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Contrasting physical and biological drivers of oxygen change in the northern California Current System

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Abstract. Eastern Boundary Upwelling Systems like the California Current System are among the ocean's most productive regions, shaped by distinct surface and subsurface currents and water masses. They are also vulnerable to deoxygenation, with several systems experiencing extreme low-oxygen events and associated mass mortality in recent decades. Determining potential drivers is complicated by seasonal dynamics, multiple water sources, and biological consumption. In the northern California Current System, oxygenated subarctic water mixes with oxygen depleted water from the south. We analyse three 20-year records, including one synthesized from local data, to provide valuable insights into subsurface oxygen variability. These long coastal time series are rare. We show that on the slope in spring, subsurface oxygen variations are physically driven by the relative contributions of these water masses, and their salinity and temperature ratios (a property called 'spiciness') can be used to estimate oxygen levels. Seasonally, decreasing spiciness provides evidence of springtime oxygen renewal on the shelf, before respiration consumes oxygen over summer. Since 2003, mid-depth isopycnals show increased southern water contributions in spring and summer, leading to lower oxygen in spring, but not summer, suggesting summer-time oxygen consumption may have decreased with time. On the densest isopycnal near the shelf floor ($\sim$ 200 m), where oxygen is already lowest, no changes in spiciness or oxygen have been observed. Future research should examine the use of temperature and salinity ratios to estimate oxygen levels in the wider California Current System, and how changing source water conditions and biological activity may affect the risk of low oxygen in coastal waters.

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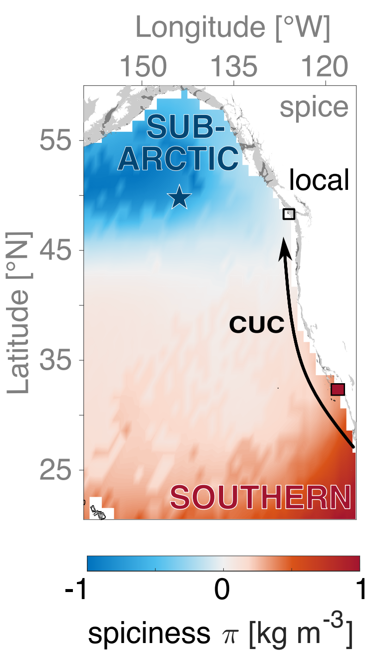
We combine

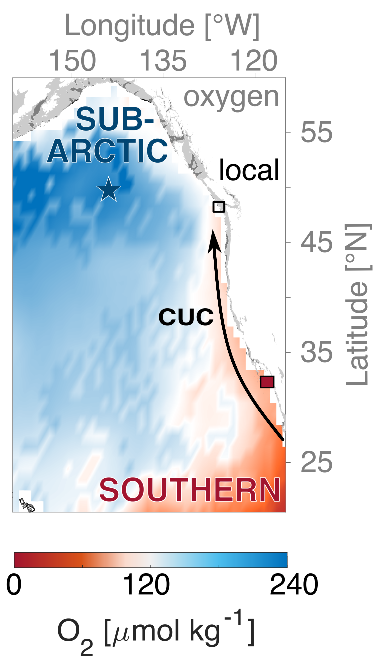


Subsurface observations of **spiciness** (temperature/ salinity) and **oxygen** from three regions:

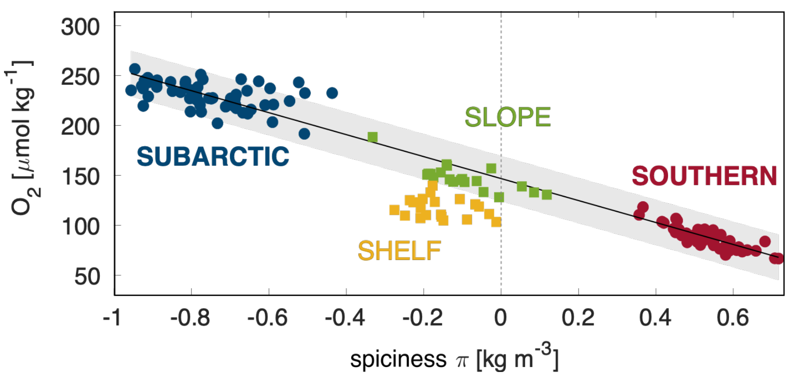
Subarctic,

local (slope / shelf),

southern



We find



Subarctic and southern source water contributions drive local spiciness.

On the slope, they also drive oxygen variability.

On the shelf, local demand further modifies observed oxygen.

*CUC - California Undercurrent

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1 Introduction

Decreasing oxygen is threatening oceans worldwide and will likely worsen in the foreseeable future (e.g., Kwiatkowski et al., 2020). Individual ocean regions experience different levels of loss (Stramma and Schmidtko, 2021). The northeast Pacific has seen one of the largest decreases in oxygen in the last five decades (Stramma et al., 2020; Ross et al., 2020). Eastern Boundary Currents like the California Current System (CCS), where upwelling brings deeper, oxygen depleted water onto highly productive continental shelves, are affected strongly by oxygen loss (Breitburg et al., 2018) since they are already lower in oxygen (Fig. 1a, red). Dangerously low oxygen events have occurred in the CCS (Chan et al., 2008), where seasonal oxygen loss is controlled by both biological drivers (respiration, Siedlecki et al., 2015) and physical drivers (upwelling, Barth et al., 2024).

The northern CCS is the most productive (Hickey and Banas, 2008). Here, both decreases in oxygen (Crawford and Peña, 2013) and extreme low oxygen events (Franco et al., 2023) have been observed. Subsurface waters are subject to two main water masses: Subarctic water is present offshore and to the north, while the California Undercurrent (CUC) brings oxygen-depleted water from the south (Fig. 1a), reaching as far as the Gulf of Alaska region (Thomson and Krassovski, 2010). Deoxygenation has been reported in both the subarctic water and the southern water (e.g., Cummins and Ross, 2020; Ren et al., 2018; Evans et al., 2020). Strong seasonal wind regimes cause summertime upwelling, which lifts denser isopycnals onto the shelf, and wintertime downwelling, which suppresses them (e.g., Thomson and Ware, 1996). The σ_θ26.6 kg m^{-3} isopycnal, which is the densest regularly upwelled isopycnal to cover the shelf floor during spring and summer, experiences the highest levels of southern water influence (Maier et al., 2025). It has not been clear to what extent these different contributions of water masses affect local oxygen.

