# Integrated ocean observing systems for assessing marine protected areas across California

**Authors**

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CENTRAL & NORTHERN CALIFORNIA OCEAN OBSERVING SYSTEM

SOUTHERN CALIFORNIA COASTAL OCEAN OBSERVING SYSTEM

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# i. Table of Contents

## ii. Executive Summary

Spatial and temporal variability in California's marine ecosystems occurs both from natural environmental variation and from human pressures including fisheries. These variations span many scales from large ocean basin scales such as the El Niño - Southern Oscillation, with major year-to year or even decadal scale shifts, to localized variations in ocean weather including the upwelling of cool, nutrient rich water occurring at the scale of km or more. This range of variation in space and time presents challenges when looking to interpret ecosystem changes in relation to management actions, including the implementation of marine protected areas (MPAs). For example, *How can changes in MPA condition be attributed to MPA management and/or other phenomena such as regional climate change?* Moreover, such management assessments require an integrative approach to data, including standardization, processing, analysis, and visualization of data from a diversity of sources. Some of these data processes are time-consuming and complex, especially for diverse environmental habitat and indicator data. *How can data from various investigators, locations, habitats, and methods be integrated to produce robust assessments of change in key indicators that are useful for MPA management?* Contemporary ocean observing systems are working to overcome these challenges in part by providing information across a wide range of scales and a broad array of variables. This includes streamlining data management and building cyberinfrastructures that allow for more timely and repeatable analysis.

Here we have used the Integrated Ocean Observing System (IOOS) framework to develop and tailor curated collections of MPA-relevant datasets and data visualization and exploration tools. These tools are supported by replicable and documented data streams and processes, allowing MPA researchers and managers to address these challenges and thereby improve their ability to attribute observed changes to natural and/or human drivers. Our work covered five scales that have been identified as being key to understanding MPA change: Basin/Quasi-Global, Large Marine Ecosystem, Region/Sub-ecosystem, Mesoscale (10s – 100s km; eddies, fronts), and Local (MPA; larval retention zones; e.g., Taylor 2007). We worked across four key objectives:

1. **Utilize large-scale satellite data and models to develop regularly updating curated data views and products.** Data was produced for all MPAs where possible and hundreds of study stations, as well as for California bioregions, and visualized in an online dashboard (mpa-dashboard.caloos.org).
2. **Utilize fine scale models nested in larger-scale simulations for MPA connectivity -** Nested models with ~800 m and ~160 m resolution have produced outputs since March 2020, producing a daily 'nowcast.'
3. **Format and assemble data from California's MPA Monitoring Program and other relevant sources for inclusion in the multi-scale curated data views** - *Multi-Agency Rocky Intertidal Network (MARINe), the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO), Reef Check California (RCCA), and the California Collaborative Fisheries Research Program (CCFRP) are in the California MPA Dashboard with others to follow.*
4. **Evaluate an emerging suite of multivariate, multi-stressor assessments -** Derivatives of Seascapes (see example summary figure on the following page), the California Harmful Algae Risk Mapping (C-HARM) and EcoCast for MPAs are available.

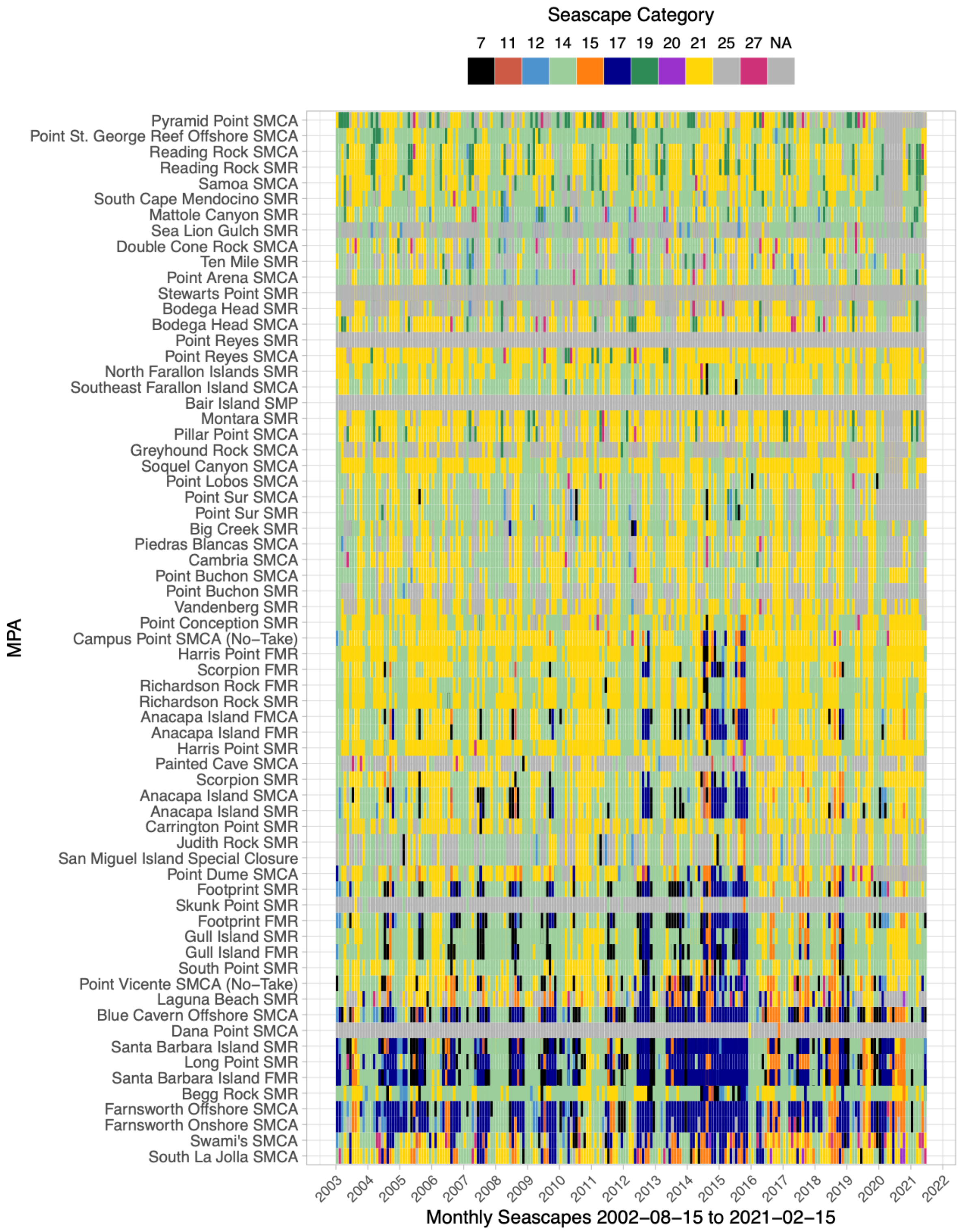
Additionally, we used these data in integrated assessments to evaluate natural and larger scale variation in relation to changes at specific MPAs. This included identifying which MPAs may have variation that is dissimilar to the bioregion in which it is located. We have also analyzed outputs from an ensemble of climate change model projections to 2099 to understand expected future change across MPAs and bioregions. *Key outputs, impacts, and accomplishments are summarized below*.

**Streamlined access to MPA data in integrated formats for expert assessments** - Assembling and using easily accessible and robust datasets for MPA assessment by many independent teams is time consuming and adds risk of incompatibility in later analysis and results. We developed and documented replicable data processing code and metadata through a central cloud-based project management and data analysis platform that can be run regularly to extract and format data for onward use. Integrated data with common time and space formatting are publicly available through DataONE and California IOOS data systems at weekly and monthly timescales wherever available. These can be updated on a regular basis. Researchers, managers, and others can thereby use common sets of up-to-date information for understanding and assessment.

**Streamlined access to MPA data via the *California MPA Dashboard*** - Identifying and processing datasets that are relevant to MPA assessments is time consuming and may lead to less efficient use of available data in MPA assessments and research by different research and management groups. We developed a California MPA Dashboard application that provides easy access and visualizations of multiple integrated MPA-targeted datasets and data digests that are relevant to research and assessment interests highlighted in the MPA action plan and working group reports. Relevant data can be easily explored and visualized through a public website interface. Datasets of interest can either be downloaded directly from the MPA Dashboard, or users can identify the data source from the MPA Dashboard and obtain data for further analysis. Researchers, managers, and other stakeholders can easily locate and explore data relevant to MPA assessments and research questions.

**Improved realism and timeliness of MPA connectivity data -** Modeling connectivity of organisms by ocean currents between MPA regions and between MPA and non-MPA regions provides quantitative information concerning how MPA regions function as a network beyond the sum of their parts. We statistically analyzed realistic virtual larval or propagule transport trajectories generated from state-of-the-science ocean circulation models coupled to larval transport models including different types of organismal behavior and durations. During the year and a half of trajectories analyzed, all MPAs studied showed connectivity with amplitudes that varied with pelagic larval duration, time of year released, and organismal behavior. Some MPAs experienced generally greater transport to and from multiple other MPAs, and spillover from MPAs to nearshore zones also resulted from ocean circulation. MPA locations within the greater Monterey Bay area were sufficiently spaced that protected regions experienced larval exchange dependent on pelagic larval duration, time of release, and larval behavior.

**Detailed estimates of ecosystem-level variation across bioregions and MPAs -** Understanding the connections between ocean conditions, biodiversity, and indicator species variation can aid our understanding of marine ecosystem dynamics and inform adaptive management strategies. We used remotely-sensed physical, chemical, and biological data to characterize the ocean conditions, or "Dynamic Seascapes", of marine and coastal waters at the landscape scale. Overall, California's marine bioregions experience similar ocean conditions, but the South Coast and Channel Islands bioregions experience a more diverse set of Seascape conditions on an overall and annual basis. Aberrant ocean conditions were also detected using Seascape classifications, including the 2015 marine heat wave ("The Blob"), which extended from Southern California MPAs north to Campus Point SMCA. These findings show that Seascape state-space classifications can be summarized at the spatial scales of MPAs, and provide wider- and longer-scale estimates of variability among California's marine waters.

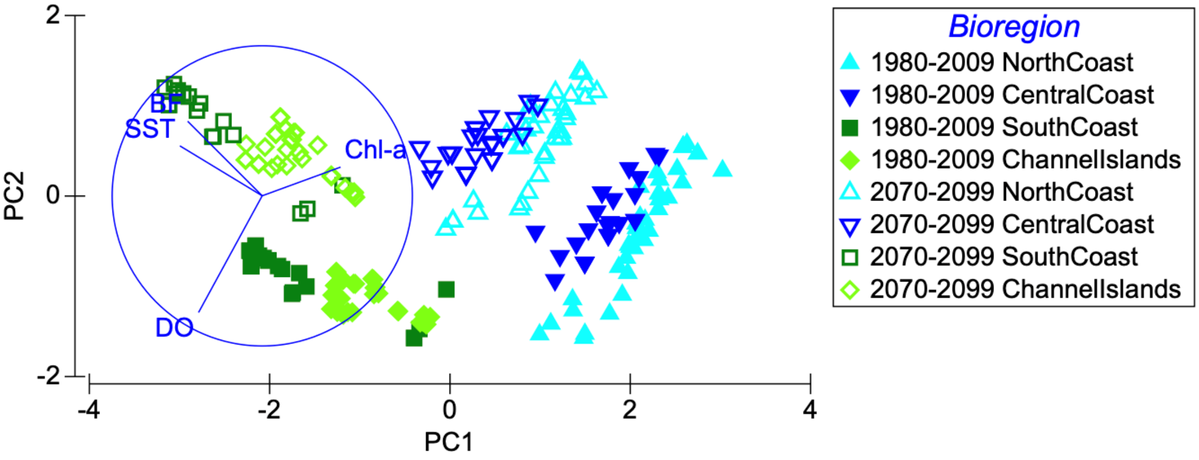


*Contemporary Seascape change at MPAs and through the network* - This figure highlights changes in Seascape composition from 2003-2021 for the California MPA network. Seascapes provide a categorized summary indicator of oceanographic conditions and their change in space and time. Each Seascape represents a unique combination of conditions (NA indicates no data available). Changes related to warming periods, particularly in 2015/16, can be observed across much of the MPA network.

**Detailed estimates of harmful algal bloom risk for California bioregions and MPAs -** Using high frequency nowcasts of harmful algal bloom (HAB) data from the California-Harmful Algae Risk Mapping (C-HARM) model and the EcoCast species distribution models, we show spatial and temporal patterns of HAB risk in MPA regions, and risk for vulnerable species to HAB impacts. C-HARM temporal patterns from 2018-2021 show that the risk of high probability of cellular domoic acid, particulate domoic acid, and *Pseudo-nitzschia* spp. blooms was already high in all bioregions and increased across all bioregions. The EcoCast and C-HARM risk maps suggest the potential increase in frequency, persistence and spatial extent of HABs over recent years and that these areas coincide with ecologically important migrating species, posing a risk of these species suffering adverse effects due to domoic acid and HABs.

**Integrated multi-scale assessments of variation and change over the past two decades** - The spatial and temporal evolution of the warming event in 2015 was the most prominent interannual signal in climate and Seascapes variation observed during the period 2003 to 2021. However, the unusual conditions that dominated that period, even into 2018, have since dissipated. This is evident in time series of the California Multivariate Ocean Climate Indicator (MOCI), Seascapes ocean habitat classifications and other ocean climate indicators. For example, the MOCI index was negative for much of 2011 to 2013 and was negative again in late 2020 across the state. While the over the last decade have been variable, long-term, multi-decadal changes associated with climate change are becoming clearer, such as with kelp loss, new records in ocean temperatures and ongoing ocean acidification.

**Detailed estimates of climate change risk for California bioregions and MPAs** - To understand the role that MPAs may play in supporting ecosystem resilience and providing societal benefits in the face of climate change, it is necessary to understand how key environmental variables are projected to change in California's state waters and in MPAs. We extracted summaries of projected change in key oceanographic variables from the downscaled climate regional ocean modeling system (ROMS) model for MPAs and bioregions from past (1980-2009) to future (2070-2099) conditions and identified areas of least change as potential 'climate refugia'. California MPAs protected higher percentages of potential 'climate refugia' from 1980-2099 compared to overall state waters, but refugia were often not spatially persistent. Some visualizations of these analyses are available in the California MPA Dashboard.



*Contemporary conditions to future change* - This figure shows the projected multivariate change in California MPAs across four different bioregions, from past (1980-2009; solid points) to future (2070-2099; open points) based on a principal components analysis of output variables from downscaled climate ROMS models. Distances between points indicate differences in environmental conditions, as summarized by the first two principal components (PC1 and PC2). Vectors (blue lines) indicate axes where change in each variable most aligns with the overall pattern.

# 1. Introduction

Marine protected areas (MPAs) face many pressures, from resource use including fisheries to climate variations and long-term change. These factors operate from local to global spatial scales over daily to decadal timescales. This wide range of variance in space and time presents serious challenges to understanding how ocean weather, climate, MPA management practices and other factors converge to shape conditions and ecological responses in MPAs. Given the range of possible influences and their scales, there is risk of interacting factors becoming indistinguishable without sufficient context (e.g., aliasing). In addition to issues with measuring such phenomena, big challenges remain in improving the timeliness and reproducibility of assessments. Two key questions arise: *How can changes in MPA condition be attributed to MPA management and/or other phenomena such as regional climate change? How can data from various investigators, locations, habitats and methods be integrated to produce robust assessments of change in key indicators that are useful for MPA management?*

A primary motivation for creating networks of high-resolution observing systems sustained over time is to understand ecosystem-level change that occurs over a wide range of scales (e.g., Taylor 2007, Ruhl et al. 2011). Management of living resources has evolved a holistic and integrated approach (e.g., Harvey et al. 2019). There are myriad connections between climate, weather, and wind-driven upwelling of ocean waters and changes in nutrient availability for primary productivity, transfers of primary productivity to various food web components including zooplankton and forage fishes, and ultimately to top predators including marine mammals and fish (e.g., Hazen et al. 2019, Ryan et al. 2019). An example of how anomalous conditions can have pervasive ecosystem impacts occurred recently with warming of a large area of the northeast Pacific including what is known as the 'Warm Blob' from ~2014-2016, with lingering signals in later years. Such large-scale phenomena can ultimately relate to important marine ecosystem changes at the coast and local areas (Barth et al. 2018). Here we provide data and tools that can bridge understanding among these mechanisms and their implied temporal and spatial scales, linking atmospheric, oceanographic and ecological habitat focused data.

This project has run in the context of the US Integrated Ocean Observing System (IOOS) and its affiliate organizations including the Global Ocean Observing System (GOOS), the Ocean Biological Information System (OBIS), and the Marine Biodiversity Observation Network (MBON, Muller-Karger et al. 2018, Benson et al. 2021). The two California Regional Associations of IOOS are the Central and Northern California Ocean Observing System (CeNCOOS), which extends from the Oregon border to Pt. Conception CA, and the Southern California Coastal Ocean Observing System (SCCOOS) that spans from Morro Bay to the Mexico border. CeNCOOS and SCCOOS have built a foundation based on the best available science and collaborative partnerships. These systems provide near-continuous coverage of surface currents along the coast from high-frequency radar (HFR) stations, oceanographic section data from six continuous glider line transects, and hundreds of other data products (i.e., data layers) from more than two dozen shore stations and moorings, all of which are now available in a new *California Ocean Observing Data Portal* (data.caloos.org). Model-assimilated observations underpin high-quality ocean and atmosphere forecasts, nowcasts, and hindcasts, all of which serve as a record for understanding the causes and consequences of natural and anthropogenic change. These efforts also include a federally accredited data and cyberinfrastructure capability that streamlines access to information and analytics for applied uses and research. For example, CeNCOOS supplies data to underpin the California Current Integrated Ecosystem Assessment and Monterey Bay National Marine Sanctuary Condition Reports (Ruhl et al. 2021).

**Project Goals and Objectives** – Our project used the Integrated Ocean Observing System (IOOS) framework to develop curated collections of datasets and model outputs that incorporate information from ocean physics, ocean biogeochemistry, and long-term ecological monitoring at spatial and temporal scales relevant to MPAs, and referenced to climatic conditions. These curated datasets integrate data from numerous sources into a virtual *California MPA Dashboard* of conditions, which enables users to create customized data visualizations to support MPA assessment from regional to statewide scales. The curated datasets also allow for integrated assessments of environmental conditions in MPAs and California state waters, which support analysis of MPA network performance. Our work bridges the five conceptual scales that have been suggested as being important when considering change in MPAs: Basin/Quasi-Global, Large Marine Ecosystem, Region/Sub-ecosystem, Mesoscale (10s – 100s km; eddies, fronts), and Local (at the MPA; retention zones, etc.; e.g., Taylor 2007). Our project scope originally included three in-person meetings with other California MPA Monitoring Program researchers and program managers to facilitate data integration, curated data view specification and development feedback, connectivity assessment and ecological indicator development. While we were able to hold the first meeting in January 2020 (Milestone 1), the remaining engagement was managed through a series of smaller virtual meetings (Milestones 2 and 3). We worked across four key objectives (see Appendix A1 for a complete list of proposed milestones and deliverables):

1. **Utilize large-scale satellite data and models to develop regularly updating curated data views and products that quantify relationships between large-scale phenomena, features and variations, and conditions at 24 spatial areas of integration including select Tier 1 and 2 MPA locations across the state (*Section 2. Data Standardization, Curation, Integration, and Visualization with the California MPA Dashboard*).** This objective evolved to provide visualizations and access to curated datasets for a more complete selection of MPAs via the *California MPA Dashboard* (**Deliverable 2**). Ultimately this included all MPAs with varying levels of data availability depending on when specific observation, sampling, satellite, or modeling efforts started. The size and shape of MPAs, locations closer to greater areas of land such as in estuaries, and propensity for cloudiness also limited the times and places where we have robust time series.
2. **Utilize fine-scale models nested in larger-scale simulations to develop regularly updating information products that quantify changing conditions, including MPA connectivity, at finer scales, and integrate results into our products and our multi-scale curated data views (*Section 3. High-Resolution Circulation and Connectivity Modeling*).** The establishment of the data assimilative West Coast Operational (Ocean) Forecast System (WCOFS) has enabled us to create a two-tiered nested model with ~800 m and ~160 m resolution focused on the central coast and Monterey Bay respectively. Outputs include data since March 2020, producing a daily 'nowcast' of conditions including connectivity between different coastal areas, including all MPAs within the model domain. The particle tracking data are available through a publicly accessible server (**Deliverable 4**) which is now running and updating routinely (**Deliverable 5**). These data can be considered in the context of specific cases of biologically-relevant modes of dispersal (e.g., behavior, pelagic larval duration) for eggs, larvae, zoospores, and other propagules. Customizable visualizations of connectivity for a wide range of these dispersal modes are included in the California MPA Dashboard (**Deliverable 6**). This effort included delivery of recommendations on particle tracking/connectivity data needs and capabilities, and a plan to achieve high-resolution particle tracking for the historical data period, e.g., 2011 to present (**Deliverable 1**).
3. **Work with representatives from the California MPA Monitoring Program habitat expert teams, the Ocean Protection Council, and the California Department of Fish and Wildlife to format and assemble long-term ecological monitoring data from MPAs and reference regions for inclusion in the multi-scale curated data views (Objective 1), including data for key**

**performance measures and metrics (*Section 2. Data Standardization, Curation, Integration, and Visualization with the California MPA Dashboard*).** This work has so far included major data inputs from the Multi-Agency Rocky Intertidal Network (MARINe, e.g., Moritsch and Raimondi 2018), the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) covering kelp and shallow rocky areas (Hamilton et al. 2010, Young et al. 2015), Reef Check California (RCCA) covering kelp and shallow rock areas and areas of mid-depth rock and soft bottom subtidal habitat, and the California Collaborative Fisheries Research Program (CCFRP) including nearshore pelagic habitats. Data are still becoming available from some habitat teams including those working in estuary, sandy beach, and mid-depth rock and soft bottom subtidal habitats and therefore this work is ongoing (see Table A3-1). Getting these ecological monitoring data verified, quality-checked, and formatted into machine-readable forms that are compliant with data standards allows for effective and replicable data processing, analysis, archival, access, and visualization for current and future assessments, including integration into the California MPA Dashboard and ingestion into global databases such as the Ocean Biodiversity Information System (OBIS) and the Global Biodiversity Information Facility (GBIF). Datasets through 2019 were included in the first iteration of the MPA dashboard in 2020, and updated data from 2020 were incorporated in late 2021 (**Deliverables 7 and 9**). It is by integrated analysis of these data, along with MPA-specific digests of satellite and model data (Objective 1) and MPA connectivity data (Objective 2), that the California MPA Monitoring Program will be able to address many of the key research, monitoring, and management questions. We will continue to update our data holdings and tools as additional data become available from other projects. Some of these are addressed here, while others will need additional analysis as part of the MPA Decadal Management Review.

4. **Work with representatives from the California MPA Monitoring Program habitat expert teams to evaluate an emerging suite of operational, ecological models that can be synthesized into a multivariate, multi-stressor description of regional ecosystem state and then integrated with ecological monitoring data and indices to produce statewide quantitative, indicator-based assessments (*Section 4. Ecological Indicators for Seascapes and Harmful Algal Bloom Risk in MPAs*).** This has included examination of Seascapes classification of remote sensing data, the California Harmful Algae Risk Mapping (C-HARM) assessment of harmful algal bloom (HAB) risk with *Pseudo-nitzschia*, cellular domoic acid, and particular domoic acid probability, as well as EcoCast predictions of where vulnerable species occur relative to HAB risk (**Deliverable 10**). These data provide additional insight into ecological conditions along the coast for interpreting change in MPAs and reference areas alike. For example, time series of Seacapes classifications for MPAs and bioregions provides insight into the variation in the availability of oceanic habitat conditions.

Our project also expanded in scope by including assessment of climate change risk for MPAs and bioregions. This was made possible by the new availability of a set of downscaled climate change model estimates extending out to 2099 using so-called ‘business as usual’ projections (Pozo Buil et al. 2021).

Together these objectives enabled us to conduct integrated assessments of change across scales and into the future (*Section 5. Integrated Assessment of Environmental Variation in MPAs* and *Section 6. Integrated Assessment of Projected Climate Change Risk in MPAs*). This work marks major advancements in the ways in which MPA analytical workflows are developed, documented, and managed, and supports higher quality assessments being delivered more efficiently now and into the future. This includes the assessments addressing the MPA Monitoring Action Plan goals, with emphasis on providing data to understand the context of change across a wide range of scales including for habitat monitoring project data that also includes diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems. Along with other program teams, we quantified the environmental and water quality context of change in marine life populations, including fisheries of economic value, thus providing information for possible rebuilding of stocks that are depleted. The data provided is bringing understanding of how long-term change might influence perceptions of what constitutes baseline conditions (e.g., potential shifting baselines). This information helps evaluate if MPAs are achieving objectives in the context of climate variability and secular change. This enables assessments at the scale of individual MPAs, the north, central, and south coast bioregions, with the Channel Islands assessed independently, and the degree to which individual MPAs may be experiencing similar conditions to the bioregions in which they are located. Below we describe our methods for addressing the above objectives, our detailed research questions and analytical approaches, results from these activities to date and discussion placing these results in the context of the Marine Life Protection Act and MPA Action Plan goals and questions.

# 2. Data Standardization, Curation, Integration, and Visualization with the California MPA Dashboard (Objectives 1 and 3)

## 2.1 Summary

- The California MPA Dashboard enables managers, researchers, and stakeholders to explore and visualize a curated collection of MPA-relevant oceanographic, climatological, and ecological datasets, as well as outputs from ecological, climate, and circulation models.
- To curate these datasets, we developed replicable and documented data processing and metadata scripts on a central cloud-based project management and data analysis platform. This includes extraction and summarization of large oceanographic and climatological datasets to MPA scales, as well as data verification, quality checking, and standardization of ecological monitoring datasets for effective use in current and future analyses and assessments. These curated datasets are visualized in the MPA Dashboard and made available through DataONE and other use points.
- MPA Dashboard tools include datasets and visualizations that facilitate research and assessments addressing MPA Action Plan questions associated with MLPA Goals 1, 2, 4, and 6, as well as additional priority research questions from the Ocean Protection Council - Science Advisory Team's report on Climate Resilience in California's MPAs.

## 2.2 Data Integration and California MPA Dashboard Objectives

The California MPA Dashboard was developed out of the original proposal objective to "utilize large-scale satellite data and models to develop regularly curated data views and products that quantify relationships between large-scale phenomena, features and variations and conditions at 24 spatial areas of integration including select Tier 1 and 2 MPA locations across the state" (Objective 1) and to "work with the California MPA Management Program habitat expert teams to format and assemble in situ MPA monitoring data for inclusion in the multi-scale curated data views, including data for key performance measures and metrics" (Objective 3). That original proposed product has now evolved into a much more comprehensive tool for exploring and visualizing a curated collection of oceanographic, climatological, ecological monitoring, and model output datasets relevant to research and assessment of California's MPA network, including data from 122 individual MPAs and 4 reference bioregions.

This evolution and development of the California MPA Dashboard was guided by multiple rounds of engagement and feedback between the development team, other California MPA Monitoring Program projects including the ecological and habitat-specific monitoring groups, and its program managers. It was also underpinned by extensive investments in data verification, quality-checking, conversion into standard formats, and development of replicable data processing workflows to create high-quality data products for immediate and future use.

The Dashboard aims to meet the data needs of agencies, researchers, managers, and stakeholders involved in MPA assessment and research. It contains datasets and visualizations that can facilitate assessments for the following parts of the Marine Life Protection Act (MLPA) Goals and MPA Monitoring Action Plan, as well as priority research questions from the Ocean Protection Council (OPC) Science Advisory Team's report on Climate Resilience and California's MPA Network (Hofmann et al. 2021):

| *MLPA Goal 1: Protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems.* | |
|---|---|
| Example questions from MPA Action Plan | Relevant MPA Dashboard Datasets and Visualizations |
| ● Do focal and/or protected species inside of MPAs differ in size, numbers, and biomass relative to reference sites?<br>● Do the abundance, size/age structure, and/or diversity of predator and prey species differ inside MPAs, or outside areas of comparable habitat? | ● Time series of key species abundances from multiple long-term ecological monitoring; programs within and outside MPAs;<br>● Time series of oceanographic and climatological variables to provide environmental context. |

| *MLPA Goal 2: Help sustain, conserve, and protect marine life populations, including those of economic value, and rebuild those that are depleted.* | |
|---|---|
| Example questions from MPA Action Plan | Relevant MPA Dashboard Datasets and Visualizations |
| ● How do species differ in their rate of response to MPA implementation? | ● Time series of abundance for economically-valuable species from multiple long-term ecological monitoring programs within and outside MPAs. |

| *MLPA Goal 4: To protect marine natural heritage, including protection of representative and unique marine life habitats in California waters for their intrinsic value.* | |
|---|---|
| Example questions from MPA Action Plan | Relevant MPA Dashboard Datasets and Visualizations |
| ● Have unique habitats been adequately represented and protected by the current distribution and designation of MPAs? | ● Maps and spatial summaries of Seascapes within MPAs. |

| *MLPA Goal 6: To ensure that the MPAs are designed and managed, to the extent possible, as a component of a statewide network.* | |
|---|---|
| Example Questions from MPA Action Plan | Relevant MPA Dashboard Datasets and Visualizations |
| ● What are the demographic effects of siting MPAs in larval source or sink locations, and how do demographic responses to MPAs contribute to larval production and connectivity of MPAs in the network?<br>● How do other stressors impact the management of MPAs over time (e.g., water quality, oil spills, desalination plants, ocean acidification, sea level rise)? | ● Visualizations of modeled larval connectivity between MPAs and other coastal areas in the greater Monterey Bay area;<br>● Time series of key oceanographic variables (e.g., temperature, wave energy) relevant to physical and physiological stress for marine species;<br>● Visualizations of modeled risk of harmful algal blooms and domoic acid concentrations. |

| *Prioritized Climate Resilience Research Questions from OPC Science Advisory Team Report (Hofmann et al. 2021)* | |
|---|---|
| Example Questions from Report | Relevant MPA Dashboard Datasets and Visualizations |
| ● What is the spatial distribution of MPAs relative to historic and current stressor exposures, and how are those stressors likely to evolve in the future?<br>● What are physical, ecological, and biological characteristics of climate refugia? Do MPAs include or promote these conditions? Will climate refugia persist into the future?<br>● Does the California MPA network provide adequate levels of disconnection between MPAs (e.g., modularity) to ensure some populations persist in the face of climate change? | ● Color maps of projected change in key climate variables from 1980-2099;<br>● Visualizations of mean projected change in key climate variables from 1980-2099 for each individual MPA;<br>● Visualizations of potential ‘refugia’ based on projected change in key climate variables from 1980-2099 and their overlap with existing MPA boundaries. |

## 2.3 Methods

To develop data exploration and visualization features for the MPA dashboard, we generated and integrated MPA-specific summaries and digests of data from a variety of datasets, including 13 oceanographic and climatological datasets, 6 long-term ecological monitoring datasets from habitat monitoring groups in the California MPA Monitoring Program (with more anticipated from additional groups; see Table A2-1), outputs from 3 ecological models (Seascapes, California-Harmful Algae Risk Mapping (C-HARM), and EcoCast; described in *Section 4. Ecological Indicators for Seascapes and Harmful Algal Bloom Risk in MPAs*), outputs from projections of a California Current Regional Ocean Modeling System model (ROMS-NEMUCSC) coupled to downscaled climate models (Pozo Buil et al. 2021), and outputs from the high-resolution circulation and larval connectivity model (described in *Section 3. High-Resolution Circulation and Connectivity Modeling*).

Oceanographic and climatological data were obtained from various publicly available datasets, quality-checked, and, where applicable, used to generate monthly and annual summary variables at the spatial scale of each individual MPA, combined (aggregated) MPAs, and the reference bioregion. This involved creating documented, replicable data processing scripts to verify and summarize each variable from its original dataset, such that future updates to the source datasets can also be efficiently processed. See Table 2-1 for a full list of data sources and derived summary variables. We also generated monthly and annual summary variables for different habitat groups' monitoring site locations to support their individual habitat assessments (see Table 2-2). For example, the California Collaborative Fisheries Research Program (CCFRP) has used these data to show differences in temperature and wave energy between bioregions, corresponding to differences in fish community composition.

The long-term ecological monitoring datasets were obtained from the different habitat monitoring groups in the California MPA Monitoring Program, and we worked closely with representatives from these groups to understand how each dataset was collected and conduct verification and quality checks for inaccuracies or inconsistencies in the data. This process was especially important to ensure the long-term interpretability and utility of these datasets, which are mostly collected by hand in the field, and have many more points where errors or inconsistencies can be introduced compared to satellite- or sensor- derived data. Once these datasets were quality checked, we worked to standardize the data using the Darwin Core standard and made them accessible and discoverable through a variety of endpoints, including the CeNCOOS data portal, the Marine Biodiversity Observation Network (MBON) data portal, the Ocean Biodiversity Information System (OBIS), and the Global Biodiversity Information Facility (GBIF). This significant time investment into data quality and standardization allows for the effective use of these ecological monitoring datasets in current and future analyses and assessments. These standardized and quality checked datasets were used to generate ecological summary variable time series for visualization in the MPA dashboard (Table 2-1).

Outputs from the California Current climate change Regional Ocean Modeling System model (ROMS-NEMUCSC) and the Seascapes, C-HARM, and EcoCast ecological models were processed and aggregated by individual MPAs and bioregions for visualization in the MPA dashboard.

The MPA Dashboard was developed using the Shiny web application development package within the open-source R programming environment. This allowed us to rapidly iterate through prototype versions of the tool, incorporating regular feedback from the Ocean Protection Council, California Department of Fish and Wildlife, and representatives from the California MPA Monitoring Program. Detailed methods for all data processes are given in *Appendix A2.1 Extended Methods for Data Standardization and Processing*. Datasets and processes are maintained and updated by CeNCOOS staff through replicable scripts and workflows within the Axiom data infrastructure.

Table 2-1. Datasets and summary variables presently available in the MPA dashboard, including the time range of available data

| MPA DASHBOARD DATASETS | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Oceanographic and Climatological Datasets*** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Multivariate ENSO Index**<br>• Monthly Index | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Extratropical-Based Northern Oscillation Index**<br>• Monthly Index | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Pacific Decadal Oscillation Index**<br>• Monthly Index | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Biologically Effective Upwelling Transport Index (BEUTI)**<br>• Monthly Index | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Coastal Upwelling Transport Index (CUTI)**<br>• Monthly Index | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Sea Surface Temperature**<br>• Annual Mean, Maximum<br>• Monthly Mean, Maximum | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Net Primary Productivity**<br>• Annual Mean, Maximum<br>• Monthly Mean | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Attenuation of Downwelling Light at 490nm (Turbidity)**<br>• Annual Mean<br>• Monthly Mean | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Significant Wave Height**<br>• Annual Mean, Maximum, 95th Percentile<br>• Monthly Mean, Maximum, 95th Percentile | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Wave Orbital Velocity**<br>• Annual Mean, Maximum, 95th Percentile<br>• Monthly Mean, Maximum, 95th Percentile | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Wind Speed**<br>• Annual Mean<br>• Monthly Mean | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

| **MPA DASHBOARD DATASETS** | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Oceanographic and Climatological Datasets*** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Surface Aragonite Saturation**<br>• Annual Mean<br>• Monthly Mean | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | |
| **Bottom Aragonite Saturation**<br>• Annual Mean<br>• Monthly Mean | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | | | | | | | | | | |
| ***Ecological Monitoring Datasets*** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **California Collaborative Fisheries Research Program (CCFRP) Angler Surveys**<br>• Combined fish counts<br>• Combined fish CPUE | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **Multi-Agency Intertidal Network (MARINe) Rocky Intertidal Surveys**<br>• Barnacle percent cover<br>• Mussel percent cover<br>• Sea star density<br>• Black chiton density | | | | | | | | | | | | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| **Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) Kelp Forest Diver Surveys**<br>• Combined finfish density<br>• Combined rockfish (*Sebastes* spp.) density<br>• Combined basses (*Paralabrax* spp.) density<br>• California sheephead density<br>• Combined benthic invertebrate density<br>• Combined abalone (*Haliotis* spp.) density<br>• California spiny lobster density<br>• Sea urchin (*Strongylocentrotus* and *Mesocentrotus* spp.) density<br>• Combined crab density | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

| MPA DASHBOARD DATASETS | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Ecological Monitoring Datasets*** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Reef Check California Kelp Forest Diver Surveys**<br>• Combined finfish density<br>• Combined rockfish (*Sebastes* spp.) density<br>• Combined basses (*Paralabrax* spp.) density<br>• California sheephead density<br>• Lingcod density<br>• Combined benthic invertebrate density<br>• Combined abalone (*Haliotis* spp.) density<br>• Sea urchin (*Strongylocentrotus* and *Mesocentrotus* spp.) density<br>• Combined crab density | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **California Recreational Fisheries Survey (CRFS) Angler Surveys**<br>• Red abalone CPUE within 5km of MPA<br>• Dungeness crab CPUE within 5km of MPA<br>• California sheephead CPUE within 5km of MPA<br>• Lingcod CPUE within 5km of MPA<br>• California spiny lobster CPUE within 5km of MPA | | | | | | | | | | | | | | | | | | | | | | | | | | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ |
| **Kelp Canopy Satellite Data**<br>• Annual Mean | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| ***Ecological Model and Indicator Outputs*** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Seascapes** | | | | | | | | | | | | | | | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ |
| **EcoCAST** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ |
| **California Harmful Algal Risk Mapping (C-HARM)** | | | | | | | | | | | | | | | | | | | | | | | | | | | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ | ▒ |

Table 2-2. Lists of summary variables of oceanographic and climatological data processed and provided to habitat monitoring groups in the California MPA Monitoring Program.

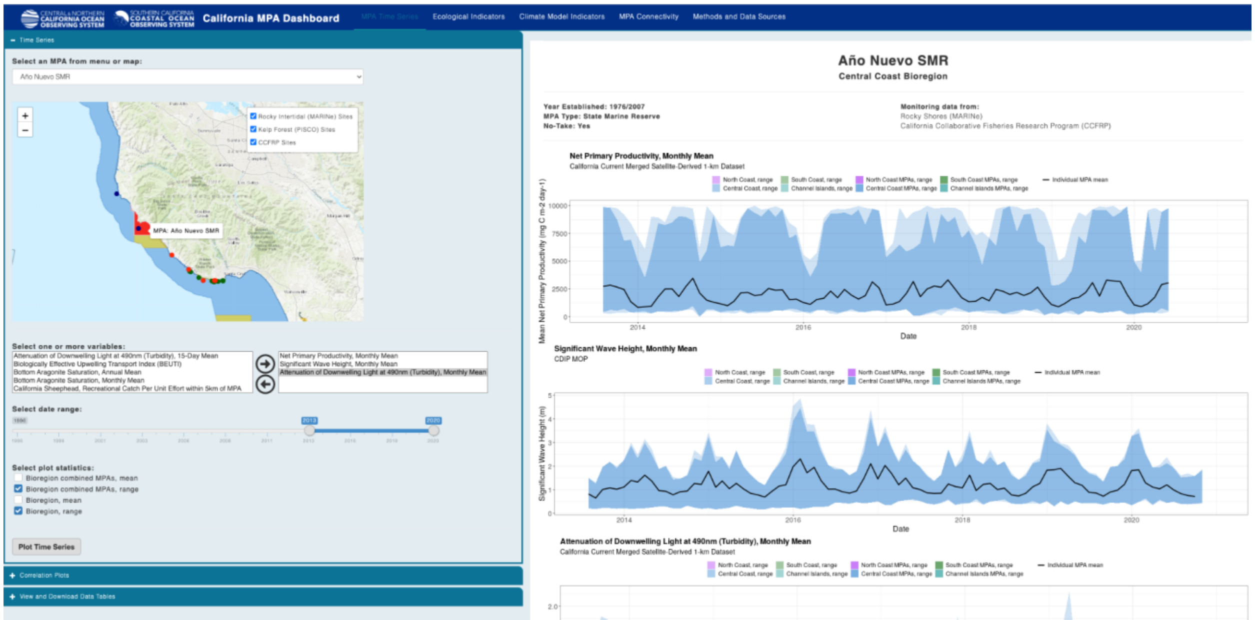
| **Habitat Monitoring Group** | **Number of Monitoring Sites** | **Summary Data Variables Provided** |
|---|---|---|
| Recreationally-Targeted Finfish<br>(CCFRP) | 31 sites<br>(432 coordinate points) | ● Net Primary Productivity, Monthly and Annual Means;<br>● Sea Surface Temperature, Monthly and Annual Means;<br>● Turbidity, Monthly Mean;<br>● Wave Height, Monthly Mean and Maximum;<br>● Wave Power, Monthly Mean and Maximum;<br>● Wind Speed, Monthly Mean and Maximum. |
| Kelp Forest Ecosystems<br>(PISCO/Reefcheck California) | 503 sites | ● Net Primary Productivity, Monthly and Annual Mean and Maximum;<br>● Sea Surface Temperature, Monthly and Annual Means;<br>● Turbidity, Monthly and Annual Means;<br>● Wave Height, Monthly Mean, Maximum, and 95th Percentile;<br>● Wave Power, Monthly Mean, Maximum, and 95th Percentile;<br>● Wind Speed, Monthly Maximum. |
| Rocky Shore Ecosystems<br>(MARINe) | 235 sites | ● Sea Surface Temperature, Monthly and Annual Means. |
| Midwater Ecosystems | 42 MPA sites | ● Net Primary Productivity, Monthly and Annual Means;<br>● Sea Surface Temperature, Monthly and Annual Means;<br>● Turbidity, Monthly Mean;<br>● Wave Height, Monthly Mean and Maximum;<br>● Wave Power, Monthly Mean and Maximum;<br>● Wind Speed, Monthly Mean and Maximum. |

## 2.4 California MPA Dashboard Features and Uses

The MPA dashboard has been designed as a tool for accessing and visualizing a curated collection of datasets from a variety of sources, which have been identified and processed specifically to be useful for answering questions about MPAs, including assessments and planning. This collection of datasets will be regularly updated as the underlying datasets are updated, and expanded as additional relevant datasets become available.

### 2.4.1 MPA Time Series

The MPA Time Series Tool enables users to browse and visualize data on how oceanographic conditions, as well as species abundances and ecological communities have changed over time within California's MPAs. This can facilitate assessments on how different species are performing inside and outside MPAs, and some of the potential drivers of change (Action Plan Questions for MLPA Goals 1 and 2, *Section 2.2 Data Integration and California MPA Dashboard Objectives*). The MPA Time Series tool generates customized plots of user-selected oceanographic, climatological, and ecological variables for individual MPAs throughout the California network, drawing from a curated group of datasets (see *Oceanographic and Climatological Datasets and Ecological Monitoring Datasets* in Table 2-1). The MPA of interest can be selected by the user from a dropdown menu or from the interactive map, which populates the list of data variables available for that MPA. These data can be visualized as linear time series or sets of scatter plots between different variables for each selected MPA, alongside reference values for aggregated MPAs within a bioregion, or for the whole bioregion. This allows for assessments of change in conditions and/or ecological indicators, as well as the potential relationships between them. Datasets of interest can be downloaded in .csv format for further use in analyses, or requested from CeNCOOS or SCCOOS.



**Select an MPA from menu or map:** Año Nuevo SMR

☑ Rocky Intertidal (MARINe) Sites
☑ Kelp Forest (PISCO) Sites
☑ CCFRP Sites

**Select one or more variables:**

Attenuation of Downwelling Light at 490nm (Turbidity), 15-Day Mean
Biologically Effective Upwelling Transport Index (BEUTI)
Bottom Aragonite Saturation, Annual Mean
Bottom Aragonite Saturation, Monthly Mean
California Sheephead, Recreational Catch Per Unit Effort within 5km of MPA

Net Primary Productivity, Monthly Mean
Significant Wave Height, Monthly Mean
Attenuation of Downwelling Light at 490nm (Turbidity), Monthly Mean

**Select date range:** 2013 – 2020

**Select plot statistics:**

☐ Bioregion combined MPAs, mean
☑ Bioregion combined MPAs, range
☐ Bioregion, mean
☑ Bioregion, range

**Año Nuevo SMR**
**Central Coast Bioregion**

**Year Established: 1976/2007**
**MPA Type: State Marine Reserve**
**No-Take: Yes**

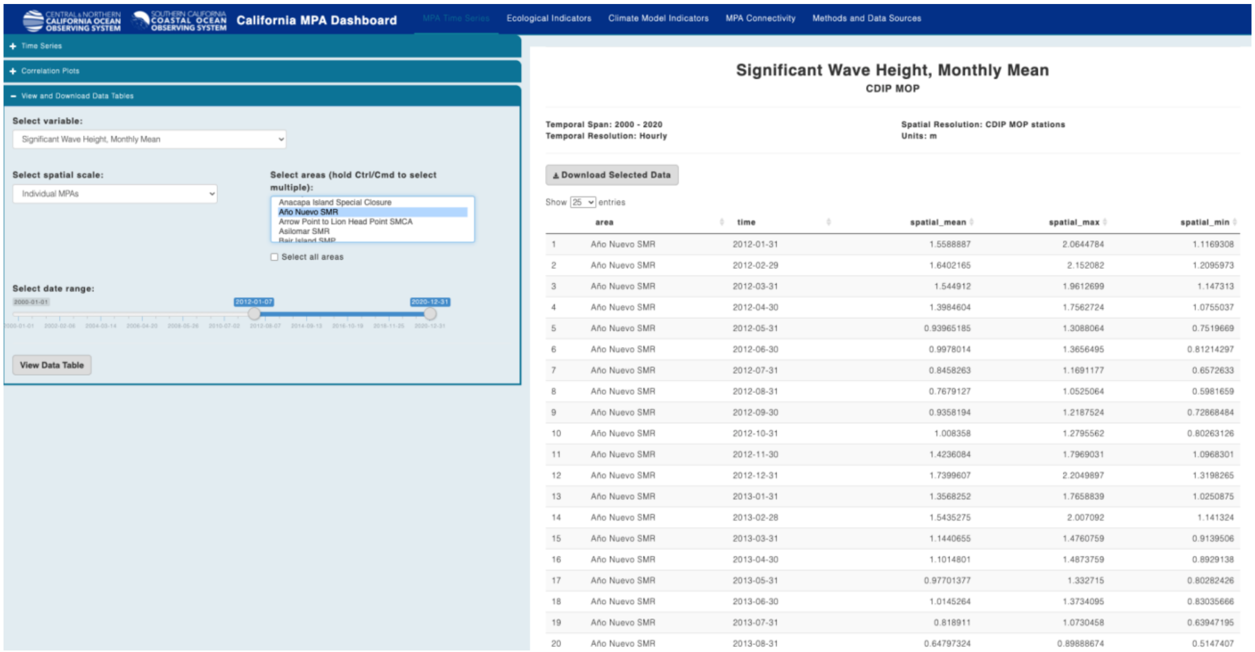
**Monitoring data from:**
Rocky Shores (MARINe)
California Collaborative Fisheries Research Program (CCFRP)

**Net Primary Productivity, Monthly Mean**
California Current Merged Satellite-Derived 1-km Dataset

**Significant Wave Height, Monthly Mean**
CDIP MOP

**Attenuation of Downwelling Light at 490nm (Turbidity), Monthly Mean**
California Current Merged Satellite-Derived 1-km Dataset

Figure 2-1. Screenshot of MPA Time Series Tool in the California MPA Dashboard - showing data from Año Nuevo SMR across selected variables and times.



