NOAA SCIENCE ADVISORY BOARD RAPIDLY CHANGING MARINE ENVIRONMENT REPORT

PRESENTED TO THE NOAA SCIENCE ADVISORY BOARD

Developed with support from the Ecosystem Sciences and Management Working Group

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NOAA Science Advisory Board with support of the Ecosystem Sciences and Management Working Group

Developing Resilience in the Face of Rapidly Changing Marine Environments

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In addition, our thanks to the many others who contributed to developing the content of this report through working group and sub-team input sessions.

Executive Summary

This short report was developed at the request of NOAA to provide advice regarding how NOAA's practices will need to evolve over the next decade to keep up with, and anticipate, possible future ocean states and the impact on ocean resources. While NOAA is not able to address every ecological forecasting need in marine and Great Lakes ecosystems, this report evaluates a subset of modeling issues that are largely under the control of NOAA.

What has worked in the past for ecosystem models may not for rapidly changing marine environments, going forward into the future. We strongly advise that the time to act is now, so that the nation can be better prepared. We urge attention to this topic, evaluating how the linked tools of modeling, observations, and data analysis can provide insights and result in optimized tools for tomorrow.

High-level recommendations are provided here, with more specific details and suggestions provided in each of the chapters.

- Evaluate how models could more thoroughly integrate biological processes. Pay particular attention to the cumulative impacts of multiple stressors at different time scales, and specifically in the context of a rapidly changing ecosystem.
- Provide innovative ways to stimulate fundamental ecosystem understanding and associated model development.
- Focus on enabling models that are fit for purpose, but also that contain enough detail to be useful: highlight need for increased model skill assessment.
- Create better understanding of how humans respond to change by facilitating the collection of relevant data on human behavior using emerging observational tools
- Establish strategic and investigative priorities for integrative modeling investments based on effectiveness versus relative ease
- Use traditional and emerging social science data collection methods to model human behavior and inform marine and coastal program design
- Create (internal and external) capacity and institutional pathways to develop, use and apply social science methods as critical components of adaptive management
- Expand and integrate the engagement tool box and cultivate a one-NOAA culture and community around rightsholder and stakeholder engagement
- Make a stronger commitment as a science agency to elevating and training engagement personnel within the agency workforce, and to hiring people with a deep understanding of co-production

Introduction

Background
It is well documented that the marine and large freshwater systems of the United States are not just changing but are changing at ever increasing rates, as noted by the Intergovernmental Panel on Climate Change in its 2019 report (Bindhoff et al): *"it is likely that the rate of ocean warming has increased since 1993."* While many avenues of scientific inquiry continue into the precise nature, mechanics, and the ecological and human consequences of this change, climate remains one of the most pressing change-inducing stressors on these water systems. While the specific system and functional changes may take many different forms or pathways in the marine environment (the oceans) and in freshwater systems (the Great Lakes), the rates of change are also far outstripping our ability to monitor and measure these changes, assess their consequences, and adapt human systems and infrastructure to them.

From this warming phenomenon flows myriad other system changes (Johnson et al. 2022). Rapid changes are occurring in fundamental ocean hydrographic structures, as well as biogeochemical properties, with cascading impacts within the ecosystem, manifesting themselves as marine heat waves, reduced sea ice, increases in ocean acidification and harmful algal blooms. These changes are impacting diverse ecosystem structures and functions from the base of the food web to the upper trophic levels, with consequences for the overall health and productivity of the oceans and Great Lakes.

Purpose
This short report was developed at the request of NOAA to provide advice regarding how NOAA's practices will need to evolve over the next decade to keep up with, and anticipate, possible future ocean states and the impact on ocean resources. Are current programs and those under development sufficient to enable resilient coastal communities and residents?

This study builds upon an original study proposal submitted by NMFS (Rapidly Changing Marine Environment) and a revision adopted by the prior SAB (Application of Emerging S&T and Public Private Partnerships To Monitor and Predict Changes in the United States' Living Marine Resources). It also incorporates input from the Leadership in Coastal Resilience and Climate and Fisheries Initiative reviews produced by the SAB and builds upon, but does not duplicate findings in two recent ESMWG products: Emerging Technologies for Improving Fish Stock Assessments and Decision Making Under Deep Uncertainty. We also incorporated input from Cisco Werner and other NOAA line office liaisons, as well as from presentations at the July 15 2021 meeting by four subject matter experts: Clarissa Anderson, Scripps; Michael Jacox, NOAA SW Fisheries Science Center; Emanuele Di Lorenzo, Georgia Institute of Technology; and Jason Link, NOAA Fisheries.

Approach
We have developed this report in three major sections where we believe NOAA can delve deeper and build additional action and capacity to understand, respond to, and plan for rapid

change in marine environments. In each of these three we focus largely on the interface between hydrogeological systems and events and the human domain.

1. Chapter 1 focuses on ecological and multi-stressor forecasting. Climate change is resulting in a rapidly changing marine environment with impacts on multiple variables (e.g., temperature, oxygen, pH). Stakeholders, including resource managers and users such as fishermen, want to know not only what those changes are now, but also what they will be in the near to mid-term future. Numerical models, especially compared to and validated by field data, can be effective at confirming underlying mechanisms of ecosystem change, and can be used for forecasting, nowcasting, and hindcasting, with numerous successful applications. However, rapid change (and increases to the rate of change) requires assessing ecological responses to multiple stressors, which is an emerging topic that amplifies long-standing challenges in ecosystem modeling as well posing new challenges.
2. Chapter 2 evaluates some ideas of how social science might be used by NOAA in anticipating fisheries, ecosystems, restoration, and coastal risk management needs and applying such information for effective adaptation approaches under rapid system change. Efforts to include people as drivers of change, as beneficiaries of environmental management, and as sources of innovative problem solving, have not been systematically considered in NOAA models for system forecasting and policy analysis. Some examples where behavior has been included in models or forecasts suggest that the benefits of integrating human behavior (e.g., to design effective policy) could be substantial.
3. Chapter 3 highlights best practices and new approaches to incorporating collaborative science, also referred to as participatory science, and more recently co-design and co-production in NOAA's scientific programs and decision making. A rapidly changing marine environment poses new challenges to authentically engaging, collaborating, and co-learning with fishermen, tribes and other relevant stakeholders and rights holders. The purpose should be to increase the ability to understand the problem jointly and develop solutions together, effectively decreasing the distances among stakeholders, acknowledging the value of different ways of knowing, increasing the likelihood of successful outcomes, and better ground truthing of change.

Considerations

In developing this report, the authors note the following:

1. Rapid change as we are now experiencing in the marine environment, is not just slow (or historic) change rates occurring at a faster pace. Current models cannot just be accelerated or run over shorter durations to achieve predictable results. What now accompanies rapid change is the likelihood of threshold shifts, system level perturbations or phase shifts, something that Stephan J Gould – in speaking to evolutionary processes – referred to as punctuated events. In these terms, Gould notes such change as different from a linear process and consisting of periods of quiescence followed by periods of episodic change. Small system level shifts near an ecological or

physical threshold may stimulate large or amplified ramifications not captured in liberalized temporal sequences or predictions. We are deeply mindful of increasing likelihoods of stochastic events and outcomes that could arise from rapid change.

