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Climate Science Strategy of the US National Marine Fisheries Service

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Abstract

Changes to our climate and oceans are already affecting living marine resources (LMRs) and the people, businesses, and economies that depend on them. As a result, the U.S. National Marine Fisheries Service (NMFS) has developed a Climate Science Strategy (CSS) to increase the production and use of the climate-related information necessary to fulfill its LMR stewardship mission for fisheries management and protected species conservation. The CSS establishes seven objectives: (1) determine appropriate, climate-informed reference points; (2) identify robust strategies for managing LMRs under changing climate conditions; (3) design decision processes that are robust to climate-change scenarios; (4) predict future states of ecosystems, LMRs, and LMR-dependent human communities; (5) determine the mechanisms of climate-change related effects on ecosystems, LMRs, and LMR-dependent human communities; (6) track trends in ecosystems, LMRs, and LMR-dependent human communities and provide early warning of change; and (7) build and maintain the science infrastructure required to fulfill NMFS mandates under changing climate conditions. These objectives provide a nationally consistent approach to addressing climate-LMR science needs that supports informed decision-making and effective implementation of the NMFS legislative mandates in each region. Near term actions that will address all objectives include: 1) conducting climate vulnerability analyses in each region for all LMRs; 2) establishing and strengthening ecosystem indicators and status reports in all regions; and 3) developing a capacity to conduct management strategy evaluations of climate-related impacts on management targets, priorities, and goals.

Implementation of the Strategy over the next few years and beyond is critical for effective fulfillment of the NMFS mission and mandates in a changing climate.

Graphical Abstract.

Key words
Adaptation; Climate policy; Ecosystem-based management; Fisheries management; Living marine resources; Marine conservation

1. Introduction

The climate and oceans are changing, and these changes are already affecting the nation's marine, estuarine, and diadromous living resources. Stewardship of these resources, hereafter termed living marine resources or LMRs, is the responsibility of the National Marine Fisheries Service (NMFS) and includes the management, conservation, and protection of LMRs while providing benefit to the nation through their sustainable use (e.g., food, materials, protection, etc.). Changes in the climate system (including ocean acidification and other alterations of aquatic systems related to increases in atmospheric CO_2 and hereafter referred to as climate change) affect the services LMRs provide and the many people, businesses, and communities that depend on them [1-3]. These varied impacts will also affect the NMFS LMR conservation and management efforts and LMR-dependent sectors at local, state, regional, national, and international levels.

Understanding, preparing for, and responding to climate impacts on LMRs can help decision makers reduce impacts, increase resilience, and advance adaptive[3] capacity of LMRs and LMR-

[3] The words "adapt," "adaptive," and "adaptation" are commonly used in the climate change literature to refer both to wild species/populations and to human institutions. When these terms are used in this document to refer to LMRs, they refer to the biological process of adaptation, which involves genetic change over time in a direction that improves fitness. Previous evolutionary changes largely determine a species' current adaptive capacity, but new adaptations might be required to maintain fitness in the face of climate change. When these terms are used to refer to changes by humans, they relate to the concept of adaptive management, which describes flexible management and decision-making procedures that are

dependent human communities [1, 3, 4]. Meeting this need requires increasing the production and use of science-based, climate-related information in nearly all aspects of LMR stewardship. Doing so is critical to fulfilling the NMFS stewardship mission to sustainably conserve and manage LMRs and their ecosystems for the benefit of the nation. To this end, NMFS has developed a Climate Science Strategy (hereafter referred to as the Strategy) to identify key steps to inform and fulfill the NMFS mission in a changing climate [5] and address the calls in the recent NOAA Strategic Plan and the 2013 Presidential Climate Action Plan for readiness to climate change [6, 7]. Here we provide a short description of the Strategy, the rationale for it, and some first steps for its implementation.

1.1 Impacts of a Changing Climate on Marine and Coastal Ecosystems

The impacts of both climate variability and change (Fig 1) on the physical, chemical, biological, and social components of marine, coastal, and freshwater ecosystems are well documented and expected to increase [Fig 2; 1, 2, 4, 8, 9]. Climate-related changes in physical and chemical conditions can have a variety of impacts on LMRs, ecosystems, and LMR-dependent human communities across a range of spatial and temporal scales [1, 10]. Assuming the effects of climate change will be uniform and consistent across species and ecosystems is inconsistent with our scientific understanding and, thus, imprudent. Studies suggest that changes in regional environmental conditions may enhance conditions for some species in that region while degrading conditions for other species, the latter being particularly important for species and stocks protected by the Endangered Species Act or Marine Mammal Protection Act or managed by the Magnuson-Stevens Fishery Conservation and Management Act [e.g., 11, 12, 13]. Furthermore, some wide-ranging species may experience positive effects of climate change in one habitat during one life stage and negative effects in another distantly located habitat during another life stage. Shifting distributions may result in gaps in management regulations; for example, most stock area definitions developed under Fishery Management Plans assume

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designed to be able to incorporate new information and make changes that will maximize the chances of achieving stated goals or objectives.

stock boundaries do not shift, yet it is clear that one of the major impacts of changing ocean conditions on LMRs is the shifting of stock boundaries [14].