Here we investigate three 20-year time-series of observed oxygen, temperature, and salinity data to examine the seasonality, trends, and drivers of subsurface oxygen on the slope and shelf in the northern CCS in relation to source water masses. To account for the dynamic upwelling / downwelling nature of the study area, we examine changes on three isopycnals from mid-depth to the sea floor. By tracking the conservative property spiciness, we study the impact of the subarctic and southern water masses on observed oxygen. The southern water that the CUC brings into our study area is warmer and saltier ('spicy'), while the subarctic water on the same isopycnal is colder and fresher ('minty', Fig. 1a (inset)). We quantify seasonal patterns in oxygen in this upwelling region and discuss how oxygen is controlled by physical advection or biological respiration in each season. Finally, we evaluate the 20-year trends in oxygen, assessing their robustness and discussing likely drivers in the context of the observed physical changes.

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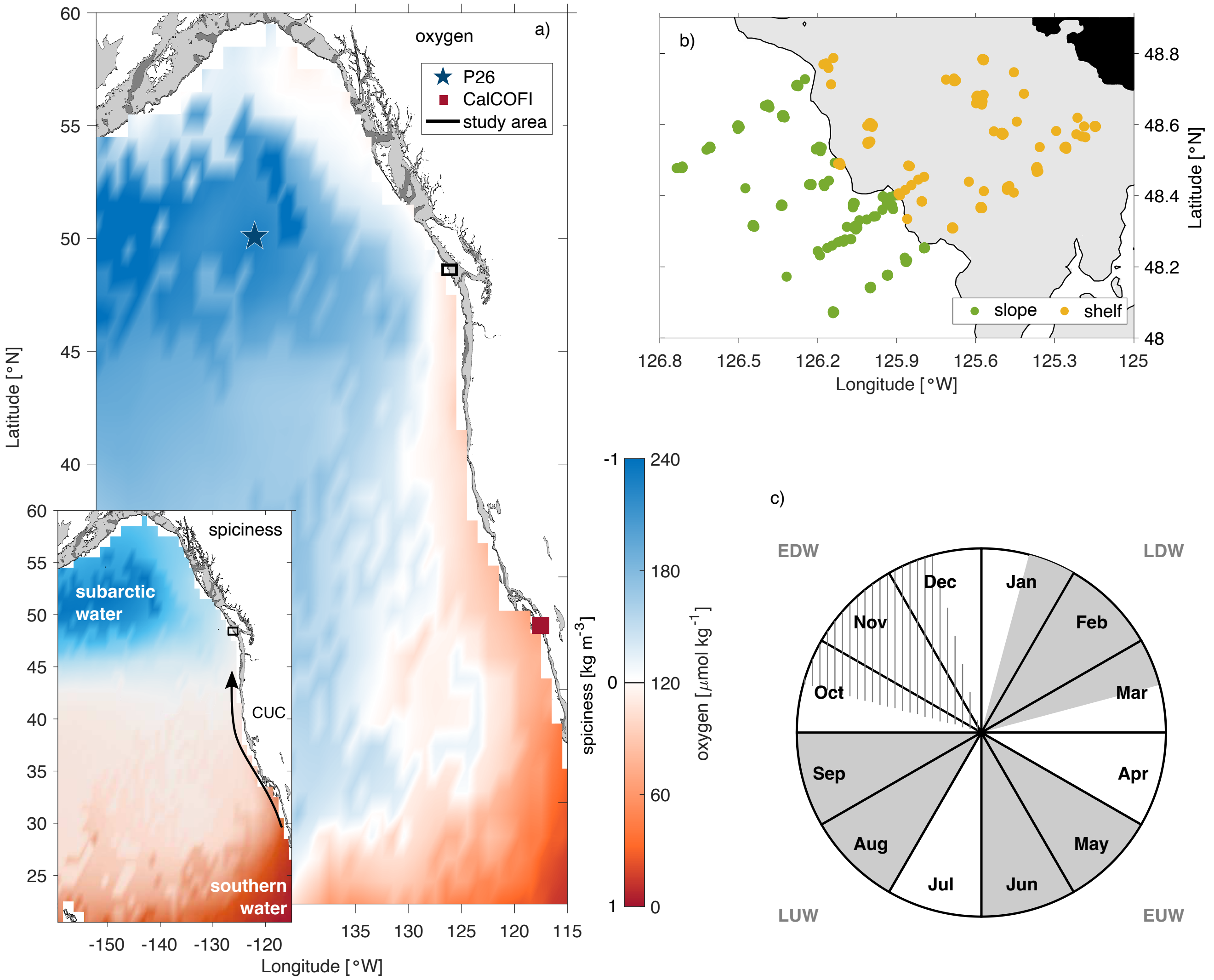

Figure 1. (a) mean oxygen on the σ_θ26.6 kg m^{-3} isopycnal (World Ocean Atlas, 1971-2000) in the northeast Pacific with the study area (black outline), Station P26 (blue star) and CalCOFI station 93.30 (red square). Inset, mean spiciness of the σ_θ26.6 kg m^{-3} isopycnal (World Ocean Atlas, 1971-2000) with the California Undercurrent (CUC, arrow). (b) Observational stations within the study area: slope (green) and shelf (yellow), with the 200 m isobath delineating the grey area. (c) dynamical seasons (Section 2.2) shaded: Late downwelling (LDW), early upwelling (EUW), and late upwelling (LUW). Data from early downwelling (EDW) are too sparse to be included in the analysis (Fig. S7).

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2 Methods

2.1 Hydrographic Data

We take advantage of two decades (2003-2023) of well-sampled Northeast Pacific time-series (Mackas, 1992; Freeland, 2007) in our study area. We use 1482 Sea-Bird CTD profiles of conductivity, temperature, depth, and oxygen (in-situ sensor measurement) from 117 cruises (Fig. S7) and quality-control the CTD oxygen by comparing it to concurrent oxygen from discrete, titrated water samples ("bottle", Text S1). The mean difference between the CTD oxygen and bottle oxygen was -0.5 ± 1 μmol kg^{-1}, with the CTD oxygen biased towards slightly lower values than the bottle oxygen. When the CTD-bottle differences are averaged within cruises, 84% of these cruise-mean differences fall within this range. Agreement between bottle and CTD oxygen improves with time (Fig. S1a, c). We discover a small tendency in early data towards lower CTD oxygen values (negative mean O_2 difference values, Fig. S1d, e); however, over time the total change in the mean oxygen difference per cruise is small: ~ 1 μmol kg^{-1} over the entire 20-year time series (Fig. S1e), and the distribution is overall centered (Fig. S1f).