2. Given the changing nature of change itself within the marine environment, we are equally mindful of the limits to the systems and models we have in place for sensing and apprehending such change and how that change will manifest in human terms. Not only are we experiencing a period of large and abrupt system level change(a), but we have, as a society, not fully invested in the sensing and informational systems (non-linear, stochastic and AI informed systems) to see and fully understand the cataclysmic nature of an event or a series of abrupt events.
3. Lastly, we frame such systems level changes as having deep and uncertain effects on people and on social systems. Particularly, we – as a community of scientists and practitioners – have generally done a good job of understanding where flooding can occur under climate change scenarios, but we have studied less the overwhelming and socially disruptive consequences of moving neighborhoods or entire communities, with resultant challenges to personal identity and belonging that are so deeply rooted to place. Further, we lack understanding of the many ways that people respond and adapt to change that influences whether behavior enforces or erodes management intent. A goal of social science research is to increase our confidence in the cultural and social significance of changes to find solutions jointly and collectively with communities, and to build versus erode social cohesion and purposefulness.

Chapter 1: Scales relevant to biology: Timescales and Multi-stressor Impacts

Increased focus on biological processes, variability, and cumulative impacts of multiple stressors.

Problem Statement

What has worked in the past for ecosystem models may not for rapidly changing marine environments, going forward into the future. The time to act is now, so that the nation can be better prepared.

Due to climate change, marine ecosystems are responding to increasing stressors that can destabilize and modify food webs, community structure, habitats, chemistry, and even oceanographic conditions. Significantly, climate change has also accelerated the rate of these changes on two scales: first by overlaying changes to the climate at rates unfamiliar in the geological record and that may be too fast for populations to adapt; and secondly by pushing populations toward the edge of their physiological tolerances/range boundaries/disease exposure/etc. that reduces the buffering in the population such that small changes in the environment can lead to rapid large changes in the ecosystem This escalation in the rate of change demands our immediate attention and not just to address current conditions, but also for projected conditions. Because changes will manifest in multiple ways, involving multiple stressors, including temperature (marine heatwaves and directional change), oxygen (hypoxia and de-oxygenation), and pH (ocean acidification), as well as more complex reactions such as changes in circulation (affecting residence times and ventilation), stratification (affecting blooms and mixing), and harmful algal bloom production. All of these stressors can directly or indirectly affect species and cause range shifts or cascading food web effects.

Numerical models have yielded much insight into the dynamics of marine ecosystems. Models, especially when compared to and validated by long-term sustained field data, can be effective at confirming underlying mechanisms and also can be used for forecasting, nowcasting, and hindcasting, with numerous successful applications. Models need to be fit for purpose and the complexity required for accurate output should scale accordingly. To date, many models have been, by necessity, simplified due to lacking or uncertain information, missing processes due to historically-based conceptual models of the populations and food webs, and the averaging of long-term datasets that might not be applicable in the changing environment. Such simplifications may affect forecasting skill.

To react to rapidly changing environments:

- We need sustained observations at multiple scales (including traditional knowledge)
- We need models that include multiple stressors and appropriate timescales to capture exposure and effects
- We need dedicated time for analysis, both to get ahead of the curve for understanding new connections and for rapid analysis of emerging issues

- We need to assess the level of complexity needed to assure a desired level of model skill to adequately address the questions posed
- We need to examine if the regulatory structure can be responsive to the speed of the ecological changes, linking with socio-ecological needs also
- We need to choose modeling priorities based on co-design with managers and other stakeholders

Challenges and Opportunities

Assessing ecological responses to multiple stressors is an emerging topic that amplifies long-standing challenges in ecosystem modeling and poses new challenges.

1. Coupled physical-biogeochemical-NPZ models are needed to generate the spatial-temporal fields of the stressors. These stressors respond to forcings on different scales. While simulation of warming, deoxygenation, and OA has greatly advanced, prediction of the outbreaks of HABs remains difficult.
    a. We need to consider modeling more than the mean values in physics and biogeochemistry because other moments and extreme values can be ecologically very important. Predicting hourly or daily minimum and maximum values and variance is likely important to ecological effects on growth, mortality, prediction, and movement. The present generation of physical and NPZ/ecosystem models likely have skill in predicting higher order dynamics of these stressors, but they have not been thoroughly evaluated for their use in ecological models to date.
2. Consider that the stressors can affect each other.
    a. For example, warming can increase deoxygenation, and warming and OA can intensify HABs. These feedbacks and interactions among the stressors would need to be added to the existing models.
3. Validation of these physical-stressor models becomes more difficult because of the need to test model skill under the many possible combinations of stressors, often only a subset have been observed in historical data.
4. Moving up the trophic levels to fish, shellfish, and top predators raises the issues about how to formulate exposure-effects for the many species or functional groups in upper trophic level models (population to MICE to food web to end-to-end). The general approach is to use laboratory experiments to derive exposure (often constant) to effects on growth, mortality, reproduction, and movement of individuals. Multi-stressors quickly result in too many combinations for empirical work: many species by multiple life stages by multiple responses by factorial combinations of stressors each at several levels. Methods are needed to design experiments so they can be used to extrapolate the exposure-effects relationships to other not-studied species.
5. Including multiple trophic levels also increases the number of interactions in ecosystems such that there can be changes in species interactions and behavior, cumulative effects, habitat modifications, trophic cascades, alternate stable states, hysteresis, and compounded anthropogenic responses.
6. The ability of the existing models to deal with unprecedented rates of change in environmental conditions and physical, biogeochemical, and ecological processes needs

to be evaluated. Most models have used historical rates that are often averaged over time and space whereas rates are changing temporally and spatially at an accelerating rate under climate change.

While NOAA has embraced the use of such ecosystem models, additional refinements are suggested. Specifically, most models may not be flexible enough to incorporate forcing from events, episodic disturbance, or other timescales that may become especially important to the biota. Additionally, most biological models assess response to a single stress variable at a time, whereas in nature, multiple stressors occur simultaneously, and can amplify or ameliorate effects. Most models do not include enough ecological complexity to assess the interactions between biotic and abiotic in the environment to truly understand many of the responses to multi-stressor events. And finally, most of the models do not account for accelerating rates of change. Each of these factors should be better assessed for their impact on ecological forecasting.

The demands on physics, biogeochemistry, biology gets amplified by considering multiple stressors and a rapidly changing ocean. We need to consider that there can be three major interactions: (1) stressor A affects Stressor B, (2) the effects on biota of Stressor A and Stressor B together differs from the effects if they were independent (additive, synergistic, etc.), and (3) there are indirect ecological effects (e.g., interspecific interactions, complex life cycles) cause nonlinear biological responses.

Lastly, the importance of sustained observations is critical for understanding multi stressor effects on biological processes and systems. The value of long-term time series is high not only for calibrating and validating models, but for helping to identify non-linear or unanticipated shifts or effects. What also must be prioritized is not just sustaining the data/observation collection and QA, but also funding data analysis adequately.

