Physical and Biogeochemical Drivers of Alongshore pH and Oxygen Variability in the California Current System

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Abstract In the California Current System (CCS), the nearshore environment experiences natural exposure to low pH and reduced oxygen in response to coastal upwelling. Anthropogenic impacts further decrease pH and oxygen below biological thresholds, making the CCS particularly vulnerable to ocean acidification and hypoxia. Results from a coupled physical-biogeochemical model reveal a strongly heterogeneous alongshore pattern of nearshore pH and oxygen in the central CCS, both in their long-term means and trends. This spatial structuring is explained by an interplay between alongshore variability in local upwelling intensity and subsequent primary production, modulated by nearshore advection and regional geostrophic currents. The model solution suggests that the progression of ocean acidification and hypoxia will not be spatially homogeneous, thereby highlighting the need to consider subregional processes when assessing natural and anthropogenic impacts on coastal ecosystems in eastern boundary current upwelling regions.

Plain Language Summary Ocean acidification and hypoxia result from decreasing pH and oxygen levels in the ocean and threaten marine organisms adapted to a specific range of conditions. Along the west coast of the United States, these impacts are particularly severe, because this region exhibits naturally lower pH and oxygen conditions. Our study uses a computer model to show that upwelling, a process in which deeper water (rich in nutrients but also low in pH and oxygen) is brought to the surface, and photosynthesis by phytoplankton, which raises pH and oxygen, are important processes controlling nearshore pH and oxygen at the surface of the ocean. The results also indicate that these processes are not uniform in space or time and are shaped by alongshore changes in the intensity of upwelling and the strength and direction of ocean currents. A key finding from our study is that threats faced by marine organisms from the future progression of ocean acidification and hypoxia along the west coast of the United States will greatly vary by location.

1. Introduction

In the California Current System (CCS), several physical and biogeochemical processes control natural exposure to low pH and oxygen conditions on daily to seasonal time scales. In spring and summer, prevailing alongshore, equatorward winds drive coastal upwelling (Huyer, 1983). As low pH, oxygen poor water is introduced from depths between 50 and 100 m to the surface via Ekman dynamics, wind-driven coastal upwelling is a dominant physical mechanism controlling nearshore pH and oxygen levels. High nutrient content in upwelled waters also supports new primary production, which acts as a biological regulator on pH and oxygen through photosynthesis and respiration. The addition of anthropogenic ocean acidification and oxygen decline to a system already experiencing low pH and oxygen exposure could push conditions below species-specific thresholds (Bograd et al., 2008; Hauri, Gruber, McDonnell, & Vogt, 2013; Hauri, Gruber, Vogt, et al., 2013). Therefore, characterizing the past and present evolution of pH and oxygen levels at local and regional scales is key to understanding how anthropogenic impacts are emerging against natural signals in the CCS.

While seasonal upwelling acts as a dominant control on environmental variability along most of the west coast of the United States, upwelling intensity and ecosystem responses are not spatially homogeneous. Atmospheric fields and ocean circulation are affected by coastline morphology (Barth et al., 2000; Pickett & Paduan, 2003), and biogeochemical variability has been similarly linked to topographic features locally modulating upwelling intensity and coastal currents (Fiechter et al., 2018; Kudela et al., 2008).
Alongshore heterogeneity in coastal upwelling and subsequent biogeochemical response is supported by CCS-wide shipboard surveys and nearshore time series, documenting a spatial pattern of low pH exposure, with local “hotspots” near topographic features (Chan et al., 2017; Feely et al., 2008). Since pH and oxygen typically covary (Baumann & Smith, 2018), low-oxygen exposure likely exhibits a similar nearshore spatial pattern. However, observations characterizing the long-term response of pH and oxygen to local physical and biogeochemical drivers in the central CCS are limited, as routine sampling occurs primarily south of Pt. Conception (~34.5°N). Thus, the finer-scale nature of pH and oxygen variability along the entirety of the central California Current (35–43°N) has yet to be fully documented and mechanistically explained.

