DRAFT Northeast Regional Action Plan to Implement the NOAA Fisheries Climate Science Strategy in 2022 - 2024

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1.0 Executive Summary

Changing climate and oceans are affecting the nation's valuable living marine resources and the many people, businesses and communities that depend on them. Warming oceans, melting sea ice, rising seas, extreme events, and acidification are impacting the distribution and abundance of species, and the structure of marine and coastal ecosystems in many regions. These impacts are expected to continue and there is much at risk.

To prepare for and respond to climate impacts on marine and coastal resources, the 2015 NOAA Fisheries Climate Science Strategy (NCSS) identified seven key objectives to increase the production, delivery, and use of climate-related information needed to fulfill the agency's mandates (e.g., fisheries management, protected resources conservation) in a changing climate. Beginning in 2016, NOAA Fisheries developed Regional Action Plans (RAPs) to implement the NCSS in each region based on regional needs and capabilities. This draft Northeast Regional Action Plan (NERAP) builds on previous efforts and describes proposed actions to continue to implement the NCSS in this region in 2022-2024.

The Northeast U.S. Continental Shelf is one of the most productive marine regions in the nation accounting for over one third of the U.S. commercial fishery annual value (NMFS, 2021). The region supports a wide array of living marine resources, from the highly valuable sea scallop and American lobster fisheries, to protected species such as Atlantic salmon and critically endangered North Atlantic right whales. Climate change is directly impacting the ocean and watersheds throughout the Northeast U.S. Over the last two decades, ocean temperature in the region has warmed faster than any other marine region in the nation. The impacts of this warming manifest in changes in species distribution, abundance, productivity, phenology, natural mortality, predator-prey interactions, and growth rates. Ocean acidification, another consequence of climate change, can affect many invertebrates and may also affect the larval stages of some vertebrates.

Since the publication of the Northeast Regional Action Plan (NERAP) in 2016, the NOAA Northeast Fisheries Science Center (NEFSC), Greater Atlantic Regional Fisheries Office (GARFO), and the Chesapeake Bay Office (CBO) have worked with many partners to make substantial progress in addressing the priority actions identified in the 2016 NERAP. However, there are still many actions needed to better inform fisheries and protected species management with relevant climate-based information. These needs include: 1) maintaining and enhancing surveys and data collection; 2) continued process-based laboratory and field studies; 3) development of climate-informed stock assessments; 4) improved regional ocean and ecosystem models; 5) translation of changing species distributions into spatial management; 6) climate vulnerability assessment and scenario planning; 7) ecosystem-based management; 8) management strategy evaluations; and 9) increased multidisciplinary science that includes economic and social indicators.

This draft update to the NERAP describes proposed actions needed over the next three years (2022 - 2024) to continue to address the goal and objectives of the NCSS in this region. The proposed 10 priority actions and the NCSS Objectives they address are listed here:

Maintaining Infrastructure (NCSS Objective 7)

NERAP Priority Action 1: Maintain ecosystem survey and data collection efforts in the Northeast U.S. Continental Shelf ecosystem including the Bottom Trawl Survey, Ecosystem Monitoring Program, Sea Scallop Survey, Northern Shrimp Survey, Clam Survey, and Protected Species Surveys and expand where possible (e.g., Gulf of Maine longline survey, data poor species, right whale prey sampling, ocean acidification monitoring).

NERAP Priority Action 2: Coordinate with other NOAA Programs, Line Offices, and partners to link living marine resource data, science, and management to climate science and research activities.

NERAP Priority Action 3: Continue to build industry-based fisheries and ocean observing capabilities.

Tracking and projecting change, understanding mechanisms (NCSS Objectives 4-6)

NERAP Priority Action 4: Continue production of the NEFSC State of the Ecosystem reports and other related products that include climate relevant information that is useful to management such as historical, forecasted, and projected biophysical conditions, marine heatwaves, species distribution and abundance shifts, biogeochemical indices, and coastal community vulnerability to sea level rise and storm surge.

NERAP Priority Action 5: Conduct laboratory and field research on the mechanistic effects of multiple climate factors (e.g. temperature, ocean acidification, dissolved oxygen) on living marine resources with the goal of informing process-based models for single species, multi-species, and the ecosystem.

NERAP Priority Action 6: Work with NOAA Oceanic and Atmospheric Research, National Weather Service, National Ocean Service, and academic partners to develop and improve regional hindcasts, forecasts, and projections of ocean and estuarine/river physics and biogeochemistry to develop and improve climate-ready management of living marine resources.

Informing Management (NCSS Objectives 1-3)

NERAP Priority Action 7: Improve spatial management of living marine resources through an increased utility of spatial and temporal distributions, abundance, productivity, migration, and phenology in management decisions.

NERAP Priority Action 8: Develop and use Vulnerability Analyses, Scenario Planning, and Management Strategy Evaluations to examine the effect of different management strategies under various climate change scenarios.

NERAP Priority Action 9: Increase social, economic, and ecosystem scientist involvement in climate change research through multidisciplinary work, including the Northeast Integrated Ecosystem Assessment, that examines relationships between various ecosystem components with the goal of enhancing ecosystem-based management with climate information.

NERAP Priority Action 10: Develop stock assessment models (e.g. WHAM) that include environmental terms (e.g., temperature, ocean acidification) with a priority for stocks that have upcoming research track assessments.

2.0 NERAP Accomplishments (FY16-FY21)

The NOAA Fisheries National Climate Science Strategy (NCSS) seeks to increase the production, delivery, and use of the climate-related information required to fulfill NOAA Fisheries mandates regarding fisheries, protected species, aquaculture, habitats, and ecosystems (Link et al. 2015). Seven interdependent objectives were defined with the goal of informing and fulfilling these mandates in a changing climate (Figure 1). Each marine region across the U.S. is unique in terms of oceanography, marine resource availability, fisheries, protected species, management, and socioeconomics. Therefore, the national strategy required Regional Action Plans (RAPs) from the various science centers and regional offices across NOAA Fisheries in order to address each region's unique set of goals and priorities.

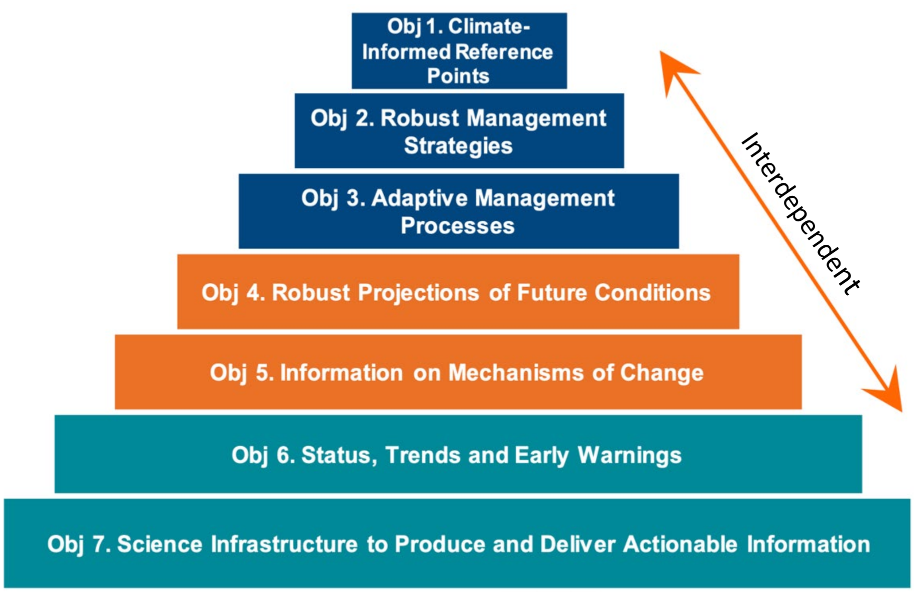

Figure 1. The NOAA Fisheries Climate Science Strategy is organized around the seven priority science objectives.

Since the publication of the Northeast Regional Action Plan (NERAP) in December of 2016 (Hare et al. 2016a), the Northeast Fisheries Science Center (NEFSC), Greater Atlantic Regional Fisheries Office (GARFO), and the NOAA Chesapeake Bay Office have made substantial progress at addressing the NERAP's priority actions, as outlined in the NCSS five year progress report (Peterson et al. 2021). Progress on the NERAP can be tracked in a variety of ways, but a primary metric for tracking research success is to track publications relative to the seven objectives outlined in the National Climate Science Strategy (Figure 2). From 2016 to 2020, over 60 peer-reviewed reports and journal articles have been published that focus on the Northeast U.S. Continental Shelf ecosystem and directly address the seven National Climate Science Strategy objectives. These publications were authored or co-authored by NEFSC, GARFO, and CBO staff and many were the result of collaborations with academic and non-governmental organizations.

