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Changes in source waters to the Southern California Bight

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ABSTRACT

Historical hydrographic data (1984–2012) from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program and global reanalysis products were used to quantify recent water mass variability off the coast of Southern California. Dissolved oxygen concentrations continued to decline within the lower pycnocline, concurrent with strong increases in nitrate and phosphate that have spatial patterns matching those of dissolved oxygen. Silicic acid also shows an increasing trend in the offshore portion of the region, but has strong and opposing trends in the upper (increasing) and lower-pycnocline (decreasing) within the Southern California Bight. The varying rates of change in the inorganic nutrients yield a more complex pattern of variability in the nutrient ratios, resulting in large decreases in the N:P and Si:N ratios within the Southern California Bight at depths that provide source waters for upwelling. Basin-scale reanalysis products are consistent with low-frequency water mass changes observed off Southern California and suggest that advection of modified source waters is the cause of the variability. The biogeochemical changes described here may have important impacts on the regional ecosystem, including a reduction of viable pelagic habitat and community reorganization.

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1. Introduction

Recent studies have demonstrated widespread impacts of climate change on marine ecosystems, including changes in species abundance, distribution and demography, community reorganization, phenological shifts, and ocean acidification (Doney et al., 2012; Poloczanska et al., 2013; Bernhardt and Leslie, 2013 and references within). Many of the observed rates of change in marine systems are comparable to, or greater than, those observed in terrestrial systems (Burrows et al., 2011; Poloczanska et al., 2013). Changes in ocean biogeochemistry are among the most significant in terms of their potential impacts on marine life, particularly in coastal ecosystems (Doney et al., 2009; Hauri et al., 2009; Keeling et al., 2010; Gruber 2011; Gruber et al., 2012; Taylor et al., 2012).

Models forced by increasing greenhouse gases predict a decline in midwater oceanic dissolved oxygen (DO) as a result of enhanced stratification and reduced ventilation (Sarmiento et al., 1998; Keeling and Garcia, 2002). Analyses of long-term oceanic datasets have revealed declining DO levels that are consistent with these climate projections (Deutsch et al., 2005, 2011; Whitney et al., 2007, 2013). In the equatorial Pacific, Stramma et al. (2008, 2010) have shown a thickening and shoaling of the Oxygen Minimum Zone (OMZ), which could result in reduced oxygen supply to the boundary upwelling systems of North and South America. In the Southern California Current, DO declines of 1–2 $\mu mol\,kg^{-1}\,y^{-1}$ have been observed in recent years (Bograd et al., 2008; McClatchie et al., 2010; Meinvielle and Johnson, 2013), while the frequency of hypoxic events has increased in the northern California Current (Chan et al., 2008; Booth et al., 2012). It is expected that changes in other key water properties will also occur, including the inorganic nutrient concentrations that drive ocean productivity (Whitney et al., 2013). Shoaling of the OMZ will likely lead to significant and complex ecological changes including

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anoxia for benthic organisms, reduction in pelagic habitat for top predators (Koslow et al., 2011), and more numerous invasions from hypoxia tolerant species (Stewart et al., 2012). Alterations in total nutrient concentrations, or the relative content of the nutrients, could lead to community reorganization within marine ecosystems (Margalef, 1962, 1978; Smayda, 1963; Karl et al., 2012; Taylor et al., 2012).

While a number of studies have investigated long-term oxygen dynamics throughout the tropical and extratropical Pacific, fewer studies have reported on long-term variability in nutrient content. This is largely due to a lack of nutrient time series of sufficient length to detect low-frequency climate signals. A long data record within the Oyashio, off the northern coast of Japan, has shown a freshening of the winter mixed layer and declining phosphate levels (Ono et al., 2001). Over a broader region of the subarctic Pacific, Ono et al. (2008) reported declines in summer near-surface nutrient levels over the period 1975–2005, accompanied by increases (decreases) in intermediate layer nutrients (oxygen) (Watanabe et al., 2008). At the long time series Station ‘P’ in the northeast Pacific, Whitney (2011) found weak increasing trends in surface layer nutrient concentrations, even though increased stratification (Freeland et al., 1997) is expected to reduce the winter resupply of mixed layer nutrients. Whitney et al. (2013) synthesized these and other observations from several time series programs throughout the North Pacific to document a long-term enrichment of subarctic pycnocline nitrate (200 Gmol y^{-1}). They suggested that this enrichment counters the effects of increased stratification, resulting in a surface nutrient supply that remains nearly constant. Di Lorenzo et al. (2009) further suggested that decadal oscillations in upper ocean nutrients in the eastern North Pacific results from atmospherically-driven changes in the strength of the North Pacific gyres.

The California Current Ecosystem (CCE) Long Term Ecological Research (LTER) site is within a productive coastal upwelling biome that is strongly influenced by remote and local physical forcing. The site is built upon more than 65 years of extensive sampling of the regional physics, chemistry, and biology, through the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program (Hewitt, 1988; Peña and Bograd, 2007). The long CalCOFI time series provide a unique opportunity to investigate climate impacts on the CCE, including changes in regional biogeochemistry and the mechanisms leading to transitions between ecosystem states. Here we use the CalCOFI dataset to investigate long-term alteration of water mass characteristics in the CCE-LTER region, focusing on inorganic nutrient concentrations, and speculate on the mechanisms and biological implications of these changes.

