Numerical Simulation of Potential Eutrophication Effects of Oil and Gas Produced Water Discharges on the Southern California Bight

Martha Sutula
Fayçal Kessouri
Christina Frieder
Nicholas Lombardo

SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT

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Martha Sutula, Fayçal Kessouri, Minna Ho and Christina Frieder

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EXECUTIVE SUMMARY

Dos Cuadras Offshore Resources (DCOR), LLC is a privately owned company categorized under Oil and Gas Exploration and Development, located in Ventura, CA. DCOR LLC is seeking a waste discharge requirement (WDR) permit from the Santa Ana Regional Board to allow the discharge of Platform Eva produced water to California State coastal waters, located approximately 2.5 miles offshore of Northern Orange County. This effluent, which was previously re-injected into the well, was noted to be elevated in ammonium (> 100 mg/L NH4). Primary productivity in marine waters is nitrogen-limited, so discharge of dissolved inorganic nitrogen has the potential to amplify primary production in coastal waters, in a process known as eutrophication, which could contribute to oxygen (O_2) and pH declines and an increased risk of toxic harmful algal blooms. For this reason, the Santa Ana Water Board sought assistance of SCCWRP to quantify the environmental effect of discharging this produced water on nearshore water quality, specifically with respect to the environmental fate and effects on algal blooms, O_2, and pH. This project provided an opportunity to test methodologies related to model uncertainty quantification for the purpose of sole source attribution modeling assessments.

The goal of this study was to utilize an ocean numerical model to:

(1) Quantify the eutrophication potential of DCOR proposed discharges, specifically with respect to (a) nitrogen loading, (b) primary productivity, (c) O_2 and pH loss.

(2) Quantify the magnitude of these environmental effects relative to model uncertainty, using methodologies[1] to interpret California Ocean Plan water quality objectives (WQO), including: (a) numeric pH and O_2 WQO and (b) narrative chemical WQO, for which the metrics of compression of calcifying and aerobic habitat and increased risk of toxic algal bloom were used as numeric translators.

(3) Evaluate the relationship of eutrophication response to nutrient loading, in order to support conversations between DCOR and the Santa Ana Water Board on allowable loads.

Our study revealed three findings that can inform discussions between the Santa Ana Water Board and DCOR LLC.

(1) After review of impacts from proposed combination of nitrogen loading from Platforms Eva plus Esther (1884 kg d^{-1}), DCOR voluntarily retired Platform Eva, then proposed a discharge of 1437 kg d^{-1} of TN loads for Eva alone (60,000 barrels/day). While these loads

[1] In California state waters, specific protocols have been established for use of O_2 field observations to assess compliance with Ocean Plan Standards (Nezlin et al. 2016), but protocols for model-based assessments methodologies have not been adopted by Water Board staff. Therefore, we take great care to note what is the limit of science and what are technically oriented policy decisions and therefore should be the focus of discussions between DCOR and the Santa Ana Board staff.

are relatively small (3% Bight wide, 9% on the LA/OC shelf) relative to other human nitrogen sources, they would contribute to a coastal ocean that already is enriched with nitrogen. Subsequent to completion of this work and as of August 10, 2025, the proposed discharge for Platform Eva was reduced to 15,000 barrels per day or the equivalent of 360 kg TN/day.

(2) We evaluated effects from the perspective of both individual (source-specific) as well as cumulative effects. The modeling predicts increased localized algal production (up to 50% on the San Pedro Shelf) due to the discharge of 60,000 barrels per day, but the shallow region of discharge means that the O_2 and pH loss in the immediate region of DCOR discharge is minimal. However, produced organic matter predicted by the model, once dispersed by currents, causes a widespread but small change up to 5% in subsurface O_2 and pH loss dispersed throughout the Bight.

(3) When these environmental effects predicted from ROMS-BEC are filtered through the lens of methodologies that could be used to interpret numeric and narrative WQO[1], we found that:

- 2013 Simulations of ambient pH and O_2 conditions that include all land-based inputs, without any DCOR proposed inputs, relative to a natural background scenario background of "no land-based inputs" are predicted to (1) trigger O_2 numeric WQO for roughly 2 months, (2) cause sublethal aerobic and marine calcifier habitat compression the same period of time, and (3) result in an increased risk of toxic HABs of up to for four months per year. These effects are predicted over a range of 10s to thousands of square kilometers for this 15-month simulation.

- DCOR proposed discharges (and the regional human nutrient discharges that dominate them) never trigger numeric pH numeric WQOs, but DCOR individual effects are predicted to contribute to a small expansion of the area that triggers O_2 WQOs and of O_2 and pH related habitat compression. They have a more substantial effect on the risk of toxic HABs, expanding the baseline area at risk up to 500 km^2 for 20-80 days of the year in the San Pedro and Santa Monica Bays. The predictions of risk of toxic HABs and aerobic habitat compression are larger than uncertainty due to intrinsic variability (model noise), our best estimate of uncertainty at this time.

(4) We provide a scaling analysis that illustrates how reductions in mass nitrogen loading from Platform Eva could result in changes in the area and duration of risk of toxic HABs, the most sensitive endpoint. We show that reductions to 15,000 barrels per day substantially reduces but does not entirely eliminate the predicted risk of DA-producing HABs. A residual risk of duration of < 15 days, thousands of kilometers in size, is persistent, even at smaller discharges of produced water.

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1. Introduction

Dos Cuadras Offshore Resources (DCOR), LLC is a privately owned company categorized under Oil and Gas Exploration and Development, located in Ventura, CA. Currently the facility is producing oil and natural gas via two platforms: Platform Eva and Platform Esther, located approximately 2.5 miles offshore of Seal Beach and Huntington Beach (Fig. 1); Platform Eva will continue to operate (NPDES No. CA 0105996), while Esther is being decommissioned. The water produced from the enhanced oil recovery system is recovered from Platform Eva (60,000 barrels per day or 2.52 million gallons per day or MGD) for injection into subsurface wells. However, the total amount of produced water that can be injected into the wells is reaching its permitted maximum. For this reason, DCOR LLC is seeking a waste discharge requirement (WDR) permit from the Santa Ana Regional Board to allow the discharge of this produced water from Platform Eva to California State coastal waters.

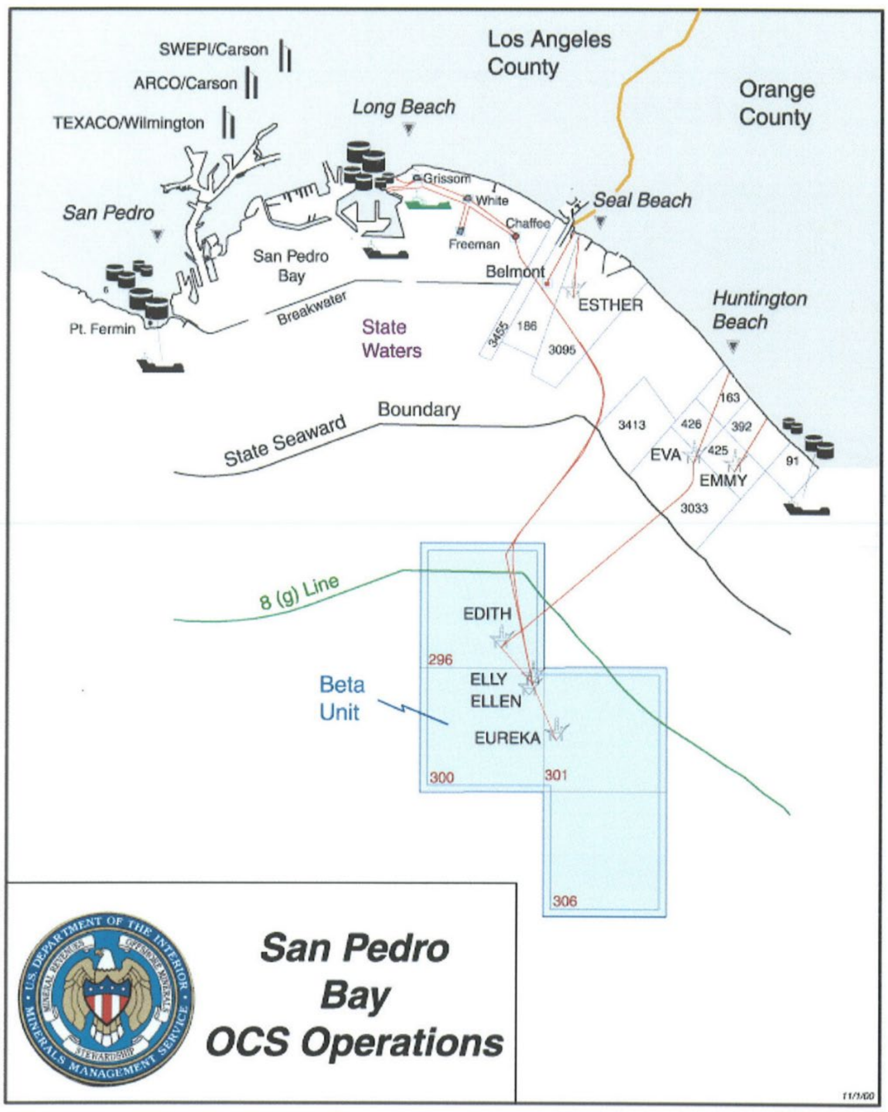

Figure 1. Location of DCOR proposed discharges from Platform Eva on the Orange County Shelf

The Santa Ana Board staff identified ammonium constituent concentrations from the two platforms as elevated (> 100 mg/L NH4). Primary productivity in marine waters is nitrogen-limited, so the discharge of dissolved inorganic nitrogen has the potential to amplify primary production in coastal waters, in a process known as eutrophication (Nixon 1995), which could contribute to oxygen (O_2) and pH declines and an increased risk of toxic harmful algal blooms. For this reason, the Santa Ana Water Board sought the assistance of SCCWRP to understand the environmental effect of discharging this produced water on nearshore water quality, specifically with respect to the environmental fate and effects on algal blooms, O2, and pH.

Management attention on the topic of toxic harmful algal blooms (HABs), O_2 and pH loss in Southern California Bight (SCB) waters has already been elevated for multiple reasons. First, climate change is causing ocean warming (T), hypoxia (H) and ocean acidification (OA), which lowers pH and its biologically relevant form—aragonite saturation state (ΩAr). These changes are driving the OAH to levels that result in the compression of habitat for marine organisms as well as an increase in the frequency and magnitude of toxic HABs (IPCC 2020). Second, coastal nitrogen export from a human population of 23 million, which include point and nonpoint source discharges to the ocean from 19 ocean outfalls and 75 rivers, are doubling the natural ocean sources of nitrogen (Howard et al. 2014). These discharges are predicted to double primary production along the coast, which causes the increase in subsurface respiration rates, with corresponding subsurface reductions in O_2 and aragonite saturate state (ΩAr) that rival or exceed that of global open-ocean O_2 loss and acidification since the pre-industrial period (Kessouri et al. 2021, 2024). These land-based nutrient inputs are predicted to reduce the potential habitat for aerobic organisms (e.g., fish and invertebrates) and shell-building organisms (calcifier) during late summer, when viable habitat is at its seasonal minimum in the SCB (Frieder et al. 2024). A region of annually recurring habitat compression is found 30 – 90 km from the mainland, southeast of Santa Catalina Island. That study predicts that habitat for both aerobic and calcifying organisms is vertically compressed in the upper 200 m of ocean waters by, on average, 25% but can be as much as 60%. Similarly, the potent neurotoxin domoic acid produced by toxic blooms of *Pseudo-nitzschia* have been linked to increased stranding of marine mammals along the Orange County coast (Smith et al. 2022). Domoic acid detection in surface waters is significantly correlated to algal biomass (chl-a), with a threshold of ≥ 3.3 µg/L chl-a associated with an increased probability of DA detection in the San Pedro/Santa Monica Bay region (Sandoval-Belmar et al. 2023). Thus, the question is whether the proposed DCOR discharges have the potential to contribute to this elevated primary productivity that exists in ambient conditions, thus increasing the risk of toxic HABs, and exacerbating pH and O_2 loss.

The goal of this study was to utilize a validated ocean numerical model (ROMS-BEC) to:

(1) Quantify the eutrophication potential of DCOR proposed discharges, specifically with respect to (a) primary productivity, (b) O_2 and pH loss.

(2) Evaluate these environmental effects using methodologies[2] to interpret California Ocean Plan WQO, including: (a) numeric pH and O_2 WQO and (b) narrative chemical WQO, for which the metrics of compression of calcifying and aerobic habitat and increased risk of toxic algal bloom were used as numeric translators; and

(3) Evaluate the relationship of eutrophication response to nutrient loading, in order to support conversations between DCOR and the Santa Ana Water Board on allowable loads.

[2] Use of these metrics and thresholds to interpret model outputs are for scientific purposes and are not intended to represent policy decisions.

2. METHODS

Overarching Approach

The study design involves the use of a validated ocean numerical model to predict the additive effect of DCOR proposed discharges to the "ambient" background of coastal water quality in the Southern California Bight. The model is a three-dimensional representation of coastal physical circulation and biogeochemical water quality that can predict mechanistically over time the effects of human discharges on the coastal ocean.

Preliminary modeling work was conducted to inform how the plumes of DCOR proposed discharges would disperse in the nearfield (at scales of 10s of meters), information that was needed to parameterize the blooms in the far field model (at scales of 1000s of meters). Then in the far-field model, six simulations were conducted (Table 1), in order to answer the following questions:

1) What is the net change in nitrogen loading that would occur to the SCB as a result of DCOR proposed discharges at 60,000 barrels per day, relative to other loading that is already occurring?

2) What is the effect of DCOR proposed discharges, alone or in combination, on algal production, pH, and O_2 loss, relative to an ambient environmental condition?

3) To what extent do the potential environmental effects have the potential to trigger metrics of California Ocean Plan WQO?

4) Is the magnitude of potential environmental effects greater than model uncertainty?

5) How do environmental effects scale with nitrogen loading from Platform Eva? In particular, how do the effects change if the amount of produced water permitted is modified from 60,000 to 15,000 barrels per day?

6)

Table 1. Description of model scenarios used to support the study.

Scenario Name	Description
CNTRL	A scenario representing "ocean only" natural nutrient cycles, upwelling, and its ecological effects, plus global CO_2 (anthropogenically enhanced)
ANTH	a scenario representing the effect of all land-based, atmospheric, and oceanic (CNTRL) sources of nutrients and their effects on coastal water quality
EVA	a scenario that includes all sources represented in ANTH, plus the combined proposed discharges of Platform Eva
ANTH2 and ANTH3	a scenario that is essentially a repeat of scenario (1), with the perturbations of oceanic boundary conditions ±1%, in order to estimate model uncertainty. This simulation would be used to estimate a minimum interpretable effect.

Nitrogen loading from DCOR proposed discharges was compared to loading from all ocean outfalls and rivers in the SCB. Model outputs were analyzed to (1) conduct a mass balance analysis to quantify the potential environmental effect, then (2) methodologies were used to interpret ocean plan WQO (Table 2). A combination of three ANTH scenarios were used to construct an envelope of modeling uncertainty due to model intrinsic variability, which was used to estimate a minimum interpretable effect. Finally, a loading scaling analysis was conducted to estimate how those effects scaled relative to the amount of loading from Platform Eva.

Table 2. Summary of metrics used to evaluate the potential effects of proposed DCOR discharges.

