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A Framework for Selecting Climate Projections for Marine Spatial Research and Planning:

A U.S. West Coast Case Study

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A Framework for Selecting Climate Projections for Marine Spatial Research and Planning:

A U.S. West Coast Case Study

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Executive Summary

This document identifies the most appropriate climate change scenarios to employ during research efforts to understand the potential impacts of climate change on marine species and traditional ocean users, particularly in light of growing marine industry development along the U.S. West Coast. Given new development projects, such as offshore energy, will have permitting lifespans of 25–35 years with potential renewals extending to the end of the century, it is important to move beyond historical data and incorporate future ocean conditions into marine spatial planning.

This report includes two key chapters:

- Overview of predicted changes to the U.S. West Coast under climate change: This section summarizes projections from high-resolution climate models forced with the highest-emission climate change scenario.
- Guidance for incorporating the latest climate projections into an analysis: This chapter provides an overview on climate models and offers comprehensive guidance for selecting appropriate climate change models to develop projections of species' spatial distributions. The chapter then outlines three recommended approaches for integrating existing climate models into species distribution models, considering factors such as the availability of downscaled models, project timelines, intended use, and the technical expertise required for implementation. This decision-tree framework (Fig. E1) is designed to inform state and federal planning processes and support regional assessments of climate–fishery–energy interactions.

Predicted Changes to the U.S. West Coast

Eastern boundary upwelling ecosystems like the California Current Ecosystem (CCE) are projected to experience significant changes in the next 30–50 years:

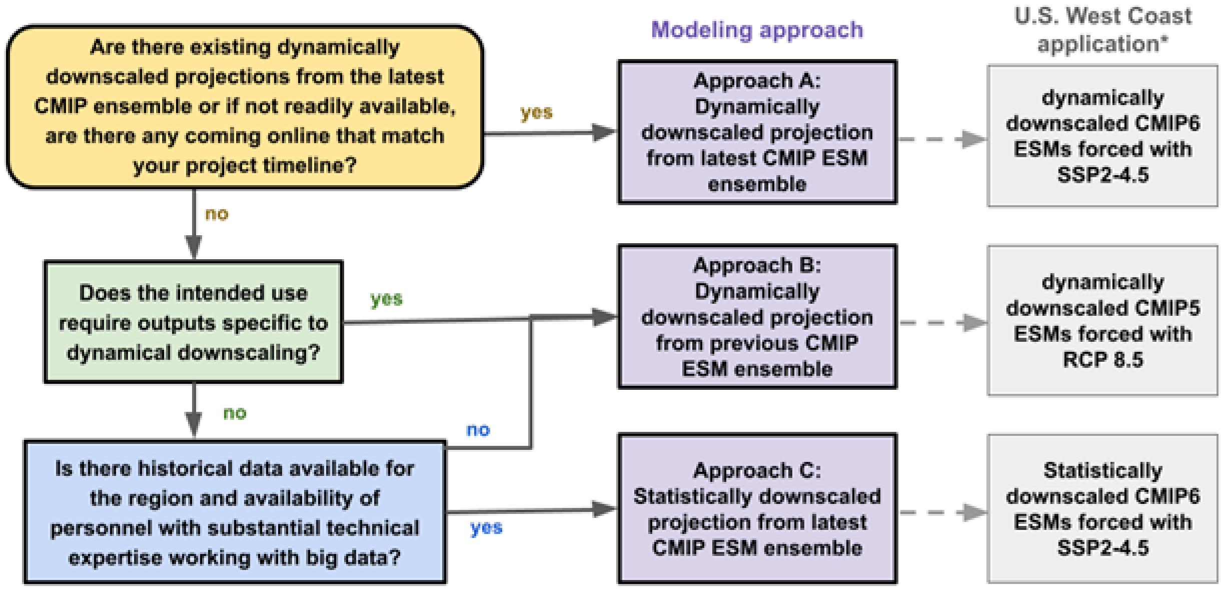
- **Ocean temperature:** Overall warming is expected across the U.S. West Coast, with variations in magnitude and spatial patterns (e.g., stronger warming offshore in the Southern California Bight).
- **Upwelling:** Changes in intensity and timing are projected, with intensification in the northern CCE and weakening in the southern and central CCE.
- **Oxygen:** Dissolved oxygen is projected to decrease across the region, with variations in bottom dissolved oxygen depending on depth and latitude.
- **Acidification:** pH is projected to decrease and partial pressure of carbon dioxide to increase consistently, leading to ocean acidification.
- **Nutrients:** Overall increases in subsurface nitrate are projected, particularly offshore, though coastal projections show high uncertainty.
- **Productivity:** Phytoplankton biomass and chlorophyll are projected to decline in the southern and central CCE, and most of the northern CCE.

Incorporating Climate Projections into Analysis

The second section outlines three recommended approaches for incorporating climate models into spatial distribution models:

1. **Approach A:** Use existing dynamically downscaled models from the latest CMIP (Coupled Model Intercomparison Project) ESM ensemble (CMIP6 forced with a middle-of-the-road scenario: SSP2-4.5): This is the ideal approach when available (available for U.S. West Coast), offering high-resolution projections.
2. **Approach B:** Use existing dynamically downscaled models from the previous CMIP ESM ensemble (CMIP5 forced with a high emissions scenario: RCP 8.5): Recommended for projects with shorter timelines or limited technical expertise, as these models are currently available and have a strong precedent of use in fisheries science.
3. **Approach C:** Statistically downscaled models from the latest CMIP ESM ensemble (CMIP6 forced with SSP2-4.5): A computationally efficient option requiring substantial historical data and technical expertise, suitable when dynamically downscaled models are not available or necessary and the project timeline allows for development.

The approaches described above differ in development, project timeline, their intended use, and prerequisite technical expertise. Approaches A and B rely on existing dynamically downscaled models, while Approach C requires the user to statistically downscale coarse resolution climate models. Given the extensive oceanographic and modeling expertise required to dynamically downscale an ESM, we did not list that approach as a feasible option for a user of this guide. The framework in Figure E1 can help determine the appropriate approach for a project.



*Recommendation at time of writing, March 2026.

Figure E1. Stepwise decision tree for selecting a climate modeling framework. See Section 3.2 for more detail.

