about both programs can be found in Huyer et al. (2007). Here, we use the most frequently visited stations: NH-5, NH-15, NH-25, NH-35, NH-45, NH-65, and NH-85 (names denote nautical miles from shore). Oxygen sensors were regularly calibrated at the factory and by Winkler titration of bottle samples collected at a few stations on every cruise (Fleischbein et al. 2003).

Beginning in 2006, the NH line has been occupied nearly continuously by Teledyne Webb Research Slocum gliders, traveling from nearshore out to NH-45 and cycling in a sawtooth pattern from 0 to 200 m (approaching within 3–5 m of the bottom). Glider temperature/conductivity and oxygen sensors are calibrated at the factory and by in-laboratory Winkler titrations, respectively, between deployments. Glider oxygen accuracy after correction for between-calibration Aanderaa optode sensor drift may be ±8 μmol kg^{-1} (manufacturer's stated accuracy) for individual measurements: this is reduced to ±1.8 μmol kg^{-1} in the averages used in this study. The Winkler method

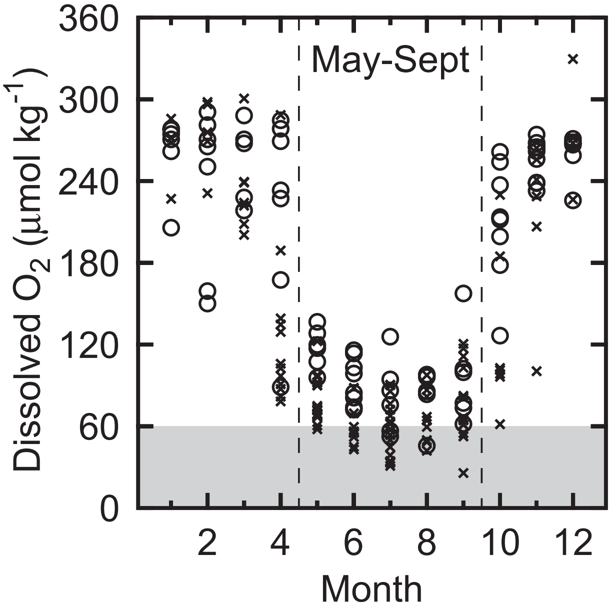

FIG. 2. Monthly near-bottom oxygen data at shelf station NH-5 from 1960–71 (open circles) and 1998–2009 (x's). The strong seasonality corresponds with the climatological upwelling season (dashed lines). Hypoxia occurs in the bottom gray shaded area (<60 μmol kg^{-1}).

has not essentially changed throughout our 50-yr period and has an estimated precision of ± 1.3 μmol kg^{-1} (Barstow et al. 1969) and accuracy of 2.9%, or ± 1.7 μmol kg^{-1}, for oxygen concentrations of 60 μmol kg^{-1} (Jalukse et al. 2008). We extract standard depth and station data from the gliders, using data within 1 km cross shore, 16 km alongshore, and 5 m vertically. We then form monthly averages. We use these glider data (2006–09) in combination with the LTOP data (1998–2005) to form the 12-yr period 1998–2009. We compare this to the 1960–71 12-yr period using a Student's *t* test for significantly different means (Press et al. 1992), to obtain most results here.

At the shelf station NH-5 close to the bottom in particular, we note strong seasonality associated with the summer upwelling season: low-oxygen water is upwelled onto the shelf and biological processes on the productive shelf cause more decrease. During the winter months with stronger downwelling winds, the oxygen signal is noisy and dominated by close contact with the surface (Fig. 2). The climatological mean upwelling season based on wind stress is May–September at this latitude (Schwing et al. 2006). The strong seasonality of NH-5 near-bottom oxygen data agrees well with this upwelling season definition (Fig. 2). Seasonality is not necessarily an issue for NH-line locations offshore and in deeper water. However, for simplicity, we use only May–September data for all remaining results and figures in the present study.

3. Oxygen sections and differences

Oxygen has declined significantly over this 50-yr period across the entire extent of the NH line (Fig. 3c). In the vicinity of the oxygen minimum depth (~800 m), oxygen has decreased by >5 μmol kg^{-1} in a 300–400-m-thick layer. In addition, we see a large region of decrease within the thermocline, centered at about 200-m depth offshore and continuing up onto the slope and shelf. The largest decrease is on the shelf, near bottom at NH-5. We also note a region of maximum decline over the slope at NH-45 and NH-35 and from 150 to 200 m in depth. This coincides with the region of average northward poleward undercurrent flow as observed in the modern era by acoustic Doppler current profiler [Pierce et al. (2000); see also top-middle panel of Fig. 12 in Huyer et al. (2007)].

