Proposal number RC25-C3-0199

Proposal Title: Assessing the Potential Impacts of Climate Change and Climate Intervention on Future Mangrove Distributions and Carbon Pools

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Objectives

Under global warming and sea level rise, mangrove forests will undergo significant alteration in their distribution patterns, belowground and aboveground biomass (BGB and AGB), and carbon stocks. Previous studies show that mangrove forests will shift poleward (Gouvêa et al., 2022; Cavanaugh et al., 2014), potentially outcompeting and occupying saltmarsh regions (Bunting et al., 2022), two coastal ecosystems that are relevant to the DoD. Several studies also show that the main drivers of this projected shift and alterations are attributed to changes in precipitation, air temperature, and suitable periods of soil inundation associated with sea level variations (Friess et al., 2022; Gilman et al., 2008). However, there are uncertainties to the combined effect of these climate drivers, the ranges of the climate drivers that impact mangrove ecosystems, and what mangroves may look like under future climate change and climate intervention (solar radiation modification - SRM) scenarios. Understanding the potential impacts of these drivers is essential for predicting changes in long term global mangrove ecosystem status. The proposed research aims to investigate the effects of these driving processes of carbon dynamics in mangrove ecosystems, improve the accuracy of carbon and climate models to better inform DoD policy makers and managers of natural infrastructure, and provide an estimate of future changes in extent and biomass of mangrove forests at global scales by contrasting climate scenarios.

Our specific objectives are:

O1. Mapping sea level rise (SLR) relevant for mangroves:

1.1 Building on current work on sea level rise impacts on mangrove ecosystems under climate scenarios (“moderate emissions”: SSP2-4.5 and “high emissions”: SSP3-7.0) and climate intervention scenarios.

O2. Create a mangrove species distribution model (SDM):

2.1 Investigate how the mangrove SDM responds to different ranges of temperature, precipitation, sea level rise, and topographic constraints.

2.2 Quantify the synergetic influence of the above interrelated variables on the global mangrove ecosystems under different climate change and intervention scenarios.

2.3 Create global mangrove data products showing modeled patterns of distribution, biomass, and extent changes under climate change and intervention scenarios.

O3. Estimate the fate of blue carbon:

3.1 Validate the key drivers of mangrove carbon stocks.

3.2 Model the effects of climate change and SRM on mangrove carbon stocks, sequestration rates and estimate the fate of blue carbon.

