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REVIEW

NOAA fisheries research geared towards climate-ready living marine resource management in the northeast United States

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Abstract

Climate change can alter marine ecosystems through changes in ocean temperature, acidification, circulation, and productivity. Over the last decade, the United States northeast continental shelf (U.S. NES) has warmed faster than any other marine ecosystem in the country and is among the fastest warming regions of the global ocean. Many living marine resources in the U.S. NES ranging from recreational and commercial fish stocks to protected species have shifted their distribution in response to ocean warming. The National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA Fisheries) is responsible for the assessment, protection, and sustainable use of the nation's living marine resources. In the U.S. NES, NOAA Fisheries has made substantial progress on climate research related to fish, fisheries, and protected species. However, more research is needed to help inform tactical management decisions with the goal of climate-ready living marine resource management. This is a major challenge because the observed physical and biological changes are unprecedented, and the majority of marine species assessments and management decisions do not utilize environmental data. Here we review the research accomplishments and key needs for NOAA Fisheries in the U.S. NES in the context of climate change and living marine resource management. Key research needs and products are: 1) Infrastructure with continued and enhanced ocean surveys that includes cooperative research with the fishing industry and other NOAA line offices and partners; 2) Tracking and projecting change, and understanding mechanisms including state of the ecosystem reporting, improved regional ocean and ecosystem hindcasts, forecasts, and projections, and continued process-based laboratory and field studies, 3) climate-informed management, including stock assessments that account for climate where possible, translation of changing species distributions into spatial management, climate vulnerability assessment and scenario planning, ecosystem-based management, management strategy evaluations, and increased multidisciplinary science that includes economic and social indicators.

1. Introduction

The U.S. northeast continental shelf (U.S. NES) ecosystem (Fig 1) is one of the most productive marine regions in the nation, accounting for over one third of the U.S. commercial fisheries annual value [1]. The region supports a wide array of living marine resources, from the highly valuable Atlantic sea scallop (*Placopecten magellanicus*) and American lobster (*Homarus americanus*) to protected species such as endangered North Atlantic right whale (*Eubalaena glacialis*) and Atlantic salmon (*Salmo salar*). Climate change is directly impacting the ocean and watersheds throughout the U.S. NES. Over the last three decades, ocean temperature in the region has warmed faster than any other marine region in North America (Fig 2). The U.S. NES, particularly the Gulf of Maine, is also among the fastest warming regions globally [2]. The impacts of this warming can manifest in changes in marine species distribution, abundance, productivity, phenology, natural mortality, predator-prey interactions, host-pathogen interactions, growth rates, and more [3]. Ocean acidification (OA), another consequence of climate change, can affect many invertebrates [4] and the early life history stages of fish [5], altering food webs and potentially human food supply.

As an agency within the U.S. Department of Commerce, the National Oceanic and Atmospheric Administration National Marine Fisheries Service (NOAA Fisheries) is responsible for the assessment, protection, and sustainable use of the nation's living marine resources. This responsibility includes assessing the impacts of climate variability and climate change on marine ecosystems that support commercial, recreational, and protected species, and the coastal communities that rely on these resources. The NOAA Fisheries Climate Science Strategy provides a framework to conduct research and produce comprehensive management strategies related to changing climate and ocean conditions [6, 7]. This strategy is based on seven priority science objectives, each of which relates to fisheries, protected species, aquaculture, habitats, and ecosystems. The seven objectives are: 1) climate-informed reference points, 2) robust management strategies, 3) adaptive management processes, 4) robust projections of future conditions, 5) information on mechanisms of change, 6) status, trends, and early warnings, and 7) science infrastructure to produce and deliver actionable information.

Fig 1. The U.S. northeast continental shelf (U.S. NES) marine ecosystem comprises the mid-Atlantic Bight, Georges Bank, and the Gulf of Maine. It is at the interface of two major currents: the warmer, saltier Gulf Stream deriving from the south, and the colder, fresher Labrador Current deriving from the north. These two currents form a recirculation gyre in the shelf slope and enter the U.S. NES via the northeast channel in the Gulf of Maine. Gulf Stream water can also enter the U.S. NES via anticyclonic warm core rings. The mid-Atlantic Bight cold pool is formed seasonally after each winter when wind forcing is reduced and the water column becomes stratified in the summer and early fall. The cold pool is critical habitat for many key commercial species such as yellowtail flounder and ocean quahog. Rivers and estuaries are also critical habitat for many diadromous species such as Atlantic salmon, river herring, and striped bass. Base map file source = https://www.shadedrelief.com/atlantic/.

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NOAA Fisheries has six regional fisheries science centers across the nation. The NOAA Fisheries Climate Science Strategy required each fisheries science center and regional office to produce an action plan addressing the needs and challenges of its region. In the U.S. Northeast, NOAA's Northeast Fisheries Science Center (NEFSC), Greater Atlantic Regional Office (GARFO), and Chesapeake Bay Office (CBO) jointly developed the Northeast Regional Action Plan (NERAP) [8], which outlines research priorities to address the objectives of the national strategy. Since the publication of the NERAP in 2016, the NEFSC, GARFO, and CBO have made substantial progress on addressing the action plan [9]. However, there are still many actions needed to better inform fisheries and protected species management with relevant climate-based information. Here we discuss the research accomplishments and key needs of NOAA Fisheries in the northeast U.S. within the context of achieving climate-ready

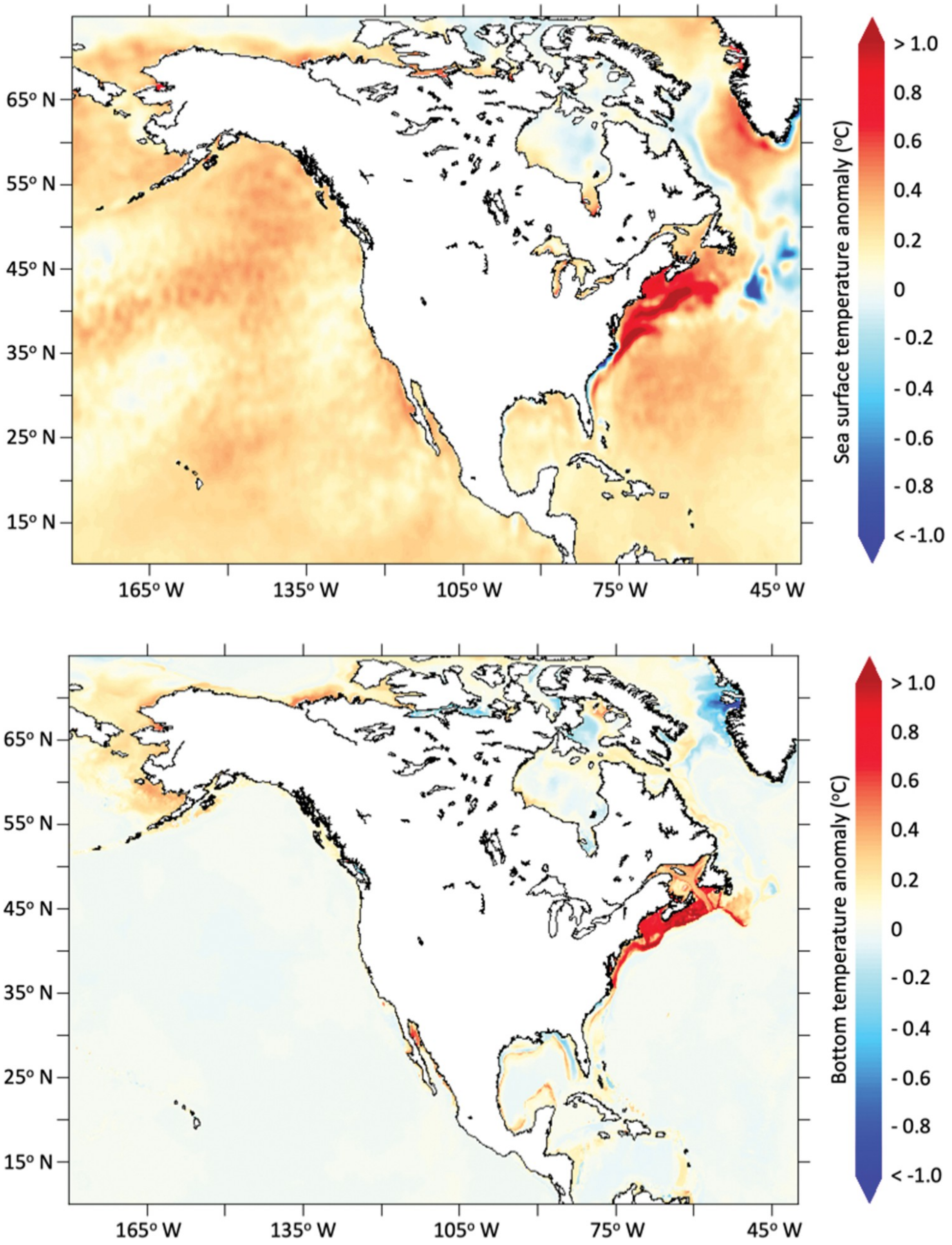

Fig 2. Decadal temperature anomaly in the ocean surface (top panel) and ocean bottom (bottom panel) throughout North America. Anomaly is based on the average temperature from 2010–2019 relative to the historical climatology from 1993–2019. Ocean surface data is from NOAA's OISST (25-km) product; ocean bottom data is from the GLORYS12v1 (1/12°) global ocean reanalysis. Shape file source = https://catalog.data.gov/dataset/tiger-line-shapefile-2019-2010-nation-u-s-2010-census-5-digit-zip-code-tabulation-area-zcta5-na.

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management of fisheries and protected species. We begin with a proposed process of informing living marine resource management with climate information that is unique to the management system in the northeast United States. We then outline the research and key needs to successfully advance climate-informed living marine resource management in the northeast U.S. These include: 1) maintaining and enhancing surveys and data collection; 2) continuing process-based laboratory and field studies; 3) developing climate-informed stock assessments;

4) improving the skill of regional ocean and ecosystem models; 5) translating changing species distributions into spatial management; 6) completing climate-vulnerability assessments and scenario planning; 7) implementing ecosystem-based management; 8) developing management strategy evaluations; and 9) increasing multidisciplinary science that includes economic and social indicators.

2. Climate-informed living marine resource management in the northeast U.S.

The enhanced warming and associated shifts in species distributions within the northeast U.S. are unprecedented and thus the management system is facing many new challenges. To help the management system respond to new ecosystem conditions and prepare for future change, NOAA Fisheries in the northeast U.S. will continue to conduct research that can aid in the development of climate-ready living marine resource management. The backbone of this research is to maintain and expand our oceanic and socio-economic surveys, as well as continued collaboration with the fishing industry. Without these fisheries-independent and fisheries-dependent data, we cannot assess contemporary change in the region; nor can we inform models that simulate ocean physics, biogeochemistry, species distribution/abundance, multi-species interactions, socio-economic factors, and end-to-end ecosystem dynamics. Similar datasets derived from coastal, estuarine, and freshwater habitats are also crucial given the large number of living marine resources in the U.S. NES that rely on these habitats. Process-based laboratory and field studies are also critical components of our research and are needed to validate relationships between the environment and organisms that are inferred from survey data. Modeling historical, forecasted (seasonal to annual), and projected (decadal) change in the U. S. NES relies on high-resolution global climate and regional ocean models that can resolve the fine-scale bathymetry and regional circulation of the U.S. NES. Given that ocean surveys are limited spatially and temporally, historical simulations, or hindcasts, from these high-resolution models can fill in data gaps and thus help understand contemporary relationships between the environment and living marine resources. Offshore wind energy development in the U.S. NES is a concurrent challenge along with climate change. While in the long-term, offshore renewable energy development will help mitigate the myriad effects of ongoing climate change on marine resources, such development simultaneously introduces new and poorly understood stresses on many commercial and protected species that NOAA Fisheries is charged to conserve and manage. Living marine resource management strategies must take all these challenges into account.