Because climate change impacts will affect LMR species in different ways, there is an urgent need for careful evaluation of climate impacts in the design, implementation, and evaluation of LMR management. Changes in species abundance, productivity, distribution, and diversity due to a changing environment may require changes to the fundamental thresholds and metrics used in LMR management (e.g., biological reference points [15, 16]). Information on what is changing and why it is changing can be used to improve early warnings, near-term forecasts, and longer-term projections of future conditions. This improved information can inform science priorities, vulnerability assessments, management strategy evaluations, and, ultimately, management decisions.

The combined physical, chemical, and biological effects of climate change on LMRs will alter the products and services people derive from marine ecosystems, including food, jobs, recreation, medicinal products, aesthetics, tourism, regional culture and sense of place, and even health benefits [17]. For example, the species available for harvest in a given region could change, requiring fishermen to develop new strategies for harvesting (e.g., switching their target species and gear types) and bycatch reduction [18]. Shifts in the distribution and/or abundance of species may also affect the location of fishing industries, working waterfronts, supply chains, and the social and economic dynamics of LMR-dependent coastal communities, cultures, and industries [9, 19, 20]. Changes in the availability of commercial fish species and fishing methods will likely pose challenges for shore-side support services from ports to processing plants, which will also be significantly influenced by climate-related factors such as sea level rise, coastal storms, and inundation. Likewise, shifts in aquaculture practices may be needed, including rethinking what species may be best suited to meet societal demands under changing climate and ocean conditions [21].

Non-climatic stressors, such as pollution, fishing, bycatch, and changes in human use of natural systems (e.g., rapid increase in human use of the Arctic), will influence the response of LMRs to climate change. In many circumstances, mitigating stressors under local or regional control (e.g., fisheries management, pollution) may help increase the persistence of species that are sensitive to climate change or to the interaction of climate change with non-climate stressors.

1.2 NMFS Stewardship Mandates

NMFS' primary legislative mandates include the Magnuson-Stevens Fishery Conservation and Management Act, Fish and Wildlife Coordination Act, Endangered Species Act, Marine Mammal Protection Act, National Aquaculture Act, Coral Reef Conservation Act, National Resource Damage Assessment, Federal Power Act, Clean Water Act, and National Environmental Protection Act (Table 1). Under the Magnuson-Stevens Fishery Conservation and Management Act, NMFS assesses and predicts the past, current, and future status of fishery stocks and harvest rates; evaluates the implications of proposed catch on the sustainability of marine resources; and identifies, protects, and restores essential fish habitat. This information is used to maintain, conserve, and rebuild fishery resources. A primary objective of the Magnuson-Stevens Fishery Conservation and Management Act is to use the best scientific information available to optimize yield on a continuing basis. The Marine Mammal Protection Act directs NMFS to assess marine mammal stocks, reduce fisheries bycatch of marine mammals, protect key habitats, and conduct stranding response and other activities. This includes the estimation of abundance, distribution, and mortality. Under the Endangered Species Act, NMFS works to identify and restore threatened and endangered species, including marine mammals, sea turtles, marine and anadromous fish, marine invertebrates, and marine plants, and their critical habitat. Under the National Aquaculture Act, NMFS provides for the development of aquaculture in the U.S. Under the National Environmental Protection Act, NMFS evaluates environmental and socio-economic impacts of all federally permitted activities. This places particular emphasis on the evaluation of cumulative impacts to LMRs and their habitats, connections, and ecosystems. Under the Fish and Wildlife Coordination Act as well as the Clean

Water Act, Rivers and Harbors Act, and Water Resources Reform Development Act, NMFS consults with other federal agencies providing habitat conservation recommendations on their proposed actions, such as issuing permits for discharges to waterways or coastal infrastructure projects that could affect fish habitats. Under the Federal Power Act, NMFS prescribes fish passage requirements for non-federal hydropower project licenses that last for 30 to 50 years. In designing management approaches to meet the LMR objectives listed above, NMFS is required under many of the mandates (and others) to consider how these decisions may affect human systems, including coastal communities and economic and social impacts. Fulfilling these mandates requires a range of science-based information and services which serves as the foundation for management action, and up-to-date science is essential for effective LMR management.

NMFS's responsibilities under many mandates include a set of common science activities such as documenting, assessing, and projecting past, present, and future abundance, distribution, production, mortality, and utilization of LMRs and their habitats. This sequence can be briefly described as: providing observation and experimental data, modeling and synthesizing data, reviewing model outputs, and providing management advice typically in the form of reference points (Fig 3). With changing climate and LMR conditions, there are a variety of increasing information needs to inform and fulfill NMFS LMR stewardship mandates [3]. Meeting these changing science requirements will be challenging given the scale and scope of the NMFS mission and expected climate-related impacts in marine, coastal, and freshwater ecosystems. For example, NMFS is responsible for providing a range of science-based assessments and management advice for the stewardship of more than 473 regulated stocks/stock complexes, 93 threatened or endangered species, and 117 marine mammal species.

