NOAA FISHERIES

DRAFT

CLIMATE SCIENCE STRATEGY

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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Objective 3: Design adaptive decision processes that can incorporate and respond to changing climate conditions.

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

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EXECUTIVE SUMMARY

The climate and oceans are changing. These changes are impacting the nation's living marine resources (LMRs), the services they provide, and the people, businesses, and economies that depend on them. These changes also impact the information and actions necessary to fulfill the National Marine Fisheries Service (NOAA Fisheries) LMR stewardship mission—to sustain LMRs and their environments for the benefit of the nation through science-based conservation and management. To fulfill this mission, NOAA Fisheries needs information on the impacts of changing conditions on LMRs, and the best approaches for sustaining LMRs and resource-dependent communities in a changing climate.

The goal of this Climate Science Strategy is to increase the production, delivery, and use of climate-related information to apprise and fulfill NOAA Fisheries' LMR stewardship mission. Although the information needed to understand, prepare for, and respond to climate change impacts on LMRs is diverse, this Strategy identifies common themes and priorities for action. The Strategy identifies seven key objectives to meet the science information requirements for fulfilling NOAA Fisheries' mandates in a changing climate.

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

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

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

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

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

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

Objective 7: Build and maintain the science infrastructure needed to fulfill NOAA Fisheries mandates under changing climate conditions.

The Strategy provides a nationally consistent path for regional efforts to address common climate-LMR science needs that support better informed decision-making and fulfillment of NOAA Fisheries' mandates. For each of the Objectives, the Strategy identifies specific actions to help achieve the Objective. The Strategy also identifies a set of priority recommendations that are common across mandates, regions, LMRs, and objectives that have high and immediate return on investment. The cross-cutting priority actions include:

1. Conduct climate vulnerability analyses in each region for all LMRs.
2. Establish and strengthen ecosystem indicators and status reports in all regions.
3. Develop capacity to conduct management strategy evaluations regarding climate change impacts on management targets, priorities, and goals.

The Strategy also identifies specific near- and medium-term recommendations to advance the seven objectives. The recommended near-term actions are grouped under the following categories:

1. Strengthen climate-related science capacity regionally and nationally.
2. Develop regional implementation plans to execute this Strategy, led by the regional Science Centers in coordination with the regional offices and other partners.
3. Ensure that adequate resources are dedicated to climate-related, process-oriented research.
4. Establish standard, climate-smart terms of reference to apply to all of NOAA Fisheries' LMR management, environmental compliance requirements, and other processes that cross multiple mandates and core policy areas.

This Strategy provides a nation-wide blueprint to help guide regional implementation plans tailored to address the specific issues, needs and priorities of each region. Implementation of the Strategy over the next 5 years is crucial for effective fulfillment of NOAA Fisheries' mission and mandates in a changing climate. Implementing these recommendations will efficiently and effectively increase the production, delivery, and use of climate-related information in NOAA Fisheries' LMR management, and thereby help reduce impacts and increase resilience of LMRs and the communities that depend on them.

LIST OF ACRONYMS

BRP – Biological Reference Point

EBM – Ecosystem-Based Management

ESA – Endangered Species Act

ESR – Ecosystem Status Report

FATE - Fisheries and the Environment

FMP – Fisheries Management Plan

FTE – Full-Time Employee

IEA – Integrated Ecosystem Assessment

LME – Large Marine Ecosystem

LMR – Living Marine Resource

MMPA – Marine Mammal Protection Act

MSE – Management Strategy Evaluation

MSA – Magnuson-Stevens Fishery Conservation and Management Act

NEPA – National Environmental Policy Act

NOAA Fisheries – National Marine Fisheries Service

NOAA - National Oceanic and Atmospheric Administration

CHAPTER 1

NOAA FISHERIES MISSION AND THE NEED FOR CLIMATE-RELATED SCIENCE

The climate and oceans are changing, and these changes are already affecting the nation's valuable marine, estuarine, and aquatic living resources (hereafter termed living marine resources or LMRs[1]). Changes in the climate system (including climatic changes and other impacts such as ocean acidification and alterations of aquatic systems; hereafter referred to as *climate change*) are affecting the services LMRs provide and the many people, businesses, and communities that depend on them (e.g., Osgood 2008; Doney et al. 2012; Melillo et al. 2014). Even at current concentrations of atmospheric greenhouse gases, these changes are affecting the products, services, uses, and benefits people derive from these ecosystems and are expected to continue affecting them for decades and centuries to come (Intergovernmental Panel on Climate Change 2013; Melillo et al. 2014). These impacts will affect NOAA's LMR management efforts and LMR-dependent sectors at a variety of levels: local, state, regional, national, and international.

Given the scale of U.S. dependence on LMRs and the scope and pace of climate-related change in marine, coastal, and freshwater ecosystems, immediate action is needed to better understand, prepare for, and respond to these changes in ways that reduce impacts and increase resilience of LMRs for current and future generations (Osgood 2008; Intergovernmental Panel on Climate Change 2013; Melillo et al. 2014). Meeting this need requires increased production, delivery, and use of science-based information related to climate change in nearly all aspects of LMR stewardship. Addressing these information needs is critical to fulfilling the NOAA National Marine Fisheries Service's (NOAA Fisheries) mission to sustain LMRs and their ecosystems for the benefit of the nation through science-based conservation and management.

The goal of this NOAA Fisheries Climate Science Strategy (hereafter referred to as the Strategy) is to identify key steps to inform and fulfill NOAA Fisheries' mission in a changing climate. It identifies seven objectives to increase the production, delivery, and use of climate-related information in fulfilling NOAA Fisheries stewardship mandates, and provides specific strategies to address them over the next 5 years.