We use CTD data from Station P26 (2003 – 2023; 50° N 145° W) in the open Northeast Pacific and bottle data from station C93.30.3 in the California Cooperative Oceanic Fisheries Investigations (CalCOFI) array (2003 – 2021, 32.85° N 117.54° W, slope; ~ 850 m depth; following Bograd et al., 2019) to represent the subarctic and southern water masses affecting the study area (blue star and red square in Fig. 1a, respectively, Maier et al., 2025). We use these source data as distributed by their respective providers, retaining values not flagged as bad or invalid.

2.2 Data Processing

We focus on three subsurface isopycnals: At the upper bound (~ 100 m), our shallowest isopycnal is $\sigma_\theta 26.0$ kg m^{-3}. As an intermediary, we examine $\sigma_\theta 26.3$ kg m^{-3}. At the lower bound (~ 200 m), we use $\sigma_\theta 26.6$ kg m^{-3} (the deepest isopycnal regularly upwelled in summer, Maier et al., 2025). We refer to these isopycnals as 26.0, 26.3, and 26.6, respectively.

Using the TEOS-10 equations (https://www.teos-10.org/), the data are converted to absolute salinity and conservative temperature, from which we obtain potential density. All profiles are interpolated in density space (0.01 kg m^{-3} step) and separated into slope or shelf (which includes the ‘Juan de Fuca eddy’, e.g., Franco et al., 2023, Text S2), based on the 200 m isobath (Fig. 1b). For each of our isopycnals, we average the available data at that potential density in a given region (slope or shelf) and a given season of each year (defined in Fig. 1c). When data exist in every year, there are 20 data points in each seasonal, regional time series.

Spiciness, where warm and salty water is considered ‘spicy’, and cold and fresh water is considered ‘minty’, is calculated for each isopycnal following McDougall and Krzysik (2015), using a reference pressure of 0 bar. The thickness of an isopycnal is defined as the difference in depth over a change in density of 0.1 kg m^{-3}, centered on the isopycnal of interest (± 0.05 kg m^{-3}).

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2.3 Trend Calculation

We analyze the trends by calculating a least squares regression for each time series and testing its robustness by bootstrapping (sample with replacement, e.g., Maier et al., 2025). We only consider a trend significant if the p-value is ≤ 0.1 and we have data for more than half of the timeseries ($N \geq 10$). Trends in our study area are calculated within each season, trends in the source waters masses are calculated using all data from all seasons. For these trends, the error in the slope is calculated using a heteroskedasticity and autocorrelation consistent error estimate (HAC, Newey and West, 1987), which accounts for non-constant variance and temporal autocorrelation in the residuals that can otherwise underestimate trend uncertainty in oceanographic time series.

The significance of changes between seasonal distributions was assessed using the Mann–Whitney U-test, a non-parametric test of whether values from one season tend to be systematically higher or lower than values from another season (Mann and Whitney, 1947).

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3 Results and Discussion

3.1 Oxygen and Spiciness

In the absence of strong biological demand, oxygen is correlated to spiciness on subsurface isopycnals in our region, with minty water holding more oxygen. We find that during early upwelling (EUW), oxygen and spiciness correlate strongly in both the northern and southern CCS (Fig. 2). On the shelf, where surface productivity is high and respiration reduces oxygen in the subsurface, we see less correlation (Fig. 2c, f, i). On the shallower slope isopycnals, where the oxygen–spiciness correlation is strong during early upwelling, the relationship weakens by late upwelling (LUW; Table S1), when summertime productivity increases biological oxygen demand.

We also observe a similar relationship between higher spiciness and lower oxygen within the southern water dataset (at C93.30, Fig. 2a, d, g, $R^2 = 0.54 – 0.74$, Table S1). High spiciness at C93.30 is driven by the presence of equatorial water, which is considerably older (longer since last at the surface) and therefore more oxygen depleted than the surrounding water (e.g., Nam et al., 2015).

Within the subarctic water (at P26), we observe a correlation between spiciness and oxygen only on 26.0 ($R^2 = 0.59$, Table S1, Fig. 2a). We do not observe any correlation on 26.6, whose oxygen levels are affected by ventilation in the NW Pacific and respiration over the 7-year transport to P26 (Franco et al., 2021; Cervania and Hamme, 2024). These multiple factors can affect oxygen without associated changes in spiciness (Sasano et al., 2018).

We calculate a theoretical mixing line (least-squares regression) between the southern and subarctic source water masses to examine how a change in spiciness associated with their changing contributions would affect oxygen on the slope and shelf (Fig. 2a, d, g). Across all slope isopycnals during EUW, the spiciness–oxygen relationship has a gradient comparable to the source water mixing line (Fig. 2b, e, h), but mean oxygen values fall below the mixing line due to the further influence of respiration. On the shelf, the range in spiciness is roughly similar to the slope, but oxygen is much lower, especially on the shallower isopycnals where respiration is strongest (Fig. 2).

The slope of the mixing lines between the end-members shows that an increase in spiciness of 0.1 kg m^{-3} is expected to lead to a decrease in oxygen of between 11 μmol kg^{-1} (26.0 and 26.3) and 13 μmol kg^{-1} (26.6). While spicier water indicates warmer and saltier water, which negatively affects oxygen solubility, the change due to solubility alone is small ($\sim$ 2 μmol kg^{-1} for a spiciness change of 0.1 kg m^{-3} in our study area). Any decrease in oxygen accompanied by an increase in spiciness would therefore not be caused by the water's ability to hold less oxygen but rather by an increase in the proportion of southern water, which is spicier and lower in oxygen.