Select variable: Significant Wave Height, Monthly Mean

Select spatial scale: Individual MPAs

Select areas (hold Ctrl/Cmd to select multiple): Año Nuevo SMR

Select date range: 2012-01-07 – 2020-12-31

**Significant Wave Height, Monthly Mean**

**CDIP MOP**

**Temporal Span: 2000 - 2020**
**Temporal Resolution: Hourly**

**Spatial Resolution: CDIP MOP stations**
**Units: m**

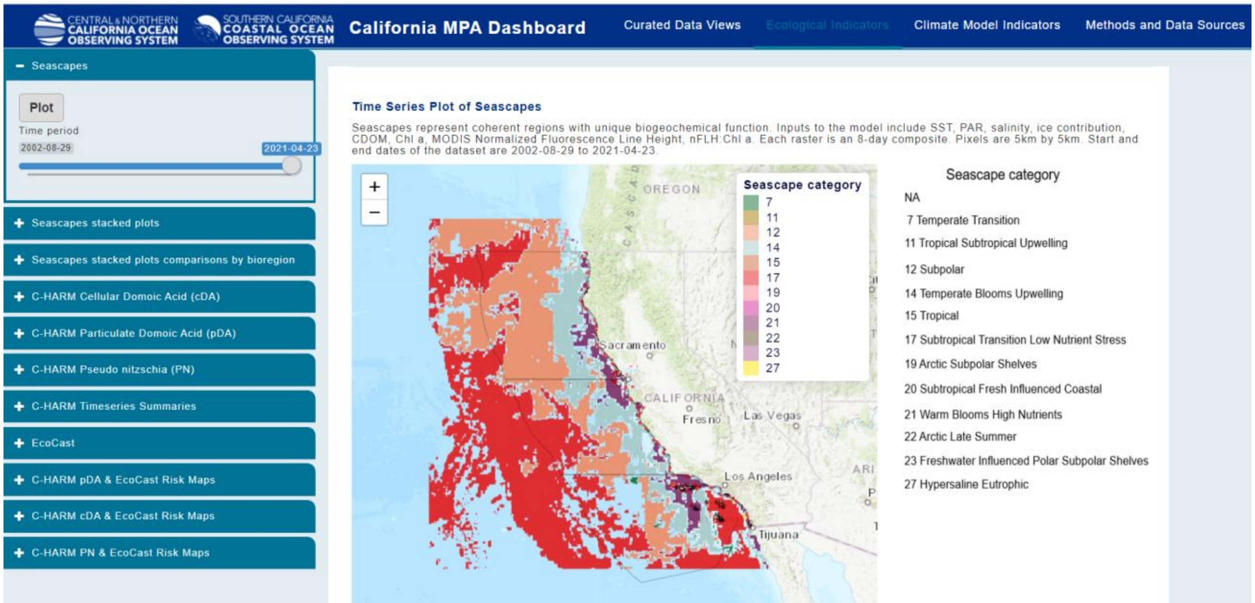
Show 25 entries

| | area | time | spatial_mean | spatial_max | spatial_min |
|---|---|---|---|---|---|
| 1 | Año Nuevo SMR | 2012-01-31 | 1.5588887 | 2.0644784 | 1.1169308 |
| 2 | Año Nuevo SMR | 2012-02-29 | 1.6402165 | 2.152082 | 1.2095973 |
| 3 | Año Nuevo SMR | 2012-03-31 | 1.544912 | 1.9612699 | 1.147313 |
| 4 | Año Nuevo SMR | 2012-04-30 | 1.3984604 | 1.7562724 | 1.0755037 |
| 5 | Año Nuevo SMR | 2012-05-31 | 0.93965185 | 1.3088064 | 0.7519669 |
| 6 | Año Nuevo SMR | 2012-06-30 | 0.9978014 | 1.3656495 | 0.81214297 |
| 7 | Año Nuevo SMR | 2012-07-31 | 0.8458263 | 1.1691177 | 0.6572633 |
| 8 | Año Nuevo SMR | 2012-08-31 | 0.7679127 | 1.0525064 | 0.5981659 |
| 9 | Año Nuevo SMR | 2012-09-30 | 0.9358194 | 1.2187524 | 0.72868484 |
| 10 | Año Nuevo SMR | 2012-10-31 | 1.008358 | 1.2795562 | 0.80263126 |
| 11 | Año Nuevo SMR | 2012-11-30 | 1.4236084 | 1.7969031 | 1.0968301 |
| 12 | Año Nuevo SMR | 2012-12-31 | 1.7399607 | 2.2049897 | 1.3198265 |
| 13 | Año Nuevo SMR | 2013-01-31 | 1.3568252 | 1.7658839 | 1.0250875 |
| 14 | Año Nuevo SMR | 2013-02-28 | 1.5435275 | 2.007092 | 1.141324 |
| 15 | Año Nuevo SMR | 2013-03-31 | 1.1440655 | 1.4760759 | 0.9139506 |
| 16 | Año Nuevo SMR | 2013-04-30 | 1.1014801 | 1.4873759 | 0.8929138 |
| 17 | Año Nuevo SMR | 2013-05-31 | 0.97701377 | 1.332715 | 0.80282426 |
| 18 | Año Nuevo SMR | 2013-06-30 | 1.0145264 | 1.3734095 | 0.83035666 |
| 19 | Año Nuevo SMR | 2013-07-31 | 0.818911 | 1.0730458 | 0.63947195 |
| 20 | Año Nuevo SMR | 2013-08-31 | 0.64797324 | 0.89888674 | 0.5147407 |

Figure 2-2 Screenshot of MPA Time Series Tool in the California MPA Dashboard - showing data download options.

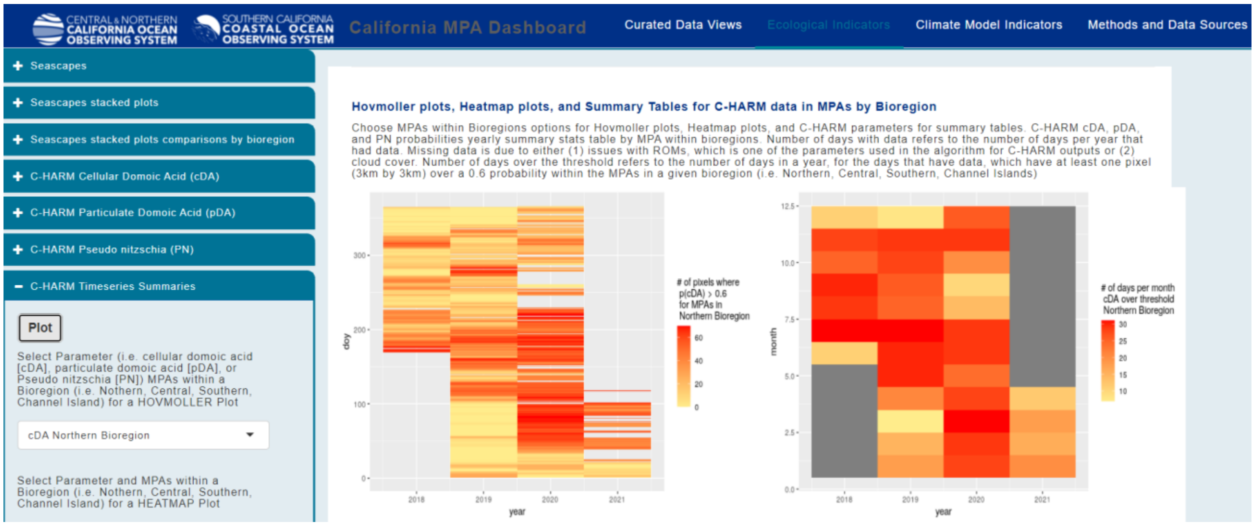
### 2.4.2 Ecological Model Outputs

The Ecological Model Outputs Tool enables users to explore and visualize dynamics of oceanographic habitat classifications (Seascapes), the risk for a key environmental stressor, harmful algal blooms (HABs), through the California Harmful Algae Risk Mapping (C-HARM), and the specific HAB risk to vulnerable species of interest (leatherback sea turtles, sea lions, and blue sharks; EcoCast bycatch mapping) within individual MPAs throughout the California MPA network, as well as their reference bioregions. Users can visualize and map the dynamics of oceanographic habitats (Seascapes) in MPA bioregions through time (Fig. 2-3), the risk of domoic acid concentrations and *Pseudo-nitzschia* (Fig. 2-4) in California MPAs over time, and the spatial overlap between HAB impacts and the species distribution of vulnerable bycatch species, relative to MPA locations. This can help improve understanding of how oceanographic habitats are represented within MPAs and how a key stressor varies in MPAs across time (Action Plan Questions for MLPA Goals 4 and 6).



Seascapes represent coherent regions with unique biogeochemical function. Inputs to the model include SST, PAR, salinity, ice contribution, CDOM, Chl a, MODIS Normalized Fluorescence Line Height, nFLH:Chl a. Each raster is an 8-day composite. Pixels are 5km by 5km. Start and end dates of the dataset are 2002-08-29 to 2021-04-23.

Figure 2-3 Screenshot of Ecological Indicators Tool in the California MPA Dashboard – showing Seascapes time variant map plots.



Choose MPAs within Bioregions options for Hovmoller plots, Heatmap plots, and C-HARM parameters for summary tables. C-HARM cDA, pDA, and PN probabilities yearly summary stats table by MPA within bioregions. Number of days with data refers to the number of days per year that had data. Missing data is due to either (1) issues with ROMs, which is one of the parameters used in the algorithm for C-HARM outputs or (2) cloud cover. Number of days over the threshold refers to the number of days in a year, for the days that have data, which have at least one pixel (3km by 3km) over a 0.6 probability within the MPAs in a given bioregion (i.e. Northern, Central, Southern, Channel Islands)

Select Parameter (i.e. cellular domoic acid [cDA], particulate domoic acid [pDA], or Pseudo nitzschia [PN]) MPAs within a Bioregion (i.e. Nothern, Central, Southern, Channel Island) for a HOVMOLLER Plot

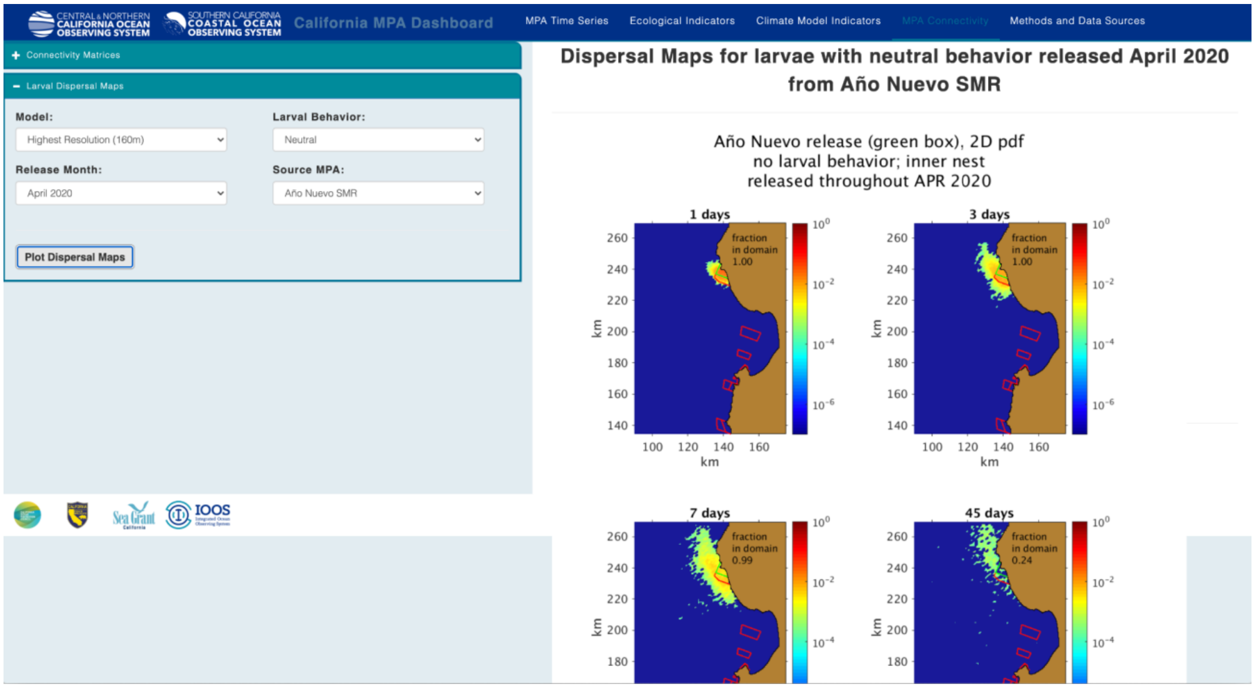
cDA Northern Bioregion

Select Parameter and MPAs within a Bioregion (i.e. Nothern, Central, Southern, Channel Island) for a HEATMAP Plot

Figure 2-4 Screenshot of Ecological Indicators Tool in the California MPA Dashboard – showing C-HARM plots and summary tables page.

### 2.4.3 MPA Connectivity

The MPA Connectivity Tool enables users to visualize and explore the projected larval connectivity between different sections of coastal habitat, including a subset of 11 MPAs, in the greater Monterey Bay region. This can help to inform assessments on connectivity between larval sources and sinks relative to the placement of MPAs, and assessments of the MPAs as a network (Action Plan Questions for MLPA Goal 6). Different scenarios for larval behavior, larval release month, and the length of the Pelagic Larval Duration can be selected to generate plots of connectivity between MPAs and non-MPA sections of coastline and plots of projected trajectories of larvae released from each MPA based on the outputs of the circulation and connectivity models described in Objective 2.



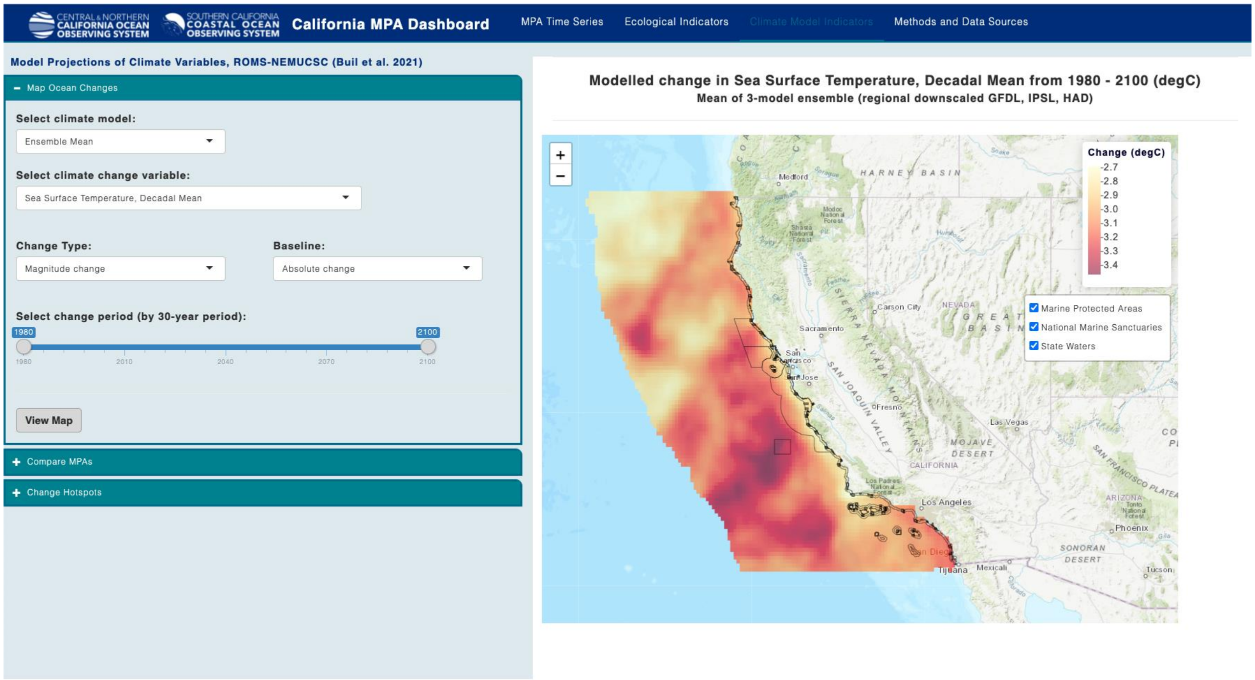
Model: Highest Resolution (160m)
Larval Behavior: Neutral
Release Month: April 2020
Source MPA: Año Nuevo SMR

**Dispersal Maps for larvae with neutral behavior released April 2020 from Año Nuevo SMR**

Figure 2-5 Screenshot of MPA Connectivity Tool in the California MPA Dashboard - showing dispersal map for modeled larval particles released from an MPA

### 2.4.4 Climate Change Model Outputs

The Climate Model Outputs Tool enables users to visualize projected changes in key oceanographic variables (Sea Surface Temperature, Chlorophyll a, Dissolved Oxygen [eventually pH]) under climate change for individual MPAs throughout California's MPA network - both in the form of spatial maps and as comparison plots with other MPAs. This can help inform work on the spatial distribution of climate stressors relative to MPAs, and explore the physical characteristics and temporal persistence of potential climate refugia (OPC Science Advisory Team Report on Climate Resilience and California's MPA network, Priority Research Questions 2, 7, 8). The Climate Model Outputs Tool generates spatial maps of projected change in each variable for the California Exclusive Economic Zone (EEZ) region, overlaid with the boundaries for California State Waters, all individual MPAs, and National Marine Sanctuaries (Fig. 2-6). The tool also generates bar plots comparing projected changes in climate variables between California MPAs, as well as visualizations of the distribution of projected 'hotspots' and 'refuges' of climate change, and how represented these areas are within MPAs (Fig. 2-7). All projected values are derived from outputs of a Regional Ocean Modeling System (ROMS) coupled with a biogeochemical model (NEMUCSC) (Fig. 2-6, Pozo Buil et al. 2021).



**Model Projections of Climate Variables, ROMS-NEMUCSC (Buil et al. 2021)**

**Select climate model:** Ensemble Mean

**Select climate change variable:** Sea Surface Temperature, Decadal Mean

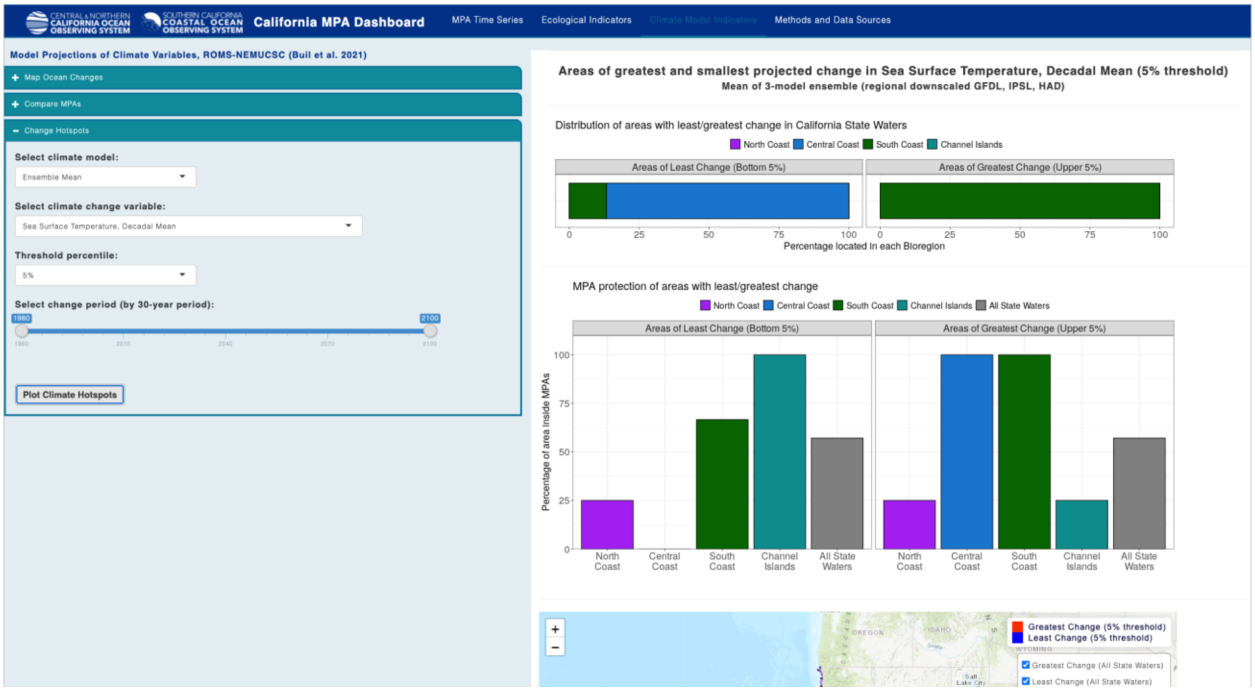
**Change Type:** Magnitude change

**Baseline:** Absolute change

**Select change period (by 30-year period):** 1980 – 2100

**Modelled change in Sea Surface Temperature, Decadal Mean from 1980 - 2100 (degC)**
**Mean of 3-model ensemble (regional downscaled GFDL, IPSL, HAD)**

Figure 2-6. Screenshot of Climate Model Indicators Tool in the CA MPA Dashboard - showing a map of projected sea surface temperature (SST) change from 1980-2099.



**Model Projections of Climate Variables, ROMS-NEMUCSC (Buil et al. 2021)**

**Select climate model:** Ensemble Mean

**Select climate change variable:** Sea Surface Temperature, Decadal Mean

**Threshold percentile:** 5%

**Select change period (by 30-year period):** 1980 – 2100

**Areas of greatest and smallest projected change in Sea Surface Temperature, Decadal Mean (5% threshold)**
**Mean of 3-model ensemble (regional downscaled GFDL, IPSL, HAD)**

Figure 2-7. Screenshot of Climate Model Indicators Tool in the CA MPA Dashboard - showing projected areas of greatest and least change for each bioregion

# 3. High-Resolution Circulation and Connectivity Modeling (Objective 2)

## 3.1 Summary

- We modeled realistic ocean circulation using two nested domains (800 m and 160 m resolution, spanning the Central California coast and the greater Monterey Bay, respectively) forced by the NOAA West Coast Operational Forecast System (WCOFS) model output for the period March 2000 through September 2021.
- On a daily basis, we seeded particles, representing virtual larvae and obeying different behavioral rules, into the modeled ocean from release/settlement cells corresponding to greater Monterey Bay MPAs and nearshore zones, and tracked their trajectories resulting from ocean transport.
- On a monthly basis, we calculated statistics of connectivity (probabilities of presence in a destination cell from a release cell) for each behavior.
- Most MPAs in the high-resolution nest area around Monterey Bay were well connected during the studied period, with connectivity being especially high going from southern to northern MPAs, especially for cases of longer larval durations. Spillover from MPAs to other non-MPA nearshore regions was also high, with MPAs supplying larvae to all modeled coastal cells in the region under the April 2020 release scenario, across multiple possible larval durations.
- While this approach is among the most advanced and high-resolution approaches available, limitations include errors in the ocean circulation model and the simplification of larval and propagule behaviors into the trajectory and connectivity estimates.

## 3.2 Circulation and Connectivity Modeling Objectives

The MPA Action Plan identifies several questions related to connectivity. Here we address several of these questions. Importantly, other data and information from the California MPA Monitoring Program are still required to give additional biological and ecological context to the trajectories.

| *MLPA Goal 6: To ensure that the MPAs are designed and managed, to the extent possible, as a component of a statewide network* | |
|---|---|
| Questions from MPA Action Plan | Relevant Circulation and Connectivity Modeling Output |
| ● What are the demographic effects of siting MPAs in larval source or sink locations, and how do demographic responses to MPAs contribute to larval production and connectivity of MPAs in the network?<br>● How does the distance and larval contribution between a source MPA and sink MPA influence the ecosystem response inside the sink MPA?<br>● How does the level of connectivity and larval supply from an MPA to areas outside of MPAs affect fisheries?<br>● Are MPAs with higher connectivity more resilient to sudden environmental disturbance as compared to more isolated MPAs with higher self-retention? | ● Assessment of source and sink dynamics for MPA and non-MPA coastal locations for the greater Monterey Bay Area;<br>● Demographic effects based on pelagic larval duration (PLD), larval behavior and time-of-release for *existing* MPAs are quantified through connectivity matrices;<br>● Multi-generational demographic effects can be assessed by propagating connectivity matrices through multiple generations and including additional effects (e.g., habitat, larval mortality, larval production);<br>● Oceanographic distance is more relevant for connectivity than geographic distance and visible in connectivity matrices for different PLDs;<br>● Higher connectivity suggests resilience to disturbance across a generation than more isolated MPAs with self-retention, though connectivity is a function of time-of-release, PLD, and behavior and thus the degree of resiliency is likely to vary by organism. |

## 3.3 Methods

### 3.3.1 Circulation Modeling

After years of development, NOAA's West Coast Operational Forecast System (WCOFS) became operational in March 2021. This model represents NOAA's first operational, data assimilative coastal ocean model in which data are used in a formal way to constrain model simulations as in weather forecasting, and it spans coastal waters from Mexico to British Columbia at 4 km resolution. For this project, we took advantage of this new product, constructing two higher resolution model nests (800 m and 160 m) focused on the Central California coast and the greater Monterey Bay (Fig. 3-1). The nests use the same Regional Ocean Modeling System (ROMS) for its dynamical core and are forced at the surface by the same atmospheric forcing as WCOFS. Lateral boundaries derive from a recalculation of

WCOFS fields at the University of California Santa Cruz (UCSC) and the model interior is weakly forced by WCOFS physical output as well.

Our calculations span March 2000 through September 2021 using a pre-operational version of WCOFS and then its operational output. Fig. 3-1 presents sea surface temperature (SST) for an example day (May 07, 2021) from both the UCSC re-implementation of WCOFS (left) and the two nested domains (right). At this time, nested modeled temperature in offshore regions tends to be cooler than WCOFS (e.g., between Pt. Reyes and Pt. Arena) though some nearshore values are warmer (e.g., Gulf of the Farallones and Monterey Bay).

*Assumption/Limitation:* We assume that WCOFS is the best current estimate of the realistic coastal ocean circulation for the period under consideration. As is true with numerical weather prediction, ocean circulation simulations are imperfect representations of nature. The modeling system likely includes both random errors and systematic errors that can be assessed in part through model data comparisons. The latter (systematic) errors in ocean circulation will lead to biases on modeled ocean transport and in connectivity statistics calculated here. We present in the appendix quantitative methods by which we assess the model output. As is true in other modeling activities (e.g., El Niño-Southern Oscillation prediction, climate modeling), biases can be reduced through ensemble calculations or multi-model approaches.

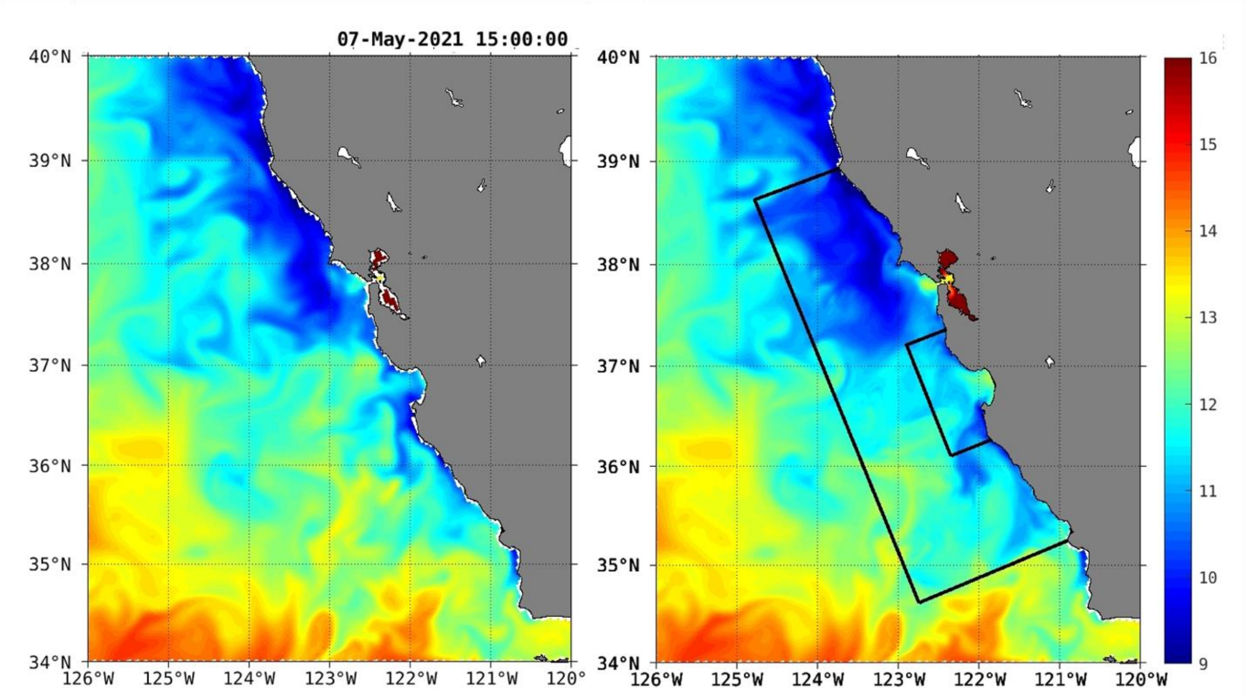


Figure 3-1. Sea Surface Temperature from the UCSC re-implementation version of WCOFS (left) and our nested configuration (right) for May 07, 2021.

### 3.3.2 Larval trajectory modeling

Floats were released from model subdomains representing both regional MPAs (Fig. 3-2a) and nearshore cells (Fig. 3-2b), tracked for 90 days, and statistics calculated for potential settlement in these subdomains with different competency windows and pelagic larval durations (PLD). Natural Bridges State Marine Reserve was not represented explicitly because its cross-shore extent is not resolved even by our 160 m resolution nest. However, one can get an idea of exchanges to and from the Natural

Bridges region through modeled nearshore regions 18 and 19 (Fig. 3-2b). Four behaviors were explicitly considered: (1) no behavior, with floats transported by the 3-dimensional ocean circulation; (2) within the surface mixed layer, with floats constrained to a mean depth of 5 m with a standard deviation in the vertical of 2.5 m; (3) beneath the surface mixed layer, with floats constrained to lie near 30 m depth with a standard deviation in the vertical of 2.5 m; (4) diel vertical migration, with floats moving between 5 +- 2.5 m depth and 30 +- 2.5 m depth on a daily basis.

*Limitations*: (1) Larval behavior is not well known in nature and likely varies greatly between organisms under consideration. Errors in depth choices will lead to biases in connectivity patterns that are difficult to quantify. (2) In nature, larval mortality is non-zero, and likely varies by organism. If a larval mortality rate is known, it is straightforward to incorporate this loss for a given PLD, and as a result, we neglected explicit incorporation of this factor in our connectivity plots. The main impact of this neglect is an overestimate of connectivity, with greatest magnitude at longest PLDs. (3) In nature, habitat is unevenly distributed across MPAs. For example, the shallow nearshore Carmel Bay MPA hosts different organisms than the deep Soquel Canyon and Portuguese Ledge MPAs. Because habitat is organism dependent, we did not account for these differences in the general connectivity calculations because it is straightforward post calculation to explicitly exclude particular linkages for different species.

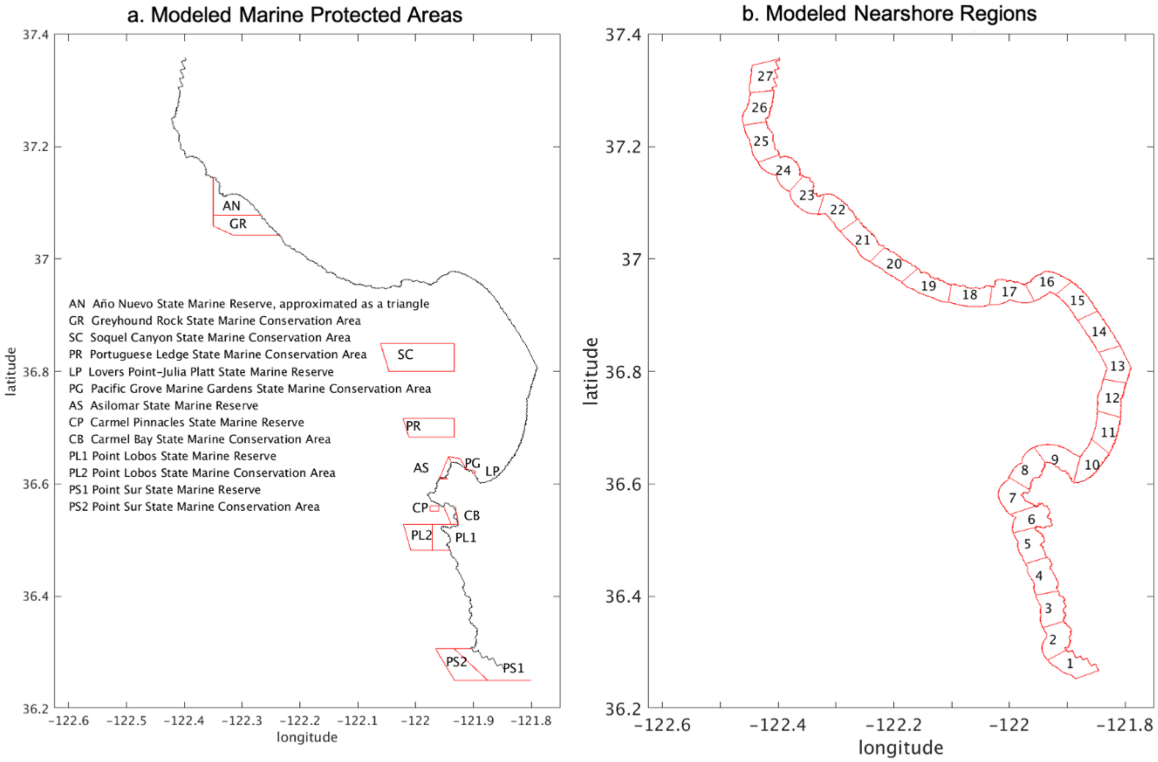


Figure 3-2. Modeled release and settlement regions for larval connectivity: (a) MPA; and (b) nearshore coastal cells, along with distinguishing notation.

## 3.4 Results and Management Implications

### 3.4.1 Example two-dimensional probability distributions

Two-dimensional probability density functions of float distributions reveal transport and dispersion within the region over different time-scales and with different behaviors. Examples for 1, 3, 7, and 45 days since release from the Pacific Grove Marine Gardens State Reserve Area are shown for April 2020 releases in Fig. 3-3 for the neutral behavior in which organisms move 3-dimensionally with the 3-dimensional currents. Floats disperse rapidly from the marine reserve, reaching the edges of nearby MPAs after 3 days and spreading more fully after 7 days. After 45 days of dispersal by ocean currents, 62% of floats released remain in the domain shown and are found to the north of release MPA. It is clear from this particular figure that the Pacific Grove MPA interacts with several regional MPAs on different time-scales.

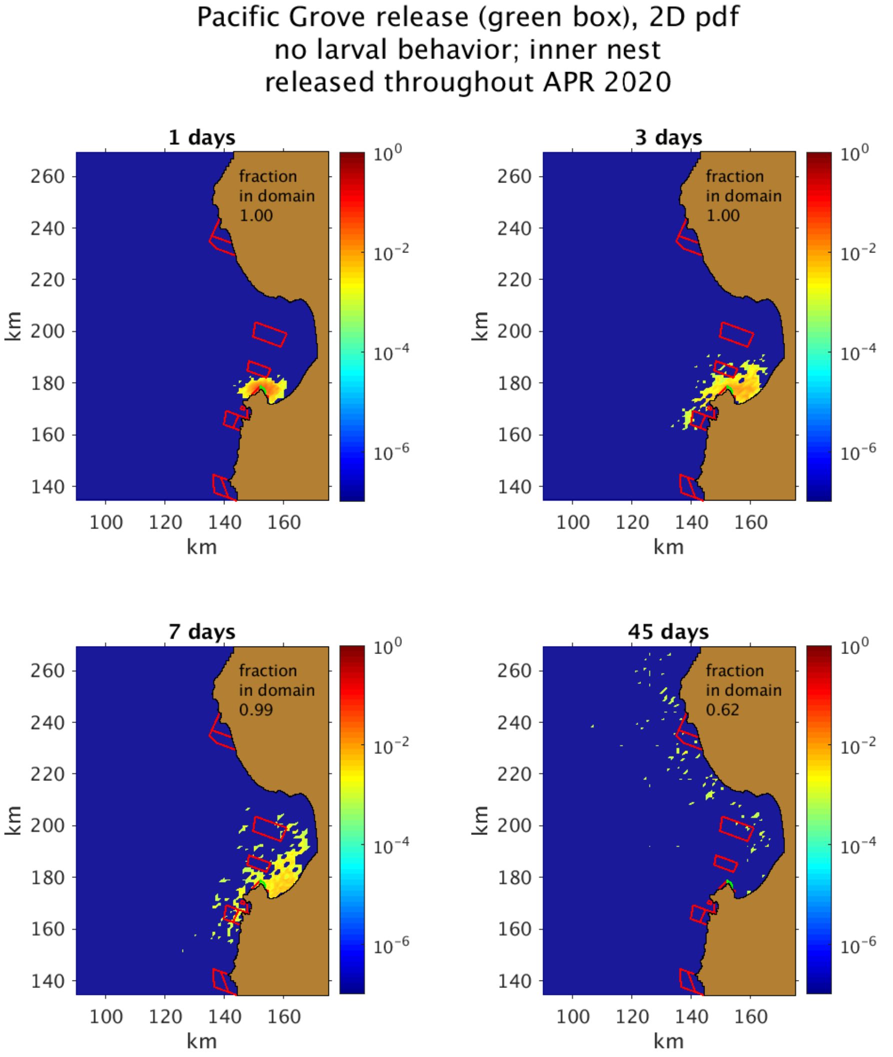


Figure 3-3. Two-dimensional probability density functions for floats released from the Pacific Grove Marine Gardens State Reserve Area in the month of April 2020 with no explicit larval behavior after 1, 3, 7, and 45 days. The fraction of total floats accounted for within the shown domain is given in the upper right corner.

A contrasting perspective can be examined in Fig. 3-4 for a behavior that keeps organisms distributed around 30 m depth with a 2.5 m standard deviation. These organisms remain largely below the surface mixed layer and, during upwelling-favorable wind conditions, experience predominantly onshore flow. As a result, this behavior exhibits smaller dispersion and greater local retention for longer than the neutral case. After 45 days of dispersal, these organisms trace out an elongated path along bathymetric contours to the north, still connecting with remote (Año Nuevo and Greyhound Rock) MPAs.

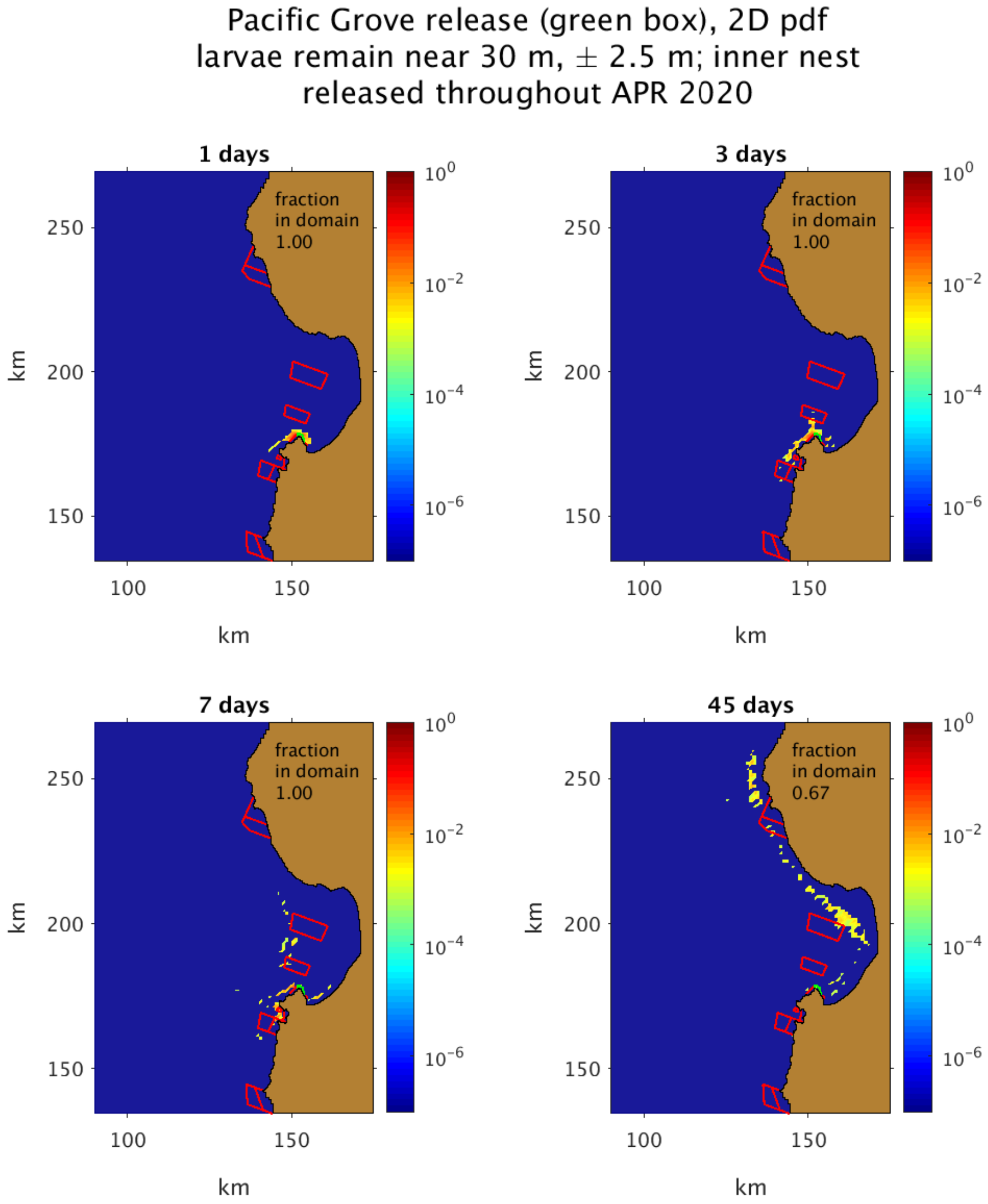


Figure 3-4. Two-dimensional probability density functions for floats released from the Pacific Grove Marine Gardens State Reserve Area in the month of April 2020 with larval behavior that keeps organisms centered at 30 m depth (Gaussian distributed with a 2.5 m standard deviation) after 1, 3, 7, and 45 days. The fraction of total floats accounted for within the shown domain is given in the upper right corner.

### 3.4.2 Example Connectivity Matrices

Connectivity matrices summarize the probabilities of floats released from one region of interest that potentially settle in another region. We refer to this as potential settlement because in nature, additional factors not modeled might influence actual settlement. Fig. 3-5 presents an example for the neutral behavior case shown in F. 3-3 for the releases in April 2020 and having a competency window of 2.5 days following a pelagic larval duration (PLD) of 7 days. For this configuration, northern MPAs such as Greyhound Rock and Año Nuevo experience predominantly local retention whereas all other MPAs generally distribute larvae throughout the region. Horizontal stripes for Point Lobos, Asilomar, Pacific Grove, Portuguese Canyon, and Soquel Canyon indicate that organisms released from many other MPAs tend to pass through these MPAs over this 2.5-day window. In contrast, Carmel Pinnacles and Lovers Point exhibit low settlement from any MPA for this behavior and release month.