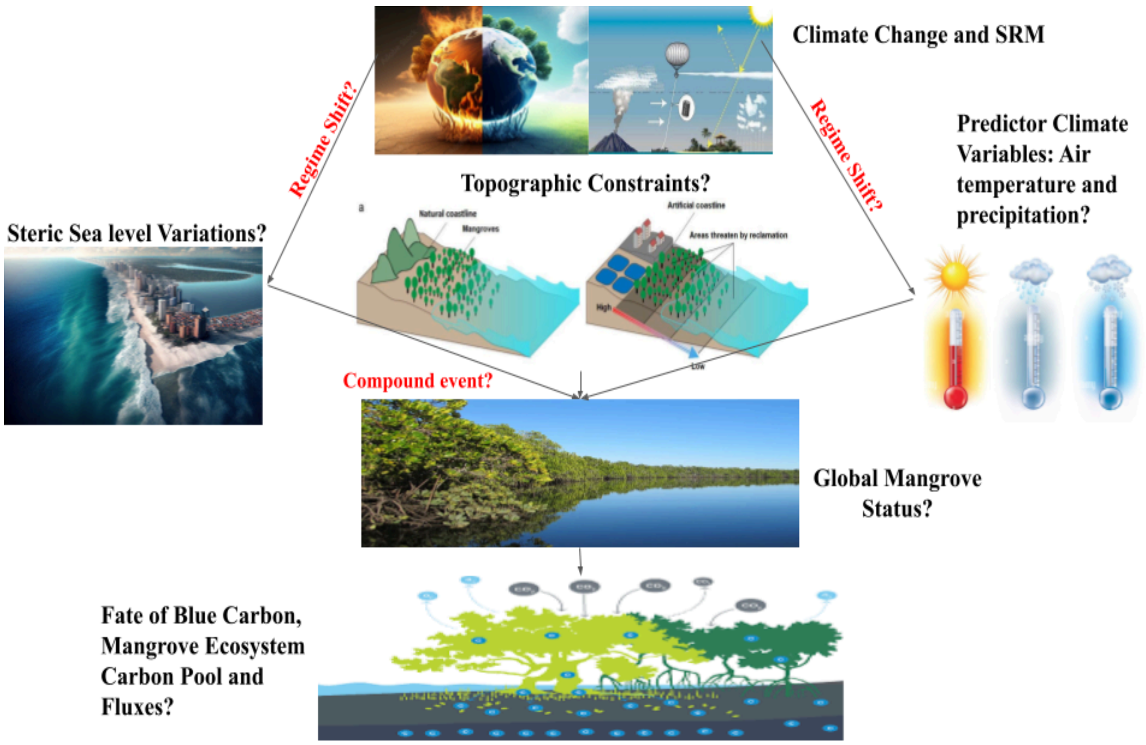

Figure 1. A conceptual framework of uncertainties this research aims to resolve: how climate change and solar radiation modification (SRM) impact sea level variations and predictor climate variables for mangrove biomes, the compound effect these variables and topographic constraints have on future global mangrove status, and finally the fate of blue carbon pools and fluxes due to projected changes in mangroves. Figure by Kesse Asante.

This proposed work adds major capacity to **resolving significant uncertainties of carbon estimates in mangrove ecosystems found on Department of Defense (DoD) installations and ranges.** Understanding how mangrove ecosystem carbon pools respond to these potential drivers and climate extremes will facilitate **the DoD's development of actionable strategies, frameworks, tools, and datasets for forecasting and projecting future greenhouse gas (GHG) emission reduction and biosequestration enhancement options across all relevant time scales to meet the need to integrate climate change mitigation, adaptation, and resilience into ecosystem and land-use decision-making processes.** Further, the proposed work will project how mangrove distributions will potentially be modified under a variety of future climate scenarios.

Background

Mangroves, seagrass, and saltmarshes provide high capture and storage rates of organic carbon and these coastal ecosystems are therefore termed as "blue carbon" ecosystems (Chatting et al., 2022; Duarte et al., 2005). These ecosystems occupy a relatively limited spatial area of approximately 0.2% of the Earth's surface (Chatting et al., 2022), but are major sinks of organic carbon. Amongst these ecosystems, mangroves have particularly gained recognition due to the ability to store and sequester relatively high amounts of carbon in both biomass and soils, storing up to five times as much organic carbon as tropical forests (Friess et al., 2022; Ward et al., 2016). In a recent study, it was estimated that the tree and sediment of mangrove forests along the world's coastlines hold ~ 3 billion metric tons of carbon - more than tropical forests (Twilley & Rovai, 2019). Understanding the changes in mangroves extent has become increasingly significant due to this carbon storage and sequestration capacity.

Mangroves have been significantly reduced in global extent over the last five decades, primarily due to deforestation for agriculture and aquaculture purposes (Bunting et al., 2022). Studies show that climate change is likely to have significant impacts on mangrove ecosystems through processes involving sea level rise, increased temperature, and changes in precipitation (Friess et al., 2022; Ward et al., 2016). However, very limited studies have attempted to accurately estimate changes of mangrove forests in response to climate change and future climate scenarios. Here, we propose to quantify the changes of mangrove ecosystems in response to climate change, particularly mangrove extent, biomass and carbon stocks, and make future projections.

