Estuarine, Coastal and Shelf Science 300 (2024) 108706

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Compound marine cold spells and hypoxic events in a nearshore upwelling system

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ARTICLE INFO

Keywords:
Dissolved oxygen
Coastal hypoxia
Coastal upwelling
Marine cold spells
Multiple stressors
Compound extreme events

ABSTRACT

Prolonged periods of extreme warm and cold seawater temperature anomalies, known as marine heatwaves (MHWs) and marine cold spells (MCSs), respectively, can have significant impacts on coastal marine ecosystems. Prior research has examined the co-occurrence of multiple extremes [low dissolved oxygen (DO) and/or low pH] during MHWs, with the impact of these compound events potentially exceeding that of a single stressor due to synergistic effects. However, we are not aware of any studies that have examined compound extreme events during MCSs, despite the ecosystem implications. Along Eastern Boundary Current Upwelling Systems (EBUS), strong-wind driven upwelling has led to reduced warming trends and persistence of MCSs, as well as an increased seasonal risk for coastal hypoxia via the cross-shelf advection of cold, low DO subthermocline waters. In this short communication, we investigated for the first time compound MCS-hypoxic events at a nearshore site in central California using several decades of nearshore water temperature data, short-term nearshore DO data, and several decades of DO data from the California Cooperative Oceanic Fisheries Investigations program. From 1988 to 2020, we identified 55 MCS events, with 50 events (~90.9%) initiated during anomalously strong upwelling. Using long-term temperature-DO relationships, we identified 20 of the 55 MCS events (~34.6%) as potential compound MCS-hypoxic events, with an average duration of 11.7 days. These compound events occurred almost exclusively during the major upwelling season (March to June) when there is a high propensity for the advection of cold, low DO subthermocline waters from the adjacent shelf into the nearshore. This work provides the first known investigation into the co-occurrence of MCS and hypoxic events in a nearshore upwelling system and provides a baseline for assessing future changes to these compound events in a changing climate, with important implications for ecosystem health in EBUS globally.

1. Introduction

Characterizing nearshore seawater temperature variability and extremes is critical for assessing marine ecosystem resilience. Periods of prolonged extreme warm water temperature anomalies, known as marine heatwaves (MHWs), have received considerable attention in the literature since they can cause long-lasting impacts to marine ecosystems and fisheries [see recent review by Smith et al. (2023)]. Extended periods of extreme cold anomalies, known as marine cold spells (MCS), although less studied compared to MHWs, have been shown to drive ecological changes of similar magnitude to MHWs (Schlegel et al., 2021). This includes impacts to individual organisms, communities, and entire ecosystems such as mass mortality of fish and invertebrates, coral bleaching, species range contraction, reduction of commercial fish catch, and shifts in marine ecosystem structure, among others [see Table 1 in Schlegel et al. (2021) and the references therein].

Globally there has been a documented decrease in the number and intensity of MCSs largely driven by warming sea surface temperatures (SST) [Schlegel et al., 2021; Wang et al., 2022a; but see also Chiswell (2022)]. However, these reported changes are typically open-ocean trends inferred from satellite-based SST time series, which have known biases and limitations in nearshore regions [Schlegel et al., 2021; see Izquierdo et al. (2022) and the references therein]. Moreover, there are often low rates of co-occurrence of MCSs between offshore and nearshore sites, as well as documented regions of "cold spots" where trends are more muted or non-existent, suggesting that local-scale

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https://doi.org/10.1016/j.ecss.2024.108706
Received 1 February 2024; Received in revised form 28 February 2024; Accepted 1 March 2024
Available online 12 March 2024

processes can be important for MCS events (Schlegel et al., 2017, 2021; Mora-Soto et al., 2022; Wang et al., 2022a). Recent work from the shallow nearshore of the California Current in central California found no statistically significant decrease in MCS frequency, duration, or intensity over the last four decades (Dalsin et al., 2023). In addition to documenting an increase in the frequency of MCSs during La Niña and negative Pacific Decadal Oscillations years (both of which are associated with cold water anomalies in the California Current), Dalsin et al. (2023) found that the initiation and maintenance of MCSs was linked with anomalously strong coastal wind-driven upwelling. Reduced warming trends along Eastern Boundary Current Upwelling Systems (EBUS), like the California Current, have led to the idea that these regions may serve as cold-water refugia in a warming planet (Seabra et al., 2019; Varela et al., 2021; García-Reyes et al., 2023).