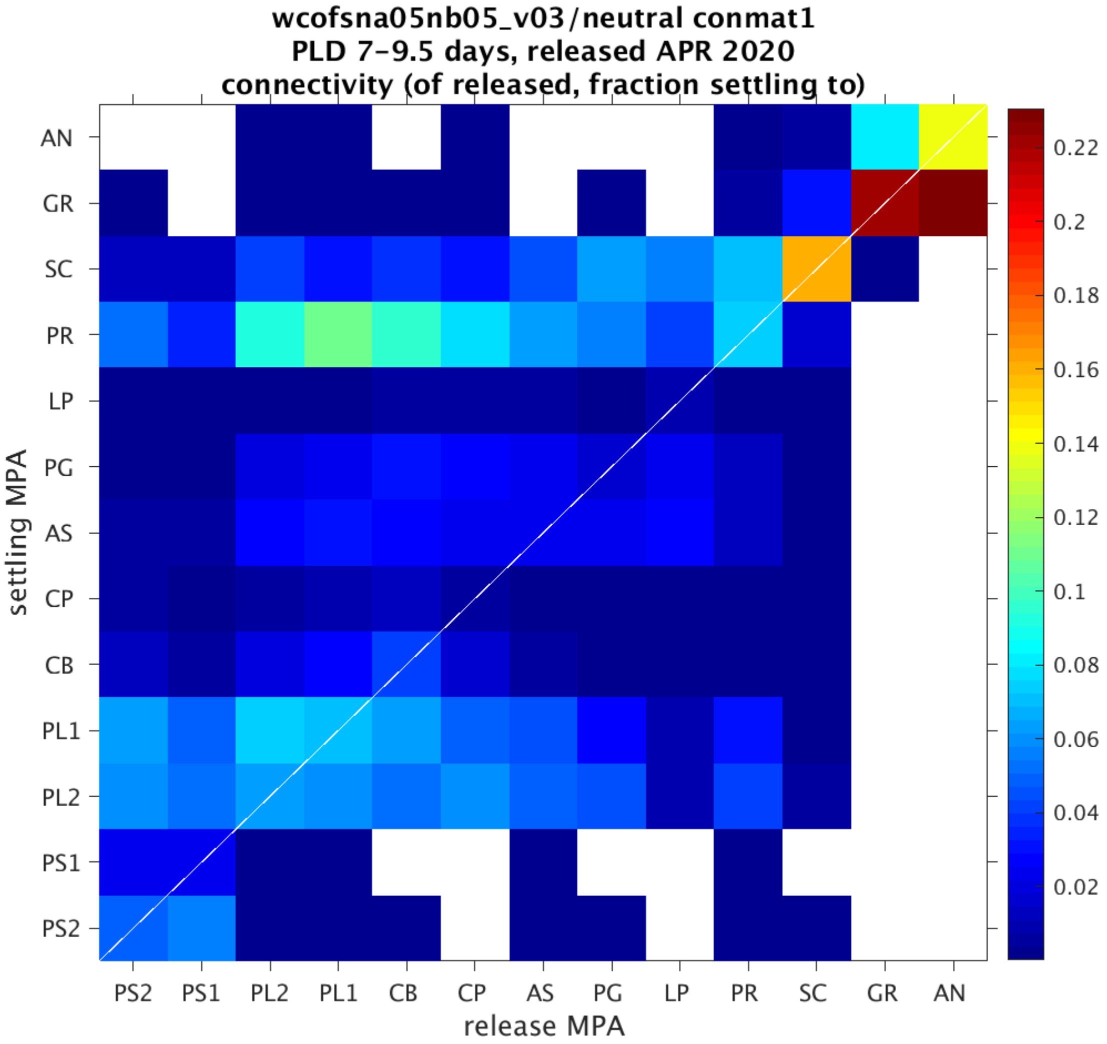


Figure 3-5. A connectivity matrix showing the probability that a float released from an MPA designated on the x-axis potentially could settle in an MPA on the y-axis during the competency window of 7-9.5 days from release during April 2020 with the neutral behavior in which floats are transported passively by 3-dimensional modeled currents. The key for MPA initials is given in Fig. 3-2.

At longer PLDs for April 2020 releases, the connectivity probabilities for this neutral case shifts to more northern MPAs (Fig. 3-6). Potential settlement within Año Nuevo and Greyhound Rock MPAs occurring between 60 and 69.5 days from release derive broadly from MPAs to their south. Probability of local retention (along the diagonal white line) is very low for all modeled MPAs for this long PLD.

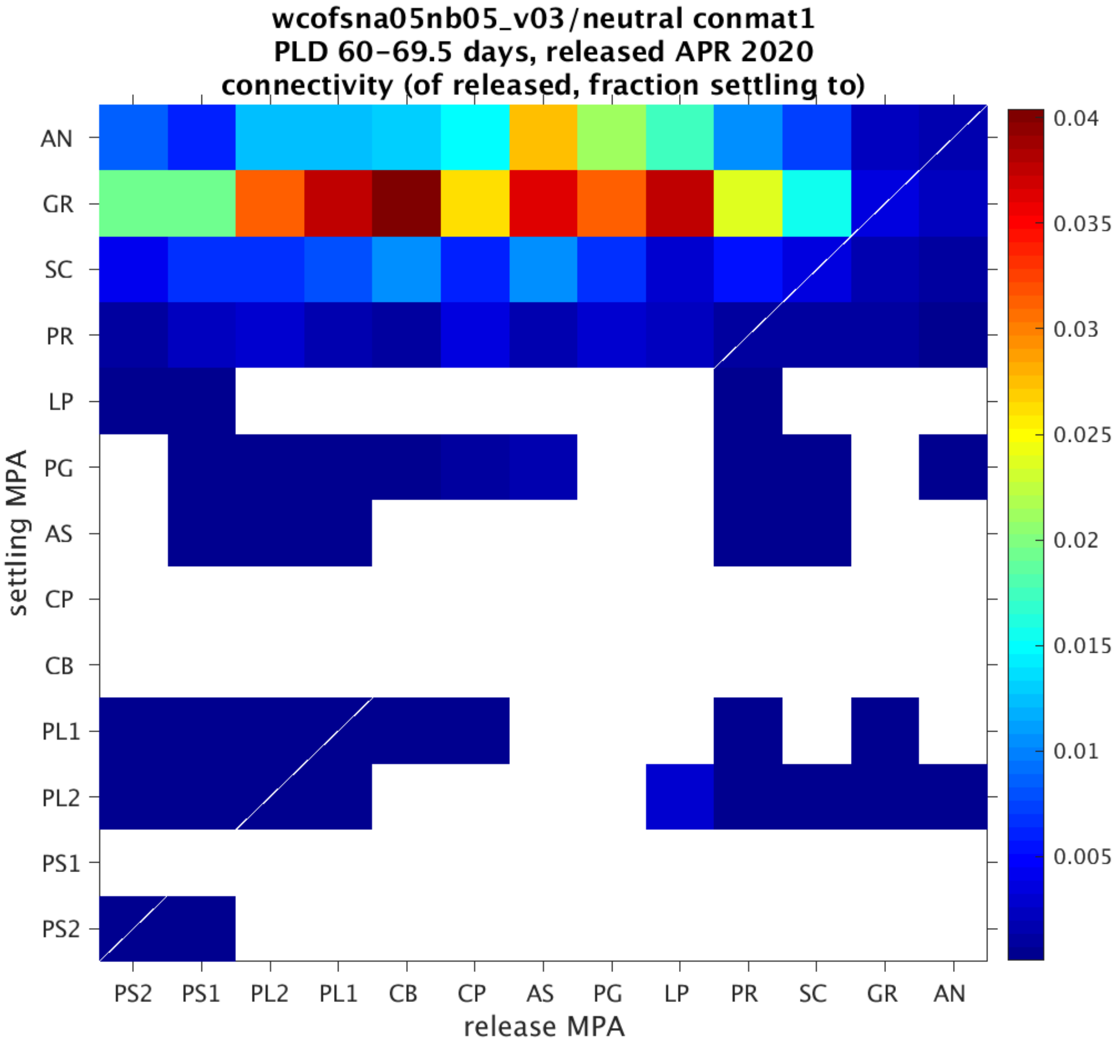


Figure 3-6. A connectivity matrix showing the probability that a float released from an MPA designated on the x-axis potentially could settle in an MPA on the y-axis during the competency window of 60-69.5 days from release during April 2020 with the neutral behavior in which floats are transported passively by 3-dimensional modeled currents. The key for MPA initials is given in Fig. 3-2.

We considered spillover effects in which MPAs potentially supply larval organisms to non-MPA nearshore regions shown in Fig. 3-2. Three examples for the neutral behavior are shown in Fig. 3-5 for April 2020 releases and PLDs of 7-9.5 days, 30-34.5 days, and 60-69.5 days. For this behavior during this release month, all nearshore cells receive virtual larvae from at least one MPA. For shorter PLDs, nearshore cells tend to have greater connectivity to geographically close MPAs. For example, competency windows between 7-9.5 days results in cells 10 and 11 in southern Monterey Bay receiving larvae from Pacific Grove and Lovers Point MPAs, and cell 21, 22, 23 receiving larvae from nearby Greyhound Rock and Año Nuevo MPAs. At longer PLDs, the connections become more geographically distributed. For example, for competency windows between 30 and 34.5 days, cells 10 and 11 in southern Monterey Bay have relatively high probabilities of receiving larvae from all MPAs south of Pacific Grove. Cells 18 and 19 (near Santa Cruz) also derive larvae from distant MPAs to the south. Though their probabilities are much smaller, larvae originating from Año Nuevo and Greyhound Rock connect to coastal cells south of Carmel Bay, along the Monterey Peninsula, and within Monterey Bay. Finally, the pattern of connectivity changes at still longer PLDs, with strong connectivity between cells 21-26 north of Santa Cruz and MPAs from Point Lobos through Lovers Point and including Portuguese Ledge and Soquel Canyon. This figure highlights that the linkages between MPA regions and coastal zones are strong with details depending on PLD and on behavior (not shown). The resulting impact of such spillover effects on fisheries is not answered by this model but is a natural next step for study.

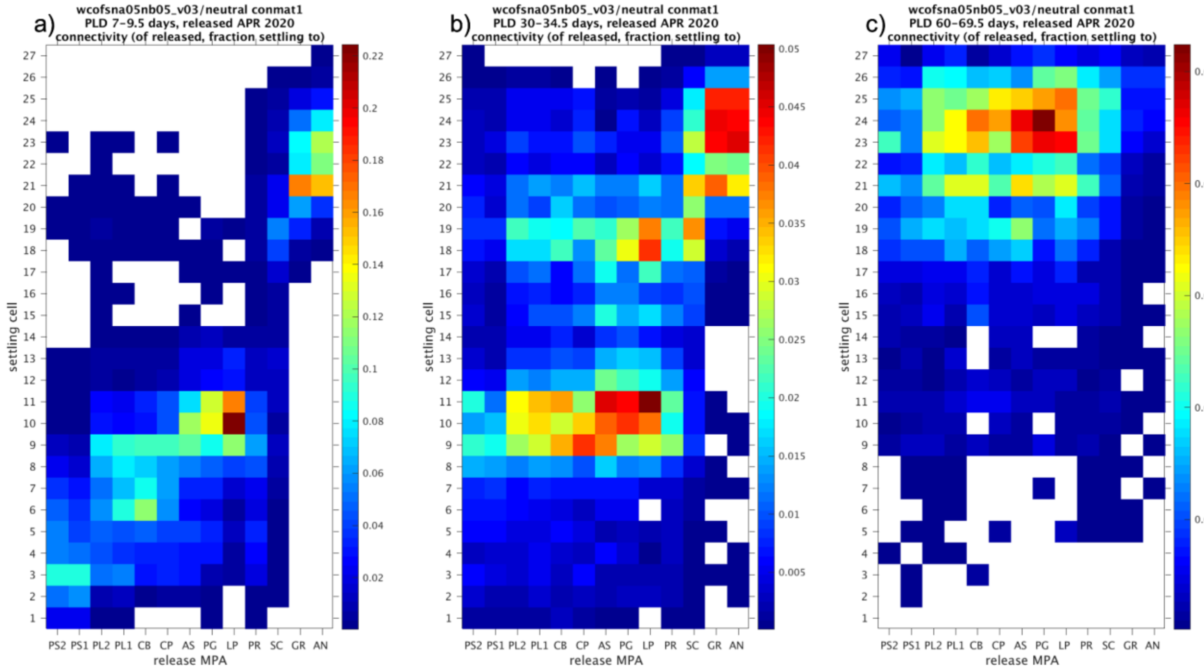


Figure 3-7. Connectivity matrices showing the probability that a float released from an MPA designated on the x-axis potentially could settle in a nearshore coastal region on the y-axis during the competency window of (a) 7-9.5 days; (b) 30-45 days; and (c) 60-69.5 days from release during April 2020 with the neutral behavior in which floats are transported passively by 3-dimensional modeled currents. The key for MPA initials and nearshore coastal subdomains is given in Fig. 3-2. Note differing color scales in each plot.

### 3.4.3 Maximum Monthly Connectivity

One synthesis of results is the maximum MPA connectivity obtained from monthly releases considering all analyzed PLD choices (7-9.5 days, 20-22.5 days, 30-34.5 days, 45-49.5 days, and 60-69.5 days), and here we present the case for diel vertical migration behavior between 5 m and 30 m depths (Fig. 3-8). This figure does not show a connectivity matrix which would be the *average* probability obtained over the period of interest. Rather it shows the *maximum* monthly probability calculated from 15 independent monthly connectivity calculations and across multiple PLD choices. Presented on a log-scale to highlight the small values, it is clear that with this behavior almost all MPAs are linked at some level. Several other broad characterizations may be also constructed from this figure. Portuguese Rock (PR) and Soquel Canyon (SC) abundantly receive larvae from all MPAs in the region. These regions sit within Monterey Bay and experience the mean circulatory structure within the bay and transient motion that effectively diffuse material laterally and link these regions to all other modeled MPAs. Asilomar, Pacific Grove (PG) and Point Lobos State Marine Conservation Area (PL2) also receive larvae broadly from many MPAs though at a lower level. In contrast, Año Nuevo (AN), Lovers Point (LP), Carmel Pinnacles (CP), and Point Sur State Marine Research (PS1) receive relatively few larvae from the MPA network. Finally, Año Nuevo and Greyhound Rock generally deliver relatively few larvae to coastal MPAs to their south. We emphasize that these results hold for the release months, PLDs, and behavior considered here and are presented as an example result, not a single figure that shows all possible connectivity for all possible behaviors.

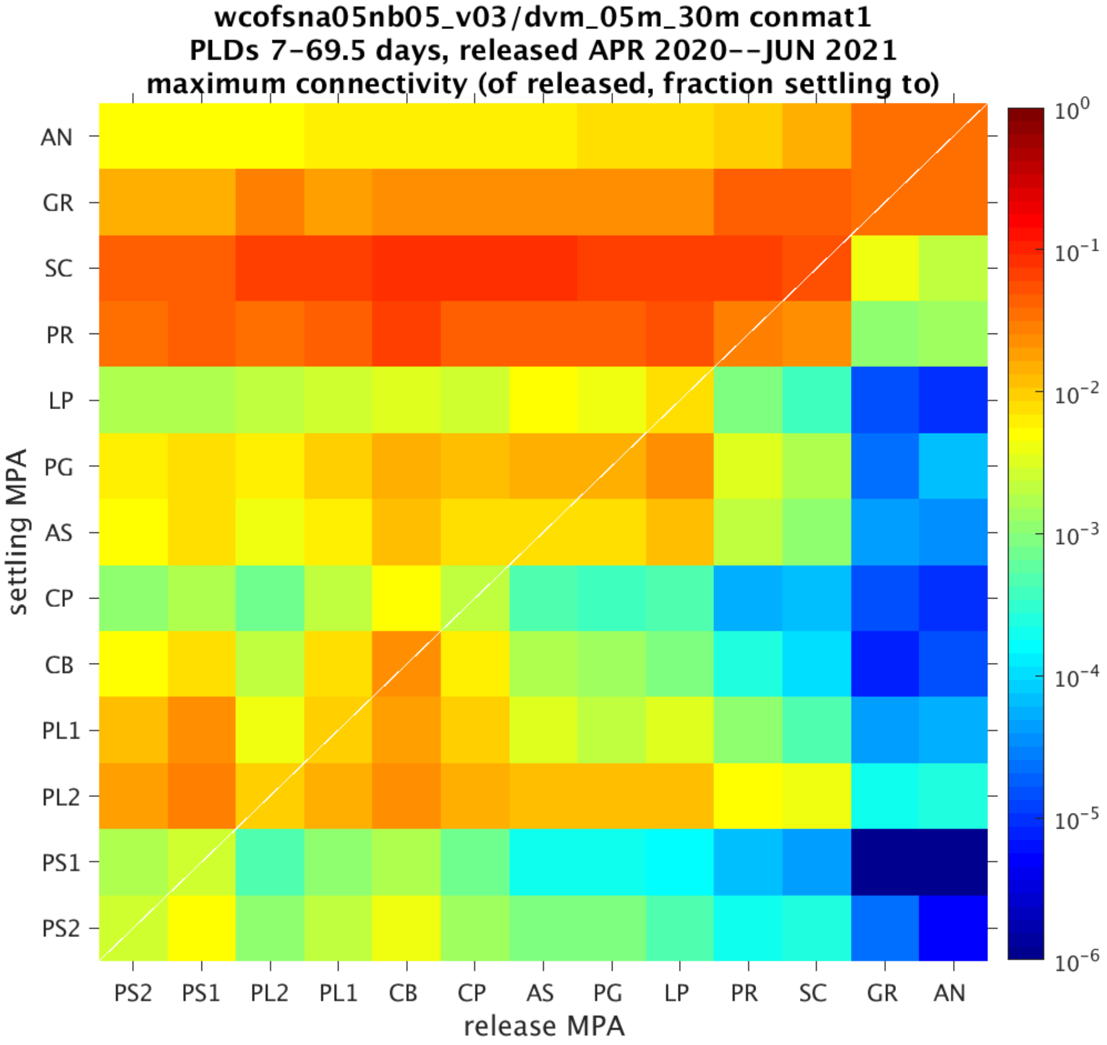


Figure 3-8. Maximum monthly connectivity obtained over all releases from April 2020 through June 2021 for PLDs analyzed (7-9.5 days, 20-22.5 days, 30-34.5 days, 45-49.5 days, and 60-69.5 days) for the diel vertical migration behavior in which organisms cycle daily between levels near 5 m depth at night and 30 m depth during daytime hours. We emphasize that this is not a connectivity matrix but rather the maximum monthly probability of connection from 15 realizations. The key for MPA initials and nearshore coastal subdomains is given in Fig. 3-2. Note the log-scale is used to highlight even very small values.

While geographical distance is a sensible first order metric to characterize connectivity, as demonstrated above it does not capture the potential realized connectivity resulting from actual oceanic flows. Oceanographic distance might better be represented by minimum, median, or average time to arrival, and should be considered in more detail in the future.

### 3.4.4 MPA Management Implications

In our results, marine connectivity depends explicitly on detailed choices of behavior, time of larval release, and PLD. For the greater Monterey Bay MPAs, connectivity is strong for different subsets of MPAs over different time-scales and behavior. Yet, overall, when considered over all time-scales and behaviors analyzed, we find that these MPAs are oceanographically connected at some level. This outcome might be anticipated by general transport properties of Monterey Bay combined with energetic submesoscale variability of coastal waters at scales of up to a few km spatially and hours to a few days temporally. The smallest amplitude connections, orders of magnitude smaller than for other linkages, were found consistently for all behaviors from Greyhound Rock and Año Nuevo releases to other MPAs of the greater Monterey Bay region. At this time, we suspect that this result may be related to a model bias of more northward transport in this region during the modeled period than likely exists in nature, but sensitivity studies with other model products are required to support or refute this result. Although we did not calculate demographic effects in this study per se, one can speculate that organisms with short PLDs will, over multiple generations and releases, fully span this collection of MPAs. For example, even with the extremely parsimonious distribution of larvae from Año Nuevo and Greyhound Rock MPAs shown in Fig. 3-5 for the diel vertical migration behavior, any redistribution to, say Point Lobos (PL2) will on a second generation be redistributed generously to many other MPAs. Organisms with longer PLDs are generally less strongly connected to local MPAs and more connected to more distant sites in one generation. A study spanning a larger meridional extent would be required to better understand the demographic implications of the long PLD cases.

The demonstrated oceanographic linkages shown here and potential further connectivity by multi-generational (i.e., demographic) steps suggest, based on ocean currents alone, some resiliency of the system to environmental disturbances. If a transient population decline were experienced by one MPA, there is support here for potential repopulation from other MPAs by ocean currents, though this statement must be qualified to emphasize that not all MPAs are equally habitable to all organisms and that is not presently considered in our modeling. For example, the shallow nearshore Carmel Bay MPA hosts different organisms than the deep Soquel Canyon and Portuguese Ledge MPAs. More broad regional environmental disturbance that impacts several MPAs likely will require longer times for recovery than impact to a single site. Resiliency should be examined much more carefully by also considering scenarios of specific organisms and their habitat, combined with demographic modeling, predation pressure, and specific environmental disturbance hypotheses.

### 3.4.5 Connectivity Modeling Roadmap for California Marine Protected Area Assessment

Given that we are here only producing high-resolution information for a portion of the MPAs, we set out to develop recommendations for connectivity mapping based on the available tools and lessons learned from this project. Here we will discuss recommendations that also include context from establishing and evaluating the WCOFS nest set focused on Monterey Bay. This is a revision from an initial roadmap provided in our reporting in summer 2020 (**Deliverable 1**).

This modeling configuration can be considered a prototype for similar operational implementations extending to other regions of the California coast. Our domain extends alongshore roughly 130 km, and California's coastline is roughly 1350 km. Thus, approximately 10 similar implementations would cover California's coastal waters in a non-overlapping fashion, somewhat more if overlap is desired. One possible route to expand on present modeling capabilities (Route 1) is that this set of nested domains be run separately from one another, operating independently and in parallel each day. With non-trivial development, larval connectivity calculations could utilize output from all nests simultaneously with particles tracking seamlessly from one domain to another. Thus, although the circulation models would be independent, larval connectivity calculations would synthesize all output, enabling connectivity estimates across the full network of MPAs. This approach is cost-effective, though it should be recognized as modestly imperfect. Ideally the circulation model nests would all be coupled to one another. At present, this more sophisticated approach is computationally prohibitive in ROMS because grid coupling significantly increases computational time and cannot be easily parallelized. Though this multi-domain configuration has independent circulation estimates for innermost coastal grids, they're not really independent as they share and are nudged to the same WCOFS solution. In practice, we believe this will be a practical and successful, if not final, approach.

A second approach toward a state-wide implementation (Route 2) is also possible. Our connectivity results for the middle and inner nests are quantitatively different but qualitatively quite similar, an outcome that stems from the weak nudging of nested subdomains to the data assimilative WCOFS output. This similarity suggests an alternate computational roadmap that is simpler and also viable for the purpose of connectivity calculation. Rather than constructing 10 multi-domain, independent nests, it would be sensible to focus only on the middle nest with resolution of 800 m, constructing one or no more than three adjacent nests to span California coastal waters.

Moving forward, these systems can be of great practical value as they provide ongoing and updated information. The WCOFS-based system we describe here begins March 10, 2020. Connectivity information represents statistical quantities that benefit from additional (i.e., multi-year) realizations. Historical reanalyses, going back, for example, to 2010 or 2001 are one approach to increase the statistics and better represent climatological connectivity. Such historical runs would necessarily use a non-WCOFS data assimilative model for the outermost domain and would generate more robust connectivity statistics than analyzing only 1.5 years of trajectories.

Like weather forecasting, hydrodynamic modeling of realistic coastal ocean currents is a challenging operation. The present system constructed for this project should be considered a baseline configuration, and we recommend future support to further develop this subsystem and improve model fidelity. Here we document quantitative evaluations of the model output against independent estimates of near surface currents which are most relevant to larval transport, and areas of agreement and discrepancy are found. Tides were not included explicitly in trajectory calculations. Rivers of the central California coast are not included in either the WCOFS outer domain or the nests developed for this project, and thus their influence is not presently known. Data assimilation for nested model configurations is an area of active research, and it is likely that future coastal ocean modeling could include this capability to better constrain high resolution model fields with observations. Furthermore, the connectivity calculations can be enhanced and refined through incorporation of habitat information (not all MPAs provide identical habitat for all organisms) and demographic calculations, elements that were neglected here.

Finally, we offer recommendations for computational requirements for a statewide system. On the UCSC computing cluster, our implementation runs on 4 recent-generation dual-processor nodes at a rate of about two computational hours per modeled day. If dedicated, these 4 nodes could narrowly manage a near real-time state-wide system of 10 similar domains (Route 1). A test configuration of a statewide single nest (Route 2) also runs at about 2 hours per modeled day on 4 nodes. For the California-wide configuration, we recommend access to a larger computing cluster of at least 20 nodes to allow parallel operation of nests and sufficient resources for historical reanalyses, ability to catch-up when inevitable compute outages occur, and to test and evaluate improved model configurations. In addition, these high-resolution fields are demanding in terms of storage. Our present multi-nested configuration for Monterey Bay only consumes approximately 1.5 TB per model year; a similarly configured California-wide implementation (Route 1) would require about 15 TB per model year, a non-negligible but manageable amount on present RAID storage systems. Route 2 requires less storage; we estimate it at 1.5 TB per model year. If tides were desired to be included in the stored fields, storage would increase by a factor of 24. Finally, we note that the final storage requirement may be reduced through careful selection of stored fields and compression techniques, but we have not at present demonstrated a smaller storage footprint and thus conservatively report the larger amount.

# 4. Ecological Indicators for Seascapes and Harmful Algal Bloom Risk in MPAs (Objective 4)

## 4.1 Summary

- Seascapes represent coherent oceanographic regions with unique biogeochemical function. Overall, California’s MPAs experience similar ocean conditions within their bioregions, but ocean conditions in the South Coast and Channel Islands MPAs are more diverse on an overall and annual basis.
- We see high mean kelp biomass associated with seascapes 11 tropical/subtropical upwelling and 27 hypersaline eutrophic, while seascape 15 tropical seas has the lowest mean kelp biomass.
- Analyses show that the frequency with which a location experiences a particular Seascape is related to the amount of kelp at that location. Although Seascapes is a global model, these findings show that Seascapes detected at resolutions relevant to MPAs capture high-level variability among California’s marine waters.
- The EcoCast and California-Harmful Algae Risk Mapping (C-HARM) risk maps show that the frequency, persistence and spatial extent of HABs has increased over recent years and that these areas coincide with ecologically important migrating species.

## 4.2 Ecological Indicators Objectives

The MPA Action Plan identifies several questions related to disturbances, biodiversity, and habitat types found within the current MPA network. We addressed these questions using multivariate ecological models (Seascapes, California-Harmful Algae Risk Mapping (C-HARM), and EcoCast) to produce statewide quantitative, indicator-based assessments. We also used other data from the long-term monitoring programs to give additional context to the ecological trends identified.

One of the original proposed objectives for these ecological models was to "produce an ecological model synthesis tool, multivariate, meta-analysis, and indicator metrics". This has been accomplished by integrating MPA-specific summaries and visualizations of Seascapes, C-HARM, and EcoCast into the MPA dashboard (see *Section 2. Data Standardization, Curation, Integration, and Visualization with the California MPA Dashboard*).

| *MLPA Goal 1: Protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems* | |
|---|---|
| Questions from MPA Action Plan | Ecological Indicators Research Objectives |
| ● Do MPAs that include multiple habitat types harbor higher species abundance or more diverse communities than those that encompass a single habitat type or less diverse habitat types?<br>● Does the nature or timing of recovery of natural communities from disturbance events differ in different types of MPAs relative to outside areas? | ● How are Seascapes changing in MPAs and with what biological relevance?<br>○ Maps and spatial summaries of Seascapes within MPAs;<br>○ Comparison of Seascapes Shannon Diversity Indices and PISCO Shannon Diversity Indices over time for selected MPAs. |

| *MLPA Goal 4: To protect marine natural heritage, including protection of representative and unique marine life habitats in California waters for their intrinsic value.* | |
|---|---|
| Question from MPA Action Plan | Ecological Indicators Research Objectives |
| ● Have unique habitats been adequately represented and protected by the current distribution and designation of MPAs? | ● Maps and spatial summaries of Seascapes within MPAs. |

| *MLPA Goal 6: To ensure that the MPAs are designed and managed, to the extent possible, as a component of a statewide network* | |
|---|---|
| Question from MPA Action Plan | Ecological Indicators Research Objectives |
| ● How do other stressors impact the management of MPAs over time (e.g., water quality, oil spills, desalination plants, ocean acidification, sea level rise)? | ● How has HAB risk (*Pseudo-nitzschia* and domoic acid concentrations) varied in MPAs?<br>○ Maps and spatial summaries of C-HARM and EcoCast. |

## 4.3 Methods

### 4.3.1 Assessing oceanographic habitat diversity with Seascapes

Seascapes are landscape-scale water masses that are characterized by their physical, biological, and chemical properties that are dynamic in time and space. These properties have the potential to predict important biological responses and ecological processes that are actionable for ocean and coastal management (Caldow et al. 2015, Kavanaugh et al. 2016, Lewison et al. 2015). Unlike static features that often characterize habitats, the variables that comprise seascapes are dynamic in time and space. Thus, Seascapes reflect short- and long-term variability in coastal and ocean areas over time and have the potential to predict biological responses relevant to spatially-explicit or adaptive ocean management frameworks (Caldow et al. 2015, Lewison et al. 2015). As Seascapes integrate local-scale data to understand landscape-scale processes, they can be used to improve our understanding of connectivity among MPA networks as well as how ecosystem-scale problems like climate change may impact MPAs. Seascapes are created from predictive model variables and remotely-sensed data variables, including: sea surface temperature (SST), photosynthetically active radiation (PAR), sea surface salinity (psu), absolute dynamic topography (ADT), ice contribution, chromophoric dissolved organic material (CDOM), chlorophyll a (Chl a), Moderate Resolution Imaging Spectroradiometer (MODIS) normalized fluorescence line height (nFLH), and the nFLH:Chl a ratio. Based on these data, water masses are categorized by the model into 33 Seascape categories of similar biochemical function (NOAA MBON, Kavanaugh et al. 2014).

A total of 12 distinct Seascape types have been identified in California waters (Table 4-1). To assess the diversity and uniqueness of oceanographic habitat conditions in California MPAs (MLPA Goal 4 Questions), we calculated the Shannon Diversity Index (SDI) of Seascapes for each individual MPA and for each bioregion, for different time periods and for the entire dataset. The SDI is a measure of diversity that accounts for both the number of different Seascapes encountered, as well as the relative proportion of those different Seascapes. We generated stacked plot visualizations of the Seascape composition for each MPA and bioregion for different time periods and for the entire dataset.

Table 4-1. List of all Seascape categories that have occurred in California waters during the model year range of 2002-2021. Note that because Seascapes were categorized and named using a global model for water masses of similar biochemical function, the nominal names of some Seascapes may not be particularly intuitive for a California-specific context, e.g., Seascape 12 “Subpolar”.

| **Seascape** | **Seascape Nominal Descriptor** |
|---|---|
| 7 | Temperate Transition |
| 11 | Tropical Subtropical Upwelling |
| 12 | Subpolar |
| 14 | Temperate Blooms Upwelling |
| 15 | Tropical |
| 17 | Subtropical Transition Low Nutrient Stress |
| 19 | Arctic Subpolar Shelves |
| 20 | Subtropical Fresh Influenced Coastal |
| 21 | Warm Blooms High Nutrients |
| 22 | Arctic Late Summer |
| 23 | Freshwater Influenced Polar Subpolar Shelves |
| 27 | Hypersaline Eutrophic |

We also investigated potential relationships between oceanographic habitat conditions and ecological communities (MLPA Goal 1 Questions) - specifically, giant and bull kelp as habitat-forming species, and kelp forest communities. We obtained satellite-derived data for kelp canopy area and estimated biomass in California coastal waters (Santa Barbara Coastal LTER et al. 2021). For each spatial pixel within California coastal waters in the kelp dataset, we identified the modal Seascape as the most frequently observed Seascape category over a three-month interval (i.e., a quarter). We compared kelp biomass and area extent by the modal Seascape to assess which Seascapes were associated with the highest kelp mass. We also compared SDI of Seascapes with the SDI of species recorded from kelp forest benthic swath surveys run by the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO).

### 4.3.2 Harmful Algal Bloom Risks through the C-HARM Model

The California-Harmful Algae Risk Mapping (C-HARM) Model generates predictions of harmful algal bloom (HAB) conditions through a combination of (1) circulation models that predict ocean physics; (2) satellite remote-sensing data of ocean color and chlorophyll patterns; and (3) statistical models for predicting bloom and toxin likelihoods (Anderson et al. 2016). These predictions show where one might encounter a *Pseudo-nitzschia* bloom and/or domoic acid event within California waters. The C-HARM model outputs include (1) the locations (spatial pixels) with a ≥60% probability of a *Pseudo-nitzschia* bloom; (2) the probability that particulate domoic acid (pDA) in a spatial pixel is at or above 500 nanograms per liter; (3) the probability that cellular domoic acid (cDA) in a spatial pixel is is at or above 10 picograms per cell. More information on the C-HARM model is given in Appendix A4.1.

To assess the risk of an important biological stressor, HABs, in MPAs over time (MLPA Goal 6 Questions), we generated plots of the number of spatial pixels within MPAs in a specific bioregion with high probability of cDA, pDA, and *Pseudo-nitzschia* (PN) counts. These are representations of risk time series. We also generated heatmap plots showing the number of days per month in which at least one pixel within the MPAs in each bioregion was considered "high risk" for harmful algal blooms (*i.e.*, cDA, pDA, and PN probability values surpassed a threshold of 0.6).

### 4.3.3 Bycatch Risk through the EcoCast model

EcoCast is a fisheries sustainability tool that helps fishers and managers evaluate how to allocate fishing effort to maintain target fish catch while minimizing bycatch of protected or threatened species. It incorporates sea surface chlorophyll concentration, sea surface temperature, sea surface winds, sea surface height, and eddy kinetic energy to predict the spatial distributions of important migratory species, including target species and bycatch species such as leatherback sea turtles, sea lions, and blue sharks. Here we use EcoCast predictions of key threatened bycatch species distributions to assess where and when they overlap with high risk of harmful algal blooms. We generated maps of the co-occurrence of high risk of harmful algal blooms ($P > 0.6$, from the C-HARM model) and high relative abundance ($P > 0$) of swordfish fisheries bycatch species, and calculated the spatial prevalence of these high-risk areas for each bioregion.

## 4.4 Results and Management Implications

### 4.4.1 Seascape Dynamics and Ecological Relevance in MPAs

#### 4.4.1.1 Seascape Diversity and Dynamics

Across California MPAs, Seascape 14 "Temperate Blooms Upwelling" and Seascape 21 "Warm Blooms, High Nutrients" appeared most frequently (Fig. 4-1 and 4-2). Seascapes also showed geographic differences, with MPAs generally being more diverse and dynamic in the South Coast and Channel Islands than in the North Coast and Central Coast, both on an annual and overall basis (Fig. 4-1 and 4-3). Aberrant ocean conditions were also detected using Seascape classifications, including the 2015 marine heat wave ("the blob"), characterized as Seascape 17 "Subtropical Transition Low Nutrient Stress", which was evident from Southern California MPAs north to Campus Point SMCA (Fig. 4-1). The time series of Seascapes also shows yearly seasonality in most MPAs. Although Seascapes is a global model, these findings show that Seascapes detected variation at resolutions relevant to MPAs to capture summary-level variability among California's marine waters.

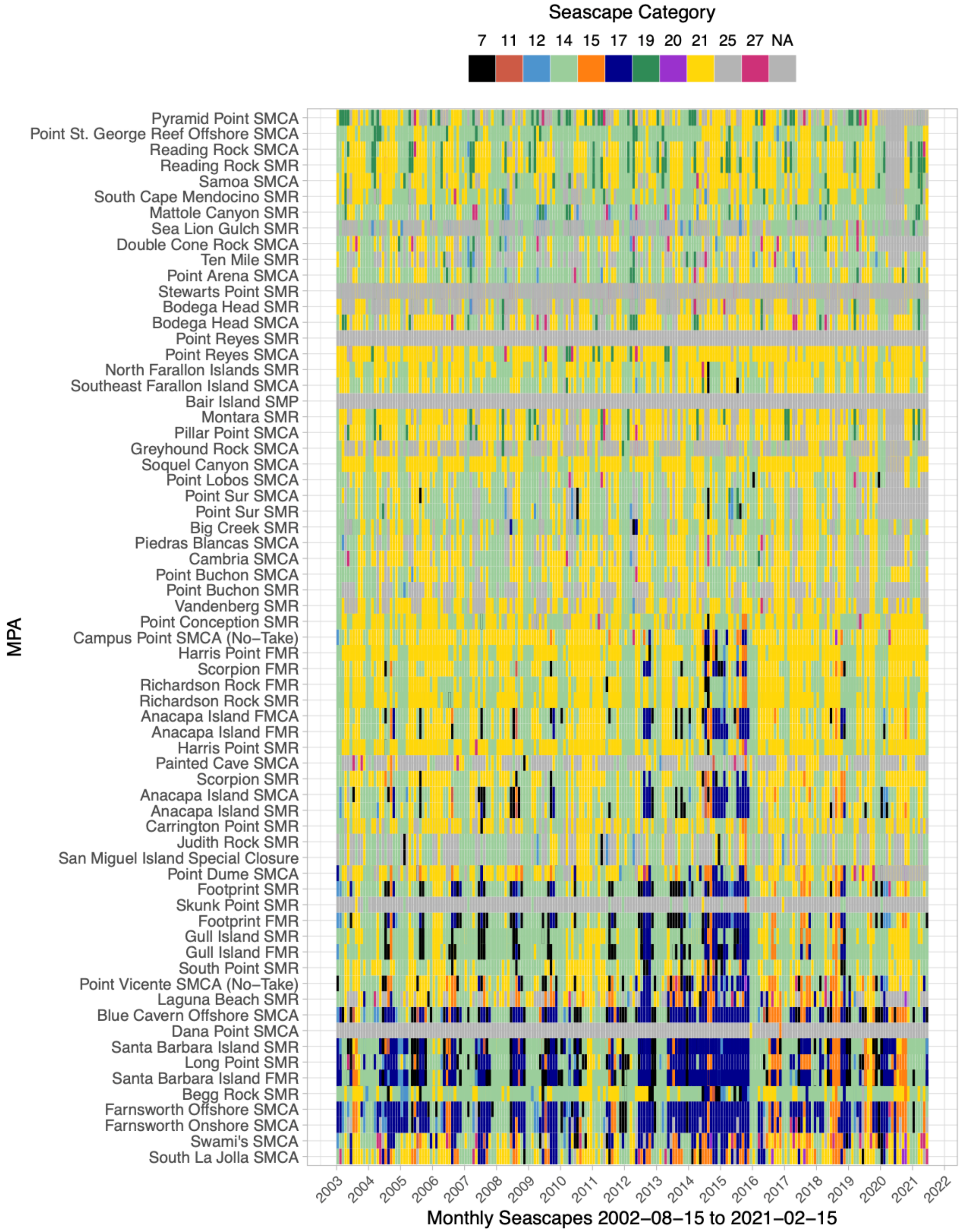


Figure 4-1. Time series of monthly Seascapes within the MPAs, ordered by latitude. Seascapes are dynamic classifications of water masses based on sea surface properties derived from satellite imagery. Data spans 2002-08-15 to 2021-02-15.

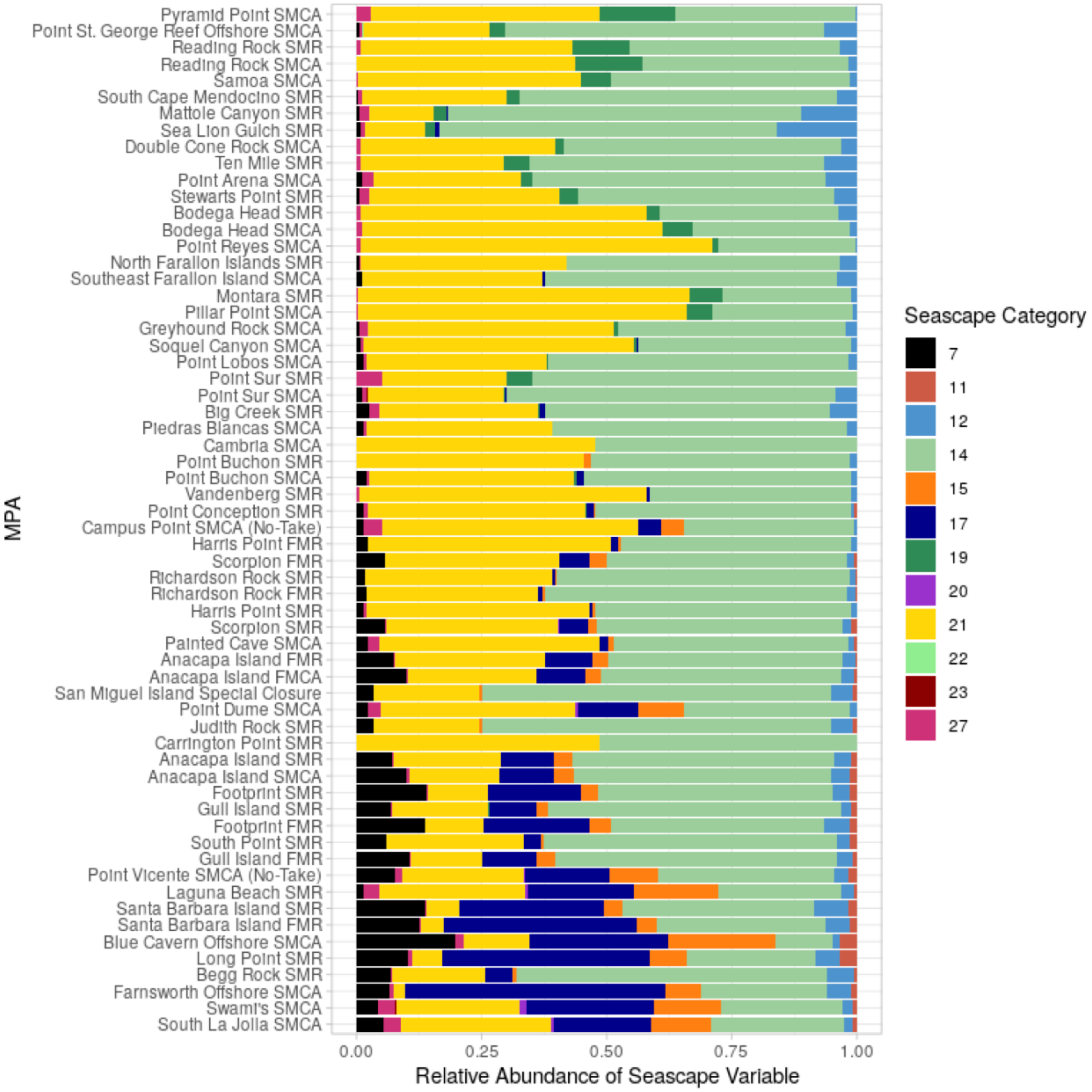


Figure 4-2. Stacked bar plots of relative abundance of Seascapes in all MPAs, ordered by latitude, throughout the entire time series. Seascapes are dynamic classifications of water masses based on sea surface properties derived from satellite imagery. Data spans 2002-08-15 to 2021-02-15.

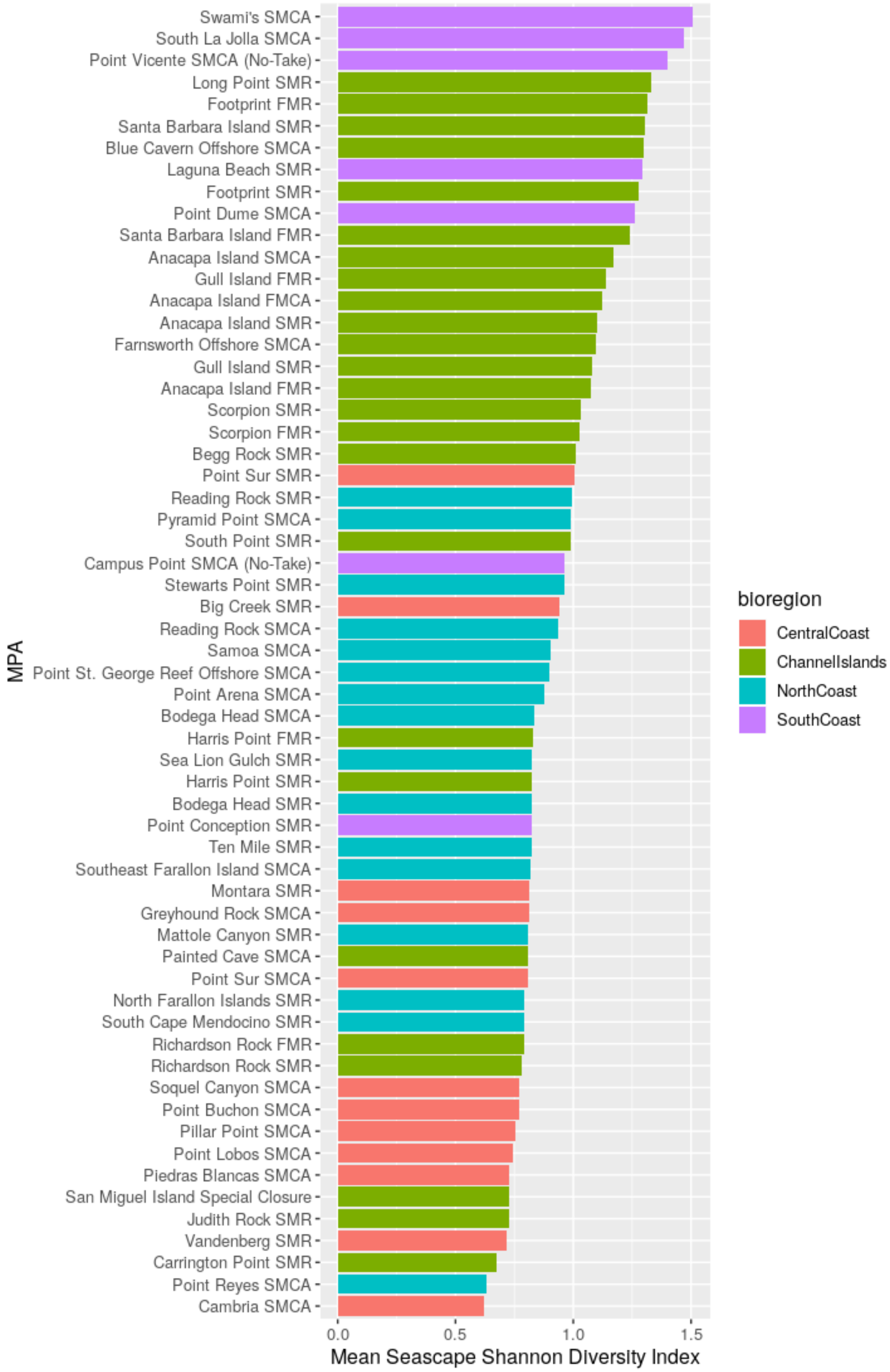


Figure 4-3. Mean Shannon Diversity Indices (SDI) of Seascape classes for all of Seascape data for MPAs from 2002-08-15 to 2021-02-15. Shannon Diversity Indices were calculated using monthly Seascape data.