We outline and illustrate the process of informing living marine resource management and stakeholders with climate information in the northeast U.S. in Fig 3 and S1 Fig. Informing management with relevant climate information is not a simple or straightforward process. Climate information can be used quantitatively (e.g. variables in a stock assessment model) or qualitatively (e.g. ecosystem and socio-economic profiles, vulnerability assessments) and can derive from historical, forecasted (seasonal to annual scale), or projected (decadal to century scale) time periods. Some management decisions may benefit from historical climate information rather than forecasted or projected information and this can depend on the identified mechanistic underpinnings between the environment and the species or stock in question. Moreover, peer-reviewed science and management strategy evaluations (MSEs) must show that including climate information in the assessment of a living marine resource significantly improves fishery harvest advice or protected species management. In the northeast U.S., research track assessments (Table 1) are the primary on-ramp to evaluate new commercial species stock assessment models that are informed with climate information. This is highlighted

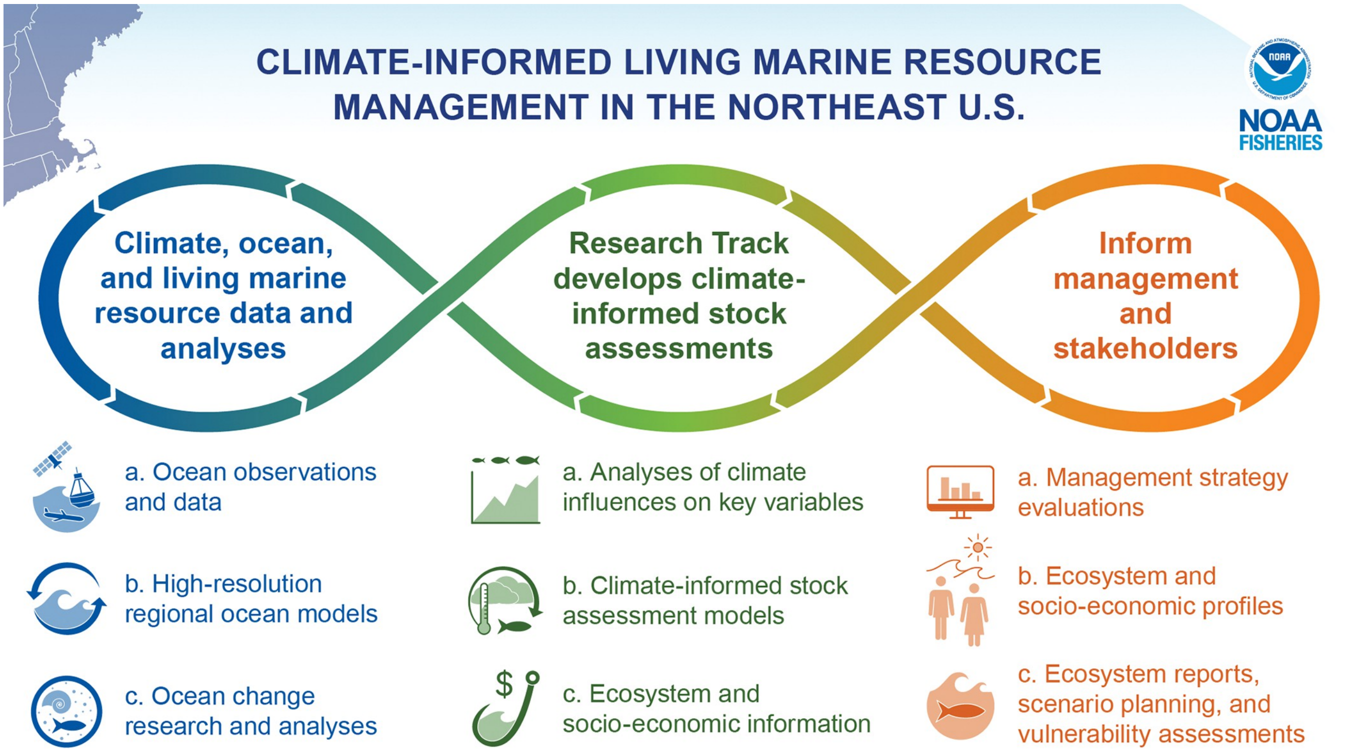

Fig 3. Process of informing living marine resource management with climate information in the northeast U.S. This begins with ocean observations, ocean models, and focused research on causal relationships between ocean change and the response of living marine resources. The second phase is Research Track that includes new analyses and review of climate influences on key biological variables (recruitment, mortality, etc.) with research results used in climate-informed stock assessment models. This includes the consideration of qualitative and quantitative ecosystem and socio-economic information. The final phase is to inform management and stakeholders with the best available science regarding climate impacts on living marine resources. This can take many forms and includes management strategy evaluations of climate-informed stock assessment models, ecosystem and socio-economic profiles, ecosystem status reports, scenario planning, and vulnerability assessments. These three phases feedback on each other such that management and stakeholders can request additional data, research, and analyses in phases 1 and 2. A more detailed version of this figure is available in the supplementary material (S1 Fig).

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in the process illustrated in Fig 3 and S1 Fig and it suggests that new climate-fisheries research is targeted and timed with upcoming research track assessments detailed in Table 1. Research track assessments can provide the basis for future management assessments that use climate information. For example, the current research track assessments for the southern New

Table 1. U.S. NES commercial species that have existing and upcoming research track assessments. Research track assessments consider changes to existing stock assessment models based on new information and research. Most of these species have life history variables that are associated with environmental variables. These associations should be considered in the research track assessment and should also influence new research on climate-enhanced stock assessments.

Survey	Annual survey frequency	Time-series
Fish and Invertebrate Bottom Trawl	Spring and Fall	1963-present
Ecosystem Monitoring (physics, biogeochemistry, plankton)	4–6 per year	1971-present
Sea Scallop	Once per year	1980-present
Northern Shrimp	Once per year	1983-present
Clam and Ocean Quahog	Once per year	1982-present
Gulf of Maine Bottom Longline	Spring and Fall	2014-present
Large Coastal Shark Bottom Longline	Spring and Summer	1986-present
Cooperative Atlantic States Shark Pupping and Nursery	Summer	1998-present
Marine Mammal and Sea Turtle Ship-Based/Aerial Surveys	Throughout year	1998-present

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England/Mid-Atlantic yellowtail flounder stock (*Limanda ferruginea*) and the northern stock of black sea bass (*Centropristis striata*) are considering ocean temperature impacts on recruitment. If these new climate-informed recruitment models are approved by the research track working groups, they can be used in future management track assessments for these stocks. Management track assessments provide routine estimates of stock status that inform management decisions.

NOAA's Climate and Ecosystem Fisheries Initiative (CEFI) is a NOAA-wide effort that aims to build an operational modeling and decision support system that improves our ability to provide living marine resource management and stakeholders with the information needed to make climate-informed decisions. High-resolution regional ocean model hindcasts, forecasts, and projections of both physical and biogeochemical variables for the northwest Atlantic are one of the modeling products that will be produced by the NOAA CEFI. These model simulations combined with a data portal and regional decision support teams will help provide actionable advice and are a core component of the climate-informed living marine resource management process in the northeast U.S. as illustrated in Fig 3 and S1 Fig. This process is bottom-up, beginning with observations, models, and targeted research to inform research track assessments, management, and stakeholders, as well as top-down such that management and stakeholders can request additional data, modeling products, research, and analyses.

The NOAA CEFI is a collaboration among multiple line offices within NOAA that includes Fisheries, National Ocean Service (NOS), and Oceanic and Atmospheric Research (OAR). The high-resolution regional ocean model simulations produced by CEFI efforts will help each NOAA Fisheries science center fill in spatial and temporal gaps in survey data using model hindcasts, predict seasonal and annual ocean change using model forecasts, and predict decadal and century-scale ocean change using model projections under climate change scenarios. These new regional model simulations can be used in a variety of ways to inform living marine resource management. For example, regional model hindcasts provide high-resolution time-series of key ocean variables such as ocean temperature, chlorophyll, primary and secondary productivity, dissolved oxygen, and plankton size class diversity. High quality historical time-series of these ocean variables are critical for research analyzing contemporary relationships and mechanistic underpinnings between living marine resources and the ocean environment. Hindcasts and forecasts can be used in management track assessments that are already built on using historical ocean and climate information. If an existing management track assessment uses ocean bottom temperature as a primary co-variate associated with recruitment, regional ocean models can provide higher resolution hindcasts/forecasts of historical/future bottom temperature (with a known uncertainty) that can then provide higher quality estimates of historical and forecasted recruitment. This information can then be used by management to make climate-informed harvest control rules. Outside of climate-informed stock assessments, these regional ocean model simulations can also be used to inform management through State of the Ecosystem Reports (SOEs), climate scenario planning, climate vulnerability assessments, ecosystem and socioeconomic profiles (ESPs), and risk assessments. Ultimately, any new management strategy that uses climate information should first be assessed in a management strategy evaluation (MSE) to determine if the addition of climate information improves the management success of the living marine resource. In the following sections, we review the research and key needs that are essential to successfully implement the process of informing living marine resource management and stakeholders with climate information in the northeast U.S. as illustrated in Fig 3 and S1 Fig.

3. Scientific surveys

3.1 Fisheries-independent surveys

Scientific surveys are at the core of the NEFSC's infrastructure. Surveys of physical, chemical, and biological ocean variables are essential to understand and track change in marine ecosystems. Skillful models, whether for single species or the entire ocean ecosystem including human dimensions, can be developed, and validated only if observations exist over sufficient temporal and spatial scales that capture seasonal, annual, and decadal variability. The NEFSC has a long history of conducting fisheries-independent surveys of the U.S. NES ecosystem ranging from ocean physics and biogeochemistry to fish, shellfish, sharks, marine mammals, sea turtles, and seabirds (Table 1). Variables measured in the NEFSC bottom trawl survey include but are not limited to species distribution, abundance, diversity, age and growth, and gut contents. However, not all survey observations are continuous (e.g., phytoplankton pigments) or have a multi-decadal time-series (e.g., Gulf of Maine Bottom Longline Survey). Since the mid 1990s, there has been a decreasing trend in the number of days at sea and stations sampled (e.g., bottom-temperature observations in Fig 4). Potentially exacerbating the decline in ocean observations is the planned offshore wind development that may impact the ecosystem, NOAA scientific surveys and assessments, protected species, and fisheries along much of the U.S. NES. This is a major concern because increased sampling is needed to properly track the rapid changes in the ecosystem, such as the increasing trend and variability of ocean temperature within the region. These changes in the ocean have been associated with distribution shifts in the living marine resources of the region [10]. Therefore, it is critical that we maintain not only our surveys but increase our survey and data collection activities to effectively track changes in the ocean, both temporally and spatially. Many NEFSC survey programs collect biological and environmental data simultaneously, and this interdisciplinary data collection has supported science to understand the effects of climate change on living marine resources. The COVID-19 pandemic dramatically curtailed NEFSC surveys in the year