Corresponding with strong upwelling in EBUS is an increased seasonal risk for coastal hypoxia via the cross-shelf advection of cold subthermocline waters, which are low in both dissolved oxygen (DO) and pH due to respiration at depth (Siedlecki et al., 2015; Connolly et al., 2010; Walter et al., 2022; Kroeker et al., 2023). Along the California Current EBUS, there has been widespread and increasing hypoxia in coastal regions (Chan et al., 2008; Barth et al., 2024), which have led to lethal and non-lethal effects on ecologically and economically important fish and invertebrates (Grantham et al., 2004). In nearshore upwelling systems, there is an increased risk for the co-occurrence of both a MCS and hypoxic event during periods of strong upwelling. Prior research in other systems has examined the co-occurrence of multiple extremes (low DO and/or low pH) during MHW events (Gruber et al., 2021; Tassone et al., 2022; Burger et al., 2022; Shunk et al., 2024), with the impact of these compound events potentially exceeding that of a single stressor event since the co-occurrence of multiple extreme stressors can interact synergistically (Boyd and Brown, 2015). However, we are not aware of any studies that have examined compound extreme events during MCSs, despite the potential ecosystem implications.

In this study and short communication, we investigate patterns and drivers of compound MCS-hypoxia events at a nearshore site along the California Current in central California. To assess the co-occurrence of these events, we utilize several decades of nearshore water temperature and MCS data from Dalsin et al. (2023), which, to our knowledge, was the first study to investigate MCSs using in-situ data from the shallow nearshore of an EBUS. We combine these MCS data with DO data

