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LETTER

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Harnessing marine microclimates for climate change adaptation and marine conservation

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Main Points

- Responses to climate change and large-scale forcing can vary widely at local scales creating marine microclimates.
- Microclimates are robust even under extreme large-scale forcing events (ENSO, climate change) potentially creating spatial refuges or 'safe spaces' for important species.
- Small/medium no-take zones, artificial reefs, and other possible spatial management can be placed to harness local variability as an adaptation or conservation measure in the face of climate change.

KEYWORDS
climate forcing, environmental variability, fisheries, local conservation, marine microclimates

Abstract

Climate change is warming, deoxygenating, and acidifying the ocean at an unprecedented rate. However, responses to large-scale forcing are variable at relatively small spatial scales, creating marine microclimates. Marine microclimates can provide spatial refuges (safe spaces) or local adaptation that may be harnessed to improve marine conservation and management. We analyze multiyear data sets within two fishing cooperatives in Baja California, Mexico, to quantify small-scale ocean variability, describe the degree to which this variability affects the abundance of species, and discuss the potential for marine microclimates to improve conservation and management efforts. We find that variation in ocean conditions and species abundances at scales of a few kilometers is striking and robust to large-scale climate forcing. We posit that incorporation of marine microclimates into fisheries management and conservation efforts can improve ecosystem sustainability by allowing local adaptation and maintenance of spatial refuges in the face of climate change.

1 | INTRODUCTION

Climate change is altering ocean conditions and increasing the frequency and severity of extreme events (Cavole et al., 2016; Sydeman, Santora, Thompson, Marinovic, & Lorenzo, 2013; Wang, Gouhier, Menge, & Ganguly, 2015). Increasing extreme events (hypoxia, heat waves, acidification) along with background environmental change portend a grim fate for marine ecosystems (Breitburg et al., 2018; Bruno et al., 2018; Hughes et al., 2018). However, climate-scale variability manifests differently in nearshore regions, creating marine microclimates that may provide a natural refuge from large-scale climate effects (Kwiatkowski & Orr, 2018; Safaie et al., 2018). Local alteration of large-scale climate responses can directly affect important coastal ecosystems (Boch et al., 2018). Marine microclimates may provide a key avenue for building adaptive capacity and enabling conservation in the face of global climate change (Cinner et al., 2018).

Generally, local management and conservation efforts are perceived to be futile in the face of larger scale climate change driven declines in ecosystem health and fisheries production (Boyce, Lewis, & Worm, 2010; Cheung et al., 2009; DeCarlo et al., 2017; Lotze & Worm, 2009; Pauly & Christensen, 1995). However, local oceanographic conditions and ecological outcomes can be dramatically different than the general predictions of climate change (O'Leary et al., 2017). Management should reflect the local manifestation of climate variability instead of responding to ubiquitous global forecasts and perceptions (Prince, 2003). Thus, it is important to identify marine microclimates so that they can be incorporated into local conservation and adaptation efforts.

In order to help understand how global climate variability manifests locally in the central Baja California region of México, we partnered with two fishing cooperatives and established a long-term collaborative program that included moorings with sensors for temperature, salinity, and dissolved oxygen around Isla Natividad (27.85°N, –115.17°W) and at El Rosario (29.86°N, –115.80°W) at the north end of Vizcaino Bay in 2013 (Figure 1). We quantified the abundance of kelp forest species through annual surveys at multiple sites to examine spatial and temporal patterns in ecologically and commercially important species. Here, we illustrate how local information on ocean environmental variability reveals the presence of marine microclimates at scales (a few kilometers) that can enable local conservation and adaptation efforts in the face of global climate change (Myers & Worm, 2003; Worm et al., 2009), thereby providing environmental data for informed local conservation and management decisions (Prince, 2003).

2 | METHODS

2.1 | Oceanographic data

Mooring sites were established on each side of Isla Natividad and Isla San Jerónimo (El Rosario) in approximately 15 m of water (Figure 1). Moorings recorded temperature, salinity, dissolved oxygen, and currents every 10 min over a 4-year period from 2013 to 2017. To assess patterns and responses of the nearshore ecosystems around Isla Natividad to global and regional scale climate variability, we compiled several large-scale data sets including satellite-derived sea surface temperature (SST), satellite-derived wind stress, and the Multivariate El Niño Southern Oscillation (ENSO) Index for the years 2006–2016 (Wolter & Timlin, 1998). We used standard time series techniques to examine differences between our three sites. Details of the in situ oceanographic monitoring, satellite and regional data used, and analyses are given in the Supplementary Material.