Effect Type	Metric	Reference
Ocean Plan Numeric WQOs	pH ± 0.2 units O_2 ±10% of natural background	State Water Board 2016
Ocean Plan Narrative Chemical WQOs	Increased probability of toxic HABs causing a marine mammal stranding event of 2 or more animals at chl-a ≥ 3.3 µg/L	Smith et al. 2022 Sandoval-Belmar et al. 2023
	O_2-related habitat compression of aerobic habitat for fish, based on ϕcrit metabolic index threshold for northern anchovy (median O_2 sensitivity for pelagic fish).	Deutsch et al. 2015 Howard et al. 2020 Frieder et al. 2024
	pH-related habitat compression of pelagic shelled organisms based on Ω_{Ar} of 1.4, representing the thresholds of sublethal effects on pteropods.	Bednarsek et al. 2019 Frieder et al. 2024

Study Geographic Context

The study domain, the SCB, stretches from Punta Colonet, Mexico, to Point Conception, and supports a coastal population of 22.7 million people (Annual Estimates of the Resident Population for Counties: April 1, 2010 to July 1, 2019). Platform Eva is located 3.3 km offshore of Huntington Beach, California in 17 m of water (Fig. 1).

DCOR proposes discharging to a region within the SCB that already receives substantial point-source inputs of nutrients. Information on these discharges are provided here because they constitute the ambient background of eutrophication that is simulated in the ANTH scenario. In this region, the majority of wastewater is disposed of through four major outfalls that discharge along the upper continental shelf at depths between 60 and 94.5 m, and a series of minor outfalls that discharge closer to shore and at shallower depths. The inorganic nitrogen rich water in these outfalls accounts for 92% of total terrestrial anthropogenic nitrogen loading in the coastal SCB (Sutula et al. 2021). Hyperion Treatment Plant (HTP) is located in Santa Monica Bay, Joint Water Pollution Control Plant (JWPCP) in San Pedro Bay, Orange County Sanitation District (OCSD) in Orange County, all three of which are in reasonable proximity to the proposed location of DCOR discharge (Fig. 2).

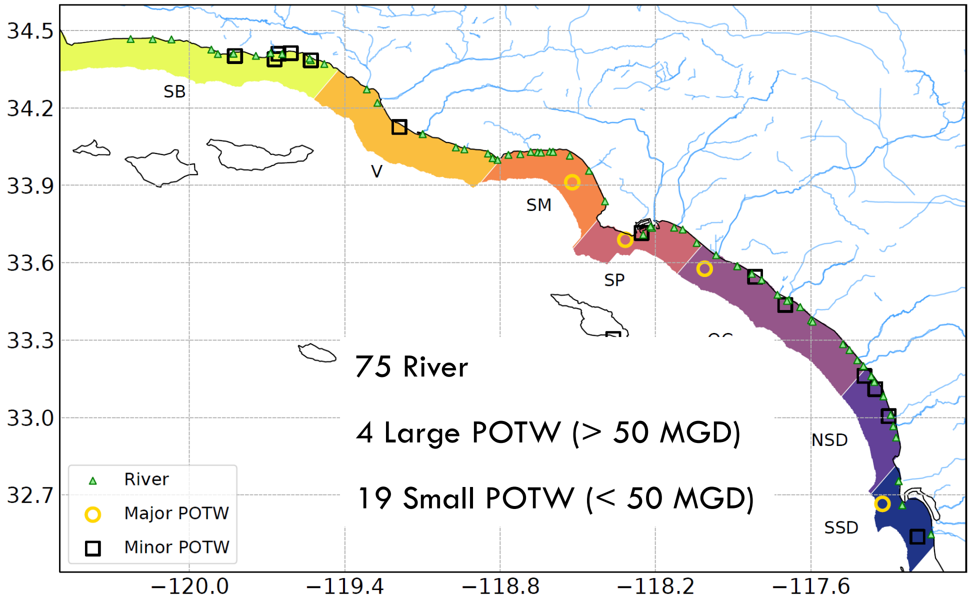

Figure 2. Location of small and large POTWs and rivers that represent land-based inputs of freshwater, nutrients and other constituents to the SCB.

Description of Ocean Numerical Model

The physical-biogeochemical model used for this study consists of the Regional Ocean Modeling system (ROMS) (Shchepetkin and McWilliams, 2005) coupled to the Biogeochemical Elemental Cycling model (BEC) (Moore et al. 2004).

ROMS is a widely adopted regional ocean model with a long history of application to the CCS (Capet et al. 2008a, 2008b, 2008c) and specifically the SCB (Dong et al. 2009; Dong and McWilliams, 2007). ROMS has been shown to be capable of capturing submesoscale processes occurring at horizontal scales of hundreds of meters or less (Kessouri et al. 2020; Dauhajre et al. 2017), a scale necessary for understanding coastal circulation, and is able to approximate the dynamics and transport of wastewater plumes (Kessouri et al. 2021; Uchiyama et al. 2014) and their fate and effects on far field scales of 10s to 100s of kilometers (Kessouri et al. 2022). ROMS has an extensive history of multiple management applications, including tracking of plumes from rivers, wastewater, sewage, and industrial spills, etc. (Guillaume et al. 2017, Ho et al. 2021, Kessouri et al. 2021a,b).

BEC is ocean biogeochemical model (Moore et al. 2013, 2004) that simulates the cycles of nutrients (nitrogen, phosphorus, silicon, iron), carbon and O_2, as driven by three phytoplankton groups (small phytoplankton, diatoms and diazotrophs) and total zooplankton biomass. BEC mechanistically simulates the fate of nutrients as they cycle through these components of the lower food web including production of algal blooms, grazing by zooplankton, and the sinking of decaying algae which will consume O_2 and lower pH in the subsurface. ROMS-BEC has been applied to simulate biogeochemical variability along the California Current System (Deutsch et al.

2021, Howard et al. 2020), and the SCB (Kessouri et al. 2021b), where it has been extensively validated against field and remote sensing observations. Recently, ROMS-BEC has been used to investigate the effects of the human nutrient discharges on algal blooms, O_2, and pH (Kessouri et al. 2021a, Kessouri et al. 2024, Frieder et al. 2024). ROMS-BEC has also been used by coastal water quality managers to investigate the potential outcomes of management actions, including nitrogen management and potable water recycling (Ho et al. 2023).

Model Configurations and Parameterization

The ROMS configuration on the US West Coasts consists of multiple nested model domains (Fig. 3) with an offline one-way nesting that downscales from 4 km horizontal resolution (USW4, green box in Fig. 3) of the U.S. West Coast with 60 vertical levels (Deutsch et al. 2021; Renault et al. 2021) to 1 km resolution (USSW1, blue box in Fig. 2) with 60 vertical levels for California state-wide (Kessouri et al. 2020), to 300m resolution (USSW03, red box in Fig. 3) for the southern California Bight (Kessouri et al. 2021a, b). Finer resolutions have been run (e.g., 100m to submeter) to study very nearshore circulation. This nested grid allows for a computationally efficient characterization of the ocean currents and circulation features (large and small scale) that are critical to capture in determining plume fate and effect.

Two specific model configurations were used in this study, representing the continuum of intermediate field plume dispersion to far field environmental effects (Fig. 4).

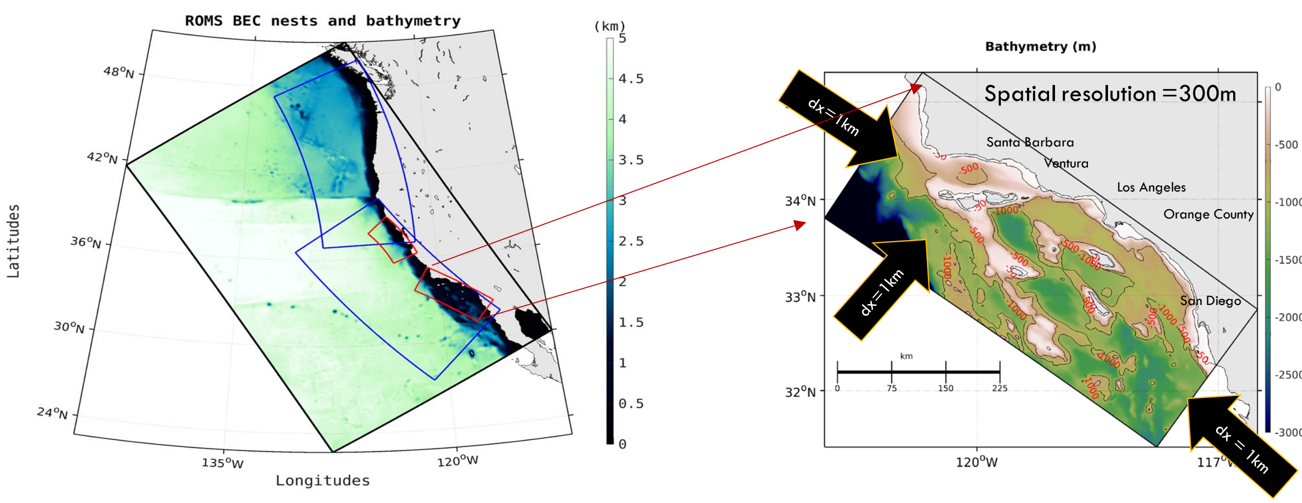

Figure 3. ROMS-BEC nests relative to coastal bathymetry (left panel), showing the green 4 km resolution grid at the scale of the US West coast, then the blue 1 km resolution grid that encompasses the California Coast, then the two red 300-m nests for the SCB and the San Francisco and Monterey Coast. The right panel shows an enlarged figure of the 300-m nest for the SCB.

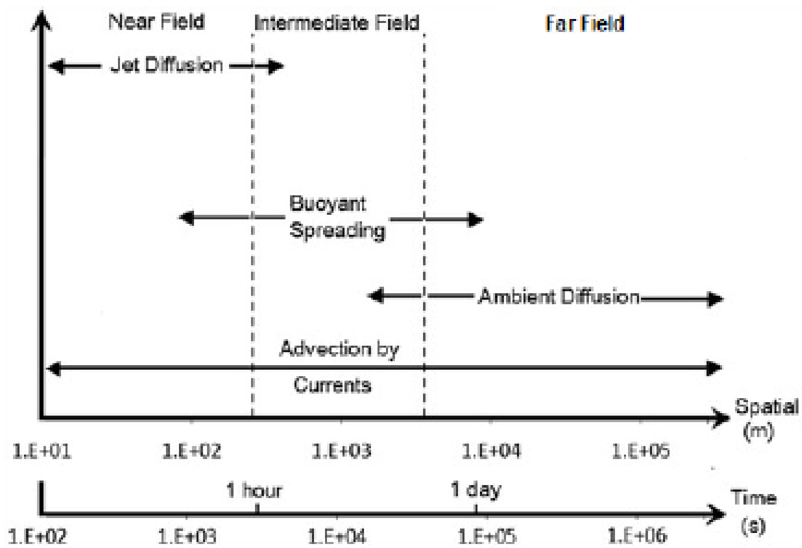

Figure 4. Physical processes of discharge submerged wastewater and corresponding length and time scales. From Ho et al. 2021, Adapted from Niu et al. 2011, Jirka et al. 1975.

First, an **intermediate field, non-hydrostatic version of ROMS** was used to investigate the physical plume rise height and dispersion for DCOR discharges, which is information that is needed to parameterize the dispersion of the plume in the far field model. We utilized a very high resolution non-hydrostatic ROMS application of Ho et al. (2021) that is capable of resolving intermediate field mixing. This approach is particularly suitable to investigate the dispersion of the plume through buoyant spreading, ambient diffusion as well as advection by currents. The model simulation was conducted on a time step of 15 seconds, saving output every 5 minutes, until neutral buoyancy was achieved. The representation of each of the discharge pipes utilized the existing diffusers, which were parameterized based on existing documentation and consultation with Dr. Walter Frick of Visual Plumes (Fig. 5; Table 3). The model utilized realistic representation of ocean currents and physical conditions of the water column at the point of location of discharges for each platform The model was tested during winter and summertime conditions, which would bracket the projected dispersion of the plume relative to water column stratification and mixed depth. However, both conditions provided roughly the same answer, so the average summer condition was used.

Table 3. Configuration of resolution non-hydrostatic ROMS according to the diffuser designs

Platform Discharge Pipe	**Eva**
Horizontal resolution	2 m
Vertical resolution	0.5 m
Domain Depth	18 m
Distribution of discharge	Uniform input 1.5 to 11.5 m above bottom
Dilution at initialization	1500:1
Run duration	4 hours of simulation time

Second, a **300-m resolution ROMS-BEC far field configuration** was utilized to investigate the environmental fate and effects of proposed DCOR discharges. The physical configuration of the model is identical to that discussed in Kessouri et al. 2021a and Kessouri et al. 2021b, to which we refer the reader for details, including validation studies. Atmospheric boundary conditions come from a simulation with the Weather Research and Forecast model (Skamarock and Klemp, 2008) run at a resolution of 6 km (Renault et al. 2021). Initial and boundary conditions for oceanic variables are taken from a 1 km-resolution simulation for the southern CCS (Kessouri et al. 2020).

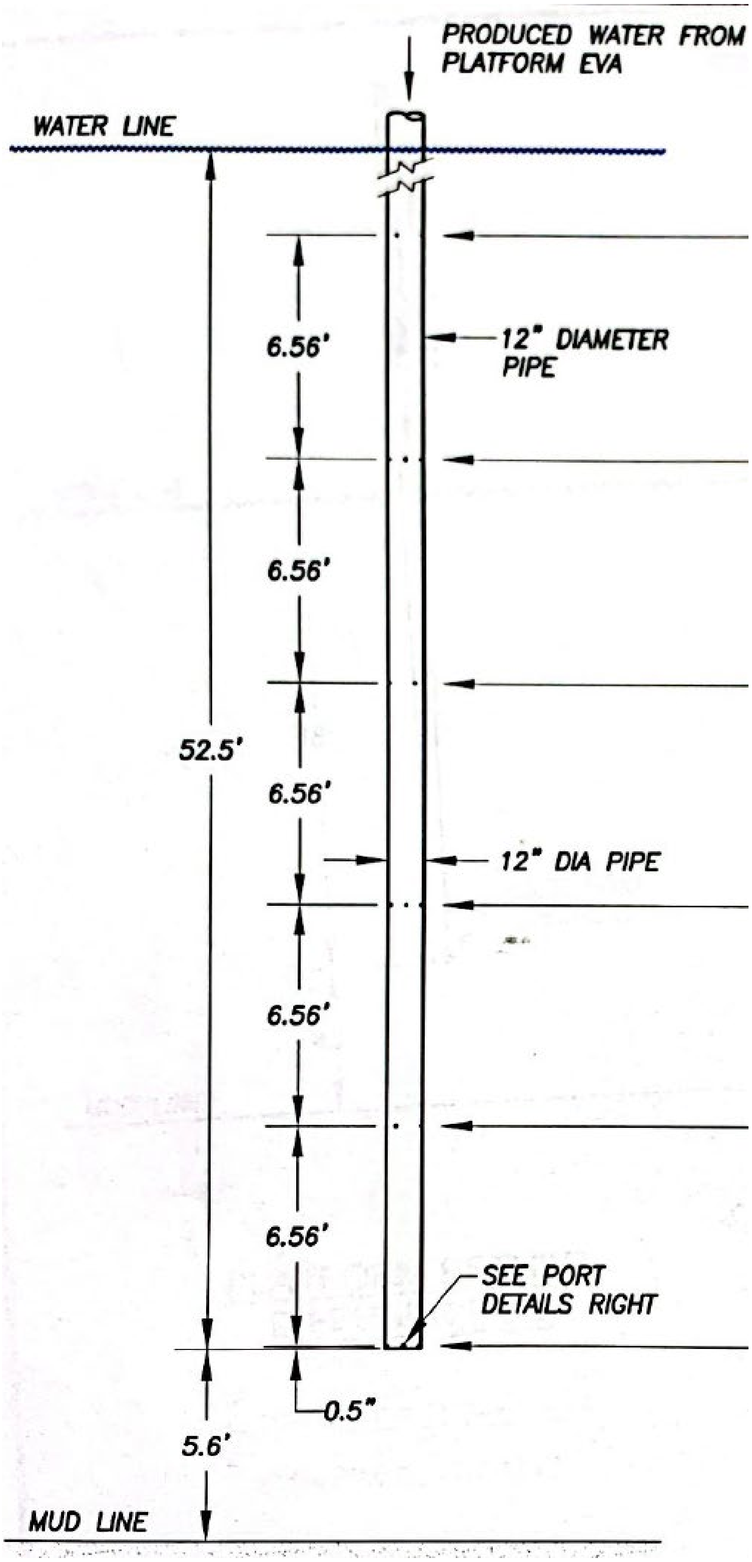

Figure 5. Representation of proposed diffusers from Platform Eva graphically within ROMS intermediate field modeling. All measurements are in feet.