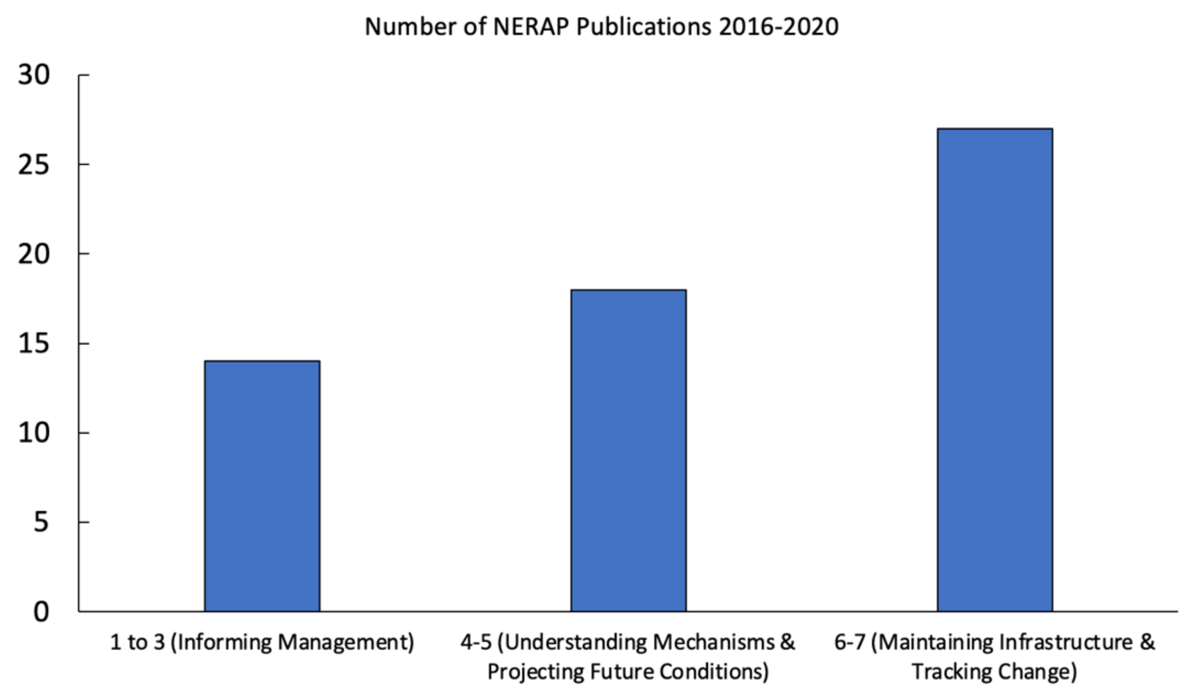

Figure 2. Number of NEFSC, GARFO, and CBO peer-reviewed publications from 2016-2020 that address the seven NCSS objectives and fifteen NERAP priorities.

2.1 Maintaining Infrastructure (NCSS Objective 7)

Much of the progress made on the NERAP would not be possible without the NEFSC's survey infrastructure. While the NEFSC has maintained its critical surveys, there has been a decline in the number of days at sea available (Figure 3), which has led to a decrease in the amount of data being collected. This is a major concern given that the ecosystem has been changing rapidly, for example, both the trend and variability of ocean temperature within the region has been increasing. These changes in the ocean have been associated with abundance, productivity, and distribution shifts in the living marine resources of the region. Therefore, it is critical that we not only maintain our surveys but increase our survey and data collection activities to effectively track changes in the ocean both seasonally and annually. Many NEFSC programs collect biological and environmental data simultaneously and this interdisciplinary data collection has supported science to understand the effect of climate change on living marine resources. Due to the COVID-19 pandemic, NEFSC surveys were impacted for the spring and summer of 2020, resulting in substantial data gaps (Figure 3). Ocean acidification monitoring is still limited spatially and temporally, but proposals are being considered to enhance sampling. The use of satellite data is essential for increasing the spatial and temporal coverage of ocean data. Progress has been made towards regional optimization of phytoplankton size class/functional type algorithms and long-term trend analyses of the 20+ year time series of ocean color data (Turner, 2020).

NEFSC scientists have collaborated with academic and NGO groups on various NERAP related projects. The majority of these projects are funded by various NOAA programs but also stem from NASA, the Lenfest Ocean Program, and the National Science Foundation. Some of our key academic and NGO partners include the Woods Hole Oceanographic Institution, Gulf of Maine Research Institute, University of Massachusetts, Rutgers University, University of Connecticut, Stony Brook, Princeton University, University of Rhode Island, and Monmouth University. Increased collaboration with Canada's Department of Fisheries and Oceans has also occurred and resulted in peer-reviewed publications (Greenan et al. 2019, Richardson et al. 2020). The Northwest Atlantic component of the DFO-NOAA Climate and Fisheries Vulnerability Science Collaboration Framework is currently being developed with the goal of enhancing collaborations between NOAA and DFO on climate research.

The recently formed NOAA Fisheries Northeast Climate Science Team can fulfill several roles in advancing the ongoing climate science work of the NEFSC and GARFO. These include: promote integration of various climate science activities across the NEFSC and GARFO; coordinate strategic engagement with partners; promote awareness of NEFSC, GARFO, and partner-based climate science activities; track progress toward climate science goals; be a representative body of the northeast region's climate science community; interface with NOAA leadership on climate science work, support, and prioritization; and target relevant funding opportunities toward NERAP priorities. The NEFSC is tracking and communicating climate research through the ecosystems and climate change webpage and the New England groundfish in a changing climate webpage.

With support from the NOAA Office of Ocean Acidification (OA) Program, the NEFSC has conducted experimental studies to understand the resilience to OA in shellfish species with both fisheries and aquaculture relevance: the Eastern Oyster, *Crassostrea virginica*, the northern surf clam, *Spisula solidissima*, and the Atlantic sea scallop, *Placopecten magellanicus*. Data from laboratory experimental studies are supporting dynamic energy budget (DEB) models that project commercially-relevant performance variables, including growth rate, time to harvest size, and reproductive potential under OA scenarios projected by Earth system models.

Another OA Program supported project includes assessments of impacts to fishing communities due to impacts on Atlantic sea scallops.

The NERAP identified the need for a Northeast Watershed Program: a coordinated, multidisciplinary effort comparable to the Northwest Fisheries Science Center Watershed Program for developing basic and applied science, including climate science, in support of the management of diadromous species in freshwater and estuarine environments. While a dedicated, funded program has not yet been achieved, a group of interested individuals representing multiple offices (NEFSC, GARFO, NMFS Office of Habitat Conservation) meet regularly to identify, fund, and implement priority studies (e.g., Collins, 2019, Lombard et al., 2021) and advance program development.

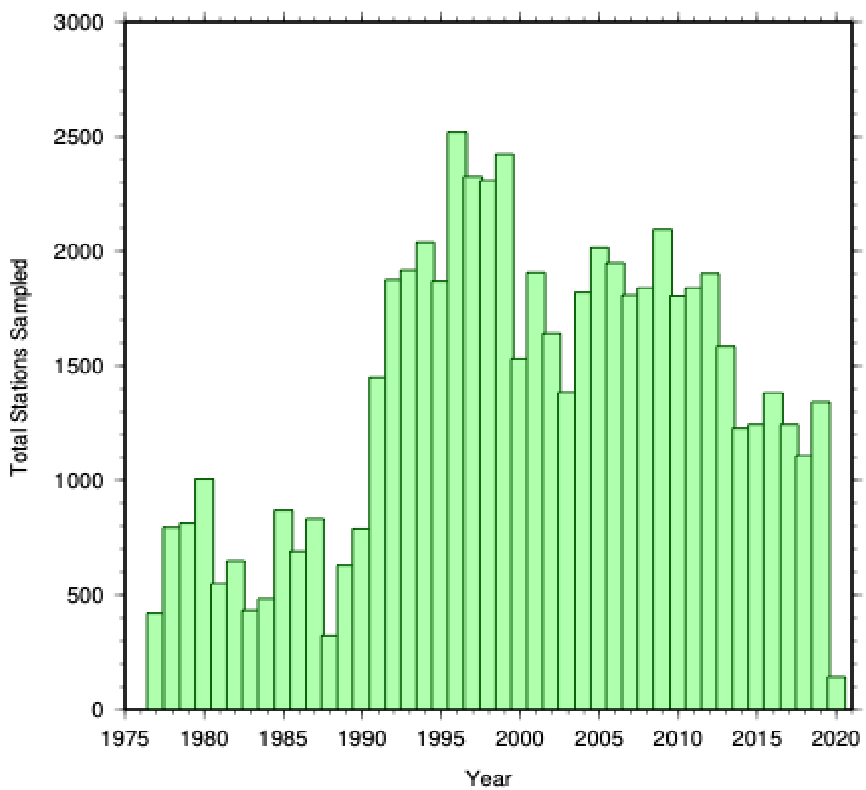

Figure 3. Number of ocean stations sampled each year by NOAA NEFSC surveys (EcoMon, bottom trawl, MARMAP, scallop, protected species, etc.).

2.2 Tracking and projecting change, understanding mechanisms (NCSS Objectives 4-6)

The majority of NERAP research has addressed objectives 4-6, which focuses primarily on tracking biophysical changes in the marine ecosystem, understanding mechanisms of change, and long-term projections of future conditions (Figure 2). Major accomplishments are highlighted in Table 1 and include annual state of the ecosystem reports for New England and the Mid-Atlantic, climate vulnerability assessments for fish/invertebrates (Hare et al. 2016b), habitat (Farr et al. in review), and fishing communities (Colburn et al. 2016). Clay et al. 2020 updates a number of ecological and biological indicators and provides an update to climate indicators for fishing communities. Tracking change in the physical and chemical state of the ocean is critical and these studies have primarily focused on temperature (Chen et al. 2020, Friedland et al. 2020a, Gawarkiewicz et al. 2019), ocean circulation (Saba et al. 2016, Caesar et al. 2018), and acidification (Meseck et al. 2018, Poach et al. 2019), variables that are key indicators of climate change in marine ecosystems. The close collaboration between the NEFSC and NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) has streamlined the use of high-resolution global climate models that are used for projecting long-term change to the Northeast U.S. Continental Shelf. The shelf is an oceanographically complex region that is challenging to model due its fine-scale bathymetry and circulation. GFDL's CM2.6 global climate model has been an integral part of our NERAP progress on projecting future conditions.