2.2 | Ecological data

Cooperative members, NGOs, and academic scientists perform ecological surveys at Isla Natividad following annual training (Micheli et al., 2012; Fulton et al., in press). The surveys are visual censuses of replicate 30 × 2 m transects (60 m^2) conducted on SCUBA between depths of 5 and 20 m in three control, fished sites, and two marine reserves (Figure 1) yearly (2006–2016) between late July and early August. A range of 11–30 transects are sampled per site every year (avg. = 20.8, total = 1,162 transects). Commercially and ecologically important fish species observed within a 2-m wide by 2-m high window along the 30-m benthic transect (120 m^3) are counted and sized. Numbers of mobile macroinvertebrates and kelp (numbers of plants and stipes, within each plant, of the giant kelp, *Macrocystis pyrifera* and the southern sea palm, *Eisenia arborea*) within the

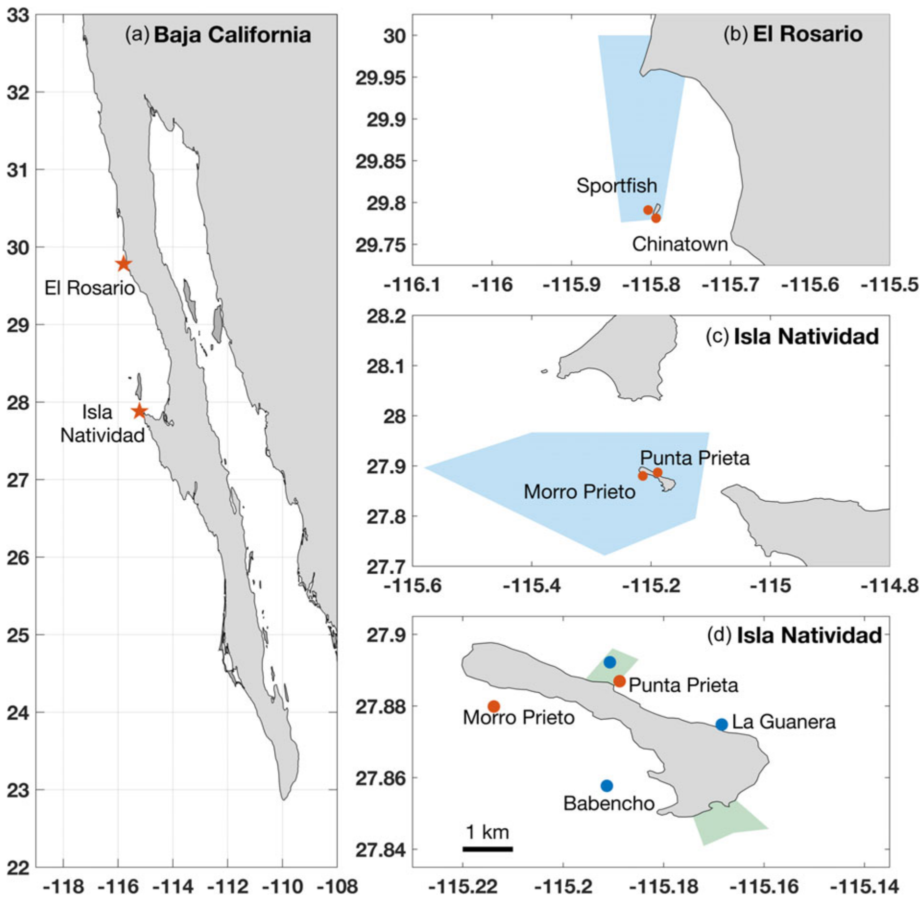

FIGURE 1 Fishing concessions and mooring locations in the Baja Vizcaino region. (a) Location of two participating cooperatives and concessions shown with mooring locations (red circles) and bathymetry (200 and 500 m depth contours). (b) El Rosario and (c) Buzos y Pescadores (Isla Natividad) with cooperative rights (blue shading) and bathymetry (20, 40, and 100 m depth contours). (d) Inset of Isla Natividad showing marine protected areas (green shading), mooring locations, survey locations (blue diamonds), and bathymetry (10, 20, and 40 m depth contours)

30 m × 2m belt transect are also enumerated and recorded. For this analysis, we focus on surveys from two sites, La Guanera (northeast, T_{avg} = 18.57 ± 2.64°C) and Babencho (southwest, T_{avg} = 15.83 ± 1.28°C). We chose these sites for several reasons: (a) Babencho is the closest to the Morro Prieto mooring, (b) the distance between the sites (2.6 km) is similar to the distance between mooring locations (2.4 km), and (c) temperature and oxygen variability during July (the period of reef surveys) at each reef site was comparable to the moorings on the respective side of the island (Punta Prieta, T_{avg} = 19.30 ± 2.41°C; Morro Prieto, T_{avg} = 16.08 ± 0.99°C).

We obtained mean biomass for algal species from the literature or web searches (Supporting Information Table 1). We computed the number and biomass of each fish species by calculating an average biomass from size (length) estimations from visual census and applying a length–width relationship obtained from FishBase (Supporting Information Table 2) (Froese & Pauly, 2017). For invertebrates, we used an average size derived from the literature (Supporting Information Table 2).