List of Acronyms

BEC	Biogeochemical Elemental Cycling model
CCE	California Current Ecosystem
CMIP	Coupled Model Intercomparison Project
CoSiNE	Carbon, Silicate, and Nitrogen Ecosystem model
ESM	Earth System Model
GFDL	Geophysical Fluid Dynamics Laboratory
HadGEM	Hadley Centre Global Environment Model
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre Simon Laplace
MOM	Modular Ocean Model
MPI	Max Planck Institute for Meteorology
NCAR	NSF National Center for Atmospheric Research
NEMUCSC	based on NEMURO developed by UCSC
NEMURO	North Pacific Ecosystem Model for Understanding Regional Oceanography
NOAA	National Oceanographic and Atmospheric Administration
NSF	National Science Foundation
pCO2	partial pressure of carbon dioxide
RCP	representative concentration pathway
ROMS	Regional Ocean Modeling System
SSP	Shared Socio-economic Pathways
SST	sea surface temperature
WRCP	World Climate Research Programme

1 Climate Change Scenarios for the U.S. West Coast

As interest in new marine industry development grows along the U.S. West coast (e.g., offshore aquaculture; oil, gas, and renewable energy extraction; critical minerals mining; and marine carbon dioxide removal activities), scientific, conservation and regulatory needs require an understanding of how marine species and traditional ocean users (e.g., fisheries, shipping) might be impacted by these new ocean-use sectors. The lifespan of new development and specific projects will vary, but initial leasing permits for new projects, such as offshore wind energy projects along the U.S. East Coast, have been set for 25–35 years (BOEM, 2024); and, if projects become successful, permit renewals for these project locations could extend to the end of the century.

However, efforts to date have only considered limited historical information to inform marine spatial planning processes, including measures of overlap, interactions, and potential conflict with marine resources and traditional ocean users (Feist et al., 2025; Wang et al., 2022; White et al., 2024). Changes in climate are driving shifts in marine species distributions (Lenoir et al., 2020). These shifts can impact marine community food webs (Pinsky et al., 2020) and have a variety of outcomes for commercial fisheries (Harvey et al., 2025; Warlick et al., 2025). Therefore, it is important to understand how future ocean conditions will affect species' distribution shifts, and by association where fisheries will operate. Understanding this fundamental change may alter our perception of interactions between new ocean-use sectors and marine ecosystems and commercial fisheries.

A variety of frameworks exist for identifying and exploring future scenarios under changing climate conditions. For example, the Pacific Fishery Management Council convened a group to develop climate change scenario narratives specific to commercial fisheries along the U.S. West coast (Pacific Fishery Management Council, 2020; Star & Kirchner, 2021). While a narrative approach is helpful for developing fishery management plans and preparing infrastructure for fisheries of the future, it is less useful for predicting spatial patterns of ecosystem responses for modeling potential conflict and overlap between industries and natural resources.

One powerful way to identify potential future interactions is to project future ocean conditions using Earth System Models (ESM), climate models that simulate physical processes such as atmospheric and oceanic circulation, as well as biogeochemical processes and human decision-making. When coupled with Intergovernmental Panel on Climate Change (IPCC) climate scenarios, which are based on a range of future projections of greenhouse gas emissions and associated socioeconomic pathways, these models can simulate a range of potential climate futures.

Below, we provide two stand-alone chapters that serve as tools to inform decision-making under climate change:

- Overview of Predicted Changes to the U.S. West Coast under Climate Change.
- Guidance for Incorporating the Latest Climate Projections into an Analysis.

In Chapter 2 we summarize projected scenarios under climate change for the U.S. West Coast based on the outputs of high spatial resolution, dynamically downscaled climate models that have been forced with the highest-emission IPCC climate change scenario (RCP 8.5). Until recently, the highest-emission IPCC scenario had been the most commonly used scenario in fisheries science; however, this highest-emission scenario is no longer considered the most plausible and there are increasing calls for modeling efforts to prioritize incorporating "middle of the road" scenarios (e.g., SSP2-4.5/RCP4.5; Burgess et al., 2023; Burgess & Dancer, 2025). Nevertheless, up to ~2075, projection uncertainty is dominated by internal and model variability, not climate scenarios (Fig 1; Frölicher et al., 2016). As shown in Figure 1, it takes several decades until the scenarios actually begin to diverge. Therefore, both middle-of-the-road and highest-emissions scenarios can provide meaningful insight into future conditions in 30–50 years.

In Chapter 3 we provide guidance for selecting the appropriate climate change models describing future ocean conditions that can be used to develop projections of spatial distributions for species-of-interest. These projections can help inform state and federal planning processes, provide measures of historical overlap and future opportunity cost, and support regional assessment of climate-fishery-energy interactions. In this chapter, we provide models relevant to the U.S. West Coast at the time of this writing; however, the decision tree described can be applied to any geographic area and future decisions.

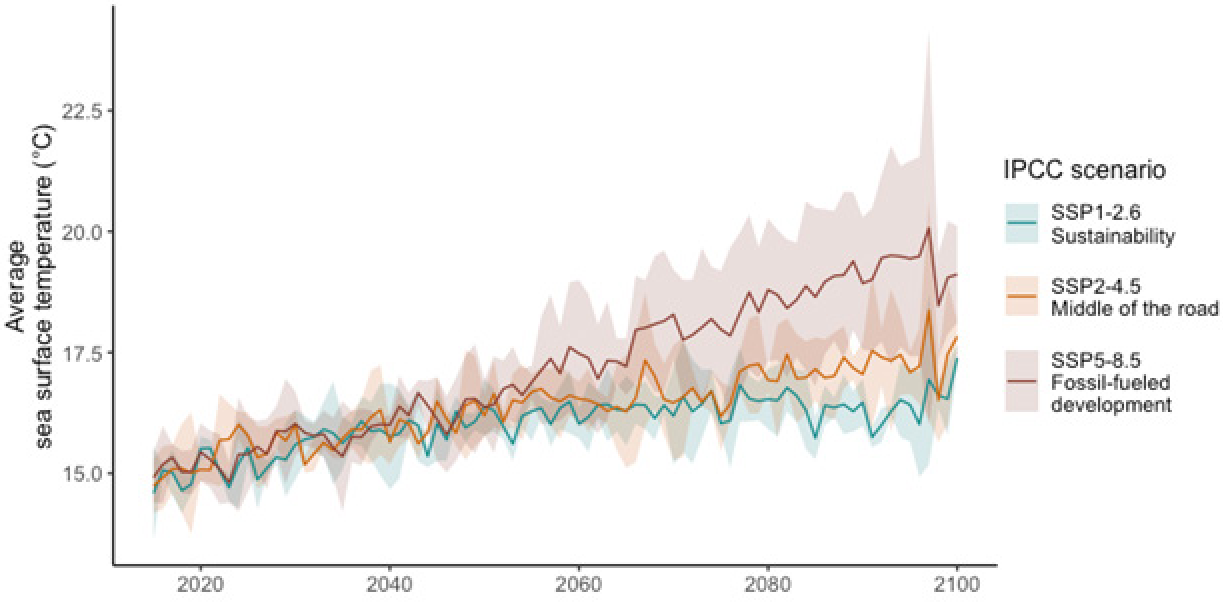


Figure 1. Projected annual mean sea surface temperature (SST) for the U.S. West Coast from 2015–2100 under different IPCC shared socioeconomic pathways (SSPs) using output from three Earth System Model outputs from the CMIP6 ensemble. Solid lines represent multi-model mean for each scenario, averaged across grid cells and models. Shaded ribbons indicate inter-model uncertainty between three ESMs (GDFL-ESM4, IPSL-CM6A, UKESM). See List of Acronyms for definitions.

