SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT AUTHORITY

THEMATIC RESEARCH PLAN

FOR

CLIMATE RESILIENCY

Last revised November 2024

Table of Contents

Introduction

Climate resiliency refers to the capacity of aquatic systems and aquatic resources to maintain their structure and functioning in the face of climate change. As global climate change shifts environmental baselines and expectations around the world, California's aquatic systems will experience pervasive, gradually intensifying combinations of environmental stressors that will fundamentally alter ecological condition and functioning; these stressors include rising water temperatures, declining dissolved oxygen levels, reduced bioavailability of dissolved minerals, rising sea levels and storm surge, and increasing hydromodification and flooding risks. Notably, these stressors transcend jurisdictional boundaries and are projected to intensify for generations to come. While the root causes of climate change need to be managed at a global scale, the aquatic ecosystem effects of climate change are manifesting at regional and local scales. Not only are there a range of different ways that these effects are manifesting, but these effects also are combining with one another and with other local environmental stressors to exert synergistic (i.e., co-occurring) effects. Because the effects of climate change both manifest locally and need to be managed locally, the actions that local managers take have an outsized influence in shaping the long-term resiliency of Southern California's aquatic systems in the face of climate change.

SCCWRP is playing a key role in helping managers to future-proof the climate resiliency of local aquatic systems. SCCWRP recognizes that as scientists build capacity to understand the current and future projected effects of climate change, managers will increasingly need to focus on identifying viable, effective solutions for promoting and optimizing long-term climate resiliency, as well as measuring the efficacy of these solutions, from both an ecological and social/community benefits perspective. Moreover, the decision-making frameworks and strategies that managers use to identify climate solutions will look very different from traditional environmental management paradigms. Instead of locally triggered environmental stressors that are managed as static, one-off and/or isolated issues, managers will be called upon to develop multi-decade planning and adaptation strategies that reflect the dynamic, co-occurring nature of climate change stressors. To that end, SCCWRP's research plan for Climate Resiliency presents a comprehensive, forward-looking vision for how managers can take advantage of a range of decision-making frameworks, tools, strategies and case studies to seamlessly integrate climate resiliency planning into routine planning and decision-making processes.

Conceptual Model

Climate resiliency is defined as the capacity of socioeconomic[1], natural, and semi-natural systems to cope with short and long-term disturbances – induced by global and local factors, extreme events, and human impacts – by adapting while simultaneously striving to maintain their

[1] socioeconomic refers to economic, social, environmental justice effects on local communities, but excludes direct effects on infrastructure

structure and essential functions. SCCWRP is focused on addressing three main questions around climate resiliency:

1. ***How will changes in key drivers associated with climate change affect the long-term health/resiliency of aquatic ecosystems?*** Through this research, SCCWRP is evaluating trajectories of response in physical and chemical stressors, the risk to habitats and biological communities associated with these projected changes, and tools to relate risk to management targets
2. ***What are solutions/actions that managers can take to help address climate change effects and ensure long-term health and resiliency of aquatic ecosystems?*** Through this research, SCCWRP is evaluating design properties and relative efficacy of a variety of traditional and nature-based strategies to inform more detailed, location-specific project designs and implementation approaches
3. ***How can the effectiveness of management actions be measured/evaluated to adaptively improve the ability to manage and protect aquatic ecosystems?*** Through this research, SCCWRP is performing comprehensive assessments of ecological, economic, and social benefits and potential undesirable consequences, as well as conducting tradeoff analysis and developing metrics to evaluate performance and inform adaptive management.

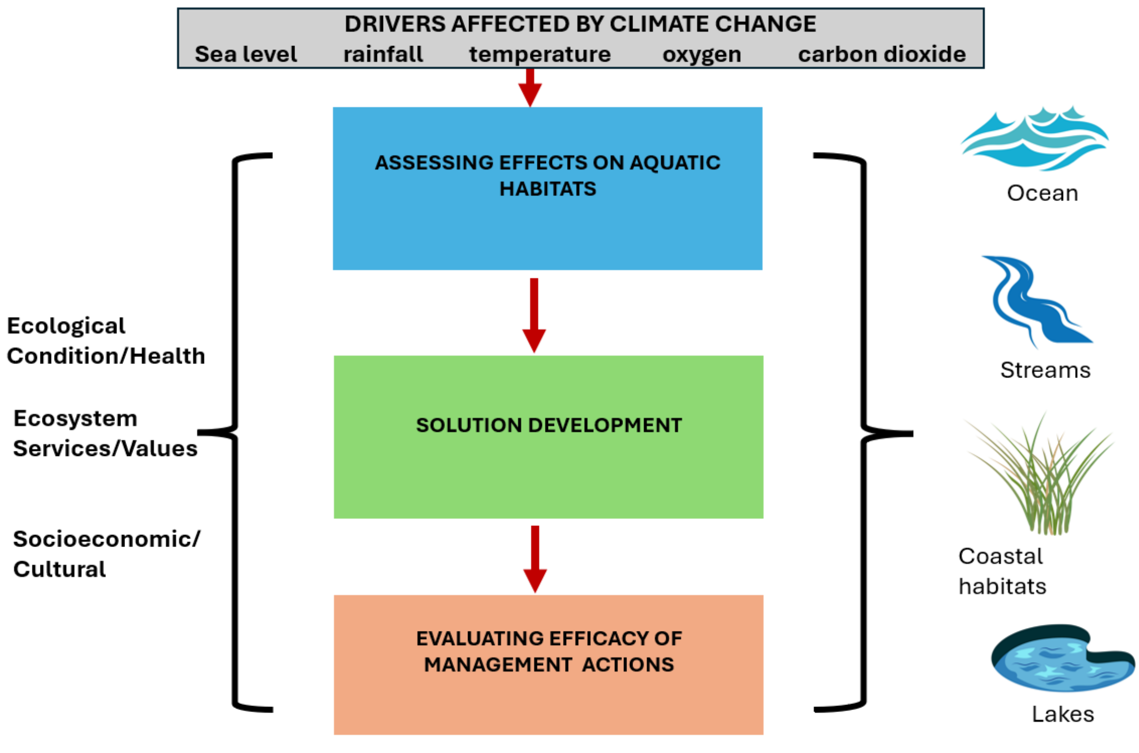

Figure 1. SCCWRP's conceptual model for climate resiliency is organized around three components designed to improve understanding of climate change effects, and then using that understanding to help develop and evaluate management solutions that promote resiliency of aquatic systems to climate change. Evaluations include ecological conditions, ecosystem services and socioeconomic and cultural effects.