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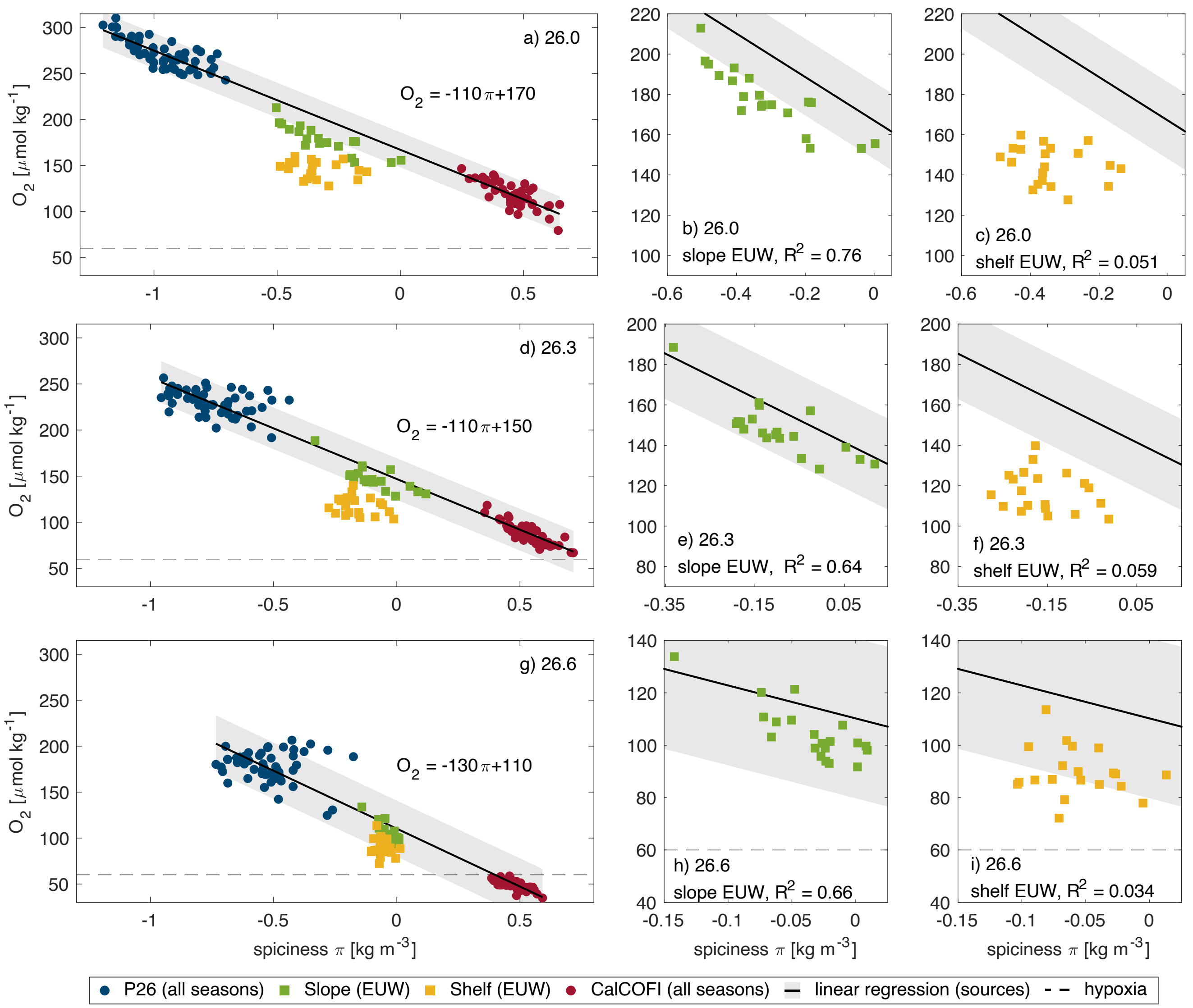

Figure 2. Correlations between spiciness and oxygen on isopycnals 26.0 (a–c), 26.3 (d–f), and 26.6 (g–i). Subarctic water (P26, blue), southern water (CalCOFI station C93.30 (slope, ∼850 m water column depth), red), slope (green), and shelf (yellow) are shown. We show only early upwelling (EUW) for the local data, where correlation is highest (Table S1). The 60 μmol kg^{-1} hypoxia boundary is marked as a dashed line. The theoretical mixing line (least-squares regression) between the source waters for each isopycnal is shown in black, with the 95% prediction interval based on regression uncertainty and data scatter shown in grey (same line for each row). The equations with slope and intercept for the regression line that describes the relationship between oxygen [μmol kg^{-1}] and spiciness [kg m^{-3}] are shown in the left column. The R^2 values shown in the middle and right columns are for the local data, not the source water regression line.

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3.2 Seasonality of oxygen in the northern CCS

Our data show that subsurface isopycnals on the slope are replenished with oxygen each spring with the onset of upwelling, before oxygen is slowly consumed by respiration. Oxygen over the slope increases significantly from late downwelling (LDW) to early upwelling (EUW) on all three isopycnals (Fig. 3a green). This increase in oxygen is concurrent with the increasing influence of subarctic water (decrease in spiciness, Fig. 3b green, which is accompanied by higher oxygen (based on the mixing lines in Fig. 2) and significant shoaling due to the onset of upwelling (Fig. 3c green). On 26.6, where the influence of the CUC is highest (Maier et al., 2025), the change in spiciness and oxygen (over the slope) are smallest, but still significant (Fig. 3a, b green).

Over the shelf, the same physical changes occur between LDW and EUW that are observed on the slope, but oxygen does not change significantly on subsurface isopycnals. The 26.6 isopycnal is completely absent from the shelf during LDW (Fig. S8e) before shoaling by $\sim$ 100 m onto the shelf in EUW (Fig. 3c, Maier et al., 2025). The 26.3 isopycnal is present on the shelf during LDW for less than half the years in our time-series (Fig. S8c). In EUW, it becomes colder and fresher (lower spiciness) with the seasonal shift in surface currents and increased influence of subarctic water (as seen on the slope); however, its oxygen content stays about the same (Fig. 3a, yellow). Above, on the 26.0 isopycnal, which is usually present on the shelf during LDW (Fig. S8a), there is an even stronger decrease in spiciness, but again no oxygen increase (Fig. 3a, b yellow). In both cases, the change in spiciness provides evidence for a springtime renewal that is not readily apparent in the oxygen data.

Substantial consumption of oxygen by organic matter must occur early in the season (EUW) over the shelf. The observed decrease in spiciness on the 26.0 isopycnal on the slope of $\sim$0.15 kg m^{-3} and shelf of $\sim$0.14 kg m^{-3} from LDW to EUW (Fig. 3b) predicts a seasonal increase in dissolved oxygen from the increased influence of subarctic water of $\sim$16 and $\sim$15 μmol kg^{-1}, respectively, which is observed on the slope, but not shelf (Table S2). Mean shelf EUW oxygen is $\sim$30 μmol kg^{-1} lower than on the slope for both isopycnals (Table S2), a difference we attribute to respiration. The respiration signal is stronger on the shelf than slope because the water column is shallower, concentrating oxygen demand, and overlying productivity is high (Ianson et al., 2003).