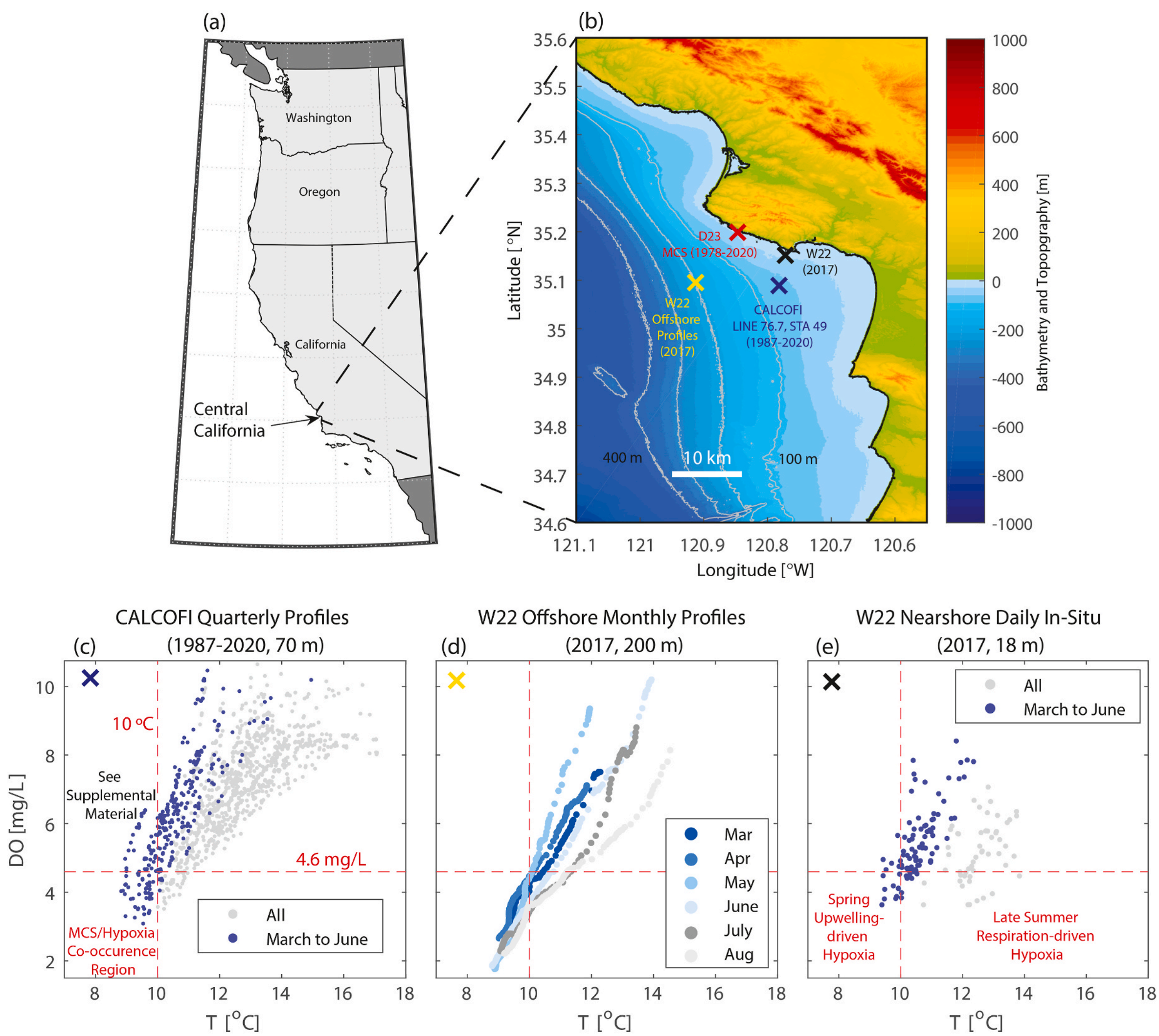

Fig. 1. (a) West Coast of the United States with central California study region. (b) Topography and bathymetry of the central California study region and the location ('X') of all nearshore and offshore datasets used in this study (W22 = Walter et al., 2022; D23 = Dalsin et al., 2023). Gray lines denote isobaths. (c) Water temperature-dissolved oxygen (T-DO) relationship from approximately quarterly offshore bottle samples from CALCOFI (1987–2020, blue 'X' in panel b, ~70 m depth). (d) T-DO relationship from approximately monthly offshore profiles from W22 (2017, yellow 'X' in panel b, ~200 m depth). (e) T-DO from daily-averaged nearshore values from W22 (2017, black 'X' in panel b, ~18 m depth), highlighting the spring-driven upwelling hypoxic regime and late-summer respiration-driven hypoxia regime. In panels c-e, data from months with seasonally strong upwelling (May to June) are colored blue, the horizontal dashed red line denotes the hypoxic threshold of 4.6 mg/L, and the vertical dashed red line denotes 10 °C.

collected from an adjacent nearshore site from Walter et al. (2022) and over three decades of DO data collected from the adjacent shelf as part of the California Cooperative Oceanic Fisheries Investigations (CALCOFI) program. This work provides the first known investigation into the co-occurrence of MCS and hypoxic events in a nearshore upwelling system and provides a baseline for assessing future changes to these compound events in a changing climate, with important implications for ecosystem health in EBUS globally.