Studies that track contemporary change and project future change in marine taxa have almost exclusively focused on changes in species distributions. Impacts of warming ocean temperature on marine species distributions is a very common research theme within the Northeast U.S. This is due to the high spatial and temporal availability of ocean temperature data combined with the long-term time series of the NEFSC's fall and spring bottom trawl survey, which is a fisheries-independent survey that samples shelf waters from Cape Hatteras, NC to the Gulf of Maine and collects temperature and species data concomitantly. These studies have analyzed a broad suite of marine taxa in the contemporary period from the 1970's onward (Kleisner et al. 2016, Friedland et al. 2019) to document observed distribution shifts associated with warming ocean temperature. Other studies have relied on the NEFSC EcoMon survey data to document shifts in zooplankton (Morse et al. 2017) and ichthyoplankton (Walsh et al. 2015, McManus et al. 2018).

Decadal-scale projections of species distribution shifts under climate change have relied on GFDL's CM2.6 (Kleisner et al. 2017, McHenry et al. 2019), which projects an enhanced warming of the U.S. Northeast Continental Shelf due to a change in regional circulation (Saba et al. 2016). The mechanisms resolved in CM2.6 corroborate contemporary observations over the last decade (Neto et al. 2021). This high-resolution global climate model has been utilized extensively for projections of protected species distributions such as loggerhead sea turtles (Patel et al. 2021) and the prey of critically endangered North Atlantic right whales (Grieve et al. 2017). Additionally, a project is underway to link available data to describe and understand how socio-economic conditions affect U.S. loggerhead nesting beach success rates. Major land threats to the loggerhead nesting sites in the U.S. include construction (armoring), ecosystem alterations (beach erosion), pollution (light), and species interactions (predation). As the range of these turtles changes due to climate change, additional socio-economic data will be needed for any new nesting beach sites.

The skill of seasonal to annual (S2A) forecasts of ocean conditions in the U.S. Northeast Continental Shelf, such as sea surface temperature, is relatively low compared to other large marine ecosystems (Stock et al. 2015). The reason for the poor skill in this region is because

SST forecasts are derived from global models that have coarse resolution in their ocean and atmosphere components. Tactical fishery and protected species management may greatly benefit from more skillful S2A forecasts of ocean conditions. Given the majority of commercial species within the region are demersal, bottom temperature forecasts may be more relevant to stock assessments and management advice. A new statistical model that forecasts bottom temperature in the U.S. Northeast Continental Shelf has significant skill for lead times up to 5 months in the Mid-Atlantic Bight and up to 10 months in the Gulf of Maine, although the prediction skill varies notably by season (Chen et al. 2021).

Estuaries and rivers are important habitats for many marine species in the U.S. Northeast and thus there is a need to understand and predict changes to these watersheds associated with climate. Many of these habitats are listed as critical or essential under the Endangered Species Act. Historical, downscaled model hindcasts of Long Island Sound (Georges et al. 2016, Schulte et al. 2017, Schulte et al. 2018) and the Chesapeake Bay (Muhling et al. 2017, Muhling et al. 2018, Ross et al. 2021) have been developed and analyzed relative to large scale climate forcing. Characterizing river flood seasonality in 90 watersheds across the Northeast U.S., and evaluating seasonality trends, was also completed (Collins, 2019).

Understanding mechanisms of climate change impacts on marine ecosystems is a critical component of studies that utilize observed relationships between the environment and marine taxa to model historical and projected change. Laboratory-based process studies at the NEFSC are at the forefront of this research at both the Milford, CT and Sandy Hook, NJ facilities. The Milford lab primarily focuses on economically and ecologically important bivalve shellfish while Sandy Hook focuses on finfish and some invertebrates. In the laboratory, physiological processes (including feeding rates) have been documented for bivalve species including oysters, scallops, and surf clams, under ocean acidification conditions (Meseck et al. 2020, Pousse et al. 2020). In the field, Milford scientists documented that total benthic bivalve abundance is correlated with sediment carbonate chemistry parameters (Meseck et al. 2018).

These studies demonstrate that from the laboratory to the field, bivalves are sensitive to ocean acidification. Research projects in collaboration with our academic partners have analyzed the impacts of changing water temperature on black sea bass aerobic scope and hypoxia tolerance (Slesinger et al. 2019); estimates of CO_2 and co-stressor effects on early life-stages of finfish such as winter flounder, summer flounder, mid-Atlantic forage fishes, and New England groundfish; and individual-based process models of CO_2 effects on winter flounder. The Sandy Hook Lab has developed a novel apparatus for testing plasticity of responses to thermal, CO_2 and dissolved oxygen regimes. These studies capture how rate processes are affected by environmental drivers and are precisely the kinds of quantitative descriptions needed in order to model climate change impacts. All of these laboratory and field studies are needed to inform single, multispecies, and ecosystem models.

2.3 Informing Management (NCSS Objectives 1-3)

A primary way management can use climate information is through climate-enhanced fishery stock assessments (Holsman et al. 2019). Progress on climate-enhanced stock assessment variables (e.g. demographics, recruitment, population growth) has been moving forward on key commercial and recreational species including southern New England yellowtail flounder (Miller et al. 2016a, Xu et al. 2018), summer flounder (O'Leary et al. 2019, O'Leary et al. 2020), winter flounder (Bell et al. 2018), northern shrimp (Cao et al. 2017), Atlantic cod (Miller et al. 2018), surf clam (Hennen et al. 2018), and black sea bass (Miller et al. 2016b). The Woods Hole Assessment Model (WHAM) was developed by scientists at the NEFSC and it can be used to support climate-enhanced stock assessments via the incorporation of time-varying processes with links to environmental covariates (Stock and Miller, 2021). A framework has been developed for incorporating climate and habitat information into fisheries management using risk assessment and management strategy evaluation (Gaichas et al. 2016). Support was provided to the Mid-Atlantic Fisheries Management Council risk assessment (Gaichas et al. 2018), which included the results from the climate vulnerability analysis and habitat shifts into a conceptual model for high risk summer flounder fisheries in 2019 (DePiper et al. 2021).

Further progress has been made on social science research that connects changes in species distributions to impacts on fishing communities. Simulation models have been developed that address various climate impacts to single species and have evaluated climate- informed reference points. This work is coupled to new research that links climate- and stock-related projections for groundfish to economic outcomes for fishermen and fishing communities. Statistical models are being developed that explain how fishermen select target stocks and landing locations. These models can then be used to understand how these two behaviors will change under various climate and policy scenarios. Other social science research projects, the first of which has been funded by the New England groundfish/climate program, include: 1) climate vulnerabilities and adaptation pathways for Northeast U.S. fishing communities, including developing indices of vulnerability to climate change for groundfish at the fishing community level; 2) stakeholder engagement in management strategy evaluation of New England groundfish in a changing ocean; 3) developing northeast fishing community indices of vulnerability to climate change based on sea surface temperature, stock size/status, and ocean acidification using the 82 species in Hare et al. (2016b); 4) developing indicators of climate vulnerability, specifically to ocean acidification, for northeast fishing communities dependent on landings of Atlantic sea scallops; and tracking socio-economic conditions impacting loggerhead nesting as nesting beaches move further north.

Important advancements have been made specific to climate and protected species. Climate scenario planning workshops and reports were completed for endangered North Atlantic right whales (Borggaard et al. 2020) and Atlantic salmon (Borggaard et al. 2019). A range-wide salmon habitat synthesis is ongoing and will describe habitat conditions suitable, including preferences and tolerances, for Atlantic salmon by life stage in freshwater and marine systems. Additional work is aimed at identifying climate-resilient habitats throughout Maine watersheds that are listed as critical habitat for Atlantic salmon. Part of this effort includes understanding where rivers are naturally high in baseflow, which is streamflow that has a relatively high proportion of inputs from groundwater and/or lake/wetland outflow. This is important because rivers with high baseflow tend to be cooler and have greater flow during summer. These areas thus provide refuge during thermal stress periods for Atlantic salmon. A model was developed to predict and map relative baseflow quantities at a high spatial resolution (~2.5 km²), providing valuable information to managers making decisions about where to conserve or restore habitat (Lombard et al. 2021). Through the Collaborative Management Strategy for the Gulf of Maine Atlantic Salmon Recovery Program, work has been done with tribal partners, the state of Maine, and non-governmental organizations to identify and protect climate resilient habitats important to Atlantic salmon (CMS 2019).

For North Atlantic right whales, short duration zooplankton sampling trips were conducted in the southern New England region during the winter and early spring (January – April) of 2019, 2020, and 2021 when right whales are in the area. Our goal is to describe vertical distribution patterns of right whale prey in relation to physical features to better understand the mesoscale processes that result in super aggregations of right whale prey. Correlations between ocean warming and right whale prey availability suggest an inverse relationship between *Calanus* spp. and ocean temperature (Sorochan et al. 2019).

Additional progress has been made to advance regional watershed science through continued coordination across the region. To better understand the impacts of historical and projected climate change in freshwater and estuarine environments, synthesis work on the diadromous fish community and ecosystem interactions of 12 NOAA trust species started in 2020. This synthesis will integrate the structure and function of diadromous fish communities in freshwater ecosystems while synthesizing their ecosystem roles and interactions in the northeast U.S. This synthesis will encompass changing environmental conditions in rivers, estuaries, and the coastal ocean. Differing rates of change and species distributions caused by climate but mitigated with habitat improvements (enhanced fish passage and restoration of stream functions) require comprehensive analyses. Through this synthesis, the research gaps and needs in two rapidly changing systems will be highlighted. Additionally, the NEFSC continues to monitor phenology changes in Atlantic salmon to better understand climate impacts and drivers on this protected species.