2 Overview of Predicted Changes to the U.S. West Coast under Climate Change

Eastern boundary upwelling ecosystems, such as the California Current Ecosystem (CCE) along the U.S. West Coast, are predicted to experience an increase in warming and a reduction in wind and upwelling intensity at low latitudes and an enhancement in these conditions in higher latitudes under the most extreme climate change scenario (Fox-Kemper et al., 2021). The high-resolution projections of the CCE under high and extreme emissions scenarios described below project overall increases in temperature and nitrate, decreases in dissolved oxygen, pH, and primary production, and variable shifts in upwelling (Table 1). Responses to future environmental conditions are expected to vary by taxa and species, as some groups may be more tolerant to changes than others (e.g., Free et al., 2019; Hoegh-Guldberg & Bruno, 2010; Liu et al., 2023)

Below, we provide more detail on the projections of ocean temperature, upwelling, oxygen, pH, nitrate, and productivity (Fig. 3, Table 1), focusing on latitudinal and longitudinal (offshore/nearshore) patterns (Fig. 2). The scenarios described below are based on outputs from climate models that have been forced with the highest emissions climate change scenario (Table 4; Howard et al., 2020; Pozo Buil et al., 2021; Siedlecki et al., 2021; Xiu et al., 2018). The climate models in Table 4 differ in the environmental variables reported and regional delineations, thus the scenario descriptions below vary by variable. Further, although the highest-emission scenario is no longer considered the most plausible (Burgess et al., 2023), there is substantial overlap in projected conditions across emission scenarios until the mid-to-late 21st century. In addition, projections from different models diverge widely. As a result, projected warming from a model with weaker warming under a high emissions scenario can overlap substantially with projections from models with stronger warming under a middle-of-the-road scenario (Drenkard et al., 2021; Pozo Buil et al., 2021).

For sea surface temperature, oxygen concentrations and productivity, we provide a projected time series (Fig. 4) for the “nearshore” (continental shelf, <200m depth) and “offshore” (continental slope and rise, >200m depth) habitat for each latitudinal region of the U.S. West Coast (North, Central and South as described in Fig. 2) using downscaled model outputs from Pozo Buil, et al. (2021).

Table 1. Summary of biogeochemical responses to climate change in the CCE for 2055–2075 from historical conditions (~1970–2010) using results from Pozo-Buil et al. 2021, Siedlecki et al. 2021, Howard et al. 2020, and Brady et al. 2017.

Variable	Overall trend
ocean temperature	overall warming (variations in magnitude and spatial patterns across projections)
upwelling	varied (increase in north, weaken in south/central), timing shift
oxygen	overall decline (bottom dissolved oxygen varies by depth and latitude across projections)
nitrate	increase in subsurface nitrate concentrations
acidification	declines in pH
productivity (chlorophyll-a)	overall decline, but drivers uncertain

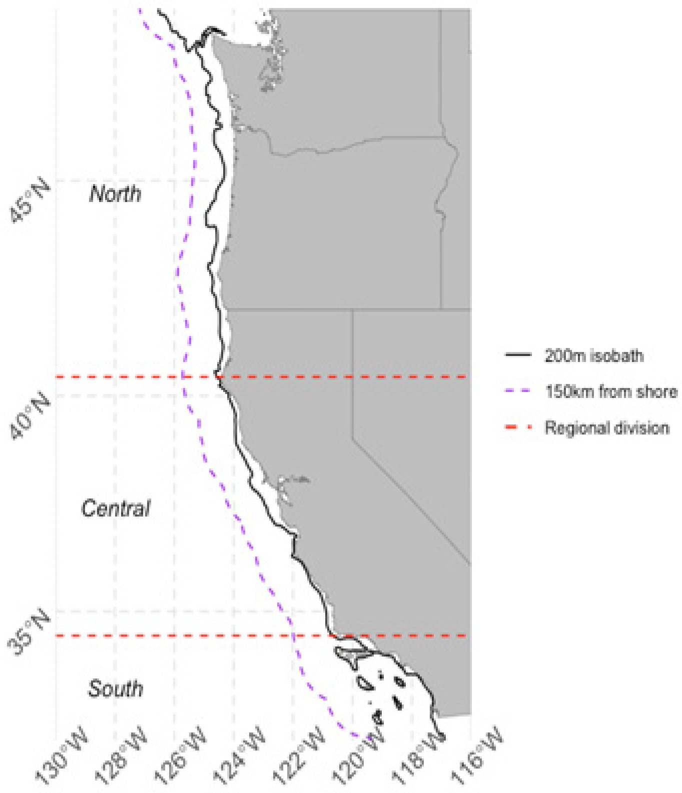


Figure 2. Map of the U.S. West Coast depicting regions (separated by red dashed line), 200m isobath (solid black line), and contour of 150km distance from shore (dashed purple line). Point Conception establishes the line between the South and Central CCE, and Cape Mendocino establishes the line between Central and North CCE.