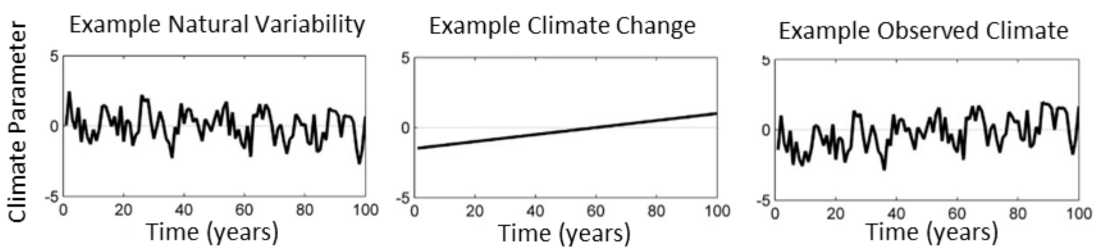
[1] Living marine resources are defined as species (and their habitats) under NOAA Fisheries' responsibility, including species that spend part of their life cycle in estuarine or freshwater, such as diadromous fishes.

The difference between natural variability and multi-decadal climate change

Natural variability is an inherent part of the Earth's climate system, and this variability acts over a range of time and space scales. At shorter time scales, this natural variability is termed weather: one day it is raining and the next day it is sunny. Seasonal natural variability occurs at the scales of months and is pronounced across temperate and boreal latitudes, where temperatures can vary by 10 to 50 ^{o}C and precipitation can vary from rain to snow. Climate also varies naturally on the inter-annual scale: one winter is mild and the next is harsh. Furthermore, there is natural climate variability at the scale of decades: El Niño Southern Oscillation (ENSO) represents multi-year variability in the surface temperature of the tropical eastern Pacific Ocean. ENSO variability has global effects; for example, it causes changes in rainfall patterns across parts of North America, Africa, and the Indian subcontinent. Other forms of inter-annual and decadal natural climate variability include the Pacific Decadal Oscillation, the North Pacific Gyre Oscillation, and the North Atlantic Oscillation, each with known basin-scale effects on weather, pelagic food webs, and fisheries.

All of these forms of natural variability in the Earth's climate system act simultaneously and in association with ongoing climate change, which is defined as a long-term change in the climate system (>50 years). Recent climate change involves global warming, ocean acidification, and changes in precipitation, winds, and ocean circulation patterns. These long-term changes will affect the average climate, but they may also change the frequency and magnitude of the processes responsible for natural variability, such as ENSO events.

The climate we experience is a combination of natural variability and long-term change. Climate change is not detectable day-to-day or year-to-year. It is detectable in the long-term trends in daily and annual temperatures. These long-term changes in the Earth's climate system pose challenges for the management of living marine resources. Information on the impacts of both climate variability and change on LMRs is very important to developing effective management approaches across multiple time scales.



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Impacts of a Changing Climate on Marine and Coastal Ecosystems

The impacts of both climate variability and change on the physical, chemical, biological, and even social components of marine, coastal, and freshwater ecosystems are well documented (Doney et al. 2012; Griffis and Howard 2013; Intergovernmental Panel on Climate Change 2013; Melillo et al. 2014). Some of the major observed and expected changes to the physical and chemical characteristics of marine and coastal environments are illustrated in Figure 1 and include the following (Doney et al. 2012; Intergovernmental Panel on Climate Change 2013; Melillo et al. 2014):

- Warmer ocean temperature.
- Reduced sea-ice thickness and extent.
- Altered storm tracks and intensity.
- Precipitation changes.
- Altered freshwater input.
- Sea level rise.
- Reduced ocean pH (i.e., acidification).
- Reduced dissolved oxygen.

These changes can result in a variety of altered conditions, including the following (Rykaczewski and Dunne 2010; Doney et al. 2012; Intergovernmental Panel on Climate Change 2013; Melillo et al. 2014):

- Salinity.
- Ocean circulation.
- Mixed layer depth.
- Upper-ocean stratification.
- Wind mixing.
- Intensity of upwelling and downwelling.
- Ecosystem connectivity.
- Nutrient availability.

These changes to the marine and coastal physical and chemical environments are known to be occurring, and their cascading effects on species, habitats, and biodiversity in these systems are expected to increase with continued changes in the climate system (Figure 1). The variety of observed or expected effects include changes to ecosystem productivity (Polovina et al. 2008; Polovina et al. 2011; Hollowed et al. 2013); the timing and magnitude of phytoplankton blooms (Steinacher et al. 2010; Behrenfeld 2011; Sigler et al. In press); thermal tolerance and habitat volumes available for LMRs (Baker et al. 2007; Nye et al. 2009b; Baker et al. 2012; Hazen et al. 2013; Pinsky et al. 2013; Lynch et al. In press); and vital rates [reproductive rate, emigration, immigration] and life history characteristics (Hare et al. 2010; Saba et al. 2012). These effects can have direct or indirect impacts on species' survival, abundance, distribution, fecundity, reproductive success, and function in an ecosystem, and thereby modify the provision of ecosystem goods and services (Ruckelshaus et al. 2013). These factors may influence the frequency, intensity, and duration of interactions among species, species phenology, distributions and abundance, and the dynamics of invasive and endangered species. We are already witnessing species range shifts (Nye et al. 2009a; Nye et al. 2009b; Cheung et al. 2010; Kotwicki and Lauth 2013; Pinsky et al. 2013), and these shifts are expected to continue, posing challenges and perhaps opportunities for resident and shifting species as they enter or leave an ecosystem.

