Quality Control Procedures for the Development, Validation and Science Applications of the Regional Ocean Modeling System with Biogeochemical Elemental Cycling Model (2019-2026)

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Technical Report 1444

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Preface

This document defines procedures and criteria that were used to develop and validate the ROMS-BEC model and its biological interpretation tools for multiple projects to investigate the effects of land-based sources of nutrients on primary production, ocean acidification and hypoxia (OAH) in the Southern California Bight (SCB). The document governs the suite of procedures that were and continue to be used by the Southern California Coastal Water Research Project (SCCWRP) and the University of California at Los Angeles Department of Earth and Atmospheric Sciences (UCLA). Included are criteria for data quality acceptability, procedures for sampling, testing (including deviations) and calibration, as well as preventative and corrective measures. The responsibilities of SCCWRP, UCLA and other collaborators are contained within. Funding for the project was derived from multiple grants to UCLA and SCCWRP from NOAA and the Ocean Protection Council. The term coastal water quality "management" and "managers" refers collectively to the federal, state and local regulators and regulated agencies (stormwater, sanitation) who are responsible for managing water quality; this term is not intended to refer to the views or intent of any specific agency to create policy. The OPC selected the specific scenarios and the types of scientific questions to which they desired answers, in consultation with the California State Water Resources Control Board (State Water Board).

Acknowledgements

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List of Acronyms and Abbreviations

ADCP	Acoustic Doppler Current Profilers
Alk	Alkalinity
ANTH	Anthropogenic simulation
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic Data
BMDL	Biogeochemical Model Development Lead
BTAL	Biological Tool Applications Lead
CalCOFI	California Cooperative Fisheries Investigation
CARS	CSIRO Atlas of Regional Seas
CbPM	Carbon-based Productivity Model
CCS	California Current System
CERSAT	Centre ERSd Archivage et de Traitement
CESM	Community Earth System Model
CFSR	Climate Forecast System Reanalysis
CIWQS	California Integrated Water Quality System
CM	Contract Manager
CMAQ	Community Multiscale Air Quality Model
CNES-CLS13	Centre National d'Etudes Spatiales- Collecte Localisation Satellites
CORE	Coordinated Ocean-ice Reference Experiments
CSIRO	Commonwealth Scientific and Industrial Research Organization
CTAG	Commission Technical Advisory Group
CTD	Conductivity, Temperature, and Depth
CTRL	Control simulation
DA	Domoic Acid
DEQ	Department of Environmental Quality
DIC	Dissolved Inorganic Carbon
DIN	Dissolved Inorganic Nitrogen
ENSO	El Niño Southern Oscillation
GCPC	Global Precipitation Climatology Project
GLODAP	Global Ocean Data Analysis Project
GPCP	Global Precipitation Climatology Project
GRACE	Gravity Recovery And Climate Experiment
HAB	Harmful Algal Bloom
HF	High-Frequency
IRP	Independent Review Panel
LACSD	Los Angeles County Sanitation District
MAL	Modeling Applications Lead
MBARI	Monterey Bay Aquarium Research Institute
ME	Nash-Sutcliffe Model Efficiency
MGD	Million Gallons per Day
MLD	Mixed Layer Depth
MODIS	Moderate-resolution Imaging Spectrometer
MPA	Marine Protected Area

MQAL	Model Quality Assurance Lead
NMS	National Marine Sanctuary
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Productivity
NSF	National Science Foundation
NWRI	National Water Research Institute
OAH	Ocean Acidification and Hypoxia
OAHT	Ocean Acidification, Hypoxia, and Warming
OC San	Orange County Sanitation
ON	Organic Nitrogen
OPC	Ocean Protection Council
PM	Project Manager
PMDL	Physical Model Development Lead
PMEL	Pacific Marine Environmental Laboratory
PN	Pseudo-Nitzschia spp.
PNAS	Proceedings of the National Academy of Sciences
POTW	Publicly Owned Treatment Plants
QA	Quality Assurance
RMP	Regional Monitoring Program
ROMS-BEC	Regional Ocean Modeling System with Biogeochemical Elemental Cycling
RSD	Ratio of Standard Divisions
SCB	Southern California Bight
SCCOOS	Southern California Coastal Oceanic Observation System
SCCWRP	Southern California Coastal Water Research Project
SCOW	Scatterometer Climatology of Ocean Winds
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SFMC	San Francisco and Monterey Coast
SMBO	Santa Monica Bay Observatory
SOCATv6	Surface Ocean C02 Atlas Database Version 6
SOP	Standard Operating Procedure
SPOT	San Pedro Ocean Time series
SST	Sea Surface Temperature
SWBQAO	State Water Board Quality Assurance Officer
UCLA	University of California at Los Angeles Dept. of Earth and Atmospheric Sciences
USW4	U.S. West Coast 4-km simulation
UW	University of Washington
VGPM	Vertically Generalized Production Model
WOA	World Ocean Atlas
WOD13	World Ocean Database 2013
WQO	Water Quality Objectives
WRF	Weather Research and Forecast

A. Introduction and Project Management

A1. Generalized Problem Definition and Background

A1.1 Problem Statement

A1.1.1 Climate change effects on ocean acidification and hypoxia (OAH) and toxic HABs

The California Current System (CCS) is one of the most productive regions of the world ocean, but upwelling results in dramatic variability in water temperature (T), oxygen (O_2) and carbon chemistry, which constrains available habitat for marine calcifiers and aerobic animals. Added to this, climate change is driving ocean acidification and hypoxia (OAH) and warming (W) beyond the envelope of natural variability (Bopp et al. 2013; Doney et al. 2012). In the CCS, these changes are among the most rapid declines of pH and O_2 in the world's oceans (Gruber et al. 2011; Chan et al. 2008, Osborne et al. 2020), compounded by increased frequency and intensity of marine heatwaves (Gruber et al. 2021), raising the potential for major ecosystem disruptions (Laruelle et al. 2018; Osborne et al. 2020; Oliver et al. 2019).

As a result, CCS coastal organisms are more frequently experiencing OAH&W conditions (Gallo et al. 2020; Send and Nam 2012), resulting in habitat compression (Meyer-Gutbrod et al. 2021; Howard et al. 2020a). Negative lethal and sublethal impacts on survival, growth, reproduction, swimming and foraging have been observed for calcifiers, such as oysters (Barton et al. 2012), pteropods (Bednaršek et al. 2014, 2017, 2018), echinoderms (Sato et al. 2018), and decapods (Bednaršek et al. 2021b). Compounding this stress, toxic harmful algal blooms (HABs), particularly *Pseudo-nitzschia* (PN) blooms that produce the potent neurotoxin domoic acid (DA), have emerged as a pervasive threat (De La Riva et al. 2009; Ekstrom et al. 2020; Lefebvre et al. 2002), exacerbated by warming, OA, and anthropogenic (a.k.a. human-sourced) nutrient loading (IPCC 2022, Wingert and Cochlan 2021).

Against this backdrop of rapid change, coastal managers, including SCCWRP Commissioners, are being challenged to assess the condition of marine resources and formulate place-based responses, particularly with respect to sensitive coastal habitats and marine protected areas (MPAs). California's climate actions strategies and policies have prioritized the investigation of anthropogenic inputs on OAHT and HABs in the CCS and their influence on regional biological vulnerability (OPC Strategic Plan 2020; OPC 2018). Managers need increased certainty about how anthropogenic nutrients may change seawater chemistry and their biological effects, and how minimizing nutrient loads could yield benefits (Sutula et al. 2021a).

A1.1.2 Need for a new ocean numerical model

The West Coast OAH Expert Panel recommended that California develop an ocean numerical model to disentangle the effects of climate change, natural variability and local nutrient inputs on OAH and its biological effects. Numerical models have become essential for the study of present-day (Deutsch et al. 2020; Cheresh and Fiechter 2020; Gruber et al. 2021) and future OAHT (Gruber et al. 2012; Xiu et al. 2018; Pozo-Buil et al. 2021; Siedlecki et al. 2021), and the resulting ecosystem impacts (Fiechter et al. 2021; Drenkard et al. 2021).

A workshop was held with state and federal water quality managers, including regulators and the regulated community, and leading academic ocean modelers to scope the needs of such a model (Sutula et al. 2014; Table 1). Workshop participants concluded that while the Regional Ocean Modeling System (ROMS), a physical model, existed and could be configured to meet these criteria, the biogeochemical model counterpart only existed at global scales (Durski et al. (2017) and would need to be adapted and downscaled to the California Coast. Most approaches that had been previously applied to the CCS relied on coarse models that, while representing the ocean's mesoscale (10-100 km), still struggle in capturing intense submesoscale variability (<1 km) observed in nearshore waters that controls the intensity of upwelling, vertical flux of nutrients and low pH and O_2 found in oceanic deep waters (García-Reyes and Largier 2012).

Table 1. Management needs for an ocean numerical model and inferred model selection criteria

Management Needs for Model, Sutula et al. (2014)	Model Selection Criteria
• **Model** needs to be able to support "place-based" assessments of effects of human inputs • Model needs to be able to predict primary production, acidification and hypoxia with fidelity on both temporal and spatial scales • 3-dimensional model with sufficient spatial resolution to disentangle natural variability, local anthropogenic inputs and climate change • Model can simulate various nutrient input scenarios • Model is validated and uncertainty that can be described and/or quantified • Biological interpretation tools can translate model outputs to endpoints that managers care about	• Model formulation is mechanistic; not tuned or assimilating data to optimize predictions • Model captures physical, biogeochemical, and lower ecosystem state/ transformation rates • Model has spatial resolution to capture subregional gradients in oceanographic drivers as well gradients occurring from eutrophication due to land-based inputs • Model can simulate scenarios of climate change, natural variability and local anthropogenic inputs • Existing model preferred, especially if the fundamental components have been validated

While biogeochemical models predict chemistry and lower trophic ecosystem, they generally do not predict the types of biological impacts of interest to water quality managers. Therefore, an additional set of tools are needed, including either a new types of biological models or a suite of biological interpretation tools that can translate outputs to endpoints (e.g. habitat capacity).

A1.1.3 Investigations of the effects of anthropogenic nutrient inputs in the Southern California Bight

The SCB is one of the most urbanized regions of the California Coast, with a coastal population of 23 million (Sutula et al. 2021). Howard et al. (2014) found that human sources of nutrients were doubling the availability of nitrogen in the nearshore of the central SCB, but this early modeling effort stopped short of investigating effects on primary productivity, biological respiration, and its contribution to OAH. Second, the SCB is home to prized marine resources, including diverse populations of marine mammals, kelp and seagrass beds, fisheries, reefs, and beaches, all of which contribute to a powerhouse coastal economy and provide recreational opportunities and subsistence fishing for this region's disadvantaged communities. This marine embayment, 100,000 km^2 in size, has heterogenous physical settings and ocean currents provide habitat for a large diversity of flora and fauna (Dailey et al. 1993), with over 350 endemic fish and 5,000 invertebrate species, as well as threatened marine mammals and seabirds. The SCB includes Channel Islands National Marine Sanctuary (NMS), the proposed Chumash Heritage Tribal NMS, and 50 state marine protected areas. The region generates approximately $22 billion a year in gross revenue and over 800,000 jobs annually in other ocean-related tourism and leisure activities (Schiff et al. 2016) and supports robust commercial and recreational fishing industries. Third, the SCB is home to two of the best marine regional monitoring programs in the world – the California Cooperative Fisheries Investigation (CalCOFI) and the SCB Regional Monitoring Program (Bight RMP), which provide key data that can be used to characterize both land-based inputs to the Bight as well as monitoring of ambient ocean water quality to validate an ocean numerical model.

A1.2 Overarching Science Questions

Four science questions are addressed by the modeling project:

- What is the effect of land-based nutrients on primary productivity, seawater pH, and O_2?
- What are the biological implications of these effects?
- What is the relative contribution of pathways of human sources of nutrients (ocean outfalls, rivers, and Mexican transboundary sources) to primary productivity, OAH and its biological effects?
- How does reduction of nutrients to ocean outfalls, alone or in combination with reduced volumes from water recovery, alter changes in seawater chemistry and biological effects?

To answer these questions, an ocean numerical model was developed, validated then applied over two project phases. Phase I (2014-2020) consisted of model development and validation at a CCS-wide scale, then in a more focused way within the SCB. Phase II consisted of the model application to answer the four applied science questions above (2021-present).

A1.3 Existing Thresholds to Interpret Effects

California has existing numeric ocean water quality objectives for pH and O_2 and narrative biological water quality objectives (SWRCB 2019). However, coastal water quality managers, represented by SCCWRP Commission, wanted to know whether/how these changes in seawater chemistry specifically translated to quantifiable biological impacts. To answer these questions, the science team utilized science on OA thresholds (Bednaršek et al. 2019, 2021a,b), on oxygen impacts on aerobic habitat (Deutsch et al. 2015; Howard et al. 2020), and on factors influencing the risk of domoic acid (DA) events that can occur from *Pseudo-nitzschia* HABs. These thresholds are synthesized here (Table 2), with quality assurance activities associated with specific methodologies to apply those thresholds found in Section B9.4. These should be considered a scientific assessment, not an impairment assessment and/or policy decision. Section 3.3 Task 5 describes these approaches, and the reader is referred to the primary literature for additional background.

Table 2. Summary of endpoints, metrics and thresholds employed to interpret model outputs in various stages of the project

Endpoint	Metric	Threshold
California Ocean Plan		
O_2	Change in oxygen concentration (mmol m^{-3})	"The dissolved oxygen concentration shall not at any time be depressed more than 10 percent from that which occurs naturally, as the result of the discharge of oxygen demanding waste* materials." (California Ocean Plan, State Water Board 2019)
pH	Change in pH	"The pH shall not be changed at any time more than 0.2 units from that which occurs naturally" (California Ocean Plan, State Water Board 2019)
Habitat Compression		
Aerobic habitat	Change in depth of aerobic pelagic habitat, defined by metabolic index (Deutsch et al. 2015)	Change in depth to Phi> Phi Crit, Northern Anchovy (Howard et al. 2020)
Calicfier habitat	Change in depth of pelagic calcifier habitat	Change in depth to Ω_{AR} = 1.4 (threshold for severe shell dissolution, Bednaršek et al. 2019, OR DEQ 2025)
Risk of Domoic Acid-Producing HABs		

Endpoint	Metric	Threshold
Chl-a	Change in vertically integrated chlorophyll-a (Chl-a)	Positive change associated with a risk of 50% probability of detecting DA (e.g., 3 mg m^{-3} for Central Bight (Sandoval-Belmar et al. 2023)[1]

A2. Project/Task Description

This section of the DOCUMENT describes the project goals and tasks, with sufficient detail in methods to make transparent how the quality assurance principles were incorporated across technical activities.

A2.1 Project Goals and Phasing

The goals of this project were three-fold:

1. Develop a Regional Oceanic Modeling System — Biogeochemical Elemental Cycling (ROMS-BEC) model of oceanic hypoxia and acidification (OAH) for the entire California Current System (CCS; Baja California to British Columbia), comprised of the circulation, biogeochemical cycles, and lower-trophic ecosystem of the CCS, with regional downscaling in the SCB and the SFMC.
2. Use the model to understand the relative contributions of natural climate variability, anthropogenically induced climate change, and anthropogenic nutrient inputs on the status and trends of OAH in the CCS.
3. Transmit these findings to coastal zone managers and help them explore the implications for marine resource management and pollution control.

The project, as directly relevant to the application of eutrophication investigations in the SCB, is proceeding in 9 tasks over two phases, described in greater detail in Sections 2.2-2.4 below.

Phase I focused on model development and validation, as well as use of the model to investigate basic science questions.

Phase II focused on the last two goals (investigations of the effects of anthropogenic inputs) and transmitting these findings to managers.

[1] Original analysis published in Sandoval-Belmar et al. (2023) had insufficient data to conduct the assessment for the San Diego SCRIPPS pier station. Therefore, application of the threshold derived for the Central Bight to the San Diego region should be appropriately caveated.

A2.2 Phase I Task Description

Phase I consisted of five major tasks, described in more detail in the sections below.

Task 1. Develop the CCS integrated earth systems model.
Task 2. Simulate a multi-decadal hindcast across the CCS and within the SCB.
Task 3. Validate the model in the CCS and the SCB, focused on gradients of eutrophication.
Task 4. Develop methodologies to interpret the biological effects of coastal eutrophication.
Task 5. Apply the model to investigate basic science questions.

Model selection criteria and planning was done in the proposal stage with the assistance of the OPC and State Water Board, refining the criteria that were initially proposed (Table 3). We assessed requirements for the model and executed project planning. This was done by clearly articulating the goals for the model, the problem the model is intended to address, its intended uses cases, and identify any potential constraints or dependencies, and by identifying a clear approach to model development testing and validation.

Task 1. Develop the CCS Model

Task 1 was comprised of five major subtasks: 1) develop the model, including any important model advances needed to accomplish project objectives, 2) set up model domains and configurations, 3) assemble oceanic and atmospheric forcing, 4) assemble land-based and atmospheric deposition for the SCB, and 5) test, verify, and conduct sensitivity analyses to ensure proper model formulation and parameterization.

CCS Model Description and Innovations

The CCS model is a coupled physical and biogeochemical model. The physical model is based on the Regional Ocean Modeling System (ROMS, www.myroms.org; Shchepetkin and McWilliams 2005), a widely used, open-source code that solves the hydrostatic, free-surface primitive equations in 3-D curvilinear coordinates. It contains state-of-art, numerical algorithms that provide an accurate and stable representation of physical processes down to fine scales and allow for "nesting" of high-resolution sub-domains within larger domains. UCLA (James McWilliams and colleagues) have been systematically developing the ROMS for over 30 years (Shchepetkin and McWilliams 2005) with the North American and South American West Coast regions as primary testbeds (Marchesiello et al. 2003; Colas et al. 2012). For this endeavor, it was dynamically coupled to the biogeochemical element cycling (BEC) model (Moore et al. 2004), which simulates the cycles of carbon (C), nutrients and O_2, driven by three phytoplankton functional groups, one zooplankton group, and suspended and sinking detritus.

The general ROMS functionality is a computational solution of the incompressible hydrostatic (Primitive) equations with a free upper surface, realistic equation of state, and parameterizations for small-scale turbulent mixing, especially in the top and bottom boundary layers. ROMS includes dynamical coupling to surface gravity waves using wave-averaged dynamical equations (McWilliams et al. 2004) and extends from the open sea into the littoral zone with parameterized depth-induced wave breaking (Uchiyama et al. 2010).

While equilibrium regional oceanic circulation models have been successfully employed for more than a decade in the CCS (Marchesiello et al. 2003; Capet et al. 2008a,b; Veneziani et al. 2009), no previous simulation has been made over a long time period using high-resolution spatial and temporal atmospheric forcing that includes the effects of wind drop-off (i.e., the cross-shore profile of decreasing wind speed toward the coast), current feedback on the surface stress (causing a dampening of the mesoscale activity; Renault et al. (2016d)), and high-frequency wind fluctuations (Renault et al. 2019).

The ecosystem and biogeochemical dynamics are predicted using the Biogeochemical Elemental Cycling (BEC) model (Moore et al. 2002; Gruber et al. 2006; Fig. 1). BEC includes three phytoplankton functional groups (diatoms, picoplankton [including dinoflagellates, coccolithophores, and other small phytoplankton], and diazotrophs), characterized by distinct biogeochemical functions (nutrient recycling, silicification, calcification, and N_2 fixation, respectively) and one generic zooplankton group. This intermediate complexity lower trophic ecosystem modeling approach is appropriate for the California Current System because the ecosystem is dominated by diatom productivity; in the central and northern Bight, including the offshore islands, diatoms average ~80% of the biomass, while in the southern Bight (e.g. Southern San Diego), diatoms average 62% of the biomass on average (Venrick 2015).

It tracks dissolved, suspended, and sinking particulates, including four different nutrients (nitrogen, silicic acid, phosphate, and iron). The ecosystem is linked to an oceanic biogeochemistry module that includes inorganic carbon (IC), alkalinity, iron, and dissolved O_2 are simulated and are coupled through a fixed phytoplankton stoichiometry. Gas exchange fluxes for O_2 and CO_2 are based on Wanninkhof (1992). The full list of equations and parameters are available in the supplemental information provided in Deutsch et al. (2021). BEC model code, including parameter settings, are available through the GitHub repository (see the remark at the end of Deutsch et al. (2021)).