3 | RESULTS

High variability in ocean conditions occurs both across and within fishing concessions (Figure 2). Temperature variation at sites on the north and south ends of Vizcaino Bay (Chinatown–Isla San Jeronimo, Morro Prieto–Isla Natividad) separated by 220 km are more correlated (R^2 = 0.74, P < 0.001; Figure 2) than sites 2.4 km apart (Morro Prieto and Punta Prieta–Isla Natividad; R^2 = 0.49, P < 0.001) after removal of the seasonal signal. Similar to Morro Prieto, Chinatown, although buffered by the much smaller Isla San Jeronimo (~ 1 km across), within the fishing concession of Ensenada cooperative (El Rosario), is located within an upwelling center and oceanographic variability is largely related to regional wind-driven upwelling. Variations in salinity and dissolved oxygen follow similar patterns to temperature at regional scales.

Mean temperatures across Isla Natividad differ primarily during the upwelling season in this region (March–July) when Morro Prieto experiences the colder waters associated with active upwelling (Figure 2). Consequently, the mean annual

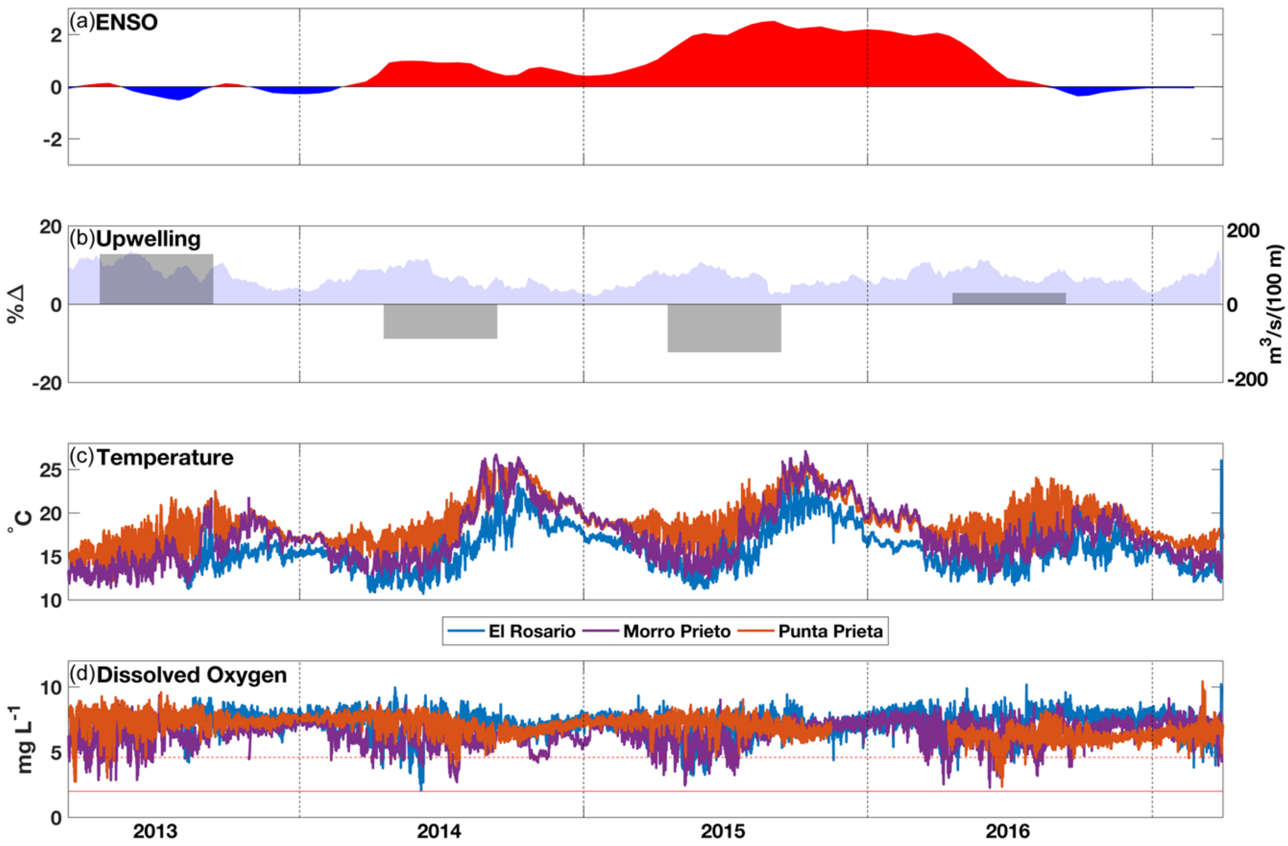

FIGURE 2 Time series of (a) ENSO index, (b) annual upwelling (wind stress) anomaly (grey bars) and upwelling index (blue), (c) temperature, and (d) dissolved oxygen at ~15 m depth from El Rosario, and Isla Natividad (Morro Prieto, Punta Prieta)

temperature change at Morro Prieto is around 12.2°C (12.4–24.6°C). In contrast, Punta Prieta, on the other side of the island (Figure 2), is not strongly affected by wind-driven upwelling due to the orientation of the coastline relative to the prevailing wind direction, and sees significantly warmer waters from Vizcaino Bay. Overall, Punta Prieta exhibits about 75% of the total annual temperature variability of Morro Prieto (mean = 9.4°C, range = 14.7–24.1°C). However, daily average differences across the island can be as much as 6°C, with discrete differences as high as 8°C.