In an era where anthropogenic climate change impacts have become more severe and emissions reductions have been slow to be implemented, several strategies for deliberate climate intervention have been proposed (National Academies of Sciences, Engineering, and Medicine, 2021). Solar radiation modification (SRM) is one potential climate intervention approach to partially counteract global warming by reflecting a portion of incoming solar radiation aimed at increasing the Earth's albedo (Zarnetske et al., 2021). The most studied SRM methods are stratospheric aerosol injection (SAI), the deliberate release of highly reflective fine particles into the stratosphere, and marine cloud brightening (MCB), which involves the purposeful enhancement of the reflectively of marine clouds (National Academies of Sciences, Engineering, and Medicine, 2021). Although several climate science studies have resulted in understanding predicted climate impacts should these strategies be implemented, nothing is known regarding the potential consequences of these changes on mangrove ecosystems (Zarnetske et al., 2021).

Climatic changes in temperature, precipitation, and SLR are significant factors that affect mangrove extent. SLR is a major potential climate change threat to mangroves ecosystems, because mangroves are sensitive to changes in inundation periods, potentially increasing tree mortality (Chatting et al., 2022; Ward et al., 2016). This can also result in mangroves shifting poleward and potentially outcompeting saltmarshes (Morris et al., 2023; Bunting et al., 2022; Ward et al., 2016). This encroachment phenomenon is attributed to the notable capacity of mangrove ecosystems to accelerate soil elevation at a rate of about 8 mm/yr, surpassing the soil elevation rates of saltmarshes by a factor of four under suitable conditions (Morris et al., 2023). Also, due to topographic constraints, where mangroves occur adjacent to artificial (human settlement and infrastructure) or natural (mountains) structures, coastal squeeze may occur (Chatting et al., 2022). Studies show that under extreme heat, salinity, and drought, mangrove extent and carbon stocks are estimated to significantly reduce (Friess et al., 2022; Ward et al., 2016). However, little is known about what the compound effect of these factors could be on mangroves extent, biomass and carbon stocks. An accurate assessment of the potential response of mangrove ecosystems to changes in temperature, precipitation and sea level variations under climate change and SRM will significantly contribute to estimating fluxes and the net balance of carbon in coastal ecosystems. These uncertainties are what the proposed research aims to resolve in alignment with the objectives outlined in the call.

Approach

The proposed research builds on the Earth system modeling expertise of PI Dr. Cheryl Harrison in biophysical modeling and climate impacts on marine ecosystems, and the extensive expertise of the lab of Dr. Robert Twilley, leading experts on mangrove and blue carbon observations and modeling. Throughout this project we will also collaborate with the Earth system climate intervention and land model development teams at NSF-NCAR (e.g., Simone Tilmes, Peter Lawrence) and DOE-ORNL (e.g., Forest Hoffman) to ensure that the methods and datasets developed are usable, follow best practices and are applicable to blue carbon and climate model components in development. This research will determine the single and combined effects of air temperature, precipitation, and sea level variations on mangrove extent, aboveground and belowground biomass, and carbon stocks under climate scenarios ("moderate emissions": SSP2-4.5 and "high emissions": SSP3-7.0) and SRM scenarios (ARISE SSP2-4.5, SAI, and MCB; Richter et al., 2022) using the NSF supported Community Earth System Model v. 2 (CESM2; Danabasoglu et al., 2020). We will approach this research in three major categories: sea level rise mapping (O1), creating a mangrove species distribution model (O2), and estimating the mangrove carbon stocks (O3), in response to both climate change and climate intervention.

Quantifying sea level rise (SLR; O1) is critical for determining impacts on mangroves.Work is underway to assess the impact of SLR globally on coastal communities, funded by a 1-year departmental fellowship and an NSF GCR grant on climate intervention (see appendix on Existing Support) supporting Harrison's PhD student Kesse Asante. Here we are collaborating with and using the methodology of NSF-NCAR's John Fasullo, who has worked extensively on exploring dynamic sea level (DSL) response of various climate forcings in CESM (Fasullo et al., 2020; Fasullo & Nerem, 2018). We expect global projections of DSL will be completed well before the proposed project begins (see timeline). For the mangrove projections, DSL will be extracted from a global gridded product for potential mangrove growing regions under the future climate scenarios outlined above. These projections, combined with maps of coastal habitat, land use, and projected population densities will be used to force a species distribution model (SDM), determining the ability of mangroves to migrate under changing sea level conditions.