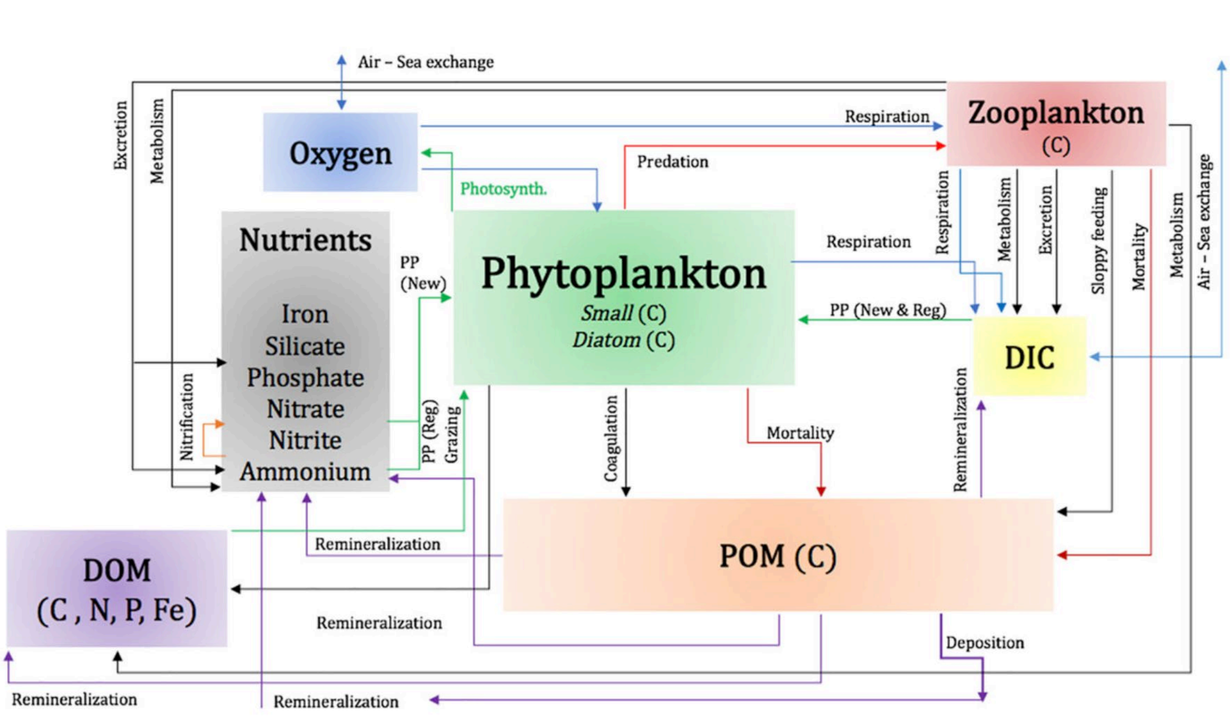

Figure. 1. From Kessouri et al. (2021b). Conceptual model of the processes influenced by eutrophication (via in the inputs of nutrients) and other environmental factors represented in ROMS-BEC and their influence on primary (phytoplankton) and secondary (zooplankton) production and the effect of respiration on O2 and dissolved inorganic carbon (DIC).

Remineralization of sinking organic matter is specified according to the mineral ballast model of Armstrong et al. (2001). We also added a nitrogen cycle, with losses to the sediments and water column. Bottom water nitrate is removed using a statistical description of sediment denitrification proposed by Middelburg et al. (1996), based on a vertically resolved diagenetic model that predicts the primary dependence of benthic denitrification to be on organic carbon sedimentation rate, with a secondary sensitivity to bottom water oxygen concentration. This statistical description of the complete diagenetic model reproduces basic controls on observed sediment fluxes, without the considerable computational cost of a sedimentary submodel.

The iron cycle includes dissolved iron, scavenged iron, and iron associated with organic matter pools and dust particles, but only dissolved iron and organically bound iron are explicitly modeled as state variables. For dissolved iron, four processes are considered: atmospheric deposition, biological uptake and remineralization, scavenging by sinking particles, and release by sediments. Atmospheric iron deposition is based on the dust climatology of Mahowald et al. (2006). We implemented a sedimentary iron source based on benthic flux chamber measurements in the California margin. An equation relating sediment iron (Fe) release as a function of bottom water O_2 is derived from data compiled by Severmann et al. (2010).

Set Up CCS and SCB Domain and Configurations

U.S. West Coast ROMS-BEC configuration is at 4-km resolution, while the subdomain grids for the CA and OR/WA coastal sectors have 1-km resolution (Fig. 2). The primary U. S. West Coast (USW4) 4-km simulation domain extends from 144.7◦W to 112.5◦W and from 22.7◦N to 51.1◦N. The 1 km nest extends from 130.7°W to 115.9°W and from 24.4°N to 40.2°N (from Tijuana to Cape Mendocino). The 4 km and 1 km models have 60 terrain- and surface-following sigma levels in the vertical (Shchepetkin and McWilliams 2005). The model has a multi-level nesting capability, and for shelf and nearshore processes, can be further nested to finer resolutions. Modeling experiments investigating submesoscale transport (captured at model resolutions ≤ 1 km) have demonstrated a ten-fold increase in vertical N fluxes relative to mesoscale transport represented by a 4 km model (Kessouri et al. 2020). For this reason, investigations of local nutrients impact are simulated at 300 m resolution in targeted coastal regions, while investigations of onshore-offshore connectivity are conducted at 100 m resolution (Dauhajre and McWilliams 2017, 2018, 2019).

The SCB model domain extends along a 450-km stretch of the coast, from Tijuana to Pismo Beach, and about 200 km offshore. The bathymetry used in this configuration comes from the Southern California Coastal Oceanic Observation System (SCCOOS) 3 Arc-Second Coastal Relief Model Development (90-m horizontal resolution). The grid is composed of 1,400 × 600 grid points, with a nominal resolution of d*x* = 300 m. The grid has 60 σ-coordinate vertical levels using the stretching function described in Shchepetkin and McWilliams (2005). The model is run with a time step of 30 s, and outputs are saved as 1-day averages.

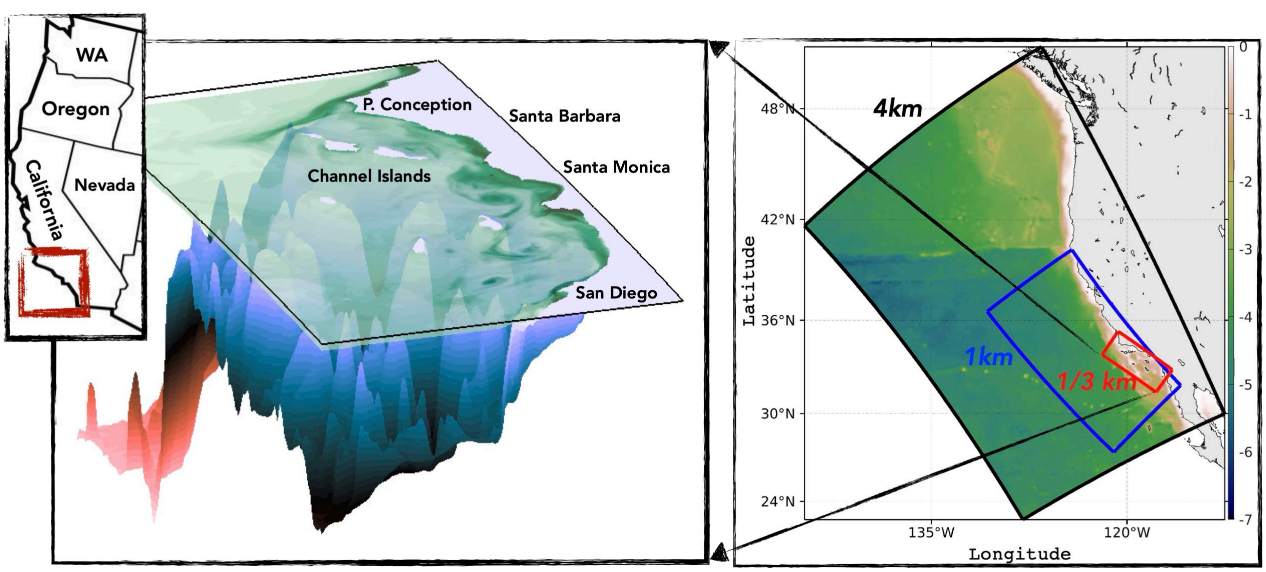

Figure 2. Configuration of U.S. West Coast ROMS-BEC, nested from 4-km resolution (CCS-wide) to 1 km (California), to 300-m SCB nest for investigations of local nutrient effects

Assemble Model Forcing

Oceanic and atmospheric forcing variables for the 4-km and the 300-m model are derived from existing models and data described in Section B2.2 (Tables 12-13), while land-based and atmospheric forcing variables for the 300-m model are derived from existing models and data described in Section B (Table 14).

In the SCB, ROMS-BEC simulations at the 300-m resolution were forced with a 1997-2017 daily time series of spatially explicit freshwater flow, N, P, silica, and organic C representing natural and anthropogenic sources (Fig. 3, Sutula et al. 2021). The sources of these data, summarized in Table 14, and their quality control is comprehensively described in Sutula et al. (2021). For brevity, these data have been compiled for: 1) POTW ocean outfalls and 2) riverine discharges. POTW effluent data were compiled from permit monitoring databases.. Riverine runoff from the SCB 75 coastal confluences is from model simulations (Sengupta et al. 2013) and monitoring data. The ocean outfall and riverine input data set were reviewed by SCCWRP's Commission Technical Advisory Group (CTAG), which include both municipal and county sanitation and stormwater agencies. Direct atmospheric deposition, derived from the Community Multi-scale Air Quality model (Byun and Schere 2006), was included in the model in runs from 1997-2000, but was removed thereafter from further simulations because it had a negligible effect on seawater chemistry. See Section B2.2 and the foundational journal articles for more details.

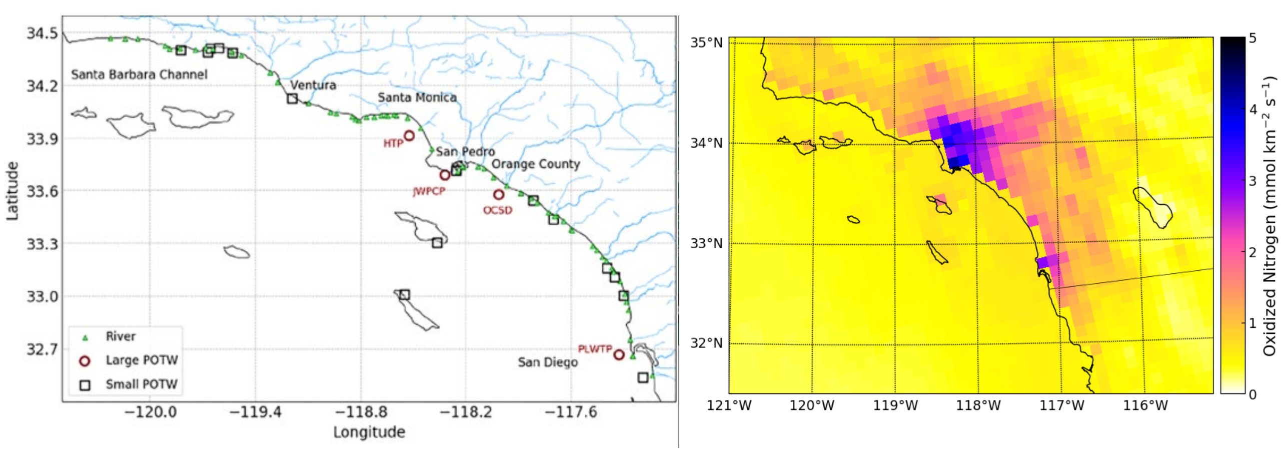

Figure 3. Examples of land-based and atmospheric nutrient and carbon inputs compiled to force 300-m model nest in the SCB 1997-2000 simulations, top left: locations of 18 POTW outfalls and locations of major riverine inputs, top right: modeled NH4 deposition.

Configuration of River and Wastewater Outfall Forcing in the Model

A detailed description of the implementation of river and outfall forcing is provided in Kessouri et al. (2021b) but summarized here. Ocean outfalls and coastal rivers are modeled as mass sources into the ocean. To accomplish this, we add explicit volume fluxes to the otherwise divergence-free flow in the ocean. The inclusion of these fluxes makes it possible to account for associated sources of tracers, while satisfying conservation laws. Specifically, our approach allows for the proper influx of fresh water in the ocean, without resorting to a “virtual salt” flux, which is a common approach in larger scale ocean models (Kang et al. 2017). Since we explicitly include known volume fluxes for both rivers and outfall pipes, specification of tracer concentration is sufficient to correctly model the source terms. The tracer evolution equations that are used in ROMS are implemented by using control volumes (Uchiyama et al. 2014). In absence of rivers and outfalls, the flow is volume conservative. The mean concentration of a tracer can be lowered if the average concentration of the flux entering the control volume is less than the mean concentration in that volume. In this manner, freshwater rivers lower the salinity of the water in which they enter. All 75 rivers and 23 POTW pipes, summarized in Sutula et al. (2021), that are considered in this study are implemented in this manner. Kessouri et al. (2021a) describes the specific approach to model each individual source, considering the specific locale of discharge and whether it has a diffuser (for POTW outfalls). For POTW inputs, at each main diffuser, the horizontal distribution of the plume is weighted in different cells, which allows the effluent to be properly diluted vertically and horizontally at this resolution and prevents the model from developing numerical instabilities.

Each large treatment plant has specialized outfall configurations that are considered for representation in the model. The distribution of the SCB rivers on one horizontal grid point (300 m wide) and similarly distribute the source vertically. The volume flux is specified over spatial horizontal and vertical functions that mimic the outcome of unresolved near field mixing above the outfall diffusers.

Test, Verify Model Behavior, and Conduct Sensitivity Analyses

Both the CCS ROMS (and its atmospheric forcing by the WRF model) and the ROMS-BEC model went through an extensive period of initial testing and process-oriented verification to ensure that its behavior conformed to expectations. This included verifying the code implementation by extracting subsets of discretized equations and verifying their convergence to theoretical solutions. This ensures that the numerical methods and equations within the model are correctly implemented and free from errors. The science team verified the model's spatial and temporal discretization, order of accuracy, stability, reproducibility, and computational performance. They assessed model accuracy by doing test simulation and comparing model output with observational data, or other model simulations to verify that the model behaved as it was expected, The data sources used in this effort are those included in Section B2, Tables 13-

16, as well as information sourced from the scientific literature. Any areas where the model deviated from expectations were investigated and targeted for further refinement and testing, as needed. BEC had been calibrated at the global scale (Moore et al. 2004), so the team used a combination of initial testing and sensitivity analyses at 5 km resolution to determine whether additional modification of BEC was necessary (C. Deutsch, personal communication). This sensitivity analyses were not documented in Deutsch et al. (2021).

When the model was downscaled to the SCB, additional testing and verification was performed to ensure that the model was behaving as anticipated. Because wastewater inputs were understood to be the major source of anthropogenic nutrient inputs (Howard et al. 2014), the science focused particular attention to how to the wastewater plumes were parameterized in the SCB model. The modeling team utilized the approach and modeling code of Uchiyama et al. (2014). The horizontal and vertical redistribution of volume flux at wastewater inputs were tested at the ocean outfalls of City of Los Angeles Hyperion, Los Angeles County Sanitation District, Orange County Sanitation District and City of Los Angeles Point Loma plants of the four major outfalls, which have flows higher than > 100 MGD. The tests consisted of comparing depth of maximum and amplitude of highly concentrated plumes in ammonium across the season for different platform. The comparisons were evaluated against POTW quarterly monitoring data (Kessouri et al. 2021a). Once the volume flux was implemented, the authors proceeded with model skill assessment and determined, based on initial model performance, that no additional calibration was required.

Task 2. Simulate a multi-decadal hindcast across the CCS and within the SCB

Model simulations were conducted across a range of scales (Table 3), starting with the California Current System (dx = 4 km), and working down in scale (and up in resolution) with fine-scale nested domains for the California Coast (dx = 1km), then even finer resolution simulation of very nearshore processes in the SCB and SFMC (dx = 300 m). These zoomed-in domains allow detailed evaluations of submesoscale processes and the continental shelf. Outputs are stored at daily averaged values.

Table 3. ROMS-BEC simulations completed or in progress across a range of scales and within the SCB nested domains. Model simulations for the SFMC are not listed. dx = resolution

Simulation	dx	Time of simulation	Applicable Project Task
L0 USWC	4 km	1994-2017	Task 1-2
L1 CC	1 km	1997-2017	Task 2-9
L2 SCB	300 m	1997-2017 ANTH, 1997-2000 2013-2017 CTRL	Task 2-9
L2 SCB	300 m	10/12- 12/2013 for the following scenarios: (1) U.S. deep ocean outfalls, (2) All U.S. outfalls (deep plus shallow), (3) All outfalls plus rivers, (4) ANTH plus Mexican beach municipal wastewater outfalls.	Task 8
L2 SCB	300 m	8/2015 – 10/2017 for the following scenarios: (1) 50% DIN reduction; 0% recycling, (2) 50% DIN reduction; 50% recycling, (3) 50% DIN reduction; 90% recycling, (4) 85% DIN reduction; 0% recycling, (5) 85% DIN reduction, 50% recycling, (6) 85% DIN reduction, 85% recycling	Task 9

Task 3. Validate the model across the CCS and within the SCB

ROMS-BEC validation was conducted across all scales of the simulations, starting with the CCS-wide validation, then working down to fine scale nested domains for the SCB (and SFMC, work not covered by this DOCUMENT), which are simulated at higher resolution. This required assembly of data in formats that were readily compared to the large output fields and with appropriate matching of spatial and temporal scales.

CCS-Wide Validation. The science team first focused on the validation of the ROMS-BEC model at 4 km resolution for regional-scale atmospheric forcing, physics, and biogeochemistry, including O_2, carbonate saturation state, primary productivity, and hydrographic parameters, demonstrating that the model captures broad patterns of critical properties in the CCS (Deutsch et al. 2021; Renault et al. 2021). The large datasets representing "snapshots" of the CCS provide the densest spatial view of its physical and biogeochemical state. These provide the best opportunity to test the tracer distributions predicted by the model. Similarly, model results validated in this way offer the only way to derive regional mass balances of important properties such as nutrients, oxygen, carbon, and acidity (pH), from data collected on major field campaigns such as the SCB Regional Monitoring Program, PMEL's coast-wide surveys, and repeat transects from the Newport Line off Oregon, the Trinidad Head line off Northern California, the MBARI line off Monterey Bay, and the 60-year network of lines by CalCOFI.

A major compilation and synthesis of cruise and mooring data from NOAA/PMEL in the CCS was formatted and synthesized to facilitate their use by the science team. The cruise data sets for 2007, 2011, 2012, and 2013 include regional distributions of dissolved inorganic carbon, total alkalinity, pH, dissolved oxygen, nutrients (nitrate, phosphate and silicate), temperature and salinity for the Pacific West Coast. These validations are critical for testing, detecting and attributing the trends that are observed in those data.

The specific datasets that were compiled and the methods used to assure quality are discussed in Section B9. Methods used to validate the CCS 4 km model are discussed in Section D2 of this DOCUMENT. The reader is referred to Renault et al. (2021) and Deutsch et al. (2021) for the primary scientific publications.

SCB Validation. Additional focused validation for the SCB 300-m resolution model, specifically focused on anthropogenically enhanced gradients in nutrients, primary production, oxygen, and pH, was conducted to gauge model utility to investigate the impacts of coastal eutrophication on ocean acidification and oxygen loss. Moreover, this was an opportunity to specifically engage stakeholders in this validation exercise to get consensus on how the model performance should be specifically assessed.

SCB validation studies were conducted in two phases. The first phase occurred from 2019 through 2021 in association with SCB ROMS-BEC model development, with model simulations conducted from 1997 to 2000, a period chosen to capture the effects of all three phases of the El Niño–Southern Oscillation (ENSO); it also captures the beginning of the "modern" state of point source control strategies in the SCB, where several large Publicly Owned Treatment Plants (POTW) were in transition from primary to secondary treatment. The second phase occurred in a more limited fashion (i.e., validation check) during the Phase II model application studies, with model simulations from 2013-2017. This latter period reflects a more modern landscape of nutrient control strategies, including nitrogen reductions and water recycling, as well as increased population growth.

The specific datasets that were compiled and the methods used to assure quality are discussed in Section B9. Methods used to validate the SCB 300 m model are discussed in Section D2 of this DOCUMENT. The reader is referred to Kessouri et al. (2021a) for the primary publication (Phase I) with additional validation documentation provided for Phase II (Kessouri et al. 2024).

Task 4. Develop biological interpretation tools

ROMS-BEC generates state variables of seawater chemistry and lower trophic ecosystem properties. Over the course of Phase II, we developed approaches to apply a suite of metrics and thresholds to post-process and interpret model output, including using existing numeric WQO (Table 3) and approaches to interpret a narrative biological WQO. The background, data sources and approaches to generate and apply thresholds are described in Section B9.4.

In Task 7, we applied these thresholds to support interpretation of the effect of land-based nutrients on OAH, synthesized in Frieder et al. (2024). Biologically relevant thresholds of OAH were also applied in Task 8 (source attribution; Kessouri et al. in prep) and in Task 9 (scenarios).

Chlorophyll-a (chl-a) thresholds indicative of the window of opportunity for DA events are applied to Task 7 (effects of land-based inputs) and Task 8 (source attribution studies).

Task 5. Apply the model to investigate basic science questions

As this project originated as a research investigation, the ROMS-BEC model was subsequently used to investigate a wide range of research topics, producing over 100 peer reviewed and published research articles. Of particular focus to this project was the factors that govern both the time-averaged and fluctuating importance of anthropogenic and climate forcing of biogeochemical cycles along the California coast, with particular attention to the regional testbeds in the SCB and the SFMC. A partial list of ROMS-BEC articles describing this work can be found here.

A2.3 Phase II Tasks

Phase II consists of 4 model application tasks, described in more detail in the subsections below.