Climate-related alterations to freshwater and estuarine systems—such as changes in the amount, location, and timing of precipitation or changes to air or sea temperatures—can affect riverine-dependent diadromous species and the many species that use estuarine habitats (Intergovernmental Panel on Climate Change 2013; Intergovernmental Panel on Climate Change 2014; Melillo et al. 2014). For example, along the U.S. West Coast, the combination of more extreme events coupled with higher temperatures causes more precipitation to fall as rain rather than as snow, which significantly changes the hydrology for listed salmon and steelhead in the region, including (Mote et al 2014):

- More flooding and scouring flows in winter (increasing sedimentation, erosion, and potentially washing out deposited eggs).
- Earlier spring freshet (likely to change juvenile migration timing with potential mismatch to estuarine and ocean conditions).
- Higher water temperatures and lower stream flows in summer and fall (reducing juvenile rearing habitat quality and quantity, potentially increasing predation and disease transmission).
- More frequent exceedance of lethal/sublethal temperature thresholds for juveniles and adults.
- Modified riparian vegetation (contributing to higher stream temperatures) by factors including greater fire frequency and insect infestation..

In many coastal areas, transformation of shorelines and estuarine habitats with sea level rise and coastal inundation can also impact coastal-dependent species. Threats also arise from ocean acidification, with particular concern for species with calcareous shells [composed of calcium carbonate] or exoskeletons (Cooley and Doney 2009; Bednaršek et al. 2014), which currently comprise about two-thirds of U.S. marine aquaculture production[2] and more than half of U.S. domestic fishery landings by value (National Marine Fisheries Service 2014) and provide habitat for many species (e.g., coral and oyster reefs).

Climate-related changes will also interact with other stressors, such as pollution, fishing, bycatch, and changes in human use of these systems (e.g., rapid increase in human use of the Arctic) to affect LMRs. Some examples of climate-related impacts on LMRs and the people who depend on them are included as case studies throughout this document. In some circumstances, mitigating other stressors that are under local or regional control (e.g., fishing impacts and pollution) may help increase the persistence of species sensitive to climate change, by increasing overall resilience and reducing synergistic impacts between climate-related and non-climate-related stressors.

Climate-related changes in physical and chemical conditions are expected to have a variety of impacts on LMRs across a range of spatial and temporal scales (Stock et al. 2011; Melillo et al. 2014). To assume that the effects of climate change will be uniform and consistent across species and ecosystems is imprudent and inconsistent with our scientific understanding. Several studies (e.g., Mueter et al. 2011; Howella and Austerb 2012; Wilderbuer et al. 2013) suggest that in any one region, some species will experience improving environmental conditions that may result in increased species productivity and increased available habitat, while other species will experience the opposite and perhaps decline in abundance. Furthermore, the sensitivity of species to climate change and the nature of the effect may vary with life stage. Understanding how climate change will affect wide-ranging species is challenging, as they may experience positive effects of climate change in one habitat during one life stage and negative effects in another distantly located habitat in another life stage. Because not all climate changes will affect LMR species in the same way, there is an urgent need for careful evaluation of the impacts of climate as well as non-climate stressors in the design, implementation, and evaluation of LMR management efforts. For example, changes in species' abundance, productivity, distribution, and diversity due to a changing environment may require changes to the biological reference points and socio-economic benchmarks used in LMR management.

The combined physical, chemical, and biological effects of climate change on LMRs will modify the products and services people derive from marine ecosystems, including food, jobs, recreation, medicinal products, aesthetics, tourism, and even health benefits (Ruckelshaus et al. 2013). For example, the species available for harvest or culture in a given region could change in space and time, requiring fishermen to develop new harvesting strategies (e.g., switching

[2] http://www.nmfs.noaa.gov/aquaculture/faqs/faq_aq_101.html#11whatkinds

their target species and gear types) or developing strategies for reducing bycatch of species new to their fishing grounds (Heenan et al. 2013). Shifts in the distribution and/or abundance of species may affect where fishermen target fish, the location of fishing industries, working waterfronts, supply chains, and the social and economic dynamics of LMR-dependent coastal communities, cultures, and industries. Changes in target 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 (e.g. flooding). 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. These and many other climate-related effects will impact NOAA Fisheries' stewardship of LMRs (e.g., for ESA-related issues see special section on climate change and NOAA Fisheries ESA work in December 2013 issue of *Conservation Biology*: Boughton and Pike 2013; Brainard et al. 2013; Busch et al. 2013; Gregory et al. 2013; Jorgensen et al. 2013; McClure et al. 2013; Seney et al. 2013; Snover et al. 2013; Wainwright and Weitkamp 2013; Walters et al. 2013) .

NOAA Fisheries Stewardship Mandates

NOAA Fisheries is responsible for the stewardship of the nation's LMRs and their habitats, interactions, and ecosystems. As discussed above, climate change is expected to have a variety of impacts on marine, coastal, and freshwater ecosystems, LMRs, and their uses, which will affect both the information and the actions required to fulfill this mission. NOAA Fisheries' main mandates are derived from numerous statutes, including the Magnuson-Stevens Fishery Conservation and Management Act (MSA), Endangered Species Act (ESA), Marine Mammal Protection Act (MMPA), National Aquaculture Act, Coral Reef Conservation Act, and the National Environmental Policy Act (NEPA) (Table 1).

- Under the MSA, NOAA Fisheries 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 analyzes impacts on essential fish habitat. This information is used to maintain, conserve, and rebuild fishery resources. A primary objective of the MSA is to use the best scientific information available to optimize yield on a continuing basis.
- The MMPA directs NOAA Fisheries 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 ESA, NOAA Fisheries works to identify, protect, and recover threatened and endangered species, including marine mammals, sea turtles, marine and anadromous

fishes, marine invertebrates, and marine plants, and their critical habitat.