The far field model simulations utilized in this study (Table 1) were constructed as follows. The duration of each of the simulations was 14 months, spanning September 2012-November 2013. The horizontal (spatial) resolution was 300-m) and the temporal resolution was a 30-second time step, which was averaged daily produce raw output.

The ANTH scenario consisted of 300-m ROMS-BEC simulations that were forced with a daily time series of spatially explicit including freshwater flow, N, P, silica, and organic C representing natural and anthropogenic sources (Sutula et al. 2021). These data have been compiled from 1996-2017 for: 1) WWTP ocean outfalls, 2) riverine discharges, and 3) atmospheric CO_2 air-sea exchange. See Sutula et al. (2021) for detailed methodologies and data sources.

ANTH2 and ANTH 3 were specifically included to place a minimum limit on the interpretation of environmental effects. The scenarios are set up using forcing that is identical to ANTH, but with perturbed initial conditions (ANTH2 and ANTH3) for which we add a random uniform variability to all state variables, including physical and biogeochemical variables in the initial condition. The perturbation is created by averaging random 3 days between August 15 and September 15, 2012, from the original ANTH scenario. The upper 95^{th} percentile of ANTH, ANTH2 and ANTH3 combined was used to provide the minimum interpretable change from the mean of these three scenarios.

One simulation were specific to DCOR, in which Platform Eva proposed produced water discharges were added to the base ANTH simulation (EVA). Intermediate field non-hydrostatic model runs were used to determine the shape of the plume from each platform in the far field model (Fig 6). Samples of Platform Eva produced water were obtained and analyzed for a suite of constituents required of all model inputs (Table 4), including dissolved inorganic nitrogen forms, pH, and ammonium.

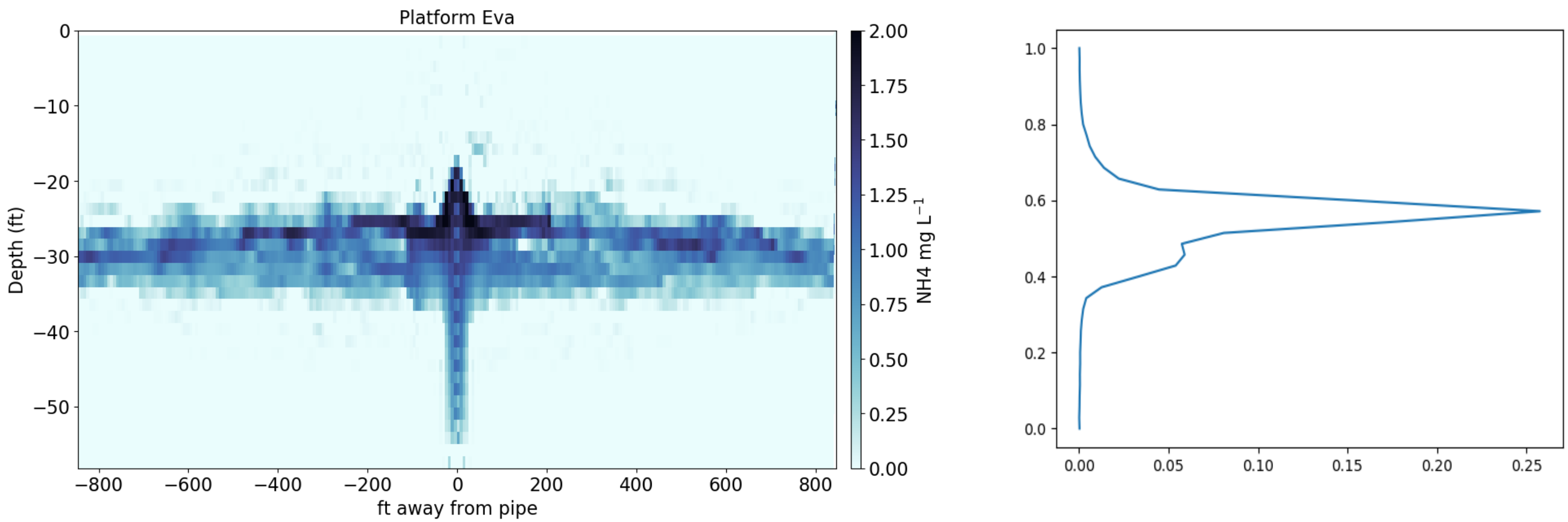

Figure 6. Left panel—visualization of plume heat maps simulated in the non-hydrostatic model for Platform Eva. The right panels show how these simulations were used to inform the formalized flux profile (unitless) used to dilute the effluent within the 300 m horizontal resolution stack of model grid cells in the far field model.

Table 4. List of constituents and the averaged concentrations from replicate samples taken from produced water discharges.

Constituent	Method	MDL	Platform Eva
Discharge depth (meters from bottom)	N/A	N/A	1.5
Flow (MGD)	Estimated	Estimated	2.52
Salinity	Field measurement via YSI Meter	N/A	22.8
Temperature (0C)		N/A	55
pH		N/A	7.1
Total Alkalinity (mg/L CaC03)	SM 2320B	4.1	8903
TDKN (mg/L)	EPA 351.2	0.2 mg/L	150
Dissolved Oxygen (mg/L)	Field measurement via YSI Meter	N/A	7.0 mg/L
Organic Nitrogen (mg/L)	By difference	0.2 mg/L	10
Ammonia (mg/L)	SM 4500-NH3 G	0.07 mg/L	140
Nitrate (mg/L)	EPA 300.0	0.03 mg/L	0.6
Nitrite (mg/L)	EPA 353.2	0.01 mg/L	0.005
TDP (mg/L)	SM 2320B	0.02 mg/L	0.53
PO4 (mg/L)	EPA 300.0	0.02 mg/L	0.019
Silicate (mg/L)	EPA 366.0	0.002 mg/L	57.6
DOC (mg/L)	SM5310-B	0.2 mg/L	1.7
Dissolved Fe (ug/L)	EPA 6010B	30 µg/L	120

Analysis Methods

The analysis methods focus on predicting effects at 60,000 barrels per day, then calculating how those effects would be reduced with a nitrogen scaling analysis.

Scenario analysis methods to answer the four study questions relied for the most part on existing methodologies, described in detail below.

Comparative Analysis of Nitrogen Loading

DCOR proposed discharges of 60,000 barrels per day will add to an ambient water quality condition in the nearshore that is already enriched with nitrogen. To provide this important context for the DCOR proposed discharges, we quantified by subregion the existing nitrogen loading to the nearshore, then quantified how much DCOR proposed discharges would add to that loading.

Effect of DCOR Proposed Discharges on Algal Production, pH, and O_2 Loss

To quantify the effect of DCOR proposed discharges of 60,000 barrels/day alone or in combination, on algal production, pH, and O_2 loss, relative to an ambient environmental condition, we rely on previously established change assessment methodologies (Kessouri et al. 2021a) and mechanistic biogeochemical mass balance analysis (Kessouri et al. 2024).

To isolate the effect of DCOR proposed discharges, we subtracted ANTH from EVA (the simulations that includes both ANTH and Platform Eva proposed discharges), so that the remaining effect can be attributed specifically to DCOR discharges. The change assessment relies on a mass balance analysis of net primary productivity (NPP) and respiration, which is the process which links the production of organic matter to pH and O_2 loss. Model output of DIC, alkalinity, silicate, phosphate, temperature, and salinity are used to calculate pH using CO2SYS (Humphreys et al. 2022). Previous analyses have illustrated that land-based inputs altered rates of respiration and remineralization between 0-600m, but most changes occur between 50-150 m. For this reason, monthly averages of the biogeochemical states and rates were calculated for water column depths between 0 and 200 m.

Interpretation of Environmental Effects Vis-a-Vis Numeric Ocean Plan WQO

Model outputs were analyzed to what extent DCOR discharges of 60,000 barrels per day were causing environmental effects of sufficient magnitude to trigger ocean plan WQO (Table 2). Metrics representing these WQO can be divided into two categories: 1) numeric ocean WQOs for pH and O_2 and 2) using methodologies to interpret the narrative chemical WQO, which states "Nutrient materials shall not cause objectionable aquatic growths or degrade indigenous biota."

Important context for this analysis is that the precise methods to determine whether or how an environmental effect trigger a WQO are policy decisions. However, in order to expedite the conversation between DCOR and the Santa Ana Water Board staff on the permit application, we developed and applied an assessment framework representing multiple lines of evidence that can be used to interpret relevance of the findings for Ocean Plan WQO. This assessment framework can be modified as directed by Board staff to come more directly into alignment with their specific policies. These assessment frameworks are described in detail below.

DCOR's proposed discharge of 60,000 barrels/day has the potential to augment eutrophication, but the ambient environment is already nitrogen-enriched and is demonstrating evidence of eutrophication (Kessouri et al, 2021a,b, 2024). Considering this situation, the assessment framework can be applied in two modes: 1) single source effect, in which we can estimate the incremental effect of DCOR proposed discharges and 2) in a cumulative effects assessment mode, which identifies how much the ambient environment already triggers thresholds and how adding DCOR discharges would modify that ambient baseline effect. Therefore, where possible we provide the incremental effect of DCOR proposed discharges and then the cumulative effect of all discharges to provide context for permitting discussions.

For pH and O_2 numeric WQO (Table 2), maps were generated based on the cumulative number of days that the water column exceeded these numeric values relative to ANTH. For pH, changes were assessed over 50-150 m depth, and we found that the WQO of ±0.2 pH units were never triggered, neither in ANTH nor EVA simulations. For that reason, we focused on the numeric O_2 WQO for further analysis.

For O_2, we modified the methodology of Nezlin et al. (2016), which utilizes CTD profiles taken in the impact area and compares them to a "reference" region, based on exceedances of -10% when the impact and reference profile values are matched based on isopycnal (density) surfaces in increments of 0.1. This core comparison methodology is valid, except that work has now been published to show that nowhere on the shelf can be called "reference," because of the widespread extent of anthropogenic nutrient impacts on O_2 loss. For this reason, we assume "reference" can be represented as the ocean only CTRL scenario, since natural riverine nutrient inputs represent < 1% of the total nitrogen inputs to the SCB (Sutula et al. 2021) and climate change effects on ocean conditions are present in both scenarios so therefore removed from the attribution. We match model grid cells in the ANTH and EVA simulations to that same day and location in the CTRL simulation to perform the change assessment. The Nezlin et al. (2016) methodology was developed through a consensus working group of the State Water Board, SCB POTWs and SCCWRP and thus has some level of community acceptance, albeit for a different application.

In each vertical stack of model cells across the model domain for all six simulations (Table 1), the daily averaged O_2 outputs were cut into 0.1 kg/m3 density slices between 1024.7 and 1026 kg/m3, then each slice smoothed over 7 days to remove chaotic variability. Then the change relative to CTRL is computed. Photosynthesis from amplified primary production will increase O_2 in the upper 30 m of the water column but then decline further in the water column due to increased respiration. For this reason, O_2 values greater than 0 were removed, then the 10^{th} percentile of the percent change over the water column computed for each station-day. Values greater than 10% were counted each day that the threshold was triggered. Heat maps were then produced from the number of days the threshold was triggered for the following scenario comparisons: 1) ANTH-CTRL, 2) ANTH2-CTRL, 3) ANTH3-CTRL, and 4) EVA-CTRL. The first of these three were used to compute the mean and ±two standard deviations of the baseline, to provide comparative statistics and an estimate of model uncertainty.

Interpretation of Environmental Effects Vis-a-Vis Narrative Ocean Plan WQO

For narrative chemical WQO, we utilized studies that were either published or in peer review to interpret biological effects of increased productivity, acidification, and O_2 loss on marine life.

Risk of Toxic Harmful Algal Blooms (HABs). Increased productivity elevates algal biomass. The basic premise of the "risk of toxic HABs" metric is predicated on the concept that increased nutrient loading has the potential to elevate the biomass of all algal species including toxic HABs. This would particularly apply to those HAB species that are diatoms, the taxa that have some of the largest algal cells. Diatoms comprise 80% of the total biomass on average in the Southern California Bight (Bialonski et al. 2016). Thus, if anthropogenic nutrient loads increase the biomass of diatoms, then can also elevate the risk of toxic HABs species that belong to that diatom group (Kessouri et al. in review).

The diatom species *Pseudo-nitzschia* is considered one of the most significant conservation threats to marine life on the Pacific Coast (Lewitus et al. 2012) and is one of the most pervasive toxic HAB problems in the SCB (Fig. 7). It produces domoic acid (DA), a potent neurotoxin that causes amnesic shellfish poisoning and has impacts across the marine food web, including stranding and mortality of marine mammals. Sandoval-Belmar et al. (2023) and other authors have found a positive, significant correlation between chl-a (a bulk measure of algal biomass) and the detection of domoic acid (DA) in ambient observations, meaning that nutrient loads are among the major drivers of toxic *Pseudo-nitzschia* booms. Sandoval-Belmar et al. (2023) found a risk-based threshold 3.3 µg/L associated with risk of DA detection reaching 50% probability in the Central Bight. Smith et al. (2022) found that thresholds of DA at the detection limit were associated with an accelerated risk in the a "significant marine mammal stranding event," defined as 2 or more adult sea lions. Kessouri et al. (in review) has demonstrated how this suite of thresholds can be applied to ROMS-BEC predicted chlorophyll-a to predict how anthropogenic nutrient inputs can modify the window of opportunity for DA producing HABs.