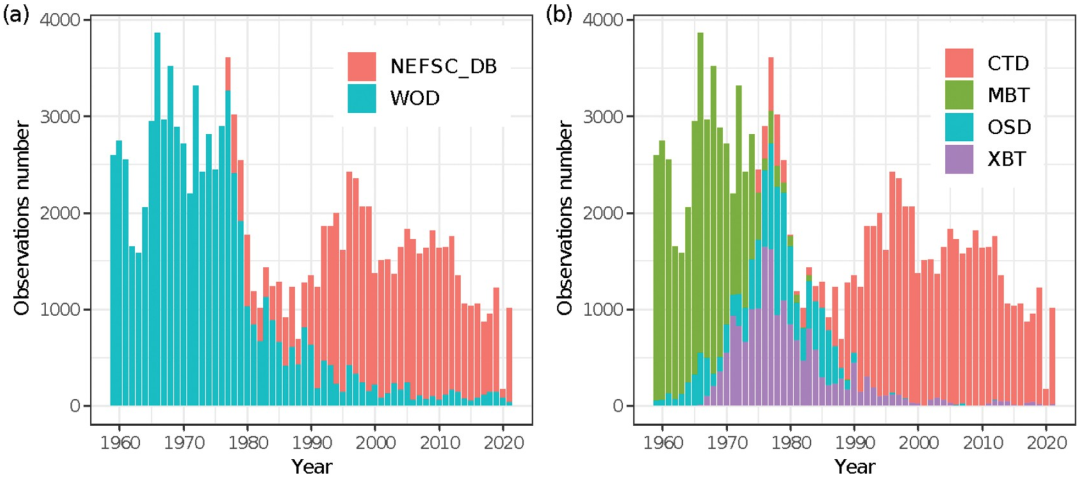

Fig 4. Number of bottom temperature observations per year for each type of oceanic probe extracted from the Northeast Fisheries Science Center oceanographic database (NEFSC_DB) and completed with the NOAA NCEI's World Ocean Database (WOD) (left panel) to include observations not present in the NEFSC_DB. The observations were collected on the northeast U.S. continental shelf on an area which covers the four Ecological Production Units (EPUs) defined by NOAA's Northeast Fisheries Science Center (https://noaa-edab.github.io/tech-doc/epu.html) The right panel indicates the type of probe used to collect the measurements; conductivity, temperature, and depth instruments (CTD), Ocean Station Data (OSD), Expendable Bathythermograph (XBT) and Mechanical Bathythermograph (MBT).

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2020, resulting in data gaps (Fig 4) but also creating opportunities for modernizing surveys to address new challenges [11].

Satellite-derived ocean color data are an essential tool for monitoring phytoplankton throughout the ocean. While standard ocean color algorithms perform well in the open ocean, they often degrade in optically complex coastal environments such as the U.S. NES [12]. Ship-based measurements of phytoplankton parameters are essential for developing and validating satellite ocean color algorithms. For example, phytoplankton pigment, imagery, and optical data collected during select NEFSC EcoMon cruises were used to optimize and validate a regional phytoplankton size class/functional type ocean-color algorithm [13]. This new satellite dataset is being used to assess the long-term trends in phytoplankton composition [14, 15] and force ecosystem models such as the Northeast U.S. Atlantis model [16]. In addition, new hyperspectral ocean color sensors, such as the National Aeronautics and Space Administration's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) instrument, have the potential to produce cutting edge products for a variety of applications, all of which require *in situ* data for product development and validation.

3.2 Fisheries-dependent data

Fisheries-dependent data are critical sources of ecosystem data that require collaboration with the fishing industry. The NEFSC Cooperative Research Branch organizes and leads many programs with stakeholders and the industry. One example is the Environmental Monitors on Lobster Traps and Large Trawlers (eMOLT) program [17], where oceanographic sensors are deployed on fishing gear, including lobster traps, bottom trawls, dredges, gill nets, and longlines. Data from eMOLT and other industry-based environmental monitoring programs are used to inform regional ocean models and predict future oceanographic conditions [18]. Another example is the Study Fleet program [19], which engages fishermen in collecting detailed information about the species composition and quantities of catch, fishing effort, and the ocean environment. Data from the Study Fleet are used to understand the dynamics and distribution of fisheries and resource species over time. 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 [19]. 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 (*Paralichthys dentatus*), scup (*Stenotomus chrysops*), haddock (*Melanogrammus aeglefinus*), and shortfin squid (*Illex illecebrosus*) stock assessments [20, 21]. Industry-based surveys, such as the Northeast Area Monitoring and Assessment Program Inshore Trawl Survey, Gulf of Maine Bottom Longline Survey, the Coastal Shark Bottom Longline Survey, and the Ocean Quahog and Atlantic Surf Clam Survey, leverage the specialized ability and knowledge of fishermen and their vessels, while also enhancing trust with stakeholders [22]. Overall, collaboration with members of the fishing industry provides a unique opportunity to observe the marine environment at the time and space scales needed to detect the impacts of a changing climate.

Other fishery dependent ocean observing initiatives in the region include, but are not limited to, the Commercial Fisheries Research Foundation's (CFRF) Lobster, Jonah Crab, and Black Sea Bass Research Fleets, the Woods Hole Oceanographic Institution (WHOI) and CFRF's Shelf Research Fleet, and the NEFSC Industry-Based Biological Sampling Program (InBios). 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 [23]. 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 [17, 24]. 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 can feed into regional oceanographic models (e.g., ROMS, FVCOM) and can be paired with survey data to understand environmental drivers of resources, species, climate impacts, and other factors. 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.

3.3 Key needs

Ocean acidification monitoring is limited spatially and temporally, but proposals have been funded to enhance sampling in the short-term. However, longer term sampling of ocean acidification is needed throughout the region and not just limited to surface measurements. Ocean depth profiles of ocean pH (an indicator of ocean acidification) are needed to better understand spatial, seasonal, and interannual variability throughout the water column. NOAA Fisheries works closely with academic partners at Rutgers University where researchers have pioneered new technology to sample the ocean environment using Slocum gliders equipped with ocean pH sensors [25, 26]. These enhanced measurements can provide information on the existing state of ocean pH across depths and sub-regions where impacts to living marine resources may be strongest (e.g. scallop and surf clam habitat). These measurements, in addition to enhanced sampling of other key biogeochemical variables such as chlorophyll, nutrients, net primary productivity, and plankton composition can also help develop more skillful biogeochemical ocean models for the region. Skillful ocean model output will help to fill existing survey gaps and is critical to research aimed at identifying associations between historical ocean change and living marine resource life history variables such as recruitment, growth, and natural mortality. For example, our limited observations of ocean pH three-dimensionally and throughout the year confines the development and validation of regional ocean models tasked with resolving ocean pH seasonally. These ocean models cannot be parameterized and tuned without these measurements. A clear understanding of seasonal variability of ocean pH across the U.S. NES is needed so that we can understand the existing baseline and then produce more skillful forecasts and projections of ocean acidification to inform living marine resource management. Without more measurements of ocean pH, we cannot inform management of predicted change and impacts to living marine resources that are sensitive to ocean acidification.

New biological surveys, such as the Gulf of Maine bottom longline survey and right whale prey survey, are needed to continue to track change in key ecosystem indicators from lower to higher trophic levels across habitat types. These new surveys are needed to supplement data collected on NOAA's fishery-independent trawl and ecosystem monitoring surveys that cannot sample all regions, habitat types, and all four seasons of the year. The Gulf of Maine Bottom Longline Survey was designed to increase sampling of fish stocks associated with complex habitats that are inaccessible to bottom trawl surveys. Several aspects of the survey design and operations are novel, including stratification by "rough" and "smooth" bottom types using a rugosity index, partnership with commercial fishers in developing survey protocols, use of electronic monitoring systems to quantify hook disposition, and multi-factor classification of seafloor habitats at each survey station. The design and technology used for the Gulf of Maine Bottom Longline Survey are of increasing importance as offshore wind energy development precludes mobile-gear surveys and ecosystem-based fisheries management requires enhanced environmental and habitat information. Collaboration with industry partners is critical to the operational and scientific success of the Gulf of Maine Bottom Longline Survey, which provides information to support stock assessments, management actions, habitat studies, life history studies, and survey-comparison analyses.

Right whale prey surveys provide increased spatial and temporal resolution for key indicators of zooplankton abundance and distribution data in an southern New England, an area highly impacted by climate-induced changes and one which is also an area likely to be impacted by offshore wind development and has become increasingly important to right whales. These surveys have primarily taken place monthly in February through April, although the program is currently expanding into coverage during other seasons. These surveys are also collecting CTD and ADCP data to explore the drivers behind zooplankton aggregation as a foraging resource and document potential changes in a climate context.

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 subsurface ocean temperature. Engaging fishing vessels in collecting ecological and oceanographic data expands observing capacity in time and space and provides critical observations of the water column, near surface atmosphere, and resource species [18, 24]. These observations not only contribute to ocean modeling and prediction, but also help fishermen make decisions with regard to limiting their incidental catch and their ability to adapt to changing ocean conditions [19]. Increased interaction between scientists and fishermen is needed to help develop the relationships necessary to expand observing capacity and inform research at the time and space scales pertinent to the science and fishing communities.

Survey and data coordination with Fisheries and Oceans Canada (DFO) and the NOAA Fisheries Southeast Fisheries Science Center (SEFSC) regarding commercial species, protected species, and ecosystem indicators is critically needed to understand and track marine ecosystem change in the regions north and south of the U.S. NES. Species-distribution shifts are not bound to the U.S. NES and thus tracking change in the south Atlantic Bight (U.S. southeast) and in Canadian waters to the north is necessary to understand ecosystem change at a larger spatial scale and may benefit from increased use of animal telemetry [3, 27–30].

4. Process-based research: Understanding mechanisms

4.1 Laboratory and field research

Understanding the mechanisms of climate-change impacts on marine ecosystems is critical to properly utilize results from mechanistic studies of the relationships between the environment and marine taxa and to model historical and future change. Laboratory-based process studies at the NEFSC are at the forefront of this research at both the Milford, Connecticut and Sandy Hook, New Jersey facilities. The Milford lab primarily focuses on bivalve shellfish while Sandy Hook focuses on finfish and some invertebrates. In the laboratory, experiments on all life stages from the egg to adult are being conducted to understand the whole life-cycle response to environmental change. In addition to survival and growth measurements, physiological processes such as feeding rates, respiration, and excretion have been documented for commercial bivalve species including oysters, scallops, and surf clams under various levels of ocean acidification [31, 32]. Surf clams experienced decreased feeding and increased excretion as CO_2 levels rose [33]. These changes resulted in a net difference in growth [33], with slower growth under ocean acidification. In the field, Milford scientists documented that blue mussel (*Mytilus edulis*) selection efficiency, and rates of clearance, filtration, and assimilation all decreased under ocean acidification [34]. As bivalves progress from the pelagic to the benthic phase, environmental cues can trigger settlement. Field studies found that total benthic bivalve abundance was correlated with sediment carbonate chemistry [35]. These studies demonstrate that, from the laboratory to the field, bivalves are sensitive to ocean acidification.