Although Punta Prieta is generally warmer, it does not warm or cool as much as Morro Prieto, which sees both lower and higher extremes associated with large-scale forcing reflected in the higher variability at seasonal frequencies (Figure 3). At synoptic periods (scales of mesoscale variability and atmospheric weather patterns), both sites see similar magnitude in responses based on integrated variance over the synoptic band (Figure 3; Supporting Information Table 3). However, over diurnal and tidal band frequencies, the temperature at Punta Prieta is significantly more variable than Morro Prieto. Focusing on differences in environmental variability within the Isla Natividad concession, annual mean temperature differences across the island are not always significant (Figure 4). For example, in 2013 and 2014, Punta Prieta was on average 1.5°C warmer than Morro Prieto for the entire year. However, in 2015, during a strong ENSO event, the Punta Prieta side of the island was not significantly warmer, and still maintained high levels of diurnal and tidal variability, which could manifest as a refuge from extreme conditions (Boch et al., 2018).

Dissolved oxygen concentrations followed similar patterns with higher values at Punta Prieta on average during 2013 and 2014, but no significant differences during 2015. Morro Prieto experienced several low oxygen events that lasted for 1–3 days and coincided with bursts of intense upwelling. However, these events were not observed at Punta Prieta. Punta Prieta also experiences significant variability at semidiurnal and diurnal time scales with temperature and dissolved oxygen fluctuations as much as 4°C and 2 mg L^{-1}, respectively. In contrast, Morro Prieto has a relatively less variable environment over time periods of a few days based on integrated variance over diurnal and semidiurnal bands (Supporting Information Table 3).

High local variability in the marine environment exists across an island that is only 7 km long and averages 1 km width. The 4-year period of this study also captured an average, cool year (2014), and two anomalously warm years (2015–2016). It also captured a significant transition in global climate anomalies with a transition from cool ENSO conditions to the strongest El Niño (beginning in 2015) event

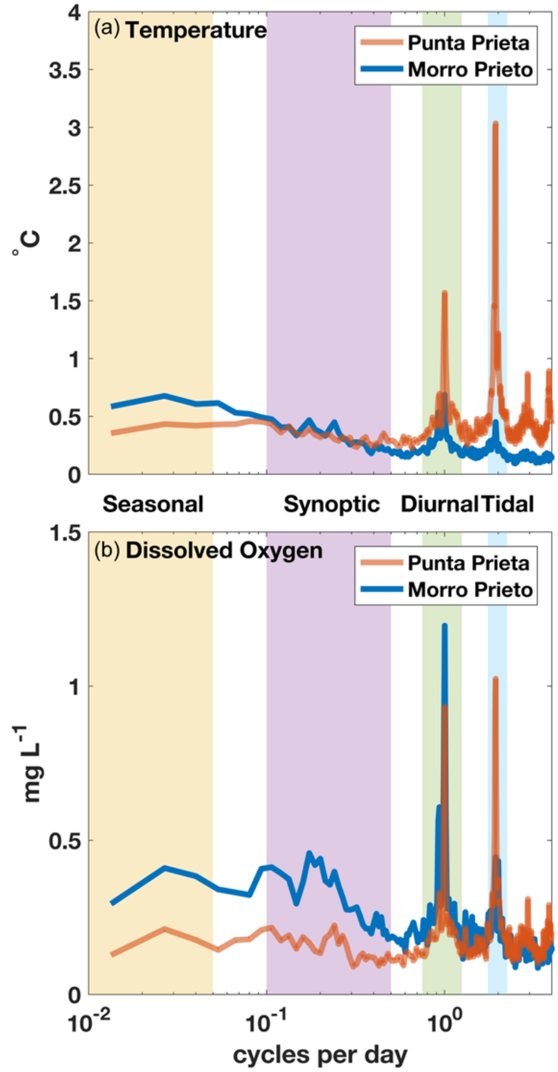

FIGURE 3 Variance spectra of (a) temperature and (b) dissolved oxygen across Isla Natividad. Variance-preserving and scaled spectra to show amount of variance (square-root for nonsquared units) in each period band (seasonal, synoptic weather, diurnal, and semidiurnal/tidal)