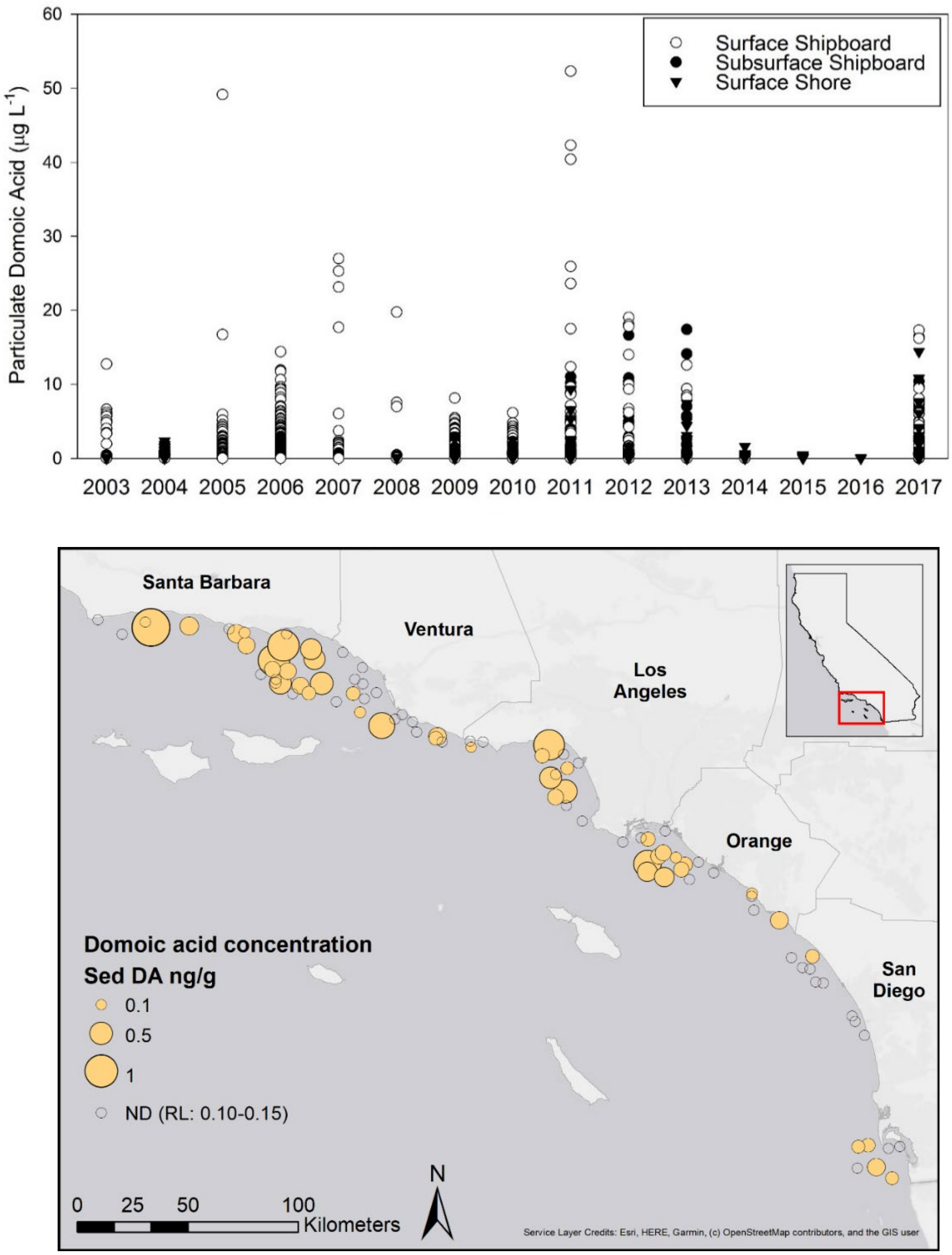

Figure 7. Top panel: from Smith et al. (2018) frequency of particulate domoic acid at pier and offshore sampling stations across the Southern California Bight. Bottom panel: from Smith et al. (2021) evidence of persistent domoic acid found in sediments in the SCB. Empty circles indicate no detection, while size of orange circle indicates magnitude of DA detected.

ROMS-BEC predicts increased productivity and algal biomass based in large part on the growth of diatoms, so predictions in the change of productivity and chl-a in modeled scenarios can be used as a proxy for potential changes in the risk of PN blooms and DA presence in the environment. We used this risk-based framework to identify the number of days that DCOR proposed discharges caused chl-a to exceed a threshold of 3.3 µg/L. Notably, in the CNTRL scenario (without land-based inputs), this threshold is exceeded at a baseline of ~20 days or less (Fig. 8). We first produced heat maps of the number of days in each cell that the ANTH and EVA simulations exceeded this threshold (cumulative impact), minus the days that the CTRL scenario exceeded this risk threshold to correct for natural background variability.

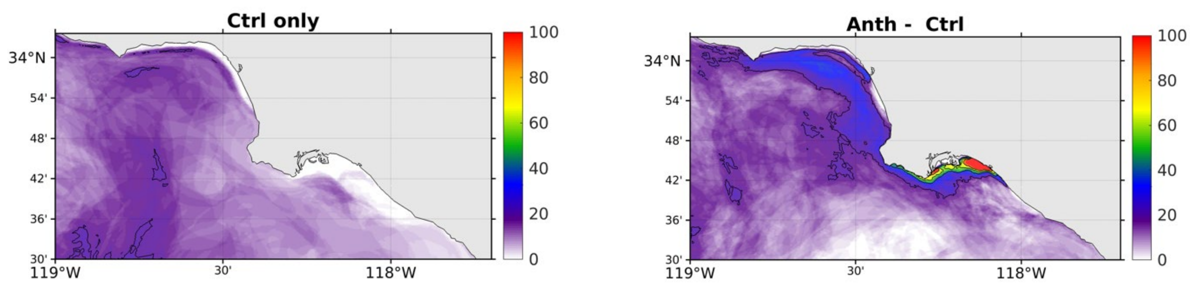

Figure 8. Baseline risk of toxic HABs in the ocean only CTRL scenario. Color bar is the number of days in which the risk based threshold of > 3.3 µg/L was exceeded.

Risk of Habitat Compression from pH and O_2 Loss. Kessouri et al. (2024) found that human nitrogen exports are causing extensive offshore subsurface O_2 and pH loss in the SCB. Frieder et al. (2024) found that these seawater chemistry changes are causing a compression of habitat for O_2 breathing organisms (e.g., fish, invertebrates) and for shell-building organisms (e.g., calcifying plankton such as pteropods). In the SCB, during the late summer, subsurface acidification and O_2 loss routinely compress aerobic and calcifier habitat capacity, at a time period when habitat capacity is already seasonally compressed. Modeled habitat capacity loss is most pronounced where excess nutrients and organic matter, which originate at the coast, are entrained and accumulating within offshore eddies (Kessouri et al. 2024). Thus, the question is whether DCOR proposed discharges have the potential to contribute meaningfully to this environmental problem.

To evaluate the potential biological effects of subsurface acidification and O_2 loss, we used the methodology of Frieder et al. (2024) to quantify changes in habitat capacity for aerobic taxa and for marine calcifiers. The concept of change to habitat capacity is based on the premise that marine organisms are directly influenced by environmental gradients in temperature, O_2, and pH— factors that have been clearly implicated in shifting species distributions (Bograd et al. 2008, Meyer-Gutbrod et al. 2021; Howard et al. 2020a, Pinsky et al. 2020). In the SCB, Frieder et al. (2024) found changes to the vertical thickness of aerobic and calcifier habitat capacity attributable to eutrophication. A region of annually recurring habitat compression is most pronounced 30 – 90 km from the mainland, southeast of Santa Catalina Island. The goal of this analysis is to document how this predicted habitat compression is altered in the nitrogen management and water recycling experiments.

For the effects of subsurface acidification on calcifier habitat capacity, we calculate the vertical thickness of optimal aragonite saturation state (ΩAr) conditions. A value of ΩAr of 1.4 is used to define the condition below which sublethal organismal responses have been documented to commonly occur, in particular for calcifying zooplankton (e.g., pteropods; Bednarsek et al. 2019, 2021a,b). Pteropods are ubiquitous, holoplanktonic calcifiers that have a well-documented, specific sensitivity to OA and serve as an important prey group for the diet of ecologically and economically important fishes, birds, and whales (Armstrong et al. 2005; Aydin et al. 2005; Karpenko et al. 2007). Notably, Frieder et al. (2024) found that the persistence of habitat compression is relatively insensitive to the choice of threshold down to a value of ~1.1.

For the effects of subsurface O_2 loss on aerobic habitat capacity, we rely on the mechanistic framework of the Metabolic Index (Φ; Deutsch et al. 2015; 2020), modified by Frieder et al. (2024). This approach integrates the sensitivity of metabolism to the combined effects of O_2 and temperature on metabolism. Φ is defined as the ratio of O_2 supply to resting demand. We calculate the habitat thickness for which Φ/ΦCRIT ≥ 1, a value below which demarcates environment in which an organism can sustain enough active energetic demands to maintain viable populations. Following the methodology of Frieder et al. (2024), we use metabolic traits for the northern anchovy (*Engraulis mordax*) as an indicator species because (1) habitat range predicted by the Metabolic Index has been validated with abundance data documenting their biogeographic distribution in the southern CCS (Howard et al. 2020); (2) northern anchovy represents the 75th percentile of known O_2 sensitivity traits for the CCS (see Table S1 in Howard et al. 2020) and (3) adult anchovy have historically been observed within 30 km offshore and from 0 to 100 m water depth (Mais 1974), a habitat that aligns with the location of documented effects on seawater chemistry from land-based nutrient inputs (Kessouri et al. 2024).

Evaluation of Effects Relative to Model Uncertainty

An inherent part of all numerical modeling is the uncertainty in the modeled predictions and in the data used to develop them. In this specific application, for scientists and coastal water quality managers to confidently use ROMS-BEC model results, the uncertainty should ideally be smaller than the predicted change attributable to anthropogenic nutrients. Model uncertainty can come from a variety of different sources (see inset box). Multiple approaches to quantifying uncertainty in coastal numerical modeling exist, including model skill assessment, ensemble runs of ROMS-BEC that add specific sources of uncertainty, or ensemble model comparisons.

SOURCES OF OCEAN NUMERICAL MODEL UNCERTAINTY

Internal (or Intrinsic) Variability: Inherent, stochastic variations (e.g., mesoscale eddies) that are a source of uncertainty in predictions.

Input Data/Forcing Uncertainty: Inaccuracy or limited resolution of data used to drive the model at its boundaries, such as oceanic, atmospheric, and terrestrial inputs.

Parameter Uncertainty: Lack of knowledge about the true values of model parameters, which are often difficult to measure directly.

Model Structural and Numerical Uncertainty: Incomplete or imperfect representation of processes in model equations, due to necessary simplifications, numerical approximations, or lack of scientific understanding.

In this study, we chose to conduct uncertainty assessment using an ensemble run approach, based on characterization of intrinsic variability. Intrinsic variability is defined as the variance in outcome parameters of interest in separate model simulations with the same or similar boundary forcing, due to the modeling of stochastic circulation processes. Stochastic processes include phenomena at the frequency of the mesoscale and higher. To induce this stochasticity, Kessouri et al. (2024) perturbated the initial conditions of oceanic boundary forcing for the ANTH scenario and repeated this exercise twice. The variance between these three simulations is used to estimate model noise from intrinsic variability from initial perturbation, a similar approach to that of Sérazin et al. (2015). We utilized the standard deviation between ANTH, ANTH2 and ANTH3 due to intrinsic variability as a simple measure of model uncertainty. This variance was used as a minimum detectable effect to limit the interpretation of the change assessment.

Nitrogen Load Scaling Analysis

The final analysis utilized the most sensitive indicator to illustrate how the risk of eutrophication would scale relative to reductions in the proposed nitrogen loading of Platform Eva.

Preliminary analysis showed that risk of toxic HABs was the most sensitive environmental effect. Therefore, we developed a simple scaling analysis to illustrate how the number of days and area of increased HAB risk would change as a function of reduction in nitrogen loading from the proposed DCOR platform. Normally, this would be done by conducting multiple scenarios in which the proposed discharges are reduced (e.g., 90%, 75%, 10 %) to model how the environmental effect scale. However, because each additional scenario is computationally expensive, we chose to make simplifying assumption that (1) primary productivity and chl-a biomass would scale linearly and proportionally with declining loads, which has been demonstrated in other ROMS-BEC modeling analysis (Ho et al. 2023) and (2) this would translate proportionally to the number of days in which chl-a exceeded the HAB risk threshold.

A substantial amount of time passed between the time this study was conducted and the report drafted (2023) and the time the final report was published. As of August 2025, the proposed discharge for Platform Eva was reduced to 15,000 barrels per day or the equivalent of 360 kg TN/day, or 25% of the original proposed discharges of Platform Eva alone or 18.5% of total 80,000 barrels/d (Eva + Esther). At the request of DCOR, we have updated the analysis of the nitrogen load scaling and expanded the discussion to reflect this current proposal.

3. RESULTS

Comparative nitrogen loads

The initial DCOR proposed discharges (60,000 barrels/day) translate to 1437 kg d^{-1} from Platform Eva. This would translate to a 9% increase in the loading of total nitrogen to the Orange County, San Pedro and Santa Monica Bay subregion, a region that already receives approximately 50% of the total nitrogen loading to the entire SCB. Bight wide, the proposed discharges would augment TN loads by 3%. If that amount of proposed discharge is reduced to 15,000 barrels per day from 60,000 barrels per day for Eva-alone, the increased loading scales accordingly (e.g., 2.125% increase in total nitrogen to the Orange County/Los Angeles subregion; 0.7% increase in TN Bightwide).

Figure 9. Change in subregional nitrogen loads by coastal region due to DCOR (red) versus all other land-based sources (92 % of which are derived from municipal wastewater ocean outfalls).

Effect of DCOR proposed discharges on algal productivity, pH, and O_2 loss

The effect of DCOR proposed discharges at 60,000 barrels/day is predicted to have an increase in algal production rate of up to 50%, localized in the San Pedro region where the platform outfalls occur, with a lower (~10%) but detectable effect offshore (Fig. 10). Fig. 11 shows the net change in chl-a as a cumulative effect when combined with all other sources of anthropogenic nutrients; ANTH alone shows a strong persistent increase in chl-a around the LA and OC coasts, the epicenter of nutrient export onto the coast. DCOR proposed discharges intensify increases in chl-a, extending to Santa Monica Bay and further north along the Ventura Coast.

The period of greatest change in mean monthly chl-a due to DCOR alone was in the winter (December-Mar; Fig. 12), when DCOR proposed discharges double the ambient baseline in the San Pedro shelf. During late spring and summer, the EVA simulation is roughly equivalent to ANTH.

Predicted change in algal production caused a minor increase in respiration, the process responsible for pH and O_2 loss. This change was up to +20% locally near the outfalls, but more typically a mean of +5% and a range of +0 to +10% on a larger throughout the nearshore Bight (Fig. 13).

Seasonally, the highest respiration rates appeared to occur during June to July timeframe (Fig. 14).