The rest of this section takes a more in-depth look at each of the three major components of SCCWRP's Climate Resiliency research theme, with a focus on articulating the overarching management questions that will be addressed for each.

1. **Assessing effects of climate change on aquatic habitats**: To develop effective solutions that promote climate resiliency, scientists first need a firm understanding of the trajectory of physical and chemical parameters in response to climate change, and how these drivers may affect biological communities. Climate change will result in changes in carbon dioxide levels, rainfall, and temperature that will, in turn, affect the physical and chemical properties of aquatic environments. These changes will interact with existing and proximate anthropogenic stressors, such as excess nutrients and sediment, to increase the likelihood of changes in the ability of aquatic environments to support beneficial uses. SCCWRP is focused on improving understanding of these complex interactions and on developing a framework, indicators, and tools for assessing the risk/vulnerability of biological communities and habitats to climate change. Via foundational observational data sets and models, SCCWRP will assess the effects of climate change and the efficacy of solutions (see next bullet). Developing robust evaluation tools will be done at scales from pilot to regional scale because most climate change drivers operate at this scale. Key questions addressed by this portion of the research plan are:
    - What is the expected trajectory of physical and chemical stressors, such as ocean acidification, hypoxia, warming, and excessive erosion or sedimentation in response to climate change, and what are the expected biological consequences?
    - What are the relevant indicators that best reflect resiliency of aquatic ecosystems to climate change, and how can those indicators be used to help identify management targets?
    - What is the risk/vulnerability of aquatic habitats to climate change, how does that risk potentially affect biological communities or human health, and what is the uncertainty associated with those risk estimates?
2. **Tools to facilitate solution development**: Support for solutions development can occur at multiple points along the trajectory of development to implementation. Tools can be developed and applied in the early phase of development to support optimization of techniques or technologies while minimizing adverse effects. They can provide a means to virtually "scale up" from pilot or benchtop to full scale. At intermediate to late-stage implementation, tools account for complex combinations of local conditions, at times utilizing multiple solutions. Evaluating the efficacy of potential solution scenarios from development to implementation and over time requires models and evaluation tools that explore how combinations of solutions may perform under a variety of different situations and in a range of different settings. Regional-scale approaches provide an opportunity to take advantage of regional data sets to parameterize, calibrate, and validate models and leverage opportunities for model testing and refinement. Key questions addressed by this portion of the research plan are:

- What conceptual approaches, observations and models can be used to quantify the positive and negative effects of climate change solutions on aquatic ecosystems and human health, and what is the uncertainty in these scientific approaches?
- How can modeling and assessment tools guide or optimize specific climate change response strategies, from development to implementation? How can these initial investigations be used to improve observations and models that inform solution applications?
- Which solution or combinations of solution represents the most appropriate approaches, when considering both benefits and adverse effects? What are the most appropriate spatial and temporal scales to evaluate solutions?

3. **Building capacity to evaluate the efficacy of climate solutions**: Developing comprehensive, robust, and adaptable tools and approaches to assessing climate resiliency management actions is key to ensuring long-term return on the resources invested in developing and implementing these actions. Performance assessment is critical to ensuring that management actions achieve their desired outcomes, improving future actions by incorporating lessons learned from experience, and providing data to support future modeling and assessment tools. Achieving these goals is particularly challenging for climate change solutions given the extended timeframes necessary to assess performance, the need to account for multiple types of benefits and costs (e.g., ecologic, social, economic), and the fact that targets may need to evolve to account for climate trajectories, which are both changing and uncertain. Key questions addressed by this portion of the research plan are:
   - How can managers comprehensively evaluate the benefits (ecologic, social, economic) and impacts of climate resiliency solutions?
   - What are appropriate management targets and the associated indicators and thresholds for evaluating performance, and how should these evolve over time to reflect changing climatic conditions and the associated expectations?
   - What can managers learn from existing "projects," and how can these lessons inform future assessments, planning and adaptive management actions?

Research Directions

SCCWRP's research agenda for Climate Resiliency is divided into three main sections: Assessing effects, solution development, and efficacy of management actions.

Assessing Effects

SCCWRP's effects assessment research is focused largely on modeling climate change effects on species and habitats of management concern, and then using the results of modeling analyses to develop assessment tools and indices. Assessment begins with predicting local and regional-scale changes in physical factors, such as warming, changes in hydrology, and sea level. Expected physical changes are then related to their potential effects on chemistry (acidification and hypoxia) and biological communities, which can be captured through a combination of statistical and deterministic models. Making this connection is key to informing management decisions. Understanding of biological effects and the degree to which critical thresholds or endpoints are met can then be used to develop assessment tools and indices for use in monitoring, performance evaluations and adaptive management.

Accomplishments

SCCWRP has made progress on multiple fronts to assess the effects of climate change in both freshwater and marine ecosystems.

OAH and warming

For more than a decade, SCCWRP, UCLA and Princeton have done extensive work to develop, validate, and apply a coupled physical-biogeochemical ocean numerical model to characterize coastal ocean acidification and hypoxia (OAH) and warming regimes, as well as investigate drivers. This modeling tool is known as the Regional Ocean Modeling System with Biogeochemical Element Cycling (ROMS-BEC). In the Bight, where SCCWRP investigations have been focused, two decades of terrestrial and atmospheric nutrient and carbon inputs, including anthropogenic sources, have been assembled as model forcing (Sutula et al. 2021). A decade of model simulations (1997-2007) was validated against available climatological, coast-wide data sets. Reanalysis solutions for West Coast at 4-km resolution and within the Bight at 300-m resolution adeptly reproduced enhanced gradients in temperature, algal production, oxygen and carbon system parameters (Renault et al. 2021, Deutsch et al. 2021, Kessouri et al. 2021b). The team also has investigated the basic patterns of OAH along the California Coast (Damien et al. 2023) and the role of physical circulation features in driving variable patterns in nutrient fluxes (Kessouri et al. 2020), algal productivity (Damien et al. 2023), and OAH (Kessouri et al. 2022). Most recently, the team completed a 20-year high resolution time series of the Bight (1997-2017), providing a solid technical foundation for investigating the spatial and temporal extent of OAH and warming that has occurred in more recent periods (Kessouri et al. 2024).