since 1997–1998, along with the North Pacific warm blob (Cavole et al., 2016). During this period, the southeast side of the island experienced more extreme annual temperatures with very little short time scale variation (Figures 2 and 3). That is, this coastal habitat has a relatively constant climate with long spells of extremely warm or cool waters (similar to a typical temperate weather pattern with prolonged cold winters and hot summers). In contrast, habitats on the northeast side of the island experience less extreme annual temperature variation and high short time scale variability (Figures 2 and 3). On this side of the island, the mean daily temperatures are more constant throughout the year, but with high diurnal and tidal variability. This variability may be attributed to internal waves—waves that travel along density interfaces in fluids that can have immense impacts on nearshore ecosystems (Woodson, 2018). Internal waves act to bring deep, cooler waters up into coastal areas such as kelp forest reefs (McPhee-Shaw et al., 2007). The tidal temperature and oxygen variability mediates the extreme temperatures so that organisms are not exposed to prolonged warm or cool periods, but instead are exposed to short (up to 6 hr) exposure to moderately warmer or cooler waters (more akin to a Mediterranean climate where temperatures are mostly rather pleasant, but highly variable from day to night).

Observed marine microclimates are coincident with pronounced differences in the reef communities across the island (Figure 5). Overall, algae, mobile invertebrates, and fishes are significantly more abundant on the northeast side of the island compared to the southwest (Figure 5). This pattern holds in spite of the expected higher nutrient flux associated with the strong upwelling that occurs on the southwest side of the island. In addition, patterns of abundance are strikingly different across the island for most species (Figure 5). Algal biomass was significantly greater on the northeast side of the island in 7 out of 11 years (2-sample t-test; $n = 41$ for all years; $P < 0.05$ in 7/11 years) with the pattern driven primarily by *M. pyrifera* (Figure 5). Invertebrate and fish biomass were significantly different in only 2 out of 11 years (2-sample t-test; $n = 48$ for all years; $P < 0.05$ in 2/10 years). However, abalone and lobster biomass were significantly different in 6 of 10 and 4 out of 10 years, respectively. Similarly, biomass of kelp bass and sheephead were significantly different in 5 of 11 and 4 of 11 years, respectively. Such differences illustrate the potential influence of marine microclimates on species abundances at relatively small spatial scales.

In response to large-scale climate drivers such as ENSO, temperatures at both sites are positively correlated with the multivariate ENSO index at a 3-month lag ($R^2 = 0.53$, $P = 0.01$ and $R^2 = 0.51$, $P = 0.006$ for the northeast and southwest sides, respectively) with overall mean monthly SSTs statistically similar during strong positive ENSO anomalies. However, the northeast side of Natividad island maintains high diurnal and tidal variability, indicating that temperatures fluctuate between extreme highs and lows every 12–24 hr. These fluctuations are reflected in the overall depth-averaged, daily water temperatures that are lower on the northeast side of the island than on the typically cooler southwest (upwelling) side of the island. Thus, in response to large-scale forcing from positive anomalies of ENSO events, sessile invertebrates on the southwest side of the island may be relatively more sensitive to environmental stressors than those on the northeast side of the island (Boch et al., 2018). The northeast side of the island, therefore, may provide a spatial refuge from extreme warming and low oxygen events even at the scale of this small island. We observed similar marine microclimates around the even smaller Isla San Geronimo in the El Rosario cooperative (Figures 1 and 6), suggesting that marine microclimates may be a common feature of the coastal ocean.