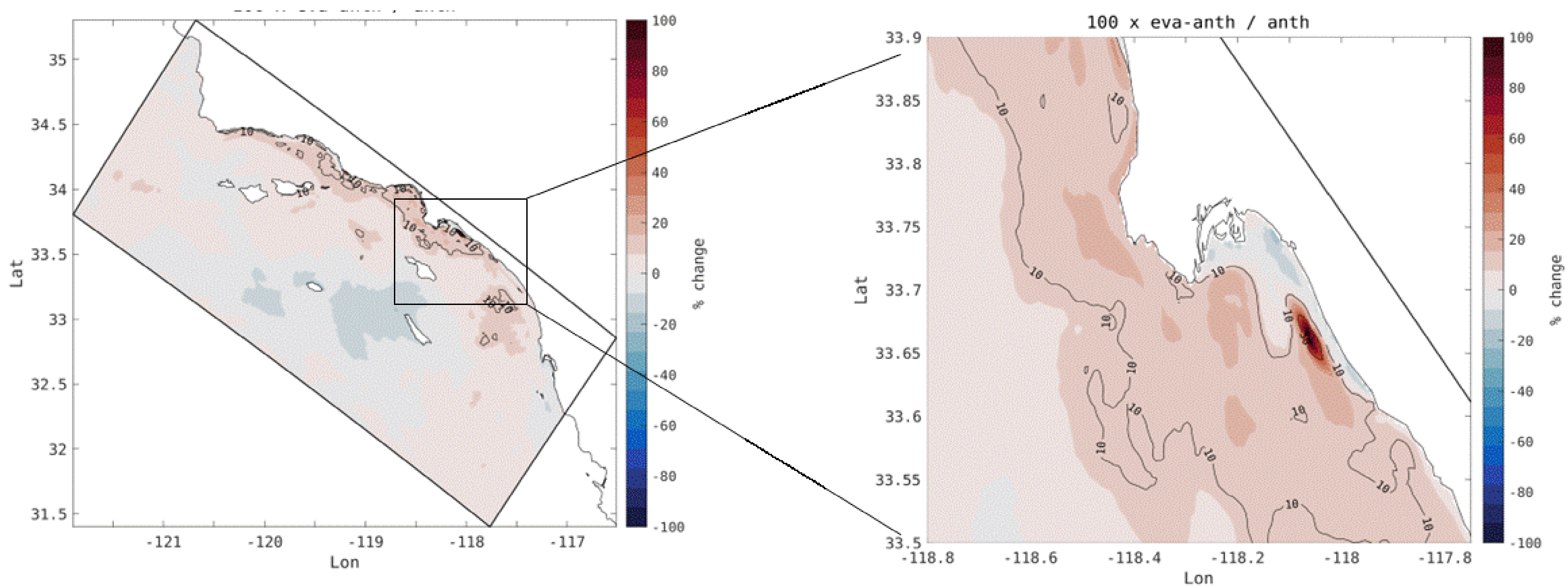

Figure 10. Net effect of Platform Eva on integrated primary production rate (algal productivity). The left panel shows then entire model domain while the right panel show a zoomed in view of San Pedro shelf. The EVA scenario is ambient condition plus initial proposed discharges of 60,000 barrels per day, while ANTH is ambient only.

Figure 11. Left Panel: net change in Chl-a (µg L^{-1}) due to land-based inputs for the ambient condition (ANTH minus CTRL) in the San Pedro and Santa Monica Bay region versus (right panel) that same net change with the additive effecte of the 60,000 barrels per day proposed discharges from Platform Eva (EVA minus CTRL).

Figure 12. Seasonality of chl-a for winter (Dec-March), Late Spring (April-June), and Summer-Fall (July-November) for the San Pedro Bay and Palos Verde Shelf for the CTRL, ANTH and EVA scenarios. The EVA scenario is ambient condition plus initial proposed discharges of 60,000 barrels per day.

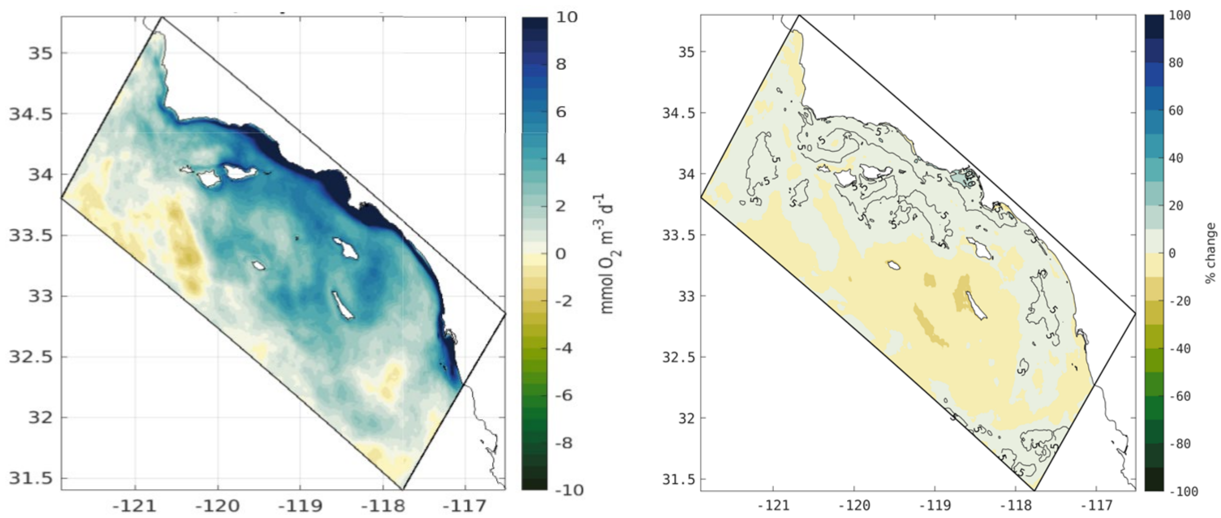

Figure 13. Left panel: Bulk change in respiration rate for ambient conditions (ANTH minus CTRL; right panel: areas that saw positive percent change in respiration rate and percent change in that rate for Platform Eva only at 60,000 barrels per day (EVA- minus ANTH)/ANTH*100), in which ambient effect is removed.

Figure 14. Month change in the respiration rate over 0-200 m due to Platform Eva only proposed discharges of 60,000 barrels per day (EVA minus ANTH)

Interpretation of effects vis-à-vis metrics of California Ocean Plan WQO

Numeric O_2 WQOs

Under ambient conditions without DCOR proposed discharges, O_2 numeric WQOs appears to be already triggered from the inputs of land-based human nutrient inputs in the range of 2 - 55 days for an area up to 1400 km^2 (Figs. 15-16). With simulations of the additive effect of Platform Eva, the range of the duration and the extent in which O_2 WQO are triggered are mostly maintained (Fig. 16), but within the bounds of model uncertainty, and therefore the effects of the produced waters from EVA on the O_2 WQO are not interpretable.

Figure 15. Distribution of area that triggers O_2 WQO as a function of frequency of duration (days) for ANTH minus CTRL and EVA minus ANTH. The collective range of ANTH, ANTH2 and ANTH3 represent model uncertainty, so regions of area-days that exceed these three model runs can be considered more certain. We found no region of the curve where EVA (ANTH+ EVA proposed discharges) of 60,000 barrels per day exceed uncertainty.

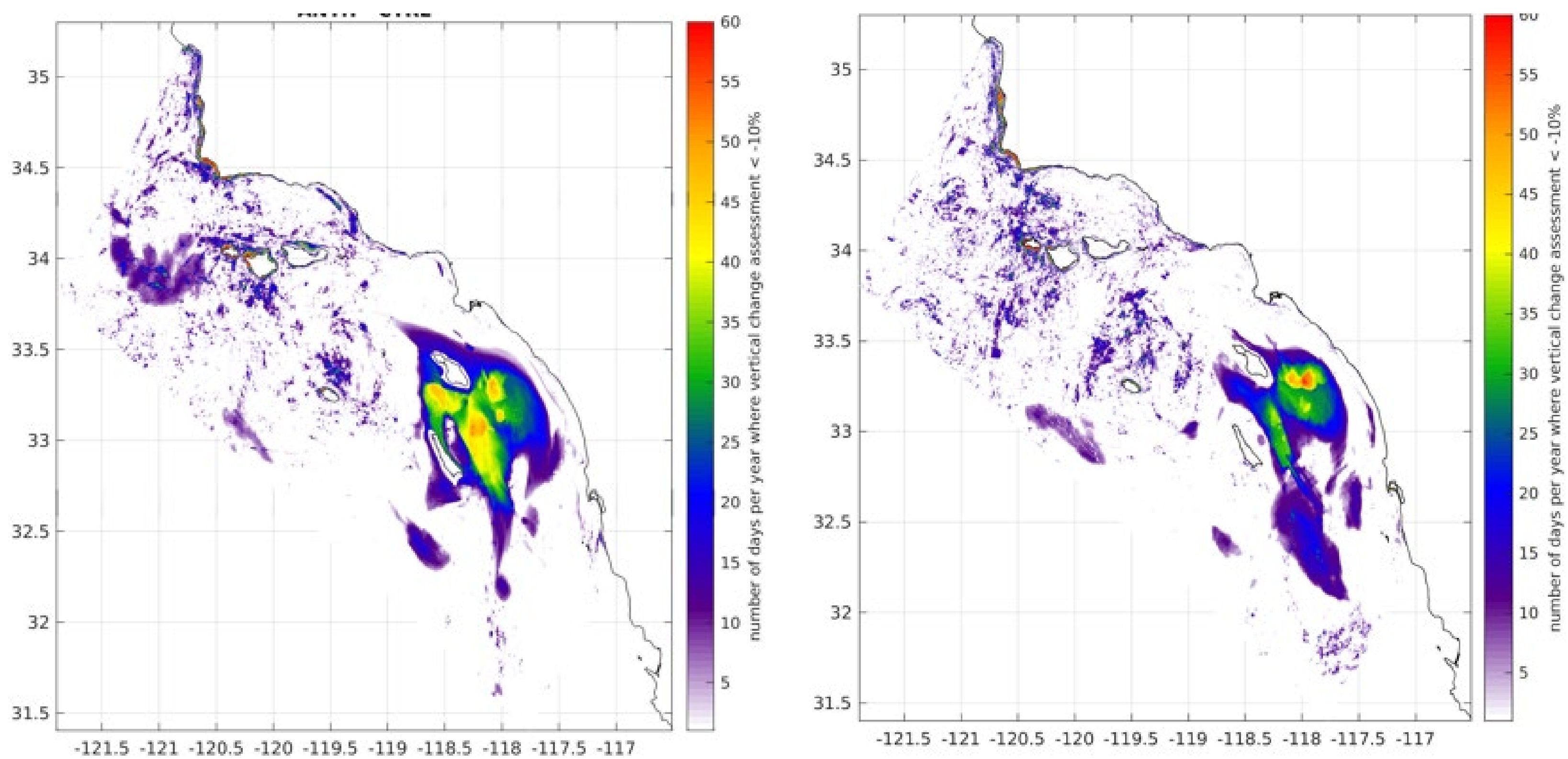

Figure 16. Heat maps of number of days per year in EVA minus CTRL (right panel) simulations trigger the O_2 numeric WQO of ±10% (both of which show the cumulative effect of Platform Eva plus ambient conditions), relative to ANTH minus CTRL (left panel), which shows the ambient condition without DCOR proposed discharges.

Narrative WQO—risk of toxic HABS

Periods of increased HABs risk are naturally occurring—this is demonstrated by the CTRL scenarios shows that the natural background in the San Pedro Bay area and very nearshore Santa Monica Bay 0-20 days (Fig. 17, top left panel). Under ambient conditions (ANTH; top right), this HAB risk appears to double to 50-60 days from natural background in Santa Monica Bay and extends up to 80 days in San Pedro Bay. With full Eva proposed discharges at 60,000 barrels/day (Fig. 17, bottom right panel), the area of risk with high duration (> 50 days) expands in Santa Monica and San Pedro Bays and also appears to cause intensification of HAB risk in Santa Monica Bay. We note that longer simulations would be required to show the long-term average predicted environmental condition that would stabilize over time.

Figure 17. Effect of DCOR proposed changes on the predicted risk of toxic HABs, showing a heat map of the cumulative number of days where chl-a > 3.3. µg L^{-1} for ocean only (top left panel), the ambient condition without DCOR (ANTH; top right panel), then the combinations of ANTH with Platforms Eva (EVA, bottom right).

Thus, proposed discharges from Platform Eva at 60,000 barrels per day are predicted to result in a net increase in the risk of toxic HABs that varies geographically (Fig. 18). The bulks of effects are north of the proposed discharge locations due to the northerly coastal current, although the model predicts changes as far south as Oceanside. Effects are concentrated in a geographic already prone to HABs (Santa Barbara Channel, Santa Monica, and San Pedro Bays). The increased duration ranged from 15 to 80 days.

These changes have a seasonal signature (Fig. 19 top panel). This translates to a difference in the monthly risk of HABs, shown by month for the baseline (ANTH) versus EVA-ANTH (Fig. 19 bottom panel). Excursions of the 3.3 mg m^{-3} threshold due to DCOR proposed discharges are most distinct for the winter period (December-April), the time period of greatest primary productivity.

These predicted effects on chl-a and risk of toxic HABs are greater than model uncertainty (Figs. 20 and 21 respectively). Effects that emerge from model uncertainty are found along the coastline of San Pedro Bay and Santa Monica Bay (Fig. 20). Other regions which cause an elevated risk are found along the Channel Islands (Fig. 21).

Figure 18. Change in the duration of predicted risk of toxic HABs (days/year) by latitude for Eva at 60,000 barrels per day (EVA minus ANTH), which removes the effect of ambient environmental conditions.

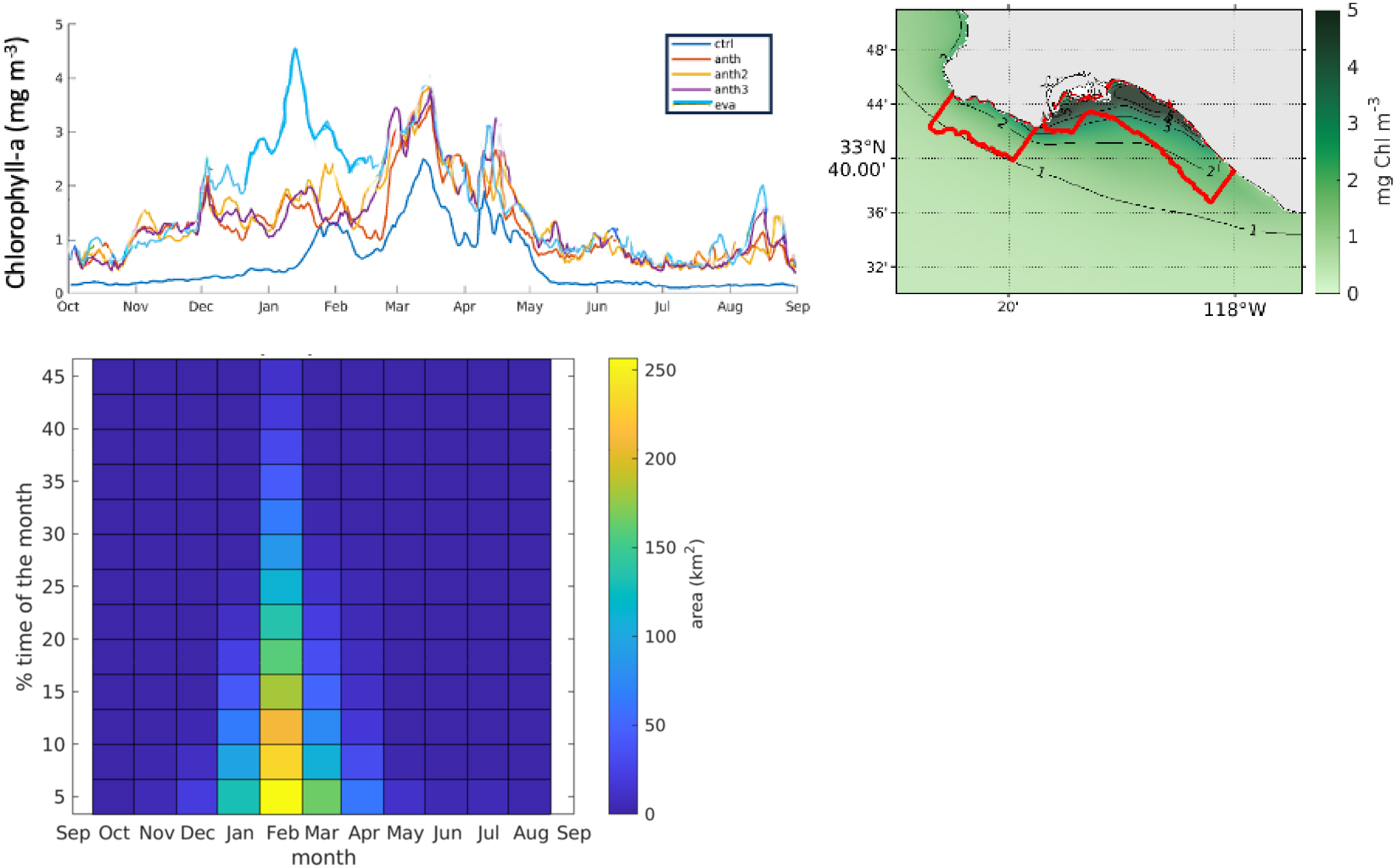

Figure 19. Top panel: Average daily chlorophyll concentration at the surface in San Pedro shelf for the different scenarios, the area contoured in red in the top right panel. Bottom panel: Heat map of the additional area (km^2) under risk of toxic HABs (> 3.3 µg/L) as a function of duration (percent of the month) by month of the year for EVA minus ANTH.