Task 6. Apply model to investigate the effects of land-based inputs on primary productivity, seawater O_2 and pH regimes in the SCB.
Task 7. Investigate the biological consequences of land-based inputs on urban eutrophication in the SCB.
Task 8. Attribute the relative contributions of pathways of human sources of nutrients (ocean outfalls, rivers, and Mexican transboundary sources) to primary productivity, OAH and its biological effects.
Task 9. Quantify how the reduction of nutrients to ocean outfalls, alone or in combination with reduced volumes from water recovery, alter changes in seawater chemistry and biological effects.

Task 6. Apply model to investigate the effects of land-based inputs on primary productivity, seawater O2 and pH regimes in the SCB.

During the transition from model development to application, scientists first tested a major hypothesis of whether SCB anthropogenic nutrient inputs could cause eutrophication to the degree to which it was detectable above the signal of natural variability. Kessouri et al. (2021a) ran two simulations, the first representing only the natural oceanic cycles of nutrients (CTRL), and the second adding inputs from land-based anthropogenic sources (ANTH). The difference between ANTH and CTRL is attributable to the effect of those land-based inputs. Kessouri et al.

(2021) predicted, based on these bookend scenarios, that land-based nutrients are having a non-trivial effect on primary production, pH and oxygen loss.

Because these model runs were for the period of 1997-2000, stakeholders were concerned that the results reflected an antiquated era of wastewater nutrient control strategies. They suggested updating the model to a more recent period. The model simulations for these bookend scenarios were updated through 2017 (Kessouri et al. 2024).

Early Simulations: 1997-2000. The purpose of this study was to assess the fate and consequences of land-based nutrients discharged in the SCB on the biogeochemistry and lower trophic ecosystem. We conducted a series of simulations with a regional high-resolution, physical-biogeochemical model. The model was forced by realistic atmospheric fields and oceanic boundary conditions and by a new reconstruction of natural, non-point-source, and point-source river and ocean outfall discharges (Sutula et al. 2021). We used a submesoscale-resolving configuration of the model, run at a horizontal resolution of 300 m over the SCB. We showed results from two hindcast simulations run for the period from January 1997 to December 2000.

The first simulation (CTRL) represented the regional biogeochemical dynamics in the absence of land-based nutrient inputs; the second (ANTH) included inputs of dissolved inorganic and organic nitrogen and phosphorus, silicate, iron, and inorganic and organic carbon from rivers, wastewater outfalls, and atmospheric deposition. While these inputs contain both natural and anthropogenic sources, we estimated that 97% of total coastal nitrogen inputs are derived from point sources of treated wastewater effluent, while 2% are derived from non-point-sources (urban and agricultural runoff) in the region (Sutula et al. 2021). Thus, ANTH largely simulates the effects of nutrient and carbon enrichment of the SCB caused by human activities. The period from January 1997 to December 2000 was chosen in order to capture the effects of the 1997-1998 El Niño.

We assessed the change on primary productivity, algal biomass (as Chl-a), change in organic matter exports, changes in the regime of O_2 and pH in the surface and subsurface, and changes in greenhouse gas emissions. We speculated on but did not assess the implications for biological impacts beyond changes in primary productivity.

The findings of the work are summarized in the Kessouri et al. (2021b) PNAS journal article.

Updated Simulations 2013-2017. In this study, the principal goal was to investigate the effects of land-based nutrients on primary productivity and OAH; however, the extent of anthropogenic influence on eutrophication beyond the coastal band, and the physical transport mechanisms and biogeochemical processes responsible for these effects had not yet been analyzed. Here, we extended the analyses to document the detailed biogeochemical mass balance of nitrogen, carbon and oxygen, their physical transport, and effects on offshore habitats. We used a similar set of simulations as was done previously (CTRL and ANTH) but now updated from 2013 through 2017 to reflect a more modern regime of human nutrient loading. We conducted nitrogen, DIC and oxygen mass balance analyses, then used a suite of analytical methods to investigate mechanisms controlling the fate and transport of anthropogenic nitrogen offshore. We (1) quantified the mean cross-shelf fluxes of DIN and algal organic nitrogen (ON) and partitioned those fluxes into two main transport terms: (a) mean currents and (b) transient eddies, which are chaotic by nature but are implicated in intensifying gradients of vertical flux, productivity, respiration, and export, and (2) calculated the relative importance of nitrification and NH production from recycled organic matter.

The findings of the work are summarized in the Kessouri et al. (2024) Nature Scientific Reports journal article.

Task 7. Investigate the biological consequences of eutrophication in the SCB.

Effects of Land-Based Inputs on OAH Regime Change on Pelagic Aerobic and Calcifier Habitat Capacity. We assessed the degree to which modeled O_2 losses and acidification due to land-based nutrient inputs translates to changes in habitat capacity. To accomplish this, we relied on two metrics that define the habitat available for aerobic metabolism and for calcification. Aerobic habitat is determined using the Metabolic Index, for which trait-based threshold varies across species. Aerobic habitat for northern anchovy, *Engraulis mordax*, is detailed but we also considered how aerobic habitat is modified for a range of species with metabolic traits that have differing oxygen and temperature sensitivities. Calcifying habitat is based on the saturation state of aragonite, for which thresholds also vary among species. We evaluated calcifier habitat capacity as the thickness of the water column where aragonite saturation state ≥ 1.4, but we also considered the sensitivity of our results to other values of aragonite saturation state.

First, we evaluated temporal and spatial patterns in aerobic and calcifier habitat capacity metrics in the SCB with output from a 20-year numerical ocean model hindcast. Second, we tested how anthropogenic nutrient inputs from land-based sources alter the vertical thickness of the habitat capacity metrics. We relied on two model scenarios, the first included natural oceanic cycles of nutrients, O_2 and carbon, to which rising global CO_2 emissions have been imposed (referred to hereafter as 'CTRL'), and the second includes both natural oceanic cycles of nutrients and inputs from land-based sources, 97% of which are anthropogenic and 95% of which are point source in origin (referred to hereafter as 'ANTH') (Sutula et al. 2021). Third, we confirmed the mechanisms by which anthropogenic nutrients contribute to the observed changes in vertical habitat capacity by analyzing changes in the biogeochemical rate processes that contribute to the O_2 and carbon cycles."

The findings of these analyses are summarized in Frieder et al. (2024) Frontiers in Marine Science journal article.

Effects of Land-Based Inputs on SCB Diatom Productivity and Risk of Domoic Acid Events. Blooms of *Pseudo-nitzschia* (PN), a toxigenic marine diatom genus, can produce the neurotoxin domoic acid (DA) that cause annual shell fishery closures and wildlife illnesses and deaths within the SCB. Unraveling the mechanisms that control these DA-producing harmful algal bloom (HAB) events is key to moving from a "reactive" to an adaptive management response, but our understanding has been limited by observational data gaps. Here, we utilized the 300 m resolution ROMS-BEC model to disentangle the environmental drivers of diatom productivity and their influence on the risk of DA-producing HABs. Model simulations, with and without anthropogenically enhanced land-based nutrient sources, were used to (1) investigate spatial and temporal patterns governing diatom productivity, (2) investigate how upwelling, cyclonic eddies, climate regime and local anthropogenic nutrients contribute to those patterns, and (3) quantify the relative contribution of natural versus anthropogenic forcing on the risk of DA-producing HABs.

Our study approach involved the use of multiple simulations of the ROMS-BEC model, the specific scenarios of which depended on the study question. We first utilized a 20-year realistic simulation of ROMS-BEC with all land-based sources to US coastal waters to identify characteristic patterns in diatom productivity within the SCB. Second, using the same simulation, we then investigated the role of physical processes such as upwelling and recurring eddies in driving diatom productivity and how those processes are modulated by climate over the 20 years of simulation. To isolate the effects of anthropogenic nutrients on diatom productivity, we conducted a change assessment by comparing a control (CTRL) simulation of "ocean only" against the one which includes the full suite of land-based inputs to U.S. coastal waters (ANTH) for the period of 2013 through 2017. These land-based sources are 97% anthropogenic and 95% point source in origin (Sutula et al. 2021). Thus, this incremental increase in productivity stimulated by land-based nutrients is largely anthropogenic in origin. Third, to quantify the additionality of anthropogenic nutrient inputs to the naturally occurring baseline "window of opportunity" of DA-producing HABs, we applied a chl-a threshold derived from LA coastal region observational data in which the risk detecting DA exceeded 50% (Chl-a > 3.3 mg m^{-3}; (Sandoval-Belmar et al. 2023). This subregional threshold was applied through the model domain. The difference in the spatial footprint, duration and intensity were quantified for the CTRL versus ANTH simulations and the additionality calculated. More intensive analyses were conducted by source pathways (outfalls, rivers) for one year (2013) to understand the relative contribution of these pathways for anthropogenic nutrient inputs (see Task 8). Collectively, these analyses expanded our understanding of what is modulating the "window of opportunity" to increase the risk of DA-producing HABs.

The findings of these analyses are summarized in Kessouri et al. (in prep-a).

Task 8. Attribute the relative contributions of pathways of human sources of nutrients to the SCB on O_2 water quality objectives and its biological effects

Previous studies have focused on the two bookend scenarios: CTRL versus ANTH, the difference of which is attributable to land-based sources. The OPC and Water Board were interested in understanding how the effects of eutrophication due to land-based inputs could be parsed among the major sources. In this study, we investigated the relative contribution of major source categories on the triggering of habitat compression and risk of toxic HABs.

To investigate the potential for habitat compression, two metrics of oxygen were used, the California Ocean Plan O_2 water quality objective (WQO; SWRCB 2019) and a biological endpoint, namely aerobic habitat thickness, calculated from the metabolic index with emphasis on northern anchovy as the sentinel species (Deutsch et al. 2015, Howard et al. 2020, Frieder et al. 2024).

To evaluate the risk of toxic HABs, we utilized the aforementioned methodology of applying a risk threshold of > 3.3 mg chl-a m^{-3}.

Scenarios used to investigate this question included:

- CTRL 2013 to 2017: natural ocean only baseline
- ANTH 2013 to 2017: anthropogenically influenced
- U.S. ocean outfalls > 100 MGD), 2013
- All U.S. outfalls, regardless of size, 2013
- All outfalls plus rivers, 2013
- ANTH plus Mexican beach municipal wastewater outfalls, 2013

The difference between different sets of scenarios can then be attributed to the major source category that represents a difference between the two: 1) deep ocean outfalls, 2) shallow ocean outfalls, 3) rivers that discharge to US coastal waters and 4) municipal wastewater beach outfalls that discharge to Mexican coastal waters.

This manuscript that summarizes OAH effects is currently being drafted (Kessouri et al. in prep-b), in preparation for submission to Estuarine Coastal Shelf Sciences. The manuscript that synthesizes source contributions to risk of DA events is in draft and undergoing CTAG subcommittee review (Kessouri et al. in prep-a).

Task 9. Quantify how the reduction of nutrients to ocean outfalls, alone or in combination with reduced volumes from water recovery, alter changes in seawater chemistry and biological effects.

Climate change is increasing drought severity worldwide. Ocean discharges of municipal wastewater are a target for potable water recycling. Potable water recycling would reduce wastewater volume; however, the effect on mass nitrogen loading is dependent on treatment. In cases where nitrogen mass loading is not altered or altered minimally, this practice has the potential to influence spatial patterns in coastal eutrophication. In responses to OPC and Water Board requests, we sought to understand the influence of nitrogen reduction and potable wastewater recycling scenarios on net primary productivity (NPP), pH, and oxygen. We modeled several theoretical scenarios of POTW nutrient controls and water recycling by combining dissolved inorganic nitrogen (DIN) reductions from 50 to 85% and recycling from 0 to 90%, applied to 19 wastewater outfalls in the SCB (Fig. 4).

Each model simulation was run for a total of 27 months during the period of August 2015-October 2017 with the first three months as spin-up time. These two years represent bookends in coastal ocean productivity, thus allowing us to understand the range in response across ocean state. To further understand how interannual variability in climate phase and ocean state affects coastal ecosystem response to nitrogen loading, the ANTH and scenarios 1 and 4 were repeated during August 1997-October 1999 period with August 2015-October 2017 land-based inputs, a period that overlaps with documented model performance and includes an El Niño/La Niña cycle. Output was stored as daily averages.

Scenarios 2, 3, 5, and 6 represent scenarios in which a portion ranging from 50% to 90% of the volume of the effluent currently being discharged to the outfall is recycled for potable reuse. In these scenarios, the final effluent outfall volume and constituent concentration was calculated for each individual outfall by a set of assumptions that governed the efficiency of water treatment and water recovery that were applied uniformly across all outfalls. These assumptions were informed by literature sources and current operating parameters at an existing potable water recycling program in the region.

The findings of the work are summarized in Ho et al. (2023) Nature Scientific Report journal article.

Summary of DIN Inputs per Scenario						
Scenario	**Inorganic N Management**	**% Outfall Volume Recycled**	**NH_4^+ (mg/L)**	**NO_3^- +NO_2^- (mg/L)**	**DIN (mg/L)**	**Load (kg DIN/day)**
CTRL	N/A	N/A	N/A	N/A	N/A	N/A
ANTH	2015-2017 loads	2015-2017 volumes	37.9	3.4	41.3	5706
Scenario 1	50% DIN reduction	0% recycling	7.6	14.1	21.7	3004
Scenario 2	50% DIN reduction	50% recycling	11.5	20.4	31.9	2804
Scenario 3	50% DIN reduction	90% recycling	23.2	39.4	62.6	2674
Scenario 4	85% DIN reduction	0% recycling	1.1	4.4	5.5	767
Scenario 5	85% DIN reduction	50% recycling	1.7	6.4	8.1	711
Scenario 6	85% DIN reduction	90% recycling	3.4	12.4	15.8	674

Figure 4. From Ho et al. (2023). List of modeling scenarios conducted for Task 9 and their flow-weighted average concentration and loading of each scenario across all outfalls.

A2.4 Project Milestones and Products

This section synthesizes the timing of the project activities that occurred over Phase I and Phase II (Table 4), and Table 5 provides a comprehensive list of products associated with each task.

Table 4. Gantt chart of project Phase I and Phase II tasks and associated activities by year.

Task/Subtask	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25
PHASE I													
T1 Develop the model													
CCS ROMS-BEC testing, calibration, sensitivity analyses	■	■											
4 km model set up, final forcing, and downscaling to the SCB		■	■	■			■	■	■	■	■	■	■
T2 Simulate hindcast				■	■	■	■	■	■	■	■	■	■
T3 Validate the model													
4 km physical validation				■	■	■	■	■	■	■	■	■	■
4 km biogeochemical validation						■	■	■	■	■	■	■	■
300 m SCB validation							■	■	■	■	■	■	■
T4 Develop the biological interpretation tools										■	■	■	■
T5 Basic science applications										■	■	■	■
PHASE II													
T6 Apply to investigate the effects of land-based inputs								■	■	■	■	■	
T7 Investigate biological effects of land-based inputs										■	■	■	
T8 Investigate the relative effects from anthropogenic sources										■	■	■	■
T9 Investigate the efficacy of nutrient reduction, with and without reductions in volume from potable water recycling										■	■		

Table 5. List of science products associated with model development, validation and applications relevant to the SCB.

Task/Subtask	Product	Digital Objective Identifier(Paste Link in Browser to Access Article Online)
Phase I		
T1. Develop the model		
CCS ROMS-BEC model testing, calibration, sensitivity analyses	No document	N/A
Model set up, forcing (CCS and SCB)	Deutsch et al. (2021) Renault et al. (2021) Kessouri et al. (2021b) Sutula et al. (2021)	10.1016/j.pocean.2021.102565 10.1016/j.pocean.2021.102564 13:e2020MS002296 10.1016/j.dib.2021.106802
T2 Simulate hindcast	4 km, 1 km and 300-m hindcast (1997-2017)	Upon request
T3 Validate the model		
4 km physical validation	Renault et al. (2021)	10.1016/j.pocean.2021.102564
4 km biogeochemical validation	Deutsch et al. (2021)	10.1016/j.pocean.2021.102565
300 m SCB validation	Kessouri et al. (2021a)	13:e2020MS002296
T4 Develop the biological interpretation tools	Frieder et al. (2024) and references cited therein Kessouri et al. in prep-a	10.3389/fmars.2022.752951
T5 Basic science applications	Kessouri et al. (2020) Kessouri et al. (2022) Frieder et al. (2022) Damien et al. (2023a) Damien et al. (2023b) Damien et al. (2024) McWilliams et al. (2024) Hoel et al. 2025	10.1029/2020GB006578 10.1029/2022JC018947 10.3389/fmars.2022.752951 10.1029/2022GB007572 10.1029/2023GL104853 10.1029/2024JC021197 10.22541/essoar.171017133.39619177/v1 10.1016/j.marpolbul.2025.117788
Phase II		
T6 Apply to investigate the (biogeochemical) effects of land-based inputs	Kessouri et al. (2021b) Kessouri et al. (2024)	10.1073/pnas.2018856118
T7 Investigate biological effects of land-based inputs	Frieder et al. (2024)	10.3389/fmars.2022.752951.
T8 Investigate the relative effects from anthropogenic sources		
Conduct simulations to attribute sources	Model outputs	Upon request
Journal article	Kessouri et al. in prep-a Kessouri et al. in prep-b	
T9 Investigate the efficacy of nutrient reduction, with and without reductions in volume from potable water recycling		
Conduct scenarios	Scenario model outputs	Upon request
Journal article	Ho et al. (2023)	10.1038/s41598-023-48588-2

A3. Quality Objectives and Criteria for Model Inputs/Outputs

This section describes the quality objectives and criteria for model inputs and outputs required to meet the project goals and objectives.

Two major quality objectives of the model inputs and outputs include :

1. Adequacy: Is the ROMS-BEC model formulation, set up and forcing of sufficient quality to be adequate to address the application questions. Sources of model uncertainty, both quantifiable and qualitative, are considered as a part of overall model adequacy.
2. Application uncertainty: For any given application, is the signal of eutrophication effects (on chemical or biological endpoints) greater than the “noise” of uncertainty?

Assessment of uncertainty is a key concept that frames both the assessment of general model adequacy and application uncertainty assessment. In general, model uncertainty can come from multiple sources including generalizations of real-world phenomena to imprecise mathematical formulations and parameterization, inexact numerical approximations of relationships, and imperfect representations of external forcing (from land, atmosphere, or ocean boundaries). Multiple approaches to quantifying uncertainty in coastal numerical modeling exist, including model skill assessment (comparison of model predictions versus observations), sensitivity analyses, and multiple model comparisons, or combinations of these approaches. In this project we specifically utilized model skill assessment and sensitivity analyses to document uncertainty in order to establish model adequacy. Forays were made into methodologies to routinely quantify uncertainty (Kessouri et al., 2024, Sutula et al. in prep), anticipating that this would be useful for future applications, but were not part of originally scoped work and thus quality objectives are not specifically provided for those approaches.

To address this first technical question, we specify the three types of quality criteria that, based on existing information, can be used to determine the adequacy of the model (quality of existing data, model performance, and peer review), which is of particular relevance to Phase I model development activities. Model calibration and sensitivity analyses is a fourth category, but the findings are available in qualitative descriptions and thus no performance criteria are prescribed.

For the work of Phases I and II covered by this DOCUMENT, no performance criteria for uncertainty quantification in science applications are specified, because work proceeded in a research mode. For any applications, model skill assessment and peer review (and stated performance criteria therein) can be considered a qualitative to semi-quantitative assessment of uncertainty.

A3.1 Acceptance Criteria for Existing Data

Various types of data are needed to develop model inputs and for use in calibrating and /or validating the ROMS-BEC model. The data needed to develop these model inputs and for use in model set up, forcing and validation have been obtained from secondary data sources. No new data were collected for this project. Only existing data have been used for the development and validation of ROMS-BEC.

The use of secondary data is for purposes other than those for which they were originally collected. These secondary data may be obtained from literature, compiled from electronic databases, and from the outputs of environmental models, among other sources. The quality of these secondary data sources must be extensively reviewed prior to use in this project. In this project, our main data sources have established standardized operating and/or quality assurance procedures governing their generation. These are documented in Section B2.

Model Development and Validation. The following acceptance criteria have been established for use of existing data or secondary model outputs in the ROMS-BEC model development and/or application:

- The forcing and validation data quality is known and documented. Exceptions where data are lacking documentation are noted.
- The science team can assess existing data or model uncertainty, on a qualitative, semi-quantitative or quantitative basis.
- Data are collected from sources to provide sufficient temporal and spatial coverage to make the ROMS-BEC model relevant for the intended applications.
- The data represent the time, location and conditions of the period being modeled.
- The model code, developmental data sets, and the procedures used to develop the model are published as journal articles (peer-reviewed; preferred) or as grey literature reports.

Table 6 provides the scoring rubric used to grade the quality of data used in the model forcing and validation studies. *Completeness* is a measure of the amount of data needed versus that available to develop model forcing and to fully validate a model. *Representativeness* is a measure of how closely the model forcing and validation data reflect actual conditions. *Comparability* expresses the confidence with which one data set can be compared to another. *Precision* speaks to both analytical repeatability as well as variability in the variable being sampled. *Documentation i*dentifies whether or to what degree the data or model outputs were generated with a QA plan or the equivalent or simply documented in a report.