Recommendations and Proposed Approaches

NOAA has made much progress in using population, food web, and ecosystem scale models in a variety of ways. The recommendations below are meant to bolster this success and propel the scientific skill and understanding of ecosystem modeling.

- Because what has worked in the past for these models may not for rapidly changing marine environments, going forward into the future, the time to act is now, so that the nation can be better prepared. We thus urge attention to this topic, evaluating how the linked tools of modeling, observations, and data analysis can provide insights and result in optimized tools for tomorrow.
- Evaluate how models could more thoroughly integrate biological processes. Pay particular attention to the cumulative impacts of multiple stressors at different time scales, and specifically in the context of a rapidly changing ecosystem.
    - Conduct an assessment of existing techniques and identification of main needs. What are existing barriers to effective biological-physical coupling within a frame of multi stressors?
    - There needs to be emphasis on modeling the full distribution of responses of

individuals in order to appropriately characterize the range of variability in the overall response to cumulative multiple stressors.
    - Identify critical connections in the ecosystem, biotic and abiotic, for inclusion to best characterize responses to stressors and disturbances.
    - Develop innovative approaches for validating models under novel (previously unobserved) conditions and for multi stressors when combinations are limited in the historical record.
- Provide innovative ways to stimulate fundamental ecosystem understanding and associated model development.
    - Utilize RFPs that encourage cross sector (federal, academia, private) collaborations.
    - Provide RFPs that focus on analysis of existing data, and also its applicability and integration to ecosystem models.
    - Embrace research from multiple scales including regional, national, and global to fill in gaps in model datasets.
    - Encourage analysis of existing data to elucidate mechanisms and connections not currently known. We cannot always know a priori what analyses or technology can aid response to and resiliency toward climate change. There is often insufficient focus on in-depth analysis of collected data and this limits revelation of unanticipated connection and new insights.
- Focus on enabling models that are fit for purpose, but also that contain enough detail to be useful: highlight need for increased model skill assessment.
    - Encourage model skill assessment across disciplines; encourage wider usage of skill assessment tools; encourage better integration of observations and modeling (e.g, validation practices, data assimilation, etc).
    - Assess examples from other countries, especially where there is evidence of practical application. The UN Decade of Ocean Science for Sustainable Development is a great opportunity to do this.

Chapter 2: Promoting resilience by incorporating people in forecasting, risk assessment, and policy to respond to rapid change

Using social sciences to generate new knowledge, refine tools, and improve the use of social science-informed insights in current decision-making processes and policies.

Problem Statement

The coastal ocean and coastal Great Lakes support diverse human uses and can be managed to ensure a wide array of amenities, uses and benefits. Yet, efforts to include people as drivers of change, as beneficiaries of environmental management, and as sources of innovative problem solving, have not been systematically considered in NOAA models for system forecasting and policy analysis. Some examples where behavior has been included in models or forecasts suggest that the benefits of integrating human behavior (e.g., to design effective policy) could be substantial. In fact, models that lack the causal or participatory human dimension of system-based stress may underestimate the potential for harm due to feedbacks or, in other cases, overestimate harm by failing to recognize how people can ameliorate change through adaptation.

This chapter evaluates some ideas of how social science might be used by NOAA in anticipating fisheries, ecosystems, restoration, and coastal risk management needs and applying findings for adaptation under rapid system change. Social science is the study of human behavior and its uses for preparing for rapid change center around anticipating and projecting behavioral responses of individuals, businesses and institutions to change. Further, insights can be used to characterize differential adaptability or resilience to stress, which has been called "... a critical element of analysis in human–environment systems" for promoting sustainability (Turner et al. 2003).

Two main uses of social science form the basis of recommendations in this chapter, 1) Using social science (or human dimensions research) to generate new knowledge and refine tools and 2) Improving the use of the social science-informed insights in current decision-making processes and policies. Knowledge of how people are likely to adapt can be applied to improve forecasts of climate change effects within socio-ecological systems, identify opportunities to promote adaptive capacity, and to test the effectiveness of policy or other interventions aimed at changing behavior. Examples of management questions that could benefit from human behavioral modeling and forecasting:

- What is the relative influence of environmental change and human behavior change on management effectiveness?
- What social changes have the potential to change the effectiveness of current management approaches?
- What data and models are needed to support adaptation of communities experiencing ocean acidification, coral bleaching, fish out-migration?
- How do or could acts of ecological restoration and/or resource management practices generate community self-value (e.g., affinity, cohesion) and self-efficacy.

Past NOAA Efforts

Prior Science Advisory Board (SAB) reports have identified overarching social science needs for effective NOAA management (SAB SSRP 2003, SAB 2009). These reports have identified that "NOAA's capacity to meet its mandates and mission is diminished by the under-representation and under-utilization of social science." (SAB SSRP 2003). NOAA has responded to these recommendations for increased social science by developing new initiatives and programs relevant to ecosystem management among other efforts such as weather risk communication and economic benefit assessment of programs. However, this response should be expanded further across the NOAA enterprise.

Within the scope of ecosystem issues, a major response by NOAA to recommendations to integrate social science was to create the integrated ecosystem assessment (IEA) program, which is a multidisciplinary science support framework for meeting diverse goals of ecosystem based management (EBM) (Harvey et al. 2021). Related efforts within fisheries management are Management Strategy Evaluations (Punt et al. 2016) and the Ecosystem Approach to Fisheries Management (e.g., Muffley et al. 2022). These approaches embed some limited social issues into fishery management decisions, such as ecosystem protection and community economic effects (Townsend et al. 2019).

These efforts have advanced understanding of socio-ecological system modeling and addressed managers' needs to consider multiple goals. However, these efforts may be insufficient to address rapid ecosystem change and increases in number and/or intensity of extreme weather events. Models generally lack direct incorporation of social dynamics and feedbacks and instead rely on projections of management effects that use historic data and relationships, despite unprecedented rates of change in ocean conditions. For instance, models have not systematically incorporated emerging human responses to shifting species, even though behavior has altered effectiveness of catch limits and other strategies.

NOAA is clearly making strides in some types of coupled or integrated socio-ecological modeling, particularly in the fisheries management area (e.g., Kasperski et al. 2021). Yet, the degree to which outputs from integrated models are meeting decision maker needs across all programs is unclear. Further, the opportunity to use such models in anticipating and planning for future change is underdeveloped. Given the challenges of rapidly changing systems, additional social science investments (people and process) appear needed to anticipate and design management approaches that directly ameliorate harm or enable adaptation. Recommendations below are organized into the two themes of generating knowledge and supporting decisions.

Using human dimensions research to generate new knowledge

We see simple to complex potential applications of social analysis and socio-ecological system models to anticipate future problems and to project benefits of actions. At a minimum, it appears that projections of human migration and socio-demographic change are not widely incorporated into forecasts used in recreational fishing management and coastal hazard assessment. For example, humans continue to move to vulnerable coastal areas and the possibility of mass human migration due to sea level rise and storm intensification will be a substantial future planning need that requires proactive planning to ameliorate forecasted problems (Text Box 1).