Coupled physical-biogeochemical models yield insight into the mechanisms shaping alongshore variability at spatiotemporal scales that observational studies cannot concurrently resolve. Existing modeling studies for the CCS have provided important knowledge about processes controlling pH and oxygen variability, and the predictability of their seasonal, interannual, and long-term evolution (Brady et al., 2020; Dussin et al., 2019; Gruber et al., 2012; Hauri, Gruber, McDonnell, & Vogt, 2013; Hauri, Gruber, Vogt, et al., 2013; Howard et al., 2020; Siedlecki et al., 2015, 2016). Many of these studies focused on regional- and basin-scale mechanisms influencing ocean acidification and hypoxia, obscuring pH and oxygen variability at finer alongshore scales (10–100 km) over which processes modulating these variables (e.g., upwelling intensity, nutrient transport, and primary production) are known to vary in the central CCS (Fiechter et al., 2018).

The present work expands on earlier modeling studies by using a coupled physical-biogeochemical model at 1/30° (~3 km) resolution and benefiting from data assimilation to characterize alongshore pH and oxygen patterns, and their drivers, in the central CCS. More specifically, the analysis examines how localized enhancements in upwelling intensity and phytoplankton biomass described by Fiechter et al. (2018) shape alongshore means and trends for pH and oxygen during 1988–2010. As such, the results contextualize the relative importance of natural pH and oxygen variability, and its potential impact on local and regional ecosystem resources, in a largely undersampled region of the CCS.

2. Methods

The physical circulation for the CCS is generated using a nested implementation of the Regional Ocean Modeling System (ROMS) (Haidvogel et al., 2008; Shchepetkin & McWilliams, 2005). The model consists of an outer domain at 1/10° (~10 km) resolution from 30°N to 48°N benefiting from physical data assimilation and a downscaled inner domain at 1/30° (~3 km) resolution from 32°N to 44°N. The physical model is forced at the surface with the 0.25° resolution Cross-Calibrated Multi-Platform (CCMP) winds of Atlas et al. (2011), and the initial and boundary conditions for the outer CCS domain are derived from the Simple Ocean Data Assimilation (SODA) reanalysis of Carton et al. (2000). Details of the downscaling method can be found in Fiechter et al. (2018).

The biogeochemical model, NEMUCSC, is a customized version of the North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMUCSC) consisting of three limiting macronutrients (nitrate, ammonium, and silicic acid), two phytoplankton size classes (nanophytoplankton and diatoms), three zooplankton size classes (microzooplankton, mesozooplankton, and predatory zooplankton), and three detritus pools (dissolved and particulate organic nitrogen and particulate silica). NEMUCSC also incorporates carbon and oxygen cycling based on the formulations of Hauri, Gruber, McDonnell, and Vogt (2013), Hauri, Gruber, Vogt, et al. (2013), and Fennel et al. (2013), respectively. The carbon submodel includes dissolved inorganic carbon (DIC), total alkalinity, and calcium carbonate, with ocean pH and pCO2 calculated from the OCMIP carbonate chemistry described in co2calc_SWS.f (http://oceanmodeling.org). Atmospheric pCO2 is based on the Mauna Loa time series and consists of a mean seasonal cycle superimposed with an annual increase of 1.5 ppmv before 1995 and 2 ppmv thereafter. In the model, DIC is decreased by primary production and calcium carbonate formation and increased by respiration, remineralization, and calcium carbonate dissolution; alkalinity is decreased by nitrification and calcium carbonate formation and increased by new primary production (nitrate removal) and calcium carbonate dissolution; and oxygen is decreased by nitrification and remineralization and increased by primary production. Initial and boundary conditions for the outer domain are derived from the monthly World Ocean Atlas climatology (Conkright & Boyer, 2002) for nutrients and oxygen, from the Global Ocean Data Analysis Project (Key et al., 2004) for total alkalinity, and from the empirical relationship of
Alin et al. (2012) for DIC using monthly temperature and oxygen. The empirical relationship is preferred over the GLODAP annual mean as it improves initial and boundary conditions for mid-depth (100–200 m) DIC concentrations in the central CCS.