Table 6. Scoring rubric to grade quality of data used in model forcing and validation studies

Metric of Data Quality	Scoring Category and Rubric		
	High Pass (HP)	Adequate Pass (AP)	Fail (F)
Comparability (C)	consistent methods, units, and scales that align with modeled state variables	Methods appropriate, but cross walking was required to align with modeled state variables	Inappropriate methods and/or misaligned units
Representativeness (R)	Data encompass the spatial and temporal scales being simulated	Data encompass either appropriate spatial or temporal scale, but one of the two is lacking	Data encompass neither spatial nor temporal scale
Completeness (T)	Ample data are available	Data are scarce, but deemed sufficient for project goals	Data completeness inadequate
Precision (P)	Precision is documented and is of high quality	Accuracy/precision is documented and is acceptable	Accuracy/precision is not documented
Documentation (D)	Data or model were generated with a QA plan or the equivalent	Data quality procedures are documented	No data quality documentation is discoverable

Biological Tools. For development of biological tools, we modified the explicit criteria, though used a similar approach to that represented in Table 6 for data used in model development or validation. To review the data quality of literature from which these thresholds or indices were derived, we scored them using three criteria: 1) amount of evidence, 2) quality of evidence, and 3) geographic applicability. For amount of evidence, we used “high pass” to denote a high amount of evidence or quality of evidence and “adequate pass” to denote a medium amount of evidence or quality of evidence, consistent with the methods of Bednaršek et al. (2019, 2021a,b). We added an element of geographic applicability to denote whether the threshold was derived from organisms found in the CCS (adequate pass) or specifically to the SCB (high pass).

Formulation of Inputs for Water Recycling and Nutrient Reduction Scenarios (Task 9). To review the data quality of literature from which these thresholds or indices were derived, we scored them using three criteria: 1) amount of evidence and 2) quality of evidence. For amount of evidence, we used “high pass” to denote a high amount of evidence or quality of evidence and “adequate pass” to denote a medium amount of evidence or quality of evidence, consistent with the methods described in Ho et al. (2023).

A3.2 Model Performance Criteria

Model performance criteria are important during two stages of model development:

(1) Model testing and calibration
(2) Model validation

A3.2.1 Model Testing, Verification and Calibration Performance Criteria

Model testing, verification, and calibration is often accomplished through a subjective trial-and-error adjustment of model coefficients (weight of evidence approach) because many interrelated factors can influence model output. The experience and judgment of the modeler is a major factor for both accurately and efficiently verifying modeling performance. At this stage, our project outputs were qualitative.

The ROMS model is built on first principles and as such does not require data assimilation, tuning or calibration. Decisions are made whether or how to adjust model resolution and which suite of processes to use in order to adequately capture the processes that contribute to the mean state and variability of the biogeochemical phenomena being modeled. These decisions are weighed against the computation cost of including those phenomena, in order to generate a parsimonious model that is “fit for purpose.” The UCLA ROMS modelers had already been using the US West Coast as a test bed for model development across a wide variety of research applications for over three decades. The ROMS configuration, including its forcing by the WRF model and the downscaling from 12 km to 300 m through successive nests, was already rigorously tested and subjected to academic peer review.

The original BEC model, adapted for the CCS, has its origins in a global three-dimensional (3-D) model developed by Moore et al. (2004). This global BEC model has been used to investigate oceanic basin-scale patterns of biomass, productivity, community structure, and carbon export and oxygen cycling as well as the sensitivities of those patterns to changes in external forcing (e.g., atmospheric dust/iron deposition). The Deutsch et al. (2021) approach to adapting the BEC model took the view that the primary parameterization of BEC was founded on the principles of the goal of understanding the fundamental mechanisms that drive biogeochemical and lower ecosystem transformations at the scale of the global ocean. The original BEC model already accounted for large scale global gradients in forcing and was based on an extensive review of primary literature of observations and earlier modeling work. Thus, changes to the original BEC parametrization were made only when completely necessary and in accordance with these same exacting principles (Deutsch et al. 2021, C. Deutsch, personal communication).

At UCLA, throughout Phase I, this was accomplished: 1) through the primary modeler developer’s focused effort, and 2) through a process of internal peer review, discussion, suggestions for targeted analyses that occurred on a weekly to biweekly basis over the course of six years in which the primary model development, testing, verification, calibration and validation took place. This was an intensive process, understanding the weight and the potential economic outcomes of the nutrient controls strategies that the work might influence, and the effort involved multiple leading ocean modelers, including Drs. James McWilliam, Curtis Deutsch, Daniele Bianchi, Jeroen Molemaker, Lionel Renault and others who collectively represent over a century of ocean modeling expertise.

3.2.2 ROMS-BEC Model Validation

ROMS-BEC originated as a research model intended for basic scientific investigations. This context is important for understanding our approach to validation in this project. Ocean modeling as a scientific discipline encompasses theory, computational simulation and data analysis for theory and model testing (validation). Advances are made through developing better simulations capabilities (i.e., mathematical, computational, etc.) as well as a means of investigating oceanic and climate phenomena and processes. Thus, ROMS and BEC have been evolving over decades from the collective and iterative contributions of a global community of ocean scientists; this is not a one-off, project-specific activity. In this context, model validation is a continuous and an integrative core component of basic research led by UCLA and others in this community.

CCS Model Validation. The CCS and, initially, the SCB ROMS-BECs were developed as academic research models. As such the validation performance criteria can be expressed as "meets or exceeds the standards for model performance that assures that the ROMS-BEC model represents an important advance in the science of earth systems modeling." This is an academic standard, met through peer-reviewed publication of the model set up, forcing and validation findings in the peer reviewed journals in this field. From the Deutsch et al. (2021) version, the model, outside of its specific applications in the SCB, has continued to evolve with incremental model validation occurring with these advances. See Task 5 (Section 3.2 for examples).

SCB Model Validation and Specific Performance Criteria. As the SCB model began its transition to eutrophication applications, stakeholders required a more transparent approach to model validation and routine performance assessment. The Kessouri et al. (2021a) publication is the first iteration of stakeholder-informed skill assessment, wherein the community contributed to the conversation on the metrics, statistics and key gradients that should be investigated as part of the exercise of documenting model performance.

Kessouri et al. (2021a) specified four basic types of performance criteria:

- The model is able to reproduce key physical and biogeochemical phenomena that are well documented in the literature; this is a qualitative criterion that is judged through peer review (i.e., journal publishing and the Independent Review Panel expert review).
- The model is able to capture the basic horizontal gradients in onshore to offshore remotely sensed imagery (e.g., SST, net primary productivity, chl-a, etc.).

- The model is able to capture biogeochemical rates of transformation; field observations of rates are sparse and typically not available for the years in which the model performance was assessed, so the criterion that we employed was that model predictions should be within the same order of magnitude of predicted rates.
- Vertical profiles of CTD data (O_2, temperature, salinity, pH) or bottle data (ammonium, nitrate) (on the scale of cruises completed over a day or week) were assessed with specific performance criteria to monthly model output, in which we scored the model skill based on specific statistics and metrics (Table 7), which are defined in Section D2.

Table 7. From Allen et al. (2007), reproduced from Kessouri et al. (2021a) Summary of statistical metrics, statistics and model performance rating.

Statistic	Excellent	Good	Reasonable	Poor
Cost function (Moll & Radach, 2003)	<1	1–2	2–3	>3
Nash–Sutcliff model efficiency (Nash & Sutcliffe, 1970)	>0.65	0.65–0.5	0.5–0.2	<0.2
Bias (Maréchal, 2004)	<|0.1|	|0.1–0.2|	|0.2–0.4|	>|0.4|
H (Welch, 1947)	0			1
Correlation coefficient	1–0.9	0.9–0.8	0.8–0.6	<0.6
p-Value	<0.05			>0.05
Ratio of standard deviations	1–0.9, 1–1.1	0.9–0.8, 1.1–1.2	0.8–0.6, 1.2–1.4	<0.6, >1.4

The science team uses scores from excellent to good to indicate adequate model performance. These scores can be applied at a subregional or season scale or summarized overall. When the score is reasonable or poor, then the science team investigates the cause to determine whether corrective actions are needed (see Section C1). Kessouri et al. (2021) noted that examples of investigations have pointed to: 1) incorrect land-based forcing, 2) poor observational data quality, 3) missing dynamics in the model such as nearshore process and/or transboundary flows, and 4) under sampling of observational data to represent the averaged month of model output; this is particularly common in the spring and fall during shifting from a well-mixed to a stratified ocean regime, or during an upwelling event. Model performance is utilized to discuss with managers about implications for confidence in predicted endpoints of interest (see Section C2). Additional context for interpretation of model performance is provided in Section D3.

We note that incorrect land-based forcing, when identified, resulted in corrective actions, while issues with observational data have been noted (e.g., chl-a, ammonium, pH) and these parameters are generally not utilized to grade model performance. Stakeholders have begun to take corrective actions to improve methodologies underlying collection of ambient ocean data (e.g., collecting pH bottle samples and developing new algorithms to generate carbonate chemistry from CTD profile data).

3.3 Peer Review

Expert peer review of the model can provide an independent determination of the adequacy of the model for the intended application when stakeholders require the expertise and confidence to make this assessment. The ROMS-BEC model and its applications have undergone two general types of peer review: 1) academic publishing by independent peer reviewers and 2) an independent panel of experts, commissioned by the OAH Model steering committee.

3.3.1 Journal Peer Review

Peer review is important for maintaining the quality, integrity, and credibility of scientific research published in academic journals. The process uses independent voluntary experts in the relevant field to review a submitted manuscript to ensure it meets established standards of quality and rigor. Multiple loops of feedback are common, as is outright rejection if the submitted work is of insufficient quality to meet the journal standards. This process of feedback helps to identify errors, assess the validity of research methods, and ensure the clarity, completeness, and soundness of the presented information.

The science team aims to maintain the highest standard of scientific reporting by publishing in the best journals in this field, for which the performance criteria are rigorous (e.g., Table 8). The performance criteria for academic publishing asks: "*Is the submitted work of sufficient quality to be published in well reputed journals with high impact factors?*"

Table 8. Sample list of journal review criteria, compiled across oceanographic journals

I. Scientific significance and originality • Does the research address a significant problem in oceanography? • Does it offer new knowledge, novel approaches, or advancements to the field? II. Methodology and model Model Description: • Is the ocean model used described adequately, including its type and key features? • Are the numerical schemes, parameterizations, and computational details outlined? Design: • Are the simulations clearly defined, including the purpose, duration, and forcing conditions? • Is the experimental setup appropriate for addressing the research questions? Data Usage: • Are the input and forcing data clearly described and their sources cited? • Is the quality of the input data assessed, and potential limitations discussed? Validation and Verification:

- Model Validation: Is the model validated against observational data using statistical metrics?
- Are limitations and uncertainties of model and observational data clearly stated?
- Are the chosen validation metrics and techniques appropriate for the application?
- Are the results of the model comparison presented clearly and transparently?
- Process-Oriented Validation: Does the manuscript evaluate the model's ability to accurately represent key oceanographic processes (e.g., mixed layer dynamics, upwelling)?
- Uncertainty Quantification: Are sensitivity analyses performed to understand the impact of uncertain parameters on model outputs? Or is uncertainty quantified?

Reproducibility:

- Are the methods described with sufficient detail to allow others to replicate the results?
- Is the model code, scripts, and input data adequately documented and accessible?
- Does the study avoid common pitfalls in ocean modeling, such as using inappropriate resolution for environmental variables compared to species records? Ignoring correlations between variables? Inadequate bathymetry in coastal models?

III. Results and discussion

- Are the interpretations and conclusions supported by the presented evidence and analysis?
- Are the implications of the findings discussed in the broader context of existing literature?
- Are the limitations of the study and potential avenues for future research clearly stated?

IV. Presentation and clarity

- Is the manuscript clearly and concisely written with appropriate terminology?
- Does the abstract clearly and concisely summarize the research and its main findings?
- Are the figures and tables clear, self-explanatory, and of high quality?
- Are citations and references appropriate and consistent?

V. Ethical considerations

- Does the manuscript adhere to ethical standards for research and publication?
- Are potential conflicts of interest disclosed?

3.3.2 Integrative Peer Review by An Independent Expert Panel

Members of the regulated community posed the question whether the model and its applications were sufficiently credible to support nutrient control discussions that could influence wastewater infrastructure upgrades, potentially costing billions of dollars. At the SCCWRP Commission's request, the National Water Research Institute (NWRI) formed a Steering Committee that would govern the process for an independent expert review of the ROMS-BEC model. That Steering Committee needed to assure that the review process was balanced, fair and transparent. The group identified the criteria including knowledge and expertise of the scientific experts that would be recruited to review the model. A group of scientific experts were empaneled to conduct an independent review of ROMS-BEC development, validation, and applications. The six-member independent review panel (IRP) published its findings in a report released in February 2025 (NWRI 2025) that answered multiple charge questions formulated by the Steering Committee in order to meet the following goals of the review:

1. Assess model readiness to answer managerially relevant science questions.
2. Advise on model uncertainty associated with addressing those questions.
3. Recommend next steps for improving the model readiness.

The performance criteria of model adequacy, as judged through this independent peer review process, is embodied in the IRP's answer to Goal 1.

Prospectively, the IRP may be asked to provide an updated assessment, but continuous or ongoing IRP review of products is not assumed or required as a part of this DOCUMENT.

A4. Distribution List

Table 9. Distribution List

Name	Agency	Address	Contact Information for Agency Lead
Stephen B. Weisberg **Martha Sutula** **Fayçal Kessouri** **Christina Frieder** **Minna Ho**	Southern California Coastal Water Research Project Authority	3535 Harbor Blvd., Suite 110, Costa Mesa CA 92626	Phone: (949) 933-2138 Email: marthas@sccwrp.org
James McWilliam **Daniele Bianchi**	UCLA Dept. of Earth & Atmospheric Sciences (EAS)	520 Portola Plaza Math Sciences Building 7127, Los Angeles, CA 90095	Phone: (310) 825-6936 Email: dbianchi@atmos.ucla.edu

A5. Project Organization

This section of the document describes the lines of communication between the participating entities, the general project organization, roles and responsibilities (Table 10, Fig. 1).

Table 10. Positions and Duties for Phase II of SCB Model Applications

Position	Name	Responsibilities
Contract and Project Manager	Martha Sutula	Project management and oversight, science communication, approves invoices and reports.
Lead-SCB Model Applications	Fayçal Kessouri	Generation of model experimental design, setup, forcing, generation of model outputs, analysis and reporting for all SCB model application.
Lead-CCS Physical Model Development and Modeling Applications Advisor	James McWilliams	ROMS development, verification, calibration, and validation.
Lead-CCS Biogeochemical Model Development	Daniele Bianchi	BEC development, verification, calibration, and validation.
Modeling Applications Advisor and Model Applications Quality Assurance Lead		Ensures that modeling quality requirements are met through routine auditing of the workflows, systems, model outputs, and products.
Modeling Applications Advisor	Curtis Deutsch	Advisory for model application.
Biological Tool Applications Lead	Christina Frieder	Biological interpretation tool application expert.

A5.1 Roles and Responsibilities

Martha Sutula of SCCWRP is the Contract Manager (CM), Project Manager (PM), and primary contact for the project. As CM, she approves reports and invoices for payment and administers subcontracts (UCLA). As the PM, she 1) reviews and approves the quality control practices 2) reviews, evaluates and documents project reports, and 3) verifies the completeness of all tasks.

Fayçal Kessouri of SCCWRP is the Modeling Applications Lead (MAL). The MAL 1) sets up the ROMS-BEC model for the SCB configuration and input decks corresponding to specific scenarios, 2) parameterizes the compilation land-based, atmospheric and ocean forcing data within the SCB in the model, 3) runs the SCB model, 4) validates the SCB model, 5) coordinates and/or runs model scenarios, and 5) is the lead author or co-author of relevant reports and journal articles on the findings.

James McWilliams of UCLA is the Physical Model Development Lead (PMDL). The PMDL 1) oversees the development of ROMS, verifies, and validates it for the California Current System (CCS) configuration, 2) provides expert advice on all aspects of model applications, and 3) co-authors relevant reports and journal articles on the findings.

Curtis Deutsch, formerly of UCLA, now at Princeton University and High Meadows Research Institute was the Biogeochemical Model Development Lead (BMDL) during Phase I (Fig. 1). As the BMDL, he 1) oversaw the development of the CCS BEC, verified, calibrated, and validated it for the CCS configuration and 2) was the lead author or co-author of relevant reports and journal articles. During Phase II, he continues to 1) provide expert advice on all aspects of model applications, 2) advise on biological indices used for the interpretation of oxygen, and 4) co-author relevant reports and journal articles on the findings.

Daniele Bianchi of UCLA is the current UCLA Biogeochemical Model Development Lead (BMDL), since the departure of Curtis Deutsch from UCLA. As the UCLA BMDL, he 1) leads model development in the San Francisco and Monterey Coast (not covered by this DOCUMENT), 2) provides expert advice on all aspects of model applications and 2) co-authors relevant reports and journal articles on the findings.

Christina Frieder of SCCWRP is the Biological Tool Applications Lead (BTAL). The BTAL developed methodologies and oversaw data analysis associated with 1) applying thresholds of ocean acidification effects on marine calcifiers and 2) applying biologically relevant indices of aerobic habitat capacity to model outputs. The BTAL is the lead author or co-author of relevant reports and journal articles on the findings.

A6. Model Quality Assurance Lead (MQAL) Independence

The Modeling Quality Assurance Lead (MQAL) fulfills the functions of a project quality assurance officer. This QA function was carried out by different individuals, depending on the phase and particular task of the project. During Phase I (2014-2020), the model development phase, this role was carried out by the project lead principal investigator, Jim McWilliams (Fig 1A). During Phase II (2021-2025), Daniele Bianchi has served the MQAL for SCB-focused model applications (Fig. 1B).

The role of the MQAL is to ensure that quality control measures described in this DOCUMENT are maintained throughout the project. This includes supervising the development of model forcing, the application of that forcing data in ROMS-BEC simulations, inspection of model outputs to ensure the model run has maintained integrity, and review of model analysis workflows to verify accurateness of analysis vis-à-vis intended objectives. The model applications MQAL is supported in this role by James McWilliams, who provides expert oversight and additional quality assurance.

The MQAL reviews and assesses all procedures during the project, including whether the procedures are performed according to protocol. The MQAL discussed all findings to the PM, including the need for corrective action. The MQAL has the authority to stop all actions if there are significant deviations from required procedures or evidence of a systematic failure.

We note that model development and early science applications are focused on the San Francisco and Monterey Coast (SFMC) are ongoing. Modeling activities in the SFMC are not the focus of this DOCUMENT and thus no further mention is made.

A7. Organizational Chart and Communications

Figs. 5 and 6 gives a visual depiction of the ROMS-BEC OAH Modeling Project personnel organization through two modeling phases: 2014-2020: Model Development (top panel A) and 2021-present: SCB Model Application (bottom Panel B). Roles for the current SCB-focused model application phase are described in Section A1.1. Fig. 6 gives the relationship between the Phase II project principal investigators and the State Water Board QA officer and Ocean Standards Unit Supervisor.

Figure 5. Organizational chart of project staff, configured by project phase: Phase I (2014-2020, Panel A) and Phase II (2021-2025, Panel B).

Figure 6. Organizational chart showing project scientific leadership (blue box) and State Water Board quality assurance review and document control (grey box) beginning in 2026 and beyond.

A8. Special Training Needs and Certification

Ocean modeling is a specialized skill that requires a combination of knowledge, specific skills, and capabilities to independently conduct this work. This section specifies the basic knowledge and skills required to independently conduct this work.

This project has been co-led by UCLA, which has the goal of education and training as a core component of its mission. Therefore, training, and the quality assurance associated with supervising trainees to conduct this work, has been a routine part of the workflow for this project over the past decade. No certification is specifically required, though it is customary for this training to be acquired during the completion of an advanced degree (e.g., masters, doctoral) or post-doctoral position. Knowledge or skills that are common among modelers that become proficient in the application of the ROMS-BEC model include:

- Knowledge of physical, chemical and biological oceanography
- Understanding of how to use model simulations to answer scientific questions and their limitations
- Geospatial statistical analyses
- ROMS and BEC modeling data management and post-processing workflows in Linux
- Computer programming (Fortran)

SCCWRP and UCLA staff stay current with the latest scientific research by reviewing new and relevant literature and attending conferences and training workshops. These scientific activities are documented in SCCWRP's Director's Reports.

A9. List of Documents and Records

There are multiple types of documentation that have been produced. Table 11 lists these types of documents and records, their distribution and storage.