Without adequately incorporating climate change, NMFS's conservation and management efforts are likely to be ineffective, produce negative results, or fail to realize potential opportunities. Any of these could have a variety of environmental, social, economic, cultural, and legal consequences. For example, the commercial and recreational fishing industry is important to the U.S. economy (generating $214 billion in sales across the broader economy in 2014) and to social systems (supporting 1.83 million fisheries-related jobs) [22]. Furthermore, subsistence and personal-use fisheries are vital to families and households across the U.S. Although the value of these services is challenging to quantify, they are vital natural capital and impossible to fully replace [17]. Given the pace and scope of expected climate impacts on marine, coastal, and freshwater ecosystems, the ability to understand, plan for, and respond to climate impacts on the nation's valuable LMRs and the people that depend on them is fundamental to fulfilling NMFS mandates in a changing climate.

1.3 The Need for a NMFS Climate Science Strategy

As evidence of climate-related impacts to LMRs continues to mount, the demand among LMR managers and other stakeholders for more information related to climate change is increasingly great. Increasing the production and use of climate-related information in the LMR advisory and regulatory documents produced each year in fulfilling NMFS stewardship responsibilities presents a significant challenge. Many other sectors (e.g., defense, transportation, land management, water management, public health, etc.) are acting to better understand and respond to climate impacts. This includes other natural resource management agencies, such as the U.S. Forest Service [23], U.S. Fish and Wildlife Service [24], National Park Service [25, 26], U.S. Department of Agriculture [27], U.S. Geological Survey [28], and U.S. Army Corps of Engineers [29]. Similar to other federal agencies, NMFS is working towards significantly extending its use of climate-related information in its decision-making and management advice and providing new types of information products, new tools, and new advice to managers, policymakers, and stakeholders [e.g., 30].

2.0 Climate Science Strategy

To meet its LMR stewardship mission in a changing climate, NMFS needs to better understand how ocean conditions will change, marine organisms and ecosystems will respond, and these responses will impact LMRs and their associated human uses. NMFS also needs information to design and implement management approaches that are robust to the uncertainties of changing marine, coastal, and freshwater ecosystems. These needs were the impetus for the development of the NMFS Climate Science Strategy. Four guiding principles shaped the development and emphasis of this Strategy:

- Common information needs exist across all NMFS major conservation mandates.
- The science-to-management process is relatively consistent across mandates, making advances in climate-related science and information applicable across multiple mandates.
- Ecosystem-based management is considered the most effective approach to achieve the desired objectives of all the respective mandates dealing with LMRs simultaneously.
- Common, climate-related tools and information can efficiently and effectively inform all of the NMFS mandates.

The Strategy is designed as a national blueprint that can provide tangible solutions to a variety of common needs, while providing a consistent framework to help address the more unique science and information needs of each mandate and region. It identifies seven objectives that need to be addressed to ensure effective LMR management in a changing climate. Posed as questions, the Strategy addresses:

1. How can climate-related effects be incorporated into management-related LMR reference points?
2. What are robust LMR management strategies in the face of climate change?
3. How can climate-related effects be addressed by adaptive LMR management processes?
4. How will the diversity, abundance, and distribution of LMRs and marine, coastal, and freshwater ecosystems change in the future, and how will these changes affect LMR-dependent human communities?
5. How and why does climate change alter ecosystems, LMRs, and LMR-dependent human communities?
6. What are the observed trends in climate, marine ecosystems, and LMRs?
7. What infrastructure is needed to produce and deliver climate science information?

From these questions, NMFS identified seven objectives for the Strategy (Fig 4). In general terms, these objectives are consistent with efforts in other sectors [18, 23-28], but here are tailored specifically for advancing climate-ready LMR management. The objectives were derived from known management needs, generalizing across mandates, identifying analytical products and the science enterprise to support those management needs, and finally noting the infrastructure needed to support that science. Each objective supports the objectives above it creating the interdependent set of science objectives shown in Fig 4. This nested and interdependent science foundation is the core of this Strategy, and critical to fulfilling the information required to meet NMFS mandates.

2.1 Objective 1: Identify appropriate, climate-informed reference points for managing LMRs.

Biological reference points are the thresholds upon which LMR management decisions are made, and, depending on their intended use, can be used to set limits or targets [15]. Development of biological reference points is a primary objective for much of the science conducted by NMFS to meet its mandates. Be they single-species measures of maximum sustainable yield, thresholds for habitat designations, potential biological removal of marine mammals, multi-species fishing rates, or a host of ecosystem indicators (Table 1), these reference points are used as limits or decision criteria to guide sustainable management of LMRs and their supporting habitats and ecosystems. Reference points are typically developed via modeling exercises that synthesize a broad suite of observational and experimental information and are peer reviewed. Strengthening NMFS' ability to incorporate consideration of climate change into the steps that lead to providing reference points is critical. As stocks, protected species, habitats, aquaculture, and ecosystems are expected to respond to climate change, the reference points for these species, systems, and human uses will need to change to reflect those different conditions. Ongoing scrutiny of reference points has already indicated the need to bolster climate-related information in the development of this management advice [31].