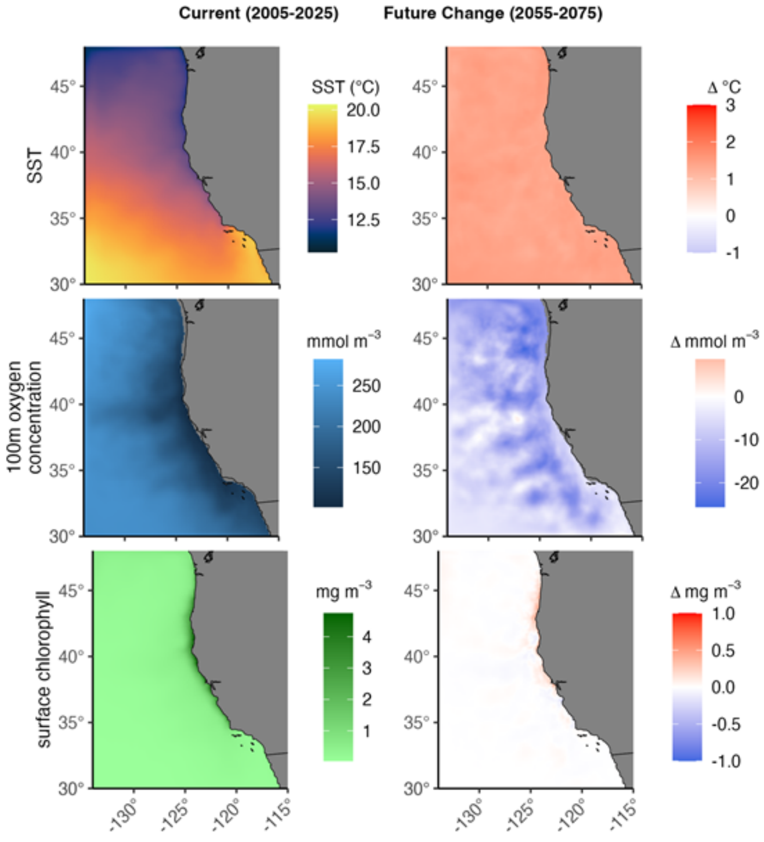


Figure 3. Sea-surface temperature, oxygen concentration at 100m, and surface chlorophyll projections for the U.S. West Coast using average values from three dynamically downscaled models for each grid cell. *Future change* plots depict the difference in conditions between projected future conditions under RCP 8.5 emissions scenario for 2055–2075 and current conditions (2005–2025). Visuals were made using model outputs from earth system models downscaled using ROMS-NEMUCSC (Pozo Buil et al., 2021).

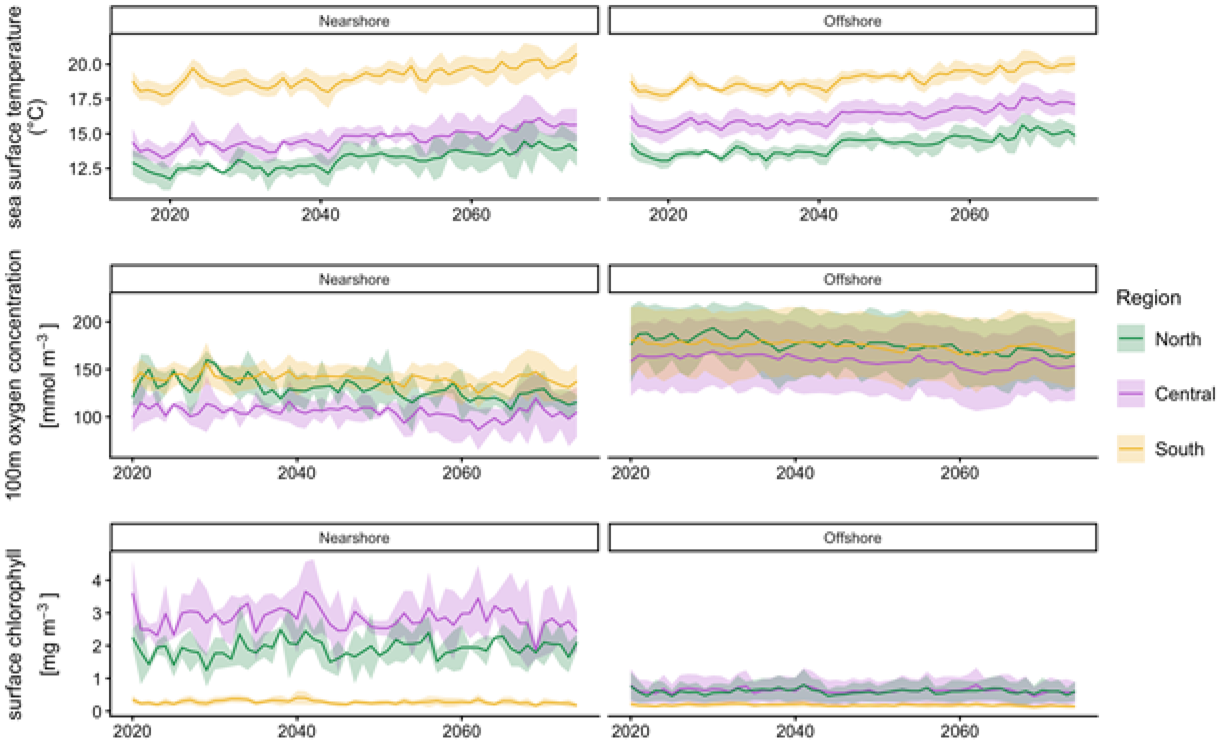


Figure 4. Sea-surface temperature, oxygen concentration, and surface chlorophyll projections under RCP 8.5 for offshore (>200m depth) and nearshore (continental shelf/<200m isobath) areas of the north, central, and south regions of the U.S. West Coast using average values from three dynamically downscaled models. Model outputs are from earth system models downscaled using ROMS-NEMUCSC (Pozo Buil et al., 2021).

2.1 Temperature

Sea-surface temperature (SST; Figs. 1, 3, 4) and bottom temperature (data not shown) are projected to increase over the entirety of the U.S. West Coast (Pozo Buil et al., 2021; Siedlecki et al., 2021). The model simulations differ in magnitude of warming (~0.5°C to over 2.55°C increase across the entire region by 2070) and spatial patterns for both SST and bottom temperature; however, all the simulations converge on an increase in temperature and a corresponding increase in stratification due to surface-intensified warming (Pozo Buil et al., 2021; Siedlecki et al., 2021, Xiu et al. 2018). Specifically, the simulations differ in whether warming is: a) homogeneous warming throughout the coast, b) increased in areas of the Southern California Bight more than 100km from shore and weaker in northern coastal waters within 100km from shore, c) relatively weaker offshore beyond 100km from shore in the Southern California Bight and extending north up to 43°N, or d) increased offshore from the 200m isobath relative to shallower areas (Pozo Buil et al., 2021; Siedlecki et al., 2021). Simulations of projected bottom temperature indicate changes of up to 2°C increases in temperature at 300m depth and overall intensified warming in shallower sections of the water column relative to abyssal regions (Pozo Buil et al., 2021; Siedlecki et al., 2021).

Ecological impacts: Shifts in ocean temperature can affect the physiology of organisms by influencing their metabolic rates, which in turn affect reproduction, behavior, and population growth (Hoegh-Guldberg & Bruno, 2010). Although some species can tolerate and even respond positively to moderate increases (e.g., Free et al., 2019), extreme increases can result in mass mortality events (Wernberg et al., 2025).

2.2 Upwelling Dynamics

Upwelling is projected to change in intensity and shift in timing across the CCE (Brady et al., 2017; Howard et al., 2020; Pozo Buil et al., 2021; Xiu et al., 2018). In particular, upwelling is projected to intensify in the northern CCE and weaken in the southern and central CCE (Pozo Buil et al., 2021) and in coastal areas (Xiu et al., 2018). Additionally, models project a shift in timing of peak upwelling with intensified springtime upwelling in central and northern CCE, and weakening of summertime upwelling (Brady et al., 2017; Howard et al., 2020).