2. Methods

2.1. Site description

Data were obtained from several studies and long-term monitoring platforms located in central California (USA), along the eastern Pacific Ocean and EBUS of the California Current (Fig. 1). This region is home to species-rich giant kelp forests, a network of marine protected areas, and economically and ecologically important recreational and commercial fisheries (Wang et al., 2022b). Similar to other EBUS, seasonal wind-driven coastal upwelling dominates the physical, chemical, and biological variability in this region with peak upwelling occurring in the spring "major upwelling season" (March to June) and more moderate upwelling in the late summer and early fall (García-Reyes and Largier, 2012; Walter et al., 2018, 2022; Barth et al., 2020; Trautman and Walter, 2021).

2.2. Data

2.2.1. Nearshore MCS events from Dalsin et al. (2023)

Long-term nearshore water temperature data and MCS event characteristics were utilized from Dalsin et al. (2023). Water temperature data were collected at 20-min intervals from 1978 to 2020 in the shallow nearshore (~3 m nominal depth) (see red "x" in Fig. 1b) and daily averages were calculated. MCS events were identified following Schlegel et al. (2021). Using the daily-averaged water temperature, the climatology and 10th percentile for each day of the year were calculated using an 11-day moving average. MCS events were then identified when the daily-averaged water temperature fell below the 10th percentile threshold for at least 5 days, capturing discrete and prolonged cold periods while accounting for seasonal variability. See Dalsin et al. (2023) for additional details.

2.2.2. Upwelling climatology and anomaly from Dalsin et al. (2023)

To examine how seasonally-variable upwelling and anomalous upwelling events impact the co-occurrence of MCS and hypoxic events, we utilized the Coastal Upwelling Transport Index (CUTI) climatology and anomaly (CUTIa) calculated in Dalsin et al. (2023). The CUTI quantifies the rate of vertical transport at varying latitudes along the US West Coast (Jacox et al., 2018). The daily product at 35° N from 1988 to 2020 was used here. A CUTI climatology for each day of the year was calculated following the same methodology as the water temperature climatology, and deviations from the climatology were used to define an anomaly product (CUTIa). Further details can be found in Dalsin et al. (2023).

2.2.3. Nearshore and shelf DO data from Walter et al. (2022)

To examine the co-occurrence of MCS and hypoxic events in the nearshore, and to develop a water temperature-DO relationship (described below), we used data detailed in Walter et al. (2022). Data were collected from a near-bottom-mounted (2 m above bed) instrument measuring water temperature and DO every 10 min from March to August 2017, from which daily averages of both water temperature and DO were calculated. This mooring was located in a local water depth of ~18 m and ~9.0 km away from the long-term water temperature data site where MCS events were calculated (see black "x" in Fig. 1b). We also utilized water temperature and DO data from monthly vertical profiles (from March to August 2017) located at the 200 m isobath on the shelf (see yellow "x" in Fig. 1b). Additional details are described in Walter et al. (2022).

2.2.4. Long-term shelf DO data from CALCOFI

Long-term water temperature and DO data from the adjacent shelf were also obtained from the California Cooperative Oceanic Fisheries Investigations (CALCOFI) sampling program. We utilized all bottle data obtained from approximately quarterly profiles from Line 76.7, Station 49 (35.08824 °N, 120.7774 °W; ~70 m depth; blue "x" in Fig. 1b) spanning from 1987 to 2020 (data available from https://calcofi.org/data/oceanographic-data/bottle-database/).

2.3. Methodology

To examine the co-occurrence of MCS and hypoxic events, we first examined the MCS events from the long-term water temperature time series from Dalsin et al. (2023). For hypoxic events, continuous DO data were not available, but instead, we developed water temperature-DO (T-DO) relationships for the region using the nearshore mooring and offshore profiles of T and DO from Walter et al. (2022) and long-term CALCOFI shelf measurements. Previous studies have utilized T-DO relationships for examining nearshore coastal DO dynamics and have shown that the low T-low DO portion of the parameter space where both MCS and hypoxic events would occur is particularly robust, especially during the upwelling season (Connolly et al., 2010; Walter et al., 2022). Thus, using the T-DO relationships, we identified a water temperature cutoff where DO values fell below a hypoxic threshold in the low T-DO region of the T-DO parameter space. This water temperature cutoff was then used to identify potential hypoxic events during MCS events. Importantly, we did not develop an explicit functional relationship for calculating DO from water temperature. Rather, we identified a simple water temperature cutoff below which there is a high likelihood of hypoxic DO concentrations given the clustering of points in the low T-DO region of the parameter space (see Results).