Most current assessments (e.g., stock assessment, ecosystem assessment, Endangered Species Act status assessment) and the reference points produced by them that are included in management plans assume that future natural variability will reflect the range of conditions observed in the past. Such reference points often do not account for the fact that ecosystems and the LMRs in them will change with the directional forcing of climate change (e.g., increase in water temperature, decrease in ocean pH). Therefore, stock assessments, biological reference points, and fisheries management plans based on these assessments may not adequately capture the future population dynamics in a changing ocean. In other situations, mandates allow managers to alter their reference points in response to changes in the environment, such as regime shifts. However, unlike regime shifts—for which estimates of past and current conditions exist—climate change is expected to create novel conditions not captured by past datasets, making identification of baseline conditions and reference points more difficult. In these circumstances, the key is to establish reference points that are robust to the shifting status of managed species [32] and associated ecosystems that support them.

Moving forward, LMR management plans (e.g., Fishery Management Plans, Fishery Ecosystem Plans, Species Recovery Plans) have a higher likelihood of conserving and sustaining LMRs if they explicitly include climate-related considerations in decision criteria. Avoiding misaligned management targets is more likely if these plans inform reference points with the best available climate-related science, including socio-economic analyses that show the consequences of neglecting climate change in biological reference points. Misaligned reference points may result in foregone revenue or missed opportunities (e.g., best times to harvest stock for commercial or subsistence take, opportunities for ecotourism) due to climate-induced changes in production, distribution, or other dynamics of LMRs that have been unaccounted for in the analysis.

2.2. Objective 2: Identify robust strategies for managing LMRs under changing climate conditions.

Identifying LMR management approaches and options that will remain biologically and socioeconomically sustainable in the face of climate-change is a critical need, as the best management decisions for LMRs today will not necessarily be the best management decisions in the future under climate change. To identify management strategies that are robust to future change, various ecosystem, socio-economic, and LMR models can be coupled with scenarios of climate change to test the performance of current and alternate management decisions under future conditions [13, 33-36]. These types of management strategy evaluations will assist in the design and evaluation of LMR management options and adaptive management strategies that are robust to a wide range of predicted future conditions.

Reports documenting management strategy evaluation efforts that cover the full range of climate, harvest, mitigation, conservation, and/or adaptation scenarios can help identify the most robust LMR management strategies. These reports should examine any documented changes to biological reference points across a range of scenarios, including a catalogue of associated LMR and socio-economic responses. Management strategy evaluation reports should also identify protection and mitigation measures, harvest control rules, and related management options that are compulsory to best manage across a suite of LMRs or ecosystems. Specific consideration should be given to fisheries prosecuted by fishermen and vessels that originate from multiple regions, and to changes in realized production or shifting distributions [e.g., multiple North Pacific fisheries are prosecuted by both West Coast and Alaska fishermen and vessels, and the best locations for harvest might shift in response to changing conditions; 37].

2.3 Objective 3: Design adaptive decision processes that can incorporate and respond to changing climate conditions.

The best practices used to examine, vet, and provide scientific advice to support management strategies and decisions can be as important as the management advice itself. Answering how climate-related effects can be incorporated into adaptive LMR management processes is a key question for NMFS. As depicted simply in Figure 3, the science and information delivery process for any of the main NMFS mandates (Table 1) follows a similar sequence: synthesize available data, review outputs, and provide information to determine the status of LMRs, habitats, or ecosystems. The resulting advice to managers provided at the end of the process is only as good as the weakest link in that process. If climate-related information is not included in this nexus between science advice and managers, decisions based on it may not result in sustainable management [e.g., 38, 39]. Numerous works have documented and evaluated management systems for LMRs and natural resources [e.g., 40, 41, 42]. We build on that work and note one key point: achieving sustainable management and conservation goals in the future will require incorporation of climate-related information into the management process.

Clearly an openness to incorporate considerations of climate-related information is an essential first step. Second, knowing where best to insert specific types of climate-related information is critical. Third, building adaptability into the management process is necessary to allow inclusion of new understanding related to climate change and the rates of environmental changes.

2.4 Objective 4: Identify future states of marine, coastal, and freshwater ecosystems, LMRs, and LMR-dependent human communities in a changing climate.

Forward-looking management of LMRs depends on robust projections of future ocean conditions and the likely responses of ecosystems, LMRs, and human communities on appropriate temporal and spatial scales. Such simulations are vital for development of management protocols that can adapt to climate change. However, linking changes in the physical-chemical system to responses of ecosystems, LMRs, and human communities is a major scientific challenge.

Projections need 1) regional and local down-scaling of global models to resolve biologically relevant local processes at appropriate management scales; 2) robust scenarios of climate change and its impacts on LMRs for use in management strategy evaluations; and 3) social and economic models for LMR-dependent human communities and economies. This list provides a sense of the magnitude, scope, and types of data-driven modeling efforts required to better project responses of marine ecosystems and LMRs under future conditions. These projections should focus on short, medium, and longer-term time-scales. The climate we experience is a combination of natural variability and long-term change (Fig 1). Natural variability occurs over short and medium term time-scales (seasons to a few decades) and is often indexed by the El Niño Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation, and other oscillations that have well documented effects on ocean fisheries and food-webs [43-45]. Projections at the 3 – 10 yr time scale are the most useful for LMR management, but have proven difficult and are not well represented in climate and ocean models, which presents both scientific and management challenges. Development of regional and national modeling teams with access to high performance computing would help NMFS tackle climate change-related modeling efforts in a coordinated and consistent way. These teams could be focused on climate change impacts to LMRs, ecosystems, and LMR-dependent human communities and on management of LMRs under climate change. Useful outputs of projections include identification of 'hotspots' (e.g., regions of high concentration of a LMR) that may help indicate how climate change will impact LMRs and the communities that depend on them and other indicators of climate change and climate change impacts on LMRs, ecosystems, and LMR-dependent human communities.