Over summer, strong biological demand significantly reduces oxygen on most isopycnals, especially over the shelf. We see no evidence of a change in water mass (no change in spiciness, Fig. 3b green, yellow) over summer, in agreement with Sahu et al. (2022). However, from early to late upwelling (EUW to LUW), we see a significant loss of oxygen on most isopycnals on the slope and shelf (Fig. 3a green, yellow, Table S2; the exception is 26.0 on the slope, where conditions are highly variable). On the shelf, respiration reduces oxygen by $\sim$20 μmol kg^{-1} on each isopycnal by LUW (Fig. 3a), yellow). We attribute this oxygen decrease to high productivity and the continuous seasonal shoaling of mid-depth isopycnals (towards higher respiration rates near the surface) throughout the full upwelling season that is observed on the shelf, but not slope (Fig. 3c). The seasonal oxygen draw-down (EUW to LUW) on the slope is roughly half that of the shelf (Fig. 3).

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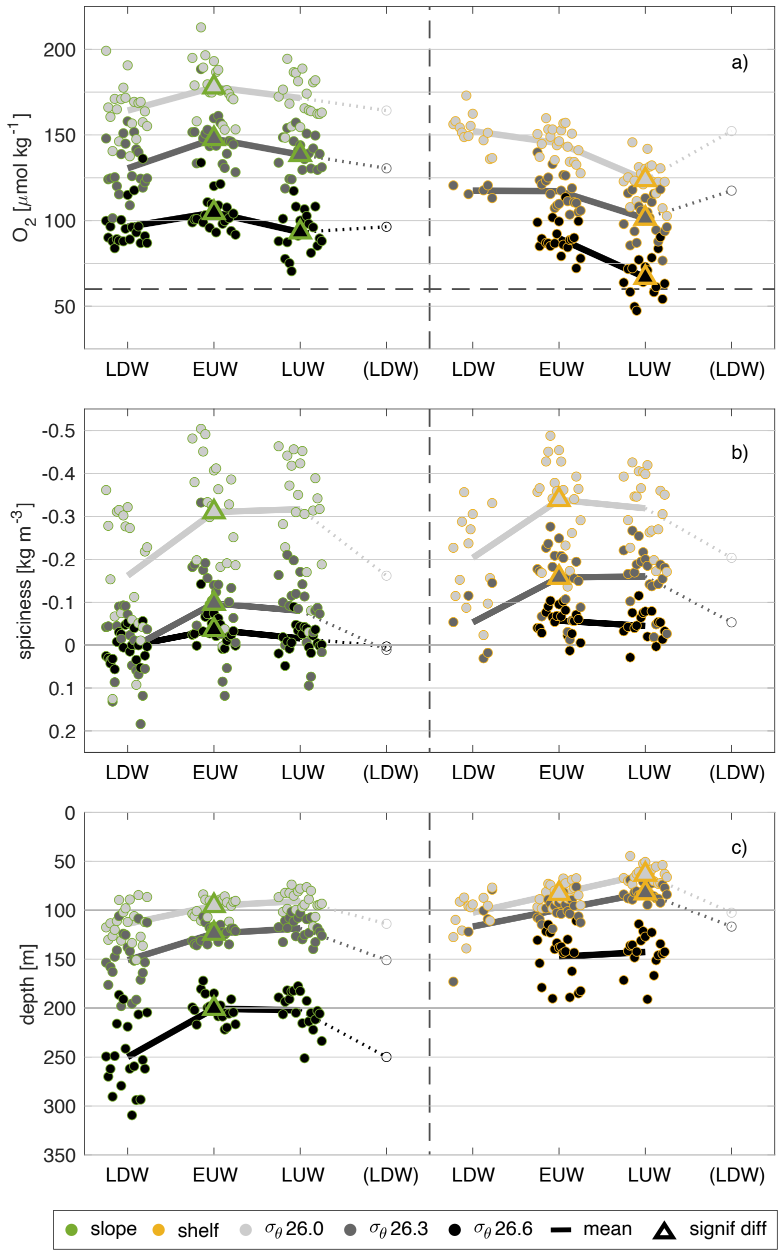

Figure 3. Seasonality of (a) oxygen, (b) spiciness (increasing downwards), and (c) depth for the 26.0 (light grey), 26.3 (dark grey) and 26.6 (black) isopycnals, for each location (slope outlined in green, shelf outlined in yellow) for LDW, EUW, LUW. The binned values (by season) for each year are shown by the clustered dots (slightly offset for legibility). The seasonal mean is shown by the thick line (dashed to show full cycle and return to LDW). The mean is highlighted with a triangle where significantly different to the previous season (Mann-Whitney test).

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3.3 Trends in spiciness and oxygen, 2003 – 2023

3.3.1 On the mid-depth isopycnals (σ_θ26.0 and 26.3 kg m^{-3})

Over the last two decades during EUW, the mid-depth isopycnals on both the slope and shelf have lost oxygen. On the slope, physical drivers control oxygen concentrations during EUW, showing that oxygen changes are driven by the changing mix of subarctic and southern water masses as indicated by spiciness changes. The observed oxygen decline on the slope (Fig. 4a) results from an increase in spiciness (Fig. 4c): We observe an increase in spiciness of 0.24 $\pm$0.09 and 0.20 $\pm$0.07kg m^{-3} on the 26.0 and 26.3 isopycnal, respectively, since 2003. Following the equations in Fig. 2a and d, this increase would explain a decrease in oxygen of roughly 30 μmol kg^{-1} on 26.0, and a decrease of roughly 20 μmol kg^{-1} on 26.3. The observed change in oxygen from the local time-series is equivalent; 26 $\pm$9 and 17$\pm$7 μmol kg^{-1} on the 26.0 and 26.3 isopycnal, respectively (Table S3).

On 26.3 on the shelf, where local respiration plays a larger role, the decrease in oxygen during EUW over the last two decades (Fig. 4b) is also accompanied by a significant increase in spiciness (Fig. 4d). Given the observed spiciness increase of 0.09 ± 0.06 kg m^{-3} on 26.3, we would expect an oxygen decline of around 10 μmol kg^{-1}, yet the measured decrease is twice as large (21 ± 3 μmol kg^{-1}, Table S2). On 26.0, where we see no significant trend in spiciness, there is still a significant decrease in oxygen of 13 ± 6 μmol kg^{-1} (Table S3). Since spiciness and oxygen correlate well on the slope (Table S1), explaining the full trend, we suggest that increased EUW consumption of oxygen on the shelf is responsible for this additional demand.