Biological consequences of OAH and warming

Although California Current Ecosystem (CCE) marine life are experiencing more frequent OAH and warming conditions that have triggered adverse outcomes for coastal ecosystems, fisheries, and coastal economies, West Coast managers have struggled to take action because coastal water quality goals for pH and oxygen are not biologically relevant (Weisberg et al. 2016). SCCWRP and its partners have made important advances to conduct and synthesize science to establish the foundation for biologically relevant assessments of pH and oxygen, and to investigate the effects of multiple stressors on the thresholds that are key to those assessments. SCCWRP championed the use of pteropods as a biological indicator of OA (Bednaršek et al. 2017), documenting that shell dissolution in these planktonic marine snails are highly sensitive to changing aragonite saturation state (Ω_{Arag}). Likewise, SCCWRP and its partners were the first to document the dissolution of mechanoreceptors on larval Dungeness crab in field studies, an OA-specific impact (Bednaršek et al., 2020). SCCWRP then led the development of biologically relevant OA thresholds through a series of expert workshops. After experimental and field data were compiled on OA stress and response for three key sensitive taxa (pteropods, echinoderms and decapods), international experts were convened to review the studies and establish consensus on thresholds for each of the three taxa (Bednaršek et al. 2019, 2021a, 2021b).

Studies of multiple OAH and warming stressors have found that biological effects are nonlinear and often synergistic (Bednaršek et al. 2022). Moreover, most experimental studies treat exposure to OAH and warming stress as a static condition, while exposure to these stressors in the ocean is highly variable. SCCWRP, which invested in a dynamic OAH exposure system to begin to characterize the effects of dynamic and multiple stressors on biological effects, found that shell dissolution increased in juvenile bivalves with increasing amplitude of OA, relative to static conditions (Bednaršek et al. 2022). Bednaršek et al. (2024) found that diel increases in carbonate saturation state within kelp beds create temporary refugia for bivalves from OA. SCCWRP and its partners also applied an ecophysiological framework, named the Metabolic Index, for evaluating marine habitat suitability that utilizes synergistic thresholds of O_2 and temperature. The application involved developing the metabolic traits for 17 commercially and ecologically important CCE species.

These OA thresholds and O_2 indices are being applied to observations and numerical model simulations by researchers across the globe, including in the Bight, to investigate the biological effects of OAH on marine resources. Howard et al. (2020) and Frieder et al. (2024) represent key examples of how these biologically relevant thresholds can be utilized to investigate OAH-related habitat compression and range contraction for calcifiers and fish in the Bight.

Coupled chemical and biological monitoring

Although CalCOFI and SCCWRP member agencies have been conducting monitoring of oxygen and pH on a quarterly basis for decades, the pH potentiometric sensors that are typically deployed are not sufficiently sensitive to detect changes in OA. Moreover, quarterly monitoring has been focused on chemistry, without documentation of biological effects. In partnership with CalCOFI, NOAA and other regional partners, SCCWRP spearheaded an effort to onboard, standardize and train regional monitoring partners in innovative techniques for monitoring of pH and its biological effects. SCCWRP and partners established the California Current Acidification Network’s best practices for monitoring of OA-relevant carbonate chemistry (McLaughlin et al. 2015). Then, partners were trained through the Southern California Bight Regional Monitoring Program, paving the way to document for the first time regional spatial and seasonal patterns in Ω_{Arag} – which is the biologically relevant form of pH – in the shallow, nearshore waters of the Bight (McLaughlin et al. 2017, 2018).

SCCWRP then onboarded methodologies to assess the effects of OA on calcifiers through measurement of shell dissolution. SCCWRP worked with experts to develop best practices for the measurement and interpretation of shell dissolution data (Frieder et al. in prep), as well as facilitated an expert working group to develop a scientific assessment methodology to utilize OA chemistry and shell dissolution data to diagnose biological effects from OA.

Management agencies are moving towards adoption of thresholds of shell dissolution and OA thresholds. An example of this is the Oregon Department of Environmental Quality use of OA threshold science to establish integrated assessment methodologies for OA in coastal waters.

Climate change effects on eutrophication and toxic harmful algal blooms in freshwater and marine habitats

SCCWRP has been at the forefront of developing conceptual models, monitoring methodologies, condition assessment toolkits, and stress-response models to support the management of eutrophication and toxic harmful algal blooms in streams, lakes and reservoirs, and estuaries. The focus is on protection of both aquatic life and human uses. This scientific toolkit has advanced most rapidly for high biomass HABs and their chemical and biological effects, while the science of toxic HABs is still in its early stages of development. Because eutrophication and toxic HAB drivers overlap with those associated with climate change (warming, high CO2, increased pulsing of nutrient loads, stratification, etc.), these toolkits are being specifically designed to account for climate change. SCCWRP accomplishments in this area will be detailed in the Eutrophication/HABs Research Plan, slated for update in Spring 2025.

Effects of sea level rise on coastal wetlands

Although sea level rise poses one of the most significant threats to coastal wetlands that provide ecological, social and economic value, analyses of the potential effects of sea level rise on coastal habitats have historically been limited to a few selected, larger wetlands in the southern California Bight. To improve regional predictions of sea level rise and to support development of the Southern California Wetland Recovery Project's Regional Strategy (which aims to create a blueprint for regional coastal habitat wetland restoration and recovery), SCCWRP and its partners developed a hypsometry-based regional model that accounts for scale-dependent factors controlling sea-level rise responses in coastal wetlands (Doughty et al. 2019). The model, which was applied to 105 coastal wetlands in Southern California, predicts that southern California could lose 50%-70% of its coastal wetlands with 1.7 meters of sea-level rise. Subsequent analysis showed that restoration strategies involving sediment augmentation and facilitated wetland transgression have the potential to largely offset losses associated with sea level rise and could lead to a net wetland gain (Stein et al. 2020).