Ecological impacts: Intensified upwelling increases nutrient supply, which can result in increased productivity; however, an associated increase in offshore transport of surface waters may result in productive hotpots being transported farther offshore (Bakun et al., 2015). Further, shifts in timing can disrupt ecosystems by creating mismatches between pulses in phytoplankton productivity and the presence of higher trophic level organisms that rely on these productivity pulses at specific points in their life cycle (Bakun et al., 2015).

2.3 Dissolved Oxygen and Acidification

Dissolved oxygen at the surface and 100m depth is projected to decrease across the entire region (Fig. 3); however, bottom dissolved oxygen projections vary by depth and latitude (Pozo Buil et al., 2021; Siedlecki et al., 2021). The differing simulations project declines in bottom dissolved oxygen along the continental shelf at latitudes >40°N, and a weak increase of bottom dissolved oxygen along the continental shelf from the southern region up to 40°N (Pozo Buil et al., 2021, Siedlecki et al., 2021). Additionally, a shoaling of the hypoxic boundary layer up to ~150m is expected in offshore waters (>100km from the coastline), but projections vary substantially along the coast (Pozo Buil et al., 2021). The projections differ in the timing for when concentrations of dissolved oxygen are expected to decrease beyond natural variability, ranging from present day to 2060 (Pozo Buil et al., 2021; Siedlecki et al., 2021).

Simultaneously, pH is projected to decrease and partial pressure of carbon dioxide ($p\mathrm{CO}_2$) is projected to consistently increase across the region, causing ocean acidification (Siedlecki et al., 2021). Increases in $p\mathrm{CO}_2$ are projected to be weaker in coastal areas (inshore of 200m isobath) and stronger in offshore areas (Siedlecki et al., 2021). Decreases in surface pH are projected to be strongest in the northern CCE relative to the rest of the region (Siedlecki et al., 2021).

Ecological impacts: Decreased oxygen and increased acidification may limit suitable habitat for various species. Oxygen is essential for respiration in all aerobic organisms, although tolerance for low oxygen conditions are species-specific (Keeling et al., 2010). As dissolved oxygen decreases at depth, species may be limited in how deep they can shift to seek refuge from warmer temperatures (Thompson et al., 2023). Further, acidification can decrease survival and growth, particularly in calcifying organisms (Kroeker et al., 2013).

2.4 Nutrients and Productivity

Subsurface nitrate is generally projected to increase by 2050, particularly in offshore waters (Howard et al., 2020; Pozo Buil et al., 2021; Siedlecki et al., 2021). However, there is high uncertainty regarding projections for concentrations of subsurface nitrate for coastal areas (<100km from shore) as simulations vary in response and spatial distribution, including coastwide increases in total nitrate, a decrease in subsurface nitrate, and increases in total nitrate limited to the southern and/or northern extents of the CCE (Pozo Buil et al., 2021; Xiu et al., 2018). Consequently, phytoplankton biomass and chlorophyll are projected to decline in the southern and central CCE, and throughout most of the northern CCE except for a shallow nearshore layer where an increase is projected (Fig. 3; Pozo Buil et al., 2021). However, due to the complexity regarding drivers of phytoplankton biomass such as changes in upwelling, nutrient availability, and ocean stratification, the interaction between the above variables is likely to play a key role in driving phytoplankton distributions in future scenarios, increasing uncertainty about these lower trophic level dynamics (Pozo Buil et al., 2021).

Ecological impacts: Shifts in primary productivity are tightly linked to any shifts in nutrient availability. As the foundation for marine foodwebs, any dramatic changes in productivity will have cascading effects throughout marine ecosystems (Bograd et al., 2023)

3 Guidance for Incorporating the Latest Climate Projections into an Analysis

Climate change models can be used to develop projections of spatial distributions for species-of-interest based on future ocean conditions. These projections can help inform state and federal planning processes, provide measures of historical overlap and future opportunity cost, and support regional assessment of climate–fishery–energy interactions. There has been increasing focus in developing such projections for many marine areas; however, there remain many species of interest for which projections have not been developed using the latest climate models. Here, we provide guidance for selecting an appropriate climate model to incorporate into new projections of species' spatial distributions. Specifically, we provide models relevant to the U.S. West Coast at the time of writing; however, the decision tree depicted in Fig. E1 can be applied to any geographic area and future decisions.

This chapter includes two sections:

1. **Overview of Climate Modeling:** Includes a brief overview of climate modeling and the key components that are included in a climate change scenario framework (e.g., Intergovernmental Panel on Climate Change (IPCC) emissions scenarios, Earth System Models (ESMs) and their spatial resolution considerations relevant to marine resources (e.g., downscaling and ocean circulation models).
2. **Recommended Climate Modeling Approaches:** Describes our recommended three approaches for incorporating existing climate and ocean models into species distribution models, considering factors such as the availability of downscaled models, project timelines, intended use, and the technical expertise required for implementation. This decision-tree framework (Fig. E1) is designed to inform state and federal planning processes and support regional assessments of climate–fishery–energy interactions.

This guide provides the best available information to date; however, the state of the field is rapidly evolving. We encourage future users to always consult the latest IPCC Assessment Reports (https://www.ipcc.ch) and updated CMIP (Coupled Model Intercomparison Project) ensembles (https://www.wcrp-cmip.org), which may offer improved representations of projected climate change scenarios. CMIP is an international climate modelling project designed to understand changes in climate that brings together dozens of modelling-focused organizations around the world to coordinate comparison of climate model simulations and make the model outputs (CMIP multi-model ensembles) publicly available (WRCP [World Climate Research Programme], 2023). Each CMIP phase, which corresponds to an IPCC Assessment Report (i.e., CMIP5 corresponds to IPCC AR5), provides experimental protocols for forcing (external climate inputs that differ from internal model dynamics) climate models with different IPCC scenarios.

While this document provides guidance on approaches to selecting appropriate modeling frameworks, it is not a protocol for climate or species distribution modeling. We direct the reader to resources such as Drenkard, et al. (2021) for guidance on climate model downscaling.

3.1 Overview of Climate Modeling

3.1.1 IPCC scenarios

Intergovernmental Panel on Climate Change (IPCC) scenarios represent possible futures, referred to as pathways, based on a range of future projections of greenhouse gas emissions. The variables included in these scenarios include greenhouse gas concentrations, aerosol emissions, land use and land cover change, human population size, GDP, urbanization, and education at 0.5–1 degree resolution in annual or monthly time steps (IPCC, 2023c).

As of the latest (6th) IPCC Assessment Report (AR6), scenarios are comprised of two components: radiative forcing (formerly Representative Concentration Pathways in IPCC 5th Assessment Report) and Shared Socio-economic Pathways (SSPs) (IPCC, 2014, 2023b).