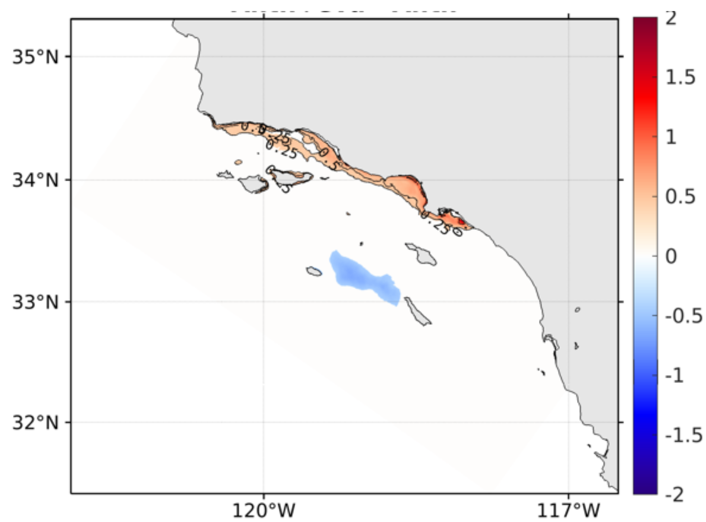

Figure 20. Left Panel: Mean change in chl-a (μg/L) over 14 months for EVA at 60,000 barrels per day minus ANTH after effects of the maximum variance in intrinsic variability runs are removed (i.e. maximum model uncertainty).

Figure 21. Number of days in which risk of toxic HAB exceeded threshold of 3.3 μg/L chl-a, in which maximum model uncertainty is removed for the ANTH minus CTRL simulation (top panel) and EVA alone (EVA minus ANTH; bottom panel), with initial discharge of 60,000 barrels per day.

Narrative WQO—marine habitat compression

Frieder et al. (2024) demonstrated that habitat compression from anthropogenic nutrients in the SCB occurs in the July-November timeframe, a period during which the habitat for aerobic organisms and for marine calcifiers is at its lowest (i.e., critical condition). DCOR proposed discharges are predicted to result in a~ 5% change from the ambient condition (ANTH) during July-October (Fig. 22). The trends are strongly covary between calcifier and aerobic habitat, though typically aerobic habitat greater during the peak period in the July -September time frame. Fig. 23 shows that this habitat compression during EVA runs shows the same spatial coherence as the ANTH simulation, meaning the majority of the signal is due to ANTH and the DCOR proposed discharges are contributing to this.

Uncertainty analysis shows that while this net habitat change is small, the magnitude of compression is greater than model uncertainty for aerobic habitat in the range of 0-7% (Fig. 24), while the magnitude of calcifier compression is roughly within bounds of model uncertainty.

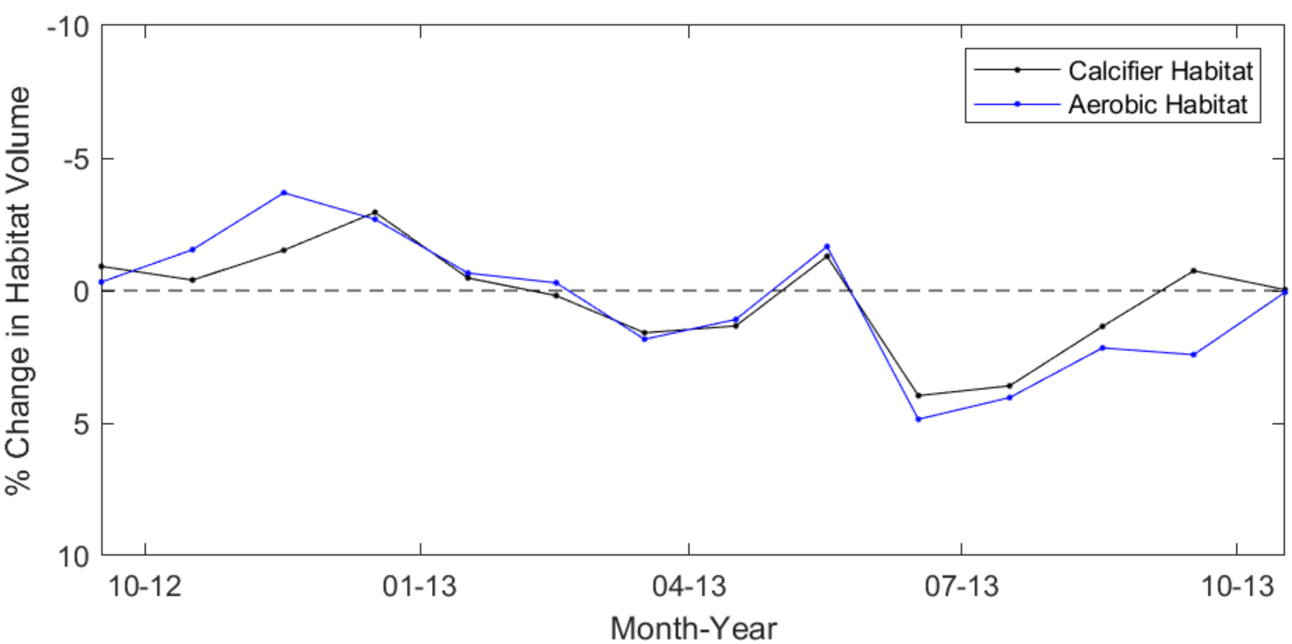

Figure 22. Temporal % change in volume of habitat from ANTH for surface dwelling calcifiers and northern anchovy over 14 month simulation due to Eva proposed discharges of 60,000 barrels per day.

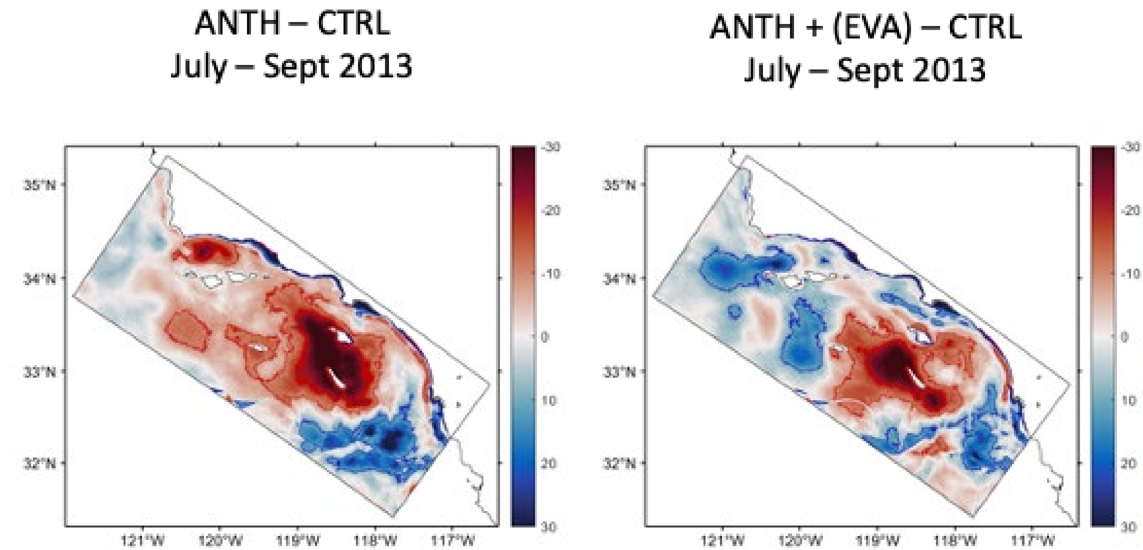

Figure 23. Change in aerobic habitat for northern anchovy (top panel) and in calcifying habitat for pteropods (bottom panel) due to cumulative impacts of ANTH (left side) and Eva at 60,000 barrels per day plus ambient conditions (EVA, right panels). Change is calculated for the three months in this set of simulations. Thin red and blue contours indicate habitat change of greater than ±10%, respectively. Thick red contour indicates habitat compression of greater than 20%.

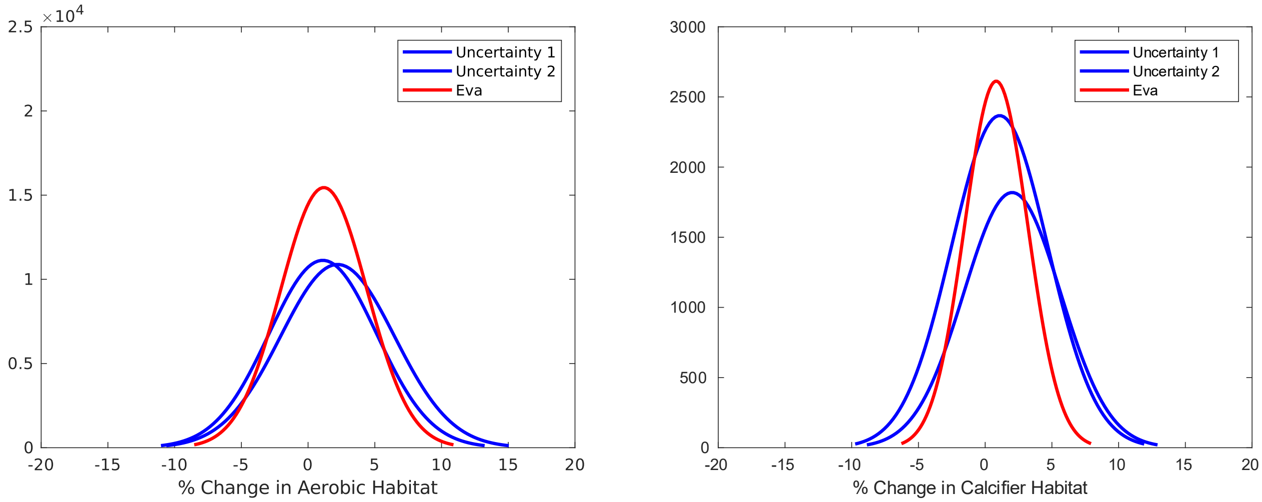

Figure 24. Histograms for % change in habitat (x axis) as a function of size of habitat patch quantified (y axis). Left panel is aerobic habitat and right panel is calcifier habitats. Blue lines indicate uncertainty analyses for ANTH minus ANTH2 and ANTH minus ANTH3. Red lines indicate change due to Eva at 60,000 barrels per day (EVA minus ANTH scenario).

Summary of Uncertainty Analysis

Uncertainty analysis communicates confidence in model findings on the individual effects of EVA alone. The magnitude of effects of proposed DCOR discharges are greater than uncertainty due to intrinsic variability, our best estimate of uncertainty at this time. Choice of endpoints matter (Table 5).

Table 5. Summary of uncertainty analysis applied to individual effects of ambient (ANTH) and incremental effect of Platform Eva at 60,000 barrels alone, in which effect of other anthropogenic inputs are removed.

Change Metric	**Change due to ANTH > greater than model uncertainty**	**Change due to Eva > uncertainty due to model intrinsic variability**
Environmental effects		
Chl-a	**Yes**	**Yes**
O_2	**Yes**	**Yes**
pH	**Yes**	No
Numeric water quality objective (WQO)		
O_2	**Yes**	No
pH	No	No
Narrative Chemical WQO		
Risk of Toxic HABs	**Yes**	**Yes**
Calcifying habitat	**Yes**	No
Aerobic habitat	**Yes**	**Yes**

We used the combined ranges of ANTH, ANTH2 and ANTH3 to constrain our interpretation, determining a "yes" of the change due to EVA was greater than that range. Based on this analysis, we found that uncertainty in ANTH was less than metrics of interpreted water quality goals in for risk of toxic HABS, and habitat compression for aerobic (O_2 breathing) organisms.

Nitrogen scaling analysis

The goal of the nitrogen scaling analysis was to provide a basis for DCOR to discuss with the Santa Ana Water Board what nitrogen loading limits might be acceptable. For this exercise we utilized the most sensitive environmental line of evidence: risk of toxic HABs. The effect of nitrogen loading on the risk of toxic HABs can be expressed as a both change in the spatial footprint as well as the duration (number of days). We applied an arithmetic scaling to the EVA minus ANTH outputs to visualize how the footprint and duration of toxic HAB risk would scale with reductions in nitrogen loading from 100% (no reduction) to 10% of the DCOR proposed loads. We use barrels per day as the absolute unit. Fig. 25 illustrates a visualization of the footprint and duration of predicted risk of toxic HABS would change, while Fig. 26 shows how the total area and duration of HABs reduces as a function of successive loads reductions.

Subsequent to completion of this work and as of August 10, 2025, the proposed discharge for Platform Eva was reduced to 15,000 barrels per day or the equivalent of 360 kg TN/day, or 25% of the original proposed TN loading from Platform Eva-alone, and 19% of total originally proposed loading (1884kg/Day. This proposed discharge, using this simplified analysis, would have the potential to extend the window of opportunity for toxic HABs up to <15 days per year, for an area on the order of 1000s of sq kilometers. This effect is persistent even at smaller discharges of produced water (.e.g., 6,000 barrels/day).