Oxygen decreases observed on density surfaces are a bit larger, and the separation between the two regions (oxygen minimum and thermocline) is no longer very clear (Fig. 3f). This is related to the fact that changes in temperature and salinity over this 50-yr period have led to a deepening of density surfaces in the 300–700-m depth range (Huyer et al. 2007). Rates of change on density surfaces are shown in Table 1. The maximum decreases (0.3–0.9 μmol kg^{-1} yr^{-1}) in the water column are seen in the $\sigma_\theta = 26.3$–26.5 range. All density surfaces here are below local surface mixed layers.

A few data points are available in the 1980s at selected stations: we include these in the time-series plots (Figs. 4a,b). At 150-m depth at the slope station NH-35, in the undercurrent core area, the 50-yr change is -0.6 ± 0.2 (95%) μmol kg^{-1} yr^{-1}. Up on the shelf at 50-m depth at NH-5 (8 m off the bottom), the change is -0.7 ± 0.2 μmol kg^{-1} yr^{-1}. Note that, in the 1960–71 period at NH-5, only 9.7% of points were below the hypoxia level (<60 μmol kg^{-1}). However, from 1998 to 2009, 36.6% of points were hypoxic.

4. Shoaling of oxygen isopleths

Interestingly, although the occurrence of oxygen <60 μmol kg^{-1} has significantly increased at NH-5, offshore the depth of the 60 μmol kg^{-1} oxygen isopleth has only shallowed slightly (5 m) over the 50-yr period (Fig. 4c). The minimal shoaling of the 60 μmol kg^{-1} surface compared to other isopleths is associated with the deepening of density surfaces in the 300–700-m depth range over this period. Below this, just above the oxygen minimum depth, we see significant shoaling of the 20 μmol kg^{-1} surface by 69 m (Fig. 4c). Up at the 90 μmol kg^{-1} level, we also note significant shoaling of 47 m and hence expansion of the OMZ. Note how,