For the hypoxic threshold, we adopt 4.6 mg/L as the cutoff following the broad comparative analysis of Vaquer-Sunyer and Duarte (2008) that identified this level as a critical lethal threshold for 10% of marine benthic communities studied. We note that different species will have different hypoxic limits and that there are likely to be region- and site-specific differences among species. Moreover, 2.0 mg/L is also sometimes used as a hypoxic threshold (e.g., Hofmann et al., 2011), but Vaquer-Sunyer and Duarte (2008) found that this was below the empirical lethal and sublethal threshold for half of the species in their analysis. While there are limited studies of hypoxic threshold data available for nearshore California Current taxa, including in Vaquer-Sunyer and Duarte (2008), the cutoff of 4.6 mg/L captures low DO events that are likely to negatively impact local ecosystems [e.g., see Mattiasen et al. (2020) for study on kelp forest fishes and Gray et al. (2002) review for organisms in the water column, both of which found deleterious effects around 4.6 mg/L]. Recognizing there are going to be species-dependent and site-specific responses, we utilize 4.6 mg/L as the low DO hypoxic threshold that could potentially negatively affect nearshore organisms.

3. Results

3.1. Example MCS-hypoxic event

During the March to August 2017 nearshore DO measurements from Walter et al. (2022), there was one MCS event (Fig. 2). In late April, there was approximately a week of anomalously strong upwelling (positive CUTIa; Fig. 2a). This led to a marked decrease in water temperatures below the seasonal climatology with the daily-averaged temperature falling below the 10th percentile MCS threshold (Fig. 2b). This MCS event had a duration of six days and a max intensity of −1.44 °C (e.g., 1.44 °C below the seasonal climatology during the MCS event). With