2.5 Objective 5: Identify the mechanisms of climate-change related effects on ecosystems, LMRs, and LMR-dependent human communities.

Process research, such as physiology studies conducted in laboratories and the field, is useful to elucidate the mechanisms underlying how and why species, ecosystems, habitats, and human systems are or may be affected by climate change. This knowledge is fundamental for identifying vulnerability to climate change and actions that may reduce climate impacts on LMRs. Process research enables an improved ability to develop robust projections of species, habitat, ecosystem, and human system change. Process research is the foundation for sound mitigation strategies, from those that avoid compromising species' adaptive capacity and resilience to those that improve aquaculture. Filling key gaps in the understanding of the underlying biogeochemical, physical, and physiological processes and interactions will improve NMFS science and management, including the models used to develop projections of the future and the design of observing systems. Climate change vulnerability assessments based on process research can help identify priorities for NMFS scientific and management efforts. In turn, opportunities for mitigation of vulnerabilities identified through these efforts may lead to increased resilience.

Laboratory and field investigations can be targeted to reduce uncertainty about species tolerance, response, and adaptive capacity to changing climate conditions and to the rate of change in environmental conditions. Laboratory experiments can also examine the direct effects of single climate factors, the direct combined effect of multiple climate factors, and the indirect effects of changing climate conditions on species interactions, energetics, and resilience. Field studies on the response of managed and ecologically important species to different environmental conditions can range from targeted, hypothesis-driven work to analysis of long-term survey data with relevant environmental parameters. Studies of ecological communities build knowledge on the functional role of biodiversity in maintaining ecosystem resilience. Ethnographic fieldwork and social science surveys can capture the processes that fishing-dependent communities use to respond and adapt to changing environmental conditions. Additionally, socio-economic analysis of LMR-user behavior over time can help explain historical patterns in resource use and how that use may change under future conditions.

Process research that is integrated at the level of the ecosystem links ocean dynamics, biodiversity, and trophic interactions with managed species and the human communities using LMRs. It provides a comprehensive understanding of species response to changing climate conditions. For example, it is not enough to simply understand the temperature preferences of a species if warming also affects the abundance or distribution of their prey, predators, and competitors. While these types of research are touched upon in some programs, creating the volume of research results commensurate with this aspect of the NMFS science mission and the mechanisms for integrating this knowledge into ecosystem-level understanding likely requires more capacity than currently exists in the NMFS.

2.6 Objective 6: Track trends in ecosystems, LMRs, and LMR-dependent human communities and provide early warning of change.

Information on the status and trends of marine, coastal, and freshwater ecosystems; LMRs; and LMR-dependent human communities is essential for tracking and providing early warning of the impacts of climate change. This information is the foundation of sound science advice and sustainable management of LMRs under changing conditions. NMFS has excelled at producing data-based assessments of LMR status and trends for science-based management. Some of these assessments explicitly incorporate climate change data [e.g., 46], but most do not [e.g., 47]. NMFS has three main needs related to this objective: 1) monitoring programs to track LMRs, ecosystem indicators, and LMR-dependent human communities, 2) development of appropriate ecosystem-wide indicators for tracking trends related to climate change and early warning signals of change, and 3) regular ecosystem status reports to present and interpret monitoring data while considering the effects of climate change.

Modifying management reference points for LMRs, ecosystems, and human systems to incorporate climate change and its impacts requires information on the status and trends of ecosystems, LMRs, and resource-dependent communities. Climate-change related biophysical data, such as observed trends in ocean temperature or food chain structure, need to be regularly incorporated into LMR, ecosystem, and habitat assessments. An important and regular product should be ecosystem status reports. Ecosystem status reports provide multi-dimensional examination of the ecosystem from physical and habitat condition to trends in LMR abundance and resource use by fleets and communities. Typically, they include brief narratives describing trends within the numerous time series analyses presented. The biological and physical indicators developed from ecosystem status reports can be used to establish future thresholds and decision criteria [48-50]. The information provided in these ecosystem status reports has also been useful for providing broader context and leading indicators to inform ecosystem-based LMR management. Adding climate change projections to these ecosystem status reports is an important need and will provide information about the projected future states of the ecosystem. The simple presentation of multivariate information in ecosystem status reports is critical in the production and delivery of climate change-related information for decision-making. One can readily envision compiling all of the regional ecosystem status reports to form a national report on climate-related LMR status, trends, and projections.

2.7 Objective 7: Build and maintain the science infrastructure required to fulfill NMFS mandates under changing climate conditions.