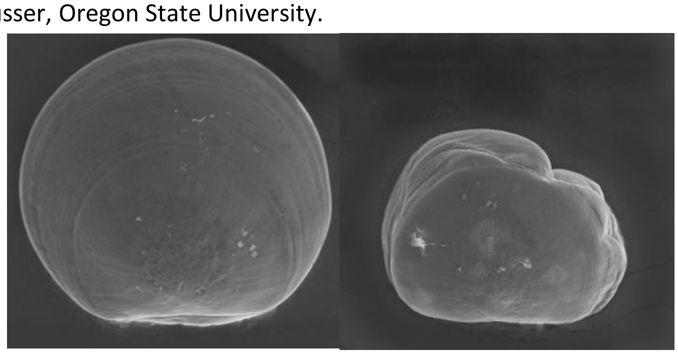
- Under the National Aquaculture Act, NOAA Fisheries provides for the development of aquaculture in the United States. Under the Coral Reef Conservation Act, NOAA Fisheries facilitates local action strategies for preserving coral reef habitat.
- Under NEPA and the National Ocean Policy, NOAA Fisheries evaluates environmental and socio-economic impacts of a variety of federally permitted activities in marine and coastal systems. This places particular emphasis on the evaluation of cumulative impacts to LMRs and their habitats, connections, and ecosystems. Similar work evaluating environmental effects of various activities is done through the MSA, ESA, Fish and Wildlife Coordination Act, and the Federal Power Act.

In designing management approaches to meet the LMR objectives listed above, NOAA Fisheries 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.

__Pacific Northwest oyster hatcheries and ocean acidification__

The first known case of an industry being directly affected by ocean acidification occurred in the Pacific Northwest's oyster hatcheries. Ocean acidification along the U.S. West Coast has been well documented, including its effects on aragonite saturation state of upwelled waters [a proxy used to estimate calcification rates] (Feely et al. 2008). In 2006, the mortality rate of cultured larvae of Pacific oyster (*Crassostrea pacifica*) at Oregon's Whiskey Creek shellfish hatchery was 80 percent greater than usual (Kelly et al. 2013). High larval mortality rates persisted at the Whiskey Creek hatchery and occurred at other hatcheries in Washington State for a few years. Wild recruitment of Pacific oysters was below levels needed to support commercial harvest in Washington's Willapa Bay during the same time period (Dumbauld et al. 2011). Hatchery managers and scientists explored a variety of possibilities for the high oyster larvae mortality, but turned their attention to ocean acidification when all of the typical causes of mortality could be ruled out. NOAA and other scientists collaborated with Pacific Northwest hatcheries to monitor the carbon chemistry of the seawater used to grow oysters and explored the link between ocean carbon chemistry and larval mortality in the hatchery. At the Whiskey Creek Hatchery, scientists found that larval production was directly correlated with aragonite saturation state of the seawater in which larval oysters were spawned and reared for the first 48 hours of life (Barton et al. 2012). Using data from carbon chemistry monitoring equipment, this hatchery and others have since successfully adapted their practices to mitigate the effects of ocean acidification on production. For example, they can now avoid drawing low pH water into the hatchery during spawning events. The shellfish industry, in collaboration with NOAA and other scientists, is exploring other adaptation practices for hatcheries, and the scientific community is exploring the feasibility of adaptation practices that could support oyster harvest from wild recruitment. Both are necessary to support the viability of the Pacific Northwest oyster industry.

Larvae of Pacific oysters at 4 days after hatching when reared in pH 8.0 (left) and pH 7.4 (right) seawater. Credit: E. Brunner and G. Waldbusser, Oregon State University.



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Fulfilling these mandates requires a range of science-based information and services to provide the foundation for management action. NOAA Fisheries' responsibilities under the MSA, ESA, MMPA, NEPA, and other 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. Briefly, this sequence can be described as follows (Figure 2):

- Providing contextual information to characterize all taxa of interest and their role in the ecosystem and for fisheries.
- Providing observational and experimental data to build an understanding of LMR abundance and dynamics given past and current environmental and socio-economic conditions.
- Modeling and synthesizing data to understand patterns in ecosystem and LMR population dynamics and make projections about how they will respond to action.
- Reviewing model outputs to validate the science.
- Providing management advice, typically in the form of reference points and catch recommendations.

Science is essential for effective LMR management, and it becomes even more important as climate change alters the historical characteristics of marine ecosystems. Currently, we lack key scientific information needed to inform LMR management decisions in a changing climate.

With changing climate and LMR conditions, there are a variety of increasing information needs to inform and fulfill NOAA Fisheries LMR stewardship mandates (Osgood 2008). Some of the major climate-related information needs (Figure 2) for effective LMR management in a changing climate are:

- Standardized data on past and current changes in marine, coastal, and freshwater ecosystems.
- Studies to develop a mechanistic understanding of contemporary and historical climate impacts on LMRs.
- Assimilation and synthesis of climate information into models used to determine stock and ecosystem status and monitoring systems.
- Future projections of the state and expected human use of marine, coastal, and freshwater ecosystems (based on contemporary and historical climate sensitivities).
- Evaluation of alternative management strategies to reduce current and future impacts of climate change on LMRs, the goods and services they provide, and the communities that depend on them.