While the simulation encompasses 1980–2010, the analysis is limited to 1988–2010 to remove spin-up effects and concentrate on the period when the model is forced by the higher-resolution CCMP winds. The results focus on the central CCS region (35°–43°N), known to exhibit strong alongshore physical and biogeochemical variability (Fiechter et al., 2018), to demonstrate the impacts of local upwelling intensification, primary production, and coastal currents on nearshore pH and oxygen. “Nearshore” variables are defined here as zonal averages from the coast to 30 km offshore, which represents a natural scaling distance for coastal upwelling in the central CCS based on the internal Rossby radius of deformation (as evidenced by the synoptic pH and oxygen maps in Figure 1, left panels). A 30-km alongshore running mean is applied to the variables to remove patchiness associated with topographic variations at scales smaller than ~10 km, which are more challenging to interpret and would detract from the analysis. Since the lowest nearshore pH and oxygen levels occur during the upwelling season, the analysis also concentrates on values averaged annually over a 4-month period coinciding with the peak magnitude of upwelling-favorable alongshore winds in the model (May to August for 35°–40°N and June to September for 40°–43°N) (Figure 1, center panels). Based on monthly mean values, upwelling season extremes for 1988–2010 range from 0.1–0.2 for pH and 0.4–0.8 ml/L for oxygen depending on latitude (Figure 1, right panels).

3. Results

In addition to existing evaluations of the 1/10° and 1/30° model solutions (temperature, salinity, and density structure in Schroeder et al., 2014; coastal circulation in Fiechter et al., 2018; surface pCO₂ and chlorophyll in Fiechter et al., 2014, 2018; and krill abundance in Fiechter et al., 2020), the model solution is compared against climatological (California Cooperative Oceanic Fisheries Investigations [CalCOFI] Lines 67 and 77) and synoptic (NOAA’s 2007 West Coast Ocean Acidification [WCOA] cruise) observations to determine its ability to reproduce physical and biogeochemical properties at various latitudes during the upwelling season (Supporting Information Figure S1). Observed springtime profiles along Lines 67 and 77 generally fall within one standard deviation of the model mean (Supporting Information Figures S2 and S3), with the largest discrepancies occurring for chlorophyll (which may partly result from fixed C:Chl used to convert diatom [C:Chl = 50] and nanophytoplankton [C:Chl = 100] concentrations in nitrogen units to chlorophyll). While reproducing synoptic values is typically more challenging, in situ measurements from the WCOA cruise at five transect locations between 34°N and 42°N generally fall within or close to the range of simulated daily means during the cruise period (May–June 2007), although certain nearshore stations exhibit larger discrepancies (Supporting Information Figures S4–S8).

Model-data correlations for temperature, nitrate, DIC, pH, and oxygen along each transect line are greater than 0.9 for climatological values and 0.75–0.95 for synoptic values. Simulated fields also exhibit similar variability as in situ measurements (standard deviation ratios between 0.75 and 1.25), resulting in root mean square errors of 0.25–0.5 times the observed standard deviations for climatological profiles and 0.5–0.75 times the observed standard deviations for synoptic profiles (Supporting Information Figure S9). Since locations with the largest errors for biogeochemical variables also exhibit the largest errors for temperature (e.g., WCOA transects near 36°N and 38°N), model-data discrepancies are presumably caused by misrepresentation of local physical processes at synoptic scales (e.g., timing and magnitude of upwelling). This interpretation is reinforced by the fact that the lowest errors for all climatological variables occur along CalCOFI Line 67, which overlaps with the WCOA transect near 36°N. Pinpointing the exact nature of synoptic discrepancies is difficult due to the scarcity of additional supporting observations (especially at nearshore stations).

The most striking feature in the model solution is the strong alongshore variability in mean nearshore pH and oxygen levels at 10-m depth (Figure 2a). The simulation identifies successive coastal regions exhibiting lower (near 36°N, 38.5°N, and 42.2°N) and higher (near 35.3°N, 36.6°N, 37.5°N, 39.7°N, and 41°N) pH and oxygen in response to alongshore variations in upwelling intensity, primary production, and regional circulation patterns. Mean nearshore pH values range from 7.91–7.93 near minima to ~7.98 near maxima, while mean nearshore oxygen values range from 5.3–5.55 ml/L near minima to 5.7–5.8 ml/L near maxima. The meridional averages (35–43°N) are ~7.95 for pH and ~5.56 ml/L for oxygen.
Coastal regions exhibiting reduced pH and oxygen occur directly equatorward of enhanced upwelling centers, as indicated by strongly positive vertical DIC flux at 40-m depth (purple shading in Figures 2a and 2b) and elevated DIC concentrations at 10-m depth (Figure 2b). The latitudinal shift between vertical flux maxima and pH and oxygen minima is attributed to the alongshore circulation (arrows in Figure 2b). For the two regions of enhanced upwelling near Pt. Arena (~38.5°N) and Cape Blanco (~42°N), alongshore currents are strongly equatorward, resulting in pH and oxygen minima expressed ~50 km to the south of vertical DIC flux maxima. Similarly, the combination of alongshore advection and time dependence of nutrient uptake and growth by phytoplankton leads to maxima in net primary production shifted by 50–100 km from enhanced upwelling centers. For the regions of intensified upwelling near Pt. Arena (~38.5°N) and Cape Blanco (~42°N), alongshore currents are strongly equatorward, resulting in pH and oxygen minima expressed ~50 km to the south of vertical DIC flux maxima. Similarly, the combination of alongshore advection and time dependence of nutrient uptake and growth by phytoplankton leads to maxima in net primary production shifted by 50–100 km from enhanced upwelling centers.