NEFSC finfish research shows that the latitudinal distributions of many marine species are shifting as the U.S. NES warms [10] and, thus, laboratory-based process studies are needed to understand the mechanisms that affect the biology of these species as ocean conditions change. Collaborations with academic partners have analyzed the impacts of changing water temperature on black sea bass (*Centropristis striata*) and spiny dogfish (*Squalus acanthias*) aerobic scope and hypoxia tolerance [36]. The findings suggest that as the U.S. NES continues to warm, it is likely that species will shift poleward or into deeper, cooler, and possibly more acidic waters. Finfish appear to be more resilient to acidification than calcifying organisms at least during their juvenile and adult life stages [37–39]. Increased acidification up to 2600 μatm had no effect on growth, survival, or otolith condition on juvenile scup (*Stenotomus chrysops*) [39]. The early life-stages of finfish appear to be more vulnerable. For example, as acidification increased there was a reduction in survival of summer flounder (*Paralichthys dentatus*) embryos but more accelerated development of larvae resulting in smaller sizes at transformation and settlement [40]. Black sea bass embryos may demonstrate resilience to future ocean acidification conditions [41] but even taxa that occupy inshore spawning and nursery habitats with notoriously variable CO_2 regimes (e.g., Atlantic silverside, *Menidia menidia*) have shown sensitivity to elevated CO_2 in multiple responses and life stages [42]. These studies highlight that the response to climate change may not be uniform among finfish species. The Sandy Hook Lab has developed a novel set of equipment for revealing the plasticity of marine species responses to thermal, CO_2, and dissolved oxygen regimes. For each environmental factor, a range of values can be studied, thus revealing the scope of species responses for any variable being measured. These scope of response data are precisely the kinds of quantitative descriptions needed to model climate change impacts [43].

4.2 Key needs

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. Although the NEFSC and partners have made progress 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 (Fig 5). Most work has focused on the early life-stages, especially the embryos and larvae, but all life stages from gametes to adults should be investigated. These experiments should focus on collecting physiological data that can be used in dynamic energy budget models, individual-based models, and ecosystem-based models. In particular, the extent of acclimation and the potential for adaptation to climate change need to be investigated. Many laboratory experiments allow for determining the thermal and CO_2 limits of the organism, but these experiments should be conducted to reveal the scope of response across a range of near-future climate conditions. Ideally, these studies are conducted concurrently with field sampling.

Laboratory and field experiments will provide much needed information to: 1) understand the effects of thermal regimes, 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 regions; 2) reveal the full scope of biological responses and potential

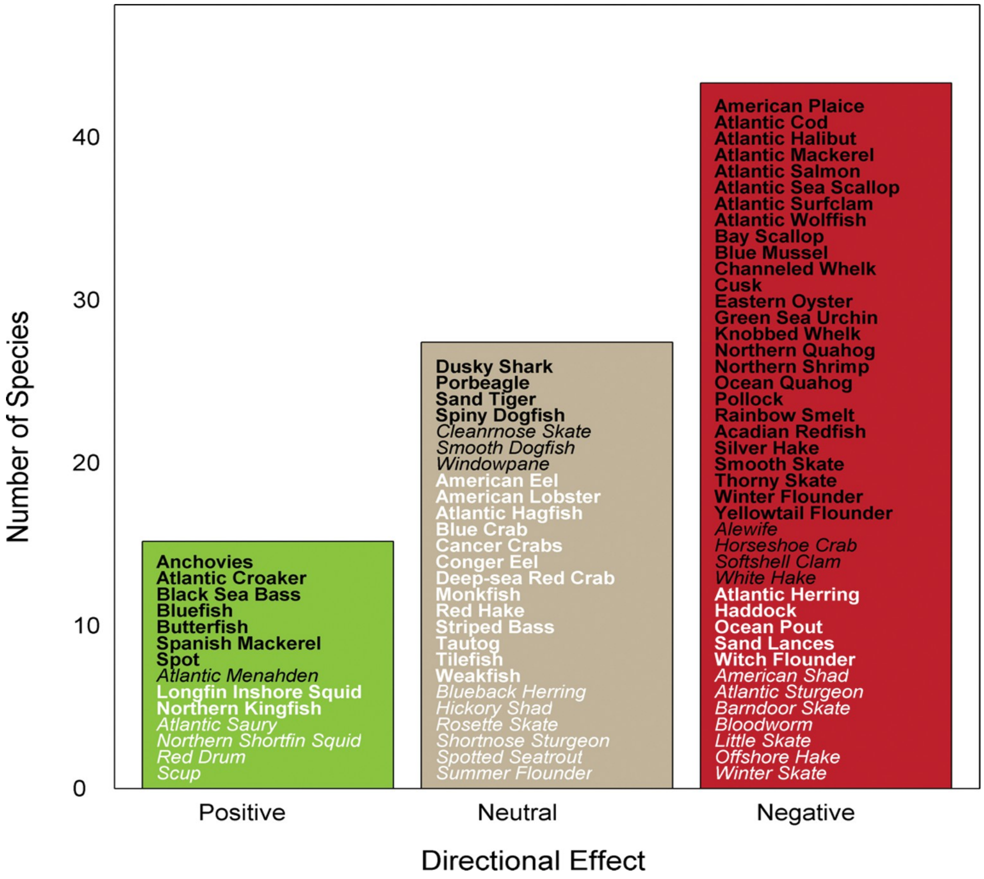

Fig 5. Directional effect of climate change on marine fauna in the U.S. NES (from Hare et al. 2016b). Colors represent expected negative (red), neutral (tan), and positive (green) effects. Certainty in score is denoted by text color and font: very high certainty (>95%, black, bold font), high certainty (90–95%, black, italic font), moderate certainty (66–90%, white or gray, bold font), low certainty (<66%, white or gray, italic font).

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for organismal adaptation of marine bivalves and finfish; and 3) quantify the biological and ecological processes (e.g., growth, consumption, and metabolism) needed by modelers to improve predictions of long-term effects that will assist resource managers.

5. Tracking contemporary change

5.1 Species distributions, ecosystem change, and risk assessment

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. These studies have analyzed a broad suite of marine taxa in the contemporary period from the 1970s onward [10, 44, 45] 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 [46] and ichthyoplankton [47, 48]. Other research and products that track contemporary change include annual State of the Ecosystem (SOE) reports for New England and the Mid-Atlantic [14, 15], Mid-Atlantic ecosystem risk assessment [49], and climate vulnerability assessments for fish/invertebrates [50]; highly migratory species (in progress), habitat [51], and fishing communities [52], and a methodology for marine mammals [53]. Several ecological and biological indicators as well as climate indicators have been updated for fishing communities [54]. Tracking change in the physical and chemical state of the ocean is ongoing; studies have focused primarily on temperature [55–57], ocean circulation [58, 59], and ocean acidification [35, 60]–variables that are key indicators of climate change in marine ecosystems. The majority of living marine resources in the U.S. NES are demersal and thus bottom temperature measurements are critical to understand the variability and trends in bottom thermal habitat. The NEFSC surveys do not measure bottom temperature throughout the entire year and there are significant spatial and temporal data gaps, especially in the winter and summer. Regional ocean circulation changes can be more pronounced in specific seasons and can be discerned through temperature change. The NEFSC has developed a new ocean bottom temperature product at a very high temporal and spatial resolution (daily, 1/12˚) that combines three different ocean models, a bias corrected regional ocean model, a global ocean reanalysis, and an ocean forecast, resulting in a daily time series from 1959-present [61]. This high-resolution bottom temperature historical time series would not be possible using *in situ* observations alone and it can be used to fill in spatial and temporal gaps in survey data and understand seasonal, interannual, and decadal variability with much less uncertainty. High-resolution hindcasts that assimilate observations are critical to studies analyzing contemporary ocean change and the response of living marine resources. The Atlantis end-to-end marine ecosystem model for the U.S. NES (NEUS Atlantis) now uses high-resolution global oceanographic hindcasts and satellite remote sensing for its environmental and primary production forcing, leading to a more realistic variation in environmental drivers and an improved simulation of the lower-trophic food web [16]. Regarding watersheds, Collins (2019) characterized river flood seasonality for 90 watersheds across the U.S. NES and evaluated seasonality trends [62]. U.S. NES rivers were also evaluated in a national study focusing on large-flood seasonality and historical occurrence trends [63].

These ocean and watershed hindcasts are critical to understanding mechanisms between environmental change and living marine resources through the association of survey data to key biophysical ocean variables in validated ocean and watershed models. For example, identifying relationships between survey abundance for a particular teleost species and zooplankton productivity in the Gulf of Maine on a seasonal basis would not be possible using ocean observations alone because there are not enough zooplankton observations in space and time.

5.2 Key needs

New research on species distribution and abundance needs to 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. These surveys cover regions and species that are outside of the fall and spring NEFSC bottom trawl survey. Some of these surveys also cover the winter and summer seasons that are not sampled by the NEFSC bottom trawl survey. Due to the high seasonal variability of the region, many species have very large seasonal migrations that are not fully captured using the NEFSC fall and spring bottom trawl survey alone. While these surveys 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 OA on species distributions and abundance is a critical research need.

Cooperative work with industry needs to continue (e.g. NEFSC Observer Program, Study Fleet, Cooperative Catchability studies, Cooperative Shark Tagging Program, Shark Research Fishery) [64]. Tagging and telemetry data needs to be incorporated into this effort where appropriate as it can document individual movement patterns over time and address knowledge gaps in seasonal migration and residency patterns, habitat use, stock identification and mixing, fisheries exposure, bycatch susceptibility, age validation and survival rates. The use of archival telemetry data to develop species distribution models has been limited and more research is needed that deploys archival tags where applicable and then uses these data to develop new, three-dimensional species distribution models. Management can't be informed of forecasted and projected species distribution change unless we are able to first develop skillful species distribution models that can reproduce contemporary change.

Changes in the distribution of commercial and recreational catches and discards needs to be examined, as spatial changes in fishing may have important implications for assessments and management. Further, most work has focused on adult stages; new research needs to be conducted on understanding distribution changes of early life stages: eggs or neonates to juveniles. In particular, the connections between life stages through the availability of appropriate habitat needs to be examined. Finally, most work has been completed on commercially exploited fish and invertebrates; emphasis needs to be given to other species including recreationally important fish, protected species, and forage species.

While more skillful ocean forecasts and long-term projections 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 as bottom temperature, circulation, stratification/mixing, pH, primary and secondary productivity, and dissolved oxygen. Tracking change in the U.S. NES does not need to be limited to *in situ* observations, which have been declining (Fig 4). Ocean model hindcasts can be used to track historical changes at much higher spatial and temporal resolutions than *in situ* measurements. There have been previous efforts to develop regional ocean model hindcasts and projections that resolve biogeochemistry [65], but more models, including those that assimilate data, are needed to assess model uncertainty and to create model ensembles of historical, forecasted, and projected ocean conditions.

6. Projecting and forecasting change

6.1 High-resolution climate and ocean models

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 U.S. NES. The shelf is an oceanographically complex region that is challenging to model because of its fine-scale bathymetry and circulation. Due to its ability to resolve these fine-scale features and dynamics, NOAA GFDL's CM2.6 global climate model [58] has been an integral part of the NEFSC's progress on projecting future conditions.

Decadal-scale projections of species distribution shifts under climate change have relied on GFDL's CM2.6 [66, 67], which projects an enhanced warming of the U.S. NES caused by a change in regional circulation [58]. The mechanisms resolved in CM2.6 corroborate contemporary observations of regional circulation change over the last decade [68, 69]. This high-resolution global climate model has been utilized extensively for projections of protected species distributions such as loggerhead sea turtles (*Caretta caretta*) [70] and the prey of North Atlantic right whales [71]. By 2024, the high-resolution climate change projections provided by CM2.6 are anticipated to be incorporated into the Northeast U.S. Atlantis model (NEUS Atlantis). NEUS Atlantis [16] simulates system-wide biological and fisheries processes for the region and can include a variety of options for parameterizing temperature and pH effects on species-specific processes (i.e., growth, reproduction, and movement). The goal of these NEUS Atlantis climate projections will be to provide relative changes in ecosystem composition, species biomass, and fisheries productivity under several climate change and management strategy scenarios to aid in strategic long-term management. NEUS Atlantis development will also be a part of a global effort to standardize how environmental interactions relevant to climate change (temperature and pH) are implemented in Atlantis models and how global climate models are downscaled and implemented in Atlantis. These efforts will ensure that results from NEUS Atlantis climate projections are comparable to those of other regions and put projected changes to the U.S NES into a global context.