At the more complex end of the modeling spectrum, models with behavioral feedbacks will be relevant to effective forecasting because they bring understanding of how social and ecological forces "enforce or erode the desired system state" (Camp et al. 2020). Integrated modeling can be designed to assess the combined effects of engineering effectiveness and human responses to change when evaluating environmental restoration coastal resilience approaches. Questions to address include, Are people receiving the intended program benefits and does their behavior limit or increase benefits on multiple dimensions? Such modeling also supports program design to maximize benefits and their equitable distribution. Analysis to better understand social values and their distribution among disadvantaged and privileged groups can be applied when choosing from alternative solutions based on projected benefits. Research to anticipate benefits could also go beyond direct effects to analyze indirect and spillover effects, such as whether environmental restoration reinforces overall community resilience (e.g., via social cohesion).

Text Box 1. Anticipating change to support human "migration with dignity"
Kiribati, a Pacific island nation with over 100,000 residents, embodies the challenges facing low-lying island nations and coastal cities around the world. Kiribati may be completely underwater within the next 30 years (IPCC 2014). Severe flooding has already destroyed much of the coastline and property and seawater is compromising freshwater ponds and food crops (ELI). Globally, 136 of the world's largest coastal cities are at risk and will suffer from sea level rise without adaptation. (IPCC 2022). As climate change advances, cities and nations without the resources to resist sea level rise and intensifying storms will generate the need to resettle large numbers of people. This mass migration will easily overwhelm the human welfare programs that are in place in many areas, particularly if residents of low-lying islands initially move to islands with higher elevations but not extensive financial resources for social safety nets. Many livelihoods in these island nations depend on fisheries, likely creating fishery management challenges if migrants and refugees turn to the ocean for sustenance. In anticipation of sea level rise, Kiribati has proactively developed a policy called migration with dignity that has trained citizens with marketable skills so that they can land on their feet when they emigrate to countries like Australia or Fiji. More information is here.

Data collection and horizon scanning

Forecasting human behavior can be served by observing or eliciting human responses to change and detecting emerging behavioral and cultural trends. Gathering observations on how people are influencing, adapting to, being harmed, or benefiting from environmental and policy changes provides the basis of human behavioral forecasting. In addition, to be better prepared for rapid change, it is helpful to conduct *horizon scanning* which is the process of identifying emerging trends or indicators of cultural changes that signal how behavior may be diverging from historic conditions.

A major impediment to measuring human responses or eliciting preferences surrounding environmental change within NOAA appears to be limitations on federal social scientists' research methods. Federal employees have difficulty conducting surveys, which are the most common kinds of social data collection, due to arduous requirements put in place by the Paperwork Reduction Act. Even simple measures of recreation participation are generally lacking (see Mazzotta et al. 2022 for a rare example). Similarly, another common approach, social media analysis, appears to be limited by cultural concerns at the institutional level. Some ways to overcome such barriers are to 1) facilitate partnerships between NOAA and external academic social scientists who have more research flexibility or 2) to streamline the survey approval process to match priorities.

Horizon scanning can be used to anticipate change, identify innovative management ideas, respond more quickly to change, and mentally prepare managers and communities. Searching news, surveying experts or the public, and using social media are all common practices to collect data that can be used for short-term management and long-term forecasting. Data mining and artificial intelligence (AI) can be used to analyze massive amounts of data for behavioral patterns to facilitate horizon scanning (Norgaard et al. 2020; Carter et al. 2015). In addition, ongoing engagement with communities, where clear communication methods are established, is a way to have “eyes on the ground” to gather ideas on what behavior may be beneficial to study. For example, a better system of conducting horizon scanning and incorporating that information in management might have anticipated the crab fishing gear conflicts with whales that have arisen, although adaptive management was ultimately effective in reducing conflict (Text Box 2).

Text Box 2. Learning from the past - A marine heat wave and a management response to domoic acid contamination led to high levels whale entanglement in fishing gear

In describing the management response to whales moving inshore due to changing ocean conditions, Santora et al. (2020) described how a lack of response to changing marine conditions led to an inadvertent exacerbation of whale entanglement issues in the California dungeness crab fishery.

“In hindsight, despite the severe socio-economic impacts associated with the extended fishery closure, fishery managers should have more rigorously evaluated the tradeoffs between the economic needs of fishers and the likely increased risk to protected resources associated with the timing of the delayed opening of the 2015–16 crab fishing season. The delayed opening ultimately led to an unusually high concentration of fishing gear being deployed in areas where thousands of whales were arriving to feeding grounds containing very little food (Figs. 2–4) that was concentrated in areas targeted by the crab fishery. Although the suite of MHW impacts were being routinely reported by the media and in scientific meetings and symposia (http://www.marineheatwaves.org/), there were limited mechanisms for integrating and conveying the cumulative ecosystem impacts across the diverse range of monitoring programs and surveys that might have provided fisheries managers with a more comprehensive understanding of potential interactions and consequences ...”

Using programs as experiments to increase understanding and improve cost-effectiveness

The knowledge needed to improve effectiveness of policies and programs can be generated by systematically tracking effects of actions, policies or behavioral interventions. Policies have highly variable effectiveness once implemented and the effectiveness of many programs is uncertain due to lack of sufficient data to tease apart causal and confounding variables. If every program were treated as an experiment by tracking inputs, outputs and outcomes, analysts could improve the ability to disentangle the reasons for variable performance of programs and methods. As one outcome, social scientists would have substantially more data with which to test theories to identify supportive conditions for specific behavioral interventions, which are experimental approaches that apply behavioral theories to encourage a beneficial behavior change in a particular community or organization. For example, behavioral interventions are already being used to encourage coastal risk planning using a combination of financial incentives (e.g., reduced flood insurance rates) and visualizations that have been shown to motivate behavior change.

Using social science-informed insights in current decision making processes: Adaptive Management

Given that future system fluctuations will exceed historical bounds, nimble adaptive management will be a critical need to respond to rapid and accelerating rates of change. Two types of changes in decision processes could be useful. The first is to use understanding of human behavior during management and program design. While some efforts to anticipate behavior change are used in program design, many programs rely on assumptions and expectations of behavior change, rather than empirical analysis. A second adaptive change would be to apply a more iterative approach to decision making under uncertainty. Deep uncertainty is an extreme case of uncertainty and is defined as potential future conditions that cannot be well characterized with existing data, models, or understanding (See SAB and ESMWG 2021). Techniques such as dynamic adaptive planning (DAP) can be used to routinely track data and information to inform an ongoing decision process. Monitoring and modeling are used to trigger a switch to an alternative risk management approach based on changing risk and new information (Supplemental Material; Text Box A).