### 4.4.1.2 Seascapes and Kelp Abundance

As kelp forests support a diverse ecosystem of marine life, knowing where and under what conditions they thrive can aid kelp protection, recovery, and management. We found that kelp canopy biomass and extent were significantly associated with the majority of detected Seascapes and were the highest in locations dominated by Seascapes with warmer sea surface temperatures and under a high range of nutrient regimes. Locations with modal Seascape 11 "Tropical/Subtropical Upwelling" and modal Seascape 27 "Hypersaline Eutrophic" were associated with higher kelp biomass (Fig.4-4) while modal Seascape 15 "Tropical Seas" was associated with the lowest mean kelp biomass.

We also found that the frequency of most Seascapes was statistically associated with differences in kelp biomass (Fig. 4-5, Table 4-2). Most notably, higher frequencies of Seascape 7 "Temperate Transition" and Seascape 21 "Warm Blooms High Nutrients" were associated with higher kelp biomass (Fig. 4-5A, H) while higher frequencies of Seascape 20 "Subtropical Fresh Influenced Coastal" and Seascape 15 "Tropical Seas" were associated with lower kelp biomass (Fig. 4-5E, G).

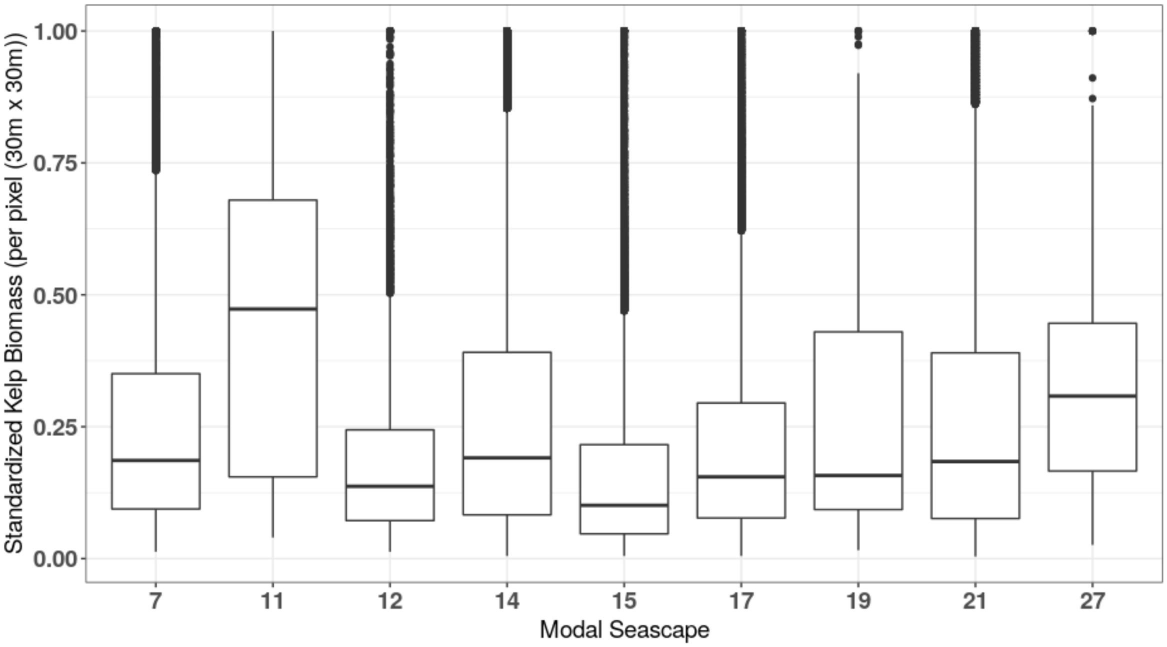


Figure 4-4. Boxplots of standardized kelp biomass vs. the modal Seascape at a location in the dataset over a quarter. Standardized kelp biomass was calculated by dividing the observed kelp biomass at a spatial pixel during a specific quarter by the maximum observed kelp biomass at that pixel in the dataset. Modal seascape is the most frequently observed Seascape at a given spatial pixel during a quarter. The boxplot represents the 25%-75% quantiles and the horizontal line represents the median. Standardized kelp biomass was calculated by dividing the observed kelp biomass at a spatial pixel (i.e., location) at a specific time by the maximum observed kelp biomass at that pixel throughout the sampling period.

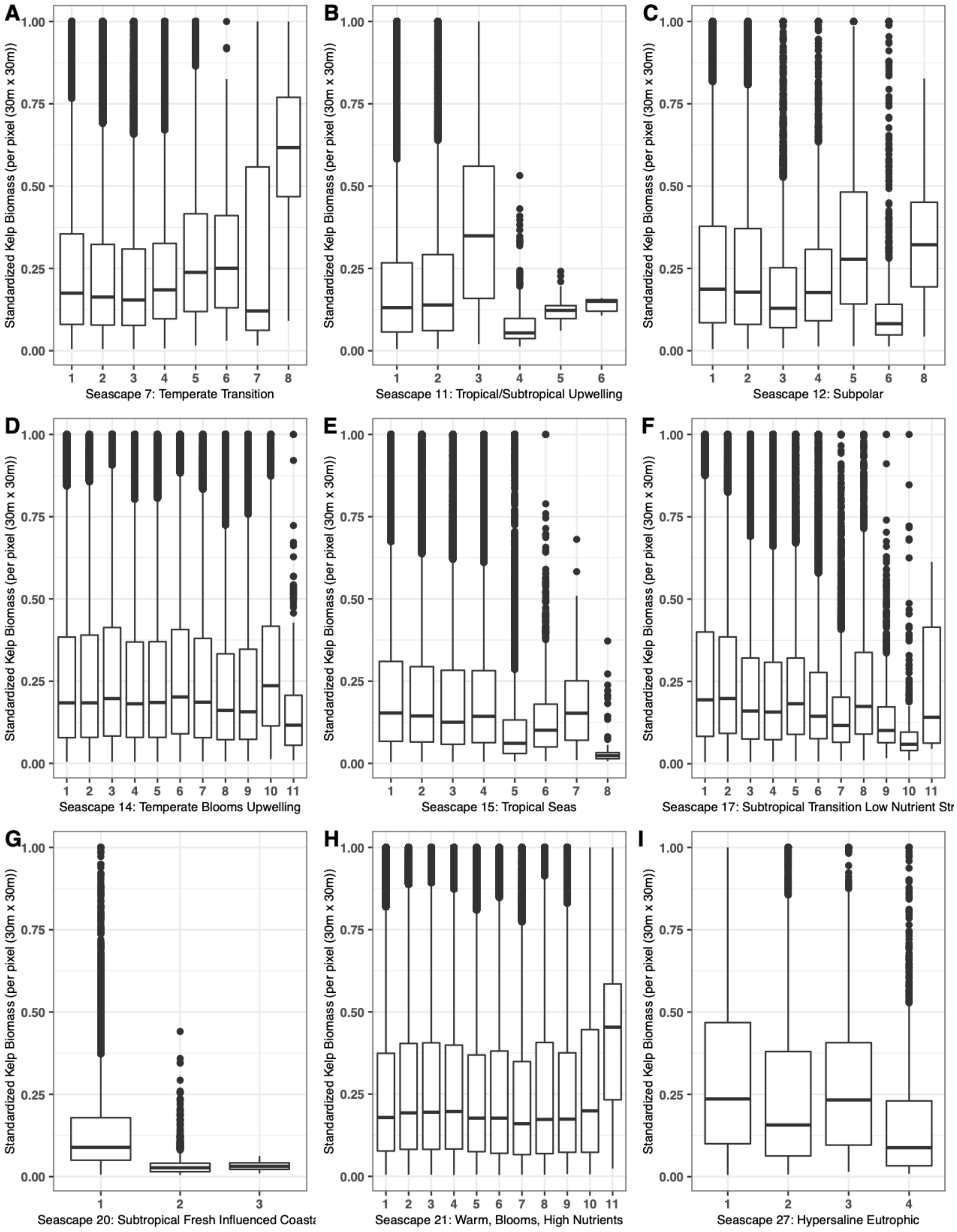


Fig 4-5. Boxplots of standardized kelp biomass vs. the number of times a given Seascape was observed at a location in the dataset over a quarter. Standardized kelp biomass was calculated by dividing the observed kelp biomass at a spatial pixel during a specific quarter by the maximum observed kelp biomass at that pixel in the dataset.

Table 4-2. Summary statistics for Kruskal-Wallis tests of kelp estimated biomass vs key Seascape variables by quarter between August 15, 2002 and February 15, 2021.The H statistic, degrees of freedom (df), and p-value are reported.

| **Test Variable** | **Degrees of Freedom (df)** | **Kruskal-Wallis H Statistic** | **P-value** |
|---|---|---|---|
| Modal Seascape | 10 | 10662 | <0.0001*** |
| No. of occurrences of Seascape 7 “Temperate Transition” | 7 | 1050 | <0.0001*** |
| No. of occurrences of Seascape 11 “Tropical/Subtropical Upwelling” | 5 | 868 | <0.0001*** |
| No. of occurrences of Seascape 12 “Subpolar” | 6 | 2101 | <0.0001*** |
| No. of occurrences of Seascape 14 “Temperate Blooms Upwelling” | 10 | 2947 | <0.0001*** |
| No. of occurrences of Seascape 15 “Tropical Seas” | 7 | 3536 | <0.0001*** |
| No. of occurrences of Seascape 17 “Subtropical Transition Low Nutrient Stress” | 10 | 5178 | <0.0001*** |
| No. of occurrences of Seascape 20 “Subtropical Fresh Influenced Coastal” | 2 | 1005 | <0.0001*** |
| No. of occurrences of Seascape 21 “Warm Blooms High Nutrients” | 10 | 2853 | <0.0001*** |
| No. of occurrences of Seascape 27 “Hypersaline Eutrophic” | 3 | 952 | <0.0001*** |

#### 4.4.1.3 Seascape Diversity and Biodiversity

Links between Seascape categorical diversity and biodiversity are MPA-specific. Relating dynamic Seascape habitat diversity with PISCO benthic community biodiversity metrics shows that there are localized, MPA-specific relationships between these metrics. Fig. 4-5 shows means for the Seascape SDI calculated using the four quarterly SDI (n = 2 for 2002, n = 4 all other years) values per year. There is a close association between PISCO SDI and Seascape SDI for Anacapa Island SMR (Channel Islands) and Point Dume SMCA (South Coast). There is also a close association between PISCO SDI and Seascape SDI for Anacapa Island SMCA with some divergence starting in 2015. Stewarts Point SMR (North Coast) PISCO SDI is higher than Seascape SDI by about 1 unit for 2010, 2011, 2017, and converges in 2018. Point Conception SMR (South Coast) PISCO SDI is 1.5-2 units (in most cases resulting in PISCO SDIs more than double than Seascape SDI) higher than the Seascape SDI except for 2007 and 2014 where they are about 0.5 units different. The largest difference in SDI at Point Conception SMR occurs in 2004-2005. More work will be done with the habitat team experts for relating biological diversity to Seascape dynamics.

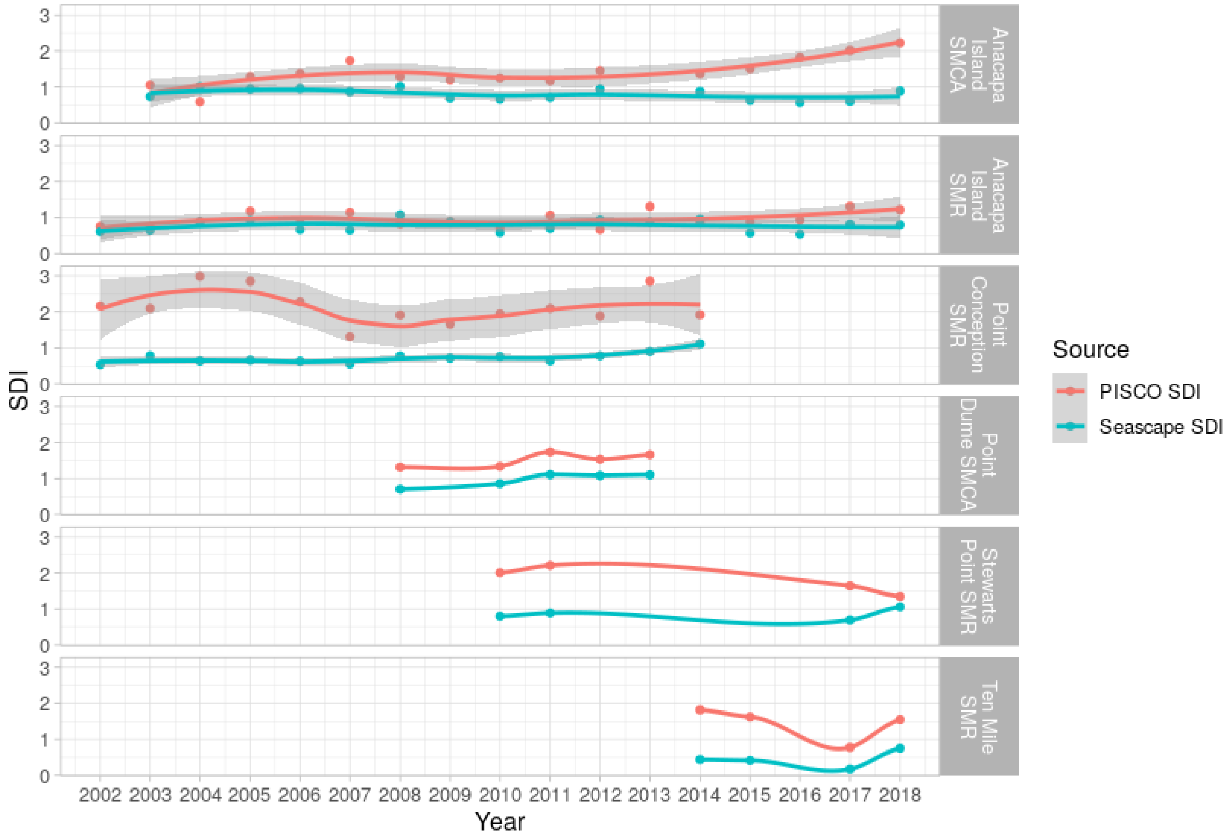


Figure 4-6. Line plots of Shannon Diversity Indices (SDI) of Seascapes and PISCO Swath data for the following MPAs: Anacapa Island SMCA, Anacapa Island SMR, Point Conception SMR, Point Dume SMCA, Stewarts Point SMR, Ten Mile SMR. The raw monthly Seascape dataset was used to calculate quarterly SDI values. The plot shows means for the Seascape SDI calculated using the four quarterly SDI (n = 2 for 2002, n = 4 all other years) values per year. The points for the PISCO Swath data show means of SDI for yearly benthic surveys taken within each MPA (n = 1-12 sites within each MPA ). The lines show 95% confidence intervals if there is data for every year.

## 4.4.2 Harmful Algal Bloom Risks

### 4.4.2.1 Spatial and Temporal Variation in MPA Harmful Algal Bloom Risks

It is important to develop rapid response capabilities to unanticipated biodiversity and fisheries emergencies such as harmful algal blooms (HABs). C-HARM temporal patterns show that across different HAB variables (cellular domoic acid, particulate domoic acid, and *Pseudo-nitzschia* concentrations), the risk of exceeding thresholds was already high in all bioregions and increased over time across all bioregions. The EcoCast and C-HARM risk maps show that the frequency, persistence and spatial extent of HABs has increased over recent years and that these areas coincide with the occurrence of ecologically important migrating species. This is especially relevant for the management and conservation of marine mammals and shore/sea birds that are known to suffer adverse effects due to domoic acid and HABs.

The plots of spatial extent (Fig. 4-7) and temporal extent (Fig. 4-8) of HAB impacts show that areas with high predicted cellular domoic acid (cDA) are larger-sized in the north and become smaller-sized with shorter event durations in the south. *Pseudo-nitzschia* (PN) concentrations showed similar trends to cellular domoic acid (Appendix Fig. A4-1, A4-2). Particulate domoic acid (pDA) has the opposite geographic trend than cDA and PN with larger areas and more long lasting events in the south (Fig. 4-9, 4-10). The percentage of the year in which high predicted cDA, pDA, and PN concentrations occur has increased to 100% across the board although it was already high across bioregions. The persistence of high cDA, pDA, PN concentrations is also high in all bioregions.

The relative mean areas of monthly risk of high HAB and high bycatch species prevalence (Fig. 4-11) captured the large red tide of 2020. We see that the trends are the same across the MPAs in all bioregions but more spatially prevalent in the MPAs in the Central and Northern Coast.

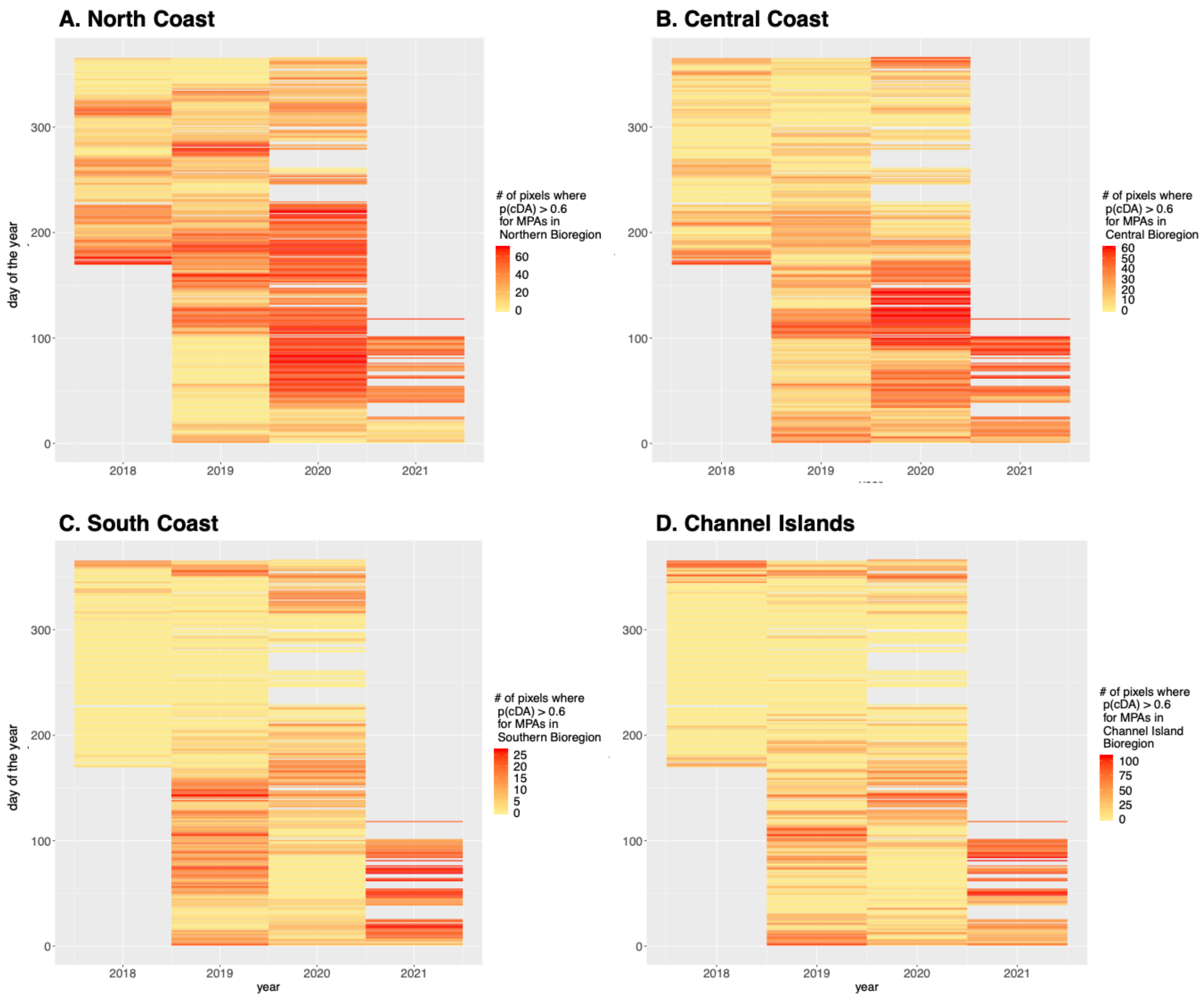


Figure 4-7. Plots showing the spatial extent (number of spatial pixels) for which there was a > 0.6 probability of cellular domoic acid (cDA) concentrations exceeding the threshold of 10 picograms/cell, for each day of the year from 2018-06-18 to 2021-02-10 for MPAs in each bioregion. The gray areas indicate no data.

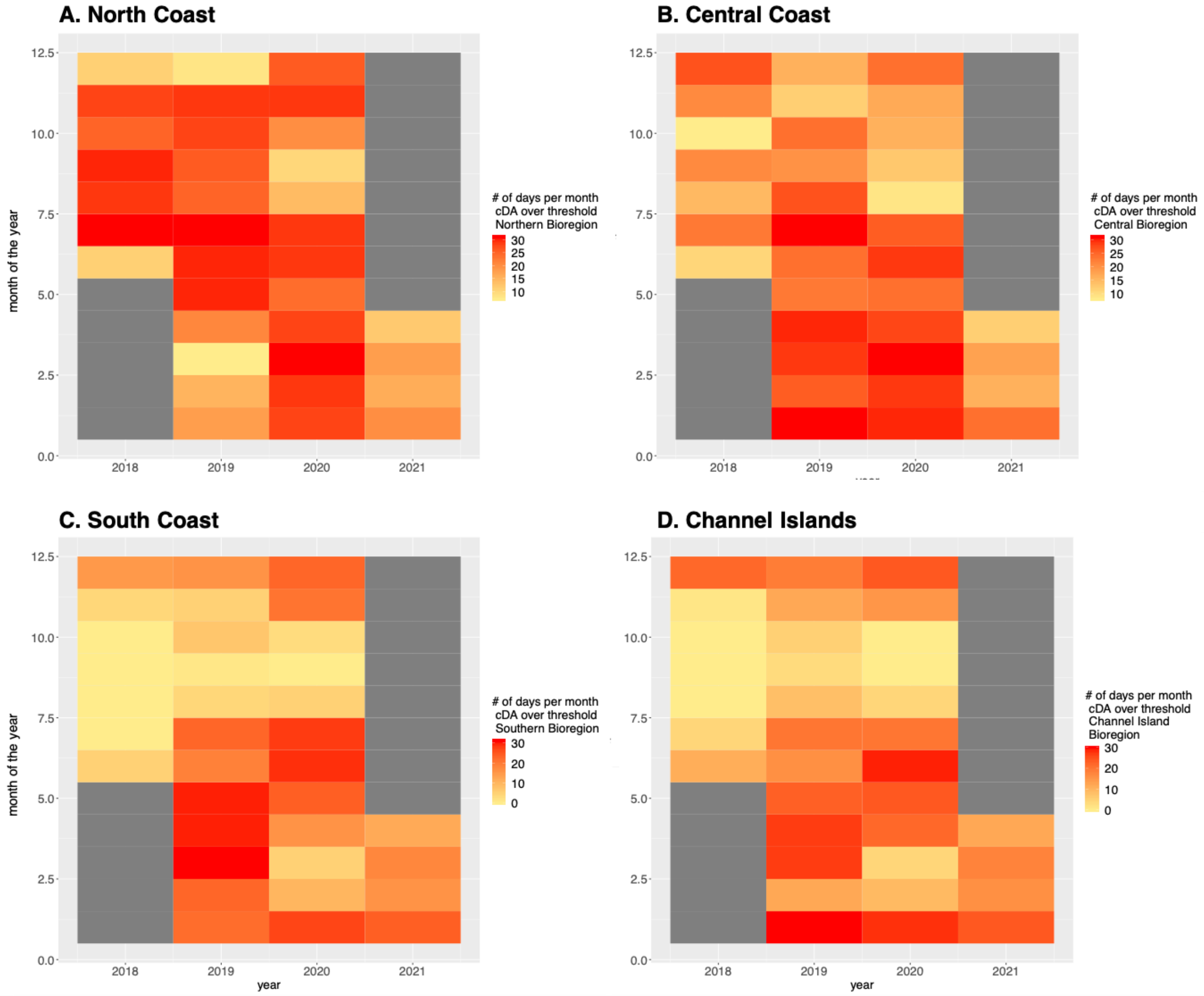


Figure 4-8. Heat map plots showing the number of days of each month from 2018-06-18 to 2021-02-10, where at least one location in the aggregated MPAs had a > 0.6 probability of cellular domoic acid concentrations exceeding the threshold of 10 picograms/cell.

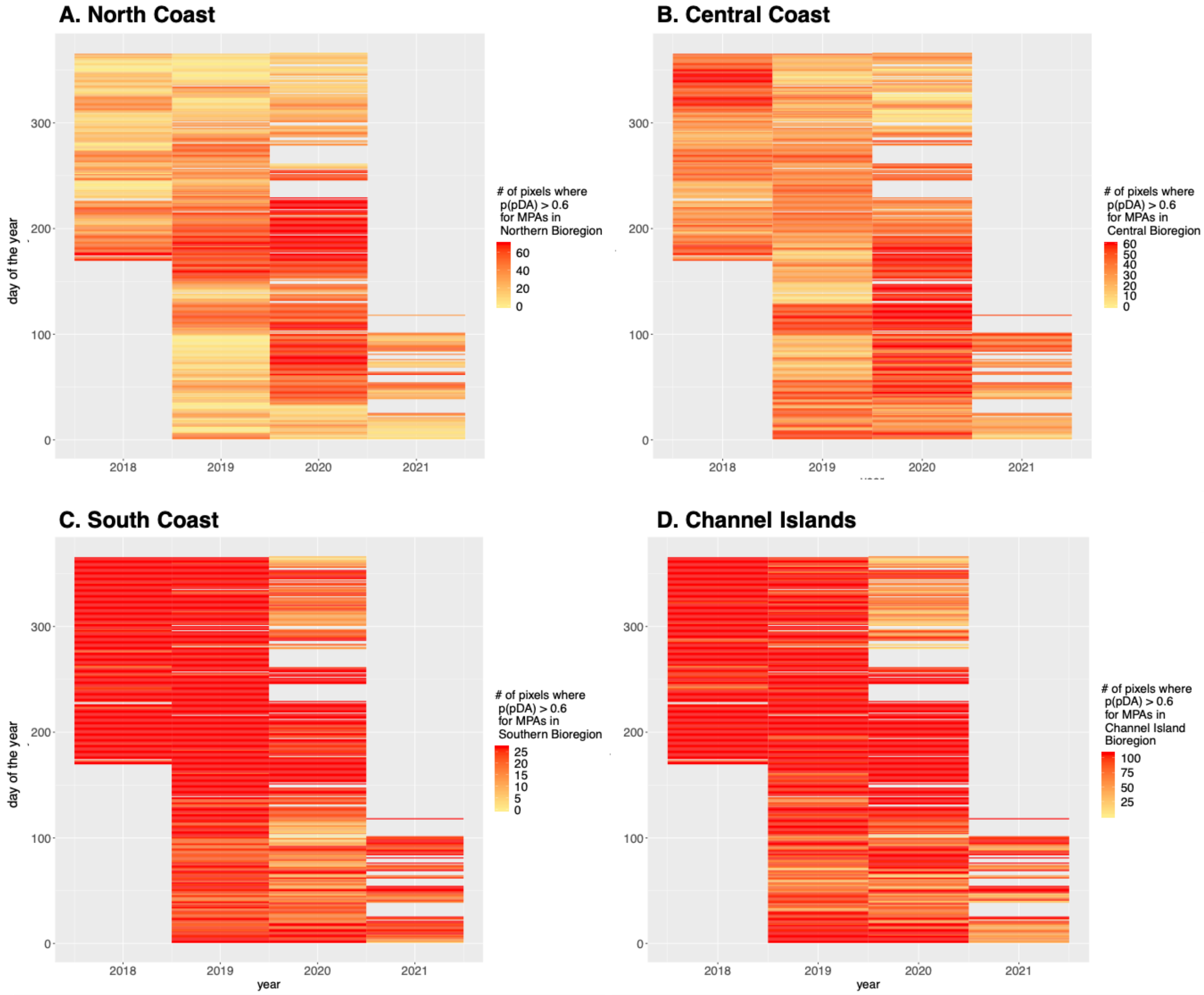


Figure 4-9. Plots showing the spatial extent (number of spatial pixels) for which there was a > 0.6 probability of particulate domoic acid (pDA) exceeding the threshold of 10 picograms/cell, for each day of the year from 2018-06-18 to 2021-02-10 for MPAs in each bioregion. The gray areas indicate no data.

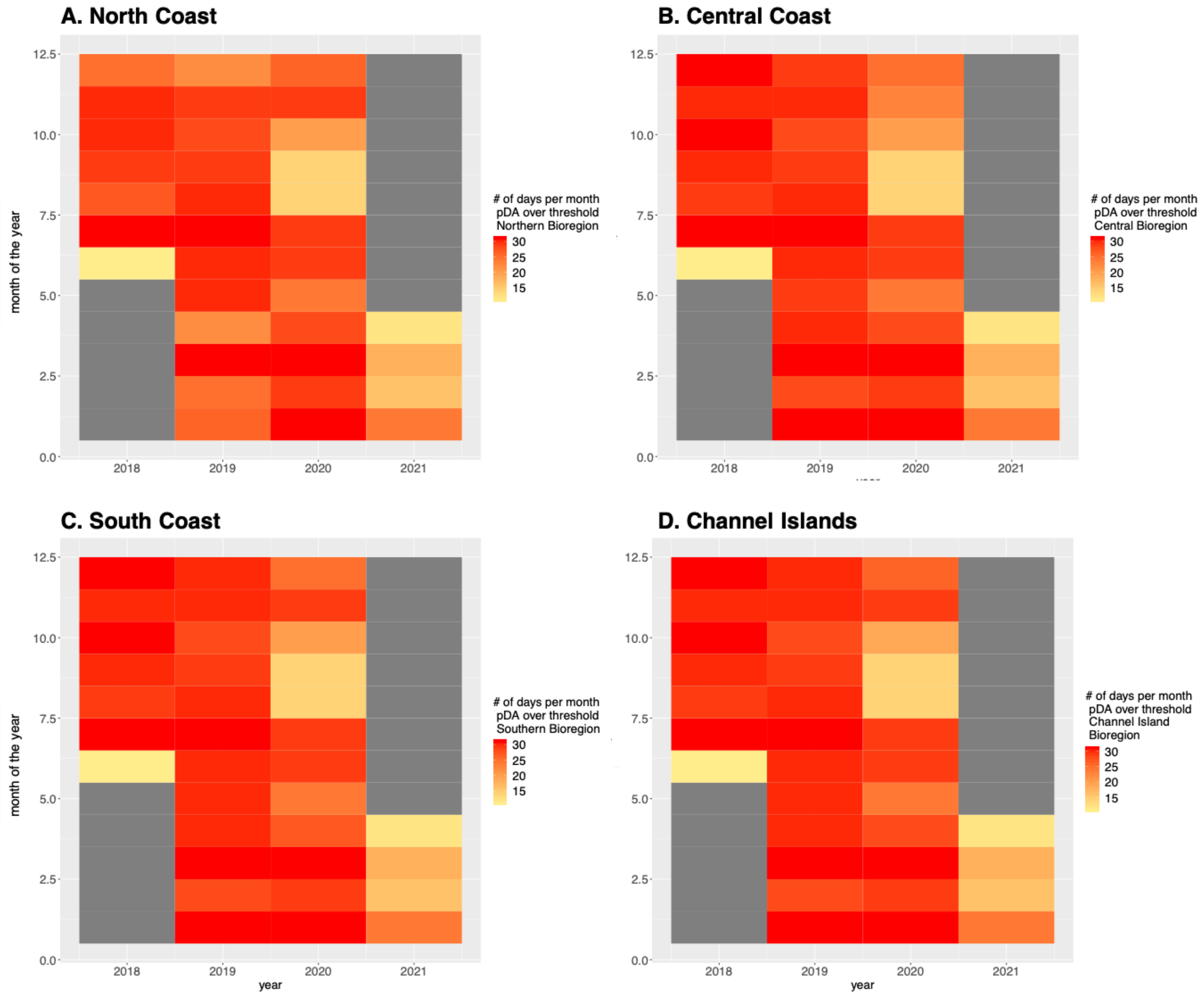


Figure 4-10. Heat map plots showing the number of days of each month from 2018-06-18 to 2021-02-10, where at least one location in the aggregated MPAs had a > 0.6 probability of particulate domoic acid (pDA) concentrations exceeding the threshold of 10 picograms/cell

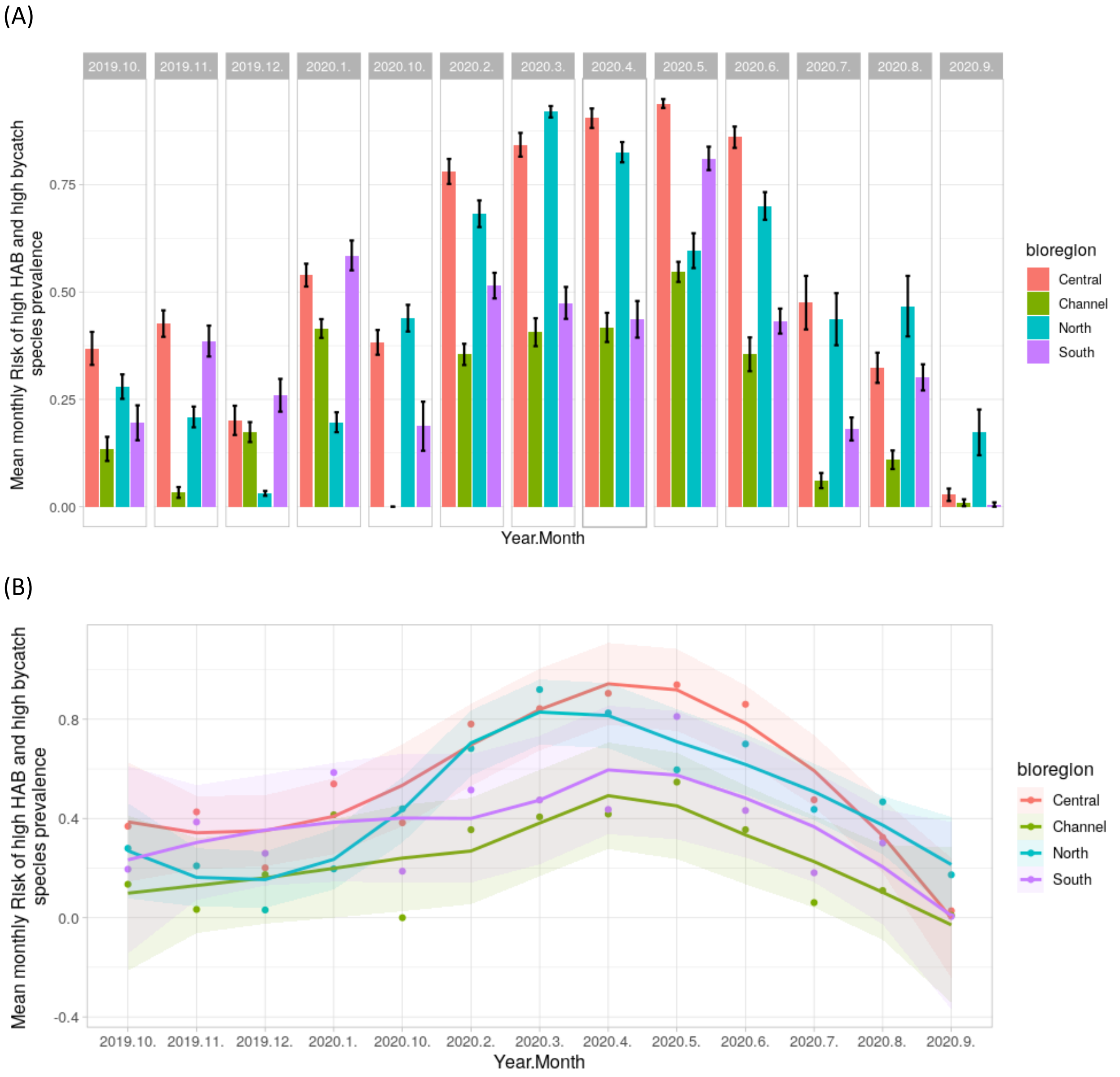


Figure 4-11. (A) Relative mean area by bioregion of monthly risk of high HAB probabilities and high relative bycatch species prevalence. These values were calculated by masking areas where C-HARM probability of cellular domoic acid concentrations were in excess of 10 picograms/cell > 0.6 and EcoCAST Relative Bycatch:Target Catch Probability Product < 0. The rasters were then masked by MPAs within each bioregion. The areas were then normalized by bioregion. The means and standard error bars were calculated using daily data. Data spans October 2019 to September 2020. (B) Same data plotted as lines with 95% confidence intervals.

# 5. Integrated Assessment of Environmental Variation in MPAs

## 5.1 Summary

- We used a curated collection of MPA-specific datasets to assess and compare changes in environmental conditions in California MPAs and bioregions over the last two decades.
- We find ongoing large-scale linkages (teleconnections) between global climate oscillations and environmental fluctuations at the bioregion scale, as shown by different climate indices.
- The spatial and temporal evolution of the warming event in 2015 was the most prominent interannual signal in climate and Seascapes variation observed during the period 2003 to 2021. However, the unusual conditions that dominated that period, even into 2018, have since dissipated. This is evident in time series of the California Multivariate Ocean Climate Indicator (MOCI), Seascapes ocean habitat classifications and other ocean climate indicators. For example, the MOCI index was negative for much of 2011 to 2013 and was negative again in late 2020 across the state.
- While the over the last decade have been variable, long-term, multi-decadal changes associated with climate change are becoming clearer, such as with kelp loss, new records in ocean temperatures and ongoing ocean acidification.
- We identified MPAs that showed the greatest differences in environmental conditions from their bioregion from year to year. Most of these outlier MPAs were located near the northern or southern edges of their bioregion, but we also found that Point Sur SMR was consistently different from the Central Coast bioregion despite being located near the center, and that Sea Lion Gulch SMR showed substantial divergence from the rest of the North Coast bioregion in 2016 due to the persistence of kelp cover at this site.

## 5.2 MPA Integrated Environmental Assessment Objectives

The MPA Action Plan, and the Science Guidance for Evaluating California's Marine Protected Area Network report from 2021, identify several questions related to understanding disturbances and stressors within the current MPA network (MLPA Goals 1 and 6). In addition, many other questions from the MPA Monitoring Action Plan involve assessing ecological change. Assessing the impact of MPA protections and other management efforts on changes to species, populations, and ecosystems requires an understanding of the underlying climate, weather, and other environmental conditions that influence these MPAs, and the state waters in which they are located, on large to small spatial and temporal scales.

To provide some of this important environmental context, we asked the following questions:

1. How have conditions changed over time from basin to California MPA bioregion scales?
2. How has the similarity of oceanographic conditions in individual MPAs changed over time relative to their bioregion?
3. Which MPAs have exhibited the greatest differences in variation from their bioregion?

We addressed these questions for a two-decade period using the datasets that were curated, processed and integrated as described in *Section 2. Data Standardization, Curation, Integration, and Visualization with the California MPA Dashboard* (see Section 2.3 and Appendix A2.1).

## 5.3 Methods

### 5.3.1 How have conditions changed over time from basin to California MPA bioregion scales?

We examined the links between environmental dynamics at large global and ocean basin spatial scales and the smaller MPA bioregion and California State Waters spatial scales that directly influence MPAs. To do this, we first examined data from global to regional climate indices that focus on various mechanisms and scales of change including atmospheric air pressure anomalies (Northern Oscillation Index; NOI), sea surface temperature (SST) variations and anomalies (Pacific Decadal Oscillation and Oceanographic Niño Index; PDO and ONI), ocean gyre circulation structure (North Pacific Gyre Oscillation; NPGO), multivariate indices (Multivariate El Niño-Southern Oscillation Index and Multivariate Ocean Climate Index; MEI and bioregional MOCI), and indices for regional to bioregion upwelling and nutrient delivery (Coastal Upwelling Transport Index and Biologically Effective Upwelling Transport Index; CUTI and BEUTI). We obtained datasets of these indices from the last two decades, 2001-2020 and conducted non-parametric Spearman rank correlations at monthly, seasonal and annual timescales to describe the degree to which the variations are correlated for the period of interest.

### 5.3.2 How has the similarity of oceanographic conditions in individual MPAs changed over time relative to their bioregion? Which MPAs have exhibited the greatest differences in variation from their bioregion, and when?

To assess how individual MPAs differed from their bioregions with respect to environmental conditions on a year-to-year basis and across time, we used the data extracted as described in *Section 2. Data Standardization, Curation, Integration, and Visualization with the California MPA Dashboard* to calculate the Euclidean distances between annual mean values for variables for each individual MPA and the bioregion within which they are located. The resulting annual Euclidian distances between the MPAs and their bioregion provide a metric for identifying the places *and* times that were the most or least similar to their bioregion based on a multivariate set of environmental variables, as well as overall mean similarities. The analysis was restricted to MPAs that had data for every variable of interest for every year between 2003 to 2020. For the North, Central, and South Coast bioregions the variables included CUTI and BEUTI calculated for 1° latitude bins, gridded wave height and energy, SST, NPP, and kelp cover. For the Channel Islands bioregion where CUTI, BEUTI, and wave data were not available, the variables included were SST, NPP, and kelp cover.

## 5.4 Results and Management Implications

### 5.4.1 How have conditions changed over time from basin to bioregion scales?

Globally, ongoing warming has continued over the last decade with ocean warming reaching new records in 2021, with the five hottest years being 2018-2021 (Cheng et al. 2022). This warming is also evident in examinations of the North Pacific generally. Other fundamental long-term changes include increasing ocean acidification with increasing atmospheric carbon dioxide concentrations and other drivers (e.g., Siedlecki et al. 2021, Kessouri et al. 2021)), as well as recent declines in kelp particularly in the north coast (e.g., McPherson et al. 2021). While these changes are clear, they have been assessed on scales of about three decades or more. When considering how change has occurred in the decade timescale since the time of MPA implementation, most monthly to interannual indices of ocean climate can be characterized by cyclical variations.

Existing climate and ocean indices provide a global to bioregion scale view of variation (Fig. 5-1). Each index incorporates information from different combinations of variables and spatio-temporal scales that quantify several modes of interannual change including frequency and intensity that influence California's coastal waters. These illustrate variations from global and Pacific Ocean scale with the Multivariate El Niño Southern Oscillation Index (MEI), environmental forcing connections (i.e., teleconnections) between ENSO forcing in the southern hemisphere and the Northeast Pacific with the Northern Oscillation Index (NOI), and within the northeast Pacific with the North Pacific Gyre Oscillation (NPGO) and Pacific Decadal Oscillation (PDO) (Table 5-1). As expected, the indices with north Pacific data inputs are less correlated to the two primary global El Niño Southern Oscillation (ENSO) indicators than to each other, and the NPGO has lower correlations at the interannual timescale. However, the broad synchrony of climatic and oceanic variation is evident particularly when examining the presence of higher (red) or lower (blue) anomalous conditions (Fig 5-1). The NOI and regional MOCI indices then illustrate teleconnections from ENSO-related variation to the MPA bioregions, with regional MOCI variation closely tracking the NOI with fewer instances or intensities of negative MOCI values from north to south respectively, particularly in the last decade (Fig 5-2, Table 5-1).

The two-decade time series for the global to regional climate indices confirms ongoing teleconnections (i.e., large-scale linkages in climatic phenomena) between climate oscillations and change in the regions from 2001-2020. The most notable shifts related to ENSO occurred in 2009 and 2015/16, which coincided with the most prominent ocean climate episode on the US West Coast, the so-called Warm Blob and its related variations. The effects of this were slow to recede with the PDO warm phase extending through 2017 and the NPGO having a persistent phase and low-intensity El Niño-related variations and warming into 2018 for much of the California Current. The persistence of low-intensity El Niño-like variations and warming is even more apparent in the regional MOCI index plots, which show this was more intense in the Central and South Coast bioregions. Importantly, data through 2020 indicate a return to nominal conditions, more similar to the period 2011-2013. Although the longer-term outlook is uncertain, at the time of writing, 2021 has experienced increased upwelling, mostly nominal temperatures at and near the coast with a seasonal NOAA Climate Prediction Center forecast of conditions tending towards La Niña through January. When examining if the indices are correlated to time, indicating secular change, the PDO and NPGO have the only notable long-term change over the period, but these generally vary over decadal periods.