Climate change effects on freshwater species distribution

Climate change-induced alterations to stream temperature and flow have the potential to impose additional stress (and risk) to threatened and endangered aquatic species, largely because these highly imperiled species have narrow and specific habitat requirements, and much of their historic habitat has been lost as result of agricultural and urban development. To help managers develop effective resource and regulatory agency actions aimed at protecting these species through conservation or mitigation of other stressors, SCCWRP has started by building an understanding of how climate change may affect likely species distribution. SCCWRP developed statistical models to estimate changes in streamflow and temperature at the reach scale for the greater Los Angeles and Ventura regions under a range of future climate scenarios (Rogers et al. 2021). The modeling work found that stream temperature is projected to increase regionally, with high-elevation stream reaches increasing most rapidly, and a regional trend towards larger high-flow magnitudes and more storm events. Meanwhile, despite the increased frequency and magnitude of storm events, high-elevation streams (which provide refuge for many species) are predicted to become drier for a greater portion of the year, while low-elevation streams are predicted to have longer hydroperiods.

SCCWRP also has pursued habitat suitability modeling to predict how changes in temperature and flow will alter species distributions. SCCWRP found that sensitive, high-altitudinal cold-water species' distributions are generally expected to contract, while lower-elevation, more generalist warm-water species distributions are expected to expand (Rogers et al. 2020). These findings pave the way for wildlife managers to prioritize conservation efforts, manage streamflow, initiate monitoring of species in vulnerable clusters, and address other stressors, such as passage barriers in areas projected to be suitable under future climate conditions.

Research Priorities

SCCWRP's effects assessment research is focused on better understanding the trajectory of physical and chemical parameters in response to climate change, and how these drivers may affect biological communities and aquatic habitats. Specifically, SCCWRP is working to (1) improve biological interpretation frameworks for OAH, temperature and pH through multi-stressor experiments and index development, (2) expand coupled chemical and biological monitoring, (3) evaluate climate change trajectories over different time scales and spatial extents, then develop frameworks to assess the risk and vulnerability of habitats to climate change, and (4) investigate the influence of climate change and local human activities on eutrophication and toxic HABs in marine and freshwater environments. This fourth research area is detailed in the **Eutrophication/HABs Research Plan**.

> ***Focus area:* Developing multi-stressor indices to characterize the effects of pH and temperature on oxygen tolerance in marine and estuarine organisms and communities**
> **Ongoing**: Given that a strong linkage is required between chemical and biological monitoring to inform management actions for marine and estuarine aquatic life, SCCWRP is working to merge the combined effects of temperature, oxygen and pH on marine aquatic life through a mechanistic physiological framework, termed

the Metabolic Index. Laboratory experiments are being conducted on juvenile Dungeness crab, *Metacarcinus magister*. Metabolic traits being measured consist of the temperature dependence of oxygen consumption, the temperature dependence of P_{CRIT} (the oxygen at which metabolic rate can no longer be sustained), and the sensitivity of P_{CRIT} to pH exposure. The physiological-type information being generated will inform the envelope of multi-stressor conditions that hinder aerobic activities of key marine taxa and provide a foundation for developing improved multi-stressor indices.

Future priorities: SCCWRP intends to pursue (1) measurement of OA and hypoxia -related metabolic traits, expansion of multi-stressor experiments, and index development to encompass a larger suite of sentinel organisms and communities for key marine and estuarine assemblages, (2) extended validation and refinement of these indices against abundance data, and (3) scientific support for update of pH and dissolved oxygen, biostimulatory (covering eutrophication and toxic HABs) and narrative biological water quality objectives, Once developed, this science will provide an expanded suite of tools for evaluating effects in multiple habitats and communicating status and trends in ways that support problem characterization and regional- and watershed-level prioritization of management actions

***Focus area:* Developing ocean monitoring approaches to effectively support coupled chemical-biological monitoring**

Ongoing: SCCWRP is working with West Coast partners to build consensus on appropriate approaches for conducting chemical, physical and biological monitoring of marine, freshwater and estuarine habitats (see Regional Monitoring Thematic Research Plan). This monitoring encompasses both stressor-specific (e.g., shell dissolution) and whole community (e.g., DNA metabarcoding) measures to understand how marine life are being affected by climate change in combination with local stressors. As these monitoring approaches are developed, SCCWRP also is supporting local partners with training to build their monitoring capacity.

Future priorities: SCCWRP intends to expand efforts to design ocean monitoring approaches that support coupled chemical-biological monitoring. SCCWRP will focus on (1) mining historical data to evolve scientific understanding of status and trends in biological communities, (2) building adequate DNA reference libraries for multiple habitats, (3) developing target (qPCR) methods to quantify changes in the abundances of sentinel organisms (e.g. pteropods, crabs, fish, etc.), (4) evaluating fish, phytoplankton and zooplankton biodiversity trends using DNA metabarcoding and (5) documenting the changes in stressor-specific (e.g. shell dissolution) and whole community response to climate change.

Focus area: **Predicting future consequences of ocean acidification, hypoxia, and warming, and evaluating their biological consequences in marine and estuarine environments**

Ongoing: SCCWRP and its partners are using ROMS-BEC modeling to quantify how much coastal ocean habitat has already been lost to increases in anthropogenic CO_2, then evaluate a range of future climate scenarios to predict the biological consequences of past and future climate change for pelagic taxa. Through this work, researchers will characterize the temporal evolution by which habitats have been altered due to global drivers, which can then provide context for investigating how potential local management actions, such as management of eutrophication, might alter this trajectory.