Coral community sensitivity to climate change

In 2009, NOAA Fisheries was petitioned to list 83 species of coral as threatened or endangered under the ESA based on widespread degradation of coral reefs over the past three decades (Gardner et al. 2003; Pandolfi et al. 2003; De'ath et al. 2012) and on predicted declines in available habitat for the coral species (Hoegh-Guldberg et al. 2007; Carpenter et al. 2008), citing anthropogenic climate change and ocean acidification as the lead factors. An extensive NOAA Fisheries review of the available scientific information and analyses of the status and extinction risk of the 83 candidate coral species (Brainard et al. 2011) considered ocean warming, disease, and ocean acidification to be the most influential threats in posing extinction risks to the coral species evaluated. Over the past three decades there have been numerous widespread mass coral bleaching and mortality events around the globe associated with anomalously warm water temperatures (Eakin et al. 2009; Burke et al. 2011), and it is expected that these coral bleaching events will continue, likely with increased frequency and severity, with ocean warming driven by climate change (Hoegh-Guldberg et al. 2007; Eakin et al. 2010; Hoeke et al. 2011). In addition to mortality caused directly by the bleaching, incidences of coral disease increase as a function of increasing temperature (Bruno and Selig 2007; Harvell et al. 2007). Corals and coral reefs are also considered to be among the most vulnerable taxa and ecosystem types to the impacts of ocean acidification, as numerous experiments have demonstrated significantly reduced ability of reef-building corals and crustose coralline algae (red algae in the order Corallinales) to calcify and create their calcium carbonate skeletons (reefs) under low pH and low aragonite and calcite saturation states [The availability of carbonate ions is crucial for marine calcifying organisms to form their skeletons or shells that are made of different crystalline forms of calcium carbonate, such as calcite and aragonite. Aragonite is more soluble than calcite. Thus, the saturation state of aragonite can be taken as an indicator for ocean acidification. http://iprc.soest.hawaii.edu/users/tobiasf/Outreach/OA/Ocean_Acidification.html] predicted this century (Langdon and Atkinson 2005; Hoegh-Guldberg et al. 2007; Kuffner et al. 2007). Finally, additional studies have indicated that thermal and acidification stresses often act synergistically, resulting in even greater impacts to corals and coral reefs (Anthony et al. 2008).

In August 2014, NOAA Fisheries made a final decision to list 20 of the candidate species as threatened. This ESA decision-making process has demonstrated the need for both field and experimental time-series observations, and projections of climate and ocean changes and the resulting ecosystem impacts of those changes. Improvements in our ability to quantify the environmental factors, their variability, and their influence on survival and reproduction of living marine resources are essential for ESA decision-making.

Meeting these changing science requirements will be challenging given the scale and scope of NOAA Fisheries' mission and expected climate-related impacts in marine, coastal, and freshwater ecosystems. For example, NOAA Fisheries is responsible for providing a range of science-based assessments and management advice for the stewardship of more than 449 regulated stocks/stock complexes,[3] 102 threatened or endangered species, and 117 marine mammal species.[4] In addition, NOAA Fisheries provides science-based information to conduct more than 2,000 habitat restoration projects nationwide[5] and protect hundreds of thousands of square kilometers of habitat. NOAA Fisheries also oversees research and siting for a growing number of sustainable marine aquaculture activities, including some designed to mitigate for climate change. To meet NEPA requirements, in 2012 alone, NOAA Fisheries conducted 106 environmental assessments, wrote 12 environmental impacts statements, and issued hundreds of categorical exclusions.[6] Under the MSA, in 2011, NOAA Fisheries provided conservation recommendations to federal and state agencies on over 4,500 individual projects.

Overall, NOAA Fisheries has direct stewardship responsibilities for LMRs in 11 Large Marine Ecosystems, comprising 16.5 million km^2, an area 1.7 times the land area of the continental United States and roughly 5 percent of the world ocean's surface area,[7] plus other stewardship responsibilities of the ESA-listed species that occur in all of the world's Large Marine Ecosystems. NOAA Fisheries also has stewardship responsibilities on the high seas and for operation of U.S. fishing vessel in other countries' EEZs through international treaties and regional fishery management organizations. Due to complex trophic interactions of marine ecosystems, climate change will likely affect marine ecosystems, including all of the managed species. In addition, climate change will likely affect consumptive and recreational human use as well as conservation of managed species. Effective stewardship of LMRs will require information related to climate change for use in the design and execution of a broad range of management actions. In addition, effective stewardship will require an understanding of how fisheries, ocean industries (e.g., shipping, military activities, shoreline development), and other human activities might modify their use of LMRs in the face of projected and actual climate-related changes in marine, coastal, and freshwater ecosystems over time.

NOAA Fisheries needs to address all these mandates simultaneously, and to do so the agency is

[3] https://www.st.nmfs.noaa.gov/sis/
[4] http://www.nmfs.noaa.gov/pr/species/index.htm
[5] http://www.habitat.noaa.gov/restoration/restorationatlas/index.html
[6] Categorical exclusion refers to a category of actions that do not individually or cumulatively have a significant effect on the human environment and for which, therefore, neither an environmental assessment nor an environmental impact statement is required.
[7] http://www.lme.noaa.gov/index.php?option=com_content&view=category&id=41&Itemid=53

implementing its LMR stewardship responsibilities in an ecosystem context (Figure 3). NOAA Fisheries has adopted a policy of ecosystem-based management (EBM) to more efficiently and effectively fulfill its mandates and promote consideration of not only cumulative effects, but also trade-offs across various management regimes and human uses, as well as the impacts of these management decisions on human systems (Executive Order 13547 of July 19th 2010; Ocean Research Advisory Panel 2013).

EBM is a national priority and leading business practice within NOAA Fisheries, NOAA, U.S. natural resource management agencies, and many leading international natural resource management organizations (MacLeod and Leslie 2009; Executive Order 13547 of July 19th 2010; National Ocean Council 2013; Ocean Research Advisory Panel 2013; U.S. Office of Science and Technology Policy 2013). It is an idea that has existed for decades in the literature (Slocombe 1993), but has only more recently begun to be implemented in practice. Within each of NOAA Fisheries' mandates, the need and benefits of considering a wide range of factors that can influence LMRs is clear. But even more so, across all of these mandates, the need to implement EBM is apparent; NOAA Fisheries will be unable to consider the full range of trade-offs, interactions, and cumulative effects required across all of the mandates under a changing climate if it proceeds otherwise (MacLeod and Leslie 2009; Link 2010). Climate and ocean change impacts are a critical part of this discussion, and adopting common approaches to climate change science that are applicable across all NOAA Fisheries LMR mandates is an important area to leverage resources and gain efficiencies via this Strategy.