3.0 Key Needs (FY22-FY24)

3.1 Maintaining Infrastructure (NCSS Objective 7)

None of the NERAP research can be successful without a solid infrastructure for ocean observations that includes both physical and biological surveys. There is concern about the decline in the number of observations per year, which is a direct result of the declining number of days at sea (Figure 3). This observation decline is occurring at a time of both increasing trend and variability of many ocean and biological variables. Skillful models, whether for single species or the entire ocean ecosystem including human dimensions, can only be developed and validated if observations exist over sufficient temporal and spatial scales that capture seasonal, annual, and decadal variability. Therefore, there is a critical need to increase the number of days at sea for the NEFSC's EcoMon survey and to broaden the suite of biogeochemical variables that are measured and include depth profiles of nutrients, plankton productivity, dissolved oxygen, and pH.

Further complicating the continuation of these ecosystem surveys is planned offshore wind development that will result in major adverse impacts on NOAA Fisheries scientific surveys along much of the shelf from Massachusetts south through North Carolina. Wind energy development impacts scientific surveys in four ways: 1) preclusion of sampling platforms from wind energy areas due to operational and safety limitations; 2) impacts on the random-stratified statistical design that is the basis for scientific assessments, advice, and analysis; 3) alteration of benthic, pelagic, and airspace habitats in and around wind energy areas; and 4) impacts on sampling efforts outside wind energy areas by increasing vessel transit time.

Progress has been made towards regional optimization of phytoplankton size class/functional type algorithms but more work is needed to use surface satellite measurements of ocean variables as indicators of ecosystem change and variability. New biological surveys, such as the Gulf of Maine longline survey and right whale prey surveys, need to continue to track change in key ecosystem indicators from lower to higher trophic levels. Additional dedicated funding for social and economic surveys and other research will also be needed to build up the time series data needed for effective modeling.

Increased collaboration with the fishing industry, through cooperative research, is also needed to enhance observed data sets of targeted and non-targeted catch as well as physical measurements such as ocean temperature (e.g., eMOLT Program). Continued collaboration with academic and non-governmental organizations needs to continue, as well as research and data coordination with Canada's DFO and the NMFS Southeast Fisheries Science Center (SEFSC) regarding commercial species, protected species, and ecosystem indicators. Continued collaboration with tribal partners, the state of Maine, and non-government organizations is also important in identifying and protecting climate resilient Atlantic salmon habitats. Further science is needed on full life cycle habitat resilience for salmon that connects changes in rivers to associated estuary and marine habitats. As such, a salmon-specific climate vulnerability assessment and management strategy evaluation would be a capstone project of the NOAA climate strategy and benefit both NOAA and partner agency managers. Better integration with the Northeast Integrated Ecosystem Assessment (IEA) Program can help translate climate information into ecosystem assessments, state of the ecosystem reports, ecosystem and socioeconomic profiles, and ecosystem status reports.

A major gap in the present infrastructure is the lack of a centralized, regional online catalog that contains ocean and climate data and model output for the region. Presently, these data and model outputs are maintained at various web portals and require additional resources to render them for regional analyses. Climate research funding also needs to continue so that targeted research projects can continue to address the priorities of the NERAP. Most funding that has addressed NERAP priorities derives from NOAA Oceanic and Atmospheric Research (OAR) Climate Program Office (CPO) and NOAA OAP programs as well as NEFSC funding from NERAP/EBFM/SAIP/IEA and the New England groundfish/climate program. In collaboration with external partners, some projects are funded by NASA, Lenfest, and NSF. While this piecemeal funding process has funded critical research that addresses NERAP priorities, a more solidified, permanent funding infrastructure designed to produce and maintain climate research is needed. The recent NOAA Climate, Ecosystem and Fisheries Initiative addresses the ocean modeling and communities of practice component of this research but the funding for the CEFI has not yet been approved.

3.2 Tracking and projecting change, understanding mechanisms (NCSS Objectives 4-6)

Projections of future change have largely focused on marine species habitat and distribution using NOAA's high-resolution global climate model CM2.6. While these long-term projections (20-80 years) could be useful for fishery management plans, management strategy evaluations, scenario planning, and vulnerability assessments over decadal periods, they are not useful for tactical management decisions that are made on a year-to-year to decadal time scale. Seasonal to annual (S2A) forecasts of ocean conditions that are tied to stock assessments would be more useful to tactical fisheries management. However, the skill of ocean forecasting models for even the most standard ocean variable, sea surface temperature, is relatively low in the U.S. Northeast marine ecosystem compared to other coastal large marine ecosystems. Improved S2A skill of bottom temperature forecasts using statistical methods has been completed but the improved skill is specific to certain regions and time periods (Chen et al. 2020). Through NEFSC and OAR CPO funding, pilot studies have started the process of a dynamical approach, which is to develop regional ocean models for the Northwest Atlantic that can run in hindcast, forecast, and projection mode. This dynamical approach directly addresses the recent NOAA Climate, Ecosystem and Fisheries Initiative and the goal is to have multiple regional ocean model simulations for the region that are based on NOAA's state-of-the-art ocean model MOM6. NOAA OAR CPO has also funded the development of annual to decadal ocean forecasts using the Scripps Coupled Ocean-Atmosphere Regional (SCOAR) modeling system.

While more skillful S2A ocean forecasts are a critical need, high-resolution biophysical ocean hindcasts are an essential need to fill temporal and spatial gaps in the observed time-series of key ocean variables such bottom temperature, circulation, pH, primary and secondary productivity, and dissolved oxygen. Tracking change to the northeast U.S. continental shelf doesn't need to be limited to *in situ* observations, which have been declining in the Northeast U.S. (Figure 3). Ocean model hindcasts, after validation, can also be used to track historical changes at a much higher spatial and temporal resolution than *in situ* measurements. These ocean hindcasts are also critical to understand mechanisms between ocean change and living marine resources through the association of changes in survey data to key biophysical ocean variables in validated ocean models. While there have been previous efforts to develop regional ocean model hindcasts and projections that resolve biogeochemistry (Zhang et al. 2019), more models, including those that assimilate data, are needed to assess model uncertainty and to create model ensembles of historical, near-term, and long-term ocean conditions.

Laboratory and field process studies that determine mechanistic links between the ocean environment and marine species are needed to inform process-based single species, multispecies, and ecosystem models. While the NEFSC and its partners have made progress on identifying mechanistic underpinnings between temperature, ocean acidification, and marine species, more studies are needed on key species that were identified to be highly vulnerable to climate change (Figure 4). These studies need to focus on multiple life history stages from larval to adult and investigate synergistic impacts of warming ocean temperature and ocean acidification.

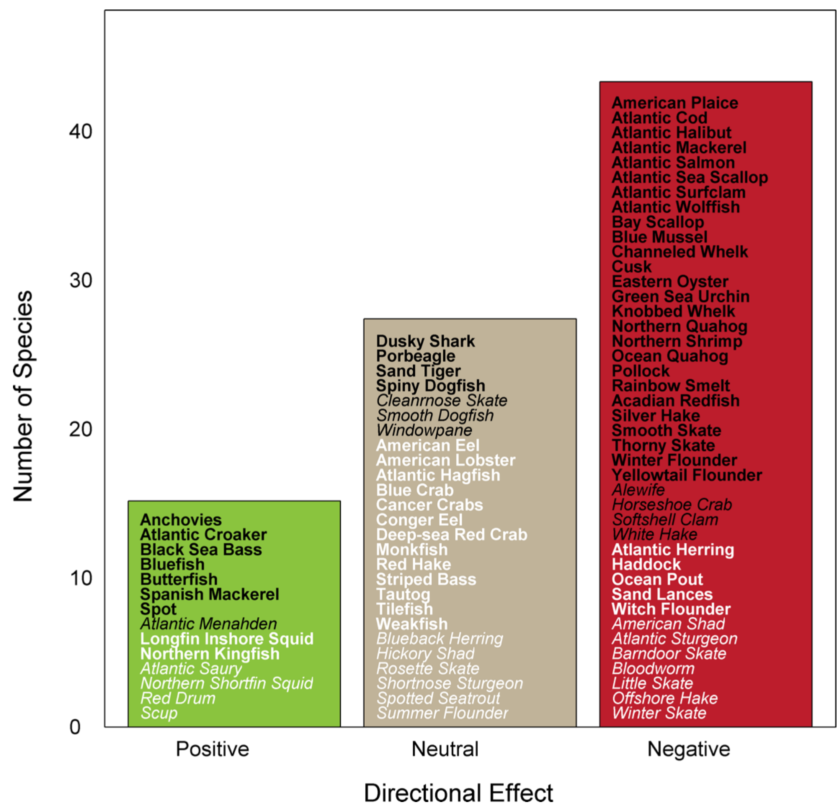

Figure 4. Directional effect of climate change from Hare et al. 2016b. Colors represent expected negative (red), neutral (tan), and positive (green) effects. Certainty in score is denoted by text font and text color: very high certainty (>95%, black, bold font), high certainty (90–95%, black, italic font), moderate certainty (66–90%, white or gray, bold font), low certainty (<66%, white or gray, italic font).