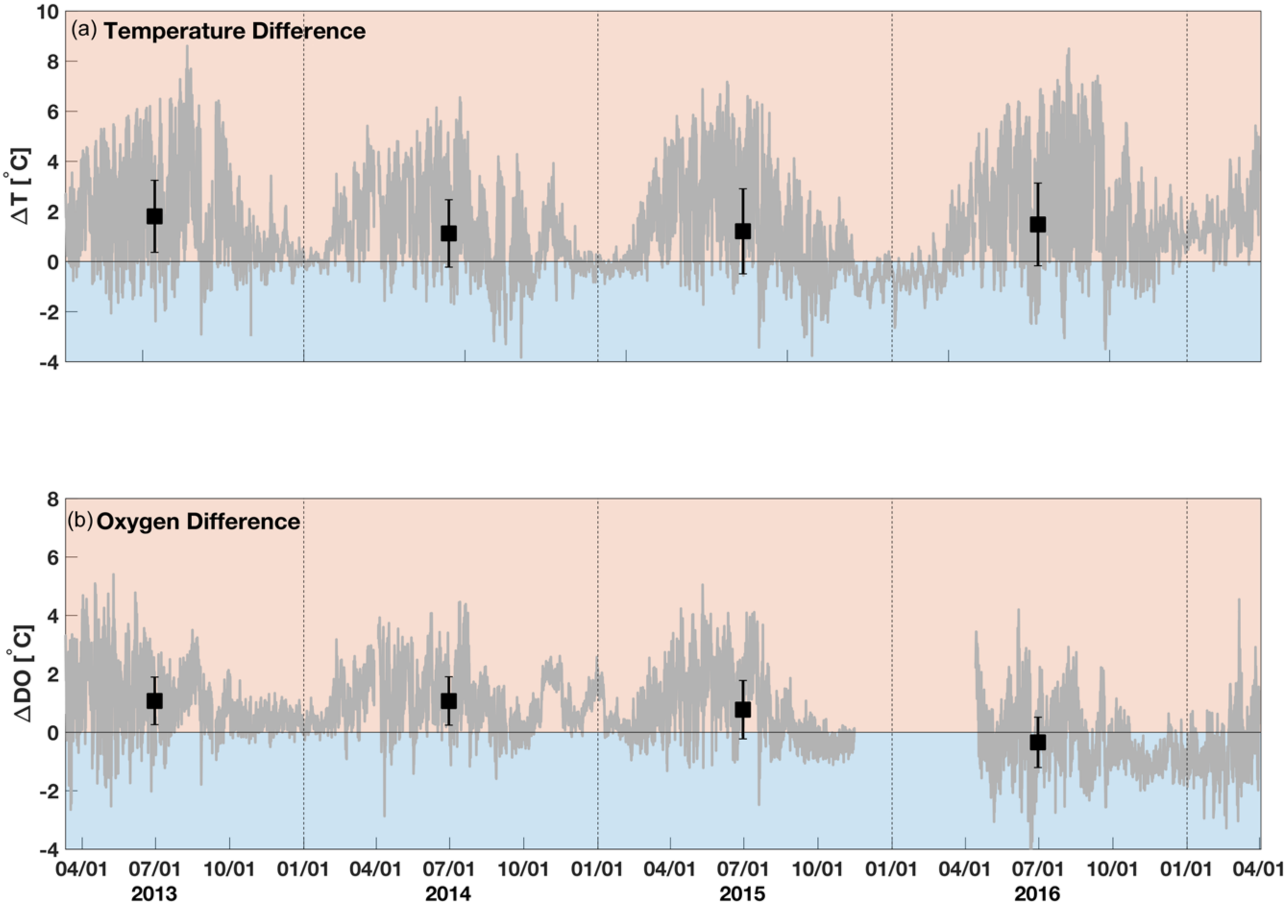

FIGURE 4 Differences in (a) temperature and (b) dissolved oxygen across Isla Natividad. Positive values (red shading) indicate higher values on northeast side of island. Black squares indicate mean daily difference with standard deviations

4 | DISCUSSION

Coastal species often exhibit variation in performance associated with large-scale climate variability (Boyce et al., 2010; Cheung et al., 2009; DeCarlo et al., 2017; Lotze & Worm, 2009; Pauly & Christensen, 1995); however, marine microclimates that allow these species to adapt to future conditions (Boch et al., 2018; Safaie et al., 2018) may also exist. Our results suggest environmental variation at the scale of kilometers could provide refuges from climate stressors, and other recent studies have demonstrated similar variation and reduced coral bleaching at scales as little as 10s of meters (Safaie et al., 2018). Small-scale variation in environmental conditions has the potential to provide spatial and temporal refuges for marine animals, and opportunities for conservation and adaptation to long-term climate trends.

Many marine species are resilient to short-term heating and hypoxia exposure, but not to longer period extremes (Kim, Barry, & Micheli, 2013; Somero et al., 2016). Mobile species, such as many finfish and lobsters, could thus take advantage of these microclimates to reduce exposure to harsh conditions. For sessile or sedentary species, such as abalone and sea urchins, microclimates may determine fine-scale distribution patterns. Conservation and management plans can harness marine microclimates, particularly for sedentary species. For example, the northeast coast of Isla Natividad may provide a refuge from extreme heat waves. By not fishing this region during strong El Nino conditions, populations may be more resilient and recover more quickly following large-scale disturbances.

We can use observed responses of the nearshore environment to large-scale climate variability such as ENSO to make predictions about the spatial variability of climate change within fishing cooperative spatial concessions. For example, with projections for a +2°C increase in global atmospheric temperatures by 2100, we can expect all waters around Isla Natividad to warm. However, the northeast side of the island may still experience high short-term variability, based on our observations. As climate variability increases (e.g., more intense and frequent ENSO events), we may expect the southwest side of the island to experience longer, more intense periods of anomalously cold or warm waters, while the northeast side will likely only see a gradual warming associated with general climate trends.