The skill of seasonal to annual (S2A) forecasts of ocean conditions in the U.S. NES, such as sea surface temperature (SST), is relatively low compared to other large marine ecosystems [72, 73]. The reason for the poor skill in this region is because SST forecasts are derived from global models that have coarse resolution in the ocean and atmosphere components. Tactical fishery and protected species management may benefit from more skillful seasonal to annual (S2A) forecasts of ocean conditions. Given that 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. NES 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 [74].

NOAA CEFI projects have begun to develop and validate regional ocean model simulations for the entire U.S. east coast, shelf, and slope seas using NOAA GFDL's state-of-art ocean model MOM6 [75] coupled to GFDL's biogeochemical model COBALT [76]. NOAA's CEFI recently produced a new MOM6 hindcast with biogeochemistry for the northwest Atlantic from 1993–2019 [77]. The next two phases of northwest Atlantic regional model development under NOAA's CEFI are seasonal, annual, and decadal forecasts followed by long-tern century scale climate change projections. Outside of NOAA's CEFI, another project is underway to develop annual to decadal ocean forecasts using the Scripps Coupled Ocean-Atmosphere Regional (SCOAR) modeling system.

Estuaries and rivers are important habitats for many marine species in the U.S. Northeast, and there is a need to understand and predict changes to these watersheds associated with climate. Many of these habitats are designated as critical habitat under the Endangered Species Act and are home to a suite of diadromous species including Atlantic salmon, shortnose and Atlantic sturgeon (*Acipenser brevirostrum* and *Acipenser oxyrinchus oxyrinchus*), American eel (*Anguilla rostrata*), Atlantic striped bass (*Morone saxatilis*), and river herring species (*Alosa pseudoharengus* and *Alosa aestivalis*). Historical, downscaled model hindcasts of Long Island Sound [78–80] and the Chesapeake Bay [81–83] have been developed and analyzed relative to large-scale climate forcing. These near-shore, very high-resolution coastal models have been shown to resolve watershed dynamics at a much higher skill than coarser global and regional ocean models.

6.2 Key needs

Projections of future change most often have focused on marine species habitat and distribution using NOAA's high-resolution global climate model CM2.6. Although 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 year-to-year to decadal time scales. Seasonal to annual (S2A) forecasts of ocean conditions that are tied to stock assessments, ecosystem models, and risk assessments are needed to inform tactical fisheries management. The S2A skill of bottom temperature forecasts using statistical methods has been improved in certain regions and time periods [74] but dynamical methods are needed to improve this skill even further and to a wider extent across the U.S. NES. Model development under NOAA's CEFI 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. The 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 regional model uncertainty in historical, forecasted, and projected ocean and watershed conditions. Finally, there is a continued need for new and improved watershed model development [78, 84] as well as statistical downscaling efforts that utilize atmospheric variables as proxies for historical, forecasted, and projected watershed conditions [82, 83, 85]. Some living marine resources in the U.S. NES rely on estuaries and/or rivers for foraging and spawning and thus there is a need for skillful model forecasts and projections of watershed habitat change to inform assessments used in management.

7. Informing living marine resource management

7.1 Climate-informed stock assessments

A primary way marine resource management can use climate information is through climate-informed fishery stock assessments [86]. Progress on identifying relationships between stock productivity or abundance trends and climate variables (e.g., demographics, recruitment, population growth) has been advancing on key commercial and recreational species, including southern New England yellowtail flounder (*Limanda ferruginea*) [87–89], summer flounder (*Paralichthys dentatus*) [90], winter flounder (*Pseudopleuronectes americanus*) [91], northern shrimp (*Pandalus borealis*) [92, 93], Atlantic cod (*Gadus morhua*) [94], surf clam (*Spisula solidissima*) [95], and black sea bass (*Centropristis striata*) [96]. The Woods Hole Assessment Model (WHAM, https://timjmiller.github.io/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 [89, 97]. WHAM is being used to investigate environmental effects in several stock assessments, including yellowtail flounder (*Limanda ferruginea*), American plaice (*Hippoglossoides platessoides*), Atlantic cod (*Gadus morhua*), and butterfish (*Peprilis triacanthus*).

One of the tasks of the ongoing subject-based research track on application of state-space models is to develop guidelines for including ecosystem and environmental effects in assessment models and for their treatment in reference points and setting catch advice. Simulation studies to determine what factors influence inferences about environmental effects on recruitment, natural mortality, growth, and catchability are underway. Preliminary results for effects on natural mortality confirm a combination of strong effects, large contrast in the covariate over time, and precise environmental, catch, and survey observations are important for reliable inferences about these effects. Finally, it is critical to point out that climate-informed stock assessments can use climate information quantitatively (as covariates in the model) or qualitatively (considering environmental conditions but not as terms in the model). This gives management more flexibility in considering the impacts of historical and forecasted ocean conditions.

7.2 Key needs

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 in the northeast region, but for all U.S. regions. The northeast U.S. fisheries management system consists of the New England Fishery Management Council (NEFMC), the Mid-Atlantic Fishery Management Council (MAFMC), the Atlantic States Marine Fisheries Commission (ASMFC), and the Greater Atlantic Regional Fisheries Office (GARFO); coordination and communication among management partners is essential for developing robust and climate-resilient fisheries management approaches. Moreover, there

Table 2. NOAA Northeast Fisheries Science Center seasonal and annual surveys of the U.S. NES marine ecosystem.

Species	Research Track Assessment Year	Environmental variables linked to life history	References
American lobster	2025	Ocean acidfication, temperature, dissolved oxygen	[162–168]
American plaice	2022	NA	NA
Atlantic cod	2023	Ocean acidfication, temperature	[169]
Atlantic herring	2025	Ocean acidfication, temperature, salinity	[170–173]
Black sea bass	2023	Ocean acidification, temperature, dissolved oxygen, salinity	[36, 41, 96]
Bluefish	2022	Ocean temperature	[174]
Butterfish	2022	Ocean temperature	[175]
Golden tilefish	2024	NA	NA
Haddock	2022	Ocean temperature, chlorophyll concentration	[176, 177]
Longfin inshore squid	2026	Ocean temperature	[178]
Sea scallop	2025	Ocean acidfication, temperature	[179, 180]
Shortfin squid	2022	Ocean temperature	[20, 181]
Spiny dogfish	2022	Ocean temperature	[182]
Winter flounder	2026	Winter surface air temperature in estuaries	[91, 183, 184]
Yellowtail flounder	2024	Summer/fall ocean temperature, Gulf Stream indices, Cold pool indices	[87–89]

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are very few operational 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 [98]. Finally, living marine resource management decisions in the U.S. that are based upon forecasted (seasonal to annual) or projected (decadal) ocean conditions are not common. Therefore, it is essential to produce new research results that assess and evaluate the use of climate and environmental information for upcoming research track stock assessments (Table 2), which may be the primary mechanism to inform management with climate-enhanced stock assessments. Research track assessments consider changes to existing stock assessment models based on new information and research. The recent Northeast Climate Integrated Modeling (NCLIM, https://gmri.org/projects/northeast-climate-integrated-modeling-nclim) project is an example of this approach, with the following goals: 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.

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. Further, both the ability to forecast environmental factors and better estimate historical environmental factors are necessary to include environmental terms in stock assessment 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.

7.3 Climate vulnerability assessments, scenario planning, and protected species

Climate vulnerability assessments can help understand the sensitivity of marine species, freshwater and marine habitat, and fishing communities to climate change. These assessments help management prepare for future changes in marine ecosystems from lower trophic levels to keystone predators and protected species up through local seafood markets and fishing communities. Initiated in the U.S. NES, NOAA Fisheries completed climate vulnerability assessments for marine species [50], habitat [51], and fishing communities [52]. The methodologies to assess the climate vulnerability of marine mammals and sea turtles have also been developed [53, 99] and a completed vulnerability assessment is forthcoming. NOAA Fisheries is collaborating with the NEFMC and MAFMC on a synthesis product for the U.S. NES marine species and habitat climate vulnerability assessments to better understand the potential vulnerability of fish stocks to climate change. Further applications of these vulnerability assessments are needed to help inform management of high-risk species and habitat under continued climate change. A climate vulnerability assessment is also in development for Atlantic highly migratory species (including tunas, billfishes, and sharks), which requires collaborations with the NOAA Fisheries Atlantic Highly Migratory Species Management Division and the Southeast Fisheries Science Center.

The uncertainty captured in vulnerability and risk assessments can be used in a process known as scenario planning [100]. Scenario planning is a method of integrating uncertainty into the planning for resource management. There are several examples where scenario planning has been used in the U.S. NES. Climate information has been incorporated into scenario planning for Atlantic salmon [101] and North Atlantic right whales [102]. Scenario planning exercises such as these can inform management strategy evaluations for harvested species and conservation planning for protected species. The Northeast Regional Coordinating Council (NRCC) has recently completed 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 was coastwide with the core team comprised of representatives from the various management bodies in the region (NEFMC, MAFMC, South Atlantic Fishery Management Council, and the ASMFC) and NOAA Fisheries (Greater Atlantic and Southern Atlantic Regional Offices, NEFSC, and NOAA Headquarters). The project worked iteratively with stakeholders to develop a series of different scenarios that 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 generated a list of data gaps, research priorities, and monitoring needs for changing conditions along the east coast of the U.S.

Stemming from the scenario planning work, a range-wide salmon habitat synthesis was completed that described habitat conditions suitable for Atlantic salmon across freshwater and marine systems. The scenario planning exercise also helped identify and prioritize a range of climate actions that were incorporated into the final recovery plan for Atlantic salmon [103], including 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 with a relatively high proportion of inputs from groundwater and/or lake/wetland outflow. River reaches with high baseflow tend to be cooler in the summer and warmer in the winter providing for longer growth periods and shorter duration of thermal stress for Atlantic salmon. Lombard et al. (2021) developed a model to predict and map relative baseflow quantities across Maine at a high spatial resolution (~2.5 km^2), providing valuable information to managers making decisions about where to conserve or restore habitat [104]. Through the Collaborative Management Strategy for the Gulf of Maine Atlantic Salmon Recovery Program, work has been initiated with tribal partners, the state of Maine, and non-governmental organizations to identify and protect climate-resilient habitats important to Atlantic salmon.

Following a recommendation of the North Atlantic Right Whale scenario planning exercise to increase research on shifting spatial and temporal distributions of right whales and prey in a changing climate, the NEFSC has implemented short-duration zooplankton and oceanography sampling trips in the southern New England region during the winter and early spring (January–April) of 2019, 2020, 2021, and 2022. This time period is when right whales are in the area and additional summer sampling occurred in August of 2021 near foraging right whales. The goal is to describe abundance, energy density, and horizontal and vertical distribution patterns of right whale prey in relation to physical features to better understand available prey resources and the mesoscale processes that result in high-density aggregations of right whale prey. Correlations between ocean warming and right whale prey availability suggest an inverse relationship between right whale's primary prey, *Calanus spp*., and ocean temperature [105].