The plots and correlations between the various indices indicate that month-to-month, and thereby seasonal and longer-term trends remain connected, even during and after unprecedented episodes such as that related to the Warm Blob. When examining the correlations with the MOCI time series at regional and seasonal scales, it is important to note that the MOCI includes the MEI, NOI, ONI and PDO in its formulation. Nonetheless, it is still worth noting that the correlations with the NOI, which quantifies relationships between the North Pacific High (NPH) climatological mean location (35°N, 130°W), Darwin (10°S, 130°E), and Tahiti (18°S, 150°W), are higher in the North and Central Coast. Whereas the South Coast has higher correlations to the more direct measures of ENSO, the MEI and ONI.

The monthly variation of key variables for each bioregion, and their correspondence to regional MOCI variation illustrates how climate variation is influencing key ecological mechanisms of change. For the North, Central, and South Coast this includes CUTI and BEUTI upwelling, SST, NPP, KD490 as a measure of turbidity, wave height and energy, and kelp cover. Channel Islands series were limited to SST, NPP, KD490, and kelp cover as upwelling and wave estimates were not available for these locations in comparable forms. Key features in this variation include the expression of ENSO events (e.g., peaking in Nov 2002 and Dec 2009), as well as variation linked to northeast Pacific Warm Blob anomaly (e.g., 2015/16 with some persistence through 2019; Fig. 5-3 to 5-6). This not only included higher SST, but increased seasonal low SST in each bioregion. Correlations between yearly means of MOCI and the rest of the variables illustrate how climate variations are relating to individual variables in each region (Tables A5-1 to A5-4). The North Coast MOCI was more highly and positively correlated to NPP than the Central Coast, South Coast, or Channel Islands regions, where the southerly sites were negatively correlated. Kelp cover was more negatively correlated to the MOCI indicators in the North Coast than Central or South Coasts or in the Channel Islands. While SST and upwelling form part of the MOCI index, SST, CUTI and BEUTI were more correlated to MOCI in the North and Central Coast than the southerly regions.

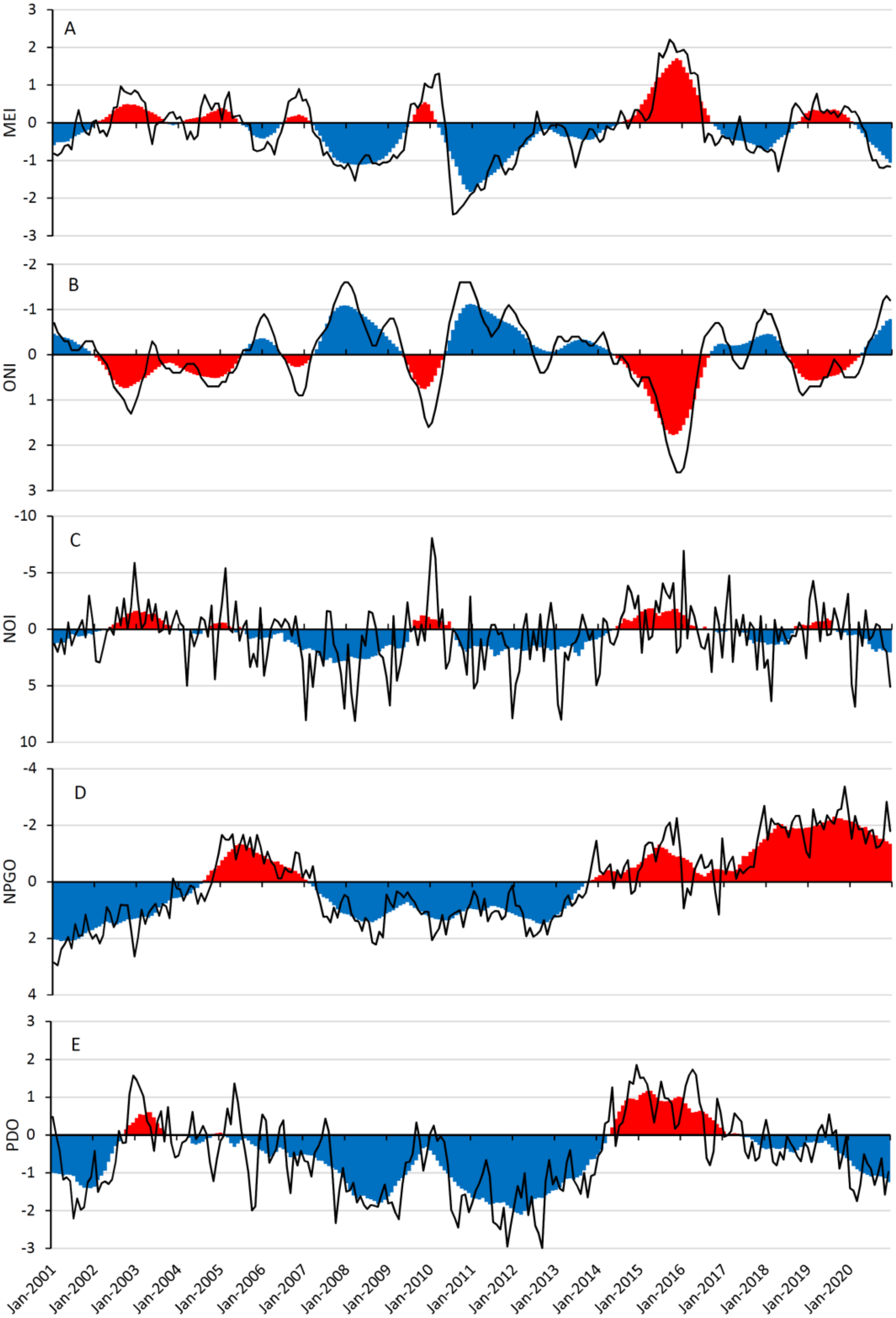


Figure 5-1. Timeseries of climate indices covering 2000-2020 including A) the Multivariate ENSO Index (MEI); B) the Oceanic Niño Index (ONI); C) the Northern Oscillation Index (NOI); D) the North Pacific Gyre Oscillation (NPGO), and E) the Pacific Decadal Oscillation (PDO). Monthly values (black line) and the 13-month running means of these indices are shown in red and blue, where the times in red indicate conditions tending towards El Niño and/or warmer conditions.

Table 5-1. Pearson correlation coefficients between the Multivariate ENSO Index (MEI), Oceanic Niño Index (ONI), the North Pacific Gyre Oscillation (NPGO), and Pacific Decadal Oscillation (PDO) at monthly, seasonal (3 month running mean), and yearly (13-month running mean) scales. Also shown are seasonal correlations between the large-scale climate indices and the bioregion-scale Multivariate Ocean Climate Index (MOCI).

| | Variables | MEI | ONI | NOI | NPGO | PDO |
|---|---|---|---|---|---|---|
| 13-mon. mean | ONI | 0.97 | | | | |
| | NOI | -0.79 | -0.83 | | | |
| | NPGO | -0.32 | -0.30 | 0.22 | | |
| | PDO | 0.77 | 0.74 | -0.78 | -0.47 | |
| Seasonal | ONI | 0.94 | | | | |
| | NOI | -0.57 | -0.63 | | | |
| | NPGO | -0.24 | -0.19 | 0.07 | | |
| | PDO | 0.63 | 0.57 | -0.53 | -0.35 | |
| Monthly | ONI | 0.92 | | | | |
| | NOI | -0.42 | -0.48 | | | |
| | NPGO | -0.23 | -0.16 | -0.01 | | |
| | PDO | 0.57 | 0.53 | -0.39 | -0.25 | |
| Seasonal | MOCI - North California | 0.50 | 0.54 | -0.74 | -0.30 | 0.69 |
| | MOCI - Central California | 0.55 | 0.58 | -0.71 | -0.50 | 0.69 |
| | MOCI - Southern California | 0.68 | 0.69 | -0.61 | -0.50 | 0.70 |

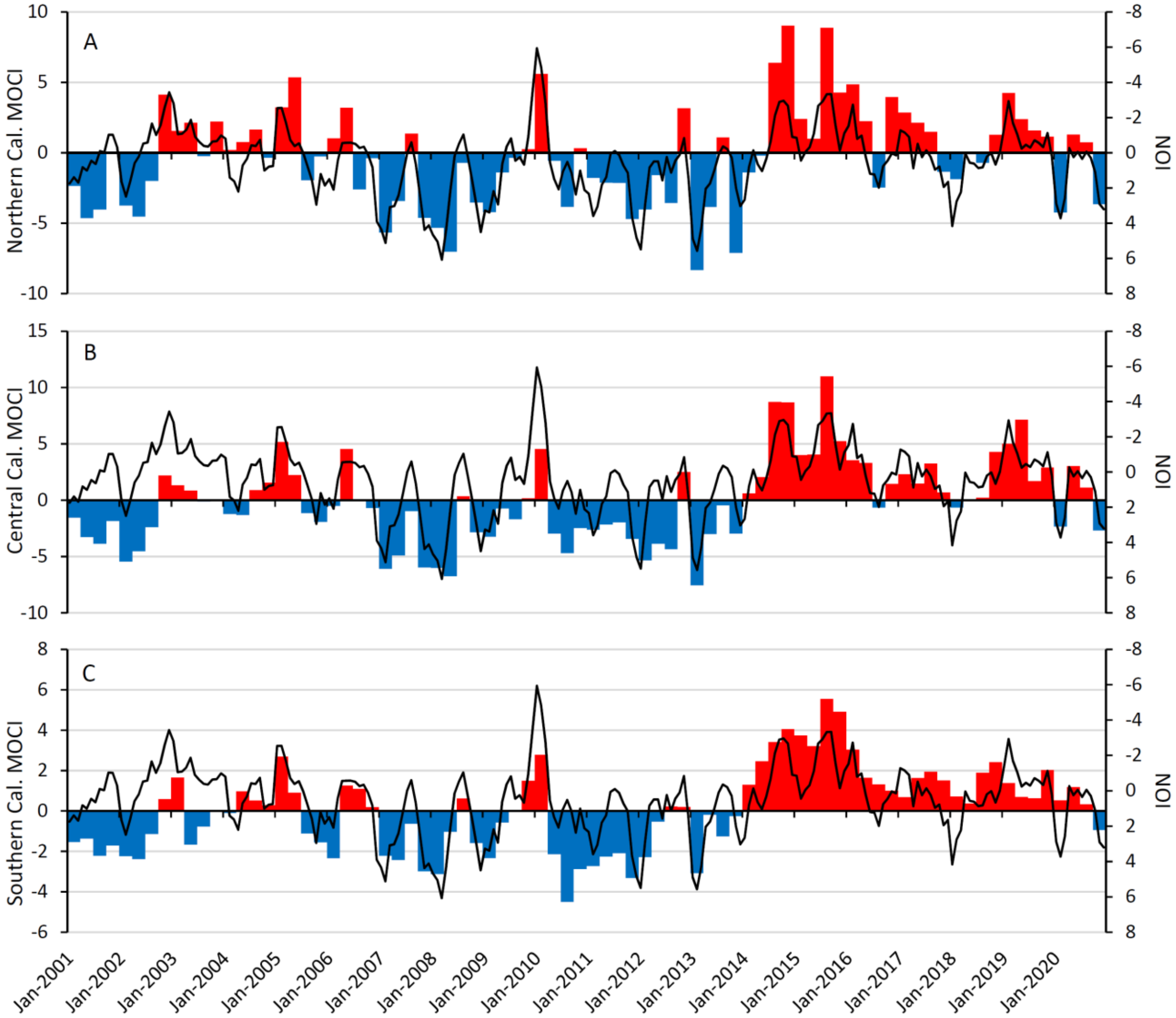


Figure 5-2. Timeseries of the California Multivariate Ocean Climate Indicator (MOCI), which is calculated as seasonal values across the A) Northern (38-42°N), B) Central (34.5-38°N), and C) Southern (32-34.5°N) bioregions (red and blue bars). Also shown with each is the Northern Oscillation Index (NOI) with a 3-month seasonal running mean (black line).

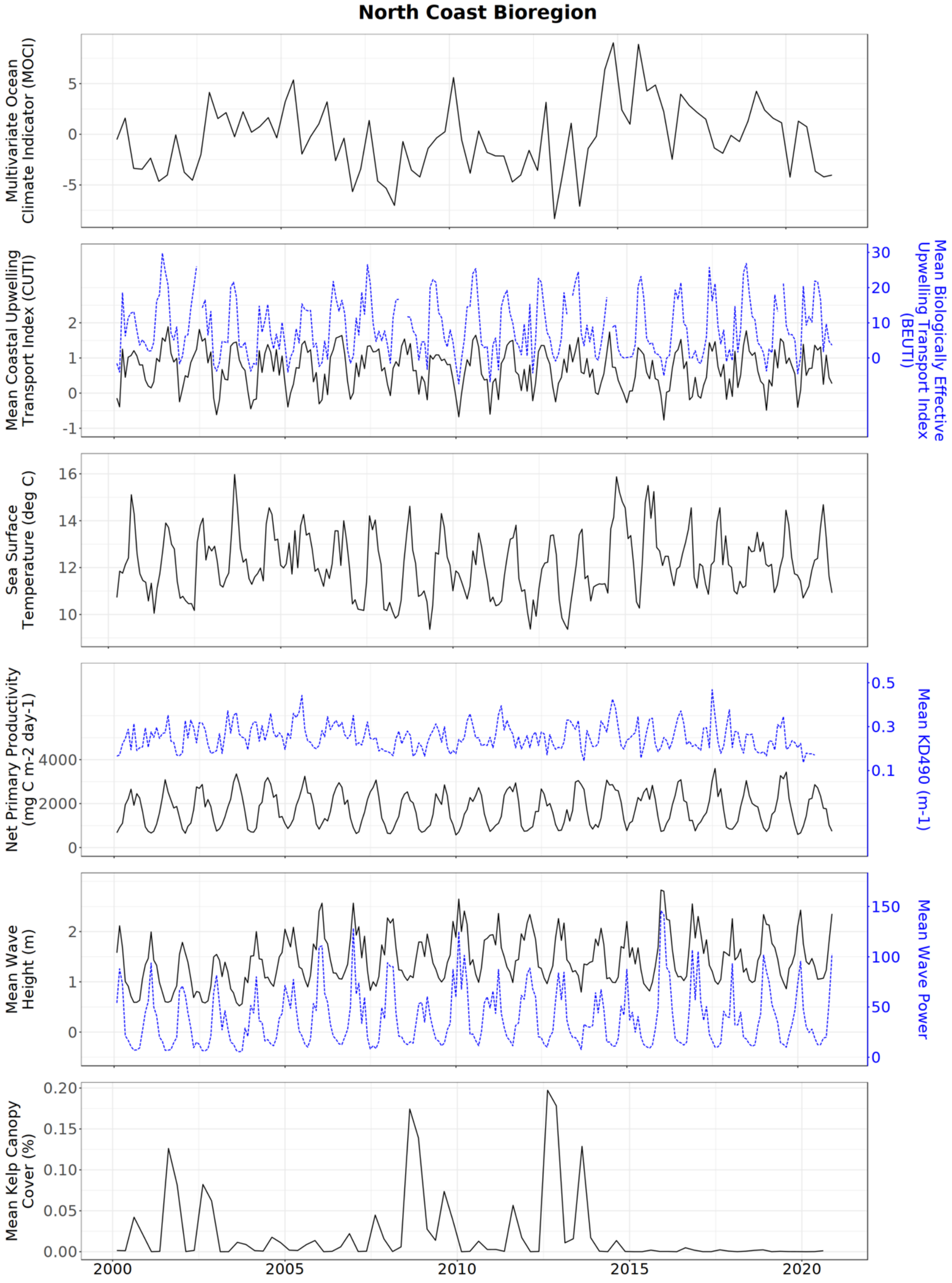


Figure 5-3. Timeseries of monthly mean values for California Multivariate Ocean Climate Indicator (MOCI), Coastal Upwelling Transport Index (CUTI), Biologically Effective Upwelling Transport Index (BEUTI), Sea Surface Temperature (SST), Net Primary Productivity (NPP), attenuation of downwelling light at 490 nm (KD490; a proxy for turbidity), Wave Height and Power, and Kelp Canopy Cover for the **North Coast** bioregion.

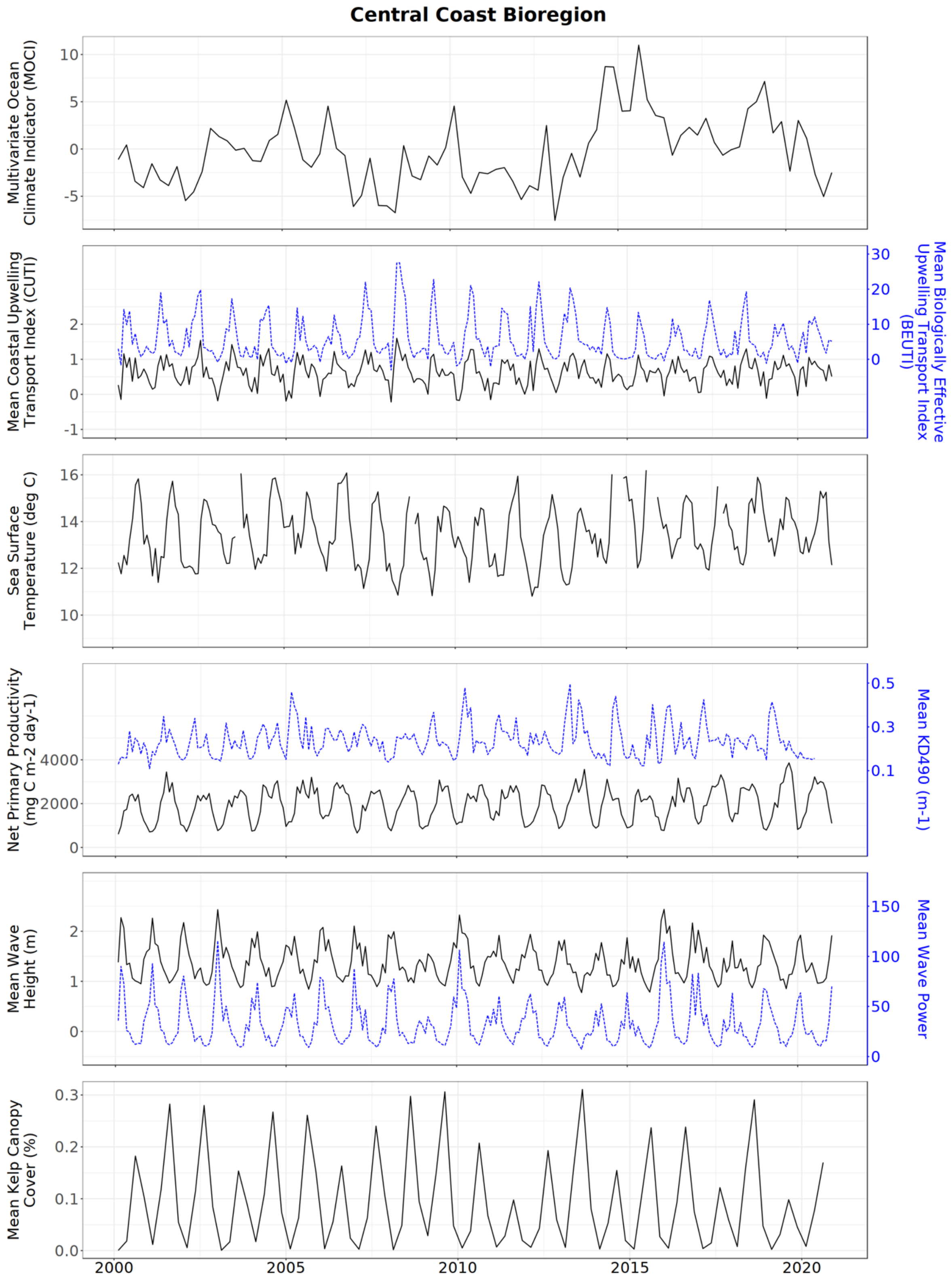


Figure 5-4. Timeseries of monthly mean values for California Multivariate Ocean Climate Indicator (MOCI), Coastal Upwelling Transport Index (CUTI), Biologically Effective Upwelling Transport Index (BEUTI), Sea Surface Temperature (SST), Net Primary Productivity (NPP), attenuation of downwelling light at 490 nm (KD490; a proxy for turbidity), Wave Height and Power, and Kelp Canopy Cover for the **Central Coast** bioregion.

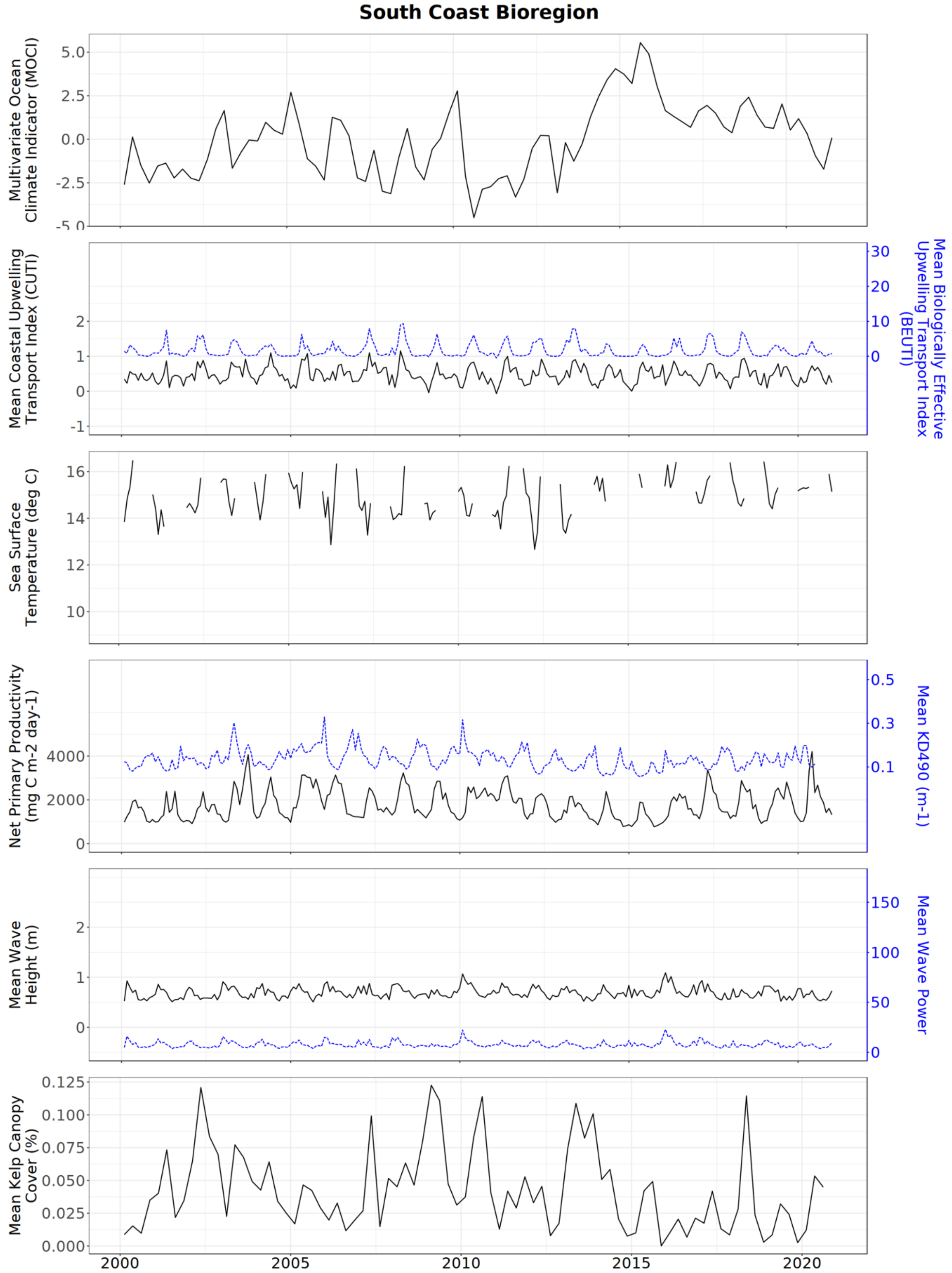


Figure 5-5. Timeseries of monthly mean values for California Multivariate Ocean Climate Indicator (MOCI), Coastal Upwelling Transport Index (CUTI), Biologically Effective Upwelling Transport Index (BEUTI), Sea Surface Temperature (SST), Net Primary Productivity (NPP), attenuation of downwelling light at 490 nm (KD490; a proxy for turbidity), Wave Height and Power, and Kelp Canopy Cover for the **South Coast** bioregion.

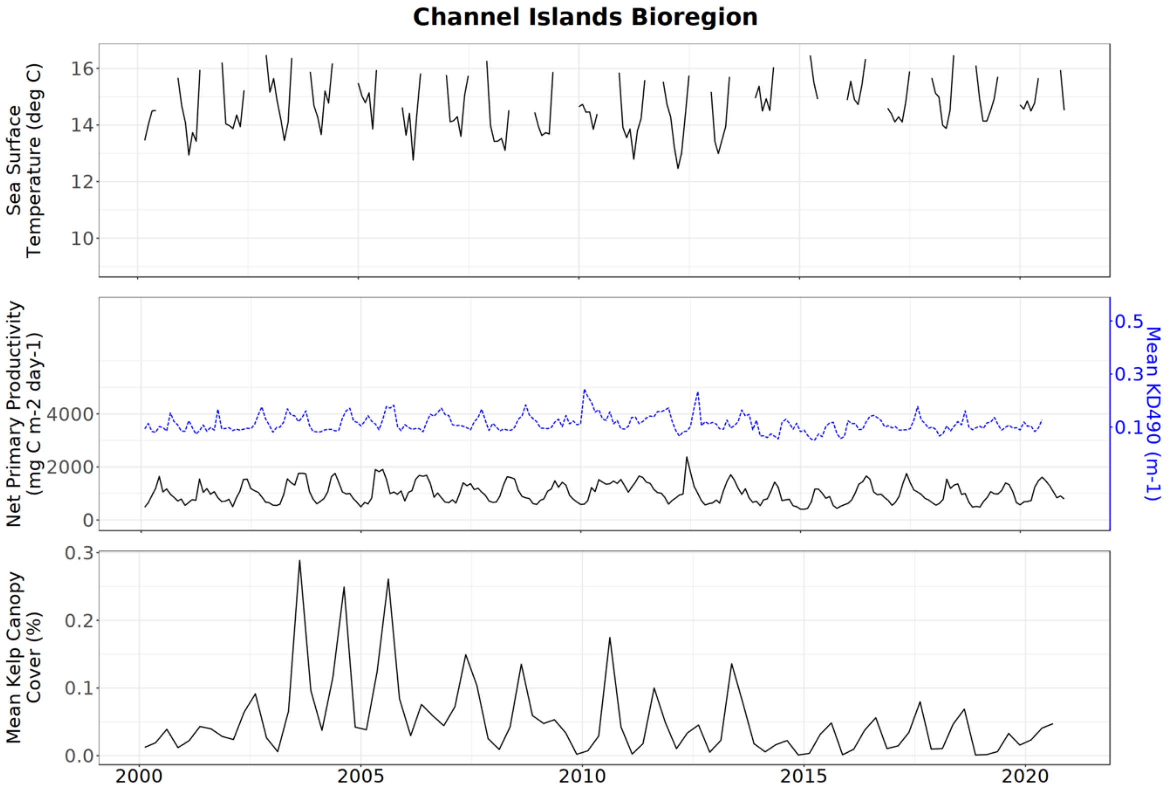


Figure 5-6. Timeseries of monthly mean values for Sea Surface Temperature (SST), Net Primary Productivity (NPP), attenuation of downwelling light at 490 nm (KD490; a proxy for turbidity), and Kelp Canopy Cover for the **Channel Islands** bioregion.

### 5.4.2 How has the similarity of oceanographic conditions in individual MPAs changed over time relative to their bioregion? Which MPAs have exhibited the greatest differences in variation to their bioregion, and when?

Based on Euclidean distances between MPAs and bioregion mean environmental conditions, the MPAs that were consistently most different from their bioregion were Sea Lion Gulch SMR and Point Reyes SMR on the North Coast, Vandenberg SMR and Point Sur SMR on the Central Coast, South La Jolla SMR and Point Conception SMR on the South Coast, and Carrington Point SMR and Judith Rock SMR in the Channel Islands (Table 5-2, Fig. 5-7). Note that the Euclidean distances for MPAs in the Channel Islands bioregion were calculated from a smaller set of input variables than those in the other bioregions.

In many cases, it was the MPAs closest to the edges of the bioregion that exhibited the greatest differences in environmental conditions from the bioregion mean (Table 5-2, Fig. 5-7). In the North Coast and South Coast, the most divergent MPAs were the northernmost and southernmost MPAs in the analysis (Sea Lion Gulch SMR and Point Reyes SMR respectively for the North Coast, Point Conception SMR and South La Jolla SMR respectively for the South Coast). In the Central Coast, the most divergent MPA, Vandenberg SMR was also the southernmost MPA assessed and is located just north of the Point Conception biogeographic and oceanographic boundary. However, the other most divergent MPA in the Central Coast was Point Sur SMR near the middle of the bioregion. The Point Sur area has been identified by representatives from the California Cooperative Fisheries Research Project (CCFRP) and the midwater ecosystems habitat monitoring groups as having distinct fish patterns. Analyses by CCFRP on fish communities within the Central Coast bioregion identified the northernmost site in their study, Año Nuevo SMR, as being more different from other sites in their study (Point Lobos, Piedras Blancas, and Point Buchon), with greater abundance of black rockfish, Cabezon, China rockfish, and kelp greenling at Año Nuevo. However, they did not have sampling data from Montara SMR and Vandenberg SMR. The MPAs in the Channel Islands bioregion did not show a latitudinal pattern as latitudinal variation in this region is small, and oceanographic variation here is less correlated with latitude.

Table 5-2. Table showing the average of annual Euclidean distance between each listed MPA and its bioregion.

| Bioregion | MPA | Eucl. Dist. | Avg. | Variables |
|---|---|---|---|---|
| **North Coast** | Sea Lion Gulch SMR | 3.80 | 2.64 | NPP, Turbidity, SST, Wave height, Wave power, BEUTI, CUTI |
| | Point Reyes SMR | 3.51 | | |
| | MacKerricher SMCA | 2.73 | | |
| | Big Flat SMCA | 2.73 | | |
| | Point Arena SMR | 2.68 | | |
| | Saunders Reef SMCA | 2.58 | | |
| | Stewarts Point SMR | 2.07 | | |
| | Double Cone Rock SMCA | 1.84 | | |
| | Ten Mile SMR | 1.79 | | |
| **Central Coast** | Vandenberg SMR | 3.72 | 2.54 | |
| | Point Sur SMR | 3.46 | | |
| | Montara SMR | 3.18 | | |
| | Pillar Point SMCA | 2.75 | | |
| | Point Lobos SMR | 2.40 | | |
| | Piedras Blancas SMR | 2.06 | | |
| | Año Nuevo SMR | 2.05 | | |
| | Big Creek SMR | 2.04 | | |
| | Greyhound Rock SMCA | 1.95 | | |
| | Point Buchon SMR | 1.77 | | |
| **South Coast** | South La Jolla SMR | 3.82 | 2.67 | |
| | Point Conception SMR | 3.10 | | |
| | Swami's SMCA | 2.85 | | |
| | Abalone Cove SMCA | 2.63 | | |
| | Point Vicente SMCA (No-Take) | 2.53 | | |
| | Campus Point SMCA (No-Take) | 2.26 | | |
| | Point Dume SMCA | 2.11 | | |
| | Laguna Beach SMR | 2.06 | | |
| **Channel Islands** | Carrington Point SMR | 3.47 | 2.26 | NPP, Turbidity, SST |
| | Judith Rock SMR | 2.95 | | |
| | Harris Point SMR | 2.87 | | |
| | Richardson Rock SMR | 2.66 | | |
| | Blue Cavern Onshore SMCA (No-Take) | 2.51 | | |
| | Santa Barbara Island SMR | 2.24 | | |
| | Scorpion SMR | 2.07 | | |
| | Anacapa Island Special Closure | 1.82 | | |
| | Anacapa Island SMCA | 1.80 | | |
| | Anacapa Island SMR | 1.72 | | |
| | South Point SMR | 1.55 | | |
| | Gull Island SMR | 1.50 | | |

When examining the specific years where the greatest MPA differences occurred, we found that environmental conditions at Sea Lion Gulch SMR showed the greatest divergence from the rest of the North Coast bioregion in 2016 across the entire dataset (Fig. 5-7). The extreme magnitude of this divergence was mostly driven by differences in kelp cover: Sea Lion Gulch SMR retained relatively high amounts of kelp in 2016, even as kelp abundance saw significant declines throughout most of the North Coast during this time period (e.g., McPherson et al. 2021).

The differences between MPAs and their bioregion builds understanding regarding the degree to which they represent unique areas, and conversely, the degree to which they are representative of regional-scale variations. These multivariate estimates of oceanographic and environmental change provide a comprehensive assessment of both the specific relative levels for the input variables, as well as the variation over time. Ten Mile SMR, Point Buchon SMR, Gull Island SMR, and Laguna Beach SMR showed the least differences.

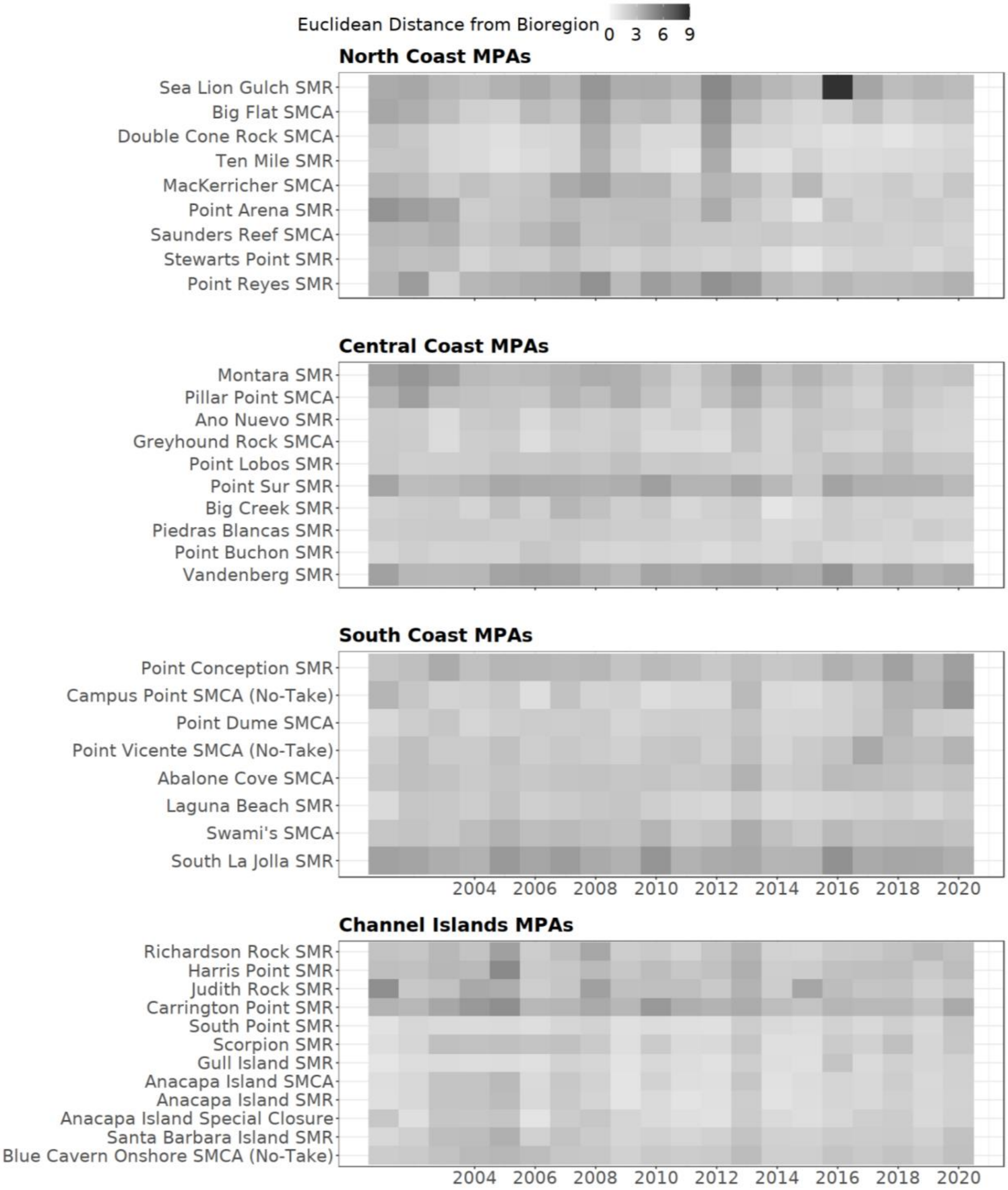


Figure 5-7. Heat map of the annual mean Euclidean distance between each listed MPA and its bioregion for the years 2003-2020. Darker cells represent greater dissimilarity between an MPA and its bioregion for that year. MPAs are ordered approximately by latitude.

# 6. Integrated Assessment of Projected Future Climate Change Risk in MPAs

## 6.1 Summary

- Projections of key oceanographic variables (sea surface temperature, buoyancy frequency as an indicator of stratification, chlorophyll-a, dissolved oxygen, CUTI metric) were obtained from a Regional Ocean Modeling System (ROMS-NEMUCSC) model coupled to climate change scenario models for 1980-2099.
- We assessed the projected change in MPAs and bioregions in these individual oceanographic variables, as well as the multivariate change using Euclidean distances and principal component analyses. We also mapped potential 'refugia' of change, i.e., in California state waters relative to MPA locations, and assessed temporal persistence of those refugia.
- We found that the four bioregions are projected to show distinct, coherent change over time and remain as distinct bioregions. There were no overlaps between past and future MPA conditions within and across bioregions, suggesting that no environmental analogs of current MPAs exist for the future (2070-2099) time period.
- The South Coast bioregion was projected to experience the greatest multivariate change and the North Coast bioregion was projected to experience the least multivariate change.
- Across all bioregions, California MPAs protected higher percentages of potential 'climate refugia' from 1980-2099 compared to overall state waters. However, we also found that across shorter time periods within the modeled time frame 'climate refugia' were not spatially persistent. The greatest level of spatial persistence was seen in the Central Coast bioregion.

## 6.2 Climate Risk Assessment Objectives

The original scope of this project was focused on contemporary patterns of change in California MPAs to support assessments of the MPA network's performance. However, we were also able to obtain and integrate model projection data from a California Current Regional Ocean Modeling System model (ROMS-NEMUCSC) coupled to global climate change models (Pozo Buil et al. 2021) to address priority research questions from the OPC Science Advisory Team's report on Climate Resilience and California's MPA Network (Hofmann et al. 2021).

The report highlights the importance of understanding the spatial distribution of MPAs relative to historic, present, and future stressors in order to understand how MPAs will perform under climate change. There is also high interest in identifying and understanding the roles of potential climate refugia, i.e., areas of reduced climate vulnerability, as a strategy for enhanced climate resilience. For example, potential refugia that experience a low magnitude or rate of environmental change could function as areas where species and populations have more time to adapt. In particular, it is important to understand where potential refugia are located relative to MPAs (Hofmann et al. 2021).

*Priority Climate Resilience Research Questions from OPC Science Advisory Team Report (Hofmann et al. 2021)*

| Priority Questions from Report | Integrated Assessment (Climate Change Risk) Research Objectives |
|---|---|
| ● What is the spatial distribution of MPAs relative to historic and current stressor exposures, and how are those stressors likely to evolve in the future?<br>● What are physical, ecological, and biological characteristics of climate refugia? Do MPAs include or promote these conditions? Will climate refugia persist into the future? | ● How different will oceanographic conditions in individual MPAs and bioregions be in the period 2070-2099 (future) relative to 1980-2009 (past)?<br>● Which MPAs and bioregions are projected to have the least or greatest amount of environmental change between the past and future?<br>● Where are environmental refugia from climate change projected to occur within California state waters, and to what extent do they overlap spatially with the MPA network?<br>● How spatially persistent are environmental refugia projected to be over time? |

## 6.3 Methods

Projections of key oceanographic variables (Sea Surface Temperature, Chlorophyll a, Dissolved Oxygen, Buoyancy Frequency, and the Coastal Upwelling Transport Index, CUTI) from 1980-2099 were obtained from model runs of the ROMS-NEMUCSC model, coupled to downscaled versions of three different Earth Systems Models (Pozo Buil et al. 2021). For each output variable, we used the composite mean across these Earth Systems Models, and then calculated 30-year temporal means.

We assessed differences between environmental conditions in each MPA between past (1980-2009) and future (2070-2099) periods using principal component analyses (PCA) with an analysis of similarities (ANOSIM) on the oceanographic variables by location. We also calculated the Euclidean distance between projected past and future conditions of each MPA and reference bioregion, as a metric of multivariate change. Because the CUTI metric is only available for mainland coastal sites and not for the Channel Islands MPAs, we ran two versions of the analyses - one with all four bioregions and without CUTI, and one that excluded the Channel Islands MPAs but included CUTI as a measure of upwelling.

We identified and mapped the lower 10th percentile of multivariate change (estimated by Euclidean distance) across California state waters as potential 'climate refugia', i.e., areas within state waters that are projected to experience the least amount of environmental change. We note that a threshold percentile of change is only one potential way to define refugia, and analyses run with a 15th percentile threshold produced qualitatively similar results. We calculated the fraction of these areas located within MPA boundaries. To assess the temporal persistence of these potential refugia, we also examined if the same areas remained in the lower 10th percentile of multivariate change across four time periods during the model run: Period 1 - Past (1980-2009), Period 2 - Present (2010-2039), Period 3 - Mid-Century Future (2040-2069), and Period 4 - End-Century Future (2070-2099). Additional details on the methods used here are found in Appendix A5.1.2.

## 6.4 Results and Management Implications

### 6.4.1 How different will oceanographic conditions in individual MPAs and bioregions be in the period 2070-2099 (future) relative to 1980-2009 (past)?

There are clear and systematic changes in MPA conditions between past and future conditions expected as a result of climate change. However, within both past and future time periods, the projected oceanographic conditions of MPAs in the North Coast and Central Coast bioregions have limited overlap, as do the projected conditions of MPAs in the South Coast and Channel Islands bioregions (Fig. 6-1). However, there were no such overlaps between MPAs in the Central Coast and South Coast MPAs, with the North Coast and Central Coast being clearly separated from the South Coast and Channel Islands MPA clusters along the PC 1 axis. Analyses of Similarities (ANOSIM) results showed that all bioregions were statistically distinct at the $\alpha = 0.05$ level (Appendix Table A5-5). Within the North and Central Coast bioregions, chlorophyll-a and dissolved oxygen concentrations accounted for much of the environmental variation among MPAs, whereas within the South Coast and Channel Islands bioregions, sea surface temperature and stratification (as indicated by buoyancy frequency) accounted for much of the variation across MPAs. The results illustrate that these four bioregions will likely exhibit distinct, coherent change over time, thus warranting the continued use of these groupings into the future for research, assessment, and management.

For MPAs across all the bioregions, the dominant drivers of change between past and future time periods were an increase in sea surface temperature and stratification (as measured by buoyancy frequency). MPAs in each bioregion remained distinct from those in other bioregions across time periods, with ANOSIM showing that future bioregions were all statistically different with respect to multivariate environmental conditions (Appendix Table A5-5). Importantly, there were also no overlaps between past and future MPA conditions, both within and across bioregions, suggesting that no environmental analogs of current MPAs exist for the 2070-2099 time period, even when comparing past lower-latitude sites with future higher-latitude sites. Therefore, based on these projections it is unlikely that coastal marine species in California will simply be able to migrate poleward to find fully analogous environmental conditions on a large scale. Species will need to be able to persist under altered environmental conditions either by drawing on existing tolerances and physiological capacities, or through adaptation over the next decades, or both. These findings did not change substantially when the analysis was re-run with the addition of the CUTI upwelling index and without the Channel Islands sites, which do not have a projected CUTI value.

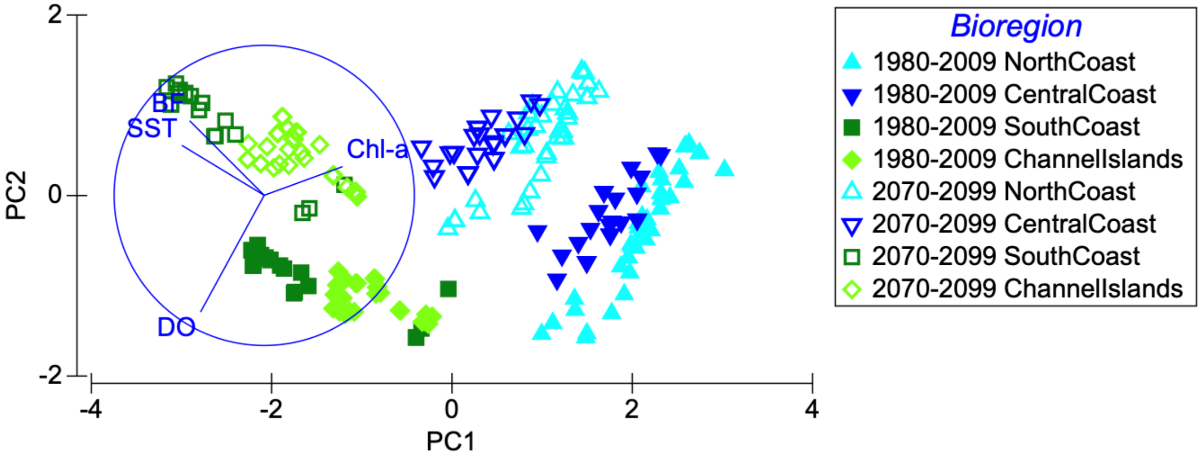


Figure 6-1. Principal component analysis of climate change illustrating the multivariate similarity of MPAs during the past (1980-2009) and future (2070-2099) periods within and across bioregions. The relative contributions of the multiple environmental variables to each of the principal component axes (PC1 and PC2) are also plotted. These include SST, buoyancy frequency (BF) as a measure of stratification, chlorophyll-a (chl-a), and dissolved oxygen (DO).