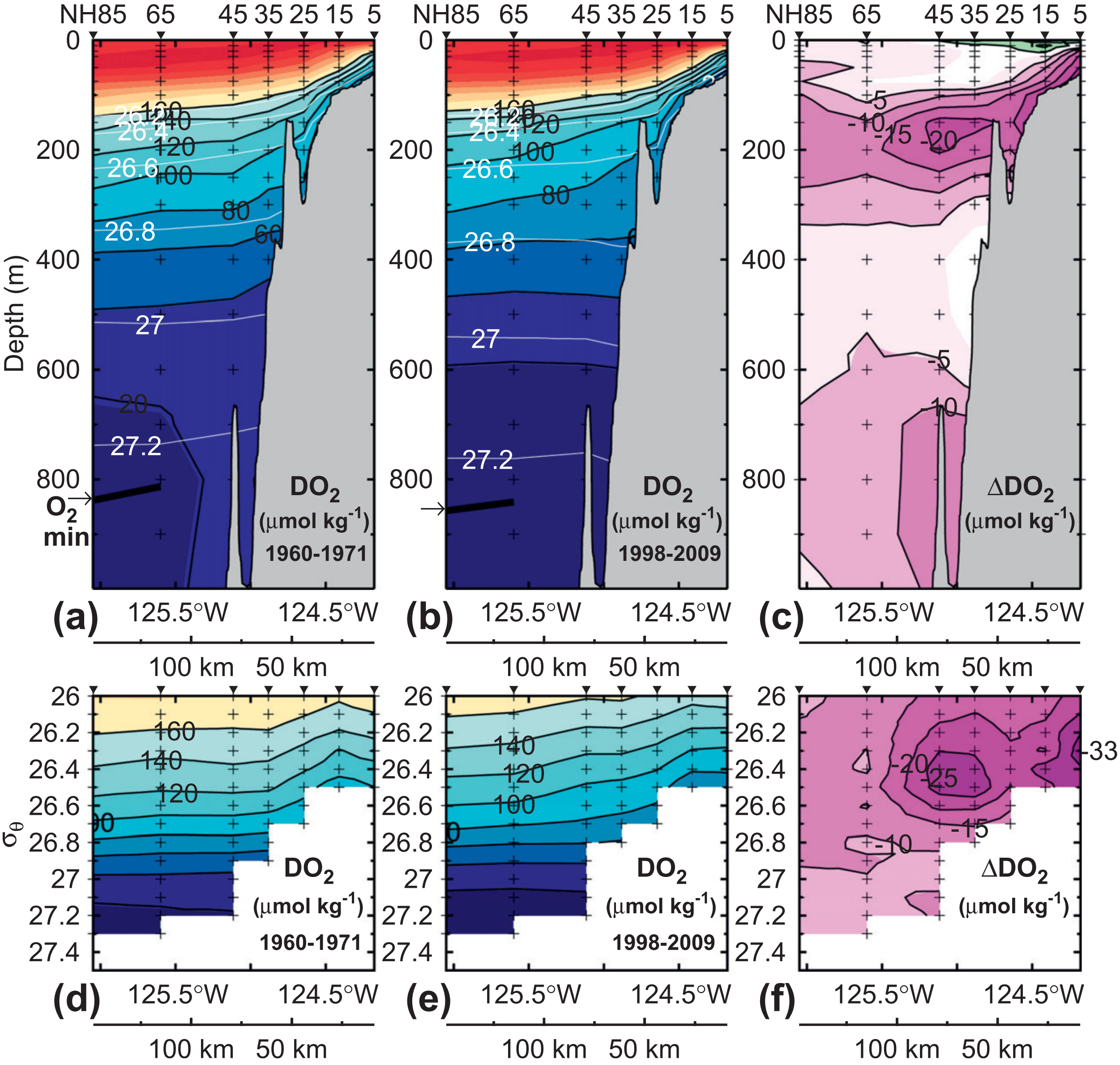

FIG. 3. NH-line sections of summertime (May–September) dissolved oxygen data for (a) 1960–71, (b) 1998–2009, and (c) the difference. The white contour lines in (a) and (b) are σ_θ surfaces. Similar sections, but with σ_θ as the vertical coordinate: (d) 1960–71, (e) 1998–2009, and (f) the difference.

during the 1960–71 period, the 90 μmol kg^{-1} level does not on average reach the continental shelf at all, whereas recently it does (Figs. 3d,e). On the shelf, biological demand for oxygen drives this down further, leading to the increased incidence of levels <60 μmol kg^{-1}.

5. Discussion

Results here agree well with the only other 50-yr oxygen record in the northeast Pacific, station P (Whitney et al. 2007). They report oxygen declines of 0.4–0.7 μmol kg^{-1} yr^{-1} on σ_θ surfaces 26.3–27.0: we note declines of 0.2–0.9 μmol kg^{-1} yr^{-1} in this σ_θ range and across all stations (Table 1). In addition, the σ_θ surface at station P with the maximum oxygen decline of 0.7 μmol kg^{-1} yr^{-1} is 26.5, which is the same σ_θ level where we see maximum declines at NH-85 and NH-65. Our NH-85 decrease at $\sigma_\theta = 26.5$ is 0.4 ± 0.3 μmol kg^{-1} yr^{-1}, thus consistent with the station P result. The northern portion of a repeated hydrographic line along 152°W (1980–2006) also shows an oxygen decline closely agreeing with station P, with maxima between σ_θ = 26.5 and 26.6 (Mecking et al. 2008).

TABLE 1. Rates of change (μmol kg^{-1} yr^{-1}) on density surfaces based on summertime differences between the two time periods 1960–71 and 1998–2009. Only significant rates (95%) are shown. The largest decrease at each station is in bold.

σ_θ	NH-85	NH-65	NH-45	NH-35	NH-25	NH-15	NH-5
26.0	—	−0.30	−0.43	−0.45	−0.47	−0.45	−0.61
26.1	−0.26	−0.30	−0.49	−0.53	−0.49	−0.51	−0.67
26.2	−0.28	−0.29	−0.57	−0.57	−0.51	−0.57	−0.79
26.3	−0.32	−0.26	−0.65	−0.64	−0.54	−0.52	**−0.86**
26.4	−0.34	−0.24	**−0.74**	−0.69	**−0.56**	**−0.73**	−0.78
26.5	**−0.37**	**−0.32**	−0.72	**−0.77**	−0.52	—	−0.79
26.6	−0.36	−0.25	−0.57	−0.56	−0.42	—	—
26.7	−0.27	−0.31	−0.40	−0.41	−0.34	—	—
26.8	−0.31	−0.24	−0.30	−0.32	—	—	—
26.9	−0.28	−0.28	−0.22	—	—	—	—
27.0	−0.23	−0.26	−0.17	—	—	—	—
27.1	−0.15	−0.21	−0.31	—	—	—	—
27.2	−0.18	−0.21	—	—	—	—	—
27.3	−0.14	−0.17	—	—	—	—	—