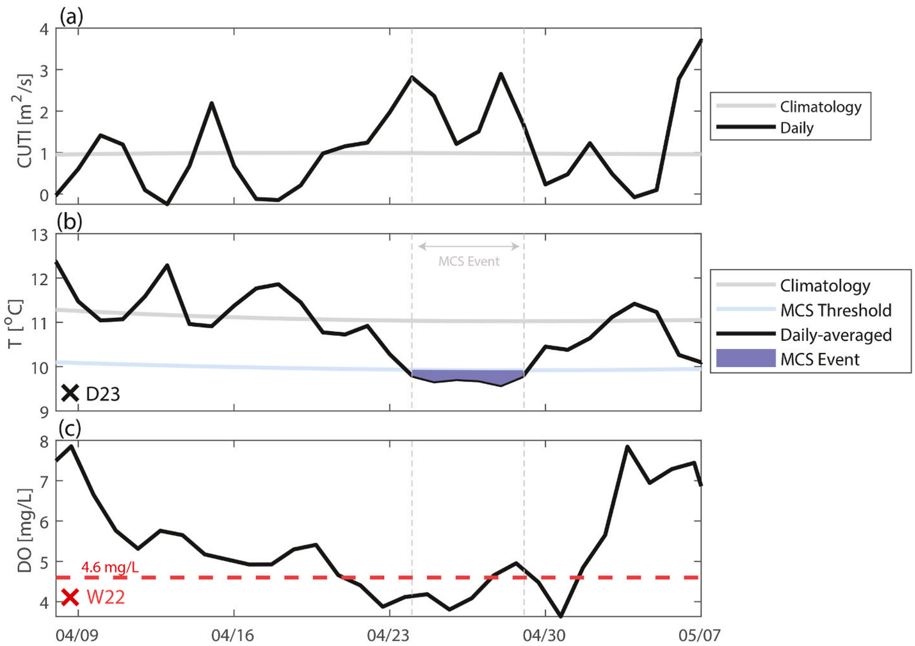

Fig. 2. Time-series example of compound MCS-hypoxic event from April 2017. (a) Daily (black) and calculated climatology (gray) of the CUTI upwelling index. (b) Nearshore water temperature data from Dalsin et al. (2023) (see black 'X' in Fig. 1b) highlighting the daily average (black), calculated climatology (gray), MCS 10th percentile threshold (light blue), and identified MCS event (dark blue fill). (c) Nearshore daily-averaged DO data from Walter et al. (2022) (see red 'X' in Fig. 1b). The horizontal dashed red line denotes the hypoxic threshold of 4.6 mg/L. The vertical dashed gray lines in each panel highlight the start and end of the MCS event.

the increase in upwelling and decrease in water temperatures below the seasonal climatology, the DO values also decreased and eventually fell below the 4.6 mg/L hypoxic threshold (Fig. 2c), highlighting the co-occurrence of a MCS and hypoxic event. This event was detailed in Walter et al. (2022), with the nearshore hypoxic event driven by the advection of low T, low DO subthermocline waters from the adjacent shelf during strong upwelling.

3.2. T-DO relationships and hypoxic threshold

The T-DO relationship from long-term CALCOFI and monthly offshore profiles from Walter et al. (2022) showed a strong positive relationship between water temperature and DO (Fig. 1c and d). In the low T-DO region of the parameter space, which corresponds with deeper shelf waters that are cold and low in DO due to respiration at depth, there was much less variance in the DO data for a given water temperature compared to the high T-DO region of the parameter space that corresponds to offshore surface waters. In the nearshore data (Fig. 1e), the data in the low T-DO region of the parameter space directly overlapped with the low T-DO offshore data. Walter et al. (2022) found that the low T-DO waters in the nearshore in this region were the result of upwelling-driven cross-shelf exchange of subthermocline waters from the adjacent shelf and primarily occurred during the spring and early summer months ("Spring Upwelling-driven Hypoxia" in Fig. 1e). This is distinct from the warmer late summer period, where nearshore hypoxic events deviate from the offshore T-DO relationship and are driven by local respiration and lack of ventilation due to strong stratification during this period ["Late Summer Respiration-driven Hypoxia" in Fig. 1e; see details in Walter et al. (2022)].

Examination of the T-DO relationship over more than three decades of CALCOFI data shows a consistent signal in the hypoxic regime (e.g., DO $<$ 4.6 mg/L). In this portion of the parameter space, water temperatures were consistently below approximately 10 °C. This is especially evident during the upwelling season from March to June (blue colors in Fig. 1c). This approximate water temperature threshold was also present in the Walter et al. (2022) profiles and nearshore data. We note the CALCOFI data show a small subset of data that fell below 10 °C, but had DO values larger than 4.6 mg/L (labelled "See Supplemental Material" in Fig. 1c). However, many of these data were isolated to only two years of data (1995 and 2001) and were also found in shallow waters less than 35 m (see Supplemental Fig. S1). The rest of the data in the low T and low DO parameter space occurred in deeper shelf waters and the relationship was consistent over the three decades (see Supplemental Fig. S1). This region of the parameter space corresponds with deeper shelf waters that are low in T and DO that are upwelled during the major upwelling season into the nearshore, resulting in these low T and DO waters in that region (e.g., "MCS-Hypoxia Co-occurrence Region"). Thus, the 10 °C water temperature is used as the hypoxic temperature cutoff to identify events where DO values are below the hypoxic threshold, particularly during the upwelling season.