3.3 Informing Management (NCSS Objectives 1-3)

There is a critical need for more focused research that can inform and enhance living marine resource tactical management decisions for commercial, recreational, and protected species. This is a very challenging task not just for the northeast region but for all U.S. regions. The northeast U.S. fisheries management system consists of two Federal councils, the Atlantic States Marine Fisheries Commission, and the Greater Atlantic Regional Fishery Office; working with management partners is essential for informing management. Moreover, there are very few operational fishery stock assessments in the U.S. and worldwide that use environmental or ecosystem data quantitatively or qualitatively to inform year to year management decisions or even longer-term fishery management plans. Finally, there are no living marine resource management decisions in the U.S. that are based on forecasted (S2A) or projected (decadal) ocean conditions. Therefore, it is essential to produce new research results that support the use of climate and environmental information for upcoming research track stock assessments, which may be the primary mechanism to inform management with climate-enhanced stock assessments. The recent Northeast Climate Integrated Modeling (NCLIM) project is an example of this approach with the goals of: 1) identifying and anticipating major ecosystem changes that influence multiple stocks or management decisions; 2) informing decision-making around impacts of shifting species; and 3) informing decision-making around changes in stock productivity. Climate information has also been used in scenario planning for Atlantic salmon (Borggaard et al. 2019) and North Atlantic right whales (Borggaard et al. 2020), but more of these exercises are needed to help inform management strategy evaluations for harvested species and conservation planning for protected species.

Progress on informing management is also based on studies that analyze human dimension variables such as socioeconomic and climate informed reference points and climate vulnerability indices for fishing communities in the region. Social vulnerability indicators for fishing communities, meanwhile, provide an important context for understanding the impact of climate change; for example, highly vulnerable communities may be more likely to have difficulty responding effectively to climate changes. End-to-end ecosystem models, such as the Northeast U.S. version of ATLANTIS (NEUS Atlantis), attempts to simulate the entire ecosystem from fundamental physical and chemical processes to food webs to fisheries management and social and economic factors. The NEUS Atlantis can be used to model human dimensions variables (management strategies, fleet behavior, and market responses) under various climate change scenarios over decadal periods. However, these sub-models have not been implemented in the current version of NEUS Atlantis. Therefore, dedicated research is needed to parameterize and validate fishery behavior, management scenarios, and market responses. Moreover, social vulnerability indicators and cultural factors impacting fishery decision making are not easily included in NEUS Atlantis and region-wide comparable data, especially for cultural factors, are currently lacking. Ultimately, with the future integration of global climate and regional ocean models, NEUS Atlantis will be able to inform management through full ecosystem-level projections under multiple climate scenarios and under an array of human behaviors.

4.0 Action Plan (FY22-FY24)

Northeast Regional Action Plan priority actions for FY22-FY24 are listed and described by NCSS objectives. Many NERAP Actions are relevant to multiple NCSS objectives but are aligned with the most relevant objective. In total, 10 NERAP priority actions are identified and each action has equal priority to others. Many of these priorities address multiple NOAA Fisheries mission elements (sustainable fisheries, protected resources, aquaculture, habitat, and ecosystem) and this plan works across all mission elements. The public comments on section 216(c) of Executive Order 14008 (Making Fisheries and Protected Resources More Resilient to Climate Change) were considered in the development of these priority actions.

Maintaining Infrastructure (NCSS Objective 7)

NERAP Priority Action 1: Maintain ecosystem survey and data collection efforts in the Northeast U.S. Continental Shelf ecosystem including the Bottom Trawl Survey, Ecosystem Monitoring Program, Sea Scallop Survey, Northern Shrimp Survey, Clam Survey, and Protected Species Surveys and expand where possible (e.g., Gulf of Maine longline survey, data poor species, right whale prey sampling, ocean acidification monitoring).

NERAP Priority Action 2: Coordinate with other NOAA Programs, Line Offices, and partners to link living marine resource data, science, and management to climate science and research activities.

NERAP Priority Action 3: Continue to build industry-based fisheries and ocean observing capabilities.

Tracking and projecting change, understanding mechanisms (NCSS Objectives 4-6)

NERAP Priority Action 4: Continue production of the NEFSC State of the Ecosystem reports and other related products that include climate relevant information that is useful to management such as historical, forecasted, and projected biophysical conditions, marine heatwaves, species distribution and abundance shifts, biogeochemical indices, and coastal community vulnerability to sea level rise and storm surge.

NERAP Priority Action 5: Conduct laboratory and field research on the mechanistic effects of multiple climate factors (e.g. temperature, ocean acidification, dissolved oxygen) on living marine resources with the goal of informing process-based models for single species, multi-species, and the ecosystem.

NERAP Priority Action 6: Work with NOAA Oceanic and Atmospheric Research, National Weather Service, National Ocean Service, and academic partners to develop and improve regional hindcasts, forecasts, and projections of ocean and estuarine/river physics and biogeochemistry to develop and improve climate-ready management of living marine resources.

Informing Management (NCSS Objectives 1-3)

NERAP Priority Action 7: Improve spatial management of living marine resources through an increased utility of spatial and temporal distributions, abundance, productivity, migration, and phenology in management decisions.

NERAP Priority Action 8: Develop and use Vulnerability Analyses, Scenario Planning, and Management Strategy Evaluations to examine the effect of different management strategies under various climate change scenarios.

NERAP Priority Action 9: Increase social, economic, and ecosystem scientist involvement in climate change research through multidisciplinary work, including the Northeast Integrated Ecosystem Assessment, that examines relationships between various ecosystem components with the goal of enhancing ecosystem-based management with climate information.

NERAP Priority Action 10: Development of stock assessment models (e.g. WHAM) that include environmental terms (e.g., temperature, ocean acidification) with a priority for stocks that have upcoming research track assessments.

4.1 Descriptions of NERAP Priority Actions

Maintaining Infrastructure (NCSS Objective 7)

NERAP Priority Action 1: Maintain ecosystem survey and data collection efforts in the Northeast U.S. Continental Shelf ecosystem including the Bottom Trawl Survey, Ecosystem Monitoring Program, Sea Scallop Survey, Northern Shrimp Survey, Clam Survey, and Protected Species Surveys and expand where possible (e.g., Gulf of Maine longline survey, data poor species, right whale prey sampling, ocean acidification monitoring).

The NEFSC has a long history of conducting surveys of the Northeast U.S. Shelf ecosystem ranging from chemistry through marine mammals and seabirds. This effort should be maintained and is fundamental to the success of the NERAP. The decreasing trend in the number of days at sea (Figure 3) during a period of increasing trends and variability in ocean conditions is very concerning. Further complicating the continuation of these ecosystem surveys is planned offshore wind development that will disrupt NOAA scientific surveys along much of the shelf from Massachusetts south through North Carolina with future impacts to surveys in the southeast region. While increasing the number of ocean observations is beyond the scope of the NERAP, it is still a critical priority to maintain the precision and accuracy of these surveys and maximize the number of observations each year. These surveys include:

- Spring and Fall Bottom Trawl Survey – 2 times per year (including Ecosystem Monitoring Program operations).
- Ecosystem Monitoring Survey – 4 times per year.
- Scallop Survey – 1 time per year.
- Northern Shrimp Survey – 1 time per year.
- Gulf of Maine Cooperative Bottom Long Line Survey
- North Atlantic Right Whale Aerial Survey
- Marine Mammal and Sea Turtle Shipboard and Aerial Surveys
- Large Coastal Shark Bottom Longline Survey
- Cooperative Atlantic States Shark Pupping and Nursery Longline/Gillnet Survey
- Clam and Ocean Quahog Survey – 1 time per year.

Protected species surveys and telemetry tagging are also critical to maintain (e.g., North Atlantic right whale, sea turtles, seals, Atlantic salmon, Atlantic Marine Assessment Program for Protected Species). To the extent possible, climate, ecosystem, and habitat information should be collected on all surveys, thereby allowing simultaneous environmental and biological data to be collected and used in a number of analyses related to other actions described here in the NERAP. Continued collection of fishery-dependent data is also critical to living marine resource management, and these data can be used to improve the scientific understanding of the effect of climate change on fisheries in the northeast U.S.

NERAP Priority Action 2: Coordinate with other NOAA Programs, Line Offices, and partners to link living marine resource data, science, and management to climate science and research activities. These include:

- *NOAA Integrated Ecosystem Assessment Program*: The northeast Integrated Ecosystem Assessment team provides several products to the region's fisheries management councils. Recognizing the importance of climate in the region, the second priority goal of the northeast IEA work plan is to integrate climate and earth system modeling to further understand past ecosystem variability and assess predictions across management-relevant time scales. This priority goal will be achieved through four related objectives. The first will be to analyze high-resolution regional physical and physical-biological simulations to understand past ecosystem variability and indicator robustness. This will include the development of diagnostics for the representation of IEA indicators and associated ecosystem status report measures in high-resolution regional earth system simulations. For those indicators successfully captured by the simulations, the IEA team will try to understand the drivers of indicator variability and the physical and biogeochemical changes associated with each indicator shift. The second objective will be to assess the seasonal to multi-decadal predictability and robustness of IEA indicators in the U.S. northeast shelf. The predictability of IEA-associated indicators will be assessed within the seasonal to multi-annual predictions associated with the first objective. In addition, CMIP6-driven climate change projections will be analyzed to understand the robustness of climate change indicators. The third objective will be to integrate regional earth system predictions and projections into the region's ecosystem status reports and other associated living marine resource applications. This objective builds off the first two and will bring the climate and earth system modeling into a product that goes before the region's fisheries management councils. The final objective is to continue development of estuarine forecasting capabilities that will complement the shelf-scale hindcast, prediction and projection capabilities in the other objectives.