Areas of elevated pH and oxygen levels also occur around 35.1–35.6°N and 39–40.2°N where strong onshore geostrophic flow occurs (arrows in Figure 2d), which opposes offshore Ekman transport and reduces coastal...
upwelling efficiency. Consequently, regions of strong onshore flow exhibit higher pH and oxygen values at 50‐m depth relative to neighboring shelf regions, due to reduced uplifting of the density and nutrient structures (Figure 2d). Since upwellled waters in the central CCS originate between 50 and 60 m (Jacox et al., 2015), increasing pH and oxygen in source waters would explain higher values at 10‐m depth. The moderate primary production peak around 39.5°N further contributes to elevating pH and oxygen at 10‐m depth in that region.

Simulated pH and oxygen trends also exhibit substantial alongshore variability and are similarly explained by trends in coastal upwelling intensity and phytoplankton biomass (trends are more clearly interpreted from state variables as biogeochemical rates are affected by the temperature trend). During 1988–2010, coastal upwelling intensified region wide, and particularly near enhanced upwelling centers, as evidenced by the strongly positive trends in vertical velocity at 40‐m depth (Figure 3b). This intensification leads to relatively more negative (or less positive) trends in nearshore pH and oxygen downstream of enhanced upwelling centers (purple shading in Figure 3). The largest negative trends for nearshore pH and oxygen occur near 36.3°N and 38°N, with annual values around −0.0025 per year and −0.004 ml/L/year, respectively (cumulative changes of about −0.06 and −0.092 ml/L over the 23‐year period). Upwelling intensification also explains regions of increasing phytoplankton biomass further downstream, locally resulting in more positive (or less negative) trends in nearshore pH and oxygen (green shading in Figure 3). Furthermore, trends in phytoplankton biomass appear to influence oxygen trends more strongly than pH trends, especially for the maximum near 37.5°N. The largest positive trends for nearshore pH and oxygen occur near 41.5°N, with annual values around 0.001 and 0.016 ml/L, respectively (cumulative changes of about 0.023 and 0.37 ml/L over the 23‐year period).

At the regional scale, the overall trend for nearshore oxygen is mainly positive north of Pt. Arena (~39°N) and near zero to the south. Between 39.5°N and 42°N, the positive trend may be explained by a weaker
trend in upwelling intensity combined with an increasing trend in phytoplankton biomass. Between 41°N and 42°N, the positive trend is apparently related to a decrease in water column remineralization associated with a negative trend in phytoplankton biomass. South of 39°N, the stronger trend in upwelling intensification is approximately balanced by the associated larger positive trend in phytoplankton biomass, leading to a weakly positive or negative oxygen trend. In contrast, the overall trend in nearshore pH is predominantly negative (i.e., acidification) south of Cape Mendocino (~40°N), near zero to the north, and appears related to the relative magnitude of the DIC and alkalinity trends at 10-m depth. North of 40°N, the trends in upwelling intensity and DIC are weaker and the alkalinity trend is more positive (due to the increasing trend in nitrate consumption by phytoplankton), resulting in a compensating effect on the pH trend. South of 40°N, the trend in alkalinity is outweighed by stronger trends in upwelling intensity and DIC, resulting in a negative pH trend.