Table 11. List of types of project documents, their distribution and storage at SCCWRP

Type	Distribution	Storage
ROMS model theory, algorithms and equations, represented as code	Public	Electronic minimum of 10 years
BEC model theory, algorithms and equations, represented as code	Public	Electronic minimum of 10 years
This document	Distribution list; public upon request	Electronic minimum of 10 years
Project workplan	Internal distribution list, granting institution, CTAG upon request	Electronic minimum of 10 years
Progress and annual reports	Granting institution	Electronic minimum of 10 years
PowerPoint Presentations	Meeting attendees	Electronic minimum of 10 years
Journal manuscripts	Public via SCCWRP website (available upon request) or journal (for fee or open access)	Electronic minimum of 10 years
Technical reports	Public via SCCWRP website	Electronic minimum of 10 years
Model outputs, data visualizations, data analysis workflows and associated code	Internal, provided upon request	GitHub, minimum of 10 years

In Phase II, responsibility for the distribution and control of review and final versions of project documents were held by the SCCWRP PM. Reports, technical memorandums, journal manuscripts, and technical presentations were developed to document progress and submit interim and final project deliverables. Electronic (PDF) versions were generated and distributed to personnel included on the distribution list. Master copies of all reports and journal articles were maintained in electronic format by SCCWRP. Quarterly Progress Reports provide a continuous record of project activities. Before the PM releases any final project documents (e.g., journal articles and annual or final project reports), the documents undergo internal review initiated by the SCCWRP and UCLA Technical Leads and the Modeling QA Lead.

SCCWRP has a comprehensive plan for document control, storage and records. During project execution, key working documents and project deliverables were stored on SCCWRP's SharePoint management system, which is backed up in the cloud, except for large data sets (e.g., model outputs). Day-to-day modeling activities and data analyses are completed on the UCLA Linux-based computer servers, then transferred to the SCCWRP SharePoint for final visualizations. After project completion, project files are retained in accordance with SCCWRP records retention policy; in general, all financial and contractual documents, as well as final project deliverables, are maintained for 3 years in active storage and after 3 years are moved to permanent storage on an external hard drive for 17 years (20 years in total).

B. Data Acquisition and Generation

B1. Identification of Project Environmental Information Operations

Environmental information operations consists of the compilation of existing information used to develop, validate, and apply ROMS-BEC to answer the applied science questions, and the management of the model outputs, analyses, and documentation generated from these activities.

B2. Methods for Environmental Information Acquisition

This section is intended to cover any field activities, environmental measurements, laboratory analyses and compilation of existing information. For this project only the compilation of existing information applies; sections on environmental measurements, including field and laboratory, have been intentionally excluded.

This section describes the approach taken for quality control of existing data, what data were compiled for use, and finally our quality assessment of each of those data streams.

B2.1 Approach to Quality Control of Existing Data

In this section, we specify the data needed to implement the project (Tables 12-15) and our application of our data quality assessment (Table 6, Section 3.1). We only utilized existing data and therefore in this section, the tables and the abbreviated text descriptions we specify the intended use of data, how the data are identified and/or acquired, and our scoring of the underlying quality of the data used for the model, including elements of completeness, representativeness, bias, precision, and other considerations, using the rubric provided in Table 6 of Section 3.1.

Existing data used in this project include field and remotely sensed observations and model simulations and existing literature (summarized in Tables 12-17 in section B2.2 -B2.5 below). When obtaining the secondary data for use in this project, all data source quality assurance procedures were reviewed for documentation, bias/precision, representativeness, completeness, and comparability of the data collected. Data screening measures were employed to ensure the validity of the data. These measures included data analyses to identify outliers and inconsistencies, checks on reporting units, constituent definitions, calculated constituents, and any missing data records (e.g., what values are assigned to missing data). Outliers are investigated but generally are not removed unless they are identified as an error, rather than just an influential outlier. This is resolved by querying the data originator, discussing the issue and getting their opinion on whether the data should be left or omitted. In the cases were that was not possible, the data were not used to err on the side of caution. Any data sources that failed quality assurance assessments (specified in Table 6, Section 3.1) were not used in the project.

B2.2 Assembly and Quality Assurance of CCS and SCB Model Setup and Forcing Data

This section describes the rationale for the existing data and model simulations that were used to develop the ROMS-BEC model, including model set up and forcing data. Tables 12 and 13 summarizes the quality assurance review of those data for the CCS and SCB, respectively, using the scoring rubric described in Table 6. We direct readers to Deutsch et al. (2021) and Renault et al. (2021) for additional details on these data sources for the CCS model, and to Kessouri et al. (2021) for the SCB model.

B2.2.1 Assemble Oceanic and Atmospheric Forcing

Forcing for 4 km Model. Initial and horizontal boundary data for T, S, surface elevation, and horizontal velocity are taken from the quarter-degree, daily averaged Mercator Glorys 2V3 product (https://marine.copernicus.eu/access-data), and applied to the outer boundary of a dx = 12 km solution, which spans a larger domain and serves as a parent grid for the CCS 4 km solution. Then successive nested subdomains were deployed to focus on the region and spatial scales of interest by the technique described in Mason et al. (2010). To improve the water mass representation, in particular the density distribution, the Mercator data are corrected using the mean monthly climatology from the World Ocean Atlas (WOA; Locarnini et al. 2013; Zweng et al. 2013) over the period 1995-2004.

ROMS requires spatially detailed patterns of wind and surface buoyancy forcing, and to obtain this we run the regional Weather Research and Forecast model (WRF; Skamarock and Klemp 2008) that downscales meteorological fields from global reanalysis models. WRF (version 3.6.1; Skamarock et al. 2008) is implemented in a configuration with two grids, similar to Renault et al. (2016b). The WRF domains are slightly larger than the ROMS domains to avoid the effect of the WRF boundary sponge (4 grid points wide). It has horizontal resolutions of 18 km and 6 km, respectively, using only the latter over the USW4 domain. The model is initialized with the

Climate Forecast System Reanalysis (CFSR with ≈ 40 km horizontal resolution; Saha et al. 2010) from 1 January 1994 and integrated for 17 years with time-dependent boundary conditions interpolated from the same six-hourly reanalysis. Forty vertical levels are used, with half of them in the lowest 1.5 km, as in Renault et al. (2016b). The model configuration is set-up with the same parameterizations as in Renault et al. (2016b) except that the WRF Single-Moment, 6-class microphysics scheme (Hong and Lim 2006) is modified to consider the spatial and seasonal variations of the droplet concentration (Jousse et al. 2016). Its Sea Surface Temperature (SST) forcing is derived from the Ostia one-day product (Stark et al. 2007) that has a spatial resolution of 5 km. The inner-nested domain (WRF6) is initialized from the outer solution (WRF18) on 1 April 1994 and integrated for 17 years. Only the period 1995-2010 is used in the model evaluations. The surface turbulent evaporation, heat, and momentum fluxes are estimated using bulk formulae (Large 2006), and the atmospheric surface fields are derived from an uncoupled WRF simulation, along with the precipitation and downwelling radiation; for these surface fluxes the temporal sampling interval is one hour.

The biogeochemical boundary conditions for nutrients (NO_3, PO_4, $Si(OH)_4$) and O_2 are taken from monthly climatological observations in the World Ocean Atlas (WOA) (García-Reyes et al. 2014). Boundary condition data for Fe is taken from global simulations with the Community Earth System Model (CESM) that used an earlier version of the same BEC ecosystem model. The ammonium boundary concentrations, being small in nature, are set to zero, but adjust rapidly to ecosystem processes in the interior of the domain. Time-dependent carbon cycle parameters, DIC and Alk, are taken from GLODAP (Key et al. 2004), with a reference year of 1995. Time-dependent atmospheric pCO_2 is also used as surface boundary condition for air-sea gas exchange. Aside from the boundary DIC, the only non-stationary forcing of the model solution comes from the physical boundary conditions and surface forcing (Renault et al. 2021).

Assemble Forcing for the 300 m SCB Model. The oceanic forcing of the 300-m domain originates from multilevel offline downscaling. A 4-km simulation is initialized and forced at the open boundaries by a preexisting 12 km resolution North-east Pacific-wide ROMS solution (Renault et al. 2021), initialized and forced on the boundaries by the Mercator Glorys2V3 model for the physics, and with reconstruction of biogeochemical fields using the world ocean database. We used climatological fields for organic material and relationships with density for nutrients. Full description of the boundary conditions and initialization of the parent configuration at 12-km can be found in Deutsch et al. (2021). The 4-km configuration is run for the period 1995-2017, after a spin-up of 2 years. A 1-km simulation is initialized and forced from the 4-km model, including initial conditions and open boundary conditions, starting in October 1996 and ending in December 2017. The 300-m simulation is initialized and forced at its boundaries by the 1-km simulation. The oceanic model is forced by hourly outputs from the atmospheric uncoupled WRF model (6 km resolution; Skamarock and Klemp 2008). Using bulk formulae (Large 2006), WRF06 provides heat, surface evaporation, momentum, and atmospheric data and is run at 6-km resolution over a domain similar to the 4-km (Renault et al. 2016) and includes a wind-current coupling parameterization necessary to attain more realistic simulations of the oceanic eddy kinetic energy and circulation (Renault et al. 2016, 2020).

B2.2.2 Assemble Land-based and Atmospheric Nutrient and Carbon Forcing

Data Sources. In the SCB, ROMS-BEC simulations at the 300-m resolution were forced with a 1997-2017 daily time series of spatially explicit freshwater flow, N, P, silica, and organic C representing natural and anthropogenic sources (Fig. 3, Sutula et al. 2021). These data have been compiled for: 1) POTW ocean outfalls, 2) riverine discharges, and 3) atmospheric CO_2 air-sea exchange.

POTW effluent data were compiled from permit monitoring databases and from literature sources (Table 13). Riverine runoff from the SCB 75 coastal confluences is from model simulations (Sengupta et al. 2013) and monitoring data. We note that the quality assurance practices with which these data were handled were derived from the Southern California Bight Regional Monitoring Program Coastal Water Quality Committee, which oversaw the assembly and synthesis of riverine and POTW ocean outfall loads during the Bight 2008 cycle (Howard et al. 2012). In subsequent iterations, which produced the Sutula et al. (2021) compilation and synthesis of data through 2017, the datasets were treated in a similar fashion, then reviewed by a stakeholder committee that include the four major POTWs and county stormwater agencies.

Direct atmospheric deposition, derived from the Community Multi-scale Air Quality model (Byun and Schere 2006), was included in the model in runs from 1997-2008, but thereafter removed from further simulations because it had a negligible effect on seawater chemistry (Howard et al. 2014, Kessouri et al. 2021b) and because of the focus on land-based nutrients.

Table 12. CCS ROMS-BEC Model Data Sources for Model Set Up and Oceanic Forcing. QA assessment categories Comparability (C), Representativeness (R), Completeness (T), Precision (P) and documentation (D) are explained in Table 6. Scoring consists of high pass (HP), adequate pass (AP), or fail (F).

Data Type	**Source and Purpose**	**QA Assessment**				
		C	R	P	T	D
Bathymetry						
4 km and 1 km resolution model bathymetry	30-second global SRTM30 bathymetry (Becker et al. 2008: *Marine Geodesy*)	HP	HP	HP	HP	HP
Oceanic forcing						
Initial and boundary data T, S, surface elevation, and horizontal velocity	Quarter-degree, daily averaged Mercator Glorys 2V3 product (http://www.myocean.eu), used in forcing of a 12-km ROMS model (1996-2010), which is then used to force 4 km model through successive downscaling (Mason et al. 2010). Then, boundary conditions from Mercator Glorys 2V3 (dx=7km) is applied on the 4km (2011-2017).	HP	HP	HP	HP	HP
Density distribution	World Ocean Atlas (WOA; Locarnini et al. 2013; Zweng et al. 2013), employed for correction of the Mercator data using the mean monthly climatology to provide an improved water mass density distribution of 4 km boundary.	HP	HP	AP	AP	HP
Atmospheric Forcing						
Atmospheric fields for physical forcing of ROMS	Regional Weather Research and Forecast model (WRF; version 3.6.1; Skamarock et al. 2008) that downscales meteorological fields from global reanalysis models. Used for dynamic and high-resolution atmospheric forcing of ROMS-BEC	HP	HP	HP	HP	HP
Biogeochemical Boundary Conditions						
Nutrients, organic matter, oxygen	Monthly climatological observations in the World Ocean Atlas (WOA) (García-Reyes et al. 2014). Used climatological fields for organic material and relationships with density for nutrients to correct at 4 km boundary derived from 12 km ROMS model or from Mercator Glorys 2V3.	AP	AP	AP	AP	HP
Fe	Global simulations with the Community Earth System Model (CESM), Mahowald et al., 2006.	AP	AP	AP	AP	AP
DIC and Alkalinity	GLODAP (Key et al. 2004), used to force time dependent DIC and alkalinity	AP	AP	AP	AP	HP
Air-sea gas exchange	Mauna Loa pCO2 extrapolated globally https://doi.org/10.3334/CDIAC/atg.035, used to force time-dependent atmospheric pCO2 is also used as surface boundary condition for air-sea gas exchange.	HP	AP	HP	HP	HP

Table 13. SCB model data sources for model set up and forcing. QA assessment categories QA assessment categories of Comparability (C), Representativeness (R), Completeness (T), Precision (P) and Documentation (D) are explained in Table 6. Scoring consists of high pass (HP), adequate pass (AP), or fail (F).

Data Type	**Source and Purpose**	**QA Assessment**				
		C	R	P	T	D
Model Set Up						
Bathymetry	SCCOOS 3 Arc-Second Coastal Relief Model Development (90-m horizontal resolution), used to set up 300 m model grid	HP	HP	HP	HP	HP
Oceanic forcing						
ROMS state variables	1 km ROMS-BEC model (Kessouri et al. 2020), used to force 300-m SCB ROMS-BEC	HP	HP	HP	HP	HP
Atmospheric Forcing						
Atmospheric fields for physical forcing of ROMS	WRF model; version 3.6.1; Skamarock et al. 2008) used as atmospheric forcing of 4 km ROMS-BEC	HP	HP	HP	HP	HP
Biogeochemical Oceanic Boundary Conditions						
All 60 BEC state variables	1 km ROMS-BEC model (Kessouri et al. 2020), used to force 300-m SCB ROMS-BEC	HP	HP	HP	HP	HP
Atmospheric Deposition						
NO3, NH4, SO4	Community Multiscale Air Quality Model (CMAQ), provided by USEPA Office of Air (Byun and Schere 2006))	HP	HP	AP	HP	HP
Land-based forcing						
POTW volume, nitrate+nitrite (NOx), ammonium (NH_4), phosphate (PO_4), temp. (T), pH, DO, turbidity	CIWQS Database and/or City of San Diego, City of LA, OC San, and LACSD-specific databases	HP	HP	HP	HP	HP
POTW outfall silicate (SIO_4), DOC or TOC, organic nitrogen (ON) and phosphorus (OP), alkalinity (Alk), iron (Fe)	CIWQS Database and/or agency specific databases, SCB Regional Monitoring Program 2008, engineering rules of thumb (described in Sutula et al. (2021))	AP	AP	HP	AP	HP
Mexican wastewater discharges and NO_X, NH4, PO_4, ON, OP, SIO_4, Alk, turbidity in Baja California Peninsula	Arreola-Serrano et al. (2022), https://doi.org/10.3389/frwa.2022.993713	HP	AP	AP	AP	AP
Measured US and Tijuana river flow	USGS, Department of Water Resources, County gauges	HP	HP	HP	HP	HP
Modeled US river flow	Ackerman and Schiff (2003), described in Sutula et al. (2021)	HP	AP	AP	AP	AP
Measured US river NO_X, NH4, PO_4, ON, OP, SIO_4, Alk, turbidity	California Environmental Data Exchange (CEDEN) database	HP	AP	HP	HP	HP
Measured Tijuana River NO_X, NH4, PO_4, ON, OP, SIO_4, Alk, turbidity	International Boundary and Water Commission United States and Mexico (2020)	HP	AP	HP	AP	HP
Modeled T, SIO_4, NO_X, NH_4, PO_4, ON and OP, Fe, Alk as unmonitored riverine constituents	Sutula et al. (2021)	HP	AP	HP	HP	HP

B2.3 Assembly and Quality Assurance of CCS and SCB Model Validation Data

This section describes the rationale for the compilation of data used to validate the ROMS-BEC model. Tables 14 and 15 summarizes the quality assurance review of those data for the CCS and SCB, respectively, using the scoring rubric described in Table 6. We direct readers to Deutsch et al. (2021) and Renault et al. (2021) for additional details on these data sources for the CCS model, and to Kessouri et al. (2021) for the SCB model.

B2.3.1 Assembly and Quality Assurance of CCS Model Validation Data Set

Data for Atmospheric and ROMS Validation. Satellite and *in situ* observations were used to evaluate the realism of both the atmospheric and oceanic simulations. Because of intermittent sampling with different instruments, we did not insist on exact time correspondences in computing climatological averages. To evaluate the performance of the atmospheric simulation in terms of cloud cover, we used remote sensing data retrieved from the Moderate-resolution Imaging Spectrometer level 2 data (MODIS; Platnick et al. (2003)). We use data from the Terra satellite, which is available twice daily around 10:30 am/pm local time, beginning in the year 2000. The Forcing for Coordinated Ocean-ice Reference Experiments (CORE; Large and Yeager 2009)) data set is used to evaluate the surface heat and freshwater fluxes. It provides monthly surface fluxes at a spatial resolution of 1◦. The monthly Global Precipitation Climatology Project (GPCP; Adler et al. (2003)) is also used to evaluate precipitation. It has a spatial resolution of 1◦. The surface stress data is from the Scatterometer Climatology of Ocean Winds (SCOW; Risien and Chelton (2008)) product based on the Quik SCAT satellite scatterometer. It provides monthly data at a 0.25◦resolution. To compute the wind-work, the surface stress daily product processed by the Centre ERSd Archivage et de Traitement (CERSAT; Bentamy and Fillon (2012)) is used. It provides daily surface stress at a spatial resolution of 25 km. SST forcing is derived from the Ostia daily product (Stark et al. 2007) that has a spatial resolution of 5 km.

We used data from CalCOFI (Bograd et al. 2003). Since 1950, hydrographic stations have been sampled on a geographically fixed grid. In this study, line 80 (off Pt. Conception; 34◦N) is used to estimate a seasonal climatology of temperature, salinity, and density, respectively, to validate the simulation from 1995 to 2010. The temperature, salinity, and density are further evaluated using the World Ocean Database 2013 (WOD13, Locarnini et al. (2013); Zweng et al. (2013)). Its fields have a resolution of 25 km and extend from the surface to the bottom of the ocean. The WOD13 dataset for that period includes the CalCOFI data and the Newport hydrographic line. The CSIRO (Commonwealth Scientific and Industrial Research Organization) Atlas of Regional Seas (CARS) climatology (Ridgway et al. 2002) provides an estimate of the monthly climatology of the Mixed Layer Depth (MLD) using a temperature threshold of $\Delta\Theta = 0.2$ ◦and $\Delta\sigma\theta = 0.03$ kg m^{-3}. Finally, the CNES-CLS13 dataset (Rio et al. 2014) is used to evaluate the simulated mean sea surface height and to estimate the geostrophic wind-work. It is a combination of GRACE satellite data, altimetry, and in situ measurements with a spatial resolution of 25 km in the analysis product. The Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) dataset, 25 km resolution, (Ducet et al. 2000) is used to evaluate the mesoscale activity simulated by USW4 and to estimate geostrophic wind-work.

Data for Biogeochemistry and Lower Ecosystem Validation. Hydrographic sampling have been conducted repeatedly along several sections off the West coast, most notably in the CalCOFI lines in the SCB, the Newport Line off Oregon, and Line P off British Columbia, the latter being at the northern edge of the 4 km model domain. These provide the best opportunity to test the tracer distributions predicted by the model. Similarly, model results validated in this way offer the only way to derive regional mass balances of important properties such as nutrients, oxygen, carbon, and acidity (pH) from data collected on major field campaigns like Bight 2008, 2013 and its predecessors led by SCCWRP, PMEL's coast-wide surveys, and repeat transects from the Newport Line off Oregon, the Trinidad Head line off Northern California, the MBARI line off Monterey Bay, and, the 60-year network of lines by CalCOFI. These data were compiled for use in the validation exercise. SCB Regional Monitoring Program's first regional survey of aragonite saturation state (McLaughlin et al. 2018) provided an important anchor in an anthropogenically impacted region. Also important is validation of biogeochemical processes key to quantifying effects of anthropogenic inputs on ocean chemistry. Towards that end, CalCOFI measurement of rate and SCCWRP studies on nitrification, primary productivity and respiration, and nitrogen uptake rates proximal and distal to POTW ocean discharges (McLaughlin et al. 2017) were used to validate model output on key biogeochemical rates.

A major compilation and synthesis of past data from NOAA/PMEL in the CCS was formatted and synthesized to facilitate their use by the modeling team. The cruise data sets for 2007, 2011, 2012, and 2013 include regional distributions of dissolved inorganic carbon, total alkalinity, pH, dissolved oxygen, nutrients (nitrate, phosphate and silicate), temperature and salinity for the Pacific West Coast. In addition, new data from the NOAA/PMEL-led 2016 cruise and mooring data in CCS coastal waters were also provided. These validations are critical for testing, detecting and attributing the trends that are observed in those data.