- *NOAA Chesapeake Bay Office* : The CBO is supporting research to understand the impacts of changing habitat and climate conditions on key species such as striped bass, summer flounder, and forage fish in the Chesapeake Bay. Specific projects include development of an estuarine habitat index for summer flounder, a nursery habitat assessment for striped bass, and seasonal summaries for the Mid Atlantic State of the Ecosystem Report. The seasonal summaries currently include CBO's Chesapeake Bay Interpretive Buoy System data as well as satellite data from CBO's cross Line Office collaboration with the NOAA Environmental Satellite Data and Information Service (NESDIS) CoastWatch program. The CBO is enhancing observational capacity to track changing habitat conditions and impacts on living resources by deploying two vertical high frequency hypoxia profilers in the Chesapeake Bay mainstem in fall 2021 and establishing a mainstem telemetry receiver array to track fish movement. The hypoxia profilers will provide data to develop fish habitat condition products over the next few years. A fishery biologist has been hired to analyze existing telemetry receiver data and develop a science plan for the new array. The CBO is also part of the NOAA funded project to develop a shellfish Regional Vulnerability Assessment (RVA) in the Chesapeake Bay, which aims to: 1) assess the vulnerability of the oyster aquaculture industry and oyster restoration to ocean acidification and other co-stressors; and 2) produce the information required by regional communities to aid in adaptation to these stressors. In achieving these goals, we will better understand which shellfish stakeholders will be able to successfully adapt, which will seek alternative livelihoods, and what specifically causes the difference between these two disparate outcomes. The CBO is also supporting efforts to synthesize information on rising water temperatures, their effects on Chesapeake Bay fisheries and habitat, and the development of a Bay Water Temperature Change Indicator related to these effects as part of a larger partnership with the Chesapeake Bay Program. Information from the NOAA Northeast Fish and Shellfish Climate Vulnerability Assessment and Habitat Climate Vulnerability Assessment are being applied to inform the synthesis. Buoy data from the NOAA Chesapeake Bay Interpretive Buoy System (CBIBS) and satellite data from the NESDIS are being evaluated for the Bay Water Temperature Change Indicator, as well as other long-term data sources. Workshops with the Chesapeake Bay Program's Scientific and Technical Advisory Committee (STAC) are being scheduled for 2022 where these efforts will inform discussions to develop recommendations on management responses to ecological impacts from rising water temperatures.

- *NOAA Fisheries Office of Aquaculture*: The following key research and action needs relevant to the interests of the Office of Aquaculture have been identified by NEFSC scientists: 1) breeding for climate resilience in oysters and other cultivated shellfish; 2) host-parasite or pathogen interactions under climate-change conditions, including biogeographic range expansion of parasites; 3) range expansion of shellfish predators, e.g., blue crabs and cow-nosed rays, that will affect regional shellfish cultivation practices; 4) diversification in the shellfish farming sector, e.g., sea scallop farming development in Maine, and hatchery production of surfclams for resource enhancement of offshore fisheries; 5) continued improvements in dependability of shellfish hatchery production, including probiotics and microbiome optimization, application of monitoring and control technologies, and improved nutrition; 6) cultivation strategies for offshore blue mussels consistent with protected species restoration goals; 7) use of cultivated shellfish in comprehensive, living shoreline restoration projects; 8) improved understanding of the factors which affect fishing community attitudes toward the development of aquaculture in their communities, and of fisher attitudes toward their possible involvement in aquaculture as an alternative or a supplement to fishing.

- *NOAA Ocean Acidification Program*: A key research and action need of the OA Office has been identified by NEFSC scientists as improved understanding of the impacts of OA on affected species and the communities that harvest them. The following research and action needs relevant NOAA Ocean Acidification Program for the Northeast Continental Shelf have been identified: 1) improved forecasting of ocean acidification across daily to decadal timescales that better quantifies the primary drivers of carbonate dynamics in context with other environmental changes (i.e., temperature, riverine influence); 2) determine how OA in concert with other stressors impacts ecologically and/or economically important marine species, with a focus on understanding the effects to aquaculture stocks; 3) evaluate costs and benefits of mitigation and adaptation strategies for communities, ecosystems, and economics; and 4) promote integration of OA understanding into regional planning and management. Components to this research include: 1) biological samples (pteropods) with EcoMon monitoring cruises for *in situ* indicators of climate change; 2) laboratory multi-generational experiments to explore climate-change adaptation potential of marine bivalves; 3) dynamic energy budget models of surf clams, oysters, and sea scallops to determine individual responses to climate change; 4) combination laboratory and field studies on Atlantic surf clams to evaluate aquaculture practices; and 5) assessment of Atlantic sea scallop vulnerability to OA and the relative social vulnerability of scallop-dependent communities to future OA conditions. These five areas of investigation are all components of this research area.

- *NOAA Ocean and Atmospheric Research, National Ocean Service (NOS), and National Weather Service (NWS)*: Collaboration with these three NOAA line offices is needed to achieve the ocean modeling objectives outlined in the NOAA Climate, Ecosystem and Fisheries Initiative. Regional ocean and watershed hindcasts, forecasts, and projections of physical and biogeochemical conditions require dedicated regional ocean model development by OAR’s Geophysical Fluid Dynamics Laboratory (GFDL), coastal ocean and watershed model development by NOS, and seasonal to annual forecasting models developed by NWS. Coordination with NOAA OAR's Climate Program Office is needed to develop targeted research requests for annual funding opportunities within MAPP, CAFA, and CVP.

- *Academic and non-governmental organizations*: Research collaborations are needed with key academic and non-governmental partners such as Rutgers University, Woods Hole Oceanographic Institution, University of Massachusetts, University of Connecticut, University of Rhode Island, University of Maryland, University of Maine, Princeton University, Gulf of Maine Research Institute, and the Lenfest Ocean Program. The Cooperative Institute for the North Atlantic Region (CINAR) is one way these academic partnerships can continue.

- *Watershed Program for the East Coast:* Diadromous species are important in the region for a variety of reasons (e.g., protected species, commercial and recreational harvest, ecosystem interactions): Atlantic salmon, Atlantic sturgeon, shortnose sturgeon, rainbow smelt, alewife, blueback herring, American eel, hickory shad, American shad, striped bass, sea-run brook trout, sea lamprey, white perch, and tomcod. These species are included in the larger group of species considered in many of the actions prioritized here, but there are also a number of specific needs that exceed the scope of the NOAA Fisheries Climate Science Strategy and this Northeast Regional Action Plan. On the West Coast, the Northwest Fisheries Science Center hosts a Watershed Program, which investigates the ecology of freshwater and estuarine ecosystems to assist with the management and recovery of Pacific salmon (*Oncorhynchus* spp.) and other NOAA trust resources. The Program provides technical support to NOAA Fisheries policy makers and regulatory staff, and collaborates with other federal and state agencies (e.g., USGS, USFWS), tribes, and educational institutions on research and outreach related to the management of Pacific salmon and other diadromous fishes. NOAA Fisheries should consider developing and funding such a program, hosted by the Northeast Fisheries Science Center, to work with partners on the East Coast.

- *Canada Department of Fisheries and Oceans (DFO):* In 2021, the DFO-NOAA Climate and Fisheries Sciences Collaboration Framework was developed to identify priority topics and issues of common interest and possible activities to address them over the next three years. The work plan is organized around three general thematic areas: 1) detecting climate-related changes/impacts (observations, monitoring); 2) understanding mechanisms of climate-related changes/impacts (research); 3) forecasting and projecting and responding to climate-related changes (modeling and adaptation). In the Atlantic region, there is already a rich history of bilateral collaboration. The Canada-US Ecosystem Science (CAUSES) Working Group's mission is to conduct ecosystem research to inform management advice for shared stocks in the Eastern U.S. and Canadian marine ecosystems through communication, discussion, and shared expertise and tools between DFO and the NEFSC and other regional research groups. In 2021, CAUSES incorporated the North Atlantic component of the bilateral DFO-NOAA Climate and

Fisheries Sciences Collaboration Framework. There is a corresponding DFO-NOAA Ocean acidification collaboration group (Collaborative Framework for Joint DFO/NOAA Ocean Acidification Research and Monitoring) that operates independently of CAUSES.

NERAP Priority Action 3: Continue to build industry-based fisheries and ocean observing capabilities.

Industry-based fisheries and ocean observing can be accomplished both through fishery independent research (e.g. surveys) as well as fishery dependent research (e.g. commercial catch and environmental data collection). The common thread in these approaches are the engagement of the fishing community in the development and design of research projects, execution of field work, and interpretation of results. The NEFSC Cooperative Research Branch leads a suite of collaborative surveys and research, but many other institutions and organizations across the northeast region support industry-based fisheries and ocean observing capabilities.

Industry-based surveys in the northeast region include, but are not limited to, the Maine-New Hampshire Trawl Survey, Northeast Area Monitoring and Assessment Program inshore trawl survey, scallop research-set-aside surveys, and the NEFSC Gulf of Maine Bottom Longline Survey. These surveys are conducted by teams of scientists and fishermen working onboard commercial fishing vessels. Each of these surveys collects fishery-independent data on the distribution and abundance of fish and invertebrate species and the environment in which they are living. Data from these industry-based surveys are used in stock assessments, and in many cases provides information about data poor species (e.g., cusk and thorny skate) and their habitats.