Radiative forcing (RCPs in AR5) refers to the expected change in the amount of radiation trapped in Earth's atmosphere from 1750 to 2100. A positive radiative forcing indicates a warming Earth, while a negative radiative forcing indicates a cooling Earth. The four RCPs are numbered according to the change in radiative forcing by 2100: +2.6, +4.5, +6.0 and +8.5 watts per square meter (IPCC, 2014).

Shared socio-economic pathways (SSPs) describe different storylines with regard to the trajectory of society, ranging from a high focus on sustainability and curbing emissions to more aggressive development of fossil fuels. These pathways represent changes in human population, economic growth, education, and rate of technological development. The five SSPs reflect sustainability focus (SSP1), middle of the road (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fueled development (SSP5); (O'Neill et al., 2016). SSPs are combined with forcing pathways of varying magnitude to produce scenarios, as described in Table 2.

Until recently, the highest-emission IPCC scenario had been the most commonly used scenario in fisheries science; however, this highest-emission scenario is no longer considered the most plausible and there are increasing calls for modeling efforts to

Table 2. IPCC Scenarios from the Sixth Assessment Report Tier 1 (Gidden et al., 2019; IPCC 2023c; O'Neill et al., 2016).

Scenario Name	Emissions	Description
SSP1-2.6	CO_2 emissions decline to net zero around 2070, followed by varying levels of net negative CO_2 emissions.	Sustainability focus: Low vulnerability with low challenges for mitigation and low forcing.
SSP2-4.5	CO_2 emissions remain around current levels until the middle of the century.	Middle of the road: Intermediate social vulnerability with intermediate forcing.
SSP3-7.0	CO_2 emissions roughly double from current levels by 2100.	Regional rivalry: High social vulnerability with relatively high forcing.
SSP5-8.5	CO_2 emissions roughly double from current levels by 2050.	Fossil-fueled development: High forcing with high social focus on fossil fuel development.

prioritize incorporating “middle of the road” scenarios such as SSP2-4.5/RCP4.5 (Burgess et al., 2023; Burgess & Dancer, 2025). Nevertheless, at shorter timescales up to 2075, projection uncertainty is dominated by internal and model variability, not climate scenarios (Fig. 2; Frölicher et al., 2016). Therefore, both middle-of-the-road and highest-emissions scenarios can provide meaningful insight into future conditions in 30–50 years, especially in geographies like the U.S. West Coast where multiple models can be compared.

3.1.2 Earth system models

General Circulation Models (also known as Global Climate Models: GCMs) simulate physical processes such as atmospheric and oceanic circulation. Earth System Models (ESMs) additionally include biogeochemical cycles and ecosystem dynamics and are used extensively in climate change impact studies dealing with marine ecosystems due to the importance of biogeochemical processes in determining distribution and abundance of key species. When coupled with IPCC climate scenarios, ESMs can simulate a range of climate futures.

At global and coarse regional scales, ESMs can provide meaningful insights into future climate variability (Jones, 2020; Stock et al., 2011). For example, ESMs clearly indicate that the global ocean will continue to warm, marine heatwaves will continue to increase in frequency, and upwelling in eastern boundary upwelling systems will weaken at low latitudes and intensify at high latitudes (IPCC, 2023a). However, the resolution of ESMs, which ranges from ~50–100km depending on the model, is often too coarse to provide meaningful regional projections, particularly for marine spatial planning that occurs at finer spatial resolutions and closer to coastlines (Drenkard et al., 2021; Pozo Buil et al., 2021). For instance, it is not possible to use an ESM to determine how coastal upwelling will change at subregional scales (e.g., at Cape Mendocino vs. Point Conception, CA). One method of making ESMs more useful at regional scales is through dynamical downscaling by using regional ocean circulation models to provide higher spatial resolution and resolve regional oceanographic features to ESMs (Fig. 5). Ocean circulation models simulate physical processes in the ocean at high resolutions. The outputs of ESMs mentioned above are used to force regional ocean models and provide insight into future ocean conditions at a higher resolution. These *downscaled models* can be used to project climate change interactions with marine species and fisheries (Drenkard et al., 2021).

Further, relying on a single ESM or scenario can misrepresent potential futures due to bias inherent to each model. To address this, it is advised to use multi-model ensembles that allow for comparing projections across various ESMs, which provide a more robust scope of inference for any given application (Brodie et al., 2022; Drenkard et al., 2021).

For the U.S. West Coast, the Regional Ocean Modeling System (ROMS, Shchepetkin & McWilliams, 2005) is the most commonly used ocean model for producing dynamically downscaled projections (e.g., see models in Table 4). The spatial coverage of one implementation, the ROMS-NEMUCSC, extends from 30°N to 48°N and –134.0°W to –115.5°W at a resolution of 10km (Veneziani et al., 2009). Additional ocean models include the ROMS Cascadia domain, which extends from 43°N to 50°N including Puget Sound with a horizontal resolution of 1.5 km (Siedlecki et al., 2021), and the latest Modular Ocean Model (MOM6) by

National Oceanographic and Atmospheric Administration's (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL), a high-resolution simulation of which is currently being developed for regional application in the NE Pacific along the North American West Coast from Baja California, Mexico to Alaska, USA (Adcroft et al., 2019; Drenkard et al., 2025). One common use of such ocean models in a marine spatial planning context is to parameterize species distribution models (SDMs), which map the distribution of animals as a function of oceanographic or biological factors. Based on a review of 30 ecological studies conducted on the U.S. West Coast that incorporated climate projections, extracted variables from ESMs that have been used in SDM projections include sea surface temperature, bottom temperature, wind stress, eddy kinetic energy, current velocity, oxygen concentration, salinity, pH, chlorophyll-a, mixed layer thickness, river flow, and precipitation (see Appendix for a list of references).

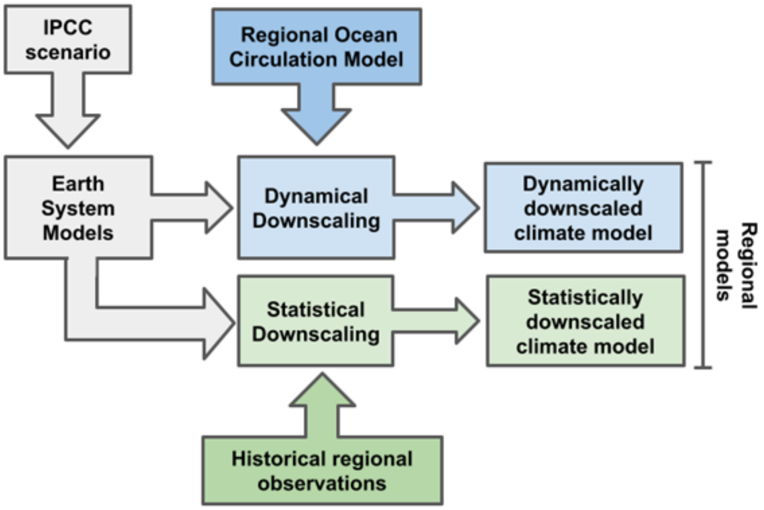


Figure 5. Simplified climate model flow chart for downscaled projections.