Future priorities: SCCWRP intends to enhance and expand the toolbox that will support decisions by regulators, stormwater and wastewater agencies regarding marine and estuarine habitat protection and management. Future research will focus on (1) quantifying model uncertainty and other Independent Review Panel recommendations to improve community acceptance of the model, (2) expanding the range of future climate scenarios to better constrain understanding of alternative futures, (2), and (3) expanding the breadth of biological assessments to include methodologies specific to benthic fauna, kelp and seagrass habitats. In addition, SCCWRP plans to extend acidification, hypoxia, and warming models into coastal estuaries and lagoons, as these systems are potentially more vulnerable to climate change effects, such as acidification, hypoxia and warming, due to their small size, shallow depth, and propensity for reduced circulation due to mouth narrowing or closure, as well as due to land-based discharges, which have greater potential to exacerbate these effects due to the location of the systems at the terminus of watersheds. SCCWRP will work to extend the capability of these models to predict changes in the windows of opportunity for toxic harmful algal blooms under future climate conditions. Estuary models will require additional data collection, model setup and validation to account for the unique features of these coastal systems relative to the open ocean. A suite of biological interpretation tools, customized for Bight estuarine biota, will also need to be developed.

Focus area: **Developing climate resiliency indicators and assessment frameworks for estuarine ecosystems**

Ongoing: To develop effective solutions and management actions for mitigating climate effects, managers need to know what habitats (ocean, coastal habitats, and inland waters) are most at risk or vulnerable to climate change, then to couple interpretation frameworks with statistical or numerical models of current or future scenarios. SCCWRP is working with partners and member agencies to develop comprehensive assessment frameworks to help understand the resiliency of coastal ecosystems to climate change stressors based on their setting, condition and function. Researchers are developing consistent, consensus-driven indicator assessment approaches that include standard metrics, operating procedures, and tools to score resiliency. These tools will help in the management of coastal ecosystems (e.g., estuarine pelagic and benthic habitats, kelp forests, reefs, SAV beds, beaches, and dunes) in the face of climate change by supporting comprehensive resilience planning – both to prioritize restoration and management actions, and to evaluate performance of mitigation, restoration and management actions.

Future priorities: SCCWRP will focus on expanding risk assessment tools to (1) identify the level of risk habitats face to climate change, (2) understand how this risk affects biological communities and human health, and (3) quantify uncertainty regarding the response of specific habitats to climate change impacts. The assessment may include map-based tools to highlight habitats that are resilient and vulnerable, as well as identify areas that could be potential future habitat (e.g., transgression zones). This research will build on existing modeling and development of resiliency indicators and will include a multi-stressor approach across a variety of spatial and temporal scales to improve understanding of the risk associated with climate change relative to other stressors. The resulting tools can help prioritize locations and management approaches with the greatest likelihood of supporting climate change adaptation.

Solution Development

SCCWRP's solutions-centered research on climate resiliency is focused on developing observational and modeling tools that allow technology developers and managers to evaluate emerging solutions in terms of their long-term efficacy, ecosystem benefits and potential for adverse unintended effects. Solutions must be evaluated for multiple benefit categories (e.g., ecological, social, economic) and how those benefits may change over time as climate change (and other stressors) evolve. Products of this research area include approaches for evaluating early implementation efforts, both to optimize techniques and technologies, and to adaptively manage and inform future actions.

Accomplishments

Ocean solutions to climate change

SCCWRP and its partners have been actively involved in using the validated ROMS-BEC ocean model (described in the Assessing Effects section above) to evaluate ocean solutions to climate change at regionally relevant scales. Early work has focused on two potential solutions: land-based nutrient management, and kelp farming.

The bulk of accomplishments to date have revolved around land-based nutrient management – specifically, quantifying the effect of anthropogenic nutrients and coastal eutrophication on OAH and its biological effects, then using the model in scenario mode to begin investigating nutrient management solutions (Kessouri et al. 2021b, Kessouri et al. 2024, Frieder al. 2024, Ho et al. 2023). Previous, current, and future work in this area will be detailed in SCCWRP's Eutrophication/HABs Thematic Research Plan (to be updated in winter 2024-2025).

The other potential solution that has emerged as a focus of investigation – kelp farming – has the potential to draw down inorganic carbon, remove nutrients, and locally buffer ocean waters from OAH, while producing a new revenue stream for California's coastal economy. To help optimize farming approaches, simulate the commercial scale up of kelp farming and investigate local to regional ecosystem impacts, SCCWRP and its partners developed MACMODs, a kelp farming submodel for ROMS-BEC (Frieder et al. 2022). Work to apply MACMODs has thus far been globally focused, to bracket understanding of the scale of solution that seaweed farming represents and its potential economic benefits (DeAngelo et al. 2023, Arzeno-Soltero et al. 2023).

Modification of sediment dredging practices to offset sea-level rise effects on wetlands
Present-day dredging practices that address water quality and/or flood risk concerns were developed decades ago, and thus few considered climate change effects during their development. In light of expanding knowledge about climate change effects, SCCWRP has built a technical foundation for managers to reconsider legacy dredging practices. To support site-scale restoration and management decisions, SCCWRP and UC Irvine developed a stochastic multi-decadal model that accounts for event-scale sedimentation patterns in coastal wetlands (Brand et al. 2021). The model was applied to Upper Newport Bay to assess the role of large storm events (i.e., greater than 20-year return interval) on marsh accretion and associated sensitive species habitat, with results showing that up to 30 cm of sediment can be deposited in a single event, but net accretion can be overestimated without consideration of biophysical processes, such as compaction (Brand et al. 2022). The outcome of this analysis suggests that less frequent or less extreme channel dredging may be an effective strategy to help coastal wetlands such as Upper Newport Bay keep pace with sea level rise.

Research Priorities

SCCWRP is working to expand efforts to evaluate nature-based solutions (NBS), including living shorelines, floodplain restoration and beneficial sediment use, as potential complements or replacements for traditional engineering practices. SCCWRP also is working to develop tools for evaluating and identifying effective potential solutions for OAH and temperature (i.e., both kelp restoration and marine carbon dioxide removal (mCDR) as potential solutions).