7.4 Key needs

The reality is that climate change is rapidly removing, changing, or shifting the habitats needed for many species. Most of the current protected stocks are defined by their unique evolutionary and often locally adapted genetic characteristics. However, those characteristics were defined by the habitats in which they evolved and increasingly those habitats are changing and cannot be restored to historical conditions, which meet the physiological/behavioral requirements of those stocks. Continued climate vulnerability assessments are important for understanding mechanisms while scenario planning is important to support climate-informed management. It is also important to continue to look to additional approaches as, for example, a Climate Vulnerability Assessment becomes unnecessary when a river or beach is simply too warm to support salmon spawning or turtle nesting. Increasingly, the real challenge lies not with science's ability to document the issue, but with the tools available for management to act upon it. These inevitable events require adaptive management strategies in an emerging field of transformational ecology that science can advise upon [106]. The United States Department of Interior has recognized this challenge across several species and their ecosystems and developed a Resist-Accept-Direct (RAD) strategy for adapting to these situations [107, 108]. NOAA fisheries has begun to consider issues in this RAD context [109] and the need for cross regional climate coordination and a climate innovation team. That team must develop strategies to address the two diverging issues- what do we do with the habitat a species/stock occupies once it can no longer support it and what do we do with the species/stock when it can no longer live in the habitat we defined as its home.

7.5 Ecosystem approaches to management

Ecosystem-based fisheries management (EBFM) was introduced as a holistic approach to fisheries management in the 1990s. EBFM considers the complex suite of biological, physical, economic, and social factors associated with managing living marine resources. NOAA Fisheries strongly supports an ecosystem approach to managing their trust resources. EBFM and an Ecosystem Approach to Fisheries Management (EAFM) can better inform decisions regarding trade-offs among and between fisheries (commercial, recreational, and subsistence), aquaculture, protected species, biodiversity, and habitats. These concepts can be extended to consider other ocean uses such as offshore energy. Considerable progress has been made in the U.S. NES towards EBFM and EAFM.

Exploring trade-offs can be accomplished through the application of the Integrated Ecosystem Assessment (IEA) process, which has been successfully used in fisheries management to track system-level changes and provide guidance regarding the expected tradeoffs of management decisions. First described by Levin et al. (2009), IEAs provide a framework for assessing cumulative and system-level impacts and tools for resource managers to achieve multiple ecosystem objectives [110]. Typically, this is done with a place-based approach that gathers data from a number of different disciplines across the socio-ecological spectrum.

Parts of the IEA process has been used by the MAFMC in their EAFM framework [111, 112]. The NEFSC and partners began producing annual SOE reports in 2017, which synthesize economic, biological, and environmental indicators aligned with fishery management objectives [113]. Over the past 6 years, many collaborators from more than 14 institutions have contributed to the reports, which apply an open science approach for both report development and for sharing indicator data [114]. The MAFMC uses the SOE reporting along with results from regional climate vulnerability analysis [50] in their annual ecosystem risk assessments [49]. The SOE indices and the risk assessment informed an EAFM conceptual model for the summer flounder fishery that links climate and other drivers with habitat, biological, fishery, economic and social components with management objectives and outcomes [115]. A management strategy evaluation of the summer flounder fishery recreational discards was completed in August 2022 (see next section).

The NEFMC is developing an EBFM approach, which uses ecosystem level productivity to provide an overall cap on fishery removals, with upper limits on catch advice for functional groups of fish species (ceilings) and species level biomass thresholds (floors). The NEFMC also conducted a management strategy evaluation to develop a harvest control rule for Atlantic herring that considered its role as forage within the ecosystem [111]. The ASMFC has also implemented ecosystem reference points for the Atlantic menhaden fishery based on menhaden's importance as forage in the ecosystem for striped bass [116, 117].

Related to Atlantic salmon recovery and proactive habitat management for river herring and their habitat, EFM approaches that integrate conservation of river, estuary, and ocean habitats and focus on connectivity between systems have been framed by NOAA and partners [118, 119]. A multispecies approach is being implemented both in planning by NOAA and State partners and ongoing state and federal permitting activities at dams. The Atlantic salmon Endangered Species Act listing is unique in recognizing the need for recovery of the full diadromous community as critical to recovery. Additionally, recent work suggests that the ecosystem services provided by diadromous fish collectively are important to climate resilience across river, estuary, and ocean habitats [120].

A framework is being developed to incorporate contextual ecosystem and socioeconomic information into the single-stock advice process. These Ecosystem and Socioeconomic Profiles (ESPs) [121] have been started for black sea bass, bluefish, and Atlantic cod. The ESPs are designed to leverage existing information and knowledge pathways and to create a structured way to incorporate diverse information into the stock advice process. This standard framework will help facilitate the interpretation of data and updates to data in future years of management. The MAFMC single stock advice process already uses stock level climate and ecosystem information when the Scientific and Statistical Committee (SSC) develops Acceptable Biological Catch (ABC) advice. The SSC determines the level of scientific uncertainty in the overfishing limit (OFL) by evaluating nine criteria for each stock, including ecosystem factors. Regional climate vulnerability analysis for each stock helps place stocks into uncertainty categories, with low risk of stock productivity change due to changing climate in a lower uncertainty category, moderate risk of stock productivity changes due to changing climate in the default uncertainty category, and high-highest risk of stock productivity change due to changing climate in the highest risk category. This framework will be able to use the additional detailed information provided in an ESP as those come online. However, each management body has different processes, so developing processes able to use climate information more directly is an important need.

Ocean use in several sectors is emerging, including offshore wind energy development and aquaculture, as the nation works to increase energy and food security while decreasing carbon emissions. The scale of these developing sectors will require full ecosystem-based management planning that ensures effective co-use and preservation of the ocean environment.

7.6 Key needs

Management partners have identified key needs through annual feedback on regional ecosystem reports. Highest priority requests include further refining ecosystem level overfishing (EOF) indicators and investigating optimum yield (OY) at the ecosystem level. Methods for evaluating ecosystem indicator trends, inflection points, and breakpoints (regimes) were also ranked highest priority as these methods apply to ecosystem level thresholds and reference points, as well as to indicators at the functional group or stock level, or to indicators of climate or habitat risk. Reference points are critical for operationalizing advice based on ecosystem indicators. Short term forecasts of environmental conditions were also ranked high priority, as was providing more information on ecosystem-level regime shifts. Incorporating ecosystem information into stock assessment and management decision making is also a high priority for management partners in the region. This can take several paths, including the research track assessment process that is designed to routinely evaluate environmental effects on each stock, and the science and ecosystem advice processes developed by regional Councils that specifies Acceptable Biological Catch and provides ecosystem risk assessments or other products. Expanding capacity to support these management advice processes is required as climate change combined with new ocean uses continues to change Northeast US ecosystems.

7.7 Management strategy evaluations

Management strategy evaluation (MSE; also called management procedures) is ideally a stakeholder-driven, collaborative process that uses simulation to evaluate the ability of management strategies (i.e. combinations of data collection methods, analyses, and harvest controls) to achieve management objectives [122, 123]. Management objectives are often competing, so the focus of MSE is on evaluating tradeoffs among strategies, to identify management approaches that best balance competing needs and ensure sustainability of fisheries while also meeting stakeholder needs. Importantly, MSE adds transparency by making the tradeoffs and logic behind decisions explicit and clear [123].

MSEs have been conducted by scientists for many years in the U.S. NES. These efforts have become more coordinated with managers and stakeholders since 2016, and climate and ecosystem interactions with managed species have played a larger role in analyses in that same period. Moreover, efforts at MSE outreach and education were initiated to improve the process for all participants as well as the quality of the MSE product.

The New England Fisheries Management Council (NEFMC) conducted a management strategy evaluation to develop a harvest control rule for Atlantic herring that considered its role as forage within the ecosystem [124]. This MSE was also the first of its kind in the region (and in the U.S. Council system) to employ an open stakeholder process to shape the objectives and analysis [111]. Stakeholders were formally involved in designing the simulation and identifying management strategies and objectives through two formal workshops, as well as through numerous other informal lines of communication. Based on the stakeholder input, the MSE evaluated the herring harvest control rules in terms of their effect on several herring predators (e.g., tuna, seabirds), the herring stock itself, and economic impacts on the herring fishing industry [124]. Ultimately, the NEFMC eliminated many harvest control rules from consideration due to their poor performance in terms of their effect on herring predators, while still being able to select a harvest control rule for herring management that was expected to meet management objectives.

The Mid-Atlantic Fisheries Management Council (MAFMC) conducted a stakeholder driven MSE within its Ecosystem Approach to Fisheries Management (EAFM) process that links summer flounder recreational fishery management with angler welfare, as well as more traditional biological objectives. Based on the EAFM risk assessment and conceptual modeling [115], key climate linked uncertainties regarding summer flounder (*Paralichthys dentatus*) distribution shifts were included in the evaluation of alternative management strategies. While the MSE identified many strategies that potentially both improve angler welfare and reduce summer flounder bycatch relative to status quo management, including distribution shifts in the simulations resulted in lower benefits across all strategies. This approach to MSE within an EAFM framework is poised to give the MAFMC a more complete picture of both potential performance of recreational fishery management measures and tradeoffs among various objectives under the uncertainties posed by climate change within the region.

A framework has also been developed for incorporating climate and habitat information directly into fisheries management using risk assessment and management strategy evaluation [125]. Support was provided to the MAFMC risk assessment [49], and in 2019 the results from the climate vulnerability analysis and habitat shifts were included into a conceptual model for high-risk summer flounder fisheries to develop questions around the MSE for that species [115].

7.8 Key needs

Continued training remains a necessity to both increase the technical capacity of MSE practitioners and improve understanding and use of MSE by management partners. Analysts with the technical expertise to conduct MSE are often educated in tangentially related fields, such as mathematics, statistics, stock assessment, and socioeconomics. Additional training, especially as it pertains to collaborative work with stakeholders, is needed. Likewise, the typical federal fisheries management decision making process functions on time scales of six to twelve months and compares a handful of management options based on analyses that usually do not use closed-loop simulations. Often in these situations the tradeoffs in the relative performance of the management options are implicit. Conducting MSEs can take several years and the tradeoffs in relative performance of the management options, and their link to management objectives, is an explicit focus. Management partners will need training in altering their existing thought processes and paradigms for evaluating management alternatives. Similarly, one of the touted benefits of MSE is greater transparency and acceptance through stakeholder engagement. Even a perfectly executed stakeholder engagement process will not achieve these benefits if managers do not effectively use the MSE results and acknowledge the breadth and possibly conflicting input of stakeholders in the final decision making [126].

Another key need is a basic acknowledgement that addressing climate and ecosystem issues will likely require open and extensive stakeholder driven MSE [126]. Climate and ecosystem issues are often considered wicked problems where uncertainty is so large that even bounding the problem or defining future states of nature is intractable. Stakeholder knowledge in these situations can be highly informative to identify likely future states of nature and are also the situations most likely to benefit from the application of MSE.

In addition to investments in training and stakeholder processes, standardizing regional climate data products would facilitate uptake of this information in scientific and management products ranging from assessments to MSEs. MSE practitioners spend considerable time developing models but may not be aware of or accustomed to working with climate model outputs or various downscaled regional products that might be important to a particular MSE. Given the time constraints of conducting MSE within management frameworks, unfamiliarity with or lack of easy access to appropriate climate model products may mean climate change signals are not considered within an MSE. Alternatively, a set of climate data products, including hindcasts and projections under different emissions scenarios, could be developed and vetted within the Northeast Region by climate model experts in consultation with population and ecosystem modelers and maintained in accessible formats for MSE analysts to use as needed. This standardized set of climate scenario information (projected temperature at surface and bottom and other habitat and ecological factors as possible) could also relate to ongoing climate vulnerability analyses and climate scenario planning in the northeast U.S.