3.1.3 Downscaling approaches

There are two primary approaches for downscaling ESMs to provide high resolution projections at regional levels: dynamical and statistical downscaling (Table 3). Both approaches require careful selection of oceanographic variables relevant to the species or marine resource of interest (Drenkard et al., 2021). Dynamical downscaling of climate projections for ocean processes requires using ESM outputs as forcing inputs of regional ocean circulation models, which simulate physical ocean processes at a higher resolution (~10km) (Drenkard et al., 2021). Dynamically downscaled models therefore result in high resolution projections that rely on the laws of physics and published projections to simulate future basin-scale responses and dynamics; however, this approach is computationally intensive and often cost-prohibitive (Drenkard et al., 2021). A less computationally intensive approach is statistical downscaling, which defines a statistical relationship between historical ESM outputs and regional time-series observations, then applies this relationship to future climate ESM outputs. A wide variety of statistical methods are available for downscaling ESM outputs, including delta downscaling, generalized additive models, and neural networks (Stock et al., 2011). Although computationally efficient, statistical downscaling requires extensive historical data, which may not always be available, and assumes that relationships between physical ocean dynamics remain consistent over time. In addition, in comparison to dynamical downscaling, statistical downscaling in general can only reproduce oceanographic dynamics manifesting at the original ESM scale, meaning

Table 3. ESM downscaling approaches, adapted from Drenkard, et al. (2021).

Downscaling approach	Definition	Strengths and Limitations
Dynamical downscaling	Numerically simulating the effects of large-scale climate processes on regional ocean conditions through a solution of differential equations of state at higher spatial resolution than prescribed by the ocean/climate forcing conditions.	**Strengths:** Great at connecting basin-scale climate forcings to regional-scale ocean responses and consistent with published projections, no historical observations necessary. **Limitations:** Computationally costly, high demand for extensive expertise and personnel time, requires an existing, validated regional ocean model.
Statistical downscaling	Extrapolating climate signals to regional scales by applying statistical relationships between contemporaneous GCM-generated climate patterns and regionally observed conditions to GCM output covering unobserved (e.g., future) time periods.	**Strengths:** Computationally efficient, automatically corrects for bias in ESM output. **Limitations:** Identical inputs downscaled using different methods yield dissimilar results, assume relationship between coarse and fine-scale features remain consistent through time, relies on having ample historical observations.

that mesoscale phenomena like eddies or coastal upwelling may not be well-captured by statistical downscaling. The results of statistical downscaling may vary depending on the methods used, which introduces uncertainty in climate change projections (Drenkard et al., 2021). In practical terms, dynamical downscaling is often undertaken as a year-long research effort by oceanographers with substantial expertise and computing power, while some simpler forms of statistical downscaling can be achieved in just months by scientists from other disciplines, although it still requires substantial technical expertise.

Either statistical or dynamical downscaling can be used to inform models of populations, species distributions, seasonality, and habitat suitability (e.g., Koenigstein et al., 2022; Lezama-Ochoa et al., 2024; Liu et al., 2023, 2025; Muhling et al., 2017). It remains to be determined whether downscaled projections are always necessary, even in dynamic upwelling ecosystems, as model outputs from downscaled projections have been found to be consistent with global models with respect to the sign of change (Siedlecki et al., 2021). Ecosystem simulations in one other region (Norwegian and Barents Seas) have also found that projected responses of many species may be consistent regardless of whether ecological models are forced with coarse resolution ESMs versus downscaled projections (Nilsen et al., 2023). Therefore, prior to embarking on a dynamical downscaling effort, it is important to carefully consider whether downscaling is necessary for the intended use. This consideration is challenging a priori; however, in situations where fine-scale hydrodynamics are presumed to be important drivers (e.g., larval dispersal models, eddy simulations, and individual-based models), dynamically downscaled models may provide higher confidence outputs (Kristiansen et al., 2024; Stock et al., 2011). Further, for applications that rely on the interaction between multiple climate variables, statistically downscaled models may not be the optimal tools as these models assume that the relationship between climate variables will remain constant through time (Stock et al. 2011).

3.2 Recommended Climate Modeling Approaches

The approaches described below are narrowed down from hundreds of potential model outputs available. Given the required experimental rigor and standards set by the Coupled Model Intercomparison Project (CMIP), an international climate modelling project designed to understand changes in climate, we recommend model outputs that are part of the CMIP model ensembles (WRCP 2023). Specifically, we recommend projections dynamically downscaled from the latest CMIP ESMs forced with specific IPCC climate scenarios based on best-available science. (Fig. E1, Approach A).

However, such models may not always be readily available as they are computationally- and time-intensive. Consequently, we provide three different scientifically substantiated approaches that differ in factors such as the availability of existing downscaled projections, expected project timeline, intended use, and available expertise of personnel:

1. Use existing regional projections dynamically downscaled from the latest CMIP ESM under relevant IPCC scenarios.
2. Use existing regional projections dynamically downscaled from the previous CMIP ESM under relevant IPCC scenarios.
3. Generate a statistically downscaled projections from the latest CMIP ESM under relevant IPCC scenarios.

All of the projections described above contain high levels of uncertainty (Frölicher et al., 2016). Thus, we recommend using outputs to assess general projected trends, rather than declarative information regarding fine-scale details of distributions at discrete time points. Congruence in trends among model outputs implies increased confidence in what the future may hold.

The approaches described above differ in project timeline, their intended use, and the need for technical expertise. Figure E1 provides a step-wise flow for selecting the appropriate approach based on the decision factors described below.

- **Timing:** At time of writing, Approach A is now available for the U.S. West Coast. However, which models are considered Approach A will depend on best-available science. Therefore, the appropriate approach will depend on whether the projections must be implemented immediately using a readily available downscaled model (Approach B) or if the project timeline allows for ~6 months for developing statistically downscaled projections (Approach C) or waiting for release of an updated dynamically downscaled projections (Approach A).
- **Intended use:** In situations where a dynamically downscaled model using ESMs from the latest CMIP (Approach A) is not available, the decision to develop a statistically downscaled projections (Approach C) or use an existing dynamically downscaled model from the previous CMIP (Approach B) depends on the project objectives (intended use). Dynamically downscaled projections are suitable for most intended uses; however, the limitations of statistically downscaled projections (Table 3) make them less ideal for applications where species are known to respond to fine-scale oceanographic features such as fronts, or when areas of interest are at the edge of major oceanographic features (e.g., northern edge of the California Current).