> ***Focus area:*** **Applying nature-based solutions to enhance climate resiliency**
> **Ongoing**: NBS incorporate elements of natural habitats and processes to provide more adaptable, multi-benefit approaches for addressing climate change effects.

NBS are often used in combination with traditional engineering approaches, and include some types of stormwater best management practices (BMPs) like bioswales. SCCWRP is working alongside its partners and member agencies to study how NBS can be applied as effective solutions for mitigating adverse changes to the health of both coastal and inland aquatic resources. Stream health is being affected by changes in temperature and rainfall patterns, while estuaries, beaches, and other coastal habitats are being affected by changes in sea level and seasonal wave action. For managing stream temperatures, SCCWRP is investigating multiple NBS, including green roofs, groundwater heat exchange, and various infiltration approaches. For managing sea level rise and wave action, SCCWRP is developing tools to evaluate, promote and assess the beneficial use of living shorelines and of dredged sediment to enhance coastal habitats and help them cope with erosion and degradation All of these NBS pilot applications will generate lessons learned that can be used to inform broader regional applications across both coastal and inland aquatic resources.

Future priorities: To expand SCCWRP's investigations of NBS, SCCWRP will focus on two principal areas. First, researchers will develop key metrics to evaluate NBS performance across multiple disciplines (ecologic, economic, and social). A key component to this work is the development of a scoring tool or calculator for use in benefit-cost analysis to estimate the combined ecological, social, and economic benefits of solutions and management actions. As nature-based projects mature over time, this research will focus on how overall performance and performance metrics may vary through time, paving the way to evaluate the longevity of project benefits. In particular, this will consider how NBS should be evaluated in consideration of changes in runoff, temperature and sediment production under future climates. Second, SCCWRP will develop and test assessment and performance tools on restoration projects to inform future assessments, planning, and adaptive management actions. Over the long term, this work will be multi-habitat (wetlands, beaches, dunes, seagrass, etc.), but in the short term, the major focus will be coastal wetland restoration, as many of California's extensive coastal wetland restoration projects were constructed with NBS in mind to reduce risk to coastal ecosystems, enhance the resilience of nearby coastal communities, and restore the capacity of coastal systems to adapt to sea level rise. Given that many of these wetland projects have not been evaluated on whether they have achieved their NBS objectives, SCCWRP research will evaluate current and future wetland restoration performance (under future climate conditions) to better understand whether this management action achieves desired outcomes, to improve future restorations by incorporating lessons learned from experience, and to provide data to further support future modeling, assessment, and performance tools.

***Focus area:* Developing tools and approaches for evaluating mCDR and other ocean-based climate solutions**

Ongoing: Although multiple types of mCDR technologies are under development in an effort to maintain global temperature rise for the remainder of this century under 1.5°C or 2°C, federal, state and local agencies do not yet have a clear picture of the effect of these technologies on marine ecosystems (both intended and unintended effects), nor is there clarity on what monitoring data, modeling, or information should be required when making regulatory or policy decisions regarding the siting and operations of these technologies within state and federal coastal waters. SCCWRP is engaging with multiple partners to develop tools and approaches for evaluating mCDR and other ocean-based climate solutions. First, SCCWRP and its partners are conducting an expert workshop to generate a conceptual framing of mCDR ecosystem benefits and adverse effects, including key indicators and metrics needed to quantify those effects. The workshop is assessing impediments or barriers to decision-making, including key knowledge and information gaps, and recommendations to address those gaps that would provide a basis for a sound strategy to guide regulatory and policy decisions. Second, SCCWRP is part of a collaborative team developing a comprehensive monitoring, reporting and verification (MRV) toolkit for mCDR. The initial focus of this work is to set up and parameterize the Marine Biogeochemistry Library (MARBL), an open-source community biogeochemistry model. The Team is focused on reproducing the core functionalities of BEC in MARBL, then validating ROMS-MARBL along the California Coast in a model ensemble comparison with ROMS-BEC. Third, SCCWRP is partnering with mCDR technology partners to inform efforts to improve CO_2 removal efficacy and reduce adverse effects. These partnerships will span the trajectory of technology development and implementation, from early development phases to late-stage commercialization.

Future priorities: SCCWRP will continue to invest in tools and approaches to fully evaluate mCDR and other ocean-based climate solutions. This work will be focused in three major areas: (1) Technology development and implementation support, expanding the partnerships and developing data visualization tools to support expanded independent use of the tools by partners, (2) Standardizing the routine applications of observations and modeling tools to conduct MRV, and (3) SCCWRP and partners will develop monitoring and modeling assessment methods to document mCDR ecosystem benefits and potential adverse effects, including key indicators and metrics needed to quantify those effects. The ultimate goal is to accurately depict the effect of the mCDR technology in space and time, at multiple scales of deployment from pilot to full scale. This work will be part of a collaborative strategy to address management concerns and questions on mCDR benefits and adverse effects, including data visualization tools to help managers understand and communicate benefits and potential adverse effects of ocean-based climate solutions.

Efficacy of Management Actions

SCCWRP's research assessing the efficacy of climate resiliency management actions is focused on developing and improving assessment tools. SCCWRP's priority is to conduct performance assessments of proposed solutions and combinations of solutions that consider multiple types of benefits and costs, as well as that help managers evaluate appropriate management targets and associated indicators and thresholds. SCCWRP has made the least in-roads in this area because many of the climate solutions implemented to date have not been in place long enough to allow for evaluation of their efficacy.

Accomplishments

SCCWRP has not yet done any work evaluating the collective efficacy of climate solutions, although SCCWRP has already begun laying a foundation to evaluating the efficacy of climate resiliency solutions by investing in the development of solutions themselves (see Solution Development section).

Research Priorities

As climate solutions reach a stage where their efficacy can be meaningfully evaluated, SCCWRP will pursue development of additional sets of tools to integrate, predict and comprehensively assess efficacy at different scales. The following future research priorities are presented in a project-agnostic fashion, meaning that SCCWRP intends to use these approaches to assess the efficacy of multiple types of climate solutions.