SDMs are tools that facilitate global change impact assessments for predicting potential future ecosystem range shifts (Desjonquères et al., 2022; Charney et al., 2021; Jinga et al., 2021). These tools are able to relate biodiversity observations (such as presence/absence and abundance) at specific regions to the dominant environmental conditions at those regions. We will use these tools to create a mangrove SDM (O2) by investigating the impact of the selected climate drivers on mangrove forests distribution and biomass under both climate change and SRM. These simulations will first be evaluated against historical datasets, to understand their capacity to accurately represent observations, in terms of model validity. And based on the resulting biodiversity-environment relationship, we will make predictions in space and time by projecting the model onto available environmental layers and global mangrove maps. The maps will be derived from Global Mangrove Watch (GMW) v2.5 (Bunting et al., 2022), as it is currently considered the most comprehensive dataset for describing spatial variations in mangrove ecosystems. To estimate the response of mangrove biomass to temperature and rainfall, we will extract bioclimatic data from WorldClim Bioclim dataset (http://www.worldclim.org/bioclim; Hutchison et al., 2014). Here we will focus on AGB and BGB as our mangrove carbon stock variables. BGB will be derived from the AGB data, using the conversion factor of 0.5, which has been consistently used across recent global carbon stock estimates in mangroves to derive BGB directly from AGB (Simard et al., 2019; Hutchison et al., 2014). We aim to apply the developed SDM to the environmental layers in Bioclim and mangrove map from GMW to create a global map of potential mangrove carbon stocks and fluxes under future climate scenarios. Collaborative efforts with the lab of Dr. Robert Twilley will facilitate this procedure to estimate the fate of blue carbon under climate scenarios (O3).

This proposed work will significantly **contribute to resolving uncertainties of estimates of carbon pool and fluxes in mangrove ecosystems found on Department of Defense (DoD) installations and ranges**, and globally as put forward in the SERDP BAA call for FY 2025 .

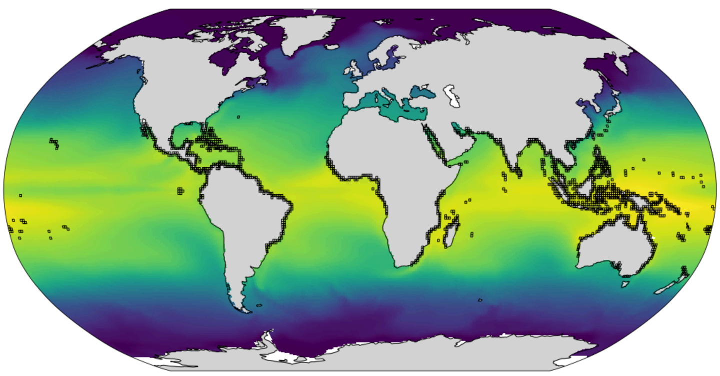

Figure 2 Map of current mangrove regions on the CESM model grid. Mangrove regions are from Global Mangrove Watch (Bunting et al. 2022). Figure by Kesse Asante.

Schedule

See **Supplemental Data Appendix** for Gantt chart of project schedule.

O1. Mapping sea level rise (SLR) relevant for mangroves
The initial phase of this research aims to map SLR relevant to mangrove ecosystems, and will occur in the first four months of **Year 1** (see Sup Table 1). This builds on research underway for general SLR impacts analysis for coastal regions and it is anticipated that by the time funding is available, the majority of this project will be completed. O1 Involves the implementation of DSL methodology mentioned above and the results will be mapped to current and potential future mangrove regions (Fig. 2).