Adequate scientific infrastructure (e.g., ship time, laboratory facilities, personnel, research funding) is critical to the science enterprise described in this Strategy. However, NMFS' existing infrastructure is not yet adequate to meet all of these science needs. There is a general need for increased capacity to link climate change, ecosystems, and LMRs. Although NMFS supports a variety of biological, physical, and human system monitoring efforts that inform LMR and ecosystem-based management, these efforts fall short of what is needed to adequately track the impacts of a changing climate. Meeting present and future needs requires an enhanced system that inventories current observing efforts, identifies gaps in these efforts, fills gaps with new observations, makes data readily available to scientists and stakeholders, and allows integration across data types. Many of the advances made for the next generation of remote and unmanned sampling and ocean observation systems are or will be operational in the next few years. Taking advantage of the efficiencies and precision that these devices can provide will open up new data sets requisite for tracking climate change (e.g., gliders to measure physical and chemistry conditions, optical and acoustic monitoring of fish populations and habitats). Collecting the required information to track and assess changing ocean conditions requires a range of these evolving technologies and tools, but also the continued use of dedicated research vessels to provide the core integrated ecosystem observations.

Similarly, given the pace, scale, and complexity of climatic changes, NMFS's current capacity to conduct process-based research will not meet demands to understand how LMRs, ecosystems, aquaculture practices, and LMR-dependent human communities may respond to changing climate conditions. Developing this capacity will require significant investment in state-of-the-art experimental facilities for rearing organisms under expected future conditions, the equipment needed to conduct research in field settings, and the up-to-date laboratory facilities required to rapidly process samples (e.g., next-generation DNA sequencing). In addition, developing this capacity will require investment in primary data collection efforts aimed at documenting how LMR-dependent human communities are being affected by climate change, identification of future vulnerabilites, and adaptation strategies that communities have developed. Finally, research is needed to assist communities in identifying their potential vulnerabilities to climate change and develop new adaptation strategies. Strong partnerships with research institutions, other U.S. federal agencies (e.g., NSF, NASA, EPA, DOE, and other NOAA line offices; Table 2), state and tribal agencies, and international organizations are critical to addressing these needs.

Many of the observing systems and modeling exercises described above, especially future projections and reconstructions of past conditions, require computing systems that can store large data sets and are fast enough to compute scenarios in a reasonable amount of time. Expansion of computing systems and supporting database infrastructure is required to meet these needs. Improved data access and data visualization tools are also necessary for both understanding and communicating the complex climate-ecosystem interactions and fully sustaining and supporting the science enterprise outlined in the Strategy.

Development and provision of climate-savvy management advice are predicated upon a workforce with the capability to analytically address the needs described throughout this Strategy. NMFS has an excellent workforce, but additional analytical capabilities, quantitative training, and increased awareness of climate-change needs are required.

NMFS partners with many research institutions and agencies to collect data, conduct research, build models, and develop scenarios that are useful for projecting future states of LMRs, ecosystems, and human systems (Table 2). Building on and strengthening these collaborations are a critical component of developing an efficient and comprehensive capacity for understanding and predicting future states. Gaps in scope and capacity of the NMFS programs will necessarily need to be filled by expanding existing and establishing new partnerships with programs outside the agency.

3. Moving Forward

This Strategy provides a blueprint for strengthening the production and use of the climate-related information needed to fulfill NMFS mandates in a changing climate. It is intended to provide a national framework that will be regionally tailored and implemented by NMFS Science Centers, Regional Offices, and their partners via regional action plans (NMFS regions are the northeast, southeast (including the northern Gulf of Mexico and part of the Caribbean), southwest, northwest, Pacific Islands, and Alaska). While some impacts of climate change on LMRs are shared across regions, each region has a unique combination of climate-related challenges, capabilities, and information needs to be assessed as part of developing Strategy action plans. These Regional Action Plans (http://www.st.nmfs.noaa.gov/ecosystems/climate/rap/index) are being developed jointly by regional scientists, managers, and stakeholders to identify key actions and priorities to address each of the seven objectives that will be implemented in each region over the next few years.

Implementation of the Strategy over the next few years is critical for effective fulfillment of the NMFS mission and mandates in a changing climate. Three activities will help NMFS address its mandates in a more climate-ready manner in the near term:

- Conduct climate change vulnerability assessments in each region for each ecosystem and its associated LMRs and LMR-dependent human communities.
- Establish and strengthen ecosystem indicators and status reports in all regions.

- Develop capacity to conduct management strategy evaluations regarding climate change impacts on management targets, priorities, and goals.

Implementing these and other activities embodied within the Strategy requires a cross-cutting effort spanning NMFS' legislative mandates (Table 1), and supporting partnerships internal and external to NOAA (Table 2). Moreover, the Strategy strengthens the need for NMFS to adopt ecosystem-based management [51, 52].

Climate change and its impacts have occurred quickly, creating challenges that could overwhelm the capabilities of NMFS scientists and managers without a shift in strategic direction. This Strategy outlines a vision for how NMFS can meet the demands of managing LMRs in a changing climate. Given its mission as a steward of marine LMRs, NMFS will use the Strategy to modify its management and conservation activities to serve the nation far into the future.