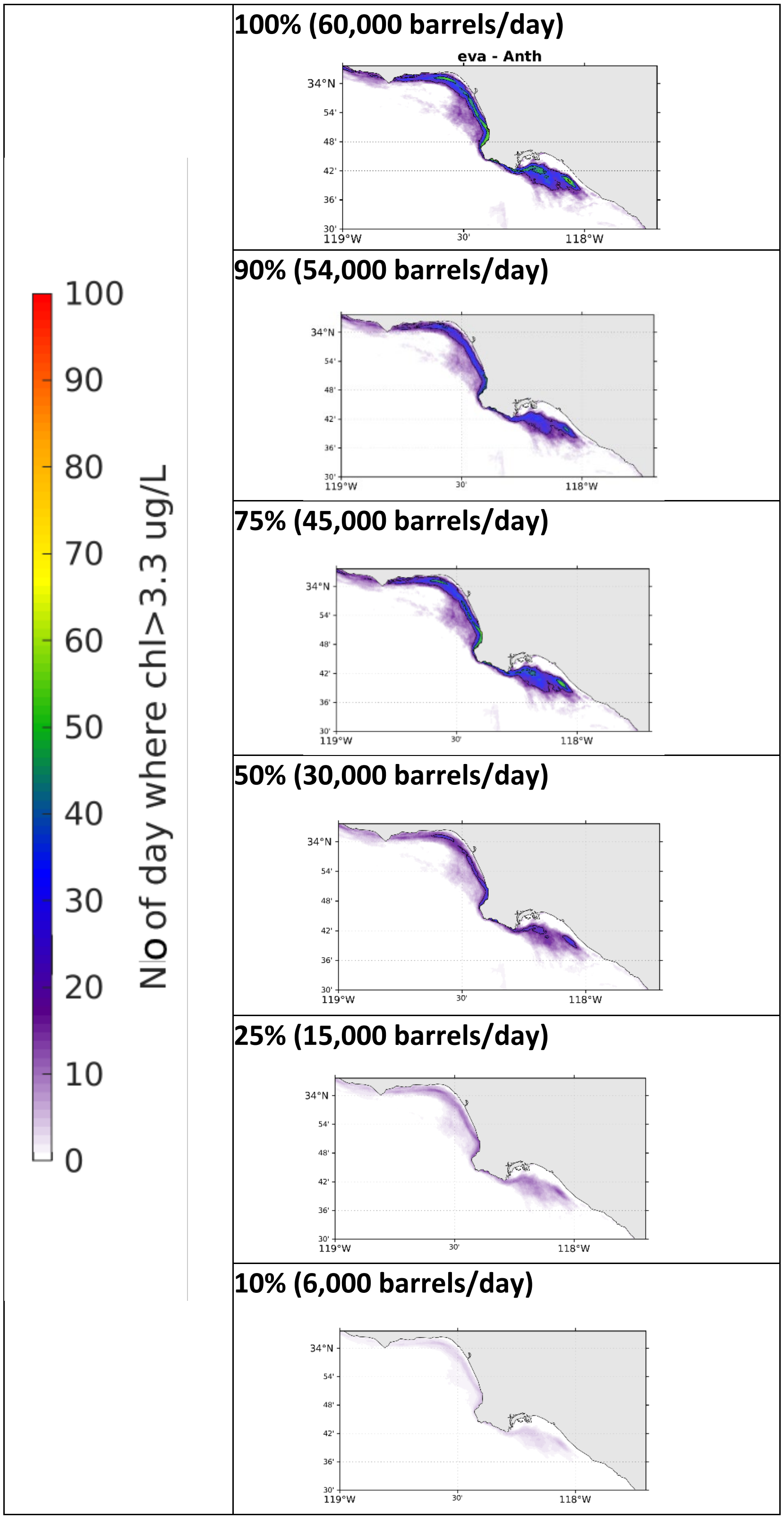

Figure 25. Visualization of the change in spatial area and duration of number of days in which chl-a exceeds toxic HAB risk threshold for EVA minus ANTH, isolating the effect of Platform Eva. The panel series represents a simulated scaling of effects based on an assumed linear reponse from 60,000 to 6,000 barrels/day (100 to10%) of nitrogen loads.

Figure 26. Top panel: Area-duration plot of the additive risk of DA-producing HABs for the mean of ANTH (black line) and the shaded variance due to intrinsic variability, showing the baseline risk of DAproducing HABs. Bottom panel: Plot of the area of risk versus the duration of risk (in days) of predicted risk in DA-producing HABs for the simulated scaling of nitrogen loads, from from 100% of total nitrogen loads (60,000 barrels/day) to 10% of nitrogen loads (6000 barrels per day) of EVA minus ANTH. Shaded area represents area below model uncertainty and therefore is not an interpretable effect. The green line shows the current proposal of 15,000 barrels per day. At this discharge, predicted effects are > ~1000 sq km only for about 15 days.

Discussion

Physical numerical modeling has routinely been used to inform permit applications for ocean outfall discharge permits, but the use of biogeochemical modeling is less common. In the SCB, ROMS-BEC has been used to document the cumulative biogeochemical and biological effects of all land-based sources of human nutrients (Kessouri et al. 2021a, 2021b, 2024, Frieder et al. 2024) and is being used to investigate management scenarios in an idealized, range-finding mode (Ho et al. 2023), and to apportion effects to point versus non-point sources (Kessouri et al in review). This study is the first of its kind to use ROMS-BEC to investigate the effects of a single site-specific source in the SCB waters. Specific protocols have been established for use of field observations to assess compliance with the California Ocean Plan (Nezlin et al. 2016); but protocols for model-based assessments methodologies have not been adopted by Water Board staff, though a quality assurance documentation is now being developed (Sutula et al. 2025a,b). Therefore, the appropriateness of scientific approaches to interpret numeric and narrative WQO should be the focus of discussions between DCOR on the Santa Ana Board staff.

Our study revealed three findings that can inform these discussions, for which we provide more interpretation and context in the ensuing discussion. We note that subsequent to completion of this work and as of August 10, 2025, the proposed discharge for Platform Eva was reduced to 15,000 barrels per day or the equivalent of 308 kg TN d^{-1}, or ~25% of the original proposed TN loading from Platform Eva. Sections on reporting on the predicted environmental effects and linkage to numeric translators of water quality objectives are specific for the full 60,000 barrels per day only, not 15,000 per day. However, we do attempt to account for this reduction in the section on “nitrogen scaling analysis.”

Environmental Effects of DCOR Proposed Discharges

We found that initial DCOR proposed TN discharge from Eva (1437 kg d^{-1}) is relatively small (3% Bight wide, 9% on the LA/OC shelf) relative to other human nitrogen sources. However, the proposed discharge would already be contributing to a coastal ocean that already is enriched with nitrogen (Kessouri et al. 2021, 2024). The modeling predicts at 60,000 barrels per day, increased localized algal production occurs (up to 50% on the San Pedro Shelf), but the shallow region of discharge means that the O_2 and pH loss in the immediate region of DCOR discharge is minimal. Produced organic matter predicted by the model, once dispersed by currents, causes a widespread but small change up to 5% in subsurface O_2 and pH loss dispersed throughout the Bight. These environmental effects are consistent with and contribute to effects described in previously published studies. Kessouri et al. (2021a, 2024) found that land-based inputs, 92% of which are from ocean outfalls (Sutula et al. 2021), are doubling algal productivity within the nearshore coastal band, which causes a region of recurrent $O_{2,}$ and pH decline in a region located

30 – 90 km from the mainland for 4 to 6 months of the year over an area of 278,400 km^2 (30% of SCB area). Kessouri et al. (2024) showed that this phenomenon occurs because of a combination of cross-shelf currents and recurring cyclonic eddies that concentrate algal organic matter. These recurring eddies are the location of predicted acidification and O_2 loss "hot spots."

Interpretation of Effects on Compliance with Numeric and Narrative WQOs

While environmental effects can be predicted by the model, the question is whether they are substantial enough to trigger established water quality goals or whether these changes are biologically relevant. When these environmental effects predicted from ROMS-BEC are filtered through the lens of methodologies that could be used to interpret numeric and narrative WQO[1], that analysis yield multiple findings. First, DCOR individual effects are predicted to contribute to a small expansion of the area that triggers O_2 WQOs but never trigger numeric pH numeric WQO. O_2 WQO were triggered in the ANTH simulation over an area up to 1,081 km^2 for a duration of up to 60 days. The additive effect of DCOR proposed discharges was small, but contributed to the cumulative effect, extending this duration by 5-10 days for up to 528 km^2 of the affected area.

Interpretation of narrative WQOs are understandably more subjective. By precedent, the Water Board has used methods from published studies to interpret biological impacts to list surface waters as impaired (e.g., use of Mazor et al. 2016 to identify impaired biology in wadeable streams) when standard does not exist or when the standard is narrative. In this study, we utilized methodologies, derived from published studies to estimate biological effects of eutrophication via several basic pathways: 1) compression of habitat of "O_2-breathing" organisms (e.g., fish and invertebrates) and of pH-sensitive shelled organisms (e.g., calcifying zooplankton) and 2) risk of toxic HABs.

Habitat Compression. Our study found that predicted seawater chemistry changes from Platform Eva proposed discharges of 60,000 barrels per day would translate to a roughly 5% effect on habitat for marine calcifiers and aerobic habitat for fish. This effect would contribute to a cumulative effect attributable to other human sources of nutrients (Frieder et al. 2024), in which a region of annually recurring habitat compression was found 30 – 90 km from the mainland, southeast of Santa Catalina Island, which represents roughly one quarter of the entire SCB. In that work, anthropogenic nutrient inputs are projected to result in vertical compression of both aerobic and calcifier habitat seasonally by, on average, 25% but can be as much as 60%. This effect can be traced to enhanced remineralization of trapped organic matter that originates from the coast within recurring eddies (Kessouri et al. 2024). The seawater chemistry changes that occur in the top 300 meters of surface waters do not correspond at levels that correspond with acute, lethal effects. However, during the late summer, subsurface acidification and O_2 loss routinely compress aerobic and calcifier habitat capacity at a time period when habitat capacity is already seasonally compressed (Frieder et al. 2024).

The findings are not limited to choice of indicator organism (e.g., northern Anchovy) because habitat loss was consistent for two-thirds of fish and invertebrates in a global database that represent the range of O_2 sensitivity in marine life (although at differing magnitudes of loss). The consequences of sublethal O_2 depletion adversely impacts marine species, assemblages, and even fisheries (Laffoley and Baxter 2019). Long-term deoxygenation trends play a role in, for example, declines in abundance of fish (Koslow et al. 2011) and shifts in zooplankton and small nekton diel migration depth (Bianchi et al. 2013). Within the SCB, northern anchovies have seasonal to interdecadal redistributions that correlate with predicted aerobic habitat capacity (Howard et al. 2020).

Risk of Toxic HABs. The use of the "risk of toxic HABs" paradigm is routinely used to derive nutrient criteria protective against toxic algal blooms in inland and estuarine waters (Yuan et al. 2014; Yuan and Pollard, 2015, Sutula et al. 2017). Our marine "risk of toxic HABs" metric is predicated on the same concept but represents a novel application that has not yet seen routine use to support water quality management conversations in California's coastal oceans. Nonetheless, it is built on solid building blocks of observation-based science (Sandoval-Belmar et al. 2023, Smith et al. 2022) and applied through a validated model that had excellent skill in predicting chl-a relative to 20 years of coastal observations (Kessouri et al. 2021b. 2024).

This endpoint was more sensitive than habitat compression. The model predicts an expansion of the baseline area at risk up to 500 km^2 for 20-80 days of the year in the San Pedro and Santa Monica Bay. This incremental effect is on top of the existing ambient baseline condition, in which relative to a natural background scenario background of "no land-based inputs" are predicted to result in an increased risk of toxic HABs of up to for four months per year and over an area thousands of square kilometers in size. Increased algal biomass predicted from the proposed DCOR discharges could extend the risk of HABs by 20-80 days per year on San Pedro shelf and Santa Monica Bay. This risk estimate is probabilistic, not deterministic, meaning that this estimated risk does not mean that a bloom will occur. The appropriate analogy is risk of chronic disease or cancer; poor diet, smoking, lack of exercise does not mean that an individual will fall ill with a chronic disease. However, these risk factors contribute to the likelihood that disease can occur and can be managed to lower the risk. Climate change is already exacerbating conditions which support HABs (higher temperature, thermal stratification, drought and associated low flows and long residence time, high irradiance, high pCO_2 waters; Burford et al. 2020). Coastal waters that are affected by eutrophication are more likely to see an amplification of this problem, in combination with other stressors (acidification, hypoxia) can heighten stress for marine organisms (Bufford et al. 2020). Given the lack of local control over this global risk factor, human nitrogen loading represents a management knob that can be wielded to mitigate the risk, albeit at substantial capital and recurring costs.

Our analysis suggests that this risk has a seasonal component. Peak season for *Pseudo-nitzschia* blooms is the spring upwelling season (Smith et al. 2018) and our model predicted that risks peak during this period during the ambient (ANTH) conditions and would be further exacerbated by additional nitrogen loading. Scientists have also observed that fall *Pseudo-nitzschia* blooms can occur; the 2022 bloom in the Santa Barbara Channel that resulted in the stranding of over 400 sea lions is a good example of this event. Our modeling demonstrated a September increase in chl-a during the simulated 2013 time period, but during that month, chl-a levels did not reach a sufficient biomass to present a toxic HAB risk. We note that the 2013 simulation year is an average ocean condition. Longer simulations that capture variability in ocean state would be necessary to better bracket the range of risk during both spring and fall diatom blooms. We also note that other HABs species are problematic for the Bight. For example, dinoflagellate blooms (e.g., red tides) are more prevalent during the summertime (Kahru et al. 2021), but our analysis does not attempt to capture these types of organisms.

Uncertainty Assessment. For coastal water quality managers to confidently use ROMS-BEC model results, the uncertainty should ideally be smaller than the predicted change attributable to anthropogenic nutrients (Sutula et al. 2016, Sutula et al. in 2026). Multiple approaches to quantifying uncertainty in coastal numerical modeling exist, including model skill assessment, sensitivity analyses, data assimilation for parameter estimation, and multiple model comparisons, or combinations of these approaches. In this analysis, we utilized one measure of model uncertainty—intrinsic variability a.k.a. model noise from the three ANTH, ANTH2 and ANTH3 simulations—to place a practical limit, the minimum interpretable effect due to DCOR proposed discharges and other anthropogenic inputs. Thus, uncertainty analysis can help us communicate confidence in model findings on the individual effects of Platform Eva alone.

The modeled individual effects from the initially proposed discharges of Eva at 60,000 barrels per day all exceeded model uncertainty due to intrinsic variability for two endpoints: 1) risk of toxic HABs and 2) aerobic habitat compression. Ultimately, other short-term, practical improvements could enhance how this approach is more routinely applied to support decisions. For example, we utilized three existing ANTH scenarios of 15 months in duration as a minimal test. Extending the simulations to encompass multiple years and climate states and increasing the number of uncertainty runs would improve estimates of intrinsic variability. Other work contributes to an assessment of model readiness or adequacy to support these types of decisions, including model validation studies (Deutsch et al. 2021, Kessouri et al. 2021b), independent expert review of the model development, validation and early applications to eutrophication studies (NWRI 2025) and quality assurance documentation (Sutula et al. 2025a,b).

Management Options. We do not presume the outcomes of permit discussions, only present science. However, SCCWRP was asked by both DCOR and Santa Ana Waterboard to investigate options to remediate these predicted environmental effects, which included reducing loads (e.g., choose to permit only one platform, reduce planned volume of discharge, or lower-total inorganic nitrogen concentration or change depth of discharge to below photic zone, which could reduce the amount of primary productivity locally within the region around the outfall.

The work of Ho et al. (2023) gives us some confidence that primary productivity and algal biomass scale with declines in inorganic nitrogen loading. We provide a scaling analysis that illustrates how reductions in mass nitrogen loading from Platform Eva could result in changes in the area and duration of risk of toxic HABs, the most sensitive endpoint. Subsequent to completion of this work and as of August 10, 2025, the proposed discharge for Platform Eva was reduced to 15,000 barrels per day or the equivalent of 360 kg TN $d^{-}1$ TN/day. This newly proposed discharge translates to roughly ~25% of the initial proposal for Platform Eva alone, which through simplified scaling analysis is predicted to narrow the window of opportunity for toxic HABs to less than 15 days, with an area thousands of square kilometers. This does not mean that toxic HABs will not occur, only that such a discharge will reduce the contribution to the non-trivial elevated risk contributed by a much larger baseline of anthropogenic nutrient inputs (Kessouri et al. in review).

REFERENCES

Aydin, K.Y., McFarlane, G.A., King, J.R., Megrey, B.A. and Myers, K.W., 2005. Linking oceanic food webs to coastal production and growth rates of Pacific salmon (Oncorhynchus spp.), using models on three scales. Deep Sea Research Part II: Topical Studies in Oceanography, 52(5-6), pp.757-780.