The total number of profiles in the World Ocean Database are plotted for NO_3 and O_2 over the entire historical data period (1955-2013). In addition to these climatological databases, we use specific repeat hydrographic lines in the SCB, off Monterey Bay, California and Newport, Oregon to evaluate the vertical and cross-shelf structure of biogeochemical variables at greater resolution. High frequency biogeochemical measurements from moorings are generally available only for more recent periods, and primarily from nearshore environments. We therefore focus our validation efforts on broad-scale measures that can be evaluated from climatological databases, namely the 2013 World Ocean Database (downloaded from https://www.nodc.noaa.gov/OC5/WOD13) and its mapped climatological representation, the World Ocean Atlas (WOA; García-Reyes et al. (2014)). Comparison to mooring data is left for planned downscaling of these simulations better suited to examine high-frequency variability (see notes on assessment of local anthropogenic impact and related "focused validation").

B2.3.2 Assemble SCB Model Validation Data Set

Ship-Based Ocean Monitoring. The SCB is home to a suite of long-running monitoring programs that make it one of the best observed coastal ecosystems in the world. Among them, the CalCOFI program (McClatchie et al. 2016), initiated in the 1950s, samples the SCB quarterly each year, collecting hydrographic and biogeochemical measurements in coordination with the SCCOOS. These observations are augmented nearshore by quarterly surveys of nearshore water column and benthic parameters conducted collaboratively since 1990 by POTW agencies as a part of their regulatory monitoring requirements (Booth et al. 2014; Howard et al. 2014; McLaughlin et al. 2018; Nezlin et al. 2018). We also use selected nutrient observations from the Santa Monica Bay Observatory (SMBO) mooring located in the Santa Monica Bay (Leinweber et al. 2009) and the San Pedro Oceanographic Time Series (SPOT) program. These programs provide good temporal and geographical coverage of both the offshore (CalCOFI) and nearshore (POTW) areas, coinciding with the model period, and include publicly available water quality data for targeted sites measured quarterly (Fig. 7). We validated model output against observed temperature, dissolved oxygen, nitrate, ammonium, chlorophyll, carbon system parameters (pH and aragonite saturation state), primary production, and nitrification (Kessouri et al. 2021b). The repository of data can be found in Kessouri, McLaughlin, et al. (2020).

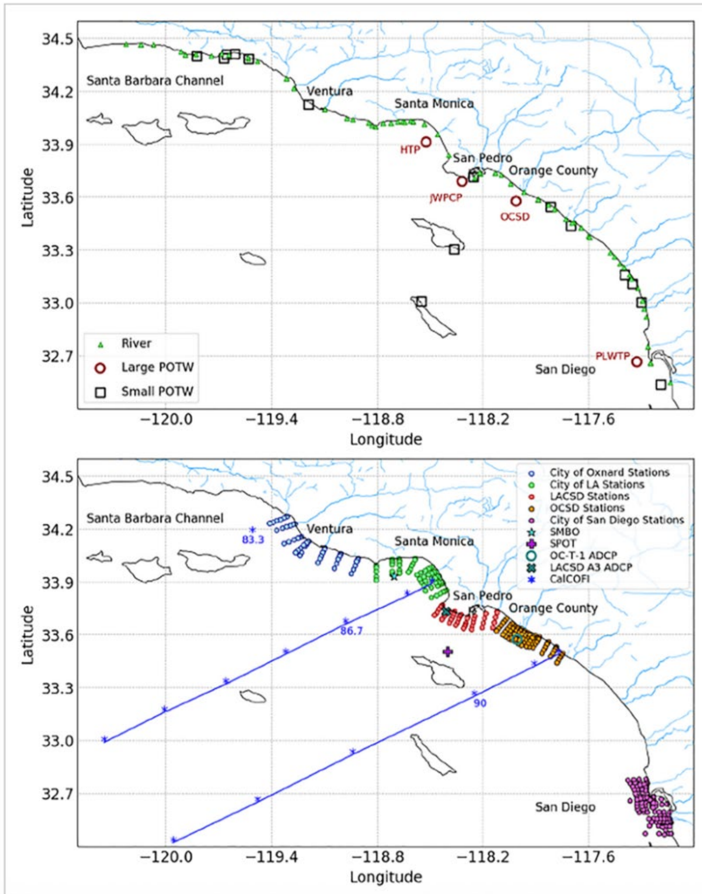

Figure. 7 From Kessouri et al. (2021b). Upper panel: Location of rivers and POTW outfalls along the Publicly Owned Treatment Plants (SCB). Lower panel: Location of stations used for validation, including POTW and CalCOFI quarterly monitoring surveys, SMBO, and SPOT data.

We note that the quality assurance practices with which these data are collected, curated and then utilized for this project differ somewhat, and merit mention of how they were further used in this project.

CalCOFI has a rigorous program of quality assurance. This includes internal data processing and correction, standard operating procedures, metadata management, and quality control reviews to confirm the data's reliability before it is being released to the public. Details on measurements, sample collection protocols, and quality assurance procedures for the CalCOFI program can be found on their website (https://calcofi.org; McClatchie et al. 2016). Similar procedures occur with the SMBO (https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0157016) and the SPOT data (https://dornsife.usc.edu/spot/).

POTW ocean monitoring data, collected by five public agencies, are collected under an approved DOCUMENT for the purposes of regulatory compliance. This group of agencies acknowledge that their individual quality assurance practices differ and that some data types (e.g. chlorophyll-a fluorescence) need additional curating for regional data syntheses of status and trends and other applications such as model validation. The Southern California Bight Regional Monitoring Program Coastal Water Quality Committee, the CTD Users Group, and other scientific working groups have performed this function in the past, and we significantly benefitted from their data products during the 1997-2000 initial model validation. Data sets have not yet been curated by the CTD Users Group for the 2013-2017 time period and thus some data types, discussed below), were not utilized as quality assurance problems were apparent (F. Kessouri, personal communication).

In situ measurements have inherent uncertainty, due to a combination of measurement sensitivity and sampling frequency and intensity, making them an imperfect "truth" with which to compare to model output. However, this uncertainty is not the same for all parameters. Both temperature and dissolved oxygen are collected using high-resolution probes, though the two programs used in this study incorporate slightly different calibration protocols for dissolved oxygen, overall, these data types have the highest confidence. Chlorophyll is measured on discrete bottle samples in the CalCOFI program, a high-quality measurement, but inferred from *in situ* fluorescence measurements in the POTW monitoring program, adding uncertainty to these measurements. The data are still useful to assess whether model captures gradients in chlorophyll-a, but not to assess absolute chlorophyll-a concentration. Nitrate and ammonium concentrations are measured on discrete bottle samples for both programs, but the detection limits are more sensitive in the CalCOFI program. Furthermore, nutrients are not measured with the same sampling density in POTW monitoring programs as sensor data.

High-Frequency (HF) Radar and Acoustic Doppler Current Profilers (ADCP). HF radar data from the SCCOOS database provide surface currents within the SCB. Seasonally averaged data from 2012 to 2020 were used to analyze trends of surface currents in the Bight compared to the model. Current data from ADCP was compiled from OC San (June 1999 to 2000) and Los Angeles County Sanitation District (LACSD; November 2000 to June 2007) to validate vertical profiles of currents.

Remote Sensing Observations. Satellite ocean color measurements for chlorophyll were used to characterize horizontal gradients at finer scales and higher density than possible with the ship-based monitoring. We use monthly averaged surface chlorophyll concentration from the period 1997 to 2000 derived from the SeaWiFS sensor at 4-km spatial resolution. Large gaps in the data set can occur because of dense cloud cover that occurs in late spring and early summer. The products of the Vertically Generalized Production Model (VGPM) net primary production algorithm (Behrenfeld & Falkowski 1997) were also considered for this validation. Despite limitations, satellite data provide a valuable representation of the spatial distribution of chlorophyll, temperature, and primary production at seasonal scales over the region.

Table 14. CCS WRF and ROMS-BEC Model Data Sources for Validation. QA assessment categories of Comparability (C), Representativeness (R), Completeness (T), Precision (P) and Documentation (D) are explained in Table 6. Scoring consists of high pass (HP), adequate pass (AP), or fail (F). for detailed discussion, see Renault et al. (2021) and Deutsch et al. (2021).

Data Type	Source	QA Assessment				
		C	R	P	T	D
Cloud cover	MODIS Terra satellite (Platnick et al. 2003)	HP	HP	AP	HP	HP
Surface heat and freshwater fluxes	CORE; Large and Yeager (2009)	HP	HP	AP	HP	HP
Precipitation	GCPC (Adler et al. 2003)	HP	HP	AP	HP	HP
Surface stress; wind-work	SCOW (Risien and Chelton 2008) processed by CERSAT (Bentamy and Fillon 2012)	HP	HP	AP	HP	HP
Sea surface temperature forcing	Ostia daily product (Stark et al. 2007)	HP	HP	AP	HP	HP
Seasonal climatology of temperature, salinity and density	CalCOFI (e.g., Bograd et al. 2003)	HP	HP	AP	HP	HP
	World Ocean Database (WOD13, Locarnini et al. (2013); Zweng et al. (2013)	HP	HP	AP	HP	HP
Mixed layer depth	CSIRO CARS Climatology Mixed Layer Depth	HP	HP	AP	HP	HP
Mean sea surface height	CNES-CLS13 dataset (Rio et al. 2014)	HP	HP	AP	HP	HP
Mesoscale activity and geostrophic wind-work	AVISO dataset (Ducet et al. 2000)	HP	HP	AP	HP	HP
Nutrients (NO_3, PO_4, SIO_4), Fe, O_2, Chlorophyll-a, Net Primary Production (NPP)	CalCOFI (e.g., Bograd et al. 2003)	HP	HP	AP	HP	HP
Nutrients (NO_3, PO_4, SIO_4), Fe, O_2	WOD13 and WOA (García-Reyes et al. 2014)	HP	AP	AP	HP	HP
Nutrients (NO_3, PO_4, SIO_4), Fe, O_2	Newport Hydrographic Line	HP	AP	AP	HP	HP
Chlorophyll-a, NPP	SeaWiFS remote sensing level 3 product (REF), NPP predicted using both vertically generalized production model (VGPM; Behrenfeld and Falkowski 1997) and the carbon-based productivity model (CbPM) 279 (Westberry et al. 2008)	HP	AP	AP	HP	HP
Fraction of NNP exported as sinking particles; export flux	Empirically derived algorithm based on Chl and SST (Dunne et al. 2005)	AP	AP	AP	HP	HP
Surface pCO_2 and associated air-sea fluxes	SOCATv6 database from 1995-2010 (Bakker et al. 2016)	HP	HP	AP	HP	HP
Aragonite saturation state, alkalinity and DIC	GLODAP2 (Lauvset et al. 2016)	HP	AP	AP	HP	HP
	NOAA PMEL coastal surveys Feely et al. (2008).	HP	AP	AP	HP	HP

Table 15. SCB model data sources for model validation. QA assessment categories of Comparability (C), Representativeness (R), Completeness (T), Precision (P) and Documentation (D) are explained in Table 12. Scoring consists of high pass (HP), adequate pass (AP), or fail (F). For detailed discussion, see Kessouri et al. (2021a). POTW monitoring surveys are collected by City of Oxnard, City of Los Angeles, LA County Sanitation District, OC San, City of San Diego.

Data Type	Source and Purpose	QA Assessment				
		C	R	P	T	D
Surface currents	High frequency Radar (hfrnet-tds.ucsd.edu/thredds/catalog.html)	HP	AP	AP	HP	HP
Vertical current profiles	Acoustic doppler current profilers, OCSan and LACSD	AP	AP	HP	HP	AP
Chlorophyll-a, NPP, Deep chlorophyll-a maximum	SeaWiFS using both VGPM (Behrenfeld and Falkowski 1997)	HP	AP	AP	HP	HP
Nutrients (NO_3, PO_4, SIO_4, NH_4), Fe, O_2, Chlorophyll-a, NPP, temperature, salinity, pH, aragonite saturation state	CalCOFI (e.g., McClatchie et al. 2016)	AP	HP	HP	HP	HP
O_2, temperature, salinity,	POTW Quarterly monitoring surveys, collected by the City of Oxnard, City of Los Angeles, LA County Sanitation District, OC San, City of San Diego	HP	HP	AP	HP	HP
Ammonium[2]		HP	AP	AP	AP	HP
Chlorophyll-a[1], potentiometric pH[1]		AP	HP	HP	AP	HP
NPP, Nitrification rates, bottle pH and alkalinity	Bight 13 Regional Monitoring Program Study (McLaughlin et al. 2017)	HP	AP	HP	HP	HP
Aragonite saturation state, alkalinity and DIC	NOAA PMEL coastal surveys (Feely et al. (2008, etc.)	AP	HP	AP	HP	HP
Chlorophyll-a, conductivity, temperature	Santa Monica Bay Observatory (SMBO; Leinweiber et al. 2009)	HP	HP	HP	HP	HP
CDOM, chlorophyll-a, PAR, temperature, salinity, O_2, nitrate, nitrite, phosphate, silicate	San Pedro Ocean Time series (SPOT) station	AP	AP	AP	AP	HP
Nitrification	Literature sources (Ward 1982 and 1987, Santoro et al. 2010)	HP	AP	AP	HP	AP
Nitrate and ammonium uptake rates	Bight 13 Regional Monitoring Program Study (McLaughlin et al. 2017)	HP	AP	AP	AP	AP
Phytoplankton growth rate and zooplankton grazing	Literature sources (Landry et al. 2009)	HP	AP	AP	AP	HP

[2] As noted in the text, CTD Users Group curated data products used for the 1997-2000 model skill assessment (Kessouri et al. 2021b). Data sets have not yet been curated by the CTD Users Group for the 2013-2017 time period and thus some data types, discussed below), were not utilized as quality assurance problems were apparent (F. Kessouri, personal communication; Kessouri et al. 2024).

B2.4 Assembly and Quality Assurance of Data for Biological Tool Development

This section presents the background and justification for methods to interpret the effects of eutrophication on OAH-related impacts to habitat capacity for pelagic organisms and on the risk of domoic acid (DA) events.

The methods related to OAH related impacts to habitat capacity were the products of multiple collaborative projects. See references and detailed methods described therein.

- OPC OA Assessment Framework
- NOAA Coastal Hypoxia
- Oregon DEQ Scientific Working Group

Section B2.4.1 and B2.4.2 describes the rationale for thresholds used; Table 16 summarizes the quality assurance review of those data for the SCB with the scoring criteria described in Section 3.1.

Table 16 Summary of literature sources considered to guide selection of thresholds used to interpret model output. Scoring consists of high pass (HP) and adequate pass (AP).

Biological Threshold Type	Source and Purpose	QA Assessment		
		Amount of Evidence	Quality of Evidence	Applic -ability
OA Threshold	Bednaršek et al. 2019, pteropods			
	Mild and severe dissolution	HP	HP	AP
	Calcification	AP	AP	AP
	Growth	AP	AP	AP
	Survival	AP	AP	AP
	Bednaršek et al. 2021b, echinoderms			
	Larval growth and development	HP	AP	AP
	Adult physiological effects, respiration	AP	AP	AP
	Bednaršek et al. 2021a, decapods			
	Hemolymph pH	HP	AP	AP
	Adult survival	HP	AP	AP
	Respiration	AP	AP	AP
	Larval survival	AP	AP	AP
	Feeding rate	AP	AP	AP
	Hatching success	AP	AP	AP
Metabolic index	Deutsch et al. 2020, metabolic scope defines limits that impact marine biodiversity	HP	HP	HP
	Howard et al. 2020, northern Anchovy	HP	HP	HP
Chl-a Threshold	Sandoval-Belmar et al. (2023) Risk of toxic PN HABs	AP	HP	HP
	Smith et al. (2023), DA threshold associated with increased risk of marine mammal stranding event	AP	AP	HP

B2.4.1 Biologically Relevant OA Thresholds and O_2 Indices

To assess whether modeled effects of anthropogenic nutrient inputs on Bight-wide subsurface oxygen loss and acidification are biologically relevant, we employed two metrics for habitat capacity, which we adapted for this purpose. One that incorporates temperature-dependent environmental oxygen as a predictor to habitat capacity and the other incorporates carbonate chemistry. We rely on the premise that these metrics provide information on the capacity of a specified location for a species, or group of species, based on either empirical or mechanistic relationships of organismal performance with the environmental condition(s) of interest. The habitat capacity metrics are applied to model outputs from scenarios with and without anthropogenic nutrient inputs in order to perform a change assessment. The metric is presented as the vertical thickness of water-column that is "suitable" given that spatial gradients in both oxygen and carbonate chemistry are greatest in the vertical dimension. These methods, detailed in Frieder et al. (2024), are summarized here.

Since modeled effects of subsurface oxygen loss and acidification due to anthropogenic nutrient inputs are shown to be localized between ~ 50 m and extend down to ~200 m (Kessouri et al. 2024), we focus our analysis on pelagic taxa. Because literature is limited on the interactive effects of oxygen and carbonate chemistry in these environments, we adapt two separate metrics to evaluate the changes in oxygen versus the changes in carbonate chemistry with an emphasis on aerobic taxa and calcifiers, accordingly.

Acidification Thresholds. For the effects of subsurface acidification on calcifier habitat capacity, we calculate the vertical thickness of optimal aragonite saturation state (Ω_{Ar}) conditions. A value of Ω_{Ar} of 1.4 is used to define the condition below which sublethal organismal responses have been documented to commonly occur (Bednaršek et al. 2019, 2021a,b). One of the primary lines of evidence for this choice is derived from a synthesis of documented effects on pteropods (Bednaršek et al. 2019), in which Ω_{Ar} thresholds for a range of sublethal to lethal responses were identified and confidence in thresholds were judged with expert consensus. Pteropods are ubiquitous, holoplanktonic calcifiers that have a well-documented, specific sensitivity to OA. These calcifiers efficiently transfer energy from phytoplankton to higher trophic levels (Lalli and Gilmer 1989; Hunt et al. 2008), and as such serve as an important prey group for ecologically and economically important fishes, bird, and whale diets (Armstrong et al. 2005; Aydin et al. 2005; Karpenko et al. 2007). Bednaršek et al. (2019) identified that Ω_{Ar} from 1.5 – 0.9 provides a risk range from mild dissolution to lethal impacts. Our selected value of Ω_{Ar} of 1.4 represents a value within observational analytical precision (± 0.2; McLaughlin et al. 2013) of thresholds where sublethal effects on calcification, growth, and severe dissolution are documented to occur (Bednaršek et al. 2019), while a value of 1.0 roughly equates to lethal effects (0.9 to 0.95; Bednaršek et al. 2019). In the epipelagic (0-200 m), conditions below saturation have not been common since the pre-industrial times to the present day but are predicted to become increasingly present as soon as the 2030s and 2040s (Hauri et al. 2013). Importantly, we perform an analysis of the sensitivity of our findings to the choice of Ω_{Ar} along this range of 1.0 to 1.4.

Aerobic Habitat. For the effects of subsurface O_2 loss on aerobic habitat capacity, we calculate the vertical thickness of the water column that has sufficient O_2 to provide ecological support for northern anchovy (*Engraulis mordax*). *E. mordax* is also holoplanktonic with greatest abundance observed in the upper 100 m (Mais 1974). Defining sufficient O_2 for ecological support relies on the mechanistic framework of the Metabolic Index (Φ; Deutsch et al. 2015, 2020). Φ is defined as the ratio of O_2 supply to resting demand. We can calculate the habitat thickness for which $\Phi/\Phi_{CRIT} \geq 1$, a value below which demarcates environment in which northern anchovy can sustain resting but not active energetic demands, thus limiting population persistence. For northern anchovy, metabolic traits have been inferred from observational datasets associated with climatological O_2 and temperature conditions (Howard et al. 2020). Among CCS species, the metabolic traits of the northern anchovy represent a median sensitivity of epipelagic fish (Deutsch et al. 2020). While we use metabolic traits for northern anchovy as our primary analysis, we consider how modeled O_2 loss across a range of conditions interacts with known metabolic traits for other species found in the region, a parallel sensitivity analysis with that of OA (see Analytical Approach for further details). Similarly, we evaluate a lethal threshold, where $\Phi < 1$ and oxygen supply is insufficient to meet oxygen demand. For northern anchovy, this calculation assumes a ratio of active to resting metabolic rates of $\Phi_{CRIT} = 3.5$ (Howard et al. 2020).

B2.4.2 Chl-a Thresholds: Effects of Increased Primary Productivity on Window of Opportunity for Toxic HABs

Blooms of *Pseudo-nitzschia* (PN), a toxigenic marine diatom genus, can produce the neurotoxin domoic acid (DA) that cause annual shellfishery closures and wildlife illnesses and deaths within SCB. Mechanisms that control the frequency and severity of PN blooms and associated toxic domoic acid events can be parsed into three fundamental components: 1) environmental drivers controlling the niche for diatom blooms, 2) drivers of the species-specific PN blooms vis-à-vis interactions within the larger plankton community and 3) controls of the magnitude of toxin production during a PN bloom event.

The basic premise of alteration of window of opportunity of DA-producing PN blooms is predicated on the concept that factors that increase diatom productivity have the potential to elevate the biomass of DA-producing PN strains. Thus, if natural or anthropogenic factors increase the biomass of diatoms, then that widens the window of opportunity for DA-producing diatoms as well.