Without adequately incorporating climate change, NOAA Fisheries' conservation and management efforts are likely to be ineffective, produce negative results, or miss positive 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 (added $199 billion to the U.S. economy in 2012) and to social systems (generated 1.7 million jobs in 2012) (NMFS 2014). The recreational fishing industry alone contributes $56 billion a year to the U.S. economy and 364,000 jobs (NMFS 2014). Furthermore, subsistence and personal use fisheries are known to be vital to families and households across the nation, including tribal communities. Beyond fisheries, LMRs help protect coastal communities from storm waves and tsunamis, support the existence of imperiled and charismatic species [charming and widely known], regulate climate, and mitigate climate change effects (e.g., carbon sequestration and storage by coastal habitats).

Although the value of these services is challenging to quantify, they are vital and impossible to replace (Ruckelshaus et al. 2013). The social, cultural, and economic consequences are vast. 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 NOAA Fisheries mandates in a changing climate.

The Need for a NOAA Fisheries Climate Science Strategy

The demand for more information related to climate change is great and increasing among managers and stakeholders as evidence continues to mount of climate-related impacts on marine and coastal ecosystems, fish, protected species, aquaculture, and habitats. Many sectors are taking significant action to better understand, plan for, and respond to climate impacts (e.g., defense, transportation, land management, water management, public health, and others). This includes natural resource agencies such as the U.S. Forest Service (Solomon et al. 2009), U.S. Fish and Wildlife Service (U.S. Fish and Wildlife Service 2010), National Park Service (National Park Service 2010; National Park Service 2012), U.S. Department of Agriculture (USDA 2011), and the U.S. Geological Survey (Burkett et al. 2013). Increasing the production, delivery, and use of climate-related information in LMR advisory and regulatory documents (e.g., assessments, decisions, and opinions) produced each year in fulfilling NOAA Fisheries stewardship responsibilities is a significant challenge. Moving forward, NOAA Fisheries must include climate-related information in their decision-making and management advice. To do so, NOAA Fisheries should develop new types of information products and new approaches to advise managers, policymakers, and stakeholders (e.g., U.S. Army Corps of Engineers 2009).

Fortunately, many quantitative tools needed to incorporate climate change into NOAA Fisheries scientific advice already exist, though improvements are needed in the use and application of these tools. Other needed tools remain undeveloped. NOAA Fisheries has a network of internal and external partnerships that could be better mobilized to help address many of these needs (in fact, partners are critical to fill some of the science and information needs; Table 2). However, many challenges remain. For example, many of the data sets needed to parameterize coupled climate-LMR or ecosystem models are not available; additional efforts are needed to collect relevant climate-related data as a regular part of the information base supporting LMR management (Osgood 2008; Hollowed et al. 2009; Stock et al. 2011). Additional action is needed to effectively structure and employ models and tools that utilize climate, biological, and ecological information. Research to better understand key mechanisms and processes linking climate-induced changes to LMRs is also needed. There is a need to identify and test how to effectively insert climate-related information into LMR management processes (Figure 2). Given that many of NOAA Fisheries' LMR mandates have common needs for climate-related information, identifying these common products and responses that can be used across all mandated needs should be a top priority. Finally, all these endeavors require adequate science infrastructure, coordination, and financial support in both the near term and the long term.

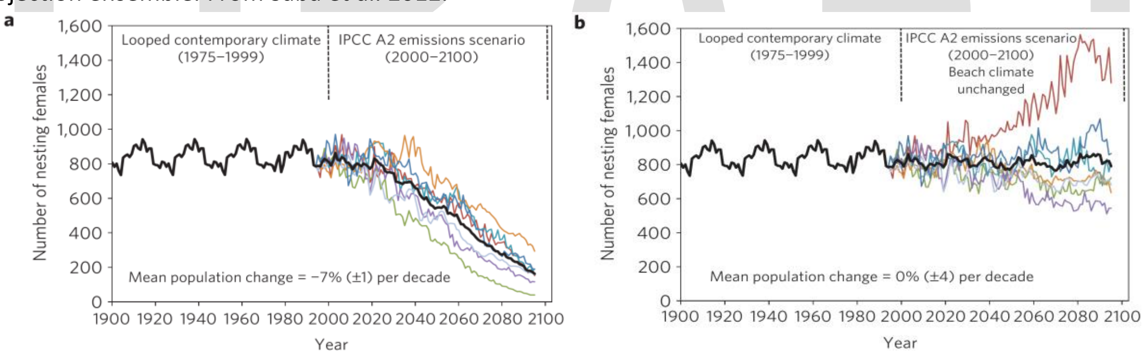
This Strategy identifies seven key areas where action by NOAA Fisheries and partners over the next 5 years can efficiently and effectively provide the information and approaches required to fulfill NOAA Fisheries' LMR stewardship mandates in a changing climate. The goal of the Strategy is to increase the production, delivery, and use of such information in these seven priority areas (Figure 4). These priority areas focus on seven main questions that need to be addressed to ensure effective LMR management in a changing climate:

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

__Projections of the response of leatherback turtles to changing climate and ocean conditions__

Leatherback turtle (*Dermochelys coriacea*) population dynamics are differentially sensitive to changes in climate and ocean conditions. Population projections under an Intergovernmental Panel on Climate Change emissions scenario indicate a 7 percent decline per decade when both ocean and nesting beach climate conditions change. A 2 to 3^{o} C warming of the nesting beach was the primary driver of the decline through reduced hatching success and hatchling emergence rate. Adjusting nesting phenology or changing nesting sites may not entirely prevent the decline, but could offset the decline rate. However, if future observations show a long-term decline, mitigation efforts such as shading and irrigation of nests may be able to preserve the nesting population (Saba et al. 2012). Predicted sea level rise could significantly impact nesting beaches through impacts from ocean inundation, loss of suitable habitat, and increased completion for best nesting sites.