- **Historical data & expertise availability:** All approaches described above require technical expertise to implement. However, developing statistically downscaled projections (Approach C) requires availability of historical data with regard to the climate variables of interest; substantial technical expertise, particularly with regard to processing large datasets; and approximately six months of dedicated project time (based on Liu, et al. 2025). For the U.S. West Coast, historical climate and oceanographic data are available at high resolution; therefore, the appropriate approach will depend on the availability of appropriate expertise for a project.

3.2.1 Approach A: Dynamically downscaled models from latest CMIP ESMs

When available, use existing dynamically downscaled ESMs from the latest CMIP ensemble forced with IPCC scenarios supported by the best available science. At the time of this writing, the latest published CMIP ensemble is CMIP6 (WCRP, 2025) and best-available science recommends forcing models with IPCC scenario SSP2-4.5 (Burgess & Dancer, 2025).

Recommendation for U.S. West Coast: Use dynamically downscaled ESMs from the CMIP6 ensemble that have been forced with the SSP2-4.5 emissions scenario.

The following ESMs from the CMIP6 ensemble will be dynamically downscaled models for the U.S. West Coast:

- GFDL-ESM4 (Dunne et al., 2020)
- IPSL-CM6A-LR (Boucher et al., 2020)
- UKESM1.0-LL (Tang et al., 2019)

3.2.2 Approach B: Dynamically downscaled models from previous CMIP ESMs

The field of climate modeling is rapidly advancing; however, previous iterations of ESMs can still provide meaningful insights into climate change responses when high resolution new iterations are not yet available. Therefore, for projects with shorter timelines and/or limited technical expertise, we recommend using existing models dynamically downscaled from the previous CMIP ESM ensemble forced with the appropriate IPCC scenario.

Recommendation for U.S. West Coast: Use outputs from existing dynamically downscaled climate models for CMIP5 ESMs forced with IPCC scenario RCP 8.5 available for the U.S. West Coast (Table 4).

The downscaled models in Table 4 use the IPCC RCP 8.5 as a climate scenario for the future projections. Although this highest-emission scenario is no longer considered the most plausible (Burgess et al., 2023), Pozo Buil et al. (2021) posit that for biogeochemical variables in particular, RCP8.5 is appropriate when multiple models are used, as the high levels of model uncertainty encompass the envelope of projected change under RCP2.6 and RCP4.5 (Drenkard et al., 2021; Pozo Buil et al., 2021). Further, projected warming for the selected ESMs overlaps with other climate scenarios (e.g., GDFL ESM2M under RCP8.5 has a similar temperature increase to the mean temperature increase for CMIP5 ESMs under RCP4.5; Pozo Buil et al., 2021).

Table 4. Examples of dynamically downscaled projections from CMIP5 available for the U.S. West Coast. See List of Acronyms for descriptions.

Model	Regional Models	ESMs	Timespan and resolution
ROMS-NEMUCSC (Pozo Buil et al., 2021)	ROMS (Regional Ocean Circulation Model) NEMUCSC (biogeochemical model)	GFDL-ESM2M IPSL-CM5A-LR HadGEM2-ES	1980–2100 at ~10km resolution
ROMS-BEC (Howard et al., 2020)	ROMS (Regional Ocean Circulation Model) BEC (Biogeochemical Elemental Cycling model)	GFDL-ESM2M IPSL-CM5A-LR HadGEM2-ES MPI-ESM-LR NCAR-CESM1 (BGC)	2071–2100 projections at 12km resolution
ROMS-Cascadia (Siedlecki et al., 2021)	ROMS-BEC (Howard et al., 2020) Cascadia (1.5km-resolution regional ocean circulation model)	GFDL-ESM2M IPSL-CM5A-LR HadGEM2-ES MPI-ESM-LR NCAR-CESM1 (BGC)	2071–2100 projections at 12km and 1.5km resolution
ROMS-CoSiNE-31 (Xiu et al., 2018)	ROMS (Regional Ocean Circulation Model) CoSiNE-31 (Carbon, Silicate, and Nitrogen Ecosystem model)	GFDL-ESM2M	1970–2049 projections at ~7km resolution

Precedent of use: These models have been used to project shifts in targeted and protected species distributions (Brodie et al., 2022; Fiechter et al., 2021; Franco et al., 2022; Lezama-Ochoa et al., 2024; Liu et al., 2023), fisher behavior, risk of displacement from traditional fishing grounds (Frawley et al., 2025; Samhouri et al., 2024; Warlick et al., 2025), and targeted species' physiological responses to projected hypoxia (Duncan et al., 2023; McClure et al., 2023).

3.2.3 Approach C: Statistically downscale latest CMIP ESMs

Generate statistically downscaled projections from the latest CMIP under the appropriate IPCC scenario. As of writing, the latest published CMIP ensemble is CMIP6 (WCRP, 2025) and best-available science recommends forcing models with multiple IPCC scenarios where possible, or a middle-of-the-road scenario (SSP2-4.5), rather than focusing only on the highest emission scenario (Burgess & Dancer, 2025).

Considerations: Although computationally efficient compared to developing dynamically downscaled models, statistical downscaling approaches require personnel time and substantial technical expertise in working with large datasets. There are a variety of methods that can be used for statistical downscaling, depending on system complexity and intended application (Stock et al., 2011).

Recommendation for U.S. West Coast: Statistically downscale ESMs from the CMIP6 ensemble that have been forced with the SSP2-4.5 emissions scenario. Select statistical downscaling method appropriate for case use.

Precedent of use:

- Liu and colleagues (2025) provide an example of statistical downscaling of CMIP5 ESMs along the U.S. West Coast for projecting the distribution of pelagic and demersal commercially important fish species.
- Kristiansen and colleagues (2024) statistically downscaled five ocean variables from CMIP6 ESMs forced with three different IPCC climate change scenarios.
- Walker and colleagues (2022) projected shifts in temperature and salinity in the Puget Sound (Washington State, USA) using ESMs from CMIP6.

4 Conclusion

Integrating future spatial distributions of important species, fisheries stocks, and fishing grounds into management of marine resources and spatial planning for new ocean uses could create a win-win scenario that helps avoid, minimize and/or provides a headstart on mitigation efforts related to potential interactions, conflict and impacts of new ocean-use sectors and the marine ecosystem now, and across the lifespan of new development. The climate modeling frameworks presented in this report are not just technical tools; they are essential strategic instruments for anticipating the redistribution of marine species and communities as offshore industry expands.

While the underlying climate models and downscaling techniques are established scientific practices, this report serves to bridge the gap between the field of climate modeling and ecological and fisheries scientists hoping to incorporate climate projections into their work. By consolidating these technical pathways into a clear, stepwise framework, we aim to lower the barrier for incorporating future ocean conditions into vital ecological and marine spatial planning research and decision-making.

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