O2. Create a mangrove species distribution model (SDM)
Building on the SLR data products, the majority of **Year 1** will be dedicated to development of the SDM, including design, forcing data preparation (extracting climate projections at mangrove regions), SDM model fitting and assessment. Moving into **Year 2**, the SDM will subsequently be used in making mangrove projections under future climate scenarios, and preparation of user-friendly data output productions, done in collaboration with the Twilley lab. Finally the results will be prepared for publication, again in collaboration with the Twilley lab, with expected submission in the middle of **Year 2.**

O3. Estimate the fate of blue carbon
The latter half of **Year 2** moving into **Year 3** will be dedicated to modeling mangrove carbon stocks, with primary emphasis on AGB and BGB global spatial variations, in collaboration with the Twilley lab. We aim to quantify the dynamic changes in mangrove biomass in response to altered temperature, precipitation, sea level variations, and present climatic conditions with the developed SDM and environmental layers from GMW v2.5. The last phase will center on making projections of mangrove carbon stocks under future climate scenarios. The aim is to quantify spatial variations in future mangrove carbon stocks, and ultimately identify regions of significant carbon stocks and fluxes. A manuscript will be prepared in the latter half of **Year 3**.

Cost
The estimated cost is ~$120K/year for 3 years, $360K total, covering 1 month of summer salary for PI Cheryl Harrison per year, and 0.5 month of salary for Co-PI Ivan Vargas-Lopez, postdoctoral researcher and lab manager for Dr. Robert Twilley. We request funds for 14 months of graduate student support per year, 12 months for Kesse Asante in the Harrison lab and 2 months for Noe Tonmam in the Twilley lab. Plus tuition, conference travel and computer equipment, etc.

Research Team
All researchers are at Louisiana State University (LSU) in the Department of Ocean and Coastal Science. The Harrison lab is also affiliated with LSU's Center for Computation and Technology. Assistant Professor Dr. Cheryl Harrison will oversee the project, supervising PhD student Kesse Asante. The Harrison lab will collaborate with Dr. Robert Twilley's lab, working closely with PhD candidate Noe Tonmam, who is an expert in the Twilley lab mangrove models, and postdoctoral researcher Dr. Ivan Vargas-Lopez. They will collaborate on the SDM development and implementation, as well as the associated carbon calculations. Dr. Twilley is fully funded in his position as Vice President for Research at LSU. Additionally, this work will build on collaborations in place with NSF-NCAR and the CESM model development and the Community Climate Intervention Strategies working groups, as well as the Climate Intervention Biology working group (https://www.climateinterventionbiology.org/), including Forrest Hoffman at Oak Ridge National Lab.

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Appointments

Fall 2021- Assistant Professor, Department of Oceanography and Coastal Science and Center for Computation and Technology, Louisiana State University, Baton Rouge, LA
2018-2021 Assistant Professor, University of Texas Rio Grande Valley, Port Isabel Lab, TX
2018 MOPGA Fellow, Mediterranean Institute of Oceanography, Marseille, FR
2018 Project Scientist, Bren School, UC Santa Barbara, CA
2017-2018 Research Associate, INSTAAR, University of Colorado Boulder, CO
2015-2017 Postdoctoral Researcher, National Center for Atmospheric Research (NCAR), Boulder, CO
2012-2015 Postdoctoral Research Scholar, Oregon State University (OSU), Corvallis, OR

Education

2012 Ph.D. Earth and Planetary Science, UC Santa Cruz, CA
2007 Master's, Earth and Planetary Science, UC Santa Cruz, CA
1997 B.A. Mathematics, Honors, UC Santa Cruz, CA
1993 A.A. Physics, Honors, Cabrillo College, Aptos, CA