2. Data and methods

2.1. CalCOFI time series

Since 1984, CalCOFI has consistently sampled six nominal lines in the southern CCE from San Diego to Pt. Conception quarterly, with target months of January, April, July, and October (Fig. 1A), with measurements of inorganic nutrients and chlorophyll. Prior to 1984, only basic hydrographic variables and dissolved oxygen were routinely measured. Stations are designated by a line and station number, with nominal station spacing of ~70 km offshore but considerably less inshore of the islands. Routine station occupations (on 66 standard stations) deploy a SeaBird CTD instrument with a 24-place rosette, which is equipped with 24 10-L plastic (PVC) Niskin bottles (Scripps Institution of Oceanography, 2012). Casts are typically made to ~525 m depth, bottom depth permitting, with continuous measurements of pressure, temperature, conductivity, dissolved oxygen and chlorophyll fluorescence. Bottle samples are taken at 20 depths, and are generally chosen to provide high resolution (< 10 m) around the subsurface chlorophyll maximum and the shallow salinity minimum of the upper thermocline. Salinity, dissolved oxygen and inorganic nutrients are determined for all depths sampled, while chlorophyll-*a* and phaeopigments are determined within the upper 200 m, bottom depth permitting. Pressures and temperatures for each water sample were derived from the CTD signals recorded just prior to *in situ* bottle sampling. Salinities were analyzed at sea from the bottle data using a Guildline model 8410 Portasal salinometer, with results quality controlled using discrete measurements from the Niskins (Scripps Institution of Oceanography, 2012). There have been more than 6700 station occupations on the CalCOFI grid off southern California between January 1984 and April 2012. CalCOFI's longevity and consistent sampling methodology allow for reliable time series analyses at a number of geographically fixed locations within the southern CCE.

Dissolved oxygen 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). Percent oxygen saturation was calculated from the equations of Garcia and Gordon (1992). Dissolved silicic acid, phosphate, nitrate and nitrite concentrations were determined at sea using an automated analyzer (Atlas et al., 1971), following procedures similar to those described in Gordon et al. (1993). Estimates of precision of these standard techniques are 0.001 °C, 0.002 for salinity, 0.02 mL L^{-1} for DO, and 0.5, 0.01, and 0.1 μmol kg^{-1} for silicic acid, phosphate, and nitrate, respectively (Scripps Institution of Oceanography, 2012). Further details of the standard sampling and

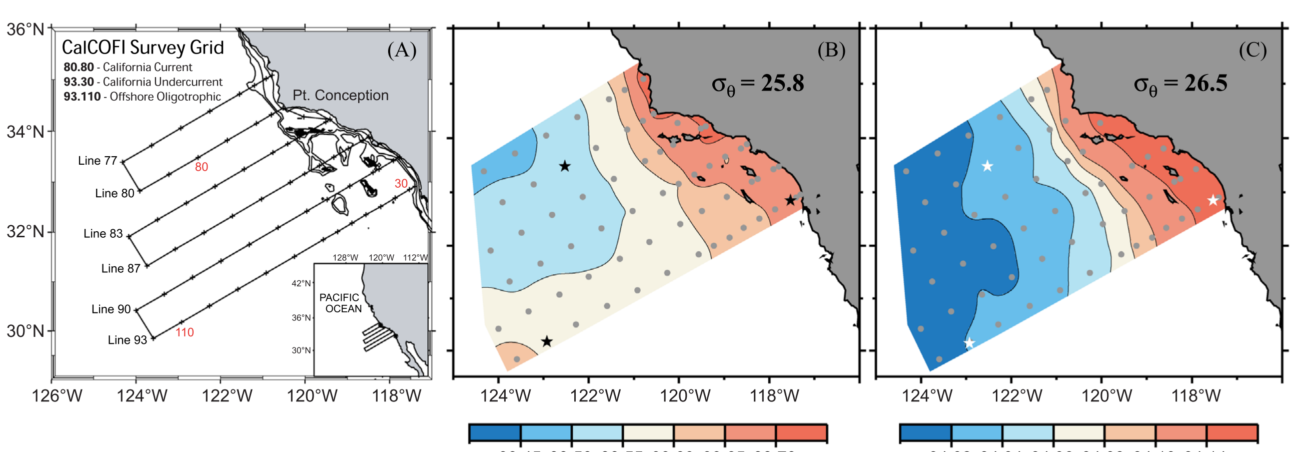

Fig. 1. (A) Nominal CalCOFI grid showing Lines and Stations. Mean salinity on the (B) σ_θ=25.8 kg m^{-3} and (C) σ_θ=26.5 kg m^{-3} isopycnal surfaces. Locations of Stations 80.80, 93.30 and 93.110 are marked with stars and all other stations with gray dots. CalCOFI salinity climatologies are for the 1984–2012 period.

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