### 6.4.2 Which MPAs and bioregions are projected to have the least or greatest amount of environmental change between the past and future?

Based on Euclidean distances, the South Coast bioregion was predicted to experience the greatest change and the North Coast bioregion was predicted to experience the least change. These patterns of change were the same for aggregated MPAs as well as for state waters (Fig. 6-2), and were also reflected in the distribution of projected change in individual MPAs - almost all the MPAs projected to have the greatest amount of change between past (1980-2009) and future (2070-2099) time periods were from the South Coast bioregion (Fig. 6-3), and almost all the MPAs projected to have the least amount of change between these periods were in the North Coast bioregion (Fig. 6-4). Point Sur SMCA in the Central Coast bioregion was the only site outside the North Coast bioregion that was among the MPAs projected to experience the least change. Note that our analyses of environmental variation show that the Point Sur SMCA site has also consistently differed from average conditions in the Central Coast bioregion (Fig. 5-7, Table 5-2). Projected change values for the full set of MPAs are plotted in Appendix Fig. A5-1.

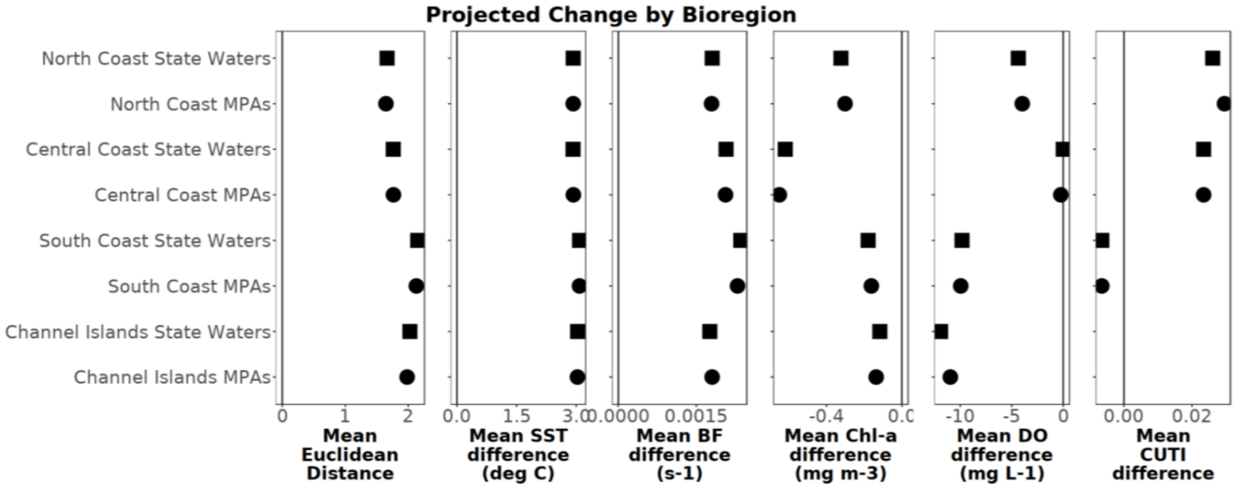


Figure 6-2. Mean Euclidean distances showing the multivariate change in environmental conditions in each bioregion, for all state waters and for just the aggregated MPAs, between the periods 1980-2009 and 2070-2099. Also shown are the mean projected change for the underlying environmental variables: surface temperature (SST), buoyancy frequency (BF) as a metric for stratification, chlorophyll-a (Chl-a), dissolved oxygen (DO) and CUTI.

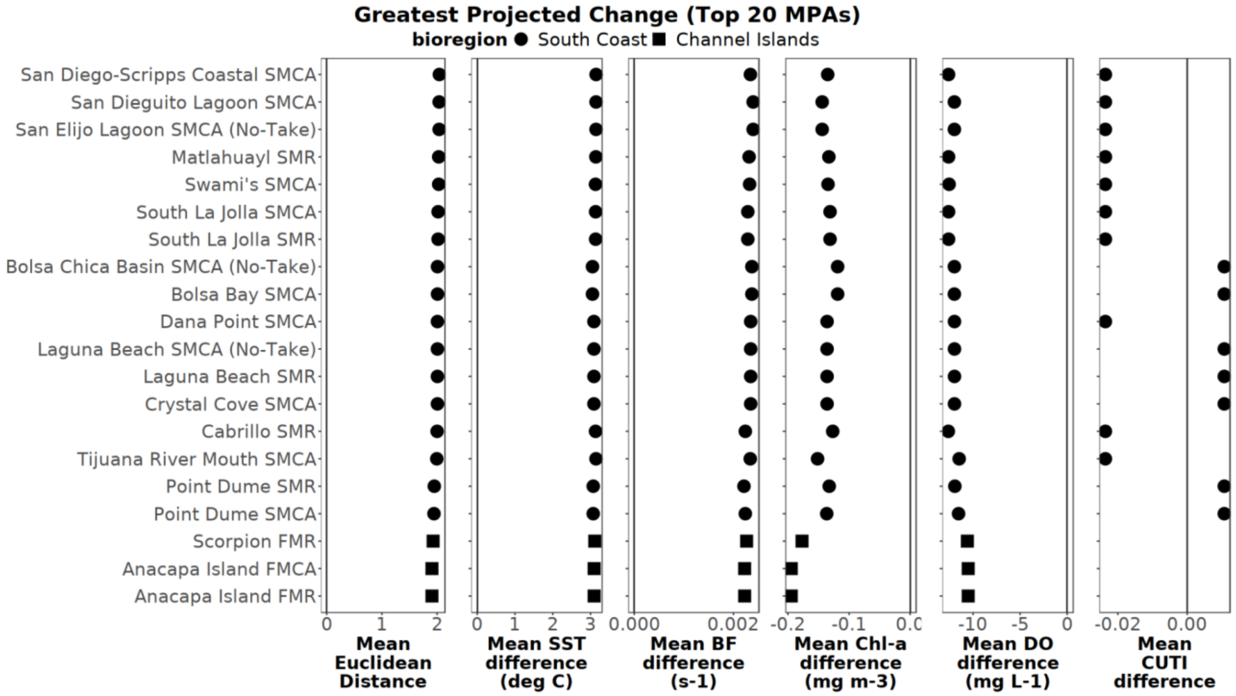


Figure 6-3. Mean Euclidean distances showing the multivariate change in environmental conditions in the MPAs projected to experience the greatest change (top 20 MPAs) between the periods 1980-2009 and 2070-2099. Also shown are the mean projected change for the underlying environmental variables: surface temperature (SST), buoyancy frequency (BF) as a metric for stratification, chlorophyll-a (Chl-a), dissolved oxygen (DO), and CUTI. CUTI values are not available for Channel Islands MPAs.

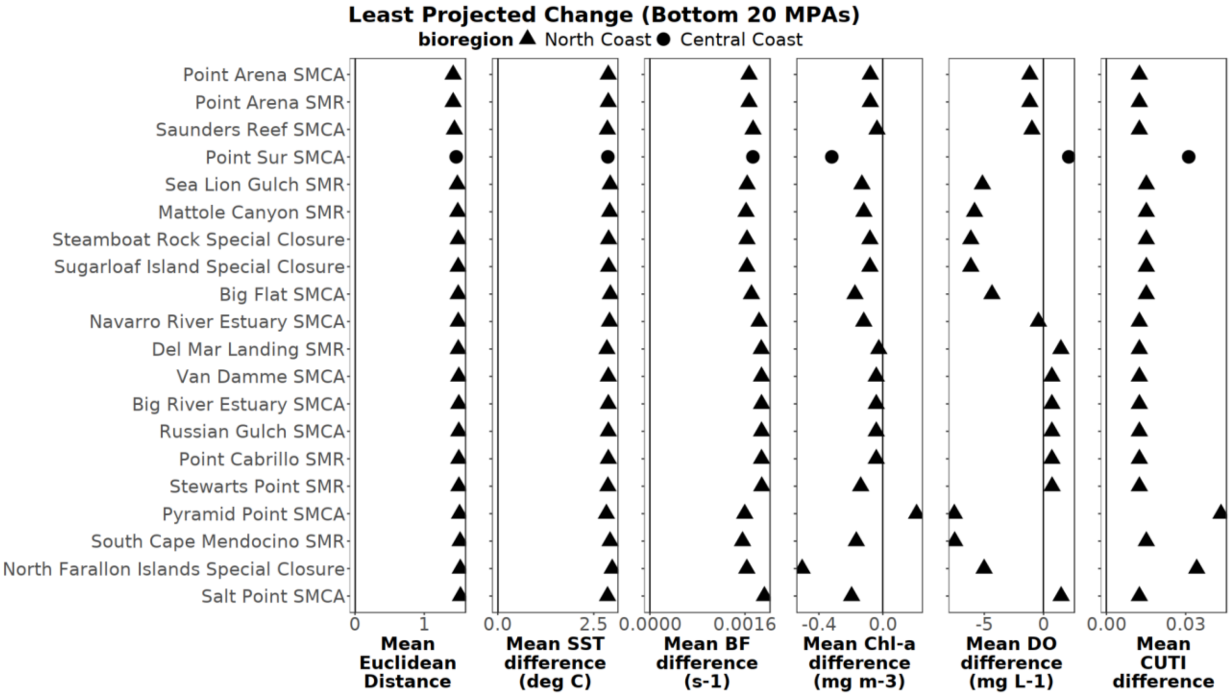


Figure 6-4. Mean Euclidean distances showing the multivariate change in environmental conditions in the MPAs projected to experience the least change (bottom 20 MPAs) between the periods 1980-2009 and 2070-2099. Also shown are the mean projected change for the underlying environmental variables: surface temperature (SST), buoyancy frequency (BF) as a metric for stratification, chlorophyll-a (Chl-a), dissolved oxygen (DO), and CUTI.

### 6.4.3 Where are environmental refugia from climate change projected to occur within California state waters, and to what extent do they overlap spatially with the MPA network?

We mapped the location of ‘environmental refugia’ for each bioregion (Fig. 6-5). In the South Coast and Channel Islands bioregions, potential refugia were clustered in the northern parts of the bioregion. In the North and Central Coast bioregions, potential refugia occurred along non-contiguous parts of the North Coast and Central Coast bioregions, though some of these areas appear to be located around geographic features - Point Arena (North Coast) and Point Sur (Central Coast).

We find that the current MPA network does an above-average job of protecting these potential environmental refugia: the percentage of refuge area that overlap MPAs (33.3-100%; Fig. 6-6) is generally higher than the total area of state waters protected by MPAs (16.13% statewide; between 13.37-19.97% among bioregions). The MPAs that contain potential refugia are listed by bioregion in Table 6-2. For example, we found that in the Central Coast Region, 33.3% of potential refugia overlapped the MPA network, specifically being protected within Point Sur SMR/SMCA and Vandenberg SMR.

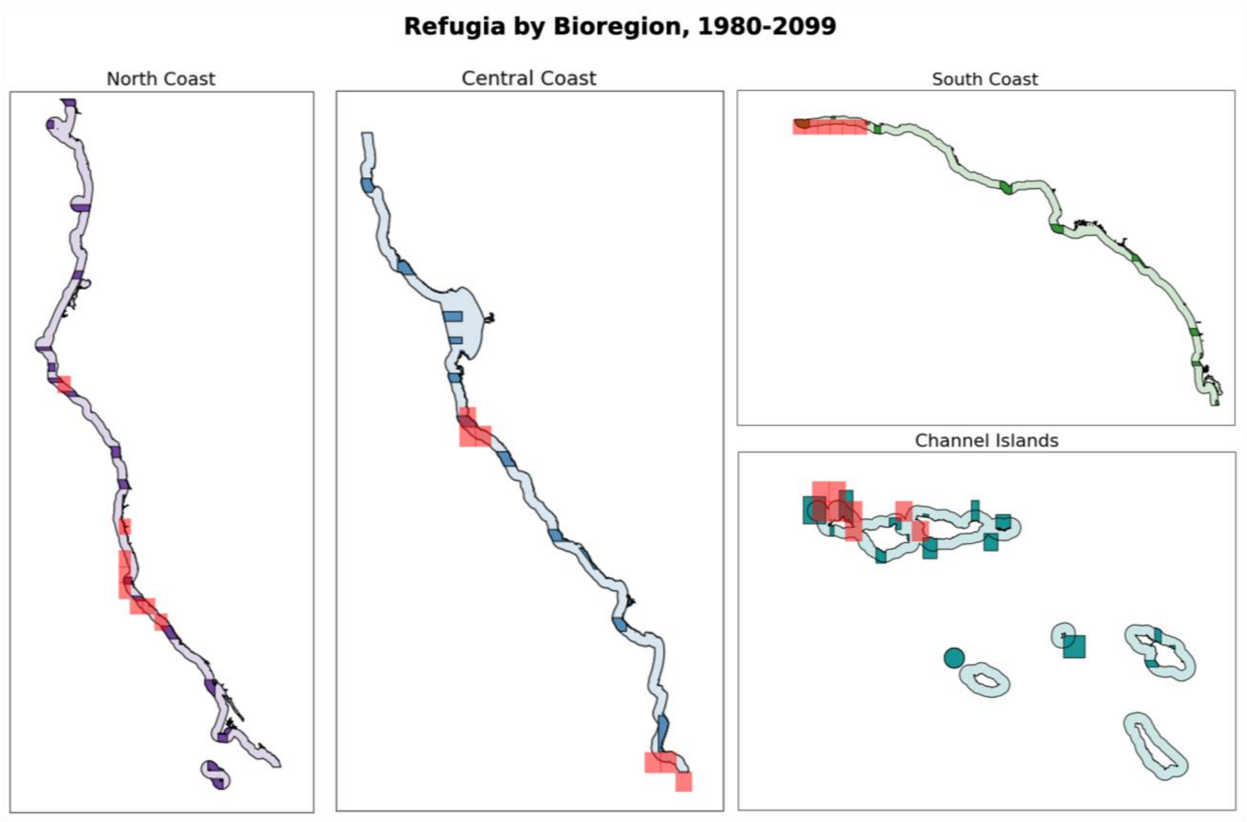


Figure 6-5. Maps of California state waters for each bioregion. Potential climate refugia, i.e., areas projected to experience the least (bottom 10%) amount of change across 5 combined climate variables (Sea Surface Temperature, Chlorophyll a, Dissolved Oxygen, Buoyancy Frequency) from 1980-2099 are indicated with red pixels. Darker polygons indicate Marine Protected Areas.

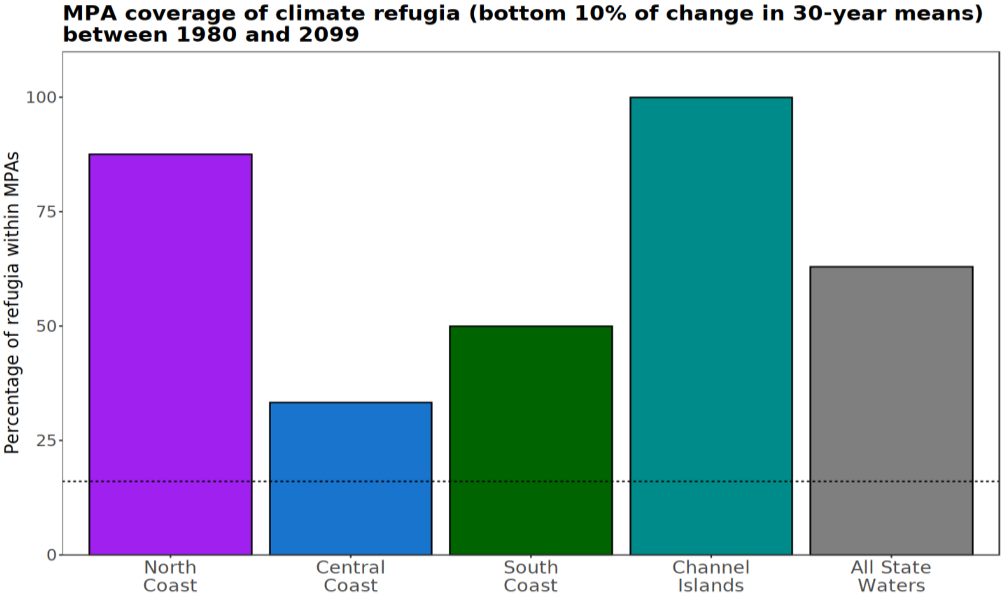


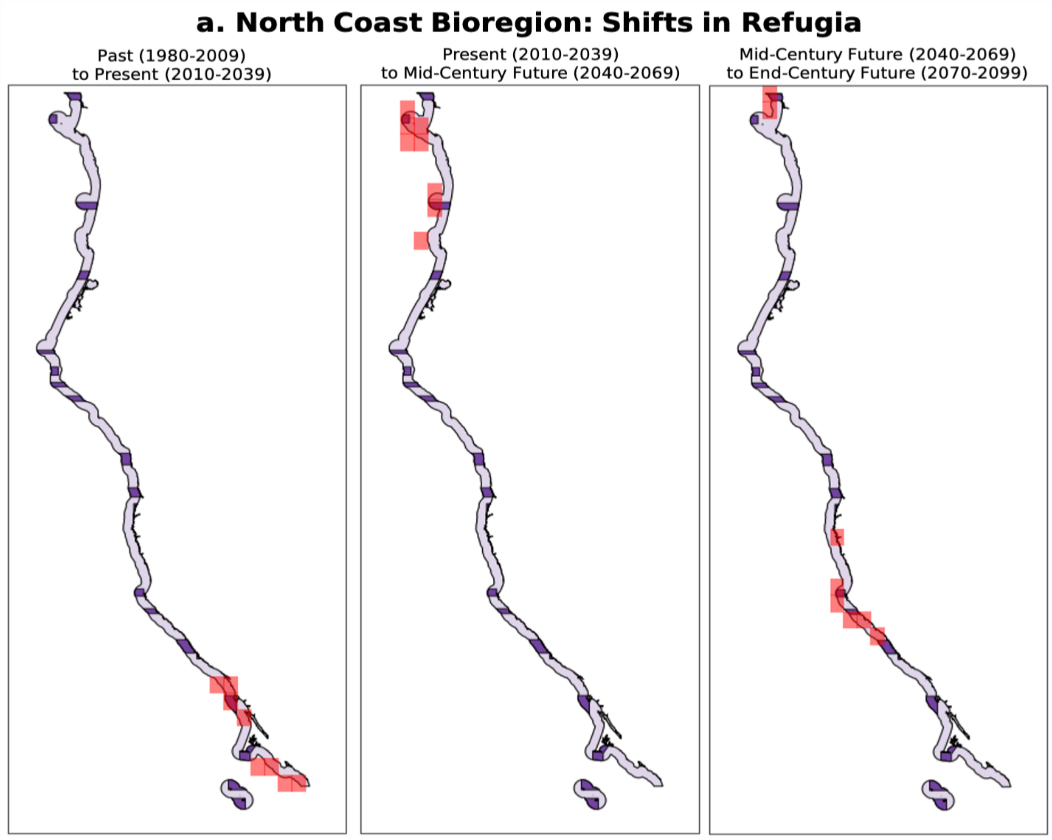
Figure 6-6. Percentage of projected ‘climate refugia’ that overlap the boundaries of MPAs, by bioregion and across all state waters. The dotted line represents the fraction of all state waters protected by MPAs (16.13%)

Table 6-2. List of Marine Protected Areas that overlap identified 'climate refugia', defined as areas projected to experience the least change (bottom 10% of state waters) in multivariate oceanographic conditions from 1980 to 2099.

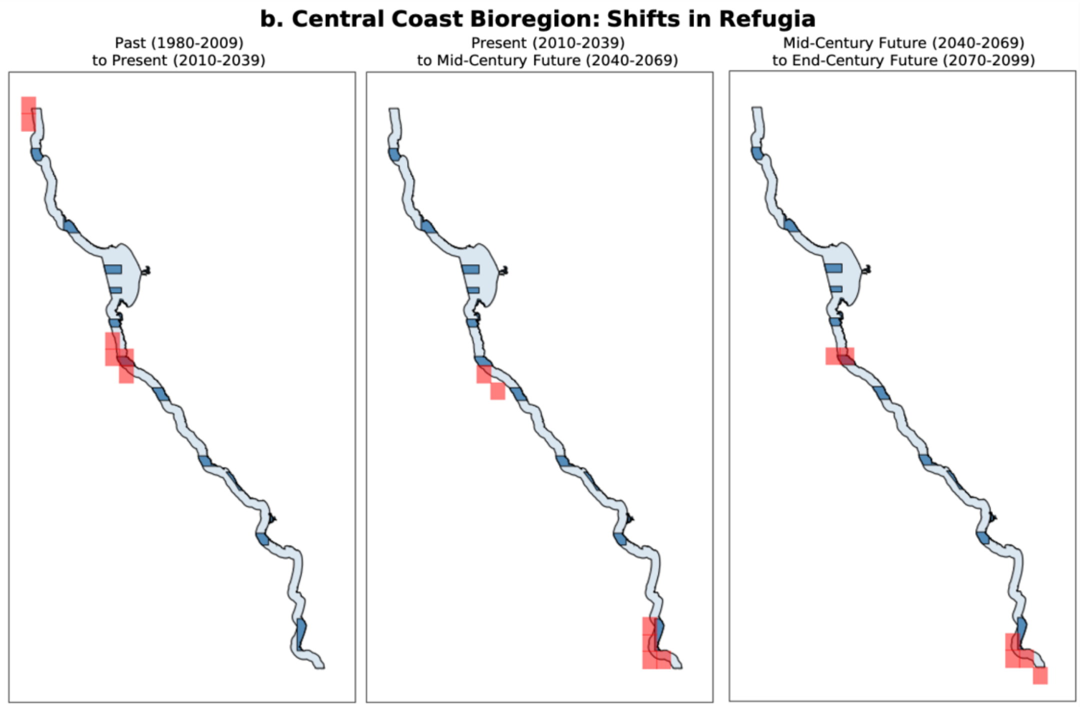
| Marine Protected Areas that overlap potential climate refugia | | | |
|---|---|---|---|
| **North Coast** | **Central Coast** | **South Coast** | **Channel Islands** |
| Sea Lion Gulch SMR<br>Big Flat SMCA<br>Point Arena SMR<br>Point Arena SMCA<br>Saunders Reef SMCA<br>Stewarts Point SMR<br>Point Cabrillo SMR<br>Russian Gulch SMCA<br>Van Damme SMCA | Point Sur SMR<br>Point Sur SMCA<br>Vandenberg SMCA | Point Conception SMR<br>Kashtayit SMCA<br>Naples SMCA | Richardson Rock SMR<br>Harris Point SMR<br>Carrington Point SMR<br>Gull Island SMR |

### 6.4.4 How spatially persistent are environmental refugia projected to be over time?

Comparisons of patterns of projected multivariate change among different time periods suggest there is generally low spatial persistence of potential environmental refugia through these different periods (Fig. 6-7, Table 6-3). The Central Coast was the only bioregion in which areas with the lowest projected multivariate change between the Past and Present periods (Periods 1-2) overlapped areas with the lowest projected multivariate change between the Mid-Century and End-Century periods (Periods 3-4). For the South Coast and Channel Islands, we found that potential refugia tended to occur in the same areas for environmental change in Past to Present periods (Period 1-2) and Present to Mid-Century periods (Period 2-3), but not between Present to Mid-Century periods (Period 2-3) and Mid-Century to End-Century periods (Period 3-4), whereas there was no overlap at all between potential refugia for different periods in the North Coast bioregion. These patterns suggest that across this modeled timescale (1980-2099), the impacts of climate change are spatially dynamic, and refugia that are persistent across space and time may not be common.

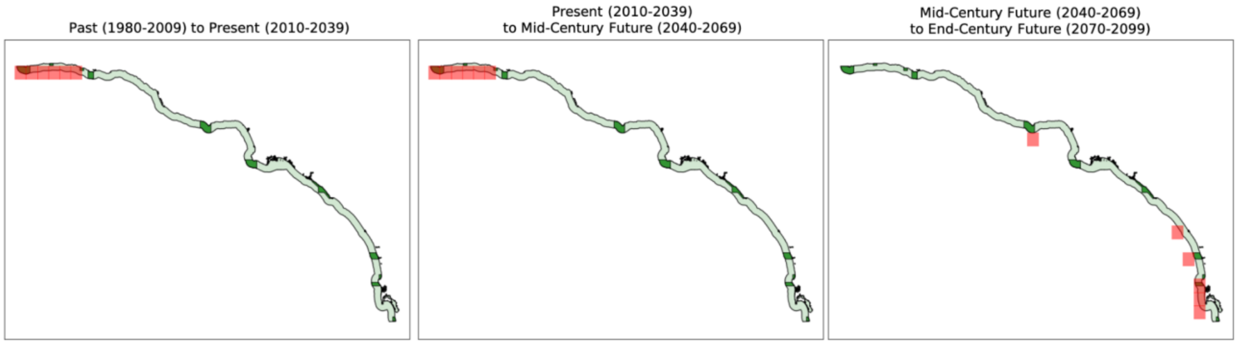


a. North Coast Bioregion: Shifts in Refugia



b. Central Coast Bioregion: Shifts in Refugia

c. South Coast Bioregion: Shifts in Refugia



d. Channel Islands Bioregion: Shifts in Refugia

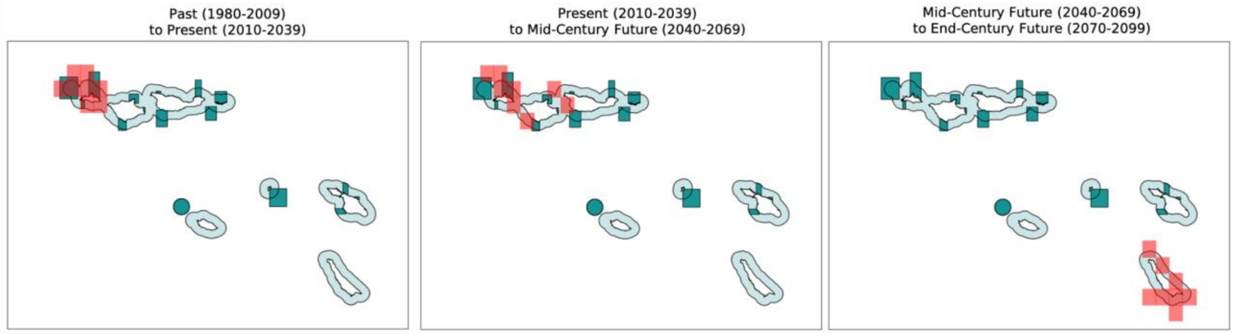


Figure 6-7. Maps of California state waters for (a) North Coast; (b) Central Coast; (c) South Coast; and (d) Channel Islands Bioregions showing shifts in the location of potential climate refugia, i.e., areas projected to experience the least (bottom 10%) amount of change across 5 combined climate variables for three consecutive time periods from 1980-2099. Potential climate refugia are indicated with red pixels for each time period. Darker polygons indicate Marine Protected Areas.

Tables 6-3 a-d. Percentage persistence of areas projected to experience the least (bottom 10%) amount of change in climate variables (Sea Surface Temperature, Chlorophyll, Dissolved Oxygen, Buoyancy Frequency) across three time periods for (a) North Coast; (b) Central Coast; (c) South Coast; and (d) Channel Islands Bioregions.

**a. North Coast Bioregion**

| | Past to Present (1980-2009 to 2010-2039) | Present to Mid-Century (2010-2039 to 2040-2069) |
|---|---|---|
| Present to Mid-Century (2010-2039 to 2040-2069) | 0% | |
| Mid-Century to End-Century (2040-2069 to 2070-2099) | 0% | 0% |

**b. Central Coast Bioregion**

| | Past to Present 1980-2009 to 2010-2039 | Present to Mid-Century 2010-2039 to 2040-2069 |
|---|---|---|
| Present to Mid-Century (2010-2039 to 2040-2069) | 16.7% | |
| Mid-Century to End-Century (2040-2069 to 2070-2099) | 33.3% | 50% |

c. South Coast Bioregion

| | Past to Present 1980-2009 to 2010-2039 | Present to Mid-Century 2010-2039 to 2040-2069 |
|---|---|---|
| Present to Mid-Century 2010-2039 to 2040-2069 | 100% | |
| Mid-Century to End-Century 2040-2069 to 2070-2099 | 0% | 0% |

d. Channel Islands Bioregion

| | Past to Present 1980-2009 to 2010-2039 | Present to Mid-Century 2010-2039 to 2040-2069 |
|---|---|---|
| Present to Mid-Century 2010-2039 to 2040-2069 | 62.5% | |
| Period 3 to Period 4 2040-2069 to 2070-2099 | 0% | 0% |

## 6.5 Limitations and Next Steps

These analyses of projected climate change in California MPAs and bioregions are based on projected variables from the ROMS-NEMUCSC model. Although this is a downscaled model, the resolution of the model spatial grid cells is also coarse in reference to the scale of many MPAs (~10 km in the horizontal dimension). Most of the estuarine MPA sites fall outside the domain of the model, and were not included in the analysis.

The model was designed to give long-term projections (e.g., on the 30-year mean time scale we used in analyses) rather than at a higher temporal resolution. Therefore, these analyses are not able to account for potential shorter-term variations that might be introduced by oscillations such as ENSO.

Other key oceanographic variables (e.g., pH and carbonate chemistry) from the model are still being worked on by the modeling team and will be incorporated into the climate change analyses when they are made available. We are looking to add additional variables in line with suggestions from the recent climate resilience report recommendations (Hofmann et al. 2021)

# Appendices

## A1. Project Milestones and Deliverables*

*Milestone 1* - Project meeting 1: meet with the habitat expert team leads to facilitate discussion on understanding the details of model and data product specification (Objective 1 and 2), data collection, methods, quality assurance/quality control, and curation (Objective 3), and use cases of ecological models and indicators (Objective 4).

> **Deliverable 1** - Report with recommendations on particle tracking/connectivity data needs and capabilities across the Phase 2 effort, and to achieve high-resolution particle tracking for the historical data period, e.g., 2011 to present.
>
> **Deliverable 2** - Produce and share large-scale model and satellite monitoring information for 24 select integrated areas including priority Tier 1 and 2 sites, the 3 bioregions, and California coastal waters (or other regions as agreed with Program leadership).
>
> **Deliverable 3** - First annual project report.

*Milestone 2* - Project meeting 2: meet with habitat expert teams and broader stakeholders to showcase developing products from Objective 1, demonstrate how to use them, and get feedback for improvements. Discuss and finalize specifications for high resolution nest model data (Objective 2), showcase ecological monitoring data integration work on initial new data streams (Objective 3), and use cases for the ecological model synthesis tool and indicator metrics (Objective 4). This milestone transitioned into bi-lateral project meetings to gain the necessary feedback, which occurred in autumn 2020.

> **Deliverable 4** - Hydrodynamic model output will be generated routinely and publicly served on a UCSC THREDDS server (Objective 2).
>
> **Deliverable 5** - Model trajectories will be calculated routinely.
>
> **Deliverable 6** - Particle trajectories analyzed for connectivity using quasi-operational model.
>
> **Deliverable 7** - Integrate 4 new ecological monitoring data sets from Phase 2 into our curated data view analytics (Objective 3).
>
> **Deliverable 8** - Second annual progress report

*Milestone 3* - Project meeting 3, meet with habitat expert teams and broader stakeholders to facilitate use of data and products in assessments and facilitate integrative statewide assessment work. This milestone transitioned into bi-lateral project meetings to gain the necessary feedback, which occurred in Spring and Fall 2021.

> **Deliverable 9** - Integrate 4 additional new ecological monitoring data sets from Phase 2 into our curated data view analytics (Objective 3).
>
> **Deliverable 10** - Produce ecological model synthesis tool, multivariate, meta-analysis, and indicator metrics (Objective 4).
>
> **Deliverable 11** - Produce updated integrated assessment data gathered in Objectives 1-4.
>
> **Deliverable 12** - Final project report - this document.

**These are as originally proposed. Any deviations are noted in the narrative*

# A2. Data Standardization, Curation, Integration, and Visualization with the MPA Dashboard Tool (Objectives 1 and 3)

## A2.1 Extended Methods for Data Standardization and Processing

### A2.1.1 Data and Source Code Access

Data were accessed and processed through the Research Workspace (researchworkspace.com, Axiom Data Science), a web-based project management and data analysis platform that allows the execution of Python-based Jupyter Notebooks. Notebooks run on the Research Workspace are in close proximity (infiniband connection) with the storage devices that hold local copies of large remote sensing and model output datasets. This allows users to easily and quickly access large datasets and minimizes internet bandwidth bottlenecks. Processing scripts are maintained and documented on the Research Workspace. Because these processing scripts have been developed with replicability of data processes and workflows as priorities, future changes or updates to source datafiles (e.g., individual variable files or MPA shapefiles) can be incorporated into these data processes to update all downstream data products.

### A2.1.2 Data Processes for Ecological Datasets

**Data verification and quality control** - To ensure the quality, integration, and preservation of MPA monitoring data, we worked closely with ecological data providers across different ecosystem and habitat types, including but not limited to habitat monitoring groups from the California MPA Monitoring Program. Initial conversations helped us understand how each dataset was collected, and subsequent verification and quality-checking identified any inaccuracies or inconsistencies in the data. These were shared with representatives from each data provider, and we co-addressed each issue. This process ranged from ensuring consistent values were used within data columns, to identifying issues with merging tables from relational databases, to returning to the original field data sheets to recover initial observations. After we co-created versions of the data that were as high quality as possible, we proceeded to the next steps, standardizing the data using Darwin Core and making it accessible and discoverable through a variety of endpoints.

**Applying the OBIS-ENV-DATA Approach with the *Darwin Core* Data Standard** - Using the OBIS-ENV-DATA approach, a diverse array of biological monitoring data was able to be converted into Darwin Core standard format. Originally, the Ocean Biodiversity Information System (OBIS) could only accept data describing the presence and absence of a particular species (De Pooter et al., 2017). Although many biological data sets can be abstracted to this level, critical data such as numbers of individuals, densities, and sizes in addition to ancillary data describing the habitat and conditions under which the organisms were observed were lost during the conversion process.

The adoption of the Event Core and ExtendedMeasurementOrFact extension allowed all of these data to be incorporated into a single Darwin Core Archive; this is the framework that was used to standardize MPA monitoring data using Darwin Core and enable their ingestion into global biodiversity databases such as OBIS and the Global Biodiversity Information Facility (GBIF). For example, using the OBIS-ENV-DATA approach, data from a survey of abalone inside and outside of MPAs along the California coast could incorporate not just presence and absence, but also counts, sizes, disease information, and site-level data on water temperature. The Occurrence Core captures the presence of a particular species in addition to the number of individuals of that species observed during a given survey (using the individualCount term). Using the ExtendedMeasurementOrFact extension terms measurementTypeID, measurementValue, and measurementUnit, in concert with occurrenceID, allows a size to be associated with each individual. In a similar fashion, one could record whether each individual was, for example, sick or healthy. Finally, the Event Core in addition to the ExtendedMeasurementOrFact extension is used to associate ancillary data, such as seawater temperature, with the site at which each survey was conducted.

**Flow into DataONE, to Onward Discovery and Use Points** - Both raw and derived (Darwin Core converted) formats of MPA monitoring data were made publicly available through a variety of outlets. First, raw data were submitted to the Ocean Protection Council DataONE node. Some data providers completed this submission directly, while others worked with CeNCOOS to jointly create DataONE submissions. As part of the submission process, EML metadata was created and a DOI was minted for each dataset.

From DataONE, monitoring data could be queried programmatically for use on other platforms. Through this mechanism, data were transferred to Axiom's Research Workspace. The Research Workspace stores and runs the Darwin Core conversion scripts, in addition to scripts necessary to prepare the data for inclusion into the California MPA Dashboard. From the Research Workspace, data can be easily made available through discovery and visualization platforms such as the CeNCOOS data portal and the Marine Biodiversity Observation Network (MBON) data portal. The derived data can also be submitted to OBIS and GBIF, where it can be queried with other datasets and contribute to global-scale biodiversity studies.

The ultimate goal of this data pipeline is to ensure consistent versions of all datasets are available through all of these discovery and use points. However, most datasets are currently in an intermediate stage due to the timelines and preferences of the data providers.

### A2.1.3 Data Processes for Oceanographic and Climatological Datasets

**General data handling -** Oceanographic and climatological data were generally processed and summarized for visualization at three spatial scales: individual MPAs in California, combined (aggregated) MPAs, and the reference bioregion. Whenever possible, oceanographic data products were developed through repeatable, community-developed access protocols and standards. Whenever possible, source data were accessed from NetCDF (Network Common Data Form, .nc) files, a binary data storage format that is widely used for oceanographic and climatological data and allows for machine-independent portability.

Data were spatially masked and aggregated by the outline of each reference and MPA site extracted from polygon shapefiles (.shp) of individual MPAs, MPAs combined by bioregion, and bioregions. The shapefile for all individual MPAs was obtained as a publicly available dataset from the California Department of Fish and Wildlife (map.dfg.ca.gov/metadata/ds0582.html). MPA polygons from this shapefile were also aggregated by bioregion to create a shapefile of combined MPAs. For non-gridded datasets, a point-in-polygon algorithm was used to check if a coordinate pair is within a region of interest (ROI) using the Shapely and Geopandas Python packages. For gridded datasets, a spatial mask was made for the ROI using the Salem Python package (salem.readthedocs.io/en/stable/). After data were spatially organized, time series were summarized into monthly and annual metrics (see Table 2-1). Generated files were saved as comma separated value (.csv) text files. These summarized time series were made publicly available through the Ocean Protection Council DataONE node (Low and Ruhl, 2021).

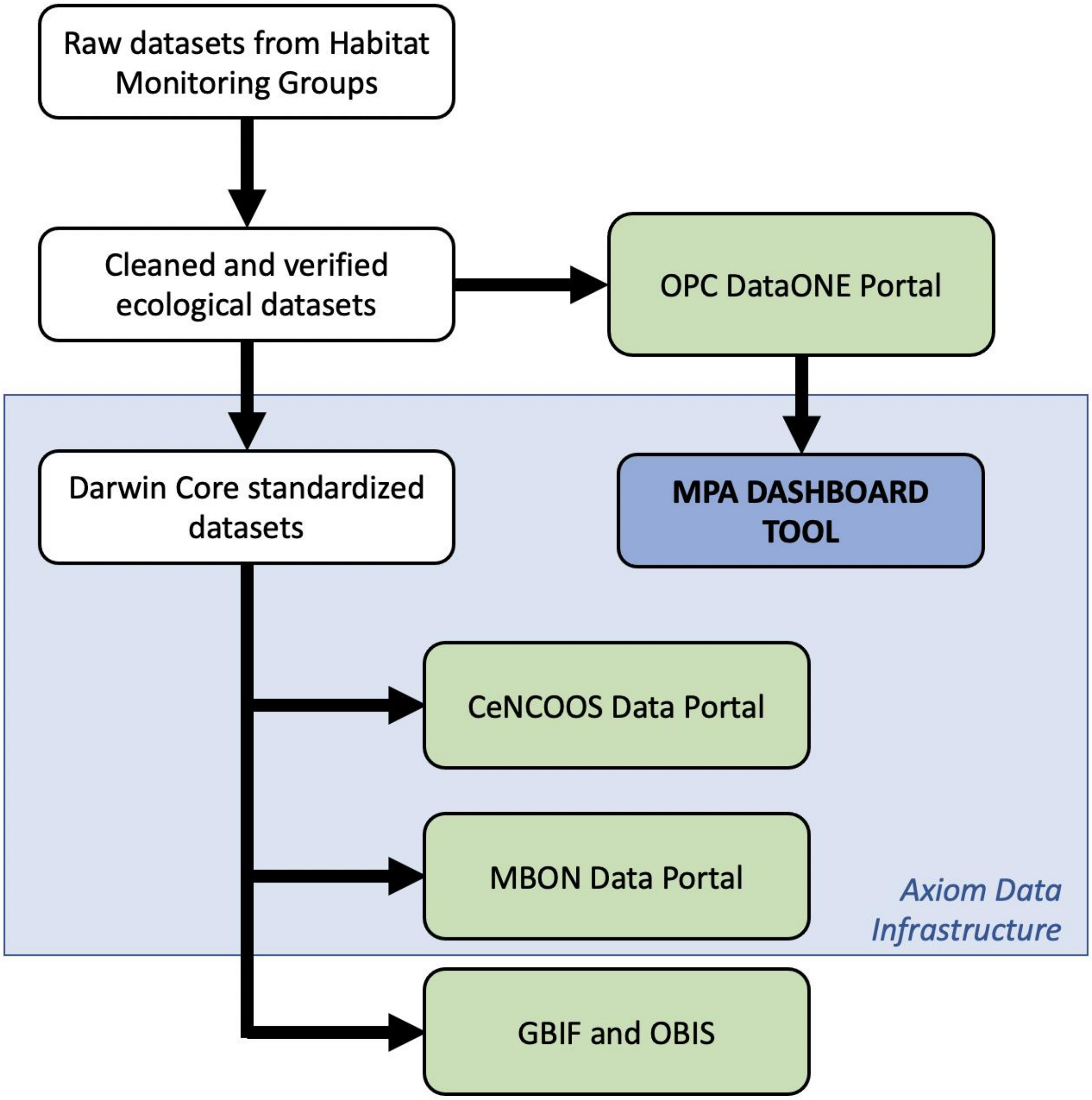


Figure A2-1. General steps in the processing and pipeline of ecological monitoring data from data providers.

### A2.1.4 Data Processes for Model Output Datasets

**Ecological Model Datasets -** The model description and data processes are given in *Ecological Indicators for Seascapes and Harmful Algal Bloom Risk in MPAs (Objective 4)*. Selected output figures and tables from the models and analyses were incorporated into the California MPA Dashboard tool. Derived data tables were made publicly available through the Ocean Protection Council DataONE node (La Valle 2021a, La Valle 2021b).

**Climate Change ROMS Output Datasets -** We obtained output variables (Sea Surface Temperature, Chlorophyll a, Dissolved Oxygen, Buoyancy Frequency, and the Coastal Upwelling Transport Index, CUTI) from a Regional Ocean Modeling System (ROMS) coupled with a biogeochemical model (NEMUCSC) based on the North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMURO), and run with three downscaled Earth System Models: Geophysical Fluid

Dynamics Laboratory (GFDL) ESM2M, Institut Pierre Simon Laplace (IPSL) CM5A-MR, and the Hadley Center HadGEM2-ES (HAD) (Pozo Buil et al. 2021). These were forced with a 'business as usual' scenario under the phase 5 of the Coupled Model Intercomparison Project (CMIP5) of the Intergovernmental Panel on Climate Change (IPCC), historical forcing (1980–2005), and the RCP8.5 climate change scenario (2006–2100). Model variable projections were output as monthly means of the climate variables from the model time range of 1980 to 2099, on a 0.1 degree (~10 km) spatial grid.

For each of the three climate models, and for an 'ensemble mean' of the three models, we aggregated each variable into 30-year mean values and calculated the projected change in 30-year means across each time step in the model time range. We spatially masked these variable change datasets by the regions of interest: (1) the boundaries of the U.S. Exclusive Economic Zone off the California coast; (2) individual MPAs; (3) combined MPAs; and (4) bioregions. We generated spatial rasters of change magnitude and percentage change for each variable for mapping these changes in the MPA dashboard. We also extracted spatial mean and quartile values of projected change in individual MPAs and the other regions of interest.

**Circulation Model Output Datasets -** The model description and data processes are reported in *High-Resolution Circulation and Connectivity Modeling (Objective 2)*. Output figures from the circulation and models were incorporated directly into the California MPA Dashboard tool.

### A2.1.5 Data Variables and Source Datasets for Oceanographic and Climatological Data

Here we outline data sources and processing for oceanographic indices and variables. Datasets were generally subset by time and space and organized as .csv files for visualization and access through the California MPA Dashboard. This integration work included steps to register data into common time and space formats for onward use.

**Oceanographic Indices -** The Multivariate El Niño-Southern Oscillation (ENSO) index (MEI.v2) is the time series of the leading combined Empirical Orthogonal Function (EOF) of five different variables (sea level pressure, sea surface temperature, zonal and meridional components of the surface wind, and outgoing longwave radiation) over the tropical Pacific basin). The Pacific Decadal Oscillation (PDO) is described as a long-lived El Niño-like pattern of Pacific climate variability in the North Pacific basin (Mantua 1999). We use the NCEI PDO index, based on NOAA's Extended Reconstruction of SSTs (ERSST Version 5). It is constructed by regressing the ERSST anomalies against the Mantua PDO index for their overlap period to compute a PDO regression map for the North Pacific ERSST anomalies. The ERSST anomalies are then projected onto that map to compute the NCEI index. It is publicly available as a monthly index from NOAA NCEI (ncdc.noaa.gov/teleconnections/pdo/).

The extratropical-based Northern Oscillation Index (NOI) is an index of climate variability based on the difference in sea level pressure anomalies at the North Pacific High in the northeast Pacific and near Darwin, Australia, in a climatologically low sea level air pressure region (Schwing et al. 2002). It represents a wide range of tropical and extratropical climate events impacting the north Pacific on intraseasonal, interannual, and decadal scales. It is publicly available as a monthly index from the NOAA Environmental Research Division (oceanview.pfeg.noaa.gov/products/noix/download).