Synergistic Activities

- Earth System Model Coordinator, FishMIP/ISIMIP fisheries model intercomparison project
- Member, Climate Intervention Biology Working Group
- Member of Community Climate Intervention Strategies (CCIS) working group
- Mentor, Mentoring Physical Oceanography Women for Increasing Retention (https://mpowir.org/MPOWIR)
- Lifetime member of the Society for Advancement of Chicanos/Hispanics and Native Americans in Science (SACNAS)

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Appointment

Fall 2023 – present. Postdoctoral Researcher, Louisiana State University, LA

Education

2023 Ph.D. Oceanography and Coastal Sciences, Louisiana State University, LA
2017 M.Sc. Renewable Natural Resources, Louisiana State University, LA
2011 B.Sc. Environmental Engineering, Zamorano Pan-American Agricultural School

Research experience

- Conducted a mangrove research project in Bahia de Los Muertos, Panama funded by the National Government of Panama.
- Led/co-led, organized, and participated in field campaigns to collect samples and data for mangrove research projects in Louisiana and Florida, including the Florida Coastal Everglades – LTER funded by the National Science Foundation.
- Evaluated primary productivity, carbon and nutrient lateral fluxes from land to coastal ocean in Wax Lake Delta and Barataria Bay, Louisiana – project funded by NASA-EPSCoR.
- Assessed water quality and hydrological connectivity effects on wild crayfish harvesting techniques in the Atchafalaya River Basin, LA.

Media coverage

- Science X news "New Research Reveals How Hurricanes Shape the Coastal Landscape in the Everglades". February 20, 2020. https://phys.org/news/2020-02-reveals-hurricanes-coastal-landscape-everglades.html
- LSU News "The delta breathes: Mapping carbon along the muddy Mississippi". October 01, 2021. https://www.lsu.edu/cce/mediacenter/news/2021/10/01-deltabreathes.php
- NOLA. "Louisiana's coast is vanishing — except for this new delta getting worldwide attention. October 23, 2023". https://www.nola.com/news/environment/louisianas-coast-is-vanishing----except-for-here/article_bb95aa18-6f78-11ee-9b8d-ab4a042bf0cc.html

Acronyms

AGB Above ground biomass

BGB Below ground biomass

CESM Community Earth System Model

CESM2 Community Earth System Model version 2

DoD Department of Defense

DOE-ORNL Department of Energy Oak Ridge National Lab

DSL Dynamic Sea Level

GHG Greenhouse Gases

GMW Global Mangrove Watch

MCB Marine Cloud Brightening

NSF-NCAR National Science Foundation National Center for Atmospheric Research

SAI Stratospheric Aerosol Injection

SDM Species Distribution Model

SLR Sea Level Rise

SRM Solar Radiation Modification

SSP Shared Socioeconomic Pathway

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Supplemental Technical Data

Table 1
Gantt chart of projected project timeline

Activities Timeline		Year 1						Year 2						Year 3					
Activity	**Month**	**2**	**4**	**6**	**8**	**10**	**12**	**2**	**4**	**6**	**8**	**10**	**12**	**2**	**4**	**6**	**8**	**10**	**12**
O1. Sea Level Rise Mapping																			
Create data products for SDM																			
O2. Mangrove SDM																			
SDM design																			
Data preparation																			
Model fitting																			
Model Assessment																			
Predictions in space and time																			
Create Global Mangrove Data Products																			
Manuscript/paper, project reporting/publication																			
O3. Fate of Blue Carbon																			
Development of carbon model																			
Climate change and mangrove carbon stocks																			
SRM and mangrove carbon stocks																			
Manuscript/paper, project reporting																			

Existing Support

PI Cheryl Harrison

NSF GCR (2022-2027, $600K LSU/$3.4M total): "Generating Actionable Research to Investigate Combined Climate Intervention Strategies for Stakeholder Use"