No trend over time is found in the dissolved oxygen during LUW on either the slope or shelf (Table S3). Following the spring transition, the residence time of upwelled water on the shelf (~May - mid-September, e.g., Sahu et al., 2022), is about the same duration as our upwelling seasons EUW and LUW (Fig. 1c). On the slope and shelf, the mean spiciness on each isopycnal during LUW is the same (within error) as during EUW (Fig. 3b; Table S2). The change in spiciness over 20 years is also similar between the two seasons (where significant; Fig. 4c, d, g, h; Table S3). We would therefore expect a similar decrease in LUW oxygen over time to that observed in EUW, but instead there is no significant trend in oxygen in LUW (Fig. 4e, f). The mechanism behind the changes in mid-depth seasonal oxygen consumption is unclear. We suggest that the absence of a LUW oxygen trend may be caused by decreased subsurface respiration. However, no recent decreases in surface productivity have been documented in the California Current System (Silsbe et al., 2025). We also see no change in isopycnal heave that would affect the respiration rate (higher rate when closer to the surface, Fig. S9f). We directly investigated changes in seasonal oxygen consumption (the difference between oxygen during EUW and LUW) with time, but trends were not significant (Fig. S10). Considering the dynamic nature of the region, large respiration fluxes, and spatial variability, more data are needed to confirm a decrease in summer respiration.

While CTD-O_2 data quality may have changed over time, we estimate that sensor bias would have resulted in a $\sim$1 μmol kg^{-1} increase over this period, a bias that would suggest the real decrease in oxygen might be even larger (Text S1). We also tested whether spiciness changes in the source water masses have substantial effects, but found them not significant (Text S3).

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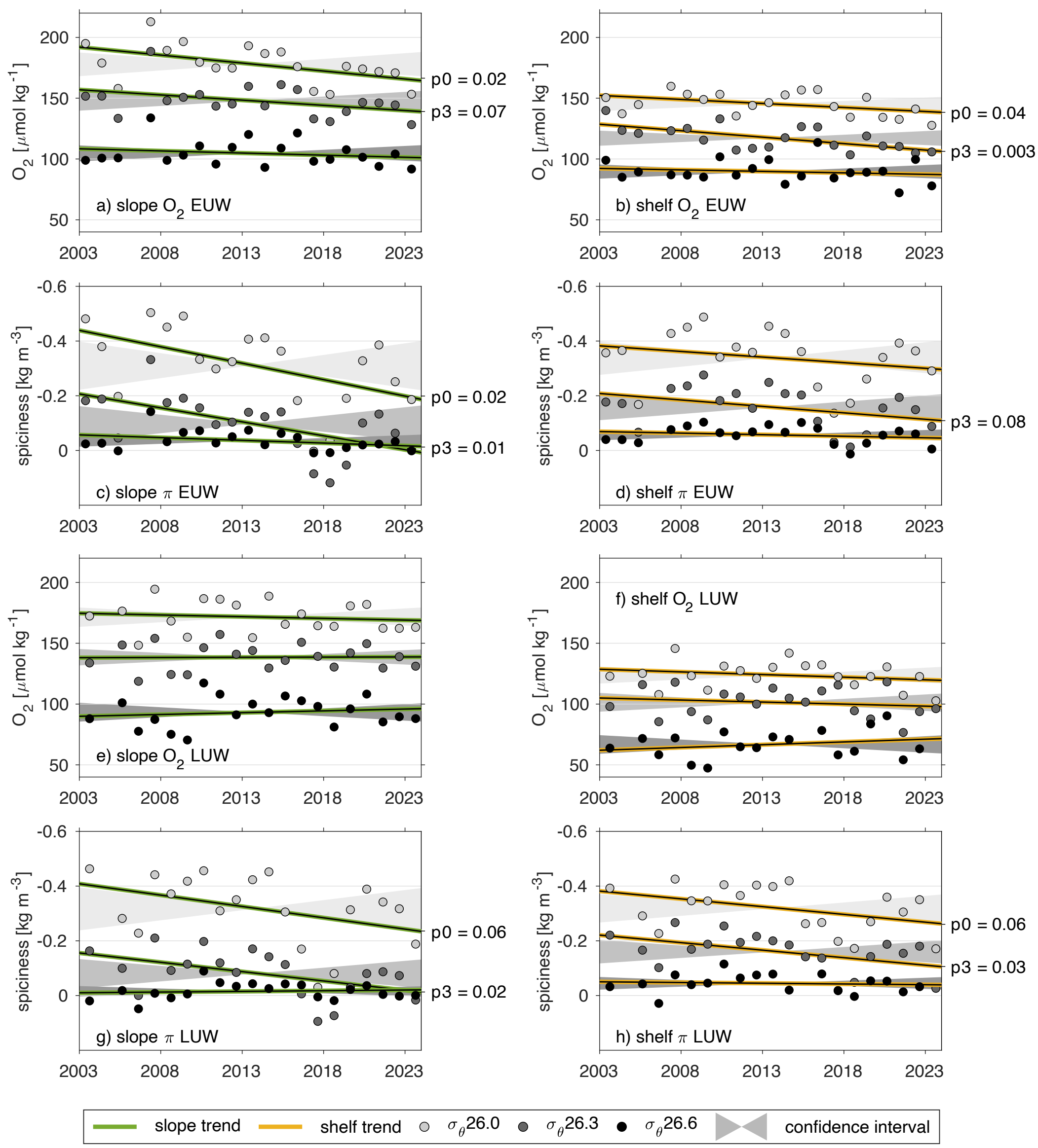

Figure 4. Time series of oxygen and spiciness (π), for EUW (spring, first and second row) and LUW (summer, third and fourth row) seasons on the 26.0 (light grey), 26.3 (dark grey) and 26.6 (black) isopycnals. The 90% confidence interval from bootstrapping is shown in the 'bow tie'-shape of the same colour. The linear trend is shown in green (slope) or yellow (shelf), and the p-value is given on the right where significant (p0 for the 26.0, and p3 for the 26.3 isopycnal).

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3.3.2 On the densest upwelled isopycnal (σ_θ26.6 kg m^{-3})

Oxygen on 26.6 has not decreased over the last 20 years in our study area. Neither the slope nor shelf show a change in oxygen during EUW or LUW (Fig. 4a, b, e, f). We also see no change in spiciness over this time frame (Fig. 4c, d, g, h), in agreement with the source-water spice/oxygen relationship (Fig. 2). This lack of a trend contrasts with the observed changes on the lighter isopycnals.