Better scenario analysis to prepare for an unknown future

Scenario analysis is a common tool for anticipating and managing uncertainty, yet this process sometimes has limited utility because of how it is implemented. Peoples' thinking is subject to cognitive biases that may lead to risks being ignored or minimized (Johnson and Levin 2009). Scenario development needs to be designed with these cognitive limitations in mind or the scenarios developed will not lead to full exploration of the most relevant issues. NOAA has developed some helpful scenario guidance that recognizes the need to anticipate unexpected events. However, current scenario planning efforts do not appear to describe or apply methods to overcome cognitive biases (e.g., Frens and Morrison 2020). Tools to overcome biases include using broad horizon scanning and facilitation techniques that encourage people to think about futures that they would rather avoid (McGonigal 2022; Erdman et al. 2015).

Using institutional science to promote nimble and effective structures and processes
There are strong institutional impediments to becoming more nimble when managing risks associated with climate change (e.g., fisheries challenges are described in Fulton 2021). One of the key impediments is time to absorb and act on new information. Thus, adaptive management can only work if people and processes are given the resources to evaluate past performance and recommend change. More generally, a great deal of institutional science has identified approaches that promote the type of governance that promotes socio-ecological resilience using tools such as decentralizing authority to promote faster response time, providing legal flexibility, and developing strategies for intentional learning (Mason 2021; Garmestani et al. 2019; Gerlak et al 2021). For example, some have called for more rapid dissemination of HAB data and management plans to affected communities to increase their capacity to adapt (Ritzman et al. 2018). Making greater use of existing social science knowledge in decision processes is likely to be critical to responding to rapid change.

Prioritizing investments for human behavioral modeling and integration
Many opportunities exist to improve forecasts and resilience management by studying, modeling and integrating human behavior into policies and programs. However, NOAA will need to consider which efforts have substantial payoff for them, such as by using a strategic planning process. To provide some initial input into strategic planning, we offer an initial assessment of the potential effort and usefulness of a variety of social science approaches (Figure 1). Brief explanations of methods are found in Supplemental Material, Table A.1.

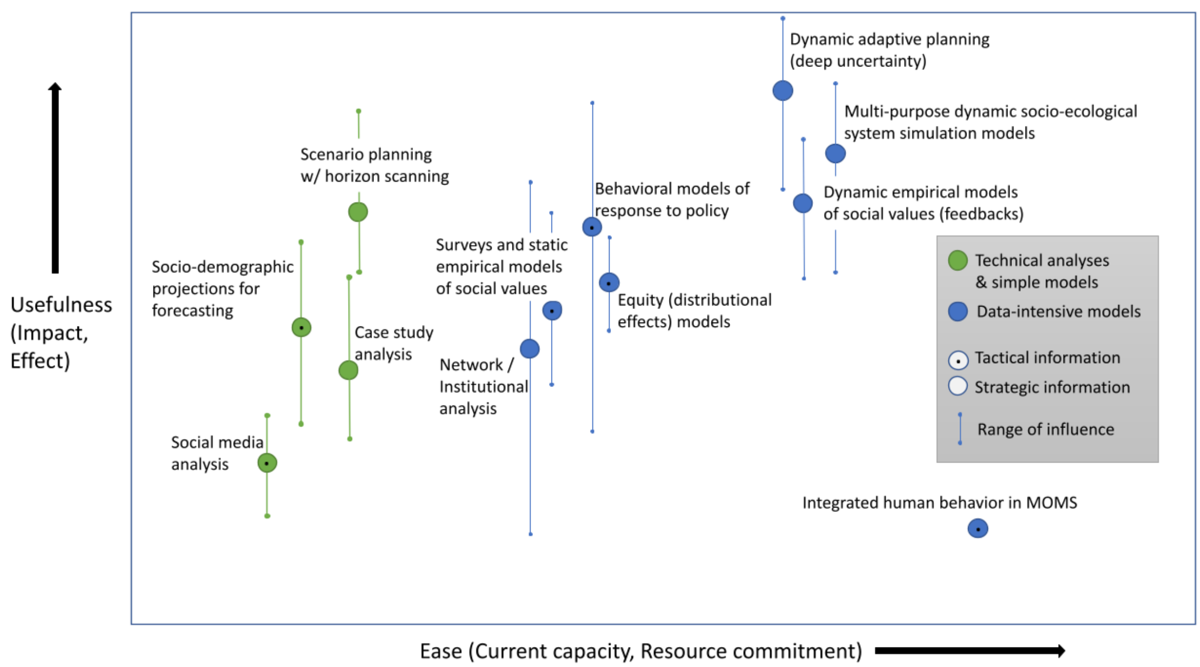

Figure 1. Effects and Ease of Social Science Methods and Models
Points represent alternative methods to analyze and predict human behavior and are distributed on the dimensions of analytic ease and decision usefulness. Ease refers to all aspects of current data availability, theoretical understanding and the time and resource commitment to building the analysis or

model. Usefulness refers to potential degree of impact or effect on decision making. A distinction is made between tactical and strategic information where tactical information is specific to a problem or program and strategic information is useful for broader questions of research or policy design. In practice, all techniques have a range of ease and usefulness, and this graphic plots models based on our opinions of the average or typical implementation.

Summary of recommendations

Below is a summary of the recommendations that can advance NOAA needs for understanding and managing changing socio-ecological systems in rapidly changing marine systems.

1. Establish strategic and investigative priorities for integrative modeling investments based on effectiveness versus relative ease
    a. See Figure 1 for some guidance on social science or integrated analytic approaches may be cost-effective, but results will vary and priorities can be usefully informed by having diverse scientists and policy actors engaged in strategic planning.
    b. Priorities will need to be supported by research infrastructure that enables analysis and integration with biophysical models

2. Use traditional and emerging social science data collection methods to model human behavior and inform marine and coastal program design
    a. Programs to address rapid change need improved understanding of how humans have responded to past change and how such behavior may be evolving. Gaps in understanding can be filled using traditional social and economic research methods and emerging tools of social data mining, and horizon scanning
    b. Learn from program implementation by treating policies and actions as experiments and by monitoring ecological and social performance outcomes.

3. Create (internal and external) capacity and institutional pathways to develop, use and apply social science methods as critical components of adaptive management
    a. Stimulate social science research that addresses adaptive management needs by engaging social scientists in problem solving and research planning
    b. Craft scenarios that explore extreme conditions, address cognitive biases, and include human behavior, to better prepare for an uncertain future
    c. Make use of institutional science to design nimble structures and processes for effectively anticipating and responding to novel conditions and rapid change

We note that some NOAA programs are making progress on these goals and internal teams may be able to assist other programs in advancing some of these goals. In other cases, additional expertise and resources appear to be needed to advance these recommendations.

Chapter 3: Collaborative science, Co-design & Co-production in a Rapidly Changing Marine Environment

Best practices and new approaches to increasing engagement with rights holders, stakeholders, and others and incorporating collaborative science, co-design, and co-production in NOAA's scientific programs and decision support products.

Problem Statement

A rapidly changing marine environment (RCME) - one that introduces heightened complexity, uncertainty and unpredictable (such as non-linear) responses - poses new challenges to managing marine and freshwater ecosystems and can thwart efforts to predict and to authentically engage, collaborate, and co-learn with fishermen, tribes and other relevant rights holders and stakeholders in NOAA's scientific programs and decision making.