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Figures

Figure 1. Natural variability in the climate system due to weather, seasons, and interannual processes (e.g., El Niño Southern Oscillation) is layered on top of directional trends due to climate change, creating the variable, but directionally shifting patterns, we observe in measurements of climate parameters.

Figure 2. General illustration of pathways (filled arrows) for impacts of climate variability and change on physical, chemical, biological, social, and economic components of marine, coastal, and freshwater ecosystems. General avenues are shown (open arrows) for reducing the impacts through human action to promote resilience and adaptation of LMRs.

Figure 3. A simplified, generic LMR management process. There are distinctions and caveats across all NMFS mandates, but this generalized version depicts the major steps required to produce management advice to fulfill NMFS mandates. A key point is that climate information can be inserted at each step in the process.

Figure 4. Seven priority objectives for the NMFS Climate Science Strategy. The ultimate goal is to provide management advice to meet NMFS mandated responsibilities, with each prior level required to support that and subsequent objectives.

Table 1. Key mandates areas for NMFS, with notes on authorities, objectives, thresholds, regulatory devices, and analytical frameworks. In general, fulfilling these NMFS mandates requires consideration of the impacts of climate and other environmental conditions on LMRs.

	NMFS Mandated Areas of Emphasis				
	Fisheries	Protected Species	Aquaculture	Habitat	Ecosystems

Primary Authorizing Mandates	Magnuson-Stevens Act	Endangered Species Act Marine Mammal Protection Act	National Aquaculture Act	Magnuson-Stevens Act Endangered Species Act Others*	National Environmental Policy Act National Ocean Policy Others**
Primary Objectives	Prevent overfishing, rebuild overfished stocks, realize full potential benefit to the nation	Conserve, protect, and recover protected marine life and the ecosystems on which they depend	Provide for the development of aquaculture in the United States	Preserve, protect, develop, and where possible, restore or enhance habitat	Consider environmental and socio-economic impacts and evaluate cumulative effects when enacting policies and planning action
Primary Thresholds	Annual Catch Limits (and Targets) linked to Optimal Yield †	Minimum Viable Population linked to Extinction Risk†† Appreciable reduction in population viability†† Recovered Populations (Optimal, Sustainable, Viable) ††	Cost-benefit ratio linked to economic and ecological viability	Fractional Areas of Degraded Habitat (or loss of essential habitat features)	Integrative Ecosystem Indicator Thresholds linked to Pressures Cumulative Production
Main regulatory or management delivery devices to achieve objectives	Fishery Management Plans	Section 4 Listings Section 7 consultations, Section 10 take permits	Permitting of aquaculture farms	Restoration Plans Essential Fish Habitat Designation Section 7 consultations, Section 10 take permits	Environmental Impact Statements and Social Impact Assessments

	Rebuilding Plans	Conservation (Recovery) Plans	Site Reviews	Conservation (Recovery) Plans Site Reviews	Fishery Ecosystem Plans
Main analytical frameworks to develop thresholds	Stock Assessments	Stock Assessments (Status Reviews)	Feasibility Assessments	Habitat Assessments	Integrated Ecosystem Assessments

*e.g. Coastal Zone Management Act; Clean Water Act; Federal Power Act; Oil Pollution Act; Fish and Wildlife Coordination Act; Coastal Wetlands Planning, Protection, and Restoration Act; American Recovery and Reinvestment Act; Coral Reef Conservation Act

** Many individual Acts have included ecosystem considerations. The challenge is to simultaneously meet ecosystem objectives of each Act.

† proxied by biomass and fishing rate limits

†† or related

Table 2. Information collected by other entities that is useful for NMFS management of living marine resources under a changing climate.

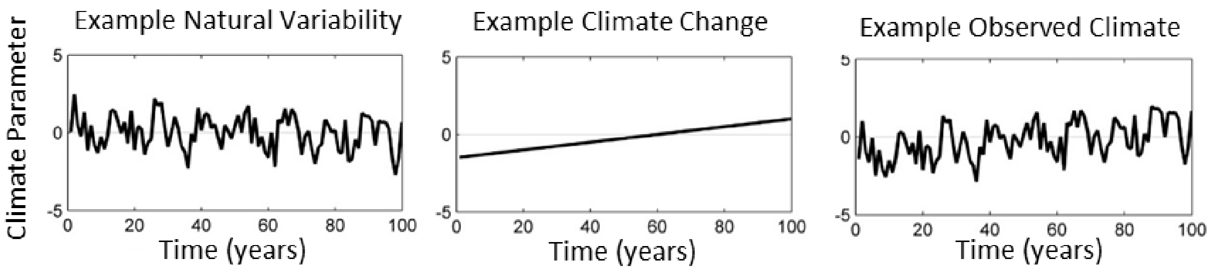
Entity	Information
NOAA	
Oceanic and Atmospheric Research	Physical and chemical ocean conditions Physical oceanographic models Coupled bio-physical models Climate monitoring and prediction
National Weather Service	Weather monitoring and prediction Storm monitoring and prediction
National Ocean Service	Shoreline monitoring Estuarine monitoring
National Environmental Satellite, Data, and Information Service	Ocean and coastal monitoring Sea ice monitoring Data management services
Integrated Ocean Observing System	Physical and chemical ocean conditions