Fishery dependent ocean observing initiatives in the region include, but are not limited to, the NEFSC Study Fleet, the Commercial Fisheries Research Foundation's (CFRF) Lobster, Jonah Crab, and Black Sea Bass Research Fleets, the NEFSC environmental Monitors on Lobster Traps and Large Trawlers Program (eMOLT), the Woods Hole Oceanographic Institution and CFRF's Shelf Research Fleet, and the NEFSC Industry-Based Biological Sampling Program (InBios). The Study Fleet engages fishermen in collecting fine-scale catch, effort, and environmental data during routine fishing practices to precisely characterize fishing effort, spatiotemporal trends in resources species catch, and associated environmental conditions. Study Fleet data have been used to develop habitat models for mackerel, butterfish, and shortfin squid, and have been integrated in catch-per-unit effort indices in the summer flounder, scup, haddock, and shortfin squid stock assessments. The CFRF's Lobster, Jonah Crab, and Black Sea Bass Research Fleets, apply a similar approach, but instead focus fishermen's efforts on collecting biological (size, sex, etc.) data from commercial catch as well as paired bottom water temperatures. These data are used to characterize commercial catch for stock assessments and to understand environmental drivers of life history characteristics and population dynamics. The WHOI/CFRF Shelf Research Fleet and eMOLT focus on leveraging fishermen's time on the water to collect oceanographic data (temperature, depth, salinity) from across the northeast region throughout the year. These data provide a more complete picture of the seasonal and fine-scale dynamics of the subsurface ocean environment than traditional semi-annual surveys. Data from these programs feed into regional oceanographic models (ROMS, FVCOM) and can be paired with fishery catch and survey data to understand environmental drivers of resources species, climate impacts, and more. Finally, InBios engages the fishing industry in collecting fish and invertebrate samples from areas and times of year otherwise not accessible to scientists, but important for understanding life history. In this way, InBios engages the fishing industry in data gaps related to age, growth, and maturity of species, which are impacted by a changing climate.

The potential for industry vessels to collect ecological and oceanographic data could increase observing capacity in the region by at least an order of magnitude and provide critical observations of the water column, near surface atmosphere, and resource species. These observations can contribute to ocean modeling and prediction, but can also help fishermen make decisions with regard to limiting their incidental catch and their ability to adapt to changing conditions. Facilitating these interactions in short term (days to years) applications would help develop the relationships necessary to make adaptive decisions in the medium term (years to decades).

Tracking and projecting change, understanding mechanisms (NCSS Objectives 4-6)

NERAP Priority Action 4: Continue production of the NEFSC State of the Ecosystem reports and other related products that include climate relevant information that is useful to management such as historical, forecasted, and projected biophysical conditions, marine heatwaves, species distribution and abundance shifts, biogeochemical indices, and coastal community vulnerability to sea level rise and storm surge.

The NEFSC Ecosystem Status Report, Ecosystem Advisories, and State of the Ecosystem reports meet one of the immediate-term actions defined in the NOAA Fisheries Climate Science Strategy. These products provide information on the current and past states of the Northeast U.S. Continental Shelf ecosystem. The information in these products is also provided to the NEFMC and MAFMC in State of the Ecosystem reports designed specifically for the Councils. The report draws on information collected across the NEFSC and academic partners from oceanographic to social indicators. The information is presented in several management contexts including driver-pressure-state-impact-response model, ecosystem services, and overfishing/overfished.

Due to the long, data-rich time-series of the NEFSC bottom trawl survey, the majority of climate-fisheries research in the region has focused on the effects of warming ocean temperature on species distribution shifts. While these studies are important and need to continue, there is also a need for research focused on process-based (e.g. food availability, growth, mortality, species interactions) distribution shifts. Understanding the synergistic impacts of warming temperature and ocean acidification on species distributions and abundance is also a critical research need. Tracking, forecasting, and projecting species abundance is not a simple task but progress is needed to help inform management.

Research should be conducted using other datasets including other NEFSC surveys, State surveys, Northeast Area Monitoring and Assessment Program (NEAMAP) surveys, Canadian DFO surveys, and SEFSC surveys. In addition, cooperative work with industry is underway and will be continued (NEFSC Observer Program, Study Fleet, Cooperative Catchability studies). Tagging data should also be incorporated into this effort where appropriate. Changes in the distribution of commercial and recreational catches and discards should also be examined as spatial changes in fishing may have important implications for assessments and management. Further, most work has focused on adult stages; work should be conducted on understanding distribution changes of early life stages: eggs to juveniles. In particular, the connections between life stages through the availability of appropriate habitat should be examined. Finally, most work has been completed on commercially exploited fish and invertebrates; emphasis should also be given to other species including recreationally important fish, protected species, and forage species.

NERAP Priority Action 5: Conduct laboratory and field research on the mechanistic effects of multiple climate factors (e.g. temperature, ocean acidification, dissolved oxygen) on living marine resources with the goal of informing process-based models for single species, multi-species, and the ecosystem.

A mechanistic understanding of the effect of climate change on behavioral, physiological, ecological, and biophysical processes is critical to inform process-based models and improve scientific advice to managers. The NEFSC currently has seawater laboratory facilities in Sandy Hook, New Jersey, and Milford, Connecticut. Both facilities have the ability to manipulate temperature, carbonate chemistry, and other factors and the ability to examine interactive effects of multiple-stressors. Scientists at these facilities have experience working with phytoplankton, mollusks, crustaceans, and fish. Joint investments by NOAA OAR Ocean Acidification Program and the NEFSC are supporting climate-related work at these facilities focused on the effect of ocean acidification on the all life stages of fish and mollusks, including biochemical, physiological, behavioral, and ecological responses.

Most work has focused on the larval stage, but more focus on all life stages from egg to adult should be investigated. These experiments should focus on collecting physiological data that can be used in dynamic energy budget models (DEB), individual based models, and ecosystem based models. In particular, the potential for adaptation/acclimation to climate change needs to be investigated. Laboratory experiments allow for determining the extreme endpoint of the organism, but these experiments should be conducted concurrently with field sampling.

Laboratory and field experiments will provide much needed information to: 1) understand the effects of ocean acidification and other environmental changes on marine bivalves (e.g. oysters, surf clams, sea scallops, and bay scallops) and finfish in the New England and Mid-Atlantic region; 2) understand biological response and potential for adaption (genetic/acclimation/plasticity) of marine bivalves (e.g. surf clams and bay scallops); and 3) provide data on biological and ecological processes (e.g., growth, consumption, metabolism) needed by modelers to improve predictions of long-term effects that will assist managers.

NERAP Priority Action 6: Work with NOAA Oceanic and Atmospheric Research, National Weather Service, National Ocean Service, and academic partners to develop and improve regional hindcasts, forecasts, and projections of ocean and estuarine/river physics and biogeochemistry to develop and improve climate-ready management of living marine resources.

The recent NOAA Climate, Ecosystem and Fisheries Initiative (CEFI) addresses the ocean modeling and communities of practice component of this priority action but the permanent funding for the CEFI has not yet been approved. However, funding has been provided for pilot studies to begin the development and validation of region ocean model simulations for the entire U.S. east coast, shelf, and slope seas using NOAA GFDL's state-of-art ocean model MOM6 (Adcroft et al. 2019) coupled to GFDL's biogeochemical model COBALT (Stock et al. 2020). NOAA OAR CPO has also funded the development of annual to decadal ocean forecasts using the Scripps Coupled Ocean-Atmosphere Regional (SCOAR) modeling system.

The CEFI is primarily focused on regional ocean modeling that doesn't resolve the small-scale dynamics of estuaries and rivers, which are critical habitat for many recreational, commercial, and protected species in the region. Therefore, there is a continued need for new and improved watershed model development (Georges et al. 2016, Bever et al. 2021) as well as statistical downscaling efforts that utilize atmospheric variables as proxies for historical, forecasted, and projected watershed conditions (Muhling et al. 2018, Ross et al. 2020, Ross et al. 2021).

There is a critical need to continue these pilot studies and start new research that improves historical, forecasted, and projected biophysical ocean, estuary, and river conditions in the region. Work is needed to test and validate these new regional models and assess model uncertainty. An end goal is to have an ensemble of regional model simulations, much like the model assessment of the Intergovernmental Panel on Climate Change (IPCC) that can be used to assess model uncertainty in historical, forecasted, and projected ocean and watershed conditions. Building a capacity to distribute model output to various communities of practice is also a priority and a major component of the CEFI. There is a need for a centralized database that maintains and distributes *in situ* ocean data, watershed data, ocean reanalysis, ocean color data, and climate and ocean model output, which is also linked to NERAP priority action 2 and will require collaboration with other NOAA line offices. This modeling effort needs to be linked to NOAA Fisheries scientific-advice processes.

Informing Management (NCSS Objectives 1-3)

NERAP Priority Action 7: Improve spatial management of living marine resources through an increased utility of spatial and temporal distributions, abundance, productivity, migration, and phenology in management decisions.

Research is needed that translates observed and forecasted shifts in species distributions, abundance, productivity, migration, and phenology into management advice. Contemporary and projected species distribution shifts have been one the more predominant climate-fisheries research themes in the northeast U.S. However, stock structure, which is largely defined spatially, needs to be reevaluated in light of documented distribution changes. Process-based models of species distributions at multiple life history stages are also needed that explore impacts of climate change that are not exclusive to ocean temperature effects on adults. Other variables that need to be considered are ocean acidification, species interactions, fishery mortality, dissolved oxygen (coastal species), and food availability. Species distribution models that estimate abundance or biomass are not common because they are difficult to develop and validate. However, management decisions are based on abundance estimates and thus understanding the spatial structure of a stock biomass historically and into the future is an essential component of climate-ready fisheries management.

NERAP Priority Action 8: Develop and use Vulnerability Analyses, Scenario Planning, and Management Strategy Evaluations to examine the effect of different management strategies under various climate change scenarios.