Collaborative science, also referred to as participatory science, and more recently co-design and co-production, involves rights holders and stakeholders throughout the scientific process. Such co-creation shifts the focus of engagement farther forward in the design and conceptualization of research instead of later in the process of more typical engagement or participation. The desired outcome of this process should be to increase our ability to understand a complex problem jointly and together develop insights, research strategies, management responses and proposed solutions. The process should decrease the distances among participants, acknowledge the value of different ways of knowing and perspectives, increase the likelihood of successful outcomes, and provide a basis for better ground-truthing of the proposed outcomes and changes.

NOAA must build on its current successes in leading and engaging in co-design and co-production work, address institutional and organizational barriers and challenges that limit effective use of such processes, and adopt best practices and new approaches in doing so. Inherently, co-design and co-production can take longer and require more partnership building earlier in the conceptualization and project development phases.

New challenges presented by RCMEs

- Episodic extreme events, while difficult to predict, are occurring more frequently, testing our ability to plan for and respond to them
- While some change is still happening gradually, other changes are happening rapidly and challenging our capacity to keep up and project an increasingly uncertain future for complex ocean processes
- In some ways we are beyond the limit of traditional scientific inquiry and our predictive historical capacity (the future is not like the past)
- A number of our systems are at ecological thresholds, making them harder to model and predict and suggest that substantial shifts in historically observed ecosystem structure and function are occuring

Not starting from scratch: NOAA success stories

The importance of engaging end-users, rights holders or stakeholders at all stages of the scientific process, and tool-development, is not new to NOAA or other federal agencies. In fact, there are many examples within NOAA of successful efforts to incorporate structures and processes that elevate partner engagement from the outset of scientific inquiry (from the issue identification stage to solution implementation stage) that have enhanced uptake and adoption of science programs. Given the complex practical and cultural challenges of broad perspective engagement at multiple times and scales, these examples provide important points-of-reference, guidance, and opportunities for reflection as we consider building from these pioneering efforts. Brief descriptions of four examples here demonstrate such efforts within NOAA:

1. National Estuarine Research Reserve System (NERRS) Science Collaborative

Since 2009, the NERRS Science Collaborative Program has been funding end-user focused proposal development, communications efforts, research and other project grants. This program elevates criteria tied to elements of collaborative research in the review of funding proposals. These criteria require end-user engagement and other perspectives throughout the project development, implementation and outreach phases of projects. Extensive guidance is provided by the NERRS Science Collaborative to assist in proposal and project development. This includes detailed information about the 'approach and mindset' required for successful collaborative projects, as well as tips for scoping, designing, implementing, and producing project communication products collaboratively to improve project success. Since its beginning, the NERRS Science Collaborative has invested $33 Million dollars in more than 147 projects, each of which has emphasized co-production of knowledge among the scientific community and end-users to inform decision-making. A 2018 evaluation of the program found that despite adding complexity and compilation to the proposal and implementation of projects, participants viewed the program's end-user engagement requirement as central to the NERRS success in fostering improved decision-making as an organizational outcome.

2. NOAA RESTORE Science Program

The NOAA RESTORE Science Program funds research, projects and monitoring to support resource management in the Gulf of Mexico. The RESTORE Science Program has promoted structures that ensure co-production throughout the scientific process by providing seminars and trainings to staff at state and federal management agencies, funding entities, nonprofits, and academic institutions. In addition, the RESTORE Science Program leverages co-production strategies in its "Planning for Actionable Science" funding program that requires partnerships between natural resource managers, researchers, and stakeholders. The Program then seeds those partnerships with funding to jointly develop and implement a research project that targets outcomes that will inform a specific management decision. The research team for these projects must include at least one natural resource manager and stakeholder as a lead or co-lead on all projects. The RESTORE Science Program also takes additional deliberate steps that ensure stakeholder engagement from the beginning, at the origin of the research process. As an example, the long-term research goals and short-term funding priorities are developed through extensive engagement with multiple stakeholder perspectives so that research priorities are co-produced by the research and end-user communities.

3. Multi-NOAA Organization Collaboration in Fisheries Science and Management: An Example With Atlantic Cod in the Gulf of Maine

In the Northeast, Atlantic Cod is currently managed as two stocks: a Gulf of Maine Stock and a Georges Bank Stock. Over the years, genetic, morphometric, tagging studies have suggested a more complex population structure which motivated a review of existing science by an Atlantic Cod Population Structure Working Group, overseen by the Northeast Fisheries Science Center, but including fishers and managers from the Greater Atlantic Regional Fisheries Office. As a part of the process, NH Sea Grant held a series of workshops where scientists and managers met with fishers to review available data to co-produce a revised understanding of Atlantic Cod Population Structure. This facilitated process focused on integrating scientific understanding from a range of approaches, with fishers' ecological knowledge (through on-the-water observations as well as two manuscripts that identified historical spawning areas identified through decades of interviews from fishers). These workshops led to a peer-reviewed publication proposing a revised Atlantic Cod Population Structure that includes six biological stocks. Additional follow-up workshops engaging scientists, managers and fishers, facilitated by NH Sea Grant as well, have been held to explore potential management responses to these new conditions. This one example demonstrates how NOAA Fisheries works closely with NH Sea Grant to facilitate co-production of scientific understanding and management response with scientists, managers and stakeholders (in this case, the Northeast Fisheries Science Center, the Greater Atlantic Regional Fisheries Office, and NH Sea Grant).

4. Great Lakes Restoration Initiative (GLRI)

The GLRI is a federally funded restoration program targeting the most historically degraded parts (mostly urban and related waterways) across the Great Lakes Region. The initiative is a collaborative partnership between 16 federal agencies, eight Great Lakes States and myriad local units of government and corporate and not-for-profit entities. The model relies on high levels of community scale agreement in addition to very high levels of integration across the entirety of the federal agencies. Solutions are crafted and implemented at local scales. NOAA has the lead for much of the habitat restoration work within the GLRI framework and is broadly coordinated with other restoration activities. To date thousands of river miles have been cleared for fish passage and nearly a half a million acres of habitats including coastal wetlands have been protected, restored or enhanced.

These are just a few examples, but certainly not the only ones, of structures and processes that could help inform a more directed, holistic, and strategic approach to stakeholder engagement and co-production of knowledge that could lead to more successful Research to Application funding programs in NOAA.