7.9 Economic and social indicators

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 evaluate climate-informed reference points. This work is coupled to new research that links climate- and stock-related projections for groundfish to economic outcomes for fishing communities. Statistical models are being developed that explain how fishermen select target stocks and landing locations. These models can be used to understand how these two behaviors may change under various climate and policy scenarios. Other social science research projects include: 1) climate vulnerabilities and adaptation pathways for U.S. NES fishing communities, including developing indices of vulnerability to climate change for groundfish at the fishing community level; 2) engaging stakeholders in management strategy evaluation of New England groundfish in a changing ocean; 3) developing U.S. NES fishing community indices of vulnerability to climate change based upon sea surface temperature, stock size/status, and ocean acidification using the 82 species evaluated in the climate vulnerability assessment [50]; 4) developing indicators of climate vulnerability, specifically to OA, for northeast U.S. fishing communities dependent upon landings of Atlantic sea scallops; and 5) tracking socio-economic conditions that could impact loggerhead sea turtle nesting as nesting beaches move farther north.

Progress on informing management is also based upon studies that analyze 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 change. End-to-end ecosystem models, such as NEUS Atlantis, attempt to simulate the entire ecosystem from fundamental physical and chemical processes to food webs to fisheries management and social and economic factors [127]. While less complex ecosystem models have been developed to inform EBFM objectives, NEUS Atlantis is the only product that simulates climate impacts and socioeconomic processes on a regional scale. The Atlantis modeling framework has been used to model human-dimension variables (e.g., 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. 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 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.

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 U.S. NES 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 U.S. NES, 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 fishermen and fishing fleet behavior (and the underlying social, economic, and cultural motivations for behavior at both individual and community levels) and socioeconomic responses to changing ecosystem conditions due to climate change.

The development and potential use of ecosystem and socioeconomic profiles (ESPs) is a critical component of this research. For example, the development of ESPs for black sea bass and bluefish are now part of the research track process. The goals of ESPs are to provide relevant ecosystem and socioeconomic information for fisheries management, to work with management bodies to identify on-ramps where ESP information can fill knowledge gaps, and to work towards an operational ecosystem approach to fisheries management (EAFM).

7.10 Key needs

Shifting species distribution and other impacts of climate change 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 that are 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 several areas, including ocean acidification projects that connect impacts to marine species to fishing behavior and 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 landed, human communities may be vulnerable to changes in ocean temperature, ocean acidification, or both. Currently, a project is underway looking specifically at the impacts of ocean acidification on fishing communities. 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, ocean acidification, 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 fishing communities' 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 specific to the fishing industry would also be beneficial to coastal communities and for measuring the impacts of management measures. But industry-focused indicators, including those for ocean acidification and ocean warming, are yet to be developed.

7.11 Watersheds and estuaries

Diadromous species rely on both marine and freshwater habitats and are important in the region for a variety of reasons (e.g., protected species, commercial and recreational harvest, ecosystem interactions); these species include Atlantic salmon, Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*), shortnose sturgeon (*Acipenser brevirostrum*), rainbow smelt (*Osmerus mordax*), alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), American eel (*Anguilla rostrata*), hickory shad (*Alosa mediocris*), American shad (*Alosa sapidissima*), striped bass (*Morone saxatilis*), sea-run brook trout (*Salvelinus fontinalis*), sea lamprey (*Petromyzon marinus*), white perch (*Morone americana*), and tomcod (*Microgadus tomcod*). Dams and road crossings have disrupted river-ocean connectivity throughout the region at multiple scales and are a primary challenge to diadromous species conservation. Ongoing work on dam removal and improved fish passage is reestablishing these connections throughout the region enhancing access to significant amounts of river and lake habitat. Additionally, it will be important to increase scientific studies on species distribution and seasonal shifts and corresponding changes in predator-prey dynamics to better inform climate-ready fisheries management, in addition to developing habitat strategies to minimize the effects of climate change on key fisheries resources.

Watersheds and estuaries throughout the region were impacted by extensive land use and land cover changes, as well as direct manipulation of streams, that began with European settlement and continue to the present [128–130]. However, impacts varied considerably across the region according to variations in anthropogenic activities and differences in physiography and surficial geology [131, 132]. Emerging climate change impacts may amplify some past disturbances [106, 109]. Habitat restoration and increased river-ocean connectivity present opportunities to improve habitat and fish populations. Habitat-focused climate solutions offer powerful management tools to both resist past transformations and direct current and future change in these systems. Climate-informed assessments of habitat quality and restoration effectiveness are needed to leverage this management toolkit.

Progress has been made to advance regional watershed science through continued coordination across the region. Projects arising through these efforts include two noted in Section 6.2 associated with Atlantic salmon: a range-wide analysis of existing and projected habitat conditions for Atlantic salmon and baseflow mapping across Maine watersheds [104]. Synthesis work on diadromous fish communities and ecosystem interactions of these twelve species was also completed [120]. It describes the structure and function of diadromous fish communities in freshwater ecosystems, synthesizes species ecosystem roles and interactions in the U. S. NES, and discusses changing environmental conditions in rivers, estuaries, and the coastal ocean. Additionally, the NEFSC continues to monitor phenology changes in Atlantic salmon to better understand climate impacts and drivers on this protected species.

The CBO funds research on assessing the drivers of climate-driven seasonal and distributional shifts of migratory species pertaining to their estuary and river habitat use in Chesapeake Bay, given the economic and ecological importance of species like summer flounder to the region. A recently CBO-funded study [133] demonstrated that summer flounder, Atlantic croaker (*Micropogonias undulatus*), spot (*Leiostomus xanthurus*), weakfish (*Cynoscion regalis*), and clearnose skate (*Raja eglanteria*) had significant decreases in the usage of Chesapeake Bay relative to the coastal ocean over time (2008–2019). The North Atlantic Oscillation, resulting in indirect temperature increases, was determined to be an important driver of the altered estuarine habitat use [133]. With increasing air, and consequently, water temperature trends in Chesapeake Bay [134, 135] and the need to better prepare for resulting shifts in recreational and commercial fisheries, the CBO led the development of near-term actionable recommendations for tidal fisheries and habitats in coordination with fisheries managers and other partners as part of the Chesapeake Bay Program's Rising Water Temperature Scientific Technical Advisory Committee (STAC) Workshop [136]. Recommendations ranged from accelerating shoreline restoration using nature-based infrastructure (e.g., living shorelines) in lieu of hardened shorelines where the placement of these projects enhances both ecological (e.g., fish habitat) and climate resilience (e.g., shoreline protection) benefits to developing a public-facing marine heat wave warning system that builds in habitat preferences of key fish species and notifies users of stressful conditions. Additional recommendations included exploring assessments for emerging prevalent fisheries from the south, such as red drum (*Sciaenops ocellatus*) and cobia (*Rachycentron canadum*), to facilitate management considerations as climate change creates conditions for these fisheries to be economically viable. Seasonal shifts in forage species, such as bay anchovy (*Anchoa mitchilli*), are also of concern in the Chesapeake Bay in relation to food availability for key predator species, such as striped bass. The CBO provided technical guidance on a forage-related project through the Chesapeake Bay Program's Sustainable Fisheries Goal Implementation Team funded by the Chesapeake Bay Trust. For this project, recommendations were developed for climate-based forage indicators related to the Atlantic Multidecadal Oscillation (index of sea surface temperature) and water temperature defined by a 5 degree Celsius degree day temperature threshold for bay anchovy and polychaetes [137]. Such indicators can be used to track and potentially forecast climate-based environmental and seasonal changes and subsequent influences on forage abundance.

7.12 Key needs

Although we know that watershed conditions and processes have changed since European settlement, we lack a detailed understanding of the extent to which such changes have substantially affected stream forms and processes and thus aquatic habitat conditions. Understanding the degree to which local stream habitats have changed is important for understanding, and planning for, potential changes associated with changing climate. Unfortunately, in the absence of detailed sub-regional studies, managers and habitat restoration practitioners may assume that the same anthropogenic activities that produced impacts in one part of the region, or another region altogether, will produce the same impacts in their geography of interest. However, local conditions like relief and surficial geology can strongly influence landscape sensitivity to disturbance. For example, Johnson et al. (2019) recently showed how the response of stream channels and valley bottoms to watershed land cover change and hydropower development in New England, a glaciated part of the northeast [132], was notably different than changes attributed to the same stressors in part of the unglaciated Mid-Atlantic [130].

Eastern Maine watersheds used as habitat by endangered Atlantic salmon are an area of the Northeast where a detailed study of how, and to what extent, stream channels, riparian corridors, and valley bottoms were altered over the historical period. Many managers and restoration practitioners believe the stream channels there were altered by historical logging activities. This hypothesis is supported by low wood volume and smaller tree size in young forests supporting an ongoing legacy of historic timber harvest and land clearing impacts [138]. Several ongoing efforts implement restoration actions in response to those changes. However, there is also evidence that channel forms and processes observed today in one of the region's rivers are consistent with the glaciated landscape [139]. A stronger understanding of eastern Maine stream morphology over the historical period is needed to reconcile shifting baselines; inform ongoing management and restoration practices: and better plan for future climate conditions in these watersheds.

To improve our understanding of how changing climate will impact northeast U.S. watersheds, we also need to expand stream temperature monitoring networks and investigate how documented changes in hydrology over recent decades have influenced stream channel forms and processes. Increasing the geographic extent over which we monitor stream temperature, while also expanding the temporal coverage throughout the year and through time, we will have a better understanding of modern thermal habitat conditions and improved calibration of stream temperature models for predicting future stream temperatures. Understanding how stream channels, and thus habitat conditions, have changed in response to climatic changes in river floods in recent decades [140, 141] will help us understand how stream habitat may continue to change with future changes in channel-forming flows.

Several science and research needs were identified to better assess and prepare for changes in fisheries and to support resilience strategies for fish habitat in the Chesapeake Bay watershed and estuary. Among these needs are improved monitoring and research on changing environmental conditions in connection with short-term and long-term living resource response to better inform ecosystem-based fisheries management. The NOAA Chesapeake Bay Office (CBO) has worked closely with the U.S. Environmental Protection Agency and other partners to secure funding for monitoring programs and has supported fisheries science research since the 1990's. The most recent competitive funding opportunity from the CBO had a priority to address climate change questions and was successful in soliciting several proposals to meet the need. However, additional, and sustained resources are required to improve our understanding of climate change impacts to fisheries and their habitats.

The CBO has moved forward with implementing 10 new dissolved oxygen and temperature sensor arrays by 2025 to provide continuous monitoring at various depths of the water column within ten minute intervals. Three of these arrays have been deployed at key water quality and living resource sites in the Chesapeake Bay. Simultaneously, CBO has established a telemetry array to track fish movements relative to environmental conditions and assess changes in fish distribution and habitat use within the estuary and along the coast. As new studies show declines in suitable habitat for species such as summer flounder due to increasing water temperatures, there is a need to integrate improved data streams in fish habitat suitability models [142, 143] and develop near real-time forecasting capabilities on the effects of changing environmental conditions for economically and ecologically important fisheries (e.g., striped bass, blue crab, eastern oyster, summer flounder, bay anchovy, menhaden). There is also a need to track potential new fisheries as southern species (e.g., white shrimp, red drum, cobia) continue to shift further north.