Management strategy evaluation (MSE) is a simulation technique that allows the evaluation of a range of management options and identifies tradeoffs in performance across the range of options. An operating model is developed to represent the “true” dynamics of the system based on current understanding. An estimation model is used to assess the state of the system based on various observing or sampling processes. Finally, the effect of different management strategies can be examined in the context of the operating and estimation model. The NEFSC should continue to develop MSEs and seek external funding to apply the approach to climate-related issues. The NEFSC should also continue and expand work with academic scientists involved in MSE work in the region. Finally, the NEFSC and GARFO should continue to work with the NEFMC, MAFMC, and ASMFC to incorporate climate factors into management frameworks. The NEFSC is currently engaged in a Summer Flounder MSE for the MAFMC which focuses on translating discards into landings in order to increase the value generated by the fishery. One of the primary drivers of the MSE is climate change, and in particular the shifting summer flounder distribution and the implications of state-level allocations based on historical fishing patterns. These types of projects should continue to be identified and supported.

Scenario planning offers a structured process that, amongst other outcomes, can help evaluate/prioritize actions associated with adapting to, and managing for, climate change. The NEFSC and GARFO should continue to develop scenario planning capabilities, and continue to apply and/or support this framework as needs arise, given its applicability to planning for a changing climate. Additionally, climate-related needs identified through completed scenario planning efforts should be tracked and furthered. These needs include, for example, assess ocean acidification impacts on prey, conduct modeling studies (present conditions and projected into future) focused on spatial and temporal movement of right whales and copepods (e.g., current and future whale habitat use and distribution) and climate, and collect long-term monitoring data on plankton, which are already underway and/or the NERAP will continue to highlight further.

The Northeast Regional Coordinating Committee (NRCC) has begun a scenario planning project focusing on two components of climate change and its impact on fisheries management. The first will be how climate change might affect stock distribution, availability, and other aspects of east coast marine fisheries and the second will be to identify what the impacts of those will have on effective future governance and fisheries management. This effort is coastwide with the core team comprised of representatives from the various management bodies in the region (New England, Mid-Atlantic, and South Atlantic Fisheries Management Councils and the Atlantic States Marine Fisheries Commission) and NOAA Fisheries (Greater Atlantic and Southern Atlantic Regional Offices, Northeast Fisheries Science Center, and NOAA Headquarters). The project will work iteratively with stakeholders through 2022 to develop a series of different scenarios that will then be used to develop a better understanding of the future challenges and opportunities facing fishery management along with a set of near-term and long-term management priorities under a range of different future conditions. In addition, the project will make policy recommendations for broader governance changes that should improve the ability to adapt to future scenarios. The project will also generate a list of data gaps, research priorities, and monitoring needs for changing conditions along the east coast of the US.

NERAP Priority Action 9: Increase social, economic, and ecosystem scientist involvement in climate change research through multidisciplinary work, including the Northeast Integrated Ecosystem Assessment, that examines relationships between various ecosystem components with the goal of enhancing ecosystem-based management with climate information.

Ecosystems include humans, and climate change acts on human communities both directly (e.g., sea-level rise) and indirectly (e.g., species range shifts). There is an ongoing effort in the NEFSC to conduct multidisciplinary work in the Northeast U.S. region that better integrates social and natural sciences. Major changes have been made to our NEUS Atlantis ecosystem model to better capture the dynamics of individual fisheries, and as a result significant updates to the human dimension sub-models need to be made. These sub-models are specific to the fishing communities and socioeconomic characteristics of the Northeast U.S., and dedicated social sciences research is needed for model parameterization and validation. This multidisciplinary model development, and the background research to support it, will improve these end-to-end ecosystem model simulations and provide insight into the relationship between fisher and fishing community behavior (and the underlying social, economic, and cultural motivations for behavior) and socioeconomic responses to changing ecosystem conditions due to climate change.

Shifting species distribution and other impacts of climate change also highlight the need for behavioral models of fishing activity in order to predict likely future responses to both changing drivers and management strategies. For example, state-level stock allocations in the Mid-Atlantic based on historical fishing patterns have become increasingly contentious, given the shifts in stock distributions observed over the past decade. Effective management necessitates an understanding of how recreational and commercial fisheries are likely to respond to these dynamics into the future.

Additional human dimensions projects are needed in a number of areas, including ocean acidification projects that connect impacts to marine species to human community vulnerability; habitat studies that connect fishers' local ecological knowledge to climate studies of oceanographic and biological changes of habitat structure and function; and continued, new, and expanded work on MSEs and risk assessments with the MAFMC and the NEFMC. Some such projects are funded and at various stages of completion. Others, such as the habitat studies are not yet funded.

It is important to understand not just the impacts of climate change in general on fishing communities, but also the impacts of specific aspects of climate change. Sea level rise risk and storm surge risk indicators for fishing communities in the Northeast and other NMFS regions are available online. Depending on the species commonly caught there, human communities may be more or less vulnerable to changes in ocean temperature, OA, or both. Currently, a project is underway looking specifically at the impacts of OA on fishing communities that land species strongly impacted by OA, using an approach based on Hare et al. 2016b and Colburn et al. 2016. In another study that is reaching its conclusion, the NEFSC developed and tested a methodology to classify Northeast U.S. fishing communities according to their vulnerability to specific climate change or climate change-related factors, including temperature, OA, and stock size and status.

Moreover, the vulnerability and resilience of fishing communities to the effects of ocean warming and OA on northeast species is dependent on the fishing community's adaptive capacity in relation to both social and environmental exposure and sensitivity factors. Measures of social well-being, sustainability, vulnerability and resilience for fishing communities are already available. Viable measures of social well-being, sustainability, vulnerability, and resilience for the fishing industry would also be beneficial to coastal communities and have yet to be applied to OA or warming specifically.

NERAP Priority Action 10: Development of stock assessment models (e.g. WHAM) that include environmental terms (e.g., temperature, ocean acidification) with a priority for stocks that have upcoming research track assessments.

Moving forward, multiple alternative stock assessment models and approaches need to be developed and evaluated. To be incorporated into operational assessments, these models and approaches need to undergo a formal scientific peer-review process. Assessments are prepared during a Northeast Regional Stock Assessment Workshop (SAW) and then reviewed by an independent panel of stock assessment experts called the Stock Assessment Review Committee (SARC). Further, both the ability to forecast environmental factors and better estimate historical environmental factors are necessary to include environmental terms in stock assessments models. An example of this approach is currently underway within the NCLIM project, which is a collaboration of the Gulf of Maine Research Institute, NEFSC, and Rutgers University. The approach focuses on stocks that have upcoming research track assessments and combines climate models, ecosystem/population models, and human dimension models to help inform the management process with a climate-informed assessment (Figure 5). A Northeast Ecosystem and Socioeconomic Profile Workshop is planned, with the aim to develop a flexible, standardized framework that helps integrate ecosystem and socioeconomic factors into fisheries decision-making. The framework is intended to provide supplemental data that will directly inform both the stock assessment process and the scientific advice for fishery management.

The Woods Hole Assessment Model (WHAM) is a tool being developed for the region that can help address this priority action. The WHAM currently has the capability to link recruitment trends or natural mortality to environmental covariates, and carry these relationships and other correlated processes forward into projections. The research track working group for Atlantic butterfish is also currently considering climate effects on the distribution of the stock and the recently formed research track working group on state-space assessment models will be exploring WHAM and its applications in climate-enhanced stock assessments for peer-review in the fall of 2023.

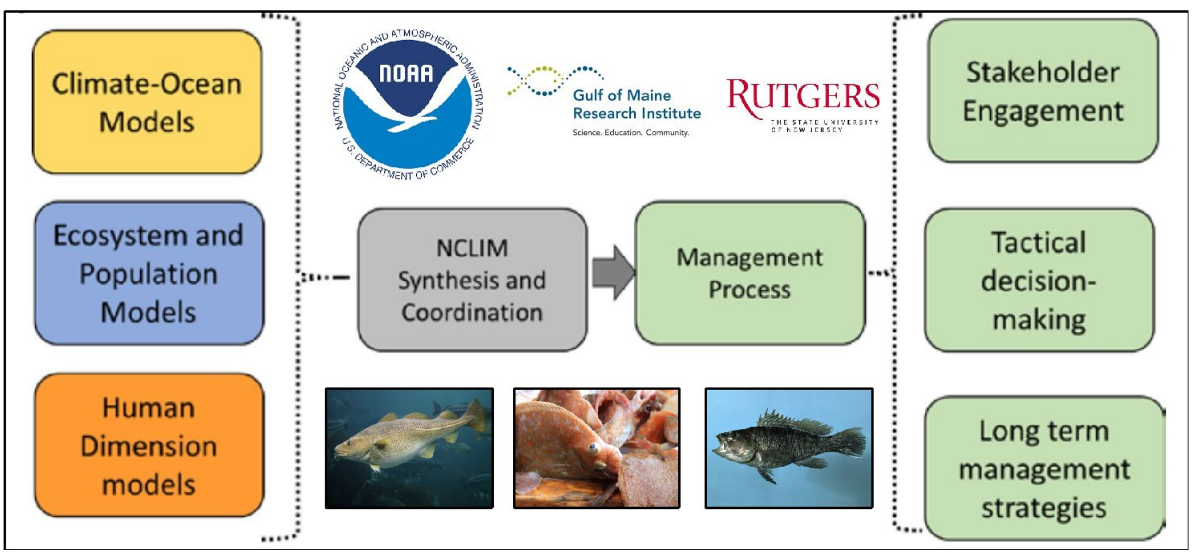

Figure 5. Schematic of the NCLIM approach to informing management with climate-enhanced stock assessment information for the upcoming research track assessments for Atlantic cod, southern New England yellowtail flounder, and black sea bass.

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