Decreasing oxygen has been documented in longer /older time series on similar depths and densities within the northern CCS. For example, Crawford and Peña (2013) found decreasing oxygen between 1978 - 2011 at 125 m depth on the shelf. Franco et al. (2021) found increasing apparent oxygen utilization from 1990 – 2019 just offshore of the study area. Both the subarctic water and the southern water have seen significant (opposing) changes in spiciness over the last 20 years (Text S4), with the subarctic water getting spicier (0.09 ± 0.07 kg m^{-3}) and the southern water getting mintier (-0.08 ± 0.02 kg m^{-3}). While these changes should result in an oxygen decrease/ increase of $\sim$11 μmol kg^{-1}, respectively, no significant change in oxygen has been observed on 26.6 in either location (Fig. S6a, b; Table S3). At P26, this change is accompanied by a significant deepening of the 26.6 isopycnal (Fig. S6e), which likely reduces respiration rates. At C93.30, the 26.6 isopycnal is always hypoxic (<60 μmol kg^{-1}; Fig. S6c), and we do not observe an increase in oxygen.

We see no trends in spiciness or oxygen on 26.6 in our study area in our 20 year timeseries (Fig. 4). The lack of trend in spiciness in this shorter time series - despite the opposing spiciness trends of similar magnitude in the source waters - suggests that their relative contributions have not changed. This result contrasts with our analysis on the shallower isopycnals, where an increase in the relative proportion of southern water is observed (subsubsection 3.3.1). On 26.6, there is no change in source water oxygen or their relative contributions (change in spiciness); thus, we do not expect a trend in oxygen on 26.6, where the biological influence is low.

There appears to be no increased risk of hypoxia (<60 μmol kg^{-1}) over the 20-year timeseries. On the shelf however, the mean oxygen value on 26.6 is already near the hypoxic threshold (67 $\pm$ 10 μmol kg^{-1} during LUW, Fig. 3, Table S2). While there is no recent trend for the overall shelf in the study area, localized hypoxia, especially within the eddy (Text S2) as well as individual extreme events have occurred recently, both locally (Franco et al., 2023), and widespread in the entire California Current System (Barth et al., 2024).

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4 Conclusions

Our results show that subsurface oxygen variability in the California Current System is driven by large-scale water mass distributions, and also affected by the presence of a strong local biological signal. On the slope, oxygen correlates well with spiciness, reflecting the relative contributions of oxygen-rich subarctic water and the spicier (warmer and saltier), oxygen-poor southern water. On the shelf, respiration obscures this physically driven signal, consuming the oxygen that is renewed each spring. The strong relationship between spiciness and oxygen on the slope during spring shows that spiciness has predictive power for oxygen levels and long-term changes.

Our results suggest oxygen renewal processes that are not directly evident in the oxygen data. Comparing the spiciness-predicted oxygen to the observed oxygen allowed us to estimate the (potentially changing) strength of the biological drivers in the area. Since spiciness and oxygen correlate well even in the most productive part of the CCS, we suggest this method may be useful in other regions of the CCS where oxygen data are sparse.

Since 2003, the influence of southern water has become stronger on mid-depth isopycnals (σ_θ26.0 and 26.3) in the northern CCS, leading to a decline of $\sim$20 μmol kg^{-1} in springtime oxygen. Because spring sets the initial oxygen conditions for the upwelling season, this trend represents a reduction in the renewal capacity and a potential precursor to even lower oxygen availability during the biologically productive months. In contrast, no late-summer oxygen decline has been observed despite similar spiciness increases, suggesting that reduced productivity or changes in respiration dynamics modulate seasonal consumption in ways that warrant further research.

On the shelf floor in summer (σ_θ26.6 kg m^{-3}), where oxygen is already lowest due to the influence of southern water, neither spiciness nor oxygen show a significant trend over the past two decades. These results are in contrast to previously reported trends in the region. Because oxygen on this isopycnal is already precariously close to the hypoxic threshold, resolving this discrepancy is paramount.

Our findings highlight the importance of investigating highly resolved coastal time-series and of using isopycnals to distinguish functionally different layers in these dynamic regions. Continued research into both large-scale physical changes and their impact on productivity and associated respiration is essential to anticipate future oxygen stress within the northern California Current System.

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Data availability. The raw data for the shelf and slope, as well as for Station P26, were taken from (https://www.waterproperties.ca/data/ (accessed April 2025). The raw data for CalCOFI Station C93.30 were taken from the CalCOFI archives: https://calcofi.org/downloads/database/CalCOFI_Database_194903-202105_csv_16October2023.zip (accessed April 2025). For additional detailed instructions on accessing and sub-sampling the raw data, see Text S4. The blended product, a seasonal integrated dataset for the isopycnals in this paper, is hosted by CIOOS Pacific: https://data.cioospacific.ca/erddap/tabledap/MichaelaMaier_CTD.html.

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Preprint. Discussion started: 28 July 2026

References

Barth, J. A., Pierce, S. D., Carter, B. R., Chan, F., Erofeev, A. Y., Fisher, J. L., Feely, R. A., Jacobson, K. C., Keller, A. A., Morgan, C. A., Pohl, J. E., Rasmuson, L. K., and Simon, V.: Widespread and Increasing Near-Bottom Hypoxia in the Coastal Ocean off the United States Pacific Northwest, 14, 3798, https://doi.org/10.1038/s41598-024-54476-0, 2024.

Bograd, S. J., Schroeder, I. D., and Jacox, M. G.: A Water Mass History of the Southern California Current System, 46, 6690–6698, https://doi.org/10.1029/2019GL082685, 2019.

Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G. S., Limburg, K. E., Montes, I., Naqvi, S. W. A., Pitcher, G. C., Rabalais, N. N., Roman, M. R., Rose, K. A., Seibel, B. A., Telszewski, M., Yasuhara, M., and Zhang, J.: Declining Oxygen in the Global Ocean and Coastal Waters, 359, eaam7240, https://doi.org/10.1126/science.aam7240, 2018.

Cervania, A. A. and Hamme, R. C.: Isopycnal Shoaling Causes Interannual Variability in Oxygen on Isopycnals in the Subarctic Northeast Pacific, 129, e2023JC020 414, https://doi.org/10.1029/2023JC020414, 2024.

Chan, F., Barth, J. A., Lubchenco, J., Kirincich, A., Weeks, H., Peterson, W. T., and Menge, B. A.: Emergence of Anoxia in the California Current Large Marine Ecosystem, 319, 920–920, https://doi.org/10.1126/science.1149016, 2008.

Crawford, W. R. and Peña, M. A.: Declining Oxygen on the British Columbia Continental Shelf, 51, 88–103, https://doi.org/10.1080/07055900.2012.753028, 2013.

Cummins, P. F. and Ross, T.: Secular Trends in Water Properties at Station P in the Northeast Pacific: An Updated Analysis, 186, 102 329, https://doi.org/10.1016/j.pocean.2020.102329, 2020.