Focus area: **Developing comprehensive regional scale benefits and impact assessment monitoring and modeling tools to evaluate the collective efficacy of climate solutions**

Future priorities: SCCWRP will focus on developing tools for cumulative, regional-scale efficacy assessments and spatial planning support. These tools will consider the ecological, social, and economic efficacy of climate resiliency solutions, and will recognize the broad suite of benefits as well as potential unintended consequences that may be associated with these solutions. The tools will integrate proposed project performance metrics and identify management targets (and how they should change over time). SCCWRP will test the assessment and performance tools on restoration projects to inform future assessments, planning, and adaptive management actions.

- ***Example***: **Evaluating the efficacy of shoreline stabilization to minimize coastal erosion and beach loss**

Coastal erosion and beach loss in southern California threatens increased flooding and infrastructure damage, impacts to wetland and marine protected areas, loss of recreational opportunities and tourism benefits for the region, and loss of public access to the ocean. A promising solution is to use sediment that has been excavated and dredged from flood control channels, harbors, reservoirs and embayments for shoreline stabilization. However, this solution has multiple potential consequences, including downcoast erosion, contamination, and benefits to one community at the expense of another. SCCWRP will focus on developing tools and approaches for assessing and communicating the ecological, social, and economic benefits of using dredged sediment for shoreline stabilization. A key component will be developing an integrated scoring tool and dashboard that allows managers to evaluate the overall benefits of shoreline stabilization, plus explore project alternatives in terms of their relative benefits and potential adverse consequences.

Focus area: **Developing "lessons learned" insights from pilot efforts to assess efficacy of climate solutions**

Future priorities: As climate solutions are implemented, there will be a need to document their performance and develop outreach materials to promote broader applications. In parallel, SCCWRP will evaluate pilot efforts assessing the efficacy of climate resiliency solutions, then use these insights to develop "lessons learned" documents, training materials and implementation guidelines. As appropriate, performance assessments of early implementation projects may be used to develop training and outreach materials that document performance and utility of solutions and that promote wider adoption. Also as appropriate, insights from these pilot evaluations may be used to ground-truth models and provide calibration and validation data for future modeling efforts that are designed to inform climate solutions.

Literature Cited

Arzeno-Soltero, I.B., B.T. Saenz, C.A. Frieder, M.C. Long, J. DeAngelo, S.J. Davis and K.A. Davis. 2023. Large global variations in the carbon dioxide removal potential of seaweed farming due to biophysical constraints. Communications Earth & Environment 4(1):185

Bednaršek N, Pelletier G, Beck MW, Feely RA, Siegrist Z, Kiefer D, Davis J, Peabody B. 2024. Predictable patterns within the kelp forest can indirectly create temporary refugia from ocean acidification. Science of The Total Environment 945: 174065. doi: 10.1016/j.scitotenv.2024.174065

Bednaršek, N., Beck, M.W., Pelletier, G., Applebaum, S.L., Feely, R.A., Butler, R., Byrne, M., Peabody, B., Davis, J. and Štrus, J. 2022. Natural analogues in pH variability and predictability across the coastal Pacific estuaries: extrapolation of the increased oyster dissolution under increased pH amplitude and low predictability related to ocean acidification. Environmental Science & Technology, 56(12), pp.9015-9028.

Bednaršek, N., P. Calosi, R.A. Feely, R.F. Ambrose, M. Byrne, K.Y. Chan, S. Dupont, J.L. Padilla-Gamino, J.I. Spicer, F. Kessouri, M. Roethler, M. Sutula, S.B. Weisberg. 2021b. Synthesis of Thresholds of Ocean Acidification Impacts on Echinoderms. Frontiers in Marine Science DOI:10.3389/fmars.2021.602601.

Bednaršek, N., R. Ambrose, P. Calosi, R.K. Childers, R.A. Feely, S.Y. Litvin, W.C. Long, J.I. Spicer, J. Strus, J. Taylor, F. Kessouri, M. Roethler, M. Sutula, S.B. Weisberg. 2021a. Synthesis of Thresholds of Ocean Acidification Impacts on Decapods. Frontiers in Marine Science 8:651102.

Bednaršek, N., R.A. Feely, E.L. Howes, B.P. Hunt, F. Kessouri, P. León, et al. 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, 227

Bednaršek, N., R.A. Feely, M.W. Beck, S.R. Alin, S.A. Siedlecki, P. Calosi, E.L. Norton, C. Saenger, J. Štrus, D. Greeley, and N.P. Nezlin. 2020. Exoskeleton dissolution with mechanoreceptor damage in larval Dungeness crab related to severity of present-day ocean acidification vertical gradients. Science of the Total Environment, 716, p.136610.

Bednaršek, N.A, T. Klinger, C.J. Harvey, S. Weisberg, R.M. McCabe, R.A. Feely, J. Newton, and N. Tolimieri. 2017. New ocean, new needs: Application of pteropod shell dissolution as a biological indicator for marine resource management. Ecological Indicators 76:240–244

Brand, M.W., K. Buffington, J.B. Rogers, K. Thorne, E.D. Stein, and B.F. Sanders 2022. Multi-decadal simulation of marsh topography under sea level rise and episodic sediment loads. Journal of Geophysical Research - Earth Surface, 127. https://doi.org/10.1029/2021JF006526

Brand, M.W., L. Guo, E.D. Stein, B.F. Sanders. 2021. Multi-decadal simulation of estuarine sedimentation under sea level rise with a response-surface surrogate model. Advances in Water Resources, 150. /doi.org/10.1016/j.advwatres.2021.103876

Damien, P., D. Bianchi, J.C. McWilliams, F. Kessouri, C. Deutsch, R. Chen, L. Renault. 2023. Enhanced Biogeochemical Cycling Along the U.S. West Coast Shelf. Global Biogeochemical Cycles DOI:10.1029/2022GB007572.

DeAngelo, J, B.T. Saenz, I.B. Arzeno-Soltero, C.A. Frieder, M.C. Long, J. Hamman, K.A. Davis and S.J. Davis. 2023. Economic and biophysical limits to seaweed farming for climate change mitigation. Nature Plants, 9(1), 45-57.