3.3. Compound MCS and hypoxic events

From 1988 to 2020, which corresponds with the overlapping time of both the MCS events from Dalsin et al. (2023) and the long-term CALCOFI data, there were 55 MCS events identified [see Fig. 2 from Dalsin et al. (2023) for interannual variability]. Of these 55 MCS events, 50 (~90.9%) had a positive upwelling anomaly (CUTIa) at the onset of the MCS event (Fig. 3). Given that the CUTI climatology was always positive over all days of the year (Fig. 3), a positive CUTIa represents stronger than normal upwelling, and thus MCS event initiation was linked with anomalously strong upwelling (see e.g., Dalsin et al., 2023). Furthermore, 20 of the 55 MCS events (~36.4%) had a minimum water temperature that was below the approximate hypoxic temperature threshold of 10 °C, with an average duration of 11.7 days and a standard deviation of 7.7 days. These compound MCS-hypoxic events primarily occurred during the major upwelling season from March to June. During this period, the seasonal upwelling (CUTI) climatology was already at its seasonal peak and the seasonal water temperature climatology was at its seasonal minimum, due to the strong upwelling of cold (and low DO) subthermocline waters (blue and black solids lines, respectively, in Fig. 3). Thus, a positive CUTIa during the onset of these MCS events during this period of climatologically strong upwelling signifies substantial upwelling strength. With this, there is a high propensity for the

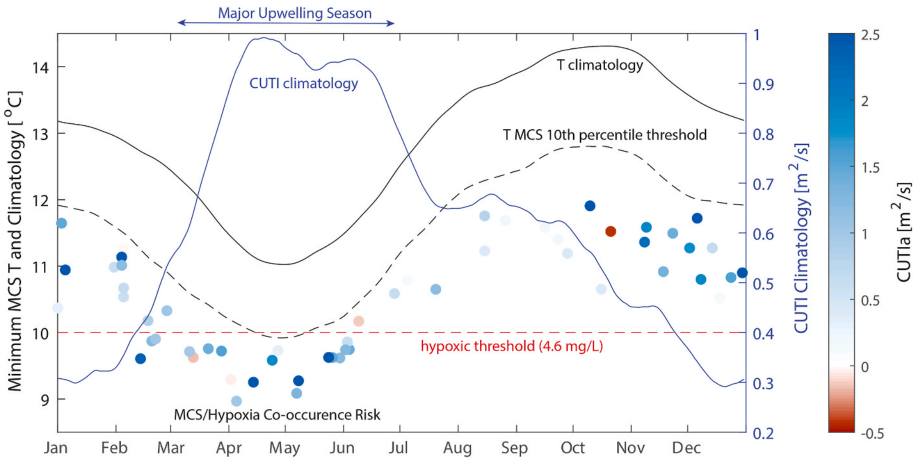

Fig. 3. (Left axis) Water temperature climatology (solid black), MCS 10th percentile threshold (dashed black), and minimum daily-averaged water temperature during a MCS event (solid circles) from Dalsin et al. (2023) (see black 'X' in Fig. 1b). (Right axis) CUTI climatology (solid blue) and CUTIa during a MCS event (color of solid circles). The major upwelling season (March to June, blue arrow on top), an approximate hypoxic threshold (dashed red line; 10 °C, corresponding to 4.6 mg/L, based on T-DO relationships in Fig. 1), and the region of MCS and hypoxia co-occurrence risk are highlighted.

advection of low DO subthermocline waters into the nearshore and compound MCS-hypoxic events.