Interestingly, the small-scale variability around the island also points to differential responses of the ecosystems to

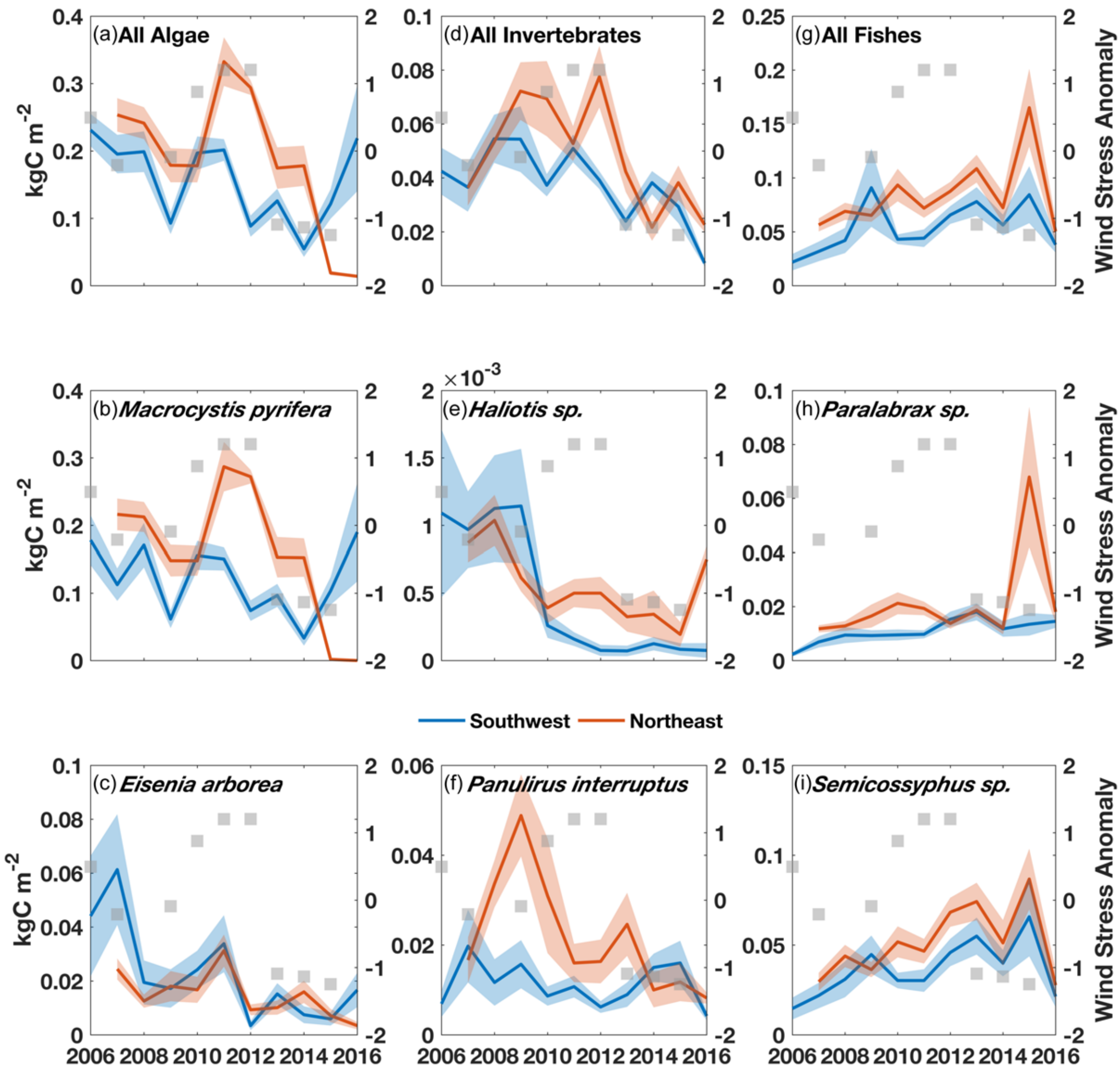

FIGURE 5 Time series of (a) all algae, (b) giant kelp (*Macrocystis pyrifera*), (c) *Eisenia arborea*, (d) all invertebrates, (e) abalones (*Haliotis spp.*), (f) red spiny lobster (*Panulirus interruptus*), (g) all fishes, (h) kelp and barred sand bass (*Paralabrax spp.*), and (I) California sheephead (*Semicossyphus pulcher*) across Isla Natividad (blue—southwest, red—northeast). Grey squares indicate the annual cumulative wind stress as a measure of upwelling (nutrient supply). Shading shows 95% confidence intervals and nonoverlap indicates significant differences in abundance between sites for that year

climate change. Historically, the southwest (upwelling) side of the island was more productive for abalone. However, since the recent die-offs (Micheli et al., 2012), abalone are now more abundant on the northeast side of the island (Figure 5). We may expect to see small-scale spatial shifts in ecosystem structure and function that are reflected in changes in the distribution of catch for commercially important species (Cavole et al., 2016; Kroeker, Micheli, Gambi, & Martz, 2011; Somero et al., 2016). These changes provide a glimmer of hope for conservation efforts where climate change is often perceived as a problem that acts on scales larger than those to which these communities can respond (Cinner et al., 2012; Defeo et al., 2013). In the presence of marine microclimates, a series of small permanent or rotating no-take reserves may provide a greater benefit than a few larger permanent protected zones. Such reserves could also be species-specific, allowing communities to harvest particular species to provide economic stability while ensuring long-term conservation.