Continued barriers and challenges

Although much progress has been made within NOAA in terms of moving project conceptualization, design and management upstream using stakeholder engagement and collaborative science, many of these efforts face continued barriers and have not reached their full potential for a variety of reasons. These include:

- A lack of resources and/or commitment on the part of both government agencies and stakeholders. Funding of engagement activities continues to be an issue, especially when the choice is presented as funding engagement or a ship survey or other scientific endeavor. A RCME provides new challenges in that standing up an engagement process takes time, and some changes are happening so fast that the process can't be adequately incorporated into decision making, especially given timelines for regulatory and management processes. On the other hand, in some cases, funding and agency support is available, but stakeholder participation is low. This can be due to multiple demands on stakeholder time, lack of actual interest in the issue, or a sense that the process will not be fruitful.
- A lack of communication across NOAA programs and line offices. Coordination of these strategies is important to avoid duplicating efforts, stakeholder overload, and "reinventing the wheel."
- A timing mis-match. Agency decision making - whether through a scientific proposal solicitation or for a regulatory action - often has a quick, time certain turnaround. The timing for engagement may interfere with stakeholder business seasons, or with subsistence hunting or commercial fishing seasons. One potential solution is developing long-term relationships over time in advance of decision making, so that engagement and co-production can take place in a timely fashion.
- Agency requirements for quality-assured quantitative data. Since many agency decisions are challenged in court, NOAA places an emphasis on supporting decisions with quantitative data, and not always in a timely fashion. Community based observations and local and traditional ecological knowledge are typically more qualitative, and although recognized, are still a challenge to incorporate formally into a decision making process.
- An ecosystem approach to management is still a work in progress, which makes engagement with communities more challenging. NOAA has made great strides in managing fish and marine mammal populations by taking into account people, other species, and ecosystem conditions.
- A lack of engagement personnel who are well-trained, have a deep understanding of both co-production and the science, and are positioned within the agency to influence the process and outcomes.
- Capacity and engagement constraints of many of the less well resourced partner organizations. While co-creation and early engagement in conceptualization may be the goal, without capacity, many of the most disaffected people and least funded organizations cannot engage a priori. If engagement in co-design and co-production happens in the development of an RFP for instance, does that preclude the partners that worked to craft the RFP as co-design collaborators, from bidding on work or further participation?

Learning from recent Indigenous initiatives: a new approach

The concept of co-production is not new, dating back to the 1970s (Cooke et al, 2021; Woodall et al, 2021). However, recently there has been new thinking and new approaches to co-design and co-production largely spearheaded by Alaska and Canada and other Arctic Indigenous peoples, highlighting the difference between Indigenous Knowledge and Local/Traditional Knowledge, and including the concept of social justice and equity: "Equity refers to ensuring that space is fairly provided for all knowledge systems and knowledge holders involved in an agreed-upon process" (Ellam Yua, et al 2022). In summer 2022 the Inuit Circumpolar Council released its Protocols for Equitable and Ethical Engagement (Inuit Circumpolar Council, 2022). This new co-production of knowledge approach has lessons that can be used by other under-served communities as well as non-Indigenous communities and reflects a new appreciation for environmental and social justice.

A new Alaska Climate and Equity pilot project launched by NOAA with the Alaska Native Tribal Health Consortium (ANTHC) could serve as a potential model. The pilot establishes a director of Tribal climate change initiatives position at ANTHC who will work with NOAA to support Tribal climate resilience in Alaska. The project, "Expanding and Connecting Tribal-Led Climate Change Capacity to Serve Indigenous Community Needs in Alaska," will establish, with NOAA funding support, a director of Tribal climate change initiatives position at ANTHC to leverage statewide relationships with Tribes. "NOAA hears loud and clear that Alaska Native perspectives, voices and leadership must drive climate change conversations and action for Tribal communities across Alaska. This project is about establishing a partnership based on trust, mutual respect, deep listening and meaningful follow-through in order to realize positive changes in achieving climate equity," said NOAA Administrator Rick Spinrad in a press release announcing the project. The Alaska pilot is one of seven regional pilots taking a place-based approach to helping communities that have been traditionally underserved by federal resources better understand, prepare for and respond to climate change.

Recommendations

1. Make a thorough inventory of all stakeholder engagement activities and ensure that there is minimal duplication, and maximum leveraging and elevation of these activities in scientific and related programs.
2. Expand and integrate the engagement tool box and cultivate a one-NOAA culture and community around rights holder and stakeholder engagement within NOAA.
3. Ensure that end users are engaged at the beginning of and throughout scientific and decision making processes, including implementation, so that engagement is bottom up, as well as top down. This includes providing the resources necessary for stakeholder and rightsholder capacity to appropriately engage.
4. Consider how best to establish long-term relationships with rights holders and stakeholders and make appropriate investments in the engagement/collaboration processes, so that rapid change can be addressed quickly. This could begin with small steps to build trust that can start immediately or in all areas, regardless of whether a large investment in a co-production process is made.

5. Make a stronger commitment as a science agency to elevating and training engagement personnel within the agency workforce, and to hiring people with a deep understanding of co-production.
6. Consider bifurcating capacity and engagement with the least-resourced organizations from project RFP work so that engagement early in the development or design does not preclude ongoing project engagement in any manner.

Conclusions

In conclusion, we know that what has worked in the past for responding to ecosystem change may not be sufficient for responding to rapidly changing marine environments in the future. We strongly advise that the time to act is now, so that the nation can be better prepared. We urge attention to this topic, evaluating how the linked tools of modeling, observations, and data analysis, together with enhanced engagement and co-production can provide insights and result in optimized tools for tomorrow.

Each of the above chapters include a list of recommended actions. To summarize, NOAA should:

- Evaluate how models could more thoroughly integrate biological processes. Pay particular attention to the cumulative impacts of multiple stressors at different time scales, and spherically in the context of a rapidly changing ecosystem
- Provide innovative ways to stimulate fundamental ecosystem understanding and associated model development
- Focus on enabling models that are fit for purpose, but also that contain enough detail to be useful: highlight need for increased model skill assessment
- Create better understanding of how humans respond to change by facilitating the collection of relevant data on human behavior using emerging observational tools
- Establish strategic and investigative priorities for integrative modeling investments based on effectiveness versus relative ease
- Use traditional and emerging social science data collection methods to model human behavior and inform marine and coastal program design
- Create (internal and external) capacity and institutional pathways to develop, use and apply social science methods as critical components of adaptive management
- Expand and integrate the engagement tool box and cultivate a one-NOAA culture and community around rightsholder and stakeholder engagement and co-production
- Make a stronger commitment as a science agency to elevating and training engagement personnel within the agency workforce, and to hiring people with a deep understanding of co-production

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Supplemental Material

Text Box A. Strategic planning using Dynamic Adaptive Policy Pathways (DAPP).

DAPP was developed as an analytical framework that facilitates decision-making under deep uncertainty (Haasnoot et al, 2013). Given the uncertainties that exist with future sea level rise, future development and land use conditions, and future water management constraints, coastal resilience studies are suited to the use of DAPP to develop plausible mitigation scenarios for sea level rise and storm surge risks. Potential actions are visually depicted with an Adaptations Pathway Map (**Figure A.1)** that indicates the effectiveness of the action to achieve the desired performance level.

DAPP relies on a few key concepts:

· Thresholds: This is a pre-specified minimum performance level. In this study, the threshold is determined by the expected annual flood damage (EAD), further discussed in this technical memorandum.

· Adaptation Tipping Points (ATP): This is the point at which the proposed action exceeds the threshold. This means that the performance of that action fails to meet the objective. In this study, with the threshold represented as a level of EAD; reaching the tipping point indicates higher estimated annual damages.