In synthesis of CCS HAB observations, Sandoval-Belmar et al. (2023) found that detection of DA in the water column was strongly and consistently correlated with increased chlorophyll-a across studies of CCS. This result is not surprising given that primary productivity is dominated by diatoms (Durski et al. 2017, Sandoval-Belmar et al. 2023). They derived a threshold from these observational data as a function of increasing chl-a. A threshold was chosen at the point in which the risk detecting DA exceeded 50% above a baseline probability of 30%. The thresholds ranged from > 1.8 mg Chl-a m^{-3} for the Santa Barbara Channel and > 3.3 mg Chl-a m^{-3} for the Central Bight to > 5.4 for Monterey Bay (Sandoval-Belmar et al. 2023). We chose to use 3.3 mg Chl-a m^{-3}, because the focus of the anthropogenic assessment is on the heightened productivity inshore in the Central and Southern Bight. Note that the DA hotspot subregions selected for this study may not be representative of the larger SCB region, so there is an assumption made with this approach to apply across a larger region. The assessment of this approach is limited due to low availability of monitoring data for DA events across the Bight. Smith et al. (2023) found that concentrations of DA at the detection limit were associated with an accelerated risk in a "significant marine mammal stranding event," defined as the stranding of 2 or more adult sea lions. We used this risk-based framework to identify the spatial footprint, number of days, and the magnitude of exceedance of the natural oceanic versus anthropogenic nutrient inputs above this chl-a threshold.

B2.5 Assembly and Quality Assurance of Data Guiding Task 9 Scenarios

As described in Ho et al. (2023), the scenarios commissioned by OPC and State Water Board to investigate the potential efficacy of reducing POTW outfall nitrogen, with and without the effect of potable water recycling, involved an experimental simulation of the final effluent quality when the reduction of volume from potable water recycling occurred. These scenarios represent a bracket of effects that range from current day land-based loading (ANTH) to a combination of nitrogen reduction and outfall discharge recycling scenarios (Scenario 1-6).

This section describes the approach, the underlying data and quality assurance practices used to determine the experimental final effluent concentrations. Table 17 summarizes the quality assurance review of those data for the purposes of developing an experimental design, the criteria for which are given in Section 3.1

Four of the six scenarios represent experimental treatments in which a portion ranging from 50% to 90% of the volume of the effluent currently being discharged to the outfall is recycled for potable reuse (see Table 1 in Ho et al. 2023). In these scenarios, the final effluent outfall volume and constituent concentration was calculated for each individual outfall by a set of assumptions that governed the efficiency of water treatment and water recovery that were applied uniformly across all outfalls. Two assumptions were informed by literature sources and current operating parameters at an existing potable water recycling program in the region (Table 18).

- Water recovery efficiency of potable water recycling is 80%, meaning 20% of any given outfall volume that is diverted from the outfall for water treatment would return to the outfall after treatment (Markus and Deshmukh 2010, Zhou et al. 2011, Subramani et al. 2014). A target of 50% recycled means that 40% of the total outfall volume is reduced, with 10% of the volume not recycled and returned to the outfall.

- Concentrate added to return volume is derived from reverse osmosis permeate concentration, which is a function of membrane recovery efficiency. Recovery efficiencies were established based on polyamide recovery efficiencies in published literature (Bódalo-Santoyo et al. 2003; Qin et al. 2005; López-Ramirez et al. 2006; Crittenden et al. 2012). Specific recovery efficiency varied by effluent constituent as follows: 85% removal of NO and NO, 95% removal of ammonium, phosphate, alkalinity, and silicate, 97% removal of organic carbon, organic nitrogen, and organic P, and 100% removal of salt and dissolved iron. High removal efficiencies of DIN forms resulted in the nitrogen loading staying roughly the same across the tier of 50% (scenarios 1-3) or 85% DIN reduction scenarios (scenarios 4-6), while volumes declined and DIN concentrations in the final effluent increased.

Table 17. Summary of data used to inform nominal decisions on water recovery efficiency and constituent-specific membrane efficiency recovery. AP = adequate pass.

Decision	**Source and Rationale**	**QA Assessment**	
		Amount of Evidence	Quality of Evidence
Water recovery efficiency	Nominal decision to put water recovery efficiency at 80%	AP	AP
	Range of literature values (Zhou et al. 2011 and Subramani et al. 2014, Markus and Deshmukh 2010)		
	Expert elicitation (Michael Stenstrom, UCLA Dept. Civil and Environmental Engineering)		
Membrane efficiency recovery	Nominal decision to establish constituent specific recovery values, which impacts the final reverse osmosis permeate concentrate	AP	AP
	Range of literature values (Bódalo-Santoyo et al. 2003, Qin et al. 2005, Lopez-Ramirez et al. 2006, Crittenden et al. 2012)		

B3. Integrity of Environmental Information

The project team works to ensure the integrity, traceability, and scientific defensibility of all model-derived environmental information is essential to meet project objectives and maintain compliance with SCCWRP and UCLA quality standards. The team put in place procedures to ensure that the environmental information was protected from loss, corruption, or inappropriate alteration throughout the modeling workflow.

B3.1 Sources and Handling of Environmental Input Data

All observational datasets used to force, initialize, or evaluate the ROMS-BEC model are subject to the data integrity controls defined in Section B2. Input datasets are stored in read-only master directories with metadata files describing data origin (provider, instrument/platform, date range), pre-processing steps (interpolation, gap filling, quality flags), spatial and temporal resolutions, transformations applied to make data compatible with ROMS-BEC.

B3.2 Model Configuration Integrity

To preserve integrity, model configuration files, including grid files, boundary forcing scripts, and pre-/post-processing codes, are tagged by scenario and run ID. Default and experimental configurations are stored separately. This ensured model outputs remained reproducible and traceable to specific configuration states.

B3.3 Model Execution and Run Management

Each model simulation is assigned a run identifier that links all associated files, including input datasets, the configuration, the boundary/initial condition files, and output files.

The computing environment (compiler versions, libraries, hardware configuration) is recorded to support reproducibility.

B3.4 Output Data Integrity and Archival

ROMS-BEC output files (NetCDF) are stored using controlled directory structures at the time of file creation. Integrity controls included automatic flagging of incomplete output files, and redundant storage on secure UCLA servers with routine backup schedules.

Post-processing scripts that derive environmental metrics on SCCWRP and UCLA local servers followed the same integrity protections.

B3.5 Protection Against Unauthorized Modification

All project directories containing model configurations, input datasets, and final outputs are assigned controlled access privileges. Only authorized modeling team members had write permissions.

B3.6 Documentation and Traceability

Integrity of environmental information was supported through traceability. For each modeling product delivered, accompanying documentation included the run identifying information and associated configuration summary, the list of all input datasets and their versions, the description of any pre- or post-processing steps, quality flags. This was intended to ensure that all information derived from ROMS-BEC was transparent, defensible, and replicable.

B4. Quality Control (QC)

QC procedures for this project ensure that all inputs, model configurations, computational workflows, and outputs of **ROMS-BEC met** required performance, reproducibility, and scientific integrity standards. QC activities focus on the full modeling chain—from acquisition of observational data used for forcing and validation, through model setup and execution, to evaluation of simulation results.

B4.1 QC of Input Data

All observational data used to drive the model are reviewed for completeness, consistency, and scientific validity prior to incorporation into the model. Data are checked for gaps, irregular timestamps, or formatting inconsistencies. Data are inspected to ensure they fall within physiologically and oceanographically reasonable ranges for the study region. When multiple sources provide overlapping data, cross-comparisons are performed to identify offsets or discrepancies that may indicate sensor issues or processing errors. Metadata for each dataset, including units, coordinate systems, vertical datums, and calibration information, are reviewed to ensure compatibility with model requirements.

Gridded atmospheric or oceanographic datasets used for boundary forcing such as WRF underwent QC to verify that their spatial resolution, temporal frequency, and grid structure are inspected visually to identify artifacts such as missing tiles, abrupt discontinuities, or unrealistic patterns. Interpolation methods used to convert any fields onto the ROMS grid are checked for smoothness and temporal continuity to avoid artificial jumps in energy or tracer fields at the boundaries.

B4.2 QC of Model Configuration

The ROMS grid and bathymetry are corrected using automated tools, then visually reviewed to ensure that the model domain is constructed correctly and minimizes numerical errors. Grid metrics are checked to confirm that they fall within recommended thresholds. Land–sea masks and coastline representations are inspected to ensure that no isolated or unintended land mask remain in the domain and that the physical geography aligns with project specifications.

Model parameterizations and settings are logged to preserve reproducibility. This process ensures that each model run is traceable and consistent with the technical design of the project.

B4.3 QC of Numerical Implementation and Model Execution

Before full simulations are conducted, spin-up tests are executed to evaluate model stability and identify potential numerical issues. These tests allowed the team to confirm that boundary conditions behave as expected and that no unphysical trends emerge during the early stages of a run. During full simulations, the model are monitored for signs of instability.

After each simulation, QC checks verify that all expected outputs are produced and that the NetCDF files are complete and uncorrupted. The temporal coverage of each file is confirmed against the intended simulation period, and a preliminary visual review is performed to identify anomalies such as unrealistic currents, temperature and biogeochemical fields, or sea surface height patterns. These initial assessments help determine whether a simulation is suitable for full validation or requires rerunning.

B4.4 QC of Model Output and Validation

Model outputs underwent expert review to ensure they represented realistic ocean dynamics. Time-averaged and climatological comparisons are used to identify deviations from historical norms. For validation, simulated fields are compared directly with in situ observations. Metrics including bias, root-mean-square error, correlation coefficients, and skill scores are calculated to quantify model performance.

Spatial comparisons with satellite observations, including sea surface temperature, sea surface height, and ocean color, provided additional context on model skill. These comparisons helped to confirm whether the model captures large-scale circulation patterns, coastal upwelling, eddy formation, and vertical stratification. When issues are detected, further sensitivity tests or refinements are conducted to improve model performance.

B4.5 Documentation and Archiving

Forcing data, configuration files, and model outputs are archived with detailed metadata describing their origin, processing steps, and QC status. In the future, a written QC summary will be prepared for each major simulation, documenting the results of all checks and noting any issues or deviations from expected behavior. This documentation ensures transparency, reproducibility, and long-term accessibility of all modeling products generated by the project.

B5. Instrument/Equipment Calibration, Testing, Inspection and Maintenance

This section covers the how the tools involved in environmental data acquisition or generation are tested, inspected and maintained. For this project, documentation of the model code and model calibration are detailed.

B5.1. Maintenance of Model Code

Maintaining the ROMS modeling system requires coordinated effort among scientific leads and project staff. In Phase I, specific responsibilities are assigned for code development, testing, documentation, and repository administration.

The UCLA ROMS- BEC modeling system is maintained through a structured framework that ensures long-term stability, reproducibility, and transparency, in collaboration with the ROMS global user community. The ROMS-BEC source code, configuration files, and scripts are stored currently as Version 1. To support reproducibility and long-term project continuity, archival copies of the model code, configuration files, input datasets, and compiled executables are maintained in institutional storage.

Model builds rely on a standardized compilation environment that defines required libraries, compiler settings, and platform configurations.

Documentation was maintained within the repository, including inline code comments and configuration notes, to support onboarding and long-term maintainability.

B5.2 Model Calibration

All models are a simplification of the phenomena they represent. When formulating the mathematical expressions of these processes, empirical relationships and parameters need to be defined. The estimation of parameters involved in formulating these mathematical expressions is called calibration, which is performed in the model development phase.

Model calibration is accomplished through an adjustment of model coefficients (weight of evidence approach) because many interrelated factors can influence model output. The experience and judgment of the modeler is a major factor to both accurately and efficiently verify model performance. Although this method balances model comparison to data with the modeler's understanding of the physical, chemical and biological characteristics of the system it does not provide a quantitative measure of the "goodness of fit."

The original BEC model, adapted for the CCS, is a three-dimensional (3-D) model developed by Moore et al. (2004). This BEC model has been used to investigate global, oceanic basin-scale patterns of biomass, productivity, community structure, carbon export and oxygen cycling as well as the sensitivities of those patterns to changes in external forcing (e.g., atmospheric dust/iron deposition). The original BEC model already accounted for large scale global gradients in forcing and was based on an extensive review of primary literature of observations and earlier modeling work. The Deutsch et al. (2021) approach to adapting the BEC model took the view that the primary parameterization of BEC was mechanistically well-founded and thus changes were made to the original BEC parameterization only when completely necessary and in accordance with these same principles (Deutsch et al. 2021, C. Deutsch, personal communication).

Given these principles, the CCS implementation of the BEC model and its calibration followed two core principles: 1) an initial comparison of model solutions versus observational data as a "goodness of fit" measure and 2) sensitivity analyses to understand changes in parameterization impact the outputs of modeled state variables and how those alterations impacted data-model goodness of fit. This was an iterative process that was conducted at the 5 km scale. This process happened before the project began (circa 2013) and records of this work were not maintained.

When the ROMS-BEC model was downscaled for the SCB, test and verification were repeated. Particular attention was paid to the forcing of land-based inputs to assure appropriate representation of this important input. No additional calibration was deemed necessary because validation performance criteria (A7.2.1 and A7.2.2) were met or exceeded over both periods (1997-2000 then 2013-2017); minor performance issues were corrected once land-based forcing data were improved.

B6. Inspection/Acceptance of Supplies and Services

Inspection and acceptance activities for the project focused on verifying that all datasets, model components, and technical deliverables meet predefined quality criteria prior to their use or incorporation into the project workflow. Acceptance procedures included the following:

- **Input Data Verification:** All input datasets (e.g., environmental monitoring data, forcing data, boundary/initial conditions, GIS layers) will be inspected for completeness, correct formatting, metadata sufficiency, and consistency with project requirements. Data will be reviewed for reasonableness, expected ranges, units, and absence of obvious anomalies. Only datasets that met the project's Data Quality Objectives (DQOs) and acceptance criteria are approved for use.

- **Model Code and Configuration Review:** Supplied model code, scripts, configuration files, and parameter sets will be checked to ensure they are complete, documented, and compatible with the modeling framework. Any developed modules and code are inspected for functionality, documentation quality, and adherence to project specifications prior to acceptance.

- **Model Calibration and Validation Products:** Model performance analyses, statistics, and diagnostic plots are reviewed by the project principal investigators to ensure they met target performance thresholds established in the document. Deliverables that did not meet performance expectations are returned for revision.

- **Interim Technical Deliverables:** Interim modeling results, summary reports, figures, and analysis products provided by project staff underwent internal review for clarity, accuracy, and conformance with analytical methods described in this DOCUMENT. Review comments are addressed before acceptance.

- **Final Deliverable Acceptance:** Final model outputs, documentation, and reports will be evaluated against project requirements, including completeness, reproducibility, transparency of assumptions, and appropriate use of methods. The Project Manager and Technical Lead will provide final approval.

- **Non-Conformance Resolution:** If any data, model components, or deliverables failed to meet acceptance criteria, corrective actions are be documented. Revised materials underwent re-inspection prior to acceptance.

B7. Environmental Information Management

This section describes how data are managed, including descriptions of the configurations of hardware and software.

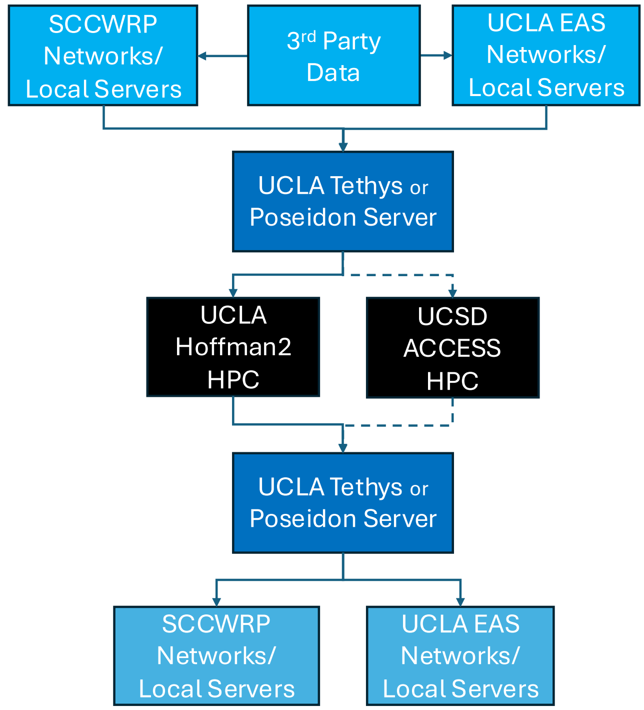

Figure 8. Visualization of UCLA and SCCWRP joint data management process for the Phase I and Phase II work

B7.1 Data Management

Our data management plan consists of three distinct stages or components: 1) SCCWRP and/or UCLA Department of Earth and Atmospheric Sciences internal databases, 2) UCLA Tethys server, which is the server in which all model forcing and raw and post-processed model outputs are stored, and 3) high performance computing centers (HPC, a.k.a. supercomputers), where the model code, model domain and forcing are configured and the simulations are run and temporarily stored.

Fig. 8 describes the flow of data used in the modeling process. At the top row of this figure, existing data consisting of model forcing, model set up, or other raw data sources are housed on UCLA EAS and SCCWRP networks or local servers (as described in A9) or acquired from third party data sources. See B7.2 and B7.3 for specific details of the types of existing data that are utilized.

These data are then pulled into the UCLA Tethys and/or Poseidon servers, where they are formatted to be used for model setup or forcing as appropriate.

At the UCLA Institute for Digital Research and Education, computing center staff operate the Hoffman2, a HPC cluster. These files are stored locally on dedicated “nodes” which have been purchased specifically for ROMS-BEC programmatic use, with Daniele Bianchi as the designated faculty sponsor. Each node purchase includes technical support, full access to the purchased nodes through the cluster’s queuing system, preferred node access for research group members, and connection to the cluster’s InfiniBand fabric. Nodes have been contributed to the cluster in preferential mode, so that they are only available to the purchaser and their research team.

The UCLA Tethys and/or Poseidon servers were also purchased by the science team to store data and model outputs. Bundled with the UCLA cost of the storage includes: 1) routine backups, 2) physical storage space, 3) infrastructure to support it, 4) administration of the users of your storage space, 5) hardware and software upgrades and 6) problem fixes.

Once the model has been executed, its outputs are temporarily stored in the Hoffman2 servers. Output files are generated in parallel chunks. Subsequently, these outputs are transferred to the UCLA Bianchi's storage system using the *rsync* utility, where they undergo necessary preparations to facilitate analysis within the same UCLA Tethys system. These preparations include joining together the individual chunks of each daily file, renaming these files to be more easily identified and accessed, computing monthly averaged output files, and compressing all output files to conserve storage space. All post-processing data management is performed by a set of python scripts which generate detailed logs to facilitate any error detection and handling. Finally, analysis and visualization are conducted in MATLAB or R on a combination of UCLA servers and SCCWRP cloud SharePoint system as necessary.

That same SCCWRP cloud SharePoint system houses project files, reports and other products that jointly constitute the "data" generated by this project (See Section A9 for more details).

Occasionally, the science team has had allocations from the University of California at San Diego (UCSD) ACCESS supercomputer. When this occurs, the data flow and processing steps are very similar to that used with the UCLA Hoffman2, with UCLA Tethys and/or Poseidon used to stage the model forcing data, then the ACCESS HPC cluster is used to run the model, temporarily store the data, until it is pulled down into UCLA Tethys or Poseidon server again.

Hardware and software configuration used to perform data management is detailed in B10.2.

B7.2 Hardware/Software Configuration

Table 19 summarizes the shared UCLA and SCCWRP hardware and software used in basic data management and analyses required for this project.

Table 19. Summary of UCLA and SCCWRP shared hardware and software used in basic data management and analyses and computing. Section B10.1 details the specific flow of data for which these hardware and software are required.

Detailed Specifications for Hardware and Software
High performance computing HPC Cluster: 27 nodes (for a total of 948 cores) on UCLA's Hoffman2-HPCS cluster, managed by UCLA's Institute for Digital Research and Education. Eleven nodes feature 2x12-core Intel Xeon E5-2650v4 CPUs; 7 nodes feature 2x18-core Intel Skylake Gold 6140 CPUs; 9 nodes 2x24-core Intel Xeon Gold 6342.
Long-term Storage The group maintains three Linux servers (32, 48, and 128 cores), installed at UCLA with shared access to ~1.5 PB of storage, used for analysis, diagnostics, and long-term archiving, named "Tethys" and "Poseidon." Both Tethys and Poseidon are accessible remotely via VPN and SSH.
Data Management and Analysis Software MATLAB R2019b/R2023b – data processing, data analysis, and visualization Ncview 2.1.2 – visualization during analysis code development NCO netCDF Operators 4.7.5 – data processing Python 3.11.4 – data processing and management R 4.5.1 – data analysis and visualization rsync 3.1.2 – data transfer between servers
Reporting and Communications Software Microsoft 365 (Word, Excel, PowerPoint, etc.) Google suite Overleaf publication preparation software Slack- science team internal communications (UCLA and UCLA affiliates F. Kessouri and M. Ho only) MS Teams -SCCWRP science team communications

C. Assessment and Oversight

Group C focuses on interim assessments conducted iteratively throughout both the model development and application processes to ensure that pre-determined modeling criteria are being achieved as the model is being developed or implemented

C1. Assessments & Response Actions

C1.1 Assessment and Response During Phase I Model Development

Model assessment and response consisted of an intensive process of internal checks and review by the mode development leadership team. At UCLA, throughout Phase I, this was accomplished: 1) through the primary modeler developer's focused effort, and 2) through a process of internal peer review, discussion, and suggestions for targeted analyses that occurred on a weekly to biweekly basis over the course of six years in which the primary model development, testing, verification, calibration and validation took place. This was an intensive process, understanding the weight and the potential economic outcomes of the scientific questions intended to address for model use, and the effort involved multiple leading ocean modelers, including Drs. James McWilliam, Curtis Deutsch, Daniele Bianchi, Jeroen Molemaker, Lionel Renault and others who collectively represent over a century of ocean modeling expertise.