Leatherback turtle nesting population projections at Playa Grande, Costa Rica in the Eastern Pacific Ocean. Colored lines are population projections based on individual global climate models and the solid black line is the projection ensemble. From Saba et al. 2012.



CHAPTER 2

INCREASING PRODUCTION, DELIVERY, AND USE OF CLIMATE-RELATED INFORMATION TO FULFILL NOAA FISHERIES MISSION

The goal of this Strategy is to increase the production, delivery, and use of climate-related information to inform and fulfill NOAA Fisheries' LMR stewardship mission. NOAA Fisheries needs to better understand the response of marine organisms and ecosystems to climate change in order to better understand the impacts of climate change on LMRs and human use of LMRs. NOAA Fisheries also needs information to design and implement management approaches that are robust to the uncertainties of changing marine, coastal, and freshwater ecosystems. The Strategy is designed to provide a national framework that can be regionally tailored and implemented through NOAA Fisheries science centers, regional offices, and their partners over the next 5 years.

This Strategy is intended to identify key climate-related information needs (Table 1). These needs were derived from existing assessments and related sources (e.g., Murawski and Matlock 2006; Osgood 2008; Griffis and Howard 2013), then generalized across mandates to identify analytical products and the science enterprise to support management needs. Finally, consideration was given to the infrastructure needed to produce and deliver the needed science.

While each NOAA Fisheries mandate has specific requirements, four main findings played a key role in shaping the content of this Strategy:

1. There are common information needs that exist across all major mandates.
2. The science-to-management process is relatively consistent across mandates, making advances in climate-related science and information applicable across multiple mandates.
3. Advances in the science and practice of ecosystem-based management are considered the most effective approach to achieve the desired objectives of all the respective mandates simultaneously.
4. There are common, climate-related tools, approaches, or information that can efficiently and effectively inform all of NOAA Fisheries' mandates.

While it is clear that there are also mandate- and region-specific needs, this Strategy is designed to provide a national blueprint that can provide tangible solutions to a variety of priority common needs and also help address the more unique science and information needs of each mandate and region. This Strategy capitalizes on these common elements and suggests an over-arching framework for action to build the needed science enterprise.

This chapter identifies seven priority areas of information and activities needed to fulfill NOAA Fisheries' mission using highly interdependent objectives, and provides strategies to address them over the next 5 years. The first three are management-oriented objectives, and the final four are science-oriented objectives:

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

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

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

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

Objective 5: Identify the mechanisms of climate impacts on ecosystems, LMRs, and LMR-dependent human communities.

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

Objective 7: Build and maintain the science infrastructure needed to fulfill NOAA Fisheries mandates under changing climate conditions.

To meet these seven objectives, NOAA Fisheries needs to identify and fill data or information gaps; maintain and bolster ongoing efforts that are climate-relevant; explore novel ways to produce and deliver salient information; and develop climate-smart management approaches. This chapter describes the information needed to address each of our objectives, plus the germane products, strategies, and delivery of each (Table 3).

Each of the seven objectives is described in the following pages. Each objective begins with a description of the LMR management objectives and/or the type of science-based information or advice needed in the form of decision criteria. The objectives are highly interdependent; the science and information from any one objective contributes to or is essential to one or more of the other objectives.

These objectives were ordered according to the main mandated responsibility areas (Table 1), deriving 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 (Figure 4). Thus, all subsequent objectives support the objectives above it (Figure 4). Building this nested and interdependent science foundation is the core of this Strategy.

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

Reference points are the thresholds upon which LMR management decisions are made. Because stocks, protected species, habitats, aquaculture, and ecosystems are expected to respond to climate change, the reference points for these species, systems, and human uses may need to change to reflect those different conditions; ongoing scrutiny of these reference points has already indicated the need to bolster climate-related information in the development of this management advice. Development of biological reference points (BRPs) is a primary objective for much of the science conducted by NOAA Fisheries to meet its mandates. Be they single-species measures of maximum sustainable yield, thresholds for habitat designations, potential biological removal of marine mammals, multispecies fishing rates, thresholds for ecosystem-level indicators, protected species recovery criteria, or a host of others (Table 1), these reference points are used as limits or decision criteria to guide sustainable management of LMRs and their habitats. These reference points are typically developed via modeling exercises that synthesize a broad suite of observational and experimental information and are peer-reviewed. This careful vetting ensures that decision criteria are effective at achieving sustainable management, species recovery, or other stewardship goals. Strengthening NOAA Fisheries' ability to incorporate consideration of climate change into all the steps that lead to providing reference points is critical.

A number of products can be routinely created to meet this objective. Novel or updated LMR management plans and documents are typically produced for each management action. Usually, documents such as Fishery Management Plans, Fishery Ecosystem Plans, Biological Opinions, Species Recovery Plans, Environmental Impact Assessments, and Social Impact Assessments inform Ecosystem Assessments, ESA Status Assessments, MMPA and MSA Stock Assessment Reports, habitat assessments, restoration reports, and EFH designations. These plans and documents provide the scientific basis for the management of LMRs (Table 1). They are regularly used by NOAA Fisheries, Regional Fishery Management Councils; Regional Ocean Councils; Regional Planning Boards; State Fishery Commissions; Regional Fishery Management Organizations; many federal, state, and local agencies and organizations; and other managers in decision making.