4. Discussion

Results from a high-resolution coupled physical-biogeochemical model are used to characterize alongshore variability in the mean states and trends of nearshore surface pH and oxygen in the central CCS during 1988–2010. The findings demonstrate a complex interplay between local- and regional-scale processes, where changes in upwelling intensity, primary production, and coastal currents establish a succession of alongshore minima and maxima in the means and trends of nearshore pH and oxygen (Figure 4). Regions of enhanced upwelling lead to a local decrease in pH and oxygen, and regions of increased primary production result in a local increase in pH and oxygen. While enhanced upwelling and vertical nutrient fluxes occur near coastal promontories, pH and oxygen minima and maxima are shifted downstream by local advection. This interpretation parallels the findings of Fiechter et al. (2018), which reported a succession of nutrients and chlorophyll peaks, driven by local-scale variability in coastal upwelling intensity and nearshore currents. Local maxima in pH and oxygen also occur in areas...
associated with onshore meanders in the geostrophic circulation, which effectively reduce coastal upwelling intensity (Marchesiello & Estrade, 2010) and increase pH and oxygen content of upwelled surface waters as nearshore isopycnal uplift is reduced. The regions of strong onshore geostrophic flow identified here near 36°N and 39°N, and subsequent impacts on coastal upwelling intensity, generally agree with existing numerical studies and observations (Centurioni et al., 2008; Jacox et al., 2014).

The strong pH minimum (~7.91) present in the model near 38°N is consistent with nearshore observations in the central CCS, which identified severe low pH exposure and synoptic values near 7.9 during the upwelling season just north of 38°N (Chan et al., 2017). The same study also indicates that exposure to low pH is more severe near Cape Blanco (~43°N) and less severe near Monterey Bay (36.5–37°N) and Cape Mendocino (~40°N), which qualitatively agrees with the local minima and maxima in nearshore pH at 10-m depth produced by the simulation. At the regional scale, in situ data from a synoptic shipboard survey describe an alongshore pattern of shallower (36–38°N and 40–44°N) and deeper (35–36°N and 38–40°N) aragonite saturation horizons (Feely et al., 2008), corresponding to regions of, respectively, offshore and onshore meanders of the geostrophic flow in the model (see Figure 2d). This finding suggests that broader alongshore patterns in nearshore pH and oxygen may be controlled by changes in the vertical density structure and upwelled source water content in response to modulations of coastal upwelling efficiency by the regional circulation.

The alongshore variability of simulated trends in pH and oxygen during 1988–2010 respond to similar physical and biogeochemical processes as the long-term means. pH and oxygen exhibit negative (or less positive) trends directly downstream of upwelling centers in response to increased nearshore supply of DIC-rich and oxygen-poor subsurface waters and positive (or less negative) trends at locations where phytoplankton biomass is increasing and enhances DIC consumption and oxygen production through photosynthesis. While simulated pH and oxygen trends are useful to identify mechanisms controlling nearshore tendencies, the magnitude of the trends may be inflated by decadal basin-scale variability in the North Pacific during 1988–2010. The rather short duration of the model run (23 years), combined with a phase transition of the North Pacific Gyre Oscillation and the Pacific Decadal Oscillation in the late 1990s (Di Lorenzo et al., 2008; Peterson & Schwing, 2003), means that the increasing trend in coastal upwelling intensity (and subsequent trends in nearshore pH and oxygen) may reflect a shift from an unproductive to a productive regime in the CCS halfway through the simulation, rather than a long-term anthropogenic signal. Despite a small change in the magnitude of mean pH and oxygen values, the simulated alongshore patterns remain consistent across the regime shift. Furthermore, since the boundary conditions for biogeochemical variables are climatological (i.e., no long-term trends in DIC, nutrients, and oxygen), anthropogenic impacts in the model are limited to oceanic physical variability and surface atmospheric forcing (i.e., changes in upwelling-favorable winds and atmospheric CO₂ concentrations).

In summary, the results presented here highlight the strong alongshore heterogeneity in mean pH and oxygen patterns in the central CCS and provide a mechanistic description of their physical and biogeochemical drivers at previously unresolved spatial scales. Since nearshore pH and oxygen trends exhibit similar alongshore variability, the progression of ocean acidification and hypoxia in this region will also not be spatially homogeneous. These findings reinforce the notion that assessment of anthropogenic impacts on coastal ecosystem processes in the CCS (and presumably in other eastern boundary current upwelling systems) should not rely on regionally averaged metrics but instead be characterized locally at relevant physical and ecological alongshore scales.
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