Deutsch, C., Frenzel, H., McWilliams, J. C., Renault, L., Kessouri, F., Howard, E., et al. 2021. Biogeochemical variability in the California Current System. Progress in Oceanography 196, 102565

Doughty, C.L., K.C. Cavanaugh, R.F. Ambrose, and E.D. Stein. 2019. Evaluating regional resiliency of coastal wetlands to sea level rise through hypsometry-based modeling. Global Change Biology.25:78-92. DOI: 10.1111/gcb.14429

Frieder, C.A., F. Kessouri, M. Ho, M. Sutula, D. Bianchi, J.C. McWilliams, C. Deutsch and E. Howard. 2024. Effects of urban eutrophication on pelagic habitat capacity in the Southern California Bight (In Revision)

Frieder, CA, Yan, C, Chamecki, M, Dauhajre, D, McWilliams, J C, Infante, J, ... & Davis, K. 2022. A macroalgal cultivation modeling system (MACMODS): Evaluating the role of physical-biological coupling on nutrients and farm yield. Frontiers in Marine Science, 214.

Frieder, CA., K.. McLaughlin, M. Sutula, N. Bednaršek, A Boyar, M. Decima, M. Elliot, R. Feely, J. Fisher, J. Jancke, R. Robertson, H. Schultz, J. Sessa, A. Stanjer. In Prep. Methods to assess shell dissolution in marine calcifiers

Ho, M., F. Kessouri, C.A. Frieder, M. Sutula, D. Bianchi, J.C. McWilliams. 2023. Effect of ocean outfall discharge volume and dissolved inorganic nitrogen load on urban eutrophication outcomes in the Southern California Bight. Scientific Reports 13:22148.

Howard, E.M., Penn, J. L., Frenzel, H., Seibel, B. A., Bianchi, D., Renault, L., et al. 2020. Climate-driven aerobic habitat loss in the California Current System. Science Advances 6, eaay3188

Kessouri, F., D. Bianchi, L. Renault, J.C. McWilliams, H. Frenzel, C.A. Deutsch. 2020. Submesoscale Currents Modulate the Seasonal Cycle of Nutrients and Productivity in the California Current System. Global Biogeochemical Cycles DOI:10.1029/2020GB006578.

Kessouri, F., L. Renault, J.C. McWilliams, P. Damien, D. Bianchi. 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 127:1-14.

Kessouri, F., M. Sutula, D. Bianchi, M. Ho, P. Damien, J.C. McWilliams, C.A. Frieder, L. Renault, H. Frenzel, K. McLaughlin, C. Deutsch. 2024. Cross-shore transport and eddies promote large scale response to urban eutrophication. Scientific Reports 14:7240.

Kessouri, F., McLaughlin, K., Sutula, M., Bianchi, D., Ho, M., McWilliams, J. C., et al. 2021a. 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, e2020MS002296

Kessouri, F., J.C. McWilliams, D. Bianchi, M. Sutula, L. Renault, C. Deutsch, R.A. Feely, K. McLaughlin, M. Ho, E.M. Howard, N. Bednarsek, P. Damien, J. Molemaker, S.B. Weisberg. 2021b. Coastal eutrophication drives acidification, oxygen loss, and ecosystem change in a major oceanic upwelling system. Proceedings of the National Academy of Sciences of the United States of America DOI:10.1073/pnas.2018856118.

McLaughlin, K., N.P. Nezlin, S.B. Weisberg, A. Dickson, J.A.T. Booth, C.L. Cash, A. Feit, J.R. Gully, M.D. Howard, S. Johnson, A. Latker, M.J. Mengel, G.L. Robertson, A. Steele, L. Terriquez. 2018. Seasonal patterns in aragonite saturation state on the southern California continental shelf. Continental Shelf Research 167:77-86

McLaughlin, K., Nezlin, N.P., Weisberg, S.B., Dickson, A.G., Booth, J.A., Cash, C.L., Feit, A., Gully, J.R., Johnson, S., Latker, A. and Mengel, M.J., 2017. An evaluation of potentiometric pH sensors in coastal monitoring applications. Limnology and Oceanography: Methods, 15(8), pp.679-689.

McLaughlin, K., Weisberg, S. B., Dickson, A. G., Hofmann, G. E., Newton, J. A., Aseltine-Neilson, D., et al. 2015. Core principles of the California Current Acidification Network: Linking chemistry, physics, and ecological effects. Oceanography 28, 160–169

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

Rogers, J.B., E.D. Stein, M.W. Beck, K. Flint, A.M. Kinoshita, R.F. Ambrose. 2021. Modeling future changes to the hydrological and thermal regime of unaltered streams using projected changes in climate to support planning for sensitive species management. Ecohydrology DOI: 10.1002/eco.2299

Rogers, J.B., E.D. Stein, M.W. Beck, R.F. Ambrose. 2020. The impact of climate change induced alterations of streamflow and stream temperature on the distribution of riparian species. PLOS One 15(11): e0242682. https://doi.org/10.1371/journal pone.0242682

Stein, E.D., C.L. Doughty, J. Lowe, M. Cooper, E. Borgnis-Sloane, D.L. Bram. 2020. Establishing Targets for Regional Coastal Wetland Restoration Planning Using Historical Ecology and Future Scenario Analysis: The Past, Present, Future Approach. Estuaries and Coasts 43:207-222. DOI: 10.1007/s12237-019-00681-4

Sutula, M., Ho, M., Sengupta, A., Kessouri, F., McLaughlin, K., McCune, K., et al. 2021. A baseline of terrestrial freshwater and nitrogen fluxes to the Southern California Bight, USA. Marine Pollution Bulletin 170, 112669. doi:https://doi.org/10.1016/j.marpolbul.2021.112669

Weisberg, S.B., N. Bednarsek, R.A. Feely, F. Chan, A.B. Boehm, M. Sutula, J.L. Ruesink, B. Hales, J.L. Largier, J.A. Newton. 2016. Water quality criteria for an acidifying ocean: Challenges and opportunities for improvement. Ocean and Coastal Management 126:31-41.