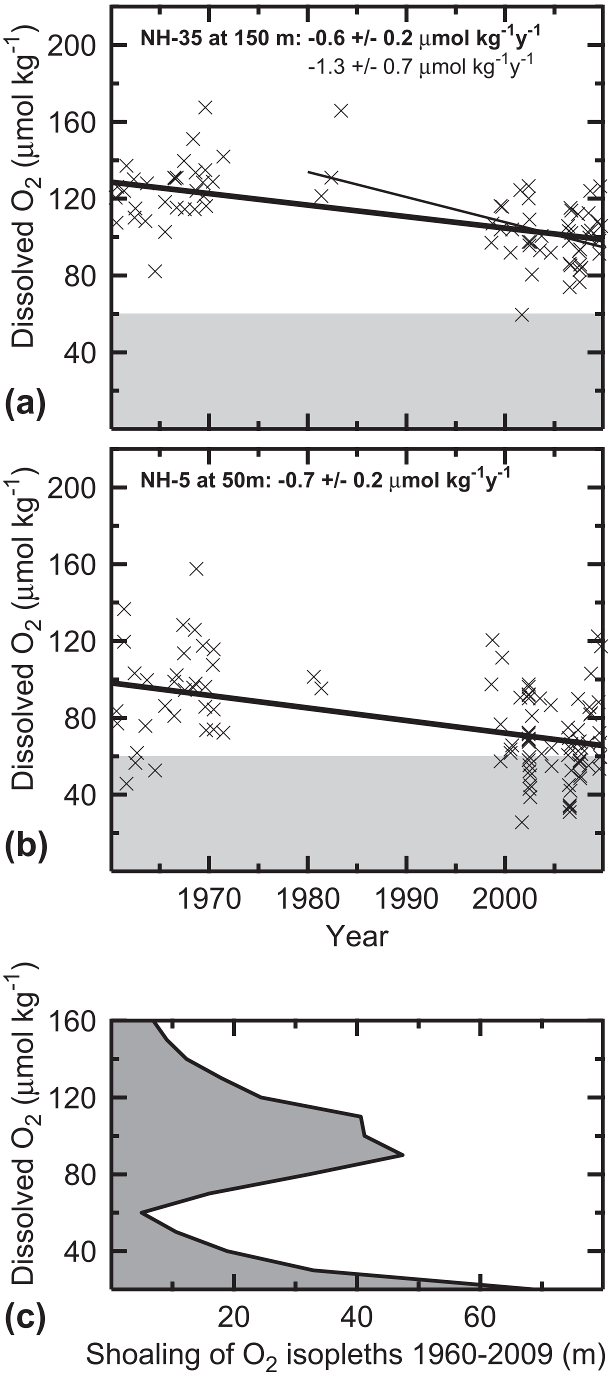

FIG. 4. Time series of dissolved oxygen at (a) the upper slope station NH-35 at 150-m depth and (b) the shelf station NH-5 at 50-m depth. Linear regression lines with 95% confidence intervals are shown. The thin line in (a) only uses data after 1980, for the purpose of comparing with some other studies. (c) Average NH-line shoaling of oxygen isopleths over time (1960–2009).

The oxygen records at station P4 and within the CalCOFI region are both available back to the mid-1980s. To compare with results at these locations, we make use of a few data points from the 1980s available in the archives at NH-35. We estimate a change from 1980 to 2009 at 150 m of −1.3 ± 0.7 μmol kg^{-1} yr^{-1}, about twice the result using the full 1960–2009 period (Fig. 4a, thin line). This agrees well with the slope station P4 result (−1.2 μmol kg^{-1} yr^{-1}; Whitney et al. 2007) and the CalCOFI one (−1.0 μmol kg^{-1} yr^{-1}; Bograd et al. 2008; McClatchie et al. 2010). It is not clear if this result arises from decadal variability or perhaps represents an acceleration of the long-term decline.