The Multivariate Ocean Climate Index (MOCI) is a regionally zonal indicator of ocean conditions that uses several of the above indicators including upwelling, sea level, wind, SST, and the MEI, PDO, NOI, and NPGO indices (García-Reyes et al. 2017). This provides a climate index that bridges between global, statewide, and bioregion-level estimates of variation. It is publicly available as a seasonal index from the Farallon Institute (faralloninstitute.org/moci), supported in part by CeNCOOS and SCCOOS.

**West Coast Upwelling Indices -** The Coastal Upwelling Transport Index (CUTI) and the Biologically Effective Upwelling Transport Index (BEUTI) are two new upwelling indices that leverage state-of-the-art ocean models as well as satellite and *in situ* data to improve upon historically available upwelling indices for the U.S. west coast (Jacox et al. 2018). CUTI provides estimates of vertical transport near the coast (i.e., upwelling/downwelling) and was developed as a more accurate alternative to the previously available Bakun Index. BEUTI provides estimates of vertical nitrate flux near the coast (i.e., the amount of nitrate upwelled/downwelled), which may be more relevant than upwelling strength when considering some biological responses. CUTI and BEUTI values are publicly available as daily indices at 1-degree latitude resolution from the NOAA Environmental Research Division (oceanview.pfeg.noaa.gov/products/upwelling/cutibeuti). For each MPA, we identified the latitude bin that is closest to the center point of the MPA and extracted the corresponding upwelling index values. For each bioregion, we calculated the mean of index values from all latitudes within the region.

**Sea Surface Temperature** - Sea Surface Temperature (SST, °C) data were obtained from the California Current merged satellite-derived 1km dataset (spg-satdata.ucsd.edu/ca1km), which is converted and remapped from the global advanced very high resolution radiometer optimal interpolation (AVHRR OI) dataset (Reynolds et al. 2007, podaac.jpl.nasa.gov/dataset/NCDC-L4LRblend-GLOB-AVHRR_OI). We downsampled the daily dataset to generate monthly and annual temporal mean, maximum, and 95th percentile values for each pixel using the resample() function in the python xarray library. We extracted spatial subsets of these monthly and annual datasets based on shapefiles for each area of interest: individual MPAs in the California network, the combined MPAs for each of four designated bioregions, and the combined state waters for these bioregions. For each of these areas of interest, we calculated a spatial mean, maximum, and minimum SST value for each dataset time point.

**Net Primary Productivity** - Net Primary Productivity (NPP, mg C $m^{-2}$ $day^{-1}$) values are calculated from merged ocean color satellite datasets for Chlorophyll a and Photosynthetically Active Radiation (PAR) using the Behrenfeld and Falkowski model (Behrenfeld and Falkowski 1997), adapted for the California Current region (Kahru et al. 2009). The dataset has a daily temporal resolution and a spatial resolution of 4 km. We downsampled the daily dataset to generate monthly and annual temporal mean, maximum, and 95th percentile values for each pixel using the resample() function in the python xarray library. We extracted spatial subsets of these monthly and annual datasets based on shapefiles for each area of interest: individual MPAs in the California network, the combined MPAs for each of four designated bioregions, and the combined state waters for these bioregions. For each of these areas of interest, we calculated a spatial mean, maximum, and minimum NPP value for each dataset time point.

**KD490 -** The coefficient of diffuse attenuation of downwelling light at 490 nm (KD490) is a proxy for turbidity, and is obtained as a standard optical parameter from ocean color satellite sensors. These KD490 data are based on the European Space Agency (ESA) Ocean Colour Climate Change Initiative (OC-CCI) version 4.2 (Sathyendranath et al., 2019, esa-oceancolour-cci.org/), using the equation from Lee et al. (2005) and bbw from Zhang et al. (2009). The dataset has a daily temporal resolution and a spatial resolution of 4km. We downsampled the daily dataset to generate monthly and annual temporal mean, maximum, and 95th percentile values for each pixel using the resample() function in the python xarray library. We extracted spatial subsets of these monthly and annual datasets based on shapefiles for each area of interest: individual MPAs in the California network, the combined MPAs for each of four designated bioregions, and the combined state waters for these bioregions. For each of these areas of interest, we calculated a spatial mean, maximum, and minimum KD490 value for each dataset time point.

**CDIP MOPS -** The CDIP Monitoring and Prediction (MOPS) model estimates nearshore wave conditions at nodes along the 15-meter isobath. Nearshore conditions are estimated using a nonstationary linear wave refraction model driven by offshore conditions that are measured in real time from *in situ* wave buoys. The model has been validated against *in situ* measurements and shown to represent nearshore conditions well in areas with relatively uniform coastal topography. The model output includes wave spectral data and bulk statistics, including significant wave height (Hs) and dominant wave period (Tp). Wave power is approximated by the product of the squared significant wave height and the dominant period (Hs^2 * Tp) (Herbich 2000). For each region of interest (MPA and Bioregions), we identified MOPS nodes that were located within the spatial boundaries and generated monthly and annual summaries (mean, maximum, and 95th percentile). If there were multiple nodes within the boundaries of a region of interest, we calculated the spatial mean, minimum, and maximum for the region of interest.

**COAMPS Gridded Wind Data** - Coupled Ocean/Atmosphere Mesoscale Prediction Systems (COAMPS, version 3; nrlmry.navy.mil/coamps-web/web/docs) is a mesoscale coupled operational atmospheric/ocean model developed and run by the Naval Research Laboratory Marine Meteorology Division. These data are ingested through the CeNCOOS cyber infrastructure and available as a CF-compliant netCDF file on the CeNCOOS THREDDS server. We obtained wind speed and direction variables from u and v wind vectors at 10 meters above sea level from the gridded nowcast output of the model. Scalar wind speed is calculated as the square root of the sum of squares of the u and v vectors and has units of meters per second. Wind direction is calculated using the trigonometric arctan function of the quotient of v divided by u and has units of degrees. We extracted spatial subsets of these monthly and annual datasets based on shapefiles for each area of interest: individual MPAs in the California network, the combined MPAs for each of four designated bioregions, and the combined state waters for these bioregions. For each of these areas of interest, we calculated a spatial mean, maximum, and minimum value for each dataset time point.

**Aragonite Saturation** - Surface (top model bin; ~10m) and bottom (last available model bin) aragonite saturation values were obtained from model runs of a nested implementation of the Regional Ocean Modeling System (ROMS-NEMUCSC) (Cheresh and Fiechter 2020). The carbonate submodel included dissolved inorganic carbon (DIC), total alkalinity (TA), calcium carbonate, ocean pH, and pCO2 and was computed using the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) carbonate chemistry (co2cal_SWS.f). Monthly and annual means were extracted from the model and we extracted spatial subsets of these monthly and annual datasets based on shapefiles for each area of interest: individual MPAs in the California network, the combined MPAs for each of four designated bioregions, and the combined state waters for these bioregions. For each of these areas of interest, we calculated a spatial mean, maximum, and minimum value for each dataset time.

### A2.1.6 Data Variables and Source Datasets for Ecological Monitoring Data

**CCFRP Angler Surveys -** The California Collaborative Fisheries Research Program (CCFRP; mlml.sjsu.edu/ccfrp) monitors 15 MPAs and 16 reference sites using fisheries-independent standardized surveys of Catch-Per-Unit-Effort (CPUE) and fish sizes. These data are presented on the OPC DataONE portal in two tables, one containing CPUE and Biomass-Per-Unit-Effort (BPUE) and one containing fish lengths. The code to produce these tables is also provided (Starr et al, 2021). From DataONE, the data tables were ingested into Axiom's Research Workspace, and mean CPUE for ecologically and recreationally important species was extracted for each MPA and its corresponding reference site for use in the California MPA Dashboard. The dashboard includes this metric for:

- Combined Fish (92 Actinopterygii, 5 Elasmobranchii)
- Combined Rockfish (*Sebastes* spp.)
- Halibut (Paralichthys californicus)

- California Sheephead (*Semicossyphus pulcher*)

In addition, Darwin Core conversion scripts, written in Python 3, were run on the Research Workspace to create a Darwin Core archive containing fish counts, fishing effort in angler-hours, and CPUE data. These derived data tables underpin the presentation of the data on the CeNCOOS and MBON data portals (CeNCOOS 2021a, MBON 2021a).

**MARINe Rocky Intertidal Surveys -** The Multi-Agency Rocky Intertidal Network (MARINe; marine.ucsc.edu) conducts long-term monitoring and biodiversity surveys of rocky intertidal sites from Alaska to Baja California, including much of the California coastline. These data are publicly available on the OPC DataONE repository; they are separated into five submissions based on survey type:

- Long-term monitoring sea star and *Katharina tunicata* counts (MARINe et al. 2021a)
- Long-term monitoring species abundance from photoquadrats and phototransects (MARINe et al. 2021b)
- Coastal Biodiversity species abundance from quadrats (MARINe et al. 2021c)
- Coastal Biodiversity species abundance from swath transects (MARINe et al. 2021d)
- Coastal Biodiversity species abundance from point contact surveys (MARINe et al. 2021e)

From DataONE, the data tables were ingested into Axiom's Research Workspace, and we extracted the following measurements for use in visualizations and analysis: barnacle percent cover, mussel percent cover, sea star abundance, black chiton (*Katharina tunicata*) abundance.

In addition, Darwin Core conversion scripts, written in Python 3, were run on the Research Workspace to create two Darwin Core archives containing sea star and *Katharina tunicata* counts and percent cover of invertebrates and algae as measured by photoquadrats and phototransects. These derived data tables have been submitted to OBIS and GBIF (Raimondi et al. 2021a, Raimondi et al. 2021b, Raimondi et al. 2021c, Raimondi et al. 2021d), and Axiom Data Science is currently working to ingest them into the CeNCOOS and MBON data portals. A similar conversion and submission process is planned for the coastal biodiversity quadrat, swath transect, and point contact survey data. These data have been received and contain surveys through 2021; we are currently developing Darwin Core conversion scripts for them. The long-term monitoring rather than the coastal biodiversity data were prioritized due to the fact that the two survey types take similar measurements, and the coastal biodiversity surveys cover fewer sites and fewer time points.

**PISCO Kelp Forest Surveys** - The Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) has conducted ecological surveys of nearshore kelp forest and rocky reef sites since 1999. SCUBA divers collect data on the density of kelp forest fish, invertebrate, and macroalgal species using transect and size frequency surveys at sites inside and outside MPAs. These data are publicly available on the Ocean Protection Council DataONE node (Carr et al. 2021), where they are presented in three tables containing fish density and size, density and size of benthic invertebrate and macroalgal species, and size frequency of select invertebrate species. Uniform Point Contact data describing the cover, substrate type, and relief of the habitat are also included. From DataONE, the data tables were ingested into Axiom's Research Workspace, and mean abundance for ecologically important species was extracted for each MPA and its corresponding reference site for use in the California MPA Dashboard. The dashboard includes this metric for:

- Fish
    - Combined finfish
    - Combined rockfish (*Sebastes* spp.)
    - California Sheephead (*Semicossyphus pulcher*)
    - Combined basses (*Paralabrax* spp.)

- Invertebrates
    - Combined invertebrates
    - Combined abalone (*Haliotis* spp.)
    - California Spiny Lobster (*Panulirus interruptus*)
    - Sea urchins (Strongylocentrotus and Mesocentrotus spp.)
    - Combined crabs

In addition, Darwin Core conversion scripts, written in Python 3, have been developed for each data type (fish density, invertebrate and macroalgal density, and invertebrate and algae size frequency). An updated version of these data (containing survey data through 2020) has been received and is currently undergoing verification and quality control. With permission from the data provider, these derived data tables will ultimately appear on CeNCOOS, MBON, OBIS, and GBIF.

**Reef Check California Kelp Forest Surveys** - Reef Check California (RCCA) trains volunteer scientific divers to conduct ecological surveys of nearshore kelp forest and rocky reef sites. SCUBA divers collect data on the density of kelp forest fish, invertebrate, and macroalgal species using transect and size frequency surveys at sites inside and outside MPAs. These data are publicly available on the Ocean Protection Council DataONE node, where they are presented in four separate submissions based on taxonomic group:

- Fish density and size (Freiwald 2020a)
- Invertebrate density and size, including additional size frequency data sets for sea urchins and abalone (Freiwald 2020b)
- Macroalgal density and size, including an additional presence/absence data set on invasive algae (Freiwald 2020c)
- Uniform Point Contact data describing the cover, substrate, and relief of the habitat (Freiwald 2020d)

From DataONE, the data tables were ingested into Axiom's Research Workspace. The California MPA Dashboard does not currently include any metrics from RCCA, however, four data layers have been added to the CeNCOOS and MBON data portals: fish, invertebrate, and macroalgal density, sea urchin size frequency, abalone size frequency, and invasive algae presence and absence (CeNCOOS 2021b, MBON 2021b). Additionally, a Darwin Core conversion script, written in Python 3, was run on the Research Workspace to create a Darwin Core archive for the fish, invertebrate, and macroalgal density and size data. These derived data tables underpin the presentation of the data on OBIS (Freiwald and LaScala-Gruenewald 2021) and GBIF (United States Geological Survey 2020).

**CRFS Recreational Catch Per Unit Effort -** The California Recreational Fisheries Survey (CRFS) program is run by the California Department of Fish and Wildlife (CDFW), and collects fishery-dependent data on California's marine recreational fisheries. Spatially explicit monthly catch and effort estimates are provided for four fishing modes (private boats, Commercial Passenger Fishing Vessels (CPFVs), beaches/banks, and man-made structures). These data are spatially explicit on a grid of 1 x 1 mile 'microblocks' that subdivides the CDFW's 10 x 10 nautical mile commercial fishing blocks to a finer spatial resolution.

CRFS data are not able to be shared publicly in their raw form, but derived data are presented in the California MPA dashboard. Data were extracted from all microblocks within a 5 km buffer zone surrounding each MPA (i.e., potential spillover areas) and within each bioregion. Mean Catch-Per-Unit-Effort (CPUE) for ecologically and recreationally important species was calculated for the 5 km zone around each individual MPA, for the combined 5 km zones around all MPAs in a bioregion, and for the entire bioregion. The dashboard includes these metrics for: Red Abalone (*Haliotis rufescens*), Dungeness

Crab (*Cancer magister*), California Spiny Lobster (*Panulirus interruptus*), California Sheephead (*Semicossyphus pulcher*), Halibut (Paralichthys californicus), Lingcod (Ophiodon elongatus), Combined Rockfish (*Sebastes* spp.)

**Kelp Canopy Area** - Kelp area canopy area values (m2) for giant kelp (*Macrocystis pyrifera*) and bull kelp (*Nereocystis luetkeana*) are derived from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) satellite imagery at a 30 x 30 m pixel resolution for all coastal areas of California, including offshore islands. These area values are divided by the pixel area (900 $m^2$) to obtain a percentage canopy cover. The data are publicly available from the Santa Barbara Coastal LTER on the Environmental Data Initiative (EDI) Data Portal (doi.org/10.6073/pasta/89b63c4b49b80fb839613e9d389d9902).

**Estuaries Vegetation and Fish Surveys -** The estuaries monitoring team led by Moss Landing Marine Laboratories conducts semi-annual vegetation and fish seine/cast net surveys to monitor estuaries along the California coast. These surveys commenced in spring 2021, and so data have not yet been incorporated into the California MPA Dashboard or shared via other discovery and use points. The team has provided some preliminary data which can be used to begin to construct data pipelines and facilitate the eventual inclusion of the larger data set. In addition, we will be working with the group to establish mechanisms for storing the data in DataONE following the conclusion of their 2021 surveys.

**Mid-Depth and Deep Reef Surveys** - The mid-depth and deep reef survey team led by Moss Landing Marine Laboratories has conducted annual surveys of reef fish abundance using submersibles, remotely operated vehicles (ROVs), baited remote underwater video (BRUV) cameras and the Benthic Observation Survey System (BOSS). These data have not yet been shared with our project team, and are not yet available on DataONE or any downstream discovery or use points. The team has let us know that it should be available by the end of the year, and we will work with them to ingest it into our project tools as soon as possible.

**North Coast Kelp Forest Surveys** - The North Coast kelp surveys led by Bodega Marine Laboratory document benthic community composition and structure on nearshore rocky reefs. SCUBA divers collect data on the density and habitat of benthic fish and invertebrate species using transect surveys at sites with varying levels of protection. Size frequency data are also available for sea urchins and abalone. Quality control and reformatting are ongoing at the time of writing. We have worked closely with the data provider to address these issues, and we are currently in the process of submitting a set of verified data tables to DataONE. In the future, we hope to facilitate sharing via other discovery and use points.

**Sandy Beaches Seabird, Kelp Wrack, and Fish Surveys** - The sandy beaches monitoring team led by researchers at the University of California, Santa Barbara conducts seabird counts, kelp wrack cover and composition surveys, and fish seine/cast net surveys to monitor sandy beach ecosystems along the California coast. These surveys commenced in spring 2019, and used the same methodology as baseline surveys conducted in 2014-2015, 2010-2011, and 2011-2013 in the north coast, north central coast, and south coast bioregions respectively.

The sandy beaches baseline data sets have been privately submitted to the OPC DataONE node (Nielsen 2013, Dugan 2021, Nielsen 2021), with the intention to make them public after review by the data providers. A subset of data from the 2019 and 2020 surveys have recently been shared with CeNCOOS, however, we have not yet been able to incorporate them into the California MPA dashboard or share them via other discovery and use points. The group has also provided data from one long-term monitoring site which has been used to begin to construct data pipelines and facilitate the eventual inclusion of the larger data set.

Table A3-1. MPA data integration tracking tool highlighting the current stages of data integration. This works to meet **Deliverables 7** and **9**. Importantly, this has expanded to include additional datasets and extends the integration from use in the California MPA Dashboard to onward availability in the IOOS portal systems and globally via OBIS and GBIF.

| Dataset | On DataONE | DwC conversion scripts complete | On IOOS portal | On OBIS | On MPA dashboard | Latest year |
|---|---|---|---|---|---|---|
| Reef Check – fish transects | Yes | Yes | | Yes | No | 2019 |
| Reef Check – invertebrate transects | Yes | Yes | | Yes | No | 2019 |
| Reef Check – algae transects | Yes | Yes | | Yes | No | 2019 |
| Reef Check – UPC data | Yes | Yes | | Yes | No | 2019 |
| Reef Check – invasive algae surveys | Yes | Yes | | N/A | No | 2019 |
| Reef Check – urchin size data | Yes | Yes | | N/A | No | 2019 |
| Reef Check – abalone size data | Yes | Yes | | N/A | No | 2019 |
| CCFRP – fish abundance and CPUE | Yes | Yes | | N/A | Yes | 2020 |
| MARINe – LTM sea star and Katharina counts | Yes | Yes | In progress | Yes | Yes | 2021 |
| MARINe – LTM intertidal species abundance, photoplot and transect data | Yes | Yes | In progress | Yes | Yes | 2021 |
| MARINe – CBS intertidal species abundance, swath data | Yes | In progress | No | No | No | 2021 |
| MARINe – CBS intertidal species abundance, quadrat data | Yes | In progress | No | No | No | 2021 |
| MARINe – CBS intertidal species abundance, point contact data | Yes | In progress | No | No | No | 2021 |
| PISCO – fish transects | Yes | Yes | No | No | Yes | 2020 |
| PISCO – swath transects | Yes | Yes | No | No | Yes | 2020 |
| PISCO – size frequency data | Yes | Yes | No | No | No | 2020 |
| Sandy beaches – wrack cover and composition | Yes (baseline only, private) | No | No | No | No | 2020 |
| Sandy beaches – kelp and seabird abundance* | Yes (baseline only, private) | No | No | No | No | N/A |
| Sandy beaches – physical characteristics | Yes (baseline only, private) | N/A | No | N/A | No | 2020 |
| Sandy beaches – surf zone fish abundance* | No* | No | No | No | No | N/A |
| CRFS – recreational catch | N/A | N/A | N/A | N/A | Yes | 2019 |
| Ecotrust – NC spatial fishing data§ | Yes (samples of post-MPA only) | N/A | N/A | N/A | No | N/A |
| Ecotrust – NCC spatial fishing data§ | Yes (samples of pre-MPA only) | N/A | N/A | N/A | No | N/A |
| Ecotrust – SC spatial fishing data§ | Yes (samples of post-MPA only) | N/A | N/A | N/A | No | N/A |
| North coast swath transects and size frequency data | In progress | Partially | No | No | No | 2019 |
| Estuaries – vegetation survey data* | No | No | No | No | No | N/A |
| Estuaries – beach seine and cast net survey data* | No | No | No | No | No | N/A |
| Mid-depth and deep survey data** | No | No | No | No | No | N/A |

* New or first year of survey data are still being assembled by the data provider and have not been received by CeNCOOS

** All survey data are still being assembled by the data provider and have not been received by CeNCOOS

§ CeNCOOS is still working with Ecotrust to establish the best way to include their before and after data in the CA MPA Dashboard

# A3 High-Resolution Circulation and Connectivity Modeling (Objective 2)

## A3.1 Extended Methods for Circulation and Connectivity Modeling

### A3.1.1 Model Evaluation

The model has been run for the period March 10, 2020 through the present and evaluated relative to high frequency radar (HF Radar) estimates of near surface currents. Fig. A3-1 highlights various quantitative measures of velocity assessment for the 1-year period 2020-08-01 through 2021-07-31 for the University of California Santa Cruz (UCSC) re-implementation of the West Coast Operational Forecast System (WCOFS) that serves as the outermost grid domain; the evaluation is shown for the sub-region that spans the innermost model nest. Over this period, WCOFS model mean surface currents are generally offshore, in the same direction as observations, though with smaller amplitude (compare vectors in (a) and (b)). The model shows somewhat more energetic motion about the mean than is observed, particularly within Monterey Bay and offshore of Pt. Sur (colors in (a) and (b) and their ratio in (f)). The complex correlation of vector currents, calculated following Kundu (1976), shows significant correlations exceeding 0.6 along the coast with reduced values within Monterey Bay and offshore and small amplitude-weighted phase angles between modeled and observed fluctuations ((c) and (d)).

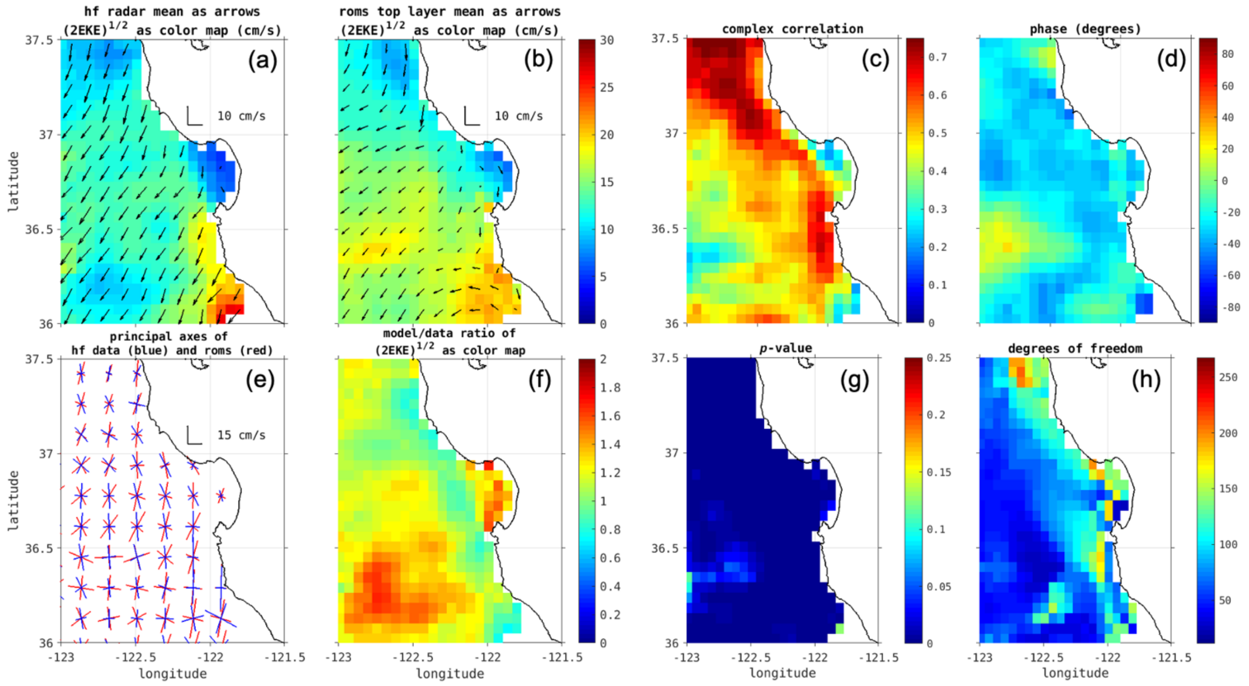


Figure A3-1. Evaluation of UCSC re-implementation of WCOFS model surface velocities against HF Radar estimated near surface velocities for the 1-year period 2020-08-01 through 2021-07-31 for the region covered by the innermost model nest (Fig. 3-1). Mean velocity vectors and square root of twice the eddy kinetic energy (EKE; units cm/s) for (a) HF Radar estimates and (b) model values. (c) Complex correlation coefficients between modeled and observed currents. (d) Amplitude weighted phase angle (degrees) between modeled and observed currents. (e) Principal axes obtained through empirical orthogonal decomposition of modeled (red) and observed (blue) currents. (f) Ratio of modeled to observed square root of twice the EKE. (g) p-value Probability that the complex correlation shown in (c) could be obtained by chance with two uncorrelated time-series. (h) degrees of freedom used in the p-value calculation.

A similar evaluation of the 160-meter resolution innermost nest domain shows that mean modeled velocities are predominantly offshore as in the observations, though somewhat weaker and more northward than HF radar estimates (Fig. A3-2). Fluctuating velocities about the mean are more energetic in the model than as observed, particularly offshore (f). Principal axes of these fluctuations are obtained through empirical orthogonal decomposition and show somewhat better alignment than for the WCOFS grid. The complex correlations (c) are significant and reveal good agreement off Pt. Sur and Pescadero and poor agreement within Monterey Bay and offshore at latitudes of Monterey Bay. Seasonal assessments of this innermost model nest (not shown) reveal high correlation of winter and springtime velocities, good correlation for summertime fields, and low and non-significant agreement in fall. During fall, model mean velocities are distinctly more northward and directed less offshore than the mean flow observed by the HF Radar.

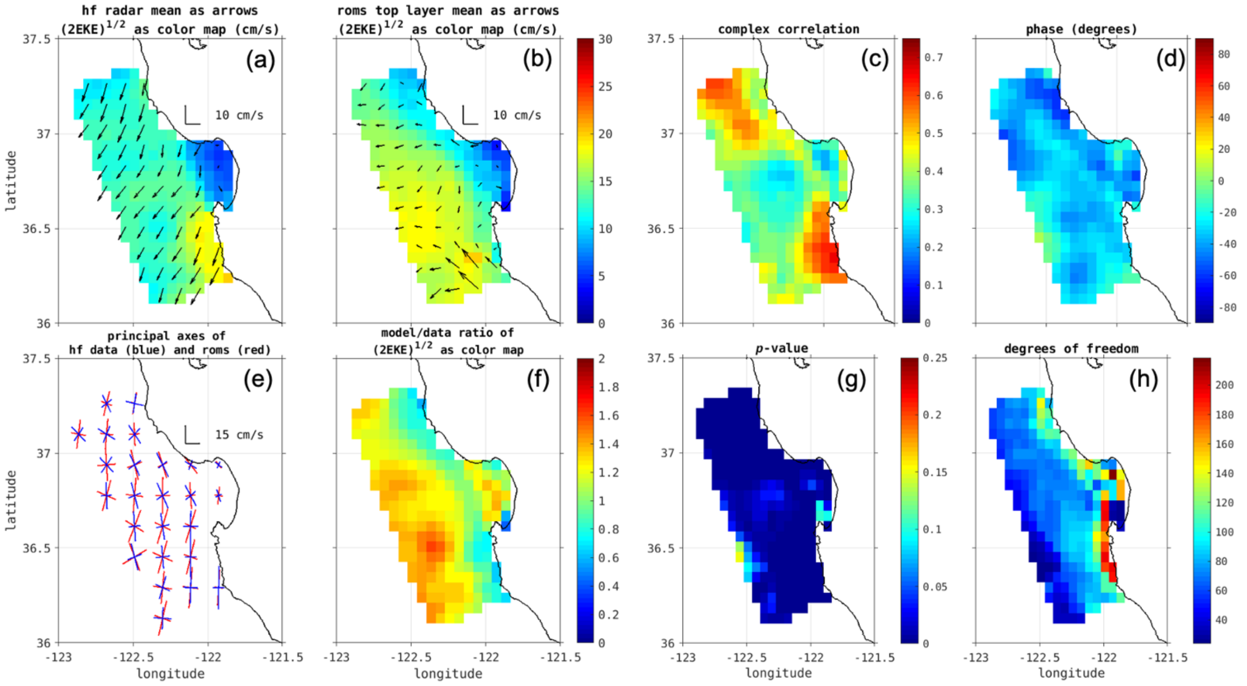


Figure A3-2. As in Fig.A3-1, but for the 160 m nest model output. Specifically, this figure shows a comparison of modeled surface velocities against HF Radar estimated near surface velocities for the 1-year period 2020-08-01 through 2021-07-31 for the region covered by the innermost model nest (Fig. 3-1). Mean velocity vectors and square root of twice the eddy kinetic energy (EKE; units cm/s) for (a) HF Radar estimates and (b) model values. (c) Complex correlation coefficients between modeled and observed currents. (d) Amplitude weighted phase angle (degrees) between modeled and observed currents. (e) Principal axes obtained through empirical orthogonal decomposition of modeled (red) and observed (blue) currents. (f) Ratio of modeled to observed square root of twice the EKE. (g) p-value Probability that the complex correlation shown in (c) could be obtained by chance with two uncorrelated time-series. (h) degrees of freedom used in the p-value calculation.

### A3.1.2 WCOFS High-Resolution Nests

A physical ocean modeling system has been developed to investigate potential larval connectivity between and among greater Monterey Bay MPAs. Our implementation uses the Regional Ocean Modeling System (ROMS; http://www.myroms.org) in a triply-nested configuration based on NOAA's West Coast Operational Forecasting System (WCOFS; tidesandcurrents.noaa.gov/ofs/dev/wcofs/wcofs_info.html) (see section 3.1.3). The outermost domain is the WCOFS 4 km resolution grid itself and its accompanying ocean state estimate that is updated on a daily basis. The 800 m middle nest spans the central coast from Pt. Buchon to Pt. Arena, and the innermost grid focuses on the greater Monterey Bay with a resolution of 160 m, extending from south of Pt. Sur to the north of Pescadero. All domains use the same ROMS configuration and are forced by the same atmospheric fields derived from NOAA's North American Model (NAM) and used for WCOFS. For the purposes of this effort, all domains are coupled in an online-nested fashion in which fields from each nest influence the solution in the adjacent nest across their coincident boundary on each time-step. Though the data assimilative WCOFS fields are discontinuous, instantaneously updated once each day, the solutions in the inner nests are continuous, meaning the initial condition on any given day is identical to the final condition of the previous day; WCOFS field discontinuities influence the middle model domain and in turn innermost domain through their boundary interactions.

By assimilating Sea Surface Height (SSH), Sea Surface Temperature (SST), and High Frequency (HF) Radar surface current estimates, the WCOFS fields are more consistent with observations than a free-running model that is not constrained by observation data. As a result, we chose to weakly nudge (with a 7-day relaxation time-scale) the middle and inner grids with oceanographic fields derived from the outermost WCOFS ocean state estimate that is run independently from the nests and referred to as the UCSC re-implementation of WCOFS. This procedure means that the middle and inner nests are only nearly free-running, constrained to ensure that their solutions maintain good agreement with available observations within their small footprint domains. The hydrodynamic model output is now being generated routinely with public availability via a UCSC THREDDS server in November 2021 (**Deliverable 4**).

### A3.1.3 Particle Tracking Simulations of Connectivity

WCOFS became operational within NOAA on March 22, 2021. Because marine connectivity estimates are statistical in nature, they benefit from long simulations that exhibit greater variability in ocean conditions. To build more robust statistics, we augmented the operational WCOFS output with a pre-operational version starting on March 10, 2020. For this project, our connectivity calculations are based on 1.5 years of model simulations. The nested model physical simulations continue presently on an ongoing basis (**Deliverable 5**).

The ROMS configuration produces physical fields (temperature, salinity, SSH, 3-dimensional velocity, and turbulent mixing coefficients). This output then drives an offline particle tracking code built on the ROMS implementation and used in many previous studies (Drake and Edwards 2009, Drake et al. 2011, Drake et al. 2013, Drake et al. 2015, Drake et al. 2018). Although the circulation model resolves tidal motion, particles are driven offline, by daily average currents with an imposed parameterization for the horizontal mixing associated with tides; this approach was chosen to reduce storage needs by a factor of 24. For each larval behavior, 3660 particles (representing larvae of various potential organisms) are released into the model domain in near coastal subregions and in MPA subregions every 12 hours over the 1.5 years of simulation. These organismal representations come with various particle lifetimes (e.g., pelagic larval duration [PLD]) and tendencies of remaining at the surface, or being entrained into the surface boundary layer or below it, or being neutrally buoyant and fully Lagrangian. This set of behaviors enables transport and connectivity exploration across a wide range of possibilities including many described in Drake et al. (2018) pertaining to kelp, rockfish, crabs, urchins, and abalone. Particles are transported by modeled ocean currents and tracked for 90 days. Connectivity statistics describe the probability that a particle leaves one subregion and enters another subregion within a competency window following a pelagic larval duration [PLD]. Larval behaviors, such as maintenance within the surface mixed layer, maintenance below the surface mixed layer, and diel vertical migration, along with the no-behavior case, are included in our study. Connectivity statistics were calculated for a variety of release dates, pelagic larval durations, competency windows, and behaviors between MPAs, and between MPAs and more general coastal subregions (**Deliverable 6**). We assessed the differences in resolution solutions between the 3 km native WCOFS scale and the 800 m and 160 m scale nests.

## A4 Methods for Ecological Indicators for Seascapes and Harmful Algal Bloom Risk in MPAs (Objective 4)

### A4.1 Extended Methods for Ecological Indicators

**Seascape Dataset** - Seascapes are created from remotely sensed data as well as predictive models. As such, weather and climatic features like cloud cover can prevent us from visualizing parts of the ocean and their corresponding seascapes. The input datasets include: sea surface temperature (SST), photosynthetically active radiation (PAR), sea surface salinity, absolute dynamic topography (ADT), ice contribution, chromophoric dissolved organic material (CDOM), chlorophyll a (Chl a), MODIS normalized fluorescence line height (nFLH), and the nFLH:Chl a ratio. These data are then modeled using probabilistic self-organizing maps (PrSOM, Anouar et al. 1998) combined with a hierarchical agglomerative classification (HAC, Jain et al. 1987) to achieve a non-linear, topology-preserving data reduction to probabilistically fit one of 33 potential seascape categories, further described at (NOAA MBON, Kavanaugh et al. 2014). This creates 33 categories of water masses that have similar biogeochemical function. Seascape data are publicly available from NOAA Coastwatch (coastwatch.noaa.gov/cw/satellite-data-products/multi-parameter-models/seascape-pelagic-habitat-classification.html) as either 8-day or monthly composites represented in geographic space at a 5 km spatial resolution.

**Seascapes in MPAs -** To assess the dynamics and diversity of Seascapes within MPAs, we spatially masked and subset the 8-day composite Seascape dataset for each MPA using the *st_intersects* function in the *sf* package in R. Note that not all MPAs have Seascapes associated with them, because this function only includes an intersection if the center of the polygon of interest, in this case the Seascape 5 x 5 km spatial pixel(s), is contained within the MPA polygon. Because many MPAs are very near the shore, this was not always the case. For the MPAs that had intersecting Seascape data, about 1-5 Seascape pixels were found within one MPA. Other reasons for missing data include cloud cover and missing salinity points in certain dates of the time series.

We generated stacked bar plots of these Seascapes by MPAs and for bioregions. These were plotted over the entire model time period (2002-08-15 to 2021-02-15), and can be visualized for user-defined time periods within the MPA Dashboard application. We also calculated Shannon Diversity Indices (SDI) for Seascapes in each MPA using the formula:

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

where H’ is the diversity index, $p_i$ is the proportion of Seascape *i* in the entire Seascape time series for the MPA of interest, and S is the total number of different Seascapes occurring in the time series. This is a measure of diversity that accounts for both the number of different Seascapes encountered, as well as the relative abundance of those different Seascapes.

**Seascapes and Kelp Abundance** - To assess potential relationships between Seascapes and kelp abundance, we obtained data on kelp area canopy area values ($m^2$) for giant kelp (*Macrocystis pyrifera*) and bull kelp (*Nereocystis luetkeana*) from the publicly available dataset by the Santa Barbara Coastal LTER on the Environmental Data Initiative (EDI) Data Portal (Santa Barbara Coastal LTER et al. 2021).are derived from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) satellite imagery at a 30 x 30 m pixel resolution for all coastal areas of California, including offshore islands. These area values are divided by the pixel area (900 $m^2$) to obtain a percentage canopy cover. Kelp data are available on a quarterly (3-month) time resolution. We also spatially masked and subset the monthly composite Seascape dataset for each MPA. We excluded the data points with more than 50% missing data due to cloud cover. The kelp dataset was subset to overlap with the Seascapes time range of 2004-2021. We accounted for a lag in one quarter between Seascape and kelp data because research shows that local biogeochemistry shows effects on kelp biomass after about a quarter of a year (3 months).

For each Seascape category, we compared the frequency of that Seascape’s occurrence in the dataset to the ranked means of the kelp biomass using Kruskal-Wallis tests. We also calculated the quarterly modal Seascape for each spatial pixel in the dataset - this is defined as the Seascape that occurred the most frequently at that given location during a given quarter. We investigated the relationship between the modal Seascape and kelp biomass by quarter using a Kruskal–Wallis test. The Kruskal–Wallis test (1952) is a nonparametric approach to the one-way ANOVA. The procedure is used to compare three or more groups on a dependent variable that is measured on at least an ordinal level.

**Seascape Habitat Diversity and Biodiversity** - To assess potential relationships between the diversity of Seascapes and biodiversity in MPAs, we obtained data from the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) swath surveys of benthic invertebrates. We calculated Shannon Diversity Indices (SDI) for these species in each MPA using the formula:

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

where H’ is the diversity index, $p_i$ is the proportion of species *i* in the entire survey dataset for the MPA of interest, and S is the total number of different species observed in the MPA.

We plotted and compared annual Shannon Diversity Indices of Seascapes and biodiversity at 6 case study MPAs for which both Seascape and PISCO survey data were available (Anacapa Island SMCA, Anacapa Island SMR, Point Conception SMR, Point Dume SMCA, Stewarts Point SMR, Ten Mile SMR) to look at the agreement and divergence between patterns in these two diversity metrics.

**C-HARM Datasets** - The California-Harmful Algae Risk Mapping (C-HARM) Model generates nowcast (same-day) and forecast (one to three day) predictions of harmful algal bloom (HAB) conditions through a combination of (1) circulation models that predict the ocean physics, (2) satellite remote-sensing data of the ocean color and chlorophyll patterns, and (3) statistical models for predicting bloom and toxin likelihoods. Specifically, the routine nowcast and forecast products of toxigenic *Pseudo-nitzschia* blooms and/or domoic acid events are produced by combining: (1) empirical logistical models (GLMs); (2) existing hydrodynamic model simulations (CA-ROMS, 3 km); (3) enhanced satellite imagery (MODIS-Aqua with gap-filling using Data Interpolating Empirical Orthogonal Functions - DINEOF); (4) community (HABMAP)/marine mammal observations (Anderson et al. 2016). These predictions are generated daily to provide a nowcast and forecasts where one might encounter a *Pseudo-nitzschia* bloom and/or domoic acid event in real time up to three days in the future. C-HARM data are available at a 3 x 3 km spatial resolution between June 19, 2018 to February 10, 2021 from the NOAA Coastwatch ERDDAP Server.

Three output variables are produced:

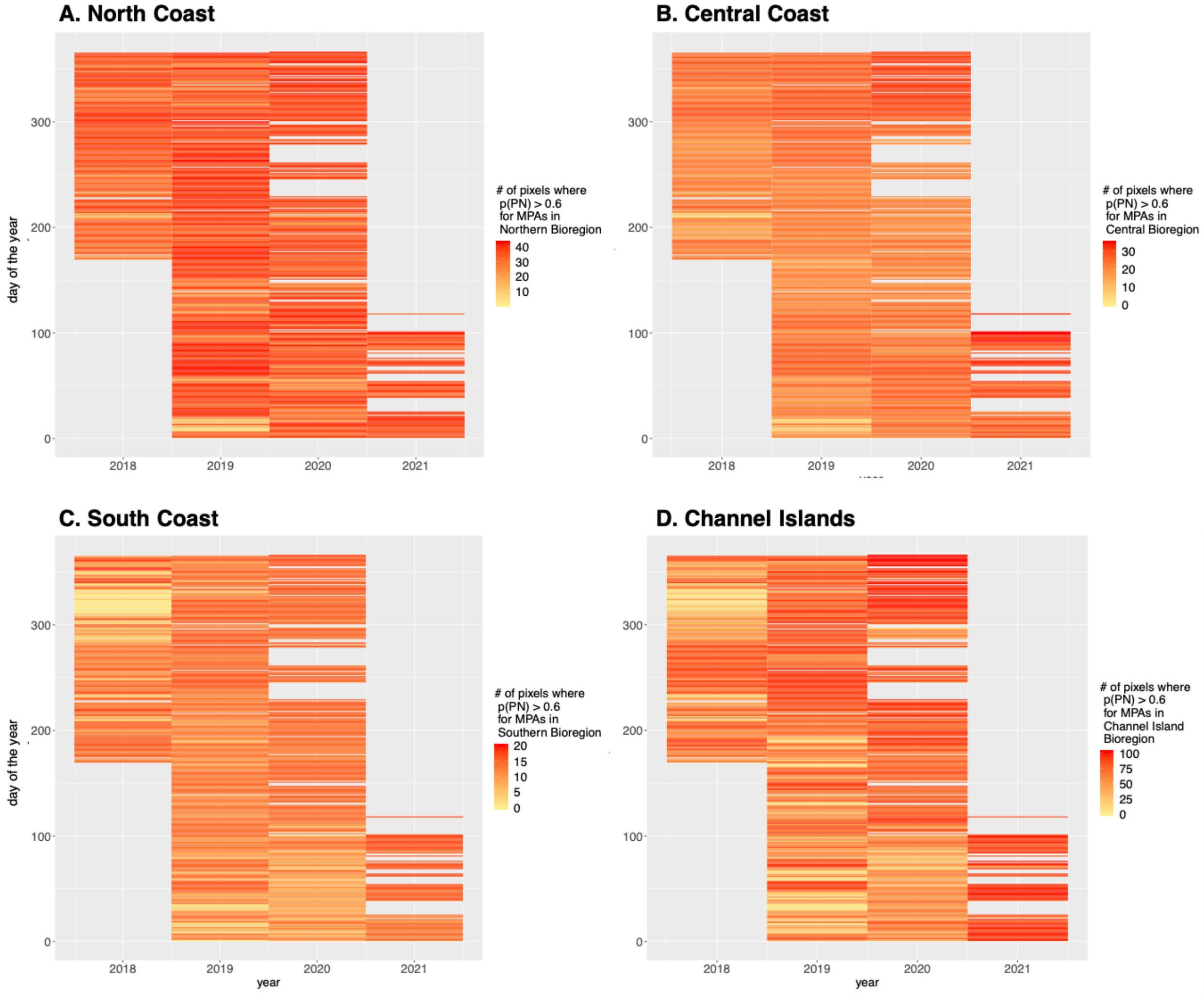
1. *Pseudo-nitzschia* Bloom Prediction shows the probability that the abundance of toxin-producing species of the diatom *Pseudo-nitzschia* is at or above the “bloom” threshold of 10,000 cells per liter. A value of 0.6, for example, means there is a 60% predicted probability of *Pseudo-nitzschia* blooms in that pixel. 0.6 was chosen as a threshold point where predictive accuracy and the probability of detection is optimized. This threshold is based on work in Trainer and Suddleson 2005, Lane et al. 2009, Anderson et al. 2009, 2011, 2016.
2. Domoic Acid Event Prediction (for particulate domoic acid) shows the probability that the domoic acid concentration in the bulk phytoplankton pool is at or above 500 nanograms per liter (= 0.5 micrograms per L). A value of 0.6, for example, means there is a 60% predicted probability of a toxic event, although there is always the possibility that concentrations lower than 500 ng/L will lead to toxins in shellfish or strandings of marine mammals and birds.
3. Domoic Acid Toxicity Prediction (for cellular DA) shows the probability that the domoic acid concentration per *Pseudo-nitzschia* (i.e. how toxic are the algal cells themselves) is at or above 10 picograms per cell (pg/cell). To give a sense of the range, the highest cellular concentrations seen in the environment have not yet exceeded 200 pg/cell in the most toxic cells. A predicted probability value of 0.6, for example, means there is a 60% probability that a 10 pg/cell level of toxicity is present in the phytoplankton, although there is always the possibility that concentrations lower than 10 will lead to toxins in shellfish or strandings of marine mammals and birds. The thresholds for cellular and particulate DA are discussed further in Anderson et al. 2009, 2011, 2016.

**EcoCast Datasets** - EcoCast is a fisheries sustainability tool that helps fishers and managers evaluate how to allocate fishing effort to maintain target fish catch while minimizing bycatch of protected or threatened species. EcoCast is based on the concept of dynamic ocean management, a new management approach that uses real-time and near real-time data to support management responses that can change in space and time, at scales relevant for animal movement and human use. The tool generates daily predictions of the spatial distributions of important migratory species, including those targeted for catch by fishers (i.e., swordfish) and vulnerable bycatch species (i.e., leatherback sea turtle, sea lions, blue shark). Key environmental variable (sea surface chlorophyll concentration, sea surface temperature sea surface winds, sea surface height, and eddy kinetic energy) are used as inputs for species distribution models to predict the spatial distributions of important migratory species. Species weightings range from -1.0 to 1.0 and are set to reflect management priorities and recent catch and bycatch events. Here, we use EcoCast predictions as indicators of where vulnerable species are distributed in MPAs and bioregions over time. EcoCast data are publicly available through NOAA CoastWatch (coastwatch.pfeg.noaa.gov/ecocast).