4. Discussion and conclusions

We document, for the first time, a high-prevalence of compound MCS-hypoxic events (e.g., 20 of the 55 MCS events observed, ~36.4%) along a nearshore site in the California Current over the last three decades. The presence of multiple-stressor extreme events can have profound and dangerous implications for marine organisms and ecosystems, as evident in the growing literature on the co-occurrence of MHWs with poor water quality conditions (e.g., low DO and/or low pH) in marine systems (Boyd and Brown, 2015; Smale et al., 2019; Gruber et al., 2021; Tassone et al., 2022; Burger et al., 2022; Shunk et al., 2024). These compound MCS-hypoxic events predominantly occurred during the major spring and early summer upwelling season when the climatological upwelling index is strongest. Moreover, their initiation was linked with anomalously strong upwelling (positive CUTIa). Given that these events occurred during a period of already strong mean upwelling, compound MCS-hypoxic events were triggered during periods of extreme upwelling strength that drive the cross-shelf transport of cold (and low DO due to respiration at depth) subthermocline waters into the nearshore from the adjacent shelf (e.g., Dalsin et al., 2023). We note that local dynamics that drive small-scale spatial differences in nearshore DO concentrations [e.g., upwelling fronts and filaments, local biological modification during bloom events, etc. – see Walter et al. (2022)] may lead to small uncertainties when determining hypoxic events from a simple temperature cutoff based on long-term data; however, regardless of the exact hypoxic cutoff used (see Methods and Fig. 1), the methodology applied here still identifies relatively low DO events that could drive deleterious sublethal responses in nearshore organisms (Vaquer-Sunyer and Duarte, 2008). It is also likely that these events coincide with extreme lows in pH, given the large covariance between pH and DO in strong upwelling systems (Kroeker et al., 2023).

The California Current, like other EBUS, is a dynamic environment on the forefront of climate change [see recent review by Bograd et al. (2023)]. While global open-ocean trends suggest that MCS events will decrease in frequency and intensity due to climate change-driven warming [Schlegel et al. (2021); Wang et al., 2022a; but see also Chiswell (2022)], EBUS have more muted warming trends due to upwelling, and as such have been termed thermal refugia for cold water species (Seabra et al., 2019; Varela et al., 2021; Dalsin et al., 2023; García-Reyes et al., 2023). Indeed, Dalsin et al. (2023), the first known study to examine nearshore MCS events in an EBUS, found that there were no decreases in MCS frequency or intensity over the last four decades. While there is large uncertainty, projected declines of DO concentrations at depth along some EBUS like the California Current could actually increase the prevalence of compound coastal MCS-hypoxic events [see Bograd et al. (2023) and the references therein]. Perhaps most important to future compound MCS-hypoxic events are changes to wind-driven upwelling. Potential increases in upwelling (e.g., Bakun hypothesis), of which there are large site-specific uncertainties, could trigger more compound events, but this could be counteracted by increases in upper-ocean warming and subsequent increases in stratification and reduction of the mixed-layer depth (Bakun, 1990; García-Reyes et al., 2015; Rykaczewski et al., 2015; Bograd et al., 2023). It is also likely that future changes to basin-scale climate modes across the North Pacific will impact these compound events, as 90% of the events documented here occurred during either a negative Pacific Decadal Oscillation or negative Multivariate El-Niño Southern Oscillation Index (MEI) [see e.g., Figure 5 from Dalsin et al. (2023)]. For example, La Niña events (negative MEI) are predicted to increase in frequency and also persist for multiple years under future warming scenarios (Cai et al., 2015; Geng et al., 2023). Finally, a better understanding of how compound MCS-hypoxic events vary across different systems, particularly in the nearshore where local processes can significantly impact dynamics and generate microclimates, is needed. Regardless of future uncertainties, compound MCS-hypoxic events need to be considered in the context of global change biology and impacts to marine ecosystems.

CRediT authorship contribution statement

Ryan K. Walter: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Michael Dalsin:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Piero L.F. Mazzini:** Writing – review & editing, Funding acquisition, Conceptualization. **Cassia Pianca:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

R. Walter was supported by NSF OCE-2242164 and P. Mazzini by NSF OCE-2242166. M. Dalsin was supported by the William and Linda Frost Fund at Cal Poly and the Santa Rosa Creek Foundation at Cal Poly. We acknowledge John Steinbeck from Tenera and Pacific Gas & Electric for assistance acquiring the Diablo Canyon water temperature data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2024.108706.

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