Local variability can also be incorporated in climate adaptation and conservation efforts. Cost effective and scalable coastal oceanographic observing systems providing information on local physical variability to local communities are key to enable them to harness variability for more effective local management. Moreover, areas that provide consistent refuges from environmental extremes under different

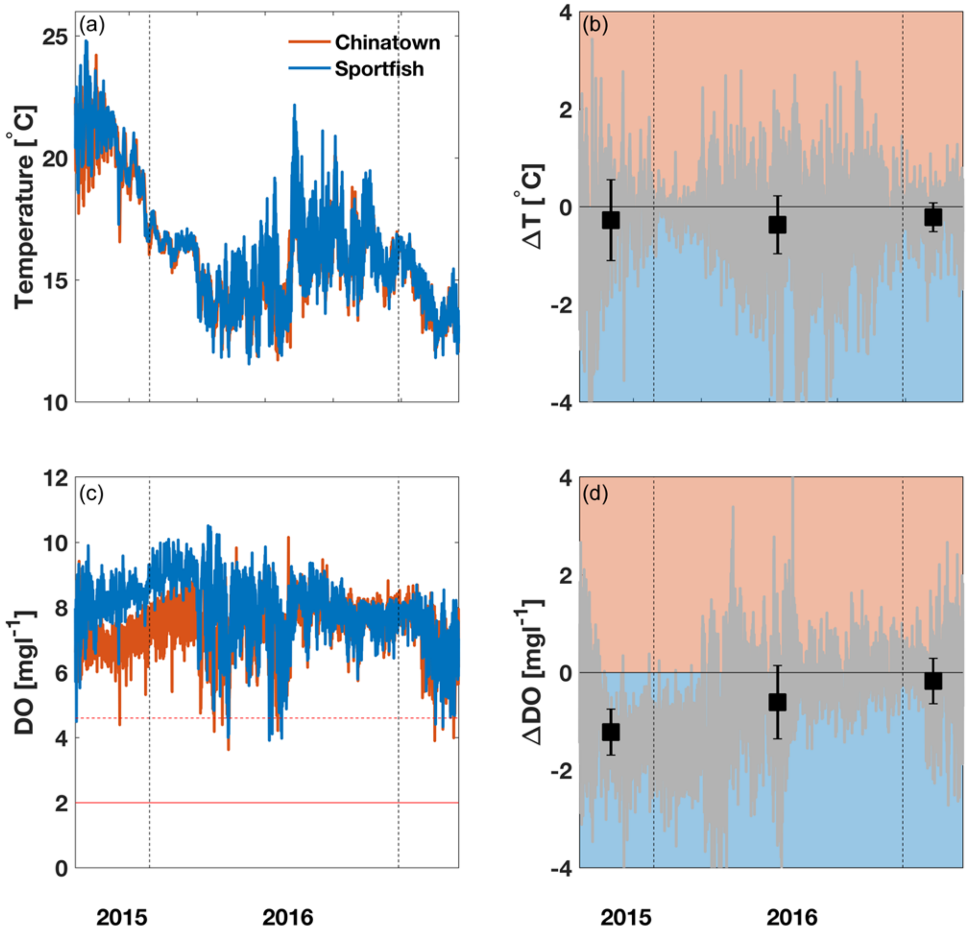

FIGURE 6 Comparison of sites across Isla San Jeronimo in the El Rosario concession. Sites are approximately 1 km apart on opposite sides of island. (a) Temperature, (b) temperature difference (ΔT), (c) dissolved oxygen, and (d) dissolved oxygen difference (ΔDO)

large-scale oceanographic regimes (Boch et al., 2018; Safaie et al., 2018) provide opportunities for restoration efforts and marine protected areas, and for supporting alternatives to wild capture fisheries for local communities (Cinner et al., 2018)—for example, by providing suitable conditions for artificial reefs, enhancement of exploited populations via juvenile outplants, and locally-owned mariculture operations. Identifying such refuges has the potential to support local adaptation to climate change and enhance marine conservation (Cinner et al., 2018).

Marine microclimates can provide spatial refuges for many species and are not currently considered in marine conservation efforts (marine protected area design). Marine protected areas that incorporate local scale variability can provide a mechanism for climate adaptation in spite of large-scale forecasts (Bruno et al., 2018). Harnessing small-scale variability in environmental conditions could provide a means of adapting to climate change similar to how microclimates have been suggested as adaptations in land-based agriculture (Lin, 2007; Smith & Olesen, 2010). Conservation and adaptation to climate change must be a collaborative effort among fishers, NGOs, the government, and scientists. Multistakeholder collaboration facilitates understanding of complex processes operating at different scales and promotes transparency and informed decision making, which will ultimately improve fisheries management and conservation efforts globally.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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