**Spatial and Temporal Risks of HABs** - We generated Hovmöller plots of the number of spatial pixels within MPAs with high probability of cellular domoic acid (cDA), particulate domoic acid (pDA), and Pseudo-nitzschia (PN) counts. These are representations of risk time series. We also generated heatmap plots showing the number of days per month in which at least one pixel within the MPAs in each bioregion was considered “high risk” for harmful algal blooms (i.e., cDA, pDA, and PN probability values surpassed a threshold of 0.6).

**HAB Risks to Threatened and Vulnerable Species** - We generated maps of the co-occurrence of high risk of harmful algal blooms ($P > 0.6$, from the C-HARM model) and high relative abundance ($P > 0$) of threatened species from the EcoCast model, and calculated the monthly spatial prevalence of these high-risk areas for each bioregion over the model time range (2018 to 2021).

## A4.2 Additional Results and Figures


A. North Coast

B. Central Coast

C. South Coast

D. Channel Islands

Figure A4-1. Plots showing the spatial extent (number of spatial pixels) for which there was a > 0.6 probability of *Pseudo-nitzchia* (PN) concentrations exceeding the threshold, for each day of the year from 2018-06-18 to 2021-02-10 for MPAs in each bioregion. The gray areas indicate no data.

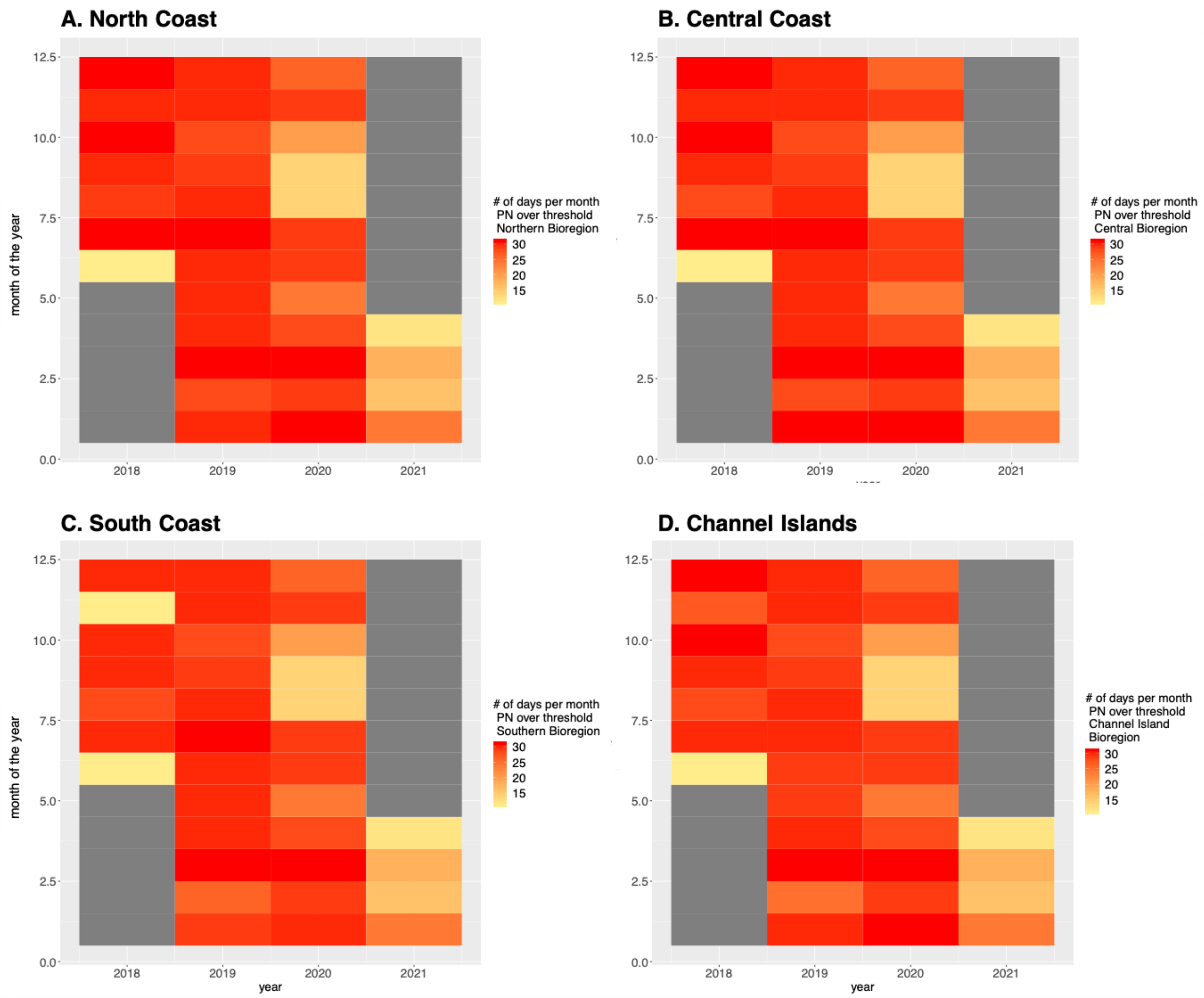


Figure A4-2. Heat map plots showing the number of days of each month from 2018-06-18 to 2021-02-10, where at least one location in the aggregated MPAs had a > 0.6 probability of *Pseudo-nitzchia* (PN) concentrations exceeding the threshold exceeding the threshold.

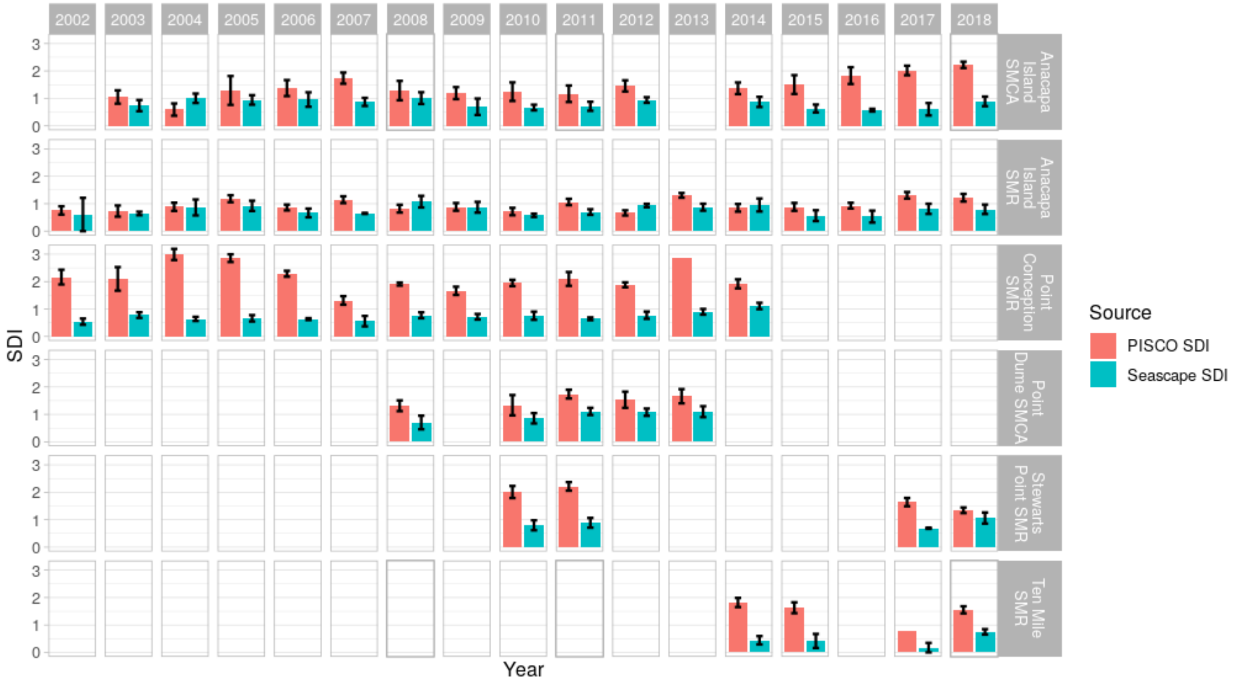


Figure A4-3. Barplots of Shannon Diversity Indices (SDI) of Seascapes and PISCO Swath data for the following MPAs: Anacapa Island SMCA, Anacapa Island SMR, Point Conception SMR, Point Dume SMCA, Stewarts Point SMR, Ten Mile SMR. The raw monthly Seascape dataset was used to calculate quarterly SDI values. The bars for the Seascape SDI show averages of those quarterly SDI values and the standard error (SE) bars were calculated using the four quarterly SDI (n = 2 for 2002, n = 4 all other years) values per year. The bars for the PISCO Swath data show means and SE of SDI for yearly benthic surveys taken within each MPA (n = 1-12 sites within each MPA).

## A5 Extended Methods and Results for Integrated Assessments

### A5.1 Extended Methods for Assessing Projected Climate Change Risk in MPAs

**Climate Model Outputs -** We obtained output oceanographic variables (Sea Surface Temperature, Chlorophyll a, Dissolved Oxygen, Buoyancy Frequency, and the Coastal Upwelling Transport Index, CUTI) from a Regional Ocean Modeling System (ROMS) coupled with a biogeochemical model (NEMUCSC) based on the North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMURO), and run with three downscaled Earth System Models: Geophysical Fluid Dynamics Laboratory (GFDL) ESM2M, Institut Pierre Simon Laplace (IPSL) CM5A-MR, and the Hadley Center HadGEM2-ES (HAD) (Pozo Buil et al. 2021). These were forced with a 'business as usual' scenario under the phase 5 of the Coupled Model Intercomparison Project (CMIP5) of the Intergovernmental Panel on Climate Change (IPCC), historical forcing (1980–2005) and the RCP8.5 climate change scenario (2006–2100). Model variable projections were output as monthly means of the climate variables from the model time range of 1980 to 2099, on a 0.1 degree (~10 km) spatial grid. For each oceanographic variable, we calculated the 30-year mean value of each spatial pixel in the dataset. We obtained these long-term mean values for each of the three climate models, and for an "Ensemble Mean" of the three models.

**Assessing change between past and future periods in MPAs and bioregions -** We extracted spatial mean values of all variables in all models for each MPA, aggregated MPAs, and bioregions within the model domain. To assess potential differences in MPA environmental conditions across time and across bioregions, we conducted Principal Components Analyses (PCAs) and Analyses Of Similarities (ANOSIM) using the multivariate Euclidean distances between MPAs. We compared projected past (1980-2009) and future (2070-2099) conditions in 130 California MPAs across the four bioregions. The past values were subtracted from the future values and the data were then normalized for PCA, including extraction of the eigenvectors to assess how each variable relates to the ordination of the MPAs and bioregions in the first and second principal components of variation. Because the CUTI metric is only available for mainland coastal sites and not for the Channel Islands MPAs, we ran two versions of the analyses - one with all four bioregions and without CUTI, and one that excluded the Channel Islands MPAs but included CUTI as a measure of upwelling. These analyses were done in PRIMER v6.

To assess which MPAs and bioregions are projected to have the least and greatest change from past to future under the modeled climate change, we ranked MPAs by the multivariate Euclidean distance between past and future conditions, using the projected Sea Surface Temperature, Chlorophyll a, Dissolved Oxygen and Buoyancy Frequency variables.

**Assessing climate refugia -** We calculated the projected change in 30-year means from the period 1980-2009 to the period 2070-2099 for each of four variables (Sea Surface Temperature, Chlorophyll a, Dissolved Oxygen, Buoyancy Frequency as a measure of stratification) for the subset of the model domain located within California State Waters. For each 0.1º pixel on the grid, we calculated the Euclidean distance between the two time periods using standardized versions of these change values. For each individual bioregion and for the whole state waters domain, we identified all pixels in the bottom 10th percentile of this Euclidean distance dataset, representing the locations within these regions that are projected to experience the least overall change across key climate variables. We then identified and calculated the percentage of these pixels that spatially overlap one or more MPAs, as an estimate of how protected these areas of ‘refugia’ are.

To assess how spatially persistent these environmental refugia are over time, we calculated Euclidean distances between the 30-year means for four time periods: Period 1 - Past (1980-2009), Period 2 - Present (2010-2039), Period 3 – Mid-Century Future (2040-2069), Period 4 – End Century Future (2070-2099) and identified pixels in the bottom 10th percentiles of each Euclidean distance dataset for each bioregion. We generated maps of these ‘refugia’ for each period and bioregion, and also calculated the percentage of these ‘refugia’ pixels that remained in the bottom 10th percentile of change across different time periods.

## A5.2 Additional Results and Figures

### A5.2.1 Additional Results and Figures for Contemporary Change

Table A5-1. Summary and correlation statistics for **North Coast** yearly environmental, oceanographic and habitat variables by bioregion for 2001-2020. These are annual data where available. Temporal coverage is noted here as missing observations and in the temporal data coverage chart (Table 2-1).

| Yearly obs. (n) | Variables | Year | North MOCI | CUTI | BEUTI | Wave height | Wave energy | SST | NPP | Kelp cover | Turbidity | Surface Ω | Bottom Ω | Wind speed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | North MOCI | 0.30 | | | | | | | | | | | | |
| 20 | CUTI | -0.32 | -0.78 | | | | | | | | | | | |
| 20 | BEUTI | 0.00 | -0.79 | 0.77 | | | | | | | | | | |
| 20 | Wave height | 0.37 | 0.18 | -0.51 | -0.25 | | | | | | | | | |
| 20 | Wave energy | 0.33 | 0.24 | -0.50 | -0.28 | 0.98 | | | | | | | | |
| 20 | SST | 0.17 | 0.92 | -0.62 | -0.79 | 0.03 | 0.13 | | | | | | | |
| 20 | NPP | 0.26 | 0.73 | -0.41 | -0.60 | -0.03 | 0.03 | 0.77 | | | | | | |
| 20 | Kelp cover | -0.63 | -0.75 | 0.40 | 0.43 | -0.13 | -0.18 | -0.73 | -0.71 | | | | | |
| 19 | Turbidity | -0.11 | 0.47 | -0.38 | -0.58 | 0.12 | 0.13 | 0.57 | 0.69 | -0.39 | | | | |
| 10 | Surface Ω | -0.52 | 0.88 | -0.45 | -0.66 | -0.28 | -0.28 | 0.94 | 0.79 | -0.77 | 0.84 | | | |
| 10 | Bottom Ω | -0.42 | 0.81 | -0.50 | -0.53 | -0.09 | -0.09 | 0.85 | 0.68 | -0.73 | 0.83 | 0.92 | | |
| 8 | Wind speed | 0.95 | -0.05 | 0.17 | 0.21 | 0.64 | 0.57 | -0.19 | -0.43 | -0.69 | -0.50 | - | - | |
| 18 | Seascapes PC1 | 0.02 | -0.74 | 0.41 | 0.68 | 0.20 | 0.06 | -0.83 | -0.88 | 0.54 | -0.66 | -0.74 | -0.57 | 0.36 |
| 18 | Seascape 7 | 0.07 | 0.46 | -0.49 | -0.46 | 0.06 | 0.07 | 0.42 | 0.45 | -0.08 | 0.05 | 0.16 | -0.02 | -0.22 |
| 18 | Seascape 12 | -0.07 | -0.70 | 0.33 | 0.55 | 0.07 | -0.01 | -0.72 | -0.68 | 0.73 | -0.69 | -0.95 | -0.93 | -0.40 |
| 18 | Seascape 14 | -0.18 | -0.65 | 0.43 | 0.55 | 0.13 | 0.10 | -0.78 | -0.79 | 0.62 | -0.77 | -0.79 | -0.69 | 0.40 |
| 18 | Seascape 17 | 0.03 | -0.07 | 0.27 | -0.07 | -0.17 | -0.24 | 0.14 | 0.14 | -0.17 | 0.20 | 0.25 | -0.08 | 0.41 |
| 18 | Seascape 19 | -0.47 | -0.27 | -0.04 | -0.13 | 0.04 | -0.03 | -0.29 | -0.24 | 0.68 | -0.22 | -0.14 | -0.26 | -0.64 |
| 18 | Seascape 21 | -0.06 | 0.72 | -0.40 | -0.69 | -0.22 | -0.08 | 0.80 | 0.81 | -0.48 | 0.62 | 0.74 | 0.57 | -0.33 |
| 18 | Seascape 23 | -0.41 | -0.26 | 0.20 | -0.14 | -0.18 | -0.19 | -0.22 | -0.13 | 0.29 | 0.03 | 0.74 | 0.63 | -0.17 |
| 18 | Seascape 25 | -0.52 | 0.44 | -0.23 | -0.70 | -0.28 | -0.23 | 0.57 | 0.49 | -0.08 | 0.51 | 0.85 | 0.62 | -0.41 |
| 18 | Seascape 27 | 0.15 | -0.17 | -0.14 | 0.23 | 0.34 | 0.31 | -0.33 | -0.16 | 0.31 | -0.18 | -0.79 | -0.57 | -0.19 |
| 18 | Seascape 28 | 0.26 | 0.12 | -0.16 | -0.07 | -0.12 | -0.16 | 0.12 | 0.21 | -0.26 | 0.36 | - | - | -0.08 |
| 18 | Seascape 30 | -0.31 | -0.39 | 0.57 | 0.41 | -0.43 | -0.36 | -0.35 | -0.27 | 0.29 | -0.22 | -0.13 | -0.13 | -0.25 |

| Yearly obs. (n) | Variables | Seascapes PC1 | Seascape 7 | Seascape 12 | Seascape 14 | Seascape 17 | Seascape 19 | Seascape 21 | Seascape 23 | Seascape 25 | Seascape 27 | Seascape 28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | Seascape 7 | -0.38 | | | | | | | | | | |
| 18 | Seascape 12 | 0.67 | 0.08 | | | | | | | | | |
| 18 | Seascape 14 | 0.73 | -0.33 | 0.57 | | | | | | | | |
| 18 | Seascape 17 | 0.00 | 0.18 | -0.05 | -0.41 | | | | | | | |
| 18 | Seascape 19 | 0.24 | 0.31 | 0.53 | 0.41 | -0.14 | | | | | | |
| 18 | Seascape 21 | -0.98 | 0.33 | -0.64 | -0.65 | -0.03 | -0.21 | | | | | |
| 18 | Seascape 23 | 0.14 | -0.16 | 0.01 | 0.30 | -0.05 | 0.33 | -0.09 | | | | |
| 18 | Seascape 25 | -0.46 | 0.31 | -0.45 | -0.39 | 0.24 | 0.26 | 0.44 | 0.36 | | | |
| 18 | Seascape 27 | 0.20 | 0.14 | 0.28 | 0.45 | -0.55 | 0.46 | -0.23 | -0.13 | -0.23 | | |
| 18 | Seascape 28 | -0.16 | -0.17 | -0.38 | -0.21 | -0.09 | -0.30 | 0.16 | -0.23 | -0.13 | 0.21 | |
| 18 | Seascape 30 | 0.13 | -0.48 | 0.14 | 0.35 | -0.25 | 0.04 | -0.11 | 0.09 | -0.11 | 0.02 | -0.17 |

Table A5-2. Summary and correlation statistics for **Central Coast** yearly environmental, oceanographic and habitat variables by bioregion for 2001-2020. These are annual data where available. Temporal coverage is noted here as missing observations and in the temporal data coverage chart (Table 2-1).

| Yearly obs. (n) | Variables | Year | Central MOCI | CUTI | BEUTI | Wave height | Wave energy | SST | NPP | Kelp cover | Turbidity | Surface Ω | Bottom Ω | Wind speed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | Central MOCI | 0.45 | | | | | | | | | | | | |
| 20 | CUTI | -0.04 | -0.36 | | | | | | | | | | | |
| 20 | BEUTI | -0.21 | -0.91 | 0.51 | | | | | | | | | | |
| 20 | Wave height | -0.38 | -0.06 | -0.40 | -0.13 | | | | | | | | | |
| 20 | Wave energy | -0.33 | 0.03 | -0.34 | -0.15 | 0.95 | | | | | | | | |
| 20 | SST | 0.46 | 0.92 | -0.10 | -0.76 | -0.14 | -0.01 | | | | | | | |
| 20 | NPP | 0.47 | 0.34 | -0.01 | -0.19 | -0.03 | -0.03 | 0.31 | | | | | | |
| 20 | Kelp cover | -0.36 | -0.35 | 0.47 | 0.41 | -0.29 | -0.26 | -0.18 | -0.17 | | | | | |
| 19 | Turbidity | 0.11 | -0.08 | -0.08 | 0.09 | 0.34 | 0.31 | -0.13 | 0.75 | -0.09 | | | | |
| 10 | Surface Ω | -0.59 | 0.66 | -0.35 | -0.66 | 0.44 | 0.38 | 0.90 | 0.28 | 0.20 | 0.35 | | | |
| 10 | Bottom Ω | -0.71 | 0.45 | -0.12 | -0.48 | 0.44 | 0.39 | 0.81 | 0.15 | 0.20 | 0.36 | 0.93 | | |
| 8 | Wind speed | 0.98 | -0.05 | -0.14 | 0.17 | 0.43 | 0.43 | -0.05 | 0.57 | -0.52 | 0.04 | - | - | |
| 18 | Seascapes PC1 | 0.20 | 0.24 | -0.13 | -0.15 | 0.36 | 0.35 | 0.28 | 0.74 | 0.02 | 0.67 | 0.76 | 0.62 | 0.17 |
| 18 | Seascape 7 | -0.10 | 0.11 | -0.35 | -0.24 | 0.47 | 0.56 | 0.04 | -0.42 | -0.09 | -0.12 | -0.34 | -0.23 | -0.27 |
| 18 | Seascape 12 | -0.13 | -0.14 | -0.25 | 0.09 | 0.14 | 0.14 | -0.27 | -0.39 | 0.06 | -0.18 | -0.47 | -0.60 | -0.52 |
| 18 | Seascape 14 | -0.36 | -0.05 | 0.05 | -0.08 | -0.31 | -0.29 | -0.11 | -0.81 | 0.06 | -0.77 | -0.52 | -0.43 | -0.43 |
| 18 | Seascape 15 | 0.35 | 0.54 | -0.01 | -0.41 | -0.45 | -0.37 | 0.65 | -0.32 | 0.07 | -0.61 | - | - | -0.30 |
| 18 | Seascape 17 | 0.24 | -0.10 | 0.17 | 0.07 | 0.14 | 0.21 | -0.05 | -0.28 | 0.02 | 0.02 | -0.73 | -0.49 | -0.15 |
| 18 | Seascape 19 | -0.46 | -0.39 | -0.15 | 0.23 | 0.08 | 0.01 | -0.53 | -0.08 | 0.11 | 0.28 | -0.36 | -0.24 | -0.10 |
| 18 | Seascape 20 | 0.16 | 0.40 | 0.07 | -0.40 | -0.35 | -0.30 | 0.40 | -0.35 | 0.07 | -0.41 | - | - | -0.25 |
| 18 | Seascape 21 | 0.10 | 0.32 | -0.20 | -0.27 | 0.34 | 0.33 | 0.34 | 0.55 | -0.01 | 0.58 | 0.86 | 0.69 | -0.14 |
| 18 | Seascape 23 | 0.12 | 0.35 | -0.40 | -0.35 | -0.16 | -0.07 | 0.35 | -0.26 | -0.26 | -0.31 | - | - | -0.41 |
| 18 | Seascape 25 | -0.10 | 0.07 | 0.39 | -0.10 | -0.39 | -0.39 | 0.13 | -0.22 | 0.19 | -0.25 | 0.08 | 0.08 | -0.63 |
| 18 | Seascape 27 | 0.28 | 0.04 | -0.60 | -0.06 | 0.05 | 0.05 | -0.06 | -0.28 | -0.33 | -0.17 | -0.64 | -0.72 | -0.02 |
| 18 | Seascape 28 | 0.26 | 0.26 | -0.02 | -0.07 | -0.02 | 0.02 | 0.16 | 0.40 | -0.30 | 0.31 | - | - | 0.08 |
| 18 | Seascape 30 | -0.07 | -0.16 | -0.30 | 0.16 | 0.35 | 0.35 | -0.16 | 0.16 | -0.02 | 0.26 | -0.08 | -0.08 | |

| Yearly obs. (n) | Variables | Seascapes PC1 | Seascape 7 | Seascape 12 | Seascape 14 | Seascape 15 | Seascape 17 | Seascape 19 | Seascape 20 | Seascape 21 | Seascape 23 | Seascape 25 | Seascape 27 | Seascape 28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | Seascape 7 | -0.22 | | | | | | | | | | | | |
| 18 | Seascape 12 | -0.23 | 0.45 | | | | | | | | | | | |
| 18 | Seascape 14 | -0.82 | 0.26 | 0.27 | | | | | | | | | | |
| 18 | Seascape 15 | -0.19 | 0.12 | -0.05 | 0.35 | | | | | | | | | |
| 18 | Seascape 17 | -0.28 | 0.58 | 0.36 | 0.24 | 0.01 | | | | | | | | |
| 18 | Seascape 19 | -0.05 | -0.06 | 0.01 | 0.14 | -0.41 | 0.00 | | | | | | | |
| 18 | Seascape 20 | -0.40 | 0.12 | 0.16 | 0.40 | 0.61 | 0.36 | -0.14 | | | | | | |
| 18 | Seascape 21 | 0.93 | -0.16 | -0.13 | -0.58 | -0.02 | -0.26 | -0.03 | -0.30 | | | | | |
| 18 | Seascape 23 | -0.16 | 0.36 | -0.05 | 0.30 | 0.50 | -0.21 | -0.23 | -0.06 | -0.02 | | | | |
| 18 | Seascape 25 | -0.36 | -0.16 | 0.23 | 0.45 | 0.24 | 0.17 | -0.39 | 0.54 | -0.22 | -0.11 | | | |
| 18 | Seascape 27 | -0.16 | 0.39 | 0.61 | 0.23 | 0.21 | 0.31 | 0.11 | 0.07 | -0.04 | 0.33 | -0.16 | | |
| 18 | Seascape 28 | 0.40 | -0.29 | 0.21 | -0.35 | -0.11 | -0.21 | 0.12 | -0.06 | 0.40 | -0.06 | -0.11 | 0.12 | |
| 18 | Seascape 30 | 0.16 | 0.31 | 0.35 | -0.30 | -0.11 | 0.13 | -0.07 | -0.06 | 0.07 | -0.06 | -0.11 | 0.33 | -0.06 |

Table A5-3. Summary and correlation statistics for **South Coast** yearly environmental, oceanographic and habitat variables by bioregion for 2001-2020. These are annual data where available. Temporal coverage is noted here as missing observations and in the temporal data coverage chart (Table 2-1).

| Yearly obs. (n) | Variables | Year | South MOCI | CUTI | BEUTI | Wave height | Wave energy | SST | NPP | Kelp cover | Turbidity | Surface Ω | Bottom Ω | Wind speed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | South MOCI | 0.57 | | | | | | | | | | | | |
| 20 | CUTI | -0.23 | -0.03 | | | | | | | | | | | |
| 20 | BEUTI | -0.19 | -0.49 | 0.51 | | | | | | | | | | |
| 20 | Wave height | -0.03 | 0.06 | 0.03 | 0.05 | | | | | | | | | |
| 20 | Wave energy | -0.09 | 0.13 | -0.04 | 0.02 | 0.90 | | | | | | | | |
| 20 | SST | 0.47 | 0.90 | -0.03 | -0.45 | 0.03 | 0.03 | | | | | | | |
| 20 | NPP | -0.01 | -0.18 | 0.00 | 0.01 | 0.41 | 0.35 | -0.22 | | | | | | |
| 20 | Kelp cover | -0.50 | -0.58 | 0.31 | 0.47 | -0.31 | -0.39 | -0.49 | -0.02 | | | | | |
| 19 | Turbidity | -0.45 | -0.42 | 0.07 | 0.01 | 0.48 | 0.42 | -0.39 | 0.88 | 0.14 | | | | |
| 10 | Surface Ω | -0.87 | 0.08 | 0.07 | -0.10 | -0.60 | -0.28 | -0.08 | -0.49 | -0.41 | -0.52 | | | |
| 10 | Bottom Ω | -0.83 | -0.02 | 0.21 | 0.09 | -0.56 | -0.28 | -0.22 | -0.48 | -0.30 | -0.49 | 0.96 | | |
| 8 | Wind speed | 0.50 | -0.95 | 0.21 | 0.45 | -0.86 | -0.64 | -0.83 | 0.71 | 0.24 | 0.54 | - | - | |
| 18 | Seascapes PC1 | -0.33 | -0.26 | 0.16 | 0.36 | 0.65 | 0.70 | -0.27 | 0.71 | -0.05 | 0.75 | 0.19 | 0.29 | 0.19 |
| 18 | Seascape 7 | 0.10 | -0.54 | -0.18 | 0.11 | -0.25 | -0.46 | -0.54 | -0.13 | 0.40 | -0.06 | -0.47 | -0.27 | 0.24 |
| 18 | Seascape 11 | -0.13 | 0.01 | 0.03 | -0.29 | -0.18 | -0.21 | 0.00 | -0.31 | 0.22 | -0.18 | 0.33 | 0.35 | -0.55 |
| 18 | Seascape 12 | 0.18 | 0.21 | -0.30 | -0.49 | -0.11 | -0.13 | 0.04 | 0.06 | -0.21 | -0.10 | -0.12 | -0.07 | -0.12 |
| 18 | Seascape 14 | -0.16 | -0.03 | 0.28 | -0.01 | -0.38 | -0.46 | -0.01 | -0.70 | 0.25 | -0.52 | -0.05 | -0.11 | -0.26 |
| 18 | Seascape 5 | 0.31 | 0.46 | -0.11 | -0.04 | -0.20 | -0.20 | 0.55 | -0.76 | -0.13 | -0.87 | 0.17 | 0.05 | -0.79 |
| 18 | Seascape 17 | 0.14 | 0.21 | -0.11 | -0.33 | -0.33 | -0.46 | 0.38 | -0.77 | 0.07 | -0.66 | -0.11 | -0.29 | -0.38 |
| 18 | Seascape 19 | 0.42 | 0.34 | -0.50 | -0.26 | -0.11 | 0.07 | 0.35 | 0.15 | -0.54 | 0.03 | -0.13 | -0.38 | 0.25 |
| 18 | Seascape 20 | 0.76 | 0.82 | -0.20 | -0.41 | -0.34 | -0.20 | 0.75 | -0.32 | -0.54 | -0.69 | 0.41 | 0.41 | 0.07 |
| 18 | Seascape 21 | -0.36 | -0.27 | 0.15 | 0.36 | 0.65 | 0.71 | -0.27 | 0.70 | -0.03 | 0.75 | 0.19 | 0.29 | 0.19 |
| 18 | Seascape 23 | -0.02 | -0.40 | -0.30 | -0.02 | 0.07 | -0.12 | -0.35 | 0.26 | -0.07 | 0.20 | - | - | - |

| Yearly obs. (n) | Variables | Seascapes PC1 | Seascape 7 | Seascape 11 | Seascape 12 | Seascape 14 | Seascape 5 | Seascape 17 | Seascape 19 | Seascape 20 | Seascape 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | Seascape 7 | -0.35 | | | | | | | | | |
| 18 | Seascape 11 | -0.30 | 0.39 | | | | | | | | |
| 18 | Seascape 12 | -0.41 | 0.07 | -0.09 | | | | | | | |
| 18 | Seascape 14 | -0.74 | 0.21 | 0.19 | 0.14 | | | | | | |
| 18 | Seascape 5 | -0.58 | 0.00 | 0.22 | -0.13 | 0.46 | | | | | |
| 18 | Seascape 17 | -0.78 | 0.23 | 0.30 | 0.06 | 0.64 | 0.64 | | | | |
| 18 | Seascape19 | 0.17 | -0.45 | -0.38 | -0.14 | -0.39 | -0.11 | -0.16 | | | |
| 18 | Seascape 20 | -0.33 | -0.26 | -0.12 | 0.35 | -0.13 | 0.30 | 0.18 | 0.32 | | |
| 18 | Seascape 21 | 1.00 | -0.36 | -0.29 | -0.43 | -0.72 | -0.57 | -0.77 | 0.17 | -0.36 | |
| 18 | Seascape 23 | 0.02 | 0.40 | 0.16 | 0.21 | -0.07 | -0.09 | -0.16 | -0.17 | -0.21 | 0.02 |

Table A5-4. Summary and correlation statistics for **Channel Islands** yearly environmental, oceanographic and habitat variables by bioregion for 2001-2020. These are annual data where available. Temporal coverage is noted here as missing observations and in the temporal data coverage chart (Table 2-1)

| Yearly obs. (n) | Variables | Year | South MOCI | SST | NPP | Kelp cover | Turbidity | Surface Ω | Bottom Ω | Wind speed |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 | South MOCI | 0.57 | | | | | | | | |
| 20 | SST | 0.35 | 0.89 | | | | | | | |
| 20 | NPP | -0.19 | -0.39 | -0.38 | | | | | | |
| 20 | Kelp cover | -0.67 | -0.48 | -0.30 | 0.58 | | | | | |
| 20 | Turbidity | -0.38 | -0.54 | -0.49 | 0.93 | 0.67 | | | | |
| 10 | Surface Ω | -0.94 | 0.15 | 0.07 | -0.48 | -0.04 | -0.49 | | | |
| 10 | Bottom Ω | -0.87 | -0.03 | -0.07 | -0.44 | 0.09 | -0.42 | 0.92 | | |
| 8 | Wind speed | 0.64 | -0.90 | -0.81 | 0.62 | 0.29 | 0.60 | - | - | |
| 18 | Seascapes PC1 | 0.24 | 0.58 | 0.60 | -0.72 | -0.35 | -0.70 | 0.62 | 0.43 | -0.52 |
| 18 | Seascape 7 | -0.17 | -0.60 | -0.57 | 0.21 | 0.09 | 0.38 | -0.36 | -0.02 | 0.38 |
| 18 | Seascape 11 | -0.50 | 0.21 | 0.49 | -0.24 | 0.24 | -0.12 | 0.12 | -0.10 | -0.83 |
| 18 | Seascape 12 | -0.52 | 0.07 | 0.06 | 0.21 | 0.36 | 0.12 | 0.74 | 0.40 | 0.05 |
| 18 | Seascape 14 | -0.39 | -0.63 | -0.57 | 0.09 | 0.38 | 0.32 | -0.21 | -0.29 | 0.38 |
| 18 | Seascape 15 | 0.68 | 0.69 | 0.50 | -0.23 | -0.59 | -0.50 | 0.14 | -0.17 | 0.17 |
| 18 | Seascape 17 | 0.15 | 0.51 | 0.58 | -0.72 | -0.26 | -0.66 | 0.62 | 0.43 | -0.52 |
| 18 | Seascape 19 | -0.31 | -0.07 | -0.03 | 0.07 | 0.27 | 0.14 | 0.25 | 0.00 | - |
| 18 | Seascape 20 | 0.16 | 0.40 | 0.40 | -0.40 | -0.30 | -0.40 | - | - | -0.41 |
| 18 | Seascape 21 | 0.10 | -0.21 | -0.30 | 0.74 | 0.18 | 0.54 | -0.05 | -0.02 | 0.57 |

| Yearly obs. (n) | Variables | Seascapes PC1 | Seascape 7 | Seascape 11 | Seascape 12 | Seascape 14 | Seascape 15 | Seascape 17 | Seascape 19 | Seascape 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| 18 | Seascape 7 | -0.14 | | | | | | | | |
| 18 | Seascape 11 | 0.21 | -0.18 | | | | | | | |
| 18 | Seascape 12 | 0.09 | -0.10 | 0.26 | | | | | | |
| 18 | Seascape 14 | -0.28 | 0.23 | 0.05 | -0.16 | | | | | |
| 18 | Seascape 15 | 0.15 | -0.61 | -0.20 | -0.18 | -0.64 | | | | |
| 18 | Seascape 17 | 0.98 | -0.12 | 0.29 | 0.05 | -0.20 | 0.04 | | | |
| 18 | Seascape 19 | 0.07 | 0.17 | 0.41 | 0.38 | 0.20 | -0.41 | 0.07 | | |
| 18 | Seascape 20 | 0.40 | -0.30 | 0.00 | 0.26 | -0.30 | 0.07 | 0.40 | -0.09 | |
| 18 | Seascape 21 | -0.73 | -0.07 | -0.44 | -0.08 | -0.22 | 0.33 | -0.79 | -0.17 | -0.40 |

### A5.2.2 Additional Results and Figures for Climate Change Risk in MPAs

Table A5-5. ANOSIM test results for pairwise comparisons of Euclidean distance similarity between the past and future conditions in MPAs when grouped by bioregion. The R score is shown indicating the degree to which the groups are distinct and the associated p-values based on 999 random permutations of the dataset (i.e. a Monte Carlo simulation), are given in parentheses. The light gray boxes highlight the comparisons between past and future conditions in each bioregion.

| | **North Coast MPAs Past (1980-2009)** | **Central Coast MPAs Past (1980-2009)** | **South Coast MPAs Past (1980-2009)** | **Channel Islands MPAs Past (1980-2009)** | **North Coast MPAs Future (2070-2099)** | **Central Coast MPAs Future (2070-2099)** | **South Coast MPAs Future (2070-2099)** |
|---|---|---|---|---|---|---|---|
| **Central Coast MPAs Past (1980-2009)** | 0.07<br>(0.053) | | | | | | |
| **South Coast MPAs Past (1980-2009)** | 0.98<br>(0.001*) | 0.98<br>(0.001*) | | | | | |
| **Channel Islands MPAs Past (1980-2009)** | 0.96<br>(0.001*) | 1.00<br>(0.001*) | 0.65<br>(0.001*) | | | | |
| **North Coast MPAs Future (2070-2099)** | 0.62<br>(0.001*) | 0.57<br>(0.001*) | 0.97<br>(0.001*) | 0.95<br>(0.001*) | | | |
| **Central Coast MPAs Future (2070-2099)** | 0.79<br>(0.001*) | 0.91<br>(0.001*) | 0.96<br>(0.001*) | 1.00<br>(0.001*) | 0.26<br>(0.001*) | | |
| **South Coast MPAs Future (2070-2099)** | 1.00<br>(0.001*) | 1.00<br>(0.001*) | 0.68<br>(0.001*) | 0.95<br>(0.001*) | 0.99<br>(0.001*) | 0.98<br>(0.001*) | |
| **Channel Islands MPAs Future (2070-2099)** | 1.00<br>(0.001*) | 1.00<br>(0.001*) | 0.84<br>(0.001*) | 0.97<br>(0.001*) | 0.98<br>(0.001*) | 0.99<br>(0.001*) | 0.67<br>(0.001*) |

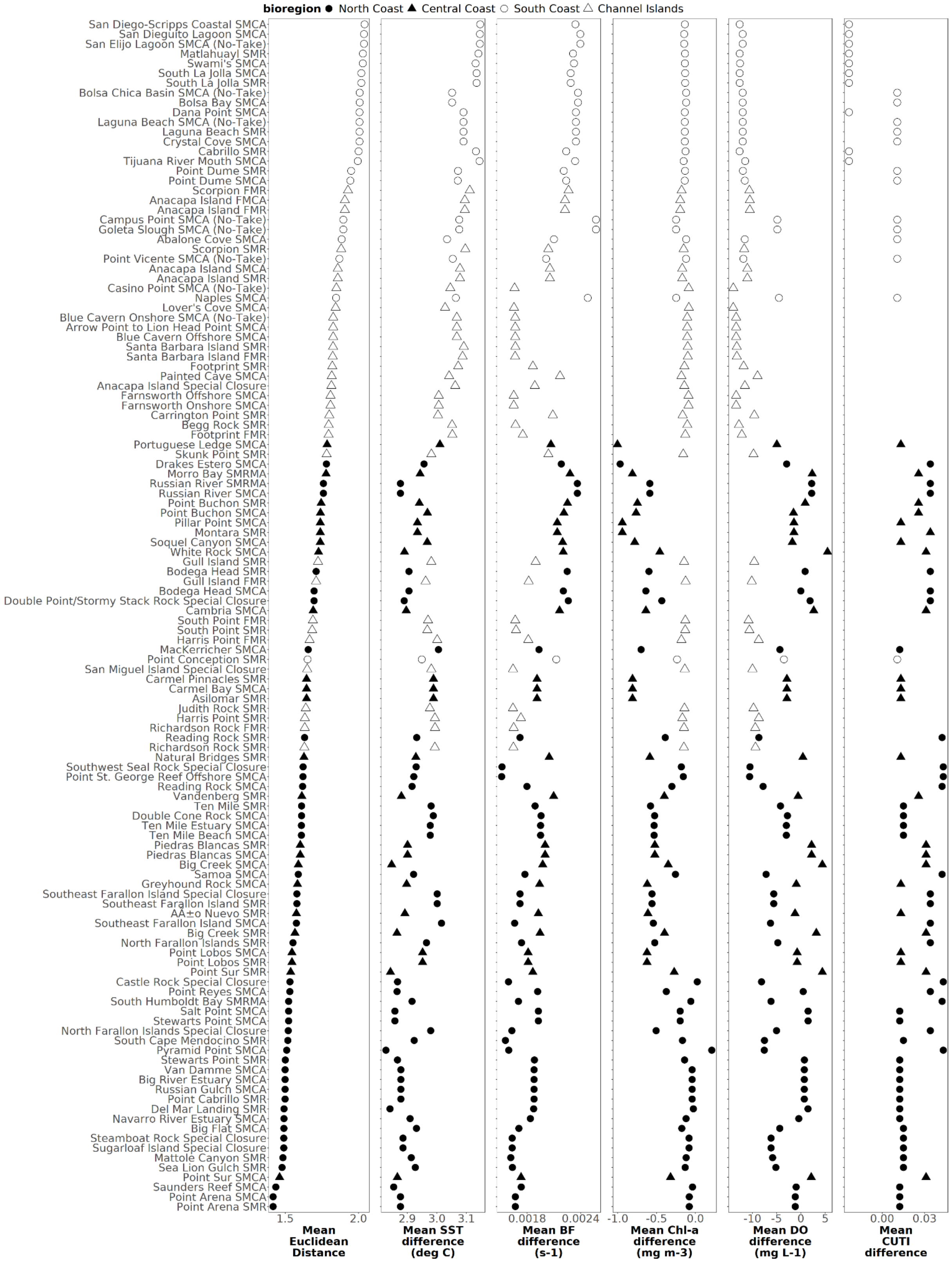


Figure A5-1. Mean Euclidean distances as an index of projected multivariate change between past and future conditions at each MPA. MPAs are ranked by the magnitude of this projected change, with the color of points indicating their bioregion.

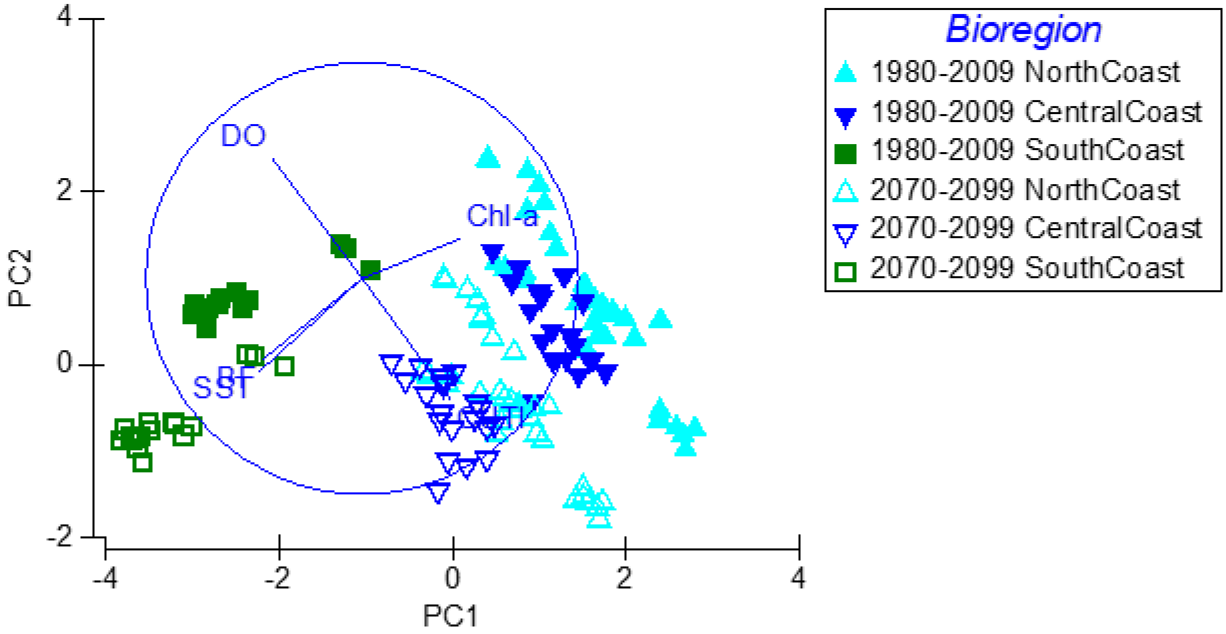


Figure A5-2. Principal component analysis of climate change illustrating the multivariate similarity of MPAs during the periods 1980-2009 and 2070-2099 within and across bioregions. This includes SST, buoyancy frequency (BF) as a measure of stratification, chlorophyll-a (chl-a), dissolved oxygen (DO), as well as the CUTI index of upwelling and nutrient delivery.

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