Evans, N., Schroeder, I. D., Pozo Buil, M., Jacox, M. G., and Bograd, S. J.: Drivers of Subsurface Deoxygenation in the Southern California Current System, 47, e2020GL089 274, https://doi.org/10.1029/2020GL089274, 2020.

Franco, A., Ianson, D., Ross, T., Hannah, C., Sastri, A., and Tortell, P.: Drivers and Potential Consequences of Observed Extreme Hypoxia Along the Canadian Pacific Continental Shelf, 50, https://doi.org/10.1029/2022GL101857, 2023.

Franco, A. C., Ianson, D., Ross, T., Hamme, R. C., Monahan, A. H., Christian, J. R., Davelaar, M., Johnson, W. K., Miller, L. A., Robert, M., and Tortell, P. D.: Anthropogenic and Climatic Contributions to Observed Carbon System Trends in the Northeast Pacific, 35, e2020GB006 829, https://doi.org/10.1029/2020GB006829, 2021.

Freeland, H.: A Short History of Ocean Station Papa and Line P, 75, 120–125, https://doi.org/10.1016/j.pocean.2007.08.005, 2007.

Hickey, B. and Banas, N.: Why Is the Northern End of the California Current System So Productive?, 21, 90–107, https://doi.org/10.5670/oceanog.2008.07, 2008.

Ianson, D., Allen, S. E., Harris, S. L., Orians, K. J., Varela, D. E., and Wong, C. S.: The Inorganic Carbon System in the Coastal Upwelling Region West of Vancouver Island, Canada, 50, 1023–1042, https://doi.org/10.1016/S0967-0637(03)00114-6, 2003.

Kwiatkowski, L., Torres, O., Bopp, L., Aumont, O., Chamberlain, M., Christian, J. R., Dunne, J. P., Gehlen, M., Ilyina, T., John, J. G., Lenton, A., Li, H., Lovenduski, N. S., Orr, J. C., Palmieri, J., Santana-Falcón, Y., Schwinger, J., Séférian, R., Stock, C. A., Tagliabue, A., Takano, Y., Tjiputra, J., Toyama, K., Tsujino, H., Watanabe, M., Yamamoto, A., Yool, A., and Ziehn, T.: Twenty-First Century Ocean Warming, Acidification, Deoxygenation, and Upper-Ocean Nutrient and Primary Production Decline from CMIP6 Model Projections, 17, 3439–3470, https://doi.org/10.5194/bg-17-3439-2020, 2020.

Mackas, D. L.: Seasonal Cycle of Zooplankton off Southwestern British Columbia: 1979–89, 49, 903–921, https://doi.org/10.1139/f92-101, 1992.

https://doi.org/10.5194/egusphere-2026-4197
Preprint. Discussion started: 28 July 2026

Maier, M., Ianson, D., and Hamme, R. C.: Trends and Variability in Depth and Spiciness of Subsurface Isopycnals on the Vancouver Island Continental Shelf and Slope, 130, e2024JC020 992, https://doi.org/10.1029/2024JC020992, 2025.

Mann, H. B. and Whitney, D. R.: On a Test of Whether One of Two Random Variables Is Stochastically Larger than the Other, 18, 50–60, https://www.jstor.org/stable/2236101, 1947.

McDougall, T. J. and Krzysik, O. A.: Spiciness, https://doi.org/info:doi/10.1357/002224015816665589, 2015.

Nam, S., Takeshita, Y., Frieder, C. A., Martz, T., and Ballard, J.: Seasonal Advection of Pacific Equatorial Water Alters Oxygen and pH in the Southern California Bight, 120, 5387–5399, https://doi.org/10.1002/2015JC010859, 2015.

Newey, W. K. and West, K. D.: A Simple, Positive Semi-Definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix, 55, 703–708, https://doi.org/10.2307/1913610, 1987.

Ren, A. S., Chai, F., Xue, H., Anderson, D. M., and Chavez, F. P.: A Sixteen-year Decline in Dissolved Oxygen in the Central California Current, 8, 7290, https://doi.org/10.1038/s41598-018-25341-8, 2018.

Ross, T., Du Preez, C., and Ianson, D.: Rapid Deep Ocean Deoxygenation and Acidification Threaten Life on Northeast Pacific Seamounts, 26, 6424–6444, https://doi.org/10.1111/gcb.15307, 2020.

Sahu, S., Allen, S. E., Saldías, G. S., Klymak, J. M., and Zhai, L.: Spatial and Temporal Origins of the La Perouse Low Oxygen Pool: A Combined Lagrangian Statistical Approach, 127, e2021JC018 135, https://doi.org/10.1029/2021JC018135, 2022.

Sasano, D., Takatani, Y., Kosugi, N., Nakano, T., Midorikawa, T., and Ishii, M.: Decline and Bidecadal Oscillations of Dissolved Oxygen in the Oyashio Region and Their Propagation to the Western North Pacific, 32, 909–931, https://doi.org/10.1029/2017GB005876, 2018.

Siedlecki, S. A., Banas, N. S., Davis, K. A., Giddings, S., Hickey, B. M., MacCready, P., Connolly, T., and Geier, S.: Seasonal and Interannual Oxygen Variability on the Washington and Oregon Continental Shelves, 120, 608–633, https://doi.org/10.1002/2014JC010254, 2015.

Silsbe, G. M., Fox, J., Westberry, T. K., and Halsey, K. H.: Global Declines in Net Primary Production in the Ocean Color Era, 16, 5821, https://doi.org/10.1038/s41467-025-60906-y, 2025.

Stramma, L. and Schmidtko, S.: Spatial and Temporal Variability of Oceanic Oxygen Changes and Underlying Trends, 59, 122–132, https://doi.org/10.1080/07055900.2021.1905601, 2021.

Stramma, L., Schmidtko, S., Bograd, S. J., Ono, T., Ross, T., Sasano, D., and Whitney, F. A.: Trends and Decadal Oscillations of Oxygen and Nutrients at 50 to 300 m Depth in the Equatorial and North Pacific, 17, 813–831, https://doi.org/10.5194/bg-17-813-2020, 2020.

Thomson, R. E. and Krassovski, M. V.: Poleward Reach of the California Undercurrent Extension, 115, https://doi.org/10.1029/2010JC006280, 2010.

Thomson, R. E. and Ware, D. M.: A Current Velocity Index of Ocean Variability, 101, 14 297–14 310, https://doi.org/10.1029/96JC01055, 1996.