The project has three main objectives: 1) Advancing state-of-science climate intervention studies through exploring the assumptions, model deficiencies, interactions, and impact assessment methods of a portfolio of climate intervention scenarios consistent with keeping warming within 1.5 degrees C from CMIP6 baseline pathways, with the climate intervention scenarios based on methods already developed by the project investigators; 2) Developing an approach for co-production of modeling products from Earth system evaluations through extensive stakeholder engagement to further actionable research into combined climate intervention scenarios and their evaluation; and 3) Designing scenario and impact assessment toolkits for the wider community to engage in investigating intervention strategies that are responsive to their unique information needs and priorities through the extension of and adaptation of the co-designed scenarios and assessment frameworks. **The Harrison lab at LSU is focusing on impact assessments using the intervention simulations, including sea level rise, coral reef bleaching, marine heat waves, and fisheries production.**

NOAA CPO (2022-2024, $86K LSU/$430K Total): "Climate Change Impacts on Reef Fish Spawning Aggregations, Larval Dispersal, and Settlement in Southeastern U.S. National Marine Sanctuaries and Surrounding Areas"

Summary of work to be completed: A multi-model approach using CMIP6 climate models will be used to assess oceanic changes at sanctuaries under the SSP2-4.5 and SSP5-8.5 climate scenarios. Conditions from these models will be used to determine the suitability of spawning habitat via the Non-Parametric Probabilistic Ecological Niche (NPPEN) model. Spawning habitat suitability will be determined for the Gray's Reef, Florida Keys, and Flower Garden Banks National Marine Sanctuaries. While Gray's Reef does not currently provide habitat for these species, it may support habitat in the future due to species range shifts. We plan to explore how use of artificial reefs and other hard substrates as spawning habitat might influence projections of range shifts. Also, we will examine how source-sink dynamics of larval dispersal may change due to climate effects on ocean circulation and changes in species distribution, phenology, and fishing pressure. The Connectivity Modeling System particle tracking model will be coupled with the high-resolution GFDL CM2.6 model to study larval dispersal and identify source or sink populations based on changing conditions inside and outside of sanctuaries. We have been in contact with researchers and managers at the National Marine Sanctuaries Office, NMFS, NCCOS, Grouper Moon Project, and Reef Environmental Education Foundation about serving on a project advisory panel to ensure relevance for sanctuary managers.

NOAA CPO (2024-2027, $86K LSU/$430K Total): "Quantifying Multi-Stressor Driven Climate Shocks to West Coast Marine Ecosystems Using Large Earth System Model Ensembles"

Marine sanctuaries along the US West Coast experience a variety of biophysical stressors which are expected to be exacerbated by climate change, including effects from marine heat waves, harmful algal blooms, and seasonal expansion of oxygen minimum zones. Variations in physical oceanographic conditions are critical in driving the onset and magnitude of these effects: for instance, the strength of upwelling in the California Current, the vertical density stratification, and the amount of advection of subtropical waters all play important roles. These regional processes are in turn modulated by modes of large-scale climate variability including the El Nino/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), which operate on interannual to multidecadal timescales. Accurately characterizing the range of climate-driven shocks to US West Coast sanctuary regions in the face of climate change thus requires assessing the impact of large-scale climate variability on ecosystem driver variables such as pH, temperature, and nutrient concentrations. Large ensembles of Earth system models provide new tools uniquely suited for this purpose, providing many (20-100+) realizations of the climate system in a physically consistent, spatially complete framework. Here we propose to use information from all available large ensembles containing biogeochemical quantities to create robust estimates of the frequency of ‘shock’ events (extreme excursions in one or more driver variables) over management-relevant time horizons ranging from 10-50 years.
Scale-appropriate information will be derived using high-resolution observational and modeling products, with a focus on NOAA large ensembles and models agreeing most closely with observational benchmarks. This information will be used to create new, climate-informed diagnostic indicators for single- and multi-stressor shocks to sanctuary ecosystems which can be readily generalized across the NOAA Office of National Marine Sanctuaries (ONMS) sanctuary system.