The model formulation, parameterization, set up, forcing, and model outputs are carefully and comprehensively evaluated during entire development process (refer to 3 Tasks 1-5 for specific activities). The Science Team specifically worked with the Commission's Technical Advisory Committee (CTAG) during the workflow to ensure 1) SCCWRP member agencies had an opportunity to review and correct the land-based input deck representing POTW ocean outfall data and riverine inputs (Sutula et al. 2021) and 2) stakeholder input was considered in how the SCB model was validated.

A second process occurred when the results are prepared for peer review and academic publishing. Journal article co-authors intensively scrutinized the draft journal articles, the associated model post-processing data management scripts, and the data analyses; co-authors always included members of the senior modeling team. After the article was submitted for review to the journal, CTAG was also invited to review the article. The lead and co-authors worked together to respond to any and all peer and CTAG review comments, which often consisted of doing additional analyses. The UCLA modeling lead and the SCCWRP PM conducted audits to ensure that the produced work both met scientific performance objectives (Section A3) and project goals (Section 3).

C1.2 Assessment and Response During Phase II Model Development

Model assessment and response consisted of an intensive process of internal checks and review by the model applications leadership team. Throughout Phase II, SCCWRP and UCLA continuously assessed and proactively addressed any problems via 1) through the primary modeler developer's focused effort, and 2) through a process of internal peer review, discussion, and suggestions for targeted analyses that occurred on a weekly to biweekly basis as model applications and model validation "checks" take place. This remains an intensive process, understanding the weight and the potential economic outcomes of the scientific questions intended to address for model use, and the effort involved multiple SCCWRP (Kessouri) and UCLA lead modelers (Bianchi, McWilliams) and other collaborators (Deutsch, Renault) who continue to provide the appropriate expertise and thoughtful guidance during model application.

The Model Quality Assurance Lead, or their designated alternative (see Section 1), conducted an inspection and detailed review of the forcing data, specific to each question (see applied science questions 2.2) before the model run was initiated. Visual model performance assessments are made throughout the simulation and then after each model simulation by the task lead, supported by the Model Applications Lead.

The Science Team worked with CTAG on the scenario experimental design to ensure SCCWRP member agencies had an opportunity to review and correct the land-based input deck that correctly represented the scenarios. For example, during the execution of work on Task 9, Ho et al. (2023) supported OC San to conduct a detailed plant mass balance to understand the effects of potable water recycling on outfall volumes and nutrient loading, then generalized this approach in an experimental design that was shared with CTAG for feedback. In addition, the science team supported CTAG to perform a peer review process of all SCCWRP technical reports and journal articles and their feedback on these works was carefully considered in revisions.

In addition, during Phase II, project performance was routinely evaluated by the MQAL, the PM and the MAL to ensure that project goals are being met and progress on tasks and deliverables was proceeding according to plan.

C2. Oversight and Reports to Management

Corrective actions have been noted either via verbal updates, or quarterly and/or annual progress reports to funding organizations. The SCCWRP PM maintained the overall responsibility for ensuring that the methodologies and processes are consistent with SCCWRP procedures to generate quality science. Proactive identification of problems regarding technical performance was the responsibility of all staff working on this project. The SCCWRP PM, ML and MQAL assessed any problems that arose during model application and recurrent validation checks and determined whether or how those required corrective actions.

This DOCUMENT can be amended in the future and when necessary, the revision will be distributed to the project distribution list (see Section A3). Significant QA issues will be reported to the funding agency within one business day of finding the issue.

D. Environmental Information Review and Usability Determination

Group D focuses on assessments performed in the final stages of model development and after the model has been applied in a given instance to evaluate whether the outcomes meet the project’s original objectives. We discuss the actions that are taken when the model does not meet performance criteria, the specific procedures during validation, and the process to reconcile with user requirements.

D1. Environmental Information Review

D1.1 Departures from Performance Criteria

Evaluation of performance criteria. Section A3 specifies the model performance criteria to characterize model adequacy for intended applications, which are summarized in Table 20. When the score is "reasonable" or lower than the science team investigates the cause to determine whether corrective actions are needed (see Section C1) and communicates the outcomes of the evaluation to project management (C2).

Actions Following Departure from Performance Criteria. When departures from performance criteria are noted, then updates to the funding agency have followed, including any corrective actions. This occurred using the mechanisms outlined in Group C (assessment and oversight), with the individuals identified in the project organization (Section 1) responsible.

Four types of actions are possible: 1) a corrective action is identified and implemented in the model, 2) improved data quality is needed for model forcing or validation, 3) a phenomena is not well understood, and basic scientific studies are needed to understand that phenomena, and 4) no corrective actions are identified, or of an indeterminate time frame; model performance is discussed with managers about implications for confidence in predicted endpoints of interest (see Section C2).

Specific examples of corrective actions have already occurred. For example, during the initial set of 1997-2000 runs, initial model validation pointed to incorrect land-based forcing for certain subregions. When this was identified, it resulted in corrective actions, which included correcting the forcing data, then rerunning the model simulation and reassessing model skill until the modeling team was satisfied that we "got the loading right." When issues with observational data have been noted (e.g., chlorophyll-a, ammonium, pH), we briefed both CTAG POTW members and made presentations to the CTAG technical subcommittee; stakeholders have responded by strategizing how to take corrective actions, including improving methodologies underlying collection of ambient ocean data (e.g., pH bottle samples for calibration).

In the case where no corrections are identified, the science team has endeavored to include in each published application of the model the appropriate caveats or limitations of the study and uncertainty.

Table 20. Summary of model adequacy performance criteria

MODEL VALIDATION Qualitative and semi-quantitative (judged through peer review during journal publishing and the Independent Review Panel expert review): • The model is able to reproduce key physical and biogeochemical phenomena that are well documented in the literature. • The model is able to capture the basic horizontal gradients in onshore to offshore remotely sensed imagery (e.g., SST, net primary productivity, chl-a, etc.). • The model is able to capture biogeochemical rates of transformation; field measured rate data are sparse and typically not available for the years in which the model performance was assessed, so the criterion that we employed was that model predictions should be within the same order of magnitude of predicted rates. Quantitative for vertical profiles of ship-based data: • CTD data (oxygen, temperature, salinity) or bottle data (nitrate) are assessed with specific performance criteria, in which model performance should be "excellent" or "good" for specific statistics and metrics, which are defined in Section D2.
PEER REVIEW OF MODEL DEVELOPMENT AND APPLICATION • Submitted work of sufficient quality to be published in well reputed journals with high impact factors • Model by IRP is determined to have appropriate formulation to investigate eutrophication

D1.2 Model Validation Methods

D1.2.1 California Current System Scale Methods

Approach. Renault et al. (2021) and Deutsch et al. (2021) comprehensively document validation of ROMS-BEC at a CCS-wide scale and key components of the validation approach are summarized here (Table 20). The validation of model simulations , consisting of evaluating model observations against relevant measurements was conducted across all scales of the numerical simulations, starting with the California Current System, and working down in scale (and up in resolution) with fine scale nested domains for the SCB, Central and Northern California, and the Pacific Northwest, and finally to the nearshore swath of the continental shelf, including the urban coastlines (Table 21). This required the assembly of data in formats readily compared to the large output fields, and with appropriate matching of spatial and temporal scales.

The main objectives of the coast-wide validation are to characterize and validate the mean seasonal behavior of the CCS circulation with good mesoscale resolution in both the ocean (dx = 4 km) and atmosphere (dx = 6 km). Overall, our aim was to provide a more comprehensive validation assessment than is customary for the purposes of scientific research investigations, both to establish the credentials of this particular model for its intended applications (basic research and investigations relevant for coastal water quality managers) and to provide an example of the state of the art for realistic regional simulations.

To facilitate comparison of model outputs to data, and particularly seasonal cycles, we defined 6 regions, dividing the CCS by distance from the coast into nearshore (0-100 km) and offshore

(100-500 km) regions, and by latitude into the Northern, Central and Southern CCS (see Deutsch et al. 2021 for depiction of regions). These designations are somewhat arbitrary but are based on a combination of topographic delineations and to ensure adequate data coverage in each region. In the physical validation, observational products were not always suitable for a coastal region and thus were collapsed when necessary. The numerical outputs for the solutions are daily averages, except when assessing the high frequency forcing importance where hourly averages outputs are saved. The winter, spring, summer, and fall seasons correspond to the months January-March, April-June, July-September, and October-December, respectively. Observations over the 1997-2010 period were used to validate atmospheric and oceanic physical and biogeochemical state variables, and processes, and phenomena (Table 5). The approaches taken to validate the physics and biogeochemistry at the CCS scale are comprehensively documented in Renault et al. (2021) and Deutsch et al. (2021).

Atmospheric and Physical Validation. The fidelity of processes and phenomena was validated by comparison to observational data for both state and rate variables with information about both spatial distributions in key parameters and changes over time. The science team examined simulated atmospheric forcing versus satellite observations for spatial patterns and seasonal variability of cloud cover and surface momentum, heat, and freshwater fluxes, as described in Renault et al. (2021), focusing on broad horizontal and vertical gradients. Comparisons were made between the simulated and observed main structure of the climatological upwelling front and cross-shore isopycnal slopes, the mean current patterns (including the Undercurrent), mesoscale eddy activity, and the wind-work energy exchange between the ocean and the atmosphere in comparison with a fully coupled simulation. Finally, the science team examined the impact of using a high frequency wind forcing to investigate the importance of synoptic wind variability to realistically represent the mesoscale activity and the ageostrophic inertial currents.

Biogeochemical Validation. The science team compared model simulations versus observations across multiple spatial and temporal scales, including the long-term mean distributions of key ecosystem metrics such as surface nutrients and productivity and subsurface O_2 and carbonate undersaturation and rates of transformation. Particular attention was paid to the spatial patterns of Net Primary Productivity (NPP) with field and remotely sensed rates. The group investigated patterns of nitrogen versus iron limitation, and spatial variations in the depth of the deep chlorophyll-a maximum relative to documented gradients in the CCS. The seasonal to interannual variability of biogeochemical properties and rates as well as the ability of the model to capture events such as the 1997-98 El Niño event was investigated, as was the trends in slower decadal shoaling of the pycnocline also accounts for the concomitant trends in hypoxic and corrosive conditions on the shelf.

Table 21. Examples of the atmospheric, oceanic physical and biogeochemical properties that were the focus of CCS validation studies (Renault et al 2021, Deutsch et al. 2021)

Physical (ROMS and WRF)	
Atmospheric: Cloud cover and shortwave radiation Surface heat flux Surface freshwater flux Surface stress	Oceanic: Surface layer T and S Interior T and S Mean sea surface height and current lower frequency variability Mesoscale activity High-frequency wind forcing
BEC Biogeochemistry and Lower Trophic Ecosystem	
Oceanic Photic zone Chlorophyll and net primary production Seasonal limitation of productivity by light and nutrients Nutrient concentrations Interannual variability in NPP Remineralization and export of carbon from the photic zone	Thermocline distributions and variability of O2 and aragonite saturation state Vertical structure Isopycnal surfaces Volume of water subject to hypoxic or undersaturated conditions

D1.2.2 SCB Methods

The conceptual approach for Phase I model performance assessment comprises three components, addressing different aspects of skill assessment: (a) statistical comparison of model output to observational data for state variables by region and season, (b) comparison of model output to observational data for biogeochemical rates, and (c) evaluation of model behavior compared to expected biogeochemical dynamics for coastal zones. Comparison of model output to observational data by region and season is designed to document model skill at reproducing the statistics (e.g., mean values and variability) of ocean physical and biogeochemical parameters at the spatiotemporal scales more relevant for evaluating human impacts on the coastal environment. Comparison of model output to observational data for biogeochemical rates assures that model is capturing the appropriate transformations in nutrients and carbon that structure the ecosystem response to eutrophication. Finally, the evaluation of model behavior compared to the expected physical and biogeochemical dynamics for coastal zones is a more qualitative evaluation of model performance to document that the model broadly reproduces oceanographic phenomena in a way that reflects our understanding of nearshore ocean environments.

During our Phase I validation studies, we conducted a statistical assessment of agreement between model predictions versus observations. Our approach reflects the fact that the hydrodynamic model, under the influence of realistic forcings (e.g., wind fields) and without data assimilation, develops its own intrinsic variability in circulation, for example, submesoscale eddies (McWilliams 2008). The resulting modeled state variables would not necessarily overlap with observations on a point-by-point basis but would be comparable to observations when averaged over appropriate spatiotemporal scales. We assessed a suite of statistics and metrics, following the methodology of Allen et al. (2007), to assess how well the model reproduces the magnitude and gradients of selected state variables, whether the model agreement has an apparent bias, and how well the model reproduces natural variability. We calculated six metrics, defined in the following, where *N* is the total number of appropriate observational data, *D* represents each individual observational datum, $\bar{D}$ is the mean of the observational data, *M* is the model estimate representing an observation, and $\bar{M}$ is the mean of the model estimate. The metrics considered include the following.

The Pearson correlation coefficient, reflecting the degree of linear correlation between the observed and model variable, and the statistical significance (*p*-value) of this correlation:

$$r_{xy} = \frac{\sum_{n=1}^{N}(D_n - \overline{D})(M_n - \overline{M})}{\sqrt{\sum_{n=1}^{N}(D_n - \overline{D})^2}\sqrt{\sum_{n=1}^{N}(M_n - \overline{M})^2}}. \quad (7)$$

The cost function (CF), which gives a nondimensional value indicative of the "goodness of fit" between two sets of data, quantifying the difference between model results and measurement data:

$$\mathrm{CF} = \frac{1}{N}\sum_{n=1}^{N}\frac{|D_n - M_n|}{\sigma_D}, \quad (8)$$

where σ_D is the standard deviation of the observations.

The bias (B; the sum of model error normalized by the data):

$$\mathrm{B} = \frac{\sum(D - M)}{\sum D}. \quad (9)$$

The ratio of the standard deviations (RSD):

$$\mathrm{RSD} = \frac{\sigma_D}{\sigma_M}, \quad (10)$$

where σ_M is the standard deviation of model outputs.

The Nash–Sutcliffe model efficiency (ME; Nash & Sutcliffe 1970), a measure of the ratio of the model error to the variability of the data:

$$\mathrm{ME} = 1 - \frac{\sum(D_n - M_n)^2}{\sum(D - \overline{D})}. \quad (10)$$

And the two-sample *t* test, or Welch's *t* test (Derrick et al. 2016; Welch 1947):

$$H = (\overline{D} - \overline{M}) / \sqrt{\frac{\sigma_D^2}{N} + \frac{\sigma_M^2}{N}} . \quad (11)$$

We score the model performance following Table 6 per the methodology of Allen et al. (2007).

Phase II studies did a check of performance based on ship-based CalCOFI and POTW monitoring data over the period of 2013 through 2017, corresponding to Phase II Task 6 efforts (See Section 6.4). The same statistics published in the seminal validation study, Kessouri et al. (2021), were used in these analyses, along with the inclusion of Taylor Diagrams, which help to visualize standard deviation, correlation, and model-data root mean squared error on one diagram (e.g., Fig. 9, from Kessouri et al. 2024).

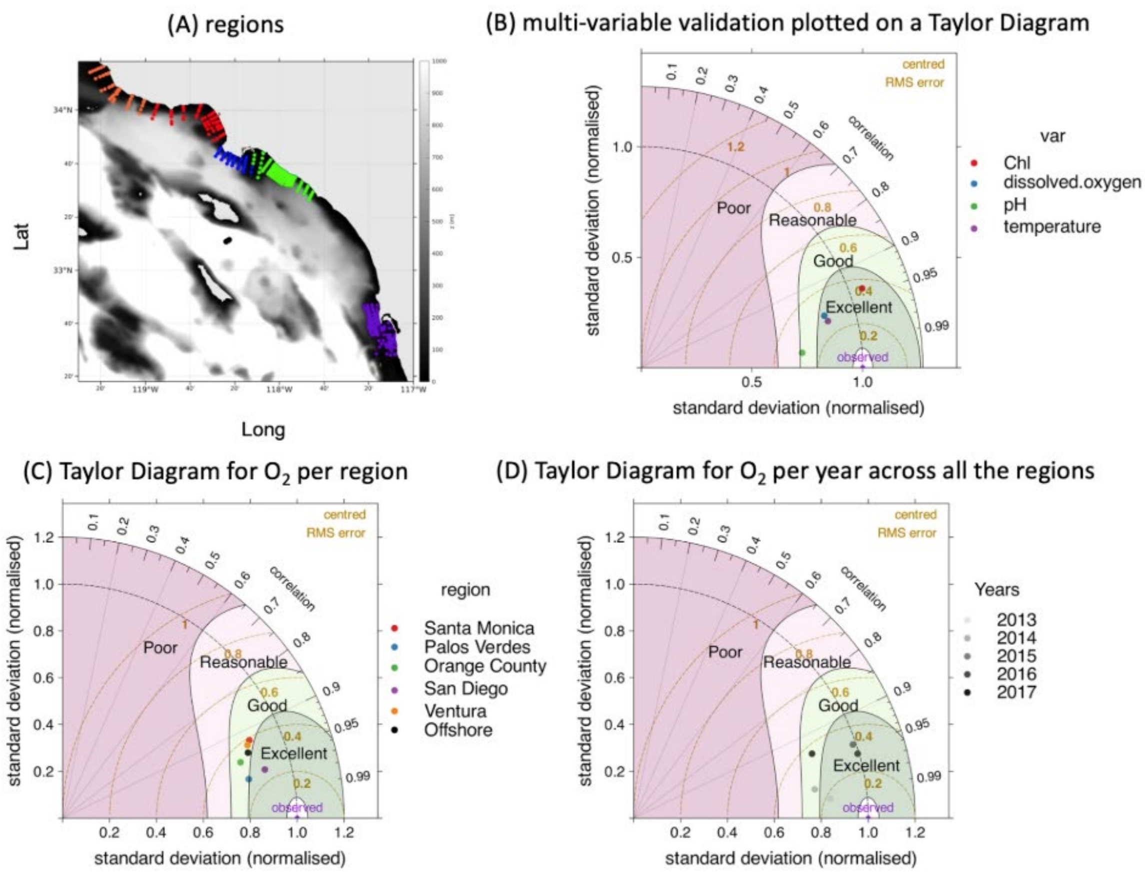

Figure 9. From Kessouri et al. (2024). A) Location of the observational stations used in this validation. The gray background represents the bottom topography. (B) Taylor diagram illustrating a validation for chlorophyll-a, dissolved oxygen, pH and temperature across all the regions. (C) same as B for oxygen, now plotted by sub-region. (D) same as B for offshore dissolved oxygen plotted by year across all the regions.

D2. Environmental Information Review

Reconciliation with user requirements has both a 10-year retrospective and prospective component. We detail the procedures used retrospectively, then talk about potential future actions, the scope of which are resource-dependent and also rely on scientific consensus and stakeholder support.

Retrospective Reconciliation Actions. During the course of the 10 year project, the science team ensured that: (1) documentation is maintained; (2) departures from validation criteria are addressed and validation methods are properly documented; (3) critiques through the peer review process are addressed to the extent possible within available resource allocations, (4) the modeling outputs are properly used and findings contextualized in addressing applied science questions 1-5 (see Section 2), (5) findings are discussed in an open and transparent process with stakeholders, providing opportunities to allow feedback both the outcomes as well as the caveats and uncertainties and (6) model input and output are shared upon request to allow access by the wider scientific community and interested stakeholders.

Prospective, Future Actions. The IRP recommendations provide a roadmap for prospective, future actions that can improve reconciliation with user requirements (NWRI 2025), specifically by improving stakeholder confidence in the models. The Steering Committee has noted that a subset of these recommendations are immediate priorities. SCCWRP has identified those actions that it intends to actively look for resources to support (Table 22). This future work may be reflected in future updates to this DOCUMENT.

Table 22. Examples of IRP categories of recommendation and specific examples of activities prioritized by SCCWRP in future science activities.

Category	Specific Examples of Activities
Enhance model and biological interpretation tools	Extend simulations through 2024. Consider additional model enhancements if warranted and prioritized updated model validation activities. Continue to collect biological validation data through the Bight Program
Quantify uncertainty	MODEL VALIDATION Assess data availability and quality to meet IRP model validation recommendations Conduct model validation through 2024, addressing as possible IRP recommendations and report to project management Include high frequency time series mooring data in updated model validations. SENSITIVITY ANALYSES Conduct a literature review and re-analysis of existing BEC sensitivity analyses previously conducted at a 5 km resolution ROUTINE UNCERTAINTY QUANTIFICATION Agree on protocol for routine uncertainty quantification
Democratize the model	Improve Model Documentation Modeling versioning and tracking system Model data dictionary Develop a Training Program Improve Model Data Visualization

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