The time series of oxygen at $\sigma_\theta = 26.8$ at station P has been correlated with a similar time series in the Oyashio region (Ono et al. 2001), with a lag of about 7 yr, consistent with what would be expected for west to east transport in the subpolar gyre system (Whitney et al. 2007). The decadal variability in station P oxygen is not correlated with the Pacific decadal oscillation (Mecking et al. 2008) or with the North Pacific Gyre Oscillation (Di Lorenzo et al. 2008) [our NH-line time series (Fig. 4) has insufficient data to address decadal variability]. In the subpolar gyre, a major factor in oxygen decline may be a reduction in outcropping of density in the vicinity of $\sigma_\theta = 26.6$ due to increased stratification in the northwest corner of the Pacific (Emerson et al. 2004; Deutsch et al. 2006). Given the similarity of the declines at our offshore station and station P, as well as the identical locations of the maxima at $\sigma_\theta = 26.5$, we infer a strong subpolar influence at the NH line. Note that an absolute change in oxygen at station P, as it travels east along $\sigma_\theta = 26.5$, will appear smaller at the NH line, because in general subarctic water is warming and losing oxygen along this isopycnal (Whitney et al. 2007). This is what we observe: NH-85 has a decrease of 0.4 μmol kg^{-1} yr^{-1}, smaller than the station P value of 0.7 μmol kg^{-1} yr^{-1}. Moreover, the relative changes at each location are nearly the same:

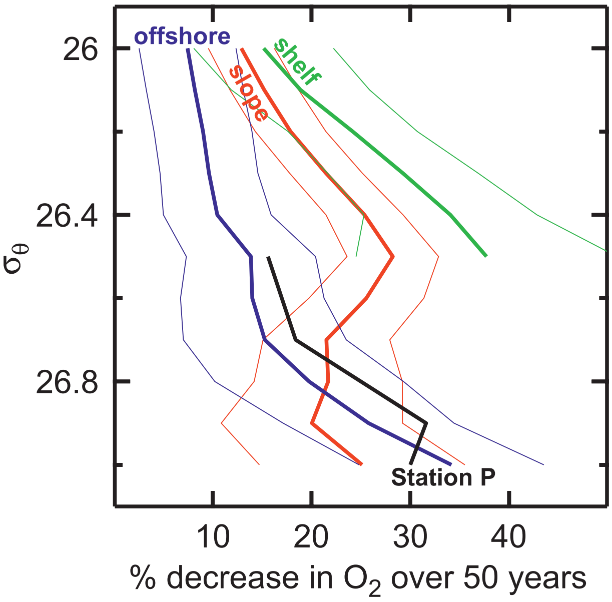

FIG. 5. Relative decrease in dissolved oxygen over 50 yr on σ_θ surfaces, in three groups: offshore (NH-85 and NH-65), slope (NH-45, NH-35, and NH-25), and shelf (NH-15 and NH-5). Thin lines are 95% confidence intervals. Also shown are station P results over a similar period (Whitney et al. 2007).

station P and NH-85 have relative decreases of 15% and 14%.

On the other hand, the core of oxygen decrease over the slope at poleward undercurrent depths (Fig. 3) implies influence from the south as well. Consistent with this, some of the largest oxygen declines in the CalCOFI region were from 200 to 300 m within the poleward undercurrent and appear to be of tropical origin (Bograd et al. 2008). The agreement of our Oregon results with station P4 off Vancouver Island is also consistent with undercurrent transport to the north (Thomson and Krassovski 2010). The thickening of the OMZ in the eastern equatorial Pacific shown by Stramma et al. (2008) might lead to a reduced oxygen supply to the entire eastern boundary current system.

To summarize, consider the percentage decrease in oxygen on σ_θ levels in three groups (Fig. 5): offshore (NH-85 and NH-65), slope (NH-45, NH-35, and NH-25), and shelf (NH-15 and NH-5). The agreement between the offshore end of the NH line and station P is remarkably good: they are both experiencing the same long-term subpolar decrease. At $\sigma_\theta = 26.7$ and below, the slope stations are similar as well. However, above $\sigma_\theta = 26.7$, the slope group shows an additional oxygen decrease associated with the undercurrent, possibly connected with tropical OMZ expansion. Finally, after water is upwelled we note an additional bottom-intensified oxygen decrease in the shelf group (Fig. 5), implying that changes in either physical or biological shelf processes have led to decreasing oxygen over the past 50 yr. One possibility is that a subtle change in the variance structure of winds during the upwelling season has led to a change in shelf circulation, with less oxygen ventilation and/or increased export production. All three types of deoxygenation represented in Fig. 5 might be enhanced by global warming, implying severe impacts on marine habitats.

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