· Pathways: Any proposed action or sequence of actions that forms a roadmap for future are known as a pathway on the Adaptations Pathway Map.

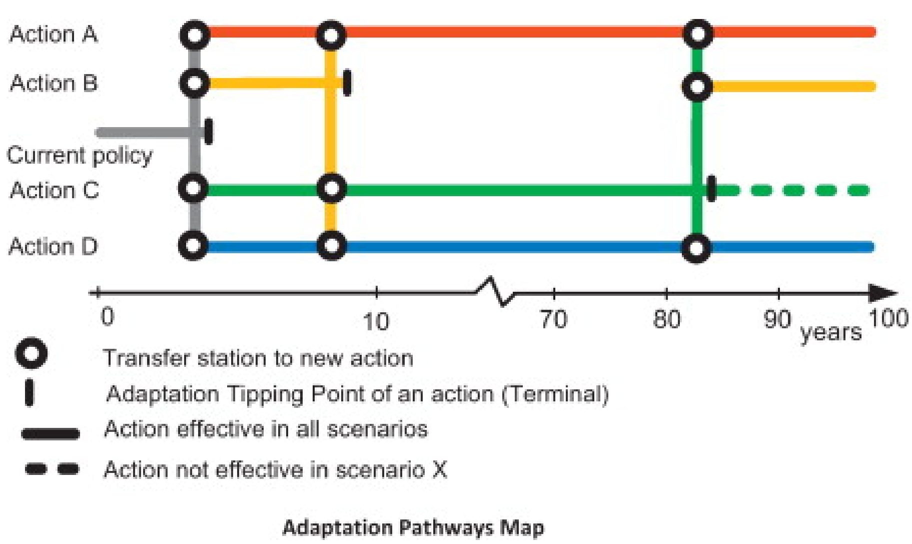

Figure A.1. Example of an Adaptations Pathway Map

Adaptation pathways can represent multiple sequences of adaptation measures to adjust to changing conditions, rather than deciding on an approach at one point in time. In Figure A.1, the example depicts that Action B is effective for almost 10 years. At this tipping point, other actions would need to be taken for the objectives to be met. A pathways map shows all the potential options and how they may be combined as conditions change. Different maps allow for examining these adaptation decisions under different assumptions about timing and or physical conditions.

One of the strengths in using the DAPP framework is the level of transparency available to decision makers. The data can be viewed with different time scales, varied geographic or jurisdictional boundaries, or different SLR projection. Each lens can yield valuable information on the impact and duration of the mitigation actions.

Table A.1. Types of analyses and models that may be relevant to NOAA decision making

Category	Recommendation	Rationale
Social media analysis	Develop capacity to use social media to understand resource use and changing behavior	Social media can provide early warning signs of management-relevant changes in behavior in socio-ecological systems (e.g., recreational fishing effort or spread of aquatic invasive species)
Socio-demographic projections	Develop or purchase demographic forecasts and spatial land use change, for use in forecasting and future risk models.	Changing socio-demographic conditions (e.g., an aging population) can be used to anticipate behavior change to the degree that behavior is correlated with individual traits or market segments (categories of people based on common preferences)
Case study analysis	Qualitative and quantitative analysis of how people have responded to change or have been effectively engaged in resource management in case studies can provide insights into behavior and expected/potential responses to change.	Case study analysis is an insightful and viable analytic tool to understand human behavior, particularly when data and resource constraints prevent original surveys or intervention tests. However, it also has limitations since many elements (e.g., reasons for success) are not always well documented.

Scenario development with horizon scanning	Develop capacity (internal personnel, external experts) to identify emerging signals of future change that could influence management needs or effectiveness	- Anticipate major changes in socio-demographic, cultural, technological conditions. - Apply future signals to scenario development to provide greater breadth in uncertainty analysis of policy and programs
Network/Institutional Analysis	This family of techniques evaluates relationships and functioning of institutions including laws, policies, government agencies, and collaborative partnerships.	By examining characteristics such as where people get information, job incentives, and ease of communication, these studies can reveal opportunities for and barriers to change that may improve program and policy effectiveness.
Surveys and Static empirical models of social values	The category includes a family of techniques to assess people's preferences at a point in time. One type of approach is a stated preference (economic) survey that is used to develop a statistical model of willingness to pay to protect a natural resource element as a function of resource conditions and other factors. However, many other relevant endpoints might be assessed including risk perceptions, benefits of government programs, and likely responses to change.	Understanding preferences can inform resource management goals, be used to estimate costs and benefits of decision alternatives, and inform risk analysis, among other uses.
Behavioral models of response to policy	These models range from conceptual to empirical and all forms can be useful for anticipating how people are likely to respond to change. However, many questions remain unexplored in how people make decisions in specific decision contexts. The field of behavioral modeling can be advanced by treating new policies and programs as behavioral interventions to be studied, with results designed to	People are “irrationally predictable” in the words of behavioral economists. They do not necessarily do what is expected. By incorporating what is understood about individual incentives and thought processes, these models are useful for anticipating how people may respond to policies and reveal potential for unanticipated adverse effects. These models could

	add to the evidence base.	be particularly insightful for fishery enforcement and coastal risk management.
Equity and distributional effects models	This category includes conceptual and empirical models relating variables of disadvantaged status to risk exposure and inequitable distribution of benefits. Social scientists have not achieved a full consensus on how to measure disadvantage and how to fairly ameliorate inequity, but this is an active area of investigation within and external to government agencies.	Modeling the distribution of environmental and socio-economic outcomes across advantaged and disadvantaged groups will support decision makers in addressing equity issues and create incentives for researchers to improve methods.
Dynamic adaptive planning (deep uncertainty)	Dynamic adaptive planning (DAP) can be a conceptual process or a decision support system that is tightly bound to empirical forecasting and risk models. DAP takes a strategic approach to risk management such that decisions are based on the risk-weighted costs and benefits of alternative decisions. New information is used to routinely update risk assessments and compare the cost of acting soon or waiting for new information. In its full form, it includes stress tests of proposed policies to evaluate performance under unlikely, but plausible, future scenarios whose probability cannot be well characterized, in order to plan for "deep uncertainty"	This approach can be highly effective at revealing how to stage decisions to avoid regret. In the coastal zone risk management realm, it is used to choose engineering designs that meet current needs without compromising opportunities to address future needs.
Dynamic empirical models of social values (with feedbacks)	This family of models is similar to the static version of social value models but includes the feedbacks that relate changing environmental and social conditions to changing preferences and behaviors	Dynamic models of social value can be used for forecasting changing costs and benefits of policies
Multi-purpose dynamic	This family of models generally	These models offer unique

socio-ecological system simulation models	represents complex models that simulate individual and/or social responses to change. They include multiple relationships and feedbacks among biophysical, social and institutional conditions.	insights into socio-ecological system dynamics not available from other techniques.
Integrated human behavior in MOMS	The existing ocean modular ocean modeling system (MOMS) could be modified to include a module of dynamic human behavior	Not recommended due to the difficulty and the generally incompatible scales of human behavior and ocean processes