For the nearshore habitats in the estuary, there is a need for more research on the siting and design of nature-based solutions and the combining of multiple habitat types, such as oyster reefs, seagrasses, and salt marshes, to enhance fish habitat resilience, while also providing other ecosystem (e.g., water quality) and community resilience (e.g., shoreline protection) benefits. For instance, *in situ* studies are needed to better understand the potential resilience benefits of incorporating both oysters and seagrasses in restoration efforts given that oysters can improve water clarity for seagrasses through their filtration capabilities [144] and seagrasses can balance carbon dioxide in the water to reduce ocean acidification effects on oysters [145]. These habitat types, when located appropriately to handle the wave energy environment, also provide shoreline and flood protection for nearby communities [146]. However, more research is needed in determining how best to construct these nature-based solutions and multi-habitat projects to maximize resilience, including the development of metrics to assess the success and effectiveness of these strategies. There is also a need to increase our understanding on how these habitat projects can provide thermal refugia for vulnerable fish species given the warming temperature trends in the Chesapeake Bay [134]. Additionally, hydrological and land-use modeling studies on watershed influences related to the warming of nearshore environments in the upper tidal tributaries and *in situ* data to assess cooling strategies (e.g., increasing stormwater infiltration, shading from forest buffers) are needed where there is important fish spawning habitat.

7.13 Offshore wind energy

As of April 2022, over 22.37 million acres of the U.S. NES have been designated by the Bureau of Ocean Energy Management (BOEM) as offshore wind leases, wind energy areas, or wind planning areas [147–149]. For the 2.349 million acres in leases that are expected to be developed by 2030 using fixed-bottom turbine technology in shallow waters (<60m), it is anticipated that over 3,411 turbine foundations will be constructed in New England and Mid-Atlantic region with over 5,466 miles of submarine export and inter-array cables connecting to shoreline offload centers. Deep water (>60 meters) offshore wind planning areas in the Mid-Atlantic (4.027 million acres) and the Gulf of Maine (14.8 million acres) will necessitate the use of floating offshore wind technology which has not yet been deployed commercially in marine waters in the U.S. [150]. Offshore wind development at the scale, magnitude, and pace proposed in the U.S. NES could have profound interactions with the marine ecosystem and NOAA trust resources.

The impacts of offshore wind development have been described in peer reviewed literature deriving from over two decades of offshore wind development data from the North Sea, recent development in Asia, and two pilot-scale projects in the U.S. Offshore wind development can have profound interactions with the marine ecosystem through the following diverse set of impact-producing effects: noise from surveys, construction, and operations [151]; socio-economic impacts on fishing communities from fisheries displacement and increased stock assessment uncertainty [152]; energy emissions from electro-magnetic fields of submarine cables [153]; habitat effects from benthic and pelagic habitat alteration and artificial reef effects from turbine and cable construction [154]; oceanographic disruption from wind and atmospheric wake effects [155, 156]; contaminant pollution from anti-corrosion measures [157]; and increased vessel activity and strike risk. Based on NEFSC data, many species in the U.S. NES will have high exposure to these stressors [158]. These effects can occur on the scale of meters (reef effects) to over 100's of kilometers (oceanographic wakes) [152]. They can also occur throughout the duration of the wind development life cycle from pre-construction geophysical and geotechnical surveys (1–3 years), construction (2–3 years), wind energy operations (30+ years), to decommissioning (2–3 years) [152]. Despite some experience in Europe, many of these impacts are not well understood beyond the scale of an individual turbine or project and there is significant uncertainty of how these effects interact with different species, habitats, and the oceanography of the U.S. NES. Furthermore, the cumulative impacts of multiple offshore wind projects have the potential to influence living marine resource population distribution, abundance, and vital rates in yet uncertain ways.

In addition to the potential changes in the marine ecosystem, offshore wind development may also disrupt NOAA's long-term scientific surveys that support NMFS living marine resource management mandates and serve as the basis for scientific assessments, advice, and analyses [159]. The environmental review associated with the first offshore wind energy project in Federal waters evaluated the impacts of wind development on NMFS scientific surveys and concluded that project-level and cumulative impacts of future wind development would have major adverse impacts on NMFS scientific surveys [147]. The four major impacts on scientific surveys from offshore wind development that have been described include: 1) preclusion of NOAA Fisheries sampling platforms from wind development areas due to operational and safety limitations; 2) impacts on the statistical design of surveys, including random-stratified, fixed station, transit, opportunistic, and other designs; 3) alteration of benthic and pelagic habitats, and airspace in and around wind energy development, requiring new compatible designs and methods to sample modified habitats; and 4) reduced sampling productivity through navigation impacts of wind energy infrastructure on aerial and vessel surveys [159]. As previously described, impacts on the timeliness, accuracy, and precision of NOAA fisheries scientific surveys to support management can result in increased uncertainty in the scientific and management decision-making process, e.g., conservation measures that are applied through fishery management council risk-management policies. This uncertainty in population or stock health can result in direct and indirect harm to fisheries and protected species populations, resource management agencies, fishing communities, other ocean users, and the American public. NOAA and BOEM are working to address unavoidable impacts to NOAA Fisheries' scientific mission by developing a national Federal survey mitigation implementation plan and future regional survey mitigation programs to address the interactions of offshore wind with NOAA Fisheries surveys [159].

7.14 Key needs

To effectively advance offshore wind development to meet the U.S. government's goal of developing 30 gigawatts of offshore wind energy by 2030, NOAA Fisheries will need to focus research and scientific efforts to address the interactions of offshore wind energy development on NOAA trust resources. There are five major areas of effort to meet this need: 1) scientific support, data analysis, and technical reviews to support the regulatory process and ensure that the best available scientific information can be considered at the planning and development stages—including applying principles and tools of ecosystem based management to offshore wind development planning; 2) design and implement fundamental research to gain understanding of the interactions of offshore wind development on the marine ecosystem and particularly on fishing communities and NOAA trust resources, such as North Atlantic right whales; 3) mitigate the impacts of offshore wind development on NOAA Fisheries surveys and data collections by implementing a northeast region survey mitigation program; 4) advance the science of mitigation where impacts to NOAA trust resources cannot be avoided, including advancing inclusive, transparent, equitable, and science-based approaches to fishing community compensatory mitigation; and 5) collaborate with NOAA partners to identify and advance scientific policy and regulatory solutions needed to ensure the sustainable development of offshore wind energy while promoting ocean co-uses and marine conservation.

The scaled development of offshore wind in the U.S. NES may be an important step in addressing the impacts of climate change. But, like any other emerging natural resource industry, the interactions of wind energy with marine resources and important ecosystem services (such as food provisioning) need to be considered and addressed up front to avoid ecosystem-scale and costly unintended consequences. To that end, NOAA has identified several key scientific actions that can be implemented to enable sustainable offshore wind development. The following scientific recommendations would benefit the effective identification of wind development areas to avoid user and resource conflicts and provide greater predictability in our ability to achieve climate mitigation goals: 1) design and apply ecosystem-based management and marine spatial planning approaches to considering wind energy development in the U.S. NES wind planning areas; 2) research and test performance of pre-commercial scale floating wind technologies prior to full-scale deployment; 3) establish and implement a Federal survey mitigation program in order to begin adapting scientific surveys and scientific observation systems in advance of construction; 4) establish and begin collecting region-wide baseline ecosystem monitoring in offshore wind areas following standardized and consistent methods; 5) establish standardized pre-construction, construction, and post construction fisheries and wildlife monitoring requirements across all projects; and 6) establish standardized regionally-specific requirements for mitigating unavoidable impacts of offshore wind development on the marine environment and fishing communities.

It is critical to evaluate where, when, and how fishing occurs (through NEFSC-developed fishing footprints) to assess economic impacts on fishing operations from other ocean uses, including offshore wind development. Existing fishing footprints are built from fishermen's Vessel Trip Reports (VTRs) because they are inclusive of regional fishing operations. However, VTRs often represent entire trips with a single location, not the full spatial extent of trips. Additionally, not all fisheries on the U.S. NES use VTRs to report their fishing activity and are therefore underrepresented in certain analyses (e.g., Highly Migratory Species, American lobster, charter/party vessels, etc.). Therefore, Allen-Jacobson et al. (2023) evaluated bias in VTR footprints using finer scale data collected by the Northeast Fisheries Science Center's Study Fleet's global positioning system (GPS) location data (ping/minute) annotated as active fishing or not fishing [160]. This research demonstrates how high-resolution fishery dependent data are needed to detect spatially explicit differences in fishing behavior, and their overlap with planned wind energy areas. Informed decisions depend on pre-construction data, so these incentives are time sensitive and should be prioritized.

8. Summary

Achieving climate-ready living marine resource management is a very challenging task for all nations across the globe that rely on marine resources. This is because many of the marine ecosystem changes observed today are unprecedented and thus there is no long-term historical context of management challenges and solutions under a rapidly changing climate. Our review of key research and needs for the proposed process of climate-informed living marine resource management of NOAA Fisheries in the northeast U.S. may help other regions and nations understand and overcome their own challenges.

High-resolution ocean observations, both spatially and temporally, should be the ideal foundation of any science organization or government agency that is tasked with providing the best available science to inform living marine resource management. However, even regions such as the northeast U.S. that are highly sampled relative to other regions still do not have enough ocean observations to keep up with the pace of marine ecosystem change. One solution to fill in these data gaps is to develop and assess high-resolution regional ocean model hindcasts that include biogeochemistry, which are one of the primary products developed by NOAA's CEFI. Critical data gaps in key ocean time series data such as ocean temperature, chlorophyll, and primary/secondary productivity can be filled in with skillful model output and thus help identify climate associations and possibly mechanistic underpinnings between ocean change and living marine resources. Identifying historical and contemporary climate associations is a first step before assessing future change. NOAA's CEFI is also developing regional ocean model forecasts and projections that can be used to inform management of predicted future change. Forecasts can inform annual fishery catch advice or protected species tactical management while projections can inform longer term management plans and fishery rebuilding plans. Marine ecosystem forecasts can be used much like weather forecasts and can thus benefit a wide range of stakeholders including fishery management councils, business and insurance sectors, coastal and fishing communities, and other blue economy information users [161].

In addition to observations and ocean models, we have discussed other critical elements that are part of our proposed process of informing living marine resource management with climate information (Fig 3). These are process-based laboratory and field studies, climate-informed stock assessments and ecosystem models, marine spatial management, climate-vulnerability assessments and scenario planning, ecosystem-based management, management strategy evaluations, and multidisciplinary science that includes economic and social indicators. Offshore wind development in the region presents new challenges that will need to be addressed while continuing efforts to advance climate-ready living marine resource management in the region. The proposed process described in Fig 3 and S1 Fig is based on the existing scientific and management framework in the northeast U.S., which may not be the same in other regions of the U.S. or in other nations around the globe. We recognize these differences and acknowledge that marine ecosystems are changing at different rates from region to region. Therefore, region specific plans to advance climate-ready living marine resource management will be needed and we hope that our proposed process can serve as a general guide.

Supporting information

S1 Fig. Process of informing living marine resource management with climate information in the northeast U.S. This is an alternate version of Fig 3. Here we outline and illustrate the process of informing living marine resource management and stakeholders with climate information in the northeast U.S. (Fig 1 and S1 Fig) that has more detailed information for each step of the process.
(TIF)

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