Federal agencies	
National Aeronautics and Space Administration	Physical ocean monitoring Ocean productivity monitoring Ocean circulation monitoring
Environmental Protection Agency	Coastal monitoring
US Geological Survey	Stream monitoring
US Department of Agriculture	Food/seafood supply and demand
US Army Corps of Engineers	River monitoring
US Census Bureau	Demographics, employment, regional economic conditions
Industry	Fishing effort Bycatch information Aquaculture performance
Academia	Physical and chemical ocean conditions Species response to changing conditions Mechanistic studies Climate models Oceanographic models Ecosystem models Life-cycle models Social and economic models Management strategy evaluation
States	Coastal monitoring Data on state-managed fisheries
Tribes	Data on tribal-run fisheries Local traditional knowledge
Countries	Data on national fisheries Data on fisheries in international waters

Highlights

- Climate change is affecting marine ecosystems.
- Diversity, abundance, and distributions of living marine resources are changing.

- Strategies are needed to sustainably manage marine resources in a changing climate.
- This NMFS Climate Science Strategy will inform living marine resource management.
- It will guide integration of climate change science across all NMFS mandates.



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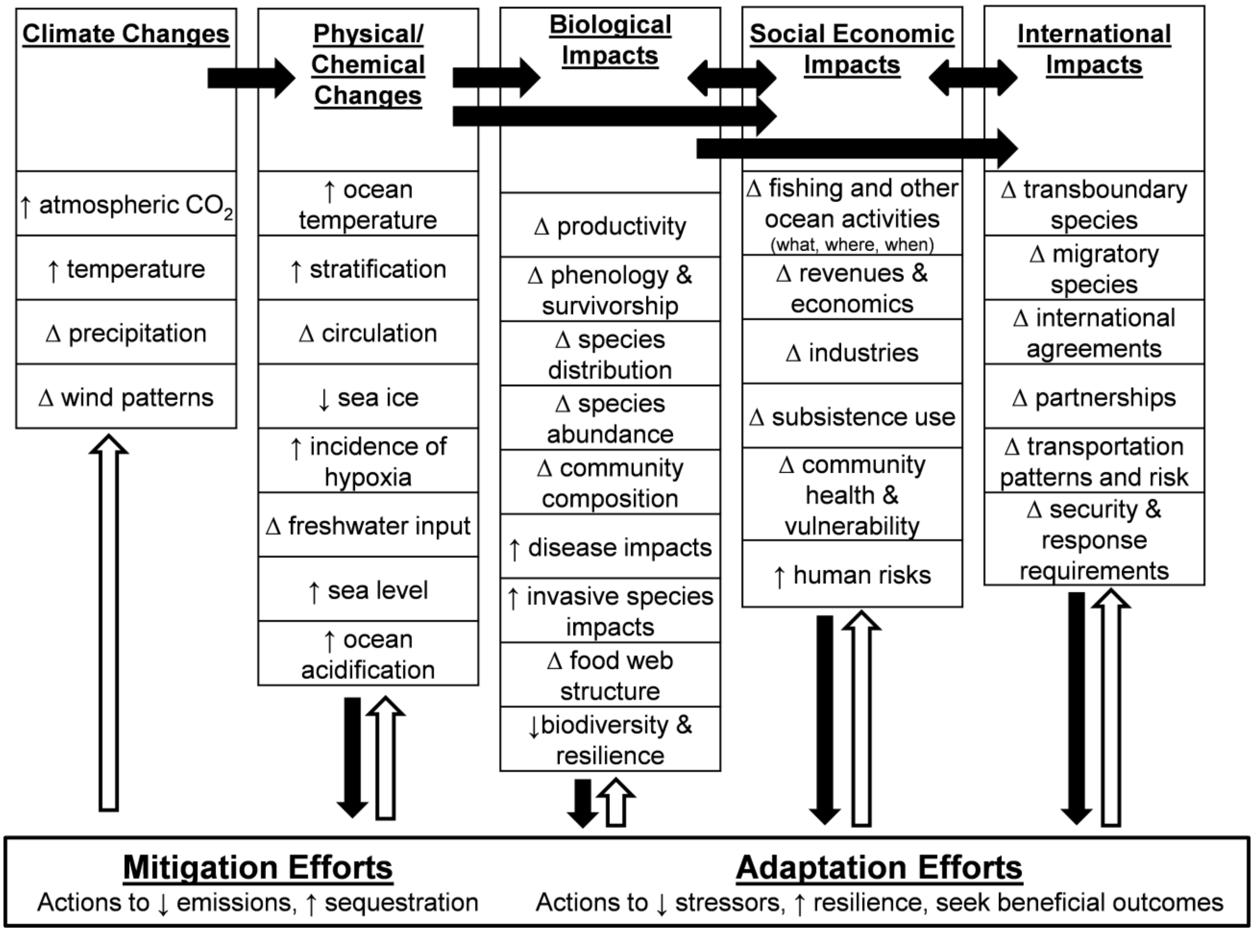

Busch et al., Figure 4