Bednaršek, N., Feely, R.A., Howes, E.L., Hunt, B.P., Kessouri, F., León, P., Lischka, S., Maas, A.E., McLaughlin, K., Nezlin, N.P. and Sutula, M., 2019. Systematic review and meta-analysis toward synthesis of thresholds of ocean acidification impacts on calcifying pteropods and interactions with warming. Frontiers in Marine Science, 6, p.227.

Bialonski S. et al. 2016. Phytoplankton dynamics in the Southern California Bight indicate a complex mixture of transport and biology, Journal of Plankton Research, Volume 38, Issue 4, July/August 2016, Pages 1077–1091, https://doi.org/10.1093/plankt/fbv122

Bianchi, D., Galbraith, E.D., Carozza, D.A., Mislan, K.A.S. and Stock, C.A., 2013. Intensification of open-ocean oxygen depletion by vertically migrating animals. Nature Geoscience, 6(7), pp.545-548.

Bograd, S.J., Castro, C.G., Di Lorenzo, E., Palacios, D.M., Bailey, H., Gilly, W., and Chavez, F.P., 2008. Oxygen declines and the shoaling of the hypoxic boundary in the California Current. Geophysical Research Letters, 35(12).

Burford, C.C. Carey, D.P. Hamilton, J. Huisman, H.W. Paerl, S.A. Wood, A. Wulff. 2020 Perspective: advancing the research agenda for improving understanding of cyanobacteria in a future of global change. Harmful Algae, 91 (2020), Article 101601, 10.1016/j.hal.2019.04.004

Capet, X., Mcwilliams, J.C., Molemaker, M.J. and Shchepetkin, A.F., 2008. Mesoscale to submesoscale transition in the California Current System. Part I: Flow structure, eddy flux, and observational tests. Journal of physical oceanography, 38(1), pp.29-43.

Capet, X., McWilliams, J.C., Molemaker, M.J. and Shchepetkin, A.F., 2008. Mesoscale to submesoscale transition in the California Current System. Part II: Frontal processes. Journal of Physical Oceanography, 38(1), pp.44-64.

Capet, X., McWilliams, J.C., Molemaker, M.J. and Shchepetkin, A.F., 2008. Mesoscale to submesoscale transition in the California Current System. Part III: Energy balance and flux. Journal of Physical Oceanography, 38(10), pp.2256-2269.

Dauhajre, D.P., McWilliams, J.C. and Uchiyama, Y., 2017. Submesoscale coherent structures on the continental shelf. Journal of Physical Oceanography, 47(12), pp.2949-2976.

Deutsch, C., Ferrel, A., Seibel, B., Pörtner, H.O. and Huey, R.B., 2015. Climate change tightens a metabolic constraint on marine habitats. Science, 348(6239), pp.1132-1135.

Deutsch, C., Frenzel, H., McWilliams, J.C., Renault, L., Kessouri, F., Howard, E., Liang, J.H., Bianchi, D. and Yang, S., 2021. Biogeochemical variability in the California Current system. Progress in Oceanography, 196, p.102565.

Deutsch, C., Penn, J.L. and Seibel, B., 2020. Metabolic trait diversity shapes marine biogeography. Nature, 585(7826), pp.557-562.

Dong, C., Idica, E.Y. and McWilliams, J.C., 2009. Circulation and multiple-scale variability in the Southern California Bight. Progress in Oceanography, 82(3), pp.168-190.

Dong, C., McWilliams, J.C. and Shchepetkin, A.F., 2007. Island wakes in deep water. Journal of Physical Oceanography, 37(4), pp.962-981.

Frieder, C. A., Kessouri, F., Ho, M., Sutula, M., Bianchi, D., McWilliams, J. C., Deutsch, C., & Howard, E. (2024). Effects of urban eutrophication on pelagic habitat capacity in the Southern California Bight. Frontiers in Marine Science, 11. https://doi.org/10.3389/fmars.2024.1392671

Ho, M., Molemaker, J.M., Kessouri, F., McWilliams, J.C. and Gallien, T.W., 2021. High-resolution nonhydrostatic outfall plume modeling: Crossflow validation. Journal of Hydraulic Engineering, 147(8), p.04021028.

Ho, M., Kessouri, F., Frieder, C. A., Sutula, M., Bianchi, D., & McWilliams, J. C. (2023). Effect of ocean outfall discharge volume and dissolved inorganic nitrogen load on urban eutrophication outcomes in the Southern California Bight. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-48588-2

Howard, E.M., Penn, J.L., Frenzel, H., Seibel, B.A., Bianchi, D., Renault, L., Kessouri, F., Sutula, M.A., McWilliams, J.C. and Deutsch, C., 2020. Climate-driven aerobic habitat loss in the California Current System. Science advances, 6(20), p.eaay3188.

Howard, M.D., Sutula, M., Caron, D.A., Chao, Y., Farrara, J.D., Frenzel, H., Jones, B., Robertson, G., McLaughlin, K. and Sengupta, A., 2014. Anthropogenic nutrient sources rival natural sources on small scales in the coastal waters of the Southern California Bight. Limnology and Oceanography, 59(1), pp.285-297.

Humphreys, M.P., Lewis, E.R., Sharp, J.D. and Pierrot, D., 2022. PyCO2SYS v1. 8: marine carbonate system calculations in Python. Geoscientific Model Development, 15(1), pp.15-43.

Jirka, A.M., and Carter, M.J., 1975. Micro semiautomated analysis of surface and waste waters for chemical oxygen demand. Analytical chemistry, 47(8), pp.1397-1402.

Karpenko, V.I., Volkov, A.F. and Koval, M.V., 2007. Diets of pacific salmon in the sea of okhotsk, bering sea, and northwest pacific ocean. N. Pac. Anadr. Fish Comm. Bull, 4, pp.105-116.

Kahru M., Clarissa Anderson, Andrew D. Barton, Melissa L. Carter, Dylan Catlett, Uwe Send, Heidi M. Sosik, Elliot L. Weiss, B. Greg Mitchell; Satellite detection of dinoflagellate blooms off California by UV reflectance ratios. Elementa: Science of the Anthropocene 21 January 2021; 9 (1): 00157. doi: https://doi.org/10.1525/elementa.2020.00157

Kessouri, F., Bianchi, D., Renault, L., McWilliams, J.C., Frenzel, H. and Deutsch, C.A., 2020. Submesoscale currents modulate the seasonal cycle of nutrients and productivity in the California Current System. Global Biogeochemical Cycles, 34(10), p.e2020GB006578.

Kessouri, F., McLaughlin, K., Sutula, M., Bianchi, D., Ho, M., McWilliams, J.C., Renault, L., Molemaker, J., Deutsch, C. and Leinweber, A., 2021. Configuration and validation of an oceanic physical and biogeochemical model to investigate coastal eutrophication in the Southern California Bight. Journal of Advances in Modeling Earth Systems, 13(12), p.e2020MS002296.

Kessouri, F., McWilliams, J.C., Bianchi, D., Sutula, M., Renault, L., Deutsch, C., Feely, R.A., McLaughlin, K., Ho, M., Howard, E.M. and Bednaršek, N., 2021. Coastal eutrophication drives acidification, oxygen loss, and ecosystem change in a major oceanic upwelling system. Proceedings of the National Academy of Sciences, 118(21), p.e2018856118.

Kessouri, F., Renault, L., McWilliams, J.C., Damien, P. and Bianchi, D., 2022. Enhancement of oceanic eddy activity by fine-scale orographic winds drives high productivity, low oxygen, and low pH conditions in the Santa Barbara Channel. Journal of Geophysical Research: Oceans, p.e2022JC018947.

Kessouri, F., Sutula, M. A., Bianchi, D., Ho, M., Damien, P., McWilliams, J. C., Frieder, C. A., Renault, L., Frenzel, H., McLaughlin, K., & Deutsch, C. (2024). Cross-shore transport and eddies promote large scale response to urban eutrophication. Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-57626-6

Kessouri, F., Sutula, M., McWilliams, J.C., Smith, J., Sandoval-Belmar M., Bianchi, D., Damien, P., Kudela, R., Anderson, C. in prep-a. Climate, anthropogenic, and mesoscale influences on diatom biomass and implication for domoic acid producing harmful algal blooms in the Southern California Bight. In preparation for submission to Frontiers in Marine Science.

Kessouri, F., Sutula, M., McWilliams, Bianchi, D., Damien, P., Ho, M., and Frieder, C. in prep-b. Relative contributions of pathways of anthropogenic nutrient loads to aerobic habitat compression and risk of domoic acid events in the Southern California Bight. In preparation for submission to Marine Pollution Bulletin.

Koslow, J.A., Goericke, R., Lara-Lopez, A. and Watson, W., 2011. Impact of declining intermediate-water oxygen on deepwater fishes in the California Current. Marine Ecology Progress Series, 436, pp.207-218.

Laffoley D, Baxter JM. Ocean deoxygenation: Everyone's problem-Causes, impacts, consequences, and solutions. Gland, Switzerland: IUCN; 2019.

Lewitus, A.J., Horner, R.A., Caron, D.A., Garcia-Mendoza, E., Hickey, B.M., Hunter, M., Huppert, D.D., Kudela, R.M., Langlois, G.W., Largier, J.L. and Lessard, E.J., 2012. Harmful algal blooms along the North American west coast region: History, trends, causes, and impacts. Harmful algae, 19, pp.133-159.

Mais, K.F., 1974. Pelagic fish surveys in the California Current.

Mazor, R.D., Rehn, A.C., Ode, P.R., Engeln, M., Schiff, K.C., Stein, E.D., Gillett, D.J., Herbst, D.B. and Hawkins, C.P., 2016. Bioassessment in complex environments: designing an index for consistent meaning in different settings. Freshwater Science, 35(1), pp.249-271.

Meyer-Gutbrod, E.L., Greene, C.H., Davies, K.T. and Johns, D.G., 2021. Ocean regime shift is driving the collapse of the North Atlantic right whale population. Oceanography, 34(3), pp.22-31.

Moore, J.C., McCann, K. and de Ruiter, P.C., 2005. Modeling trophic pathways, nutrient cycling, and dynamic stability in soils. Pedobiologia, 49(6), pp.499-510.

Moore, J.K., Lindsay, K., Doney, S.C., Long, M.C. and Misumi, K., 2013. Marine ecosystem dynamics and biogeochemical cycling in the Community Earth System Model [CESM1 (BGC)]: Comparison of the 1990s with the 2090s under the RCP4. 5 and RCP8. 5 scenarios. Journal of Climate, 26(23), pp.9291-9312.

National Water Research Institute. (2025). *Consensus Findings and Recommendations for the ROMS-BEC Model* (24-398-CASA-13). National Water Research Institute.

Nezlin, N.P., Booth, J.A.T., Beegan, C., Cash, C.L., Gully, J.R., Latker, A., Mengel, M.J., Robertson, G.L., Steele, A., and Weisberg, S.B., 2016. Assessment of wastewater impact on dissolved oxygen around southern California's submerged ocean outfalls. Regional Studies in Marine Science, 7, pp.177-184.

Niu, G.Y., Yang, Z.L., Mitchell, K.E., Chen, F., Ek, M.B., Barlage, M., Kumar, A., Manning, K., Niyogi, D., Rosero, E. and Tewari, M., 2011. The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. Journal of Geophysical Research: Atmospheres, 116(D12).

Pinsky, M.L., Selden, R.L. and Kitchel, Z.J., 2020. Climate-driven shifts in marine species ranges: Scaling from organisms to communities. Annual review of marine science, 12, pp.153-179.

Renault, L., McWilliams, J.C., Kessouri, F., Jousse, A., Frenzel, H., Chen, R. and Deutsch, C., 2021. Evaluation of high-resolution atmospheric and oceanic simulations of the California Current System. Progress in Oceanography, 195, p.102564.

Sandoval-Belmar, M., Smith, J., Moreno, A.R., Anderson, C., Kudela, R.M., Sutula, M., Kessouri, F., Caron, D.A., Chavez, F.P. and Bianchi, D., 2023. A cross-regional examination of patterns and environmental drivers of Pseudo-nitzschia harmful algal blooms along the California coast. Harmful Algae, 126, p.102435.

Sengupta, A., Sutula, M.A., McLaughlin, K., Howard, M., Tiefenthaler, L. and Von Bitner, T., 2013. Terrestrial nutrient loads and fluxes to the Southern California Bight, USA. Southern California Coastal Water Research Project 2013 Annual Report, pp.245-258.

Shchepetkin, A.F. and McWilliams, J.C., 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean modelling, 9(4), pp.347-404.

Skamarock, W.C. and Klemp, J.B., 2008. A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. Journal of computational physics, 227(7), pp.3465-3485.

Smith, J., Connell, P., Evans, R.H., Gellene, A.G., Howard, M.D., Jones, B.H., Kaveggia, S., Palmer, L., Schnetzer, A., Seegers, B.N. and Seubert, E.L., 2018. A decade and a half of Pseudo-nitzschia spp. and domoic acid along the coast of southern California. Harmful Algae, 79, pp.87-104.

Smith, J., Shultz, D., Howard, M.D., Robertson, G., Phonsiri, V., Renick, V., Caron, D.A., Kudela, R.M. and McLaughlin, K., 2021. Persistent domoic acid in marine sediments and benthic infauna along the coast of Southern California. Harmful Algae, 108, p.102103. doi.org/10.1016/j.hal.2021.102103.

Sutula, M., Ho, M., Sengupta, A., Kessouri, F., McLaughlin, K., McCune, K. and Bianchi, D., 2021. A baseline of terrestrial freshwater and nitrogen fluxes to the Southern California Bight, USA. Marine Pollution Bulletin, 170, p.112669.

Sutula, M., F. Kessouri, C. Frieder, N. Lombardo. 2025a. Quality Control Procedures for the Development, Validation and Science Applications of the Regional Ocean Modeling System with Biogeochemical Elemental Cycling Model (2019-2026). Technical Report 1444. Southern California Coastal Water Research Project. Costa Mesa, CA. www.sccwrp.org

Sutula, M., F. Kessouri, C. Frieder, and N. Lombardo. 2025b. Quantifying Uncertainty in Oxygen

Predictions of an Ocean Numerical Model: A Case Study of An Anthropogenic Nutrient Effect Assessment. Technical Report 1445. Southern California Coastal Water Research Project. Costa Mesa, CA. www/sccwrp.org

Sutula, M., Howard, M., Crowder, L., McAfee, S. (2014). Modeling in support of the management of coastal hypoxia and acidification in the California Current Ecosystem. December 10-11, 2013, Workshop Proceedings, published March 2014. SCCWRP Technical Report 829.

Sutula, M., Senn, D., Fono, L., Ho, M., Karimpour, F., Kessouri, F., King, A., Latker, A., and Markle, P. (2021b). Approaches to Quantifying Uncertainty in Coastal Eutrophication Numerical Modeling: A Workshop Summary. Joint Report of the Southern California Coastal Water Research Project (Technical Report No. 1211; www.sccwrp.org) and the San Francisco Estuary Institute (Technical Report No. 1042; www.sfei.org)

Uchiyama, Y., Idica, E.Y., McWilliams, J.C., and Stolzenbach, K.D., 2014. Wastewater effluent dispersal in Southern California bays. Continental Shelf Research, 76, pp.36-52.

Yuan, L.L., Pollard, A.I., Pather, S., Oliver, J.L. and D'Anglada, L. (2014), Managing microcystin: identifying national-scale thresholds for total nitrogen and chlorophyll a. Freshw Biol, 59: 1970-1981. https://doi.org/10.1111/fwb.12400

Yuan, L.L., Pollard, A.I. 2017 Environ. Sci. Technol. 2017, 51, 12, 6972–6980, May 31, 2017, doi.org/10.1021/acs.est.7b01410