Most current assessments, and the reference points produced by them and included in management plans, assume that 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. 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 shift their reference points in response to shifts in the environment, such as regime shifts [large, abrupt, persistent changes in the structure and function of an eco-system. A regime is a characteristic behavior of a system which is maintained by mutually reinforced processes or feedbacks]. 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 shifting status of managed species (Punt et al. In press) and associated ecosystems.

Moving forward, LMR management plans (e.g., Fishery Management Plans, Fishery Ecosystem Plans, Species Recovery Plans) need to document that decision criteria explicitly include climate-related considerations. Accounting for and, where appropriate, including the best available climate-related science to inform reference points is a necessity to avoid misaligned management targets. Additionally, many of these plans need to include socio-economic analyses that show the consequences of neglecting climate change in establishing biological reference points. Such analyses are challenging but feasible. Moreover, they are critical to demonstrating the value (both biologically and socio-economically) of managing LMRs using reference points that consider the effects of climate change. Misaligned reference points may result in foregone revenue or missed opportunities (e.g., biological, social, economic, cultural) due to climate-induced changes in production, distribution, or other dynamics of LMRs that have been unaccounted for.

Finally, a reporting tool, accessible to all stakeholders, that simultaneously tracks the status of stocks, ecosystems, and social and economic conditions over time would provide useful products for adequately achieving this objective. NOAA Fisheries has the building blocks for developing such a reporting tool, but does not currently collect information in such a comprehensive way.

Important strategies to bolster and better deliver climate-smart reference points include:

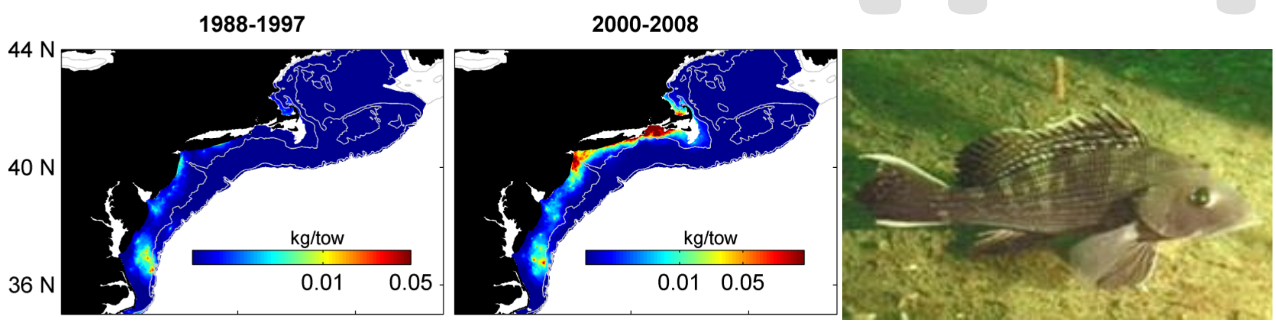
- Identify ecosystem-based reference points that include climate change and ecosystem information for all LMR management plans and strategies.
- Modify existing biological reference points that fail to include ecosystem considerations and assume that environmental conditions of the past will persist into the future.
- Communicate that ecosystem-based biological reference points improve accuracy, especially under climate change.
- Foster innovation in climate-smart scenario testing.
- Elucidate the positive opportunities associated with emerging LMRs.
- Develop scientific underpinning for Environmental Impacts Statements for climate change in each region, including comprehensive socio-economic impact analyses.

<u>*Changing fisheries behavior in response to climate-induced changes to LMRs*</u>

Climate-forced changes in species distributions are causing changes in both fishery operations and fisheries management. These changes are currently reactions; i.e., unplanned changes that are made as a result of climate change. This Strategy seeks to enable fisheries adaptation to climate change; i.e., planned changes that reduce the vulnerability of social and biological systems to climate change (Quentin Grafton 2010). Fisheries along the Northeast United States serve as an example of reactions to climate change. Fish and shellfish populations are shifting predominantly northward or to deeper waters, consistent with expected biological responses to warming waters (Nye et al. 2009b; Pinsky et al. 2013). These changes in species distribution have led to changes in the distribution of landings (Pinsky and Fogarty 2012); landings of lobster, yellowtail flounder, summer flounder, and red hake shifted northward but at a slower rate than species distributions, which suggests an increasing disconnect between fishing and species distributions.

Many fishery species are managed in part with spatial allocation systems. Along the Northeast, the Atlantic States Marine Fisheries Commission uses a state allocation system based on historical patterns in landings. As species distributions change, landings distribution change, and the state allocation system can become out of sync with the distribution of landings, fishing effort, and the distribution of the resource. NOAA Fisheries scientists are providing products to the Commission to inform their discussions about potential changes in the state allocation system. These products include maps of species distribution when the allocations were set and analyses documenting the extent and examining the case of distribution changes (Bell et al. In review). This support is ongoing and is an initial effort to develop climate adaptation for fisheries in the region.

Distribution of black sea bass in the fall over the period when state allocations were set (1988–1997) and more recently (2000–2008). A black sea bass pictured in Stellwagen Bank National Marine Sanctuary in 2001. Photo credit: NOAA Stellwagen Bank National Marine Sanctuary.



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

Identifying LMR management approaches and options that will remain biologically and socio-economically sustainable in the face of a changing climate is a critical need. In addition, we need to acknowledge and affirm that the best management practices for LMRs today may not be the best management practices in the future with changing climate and ocean conditions.

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 practices under future conditions (Battin et al. 2007; Crozier et al. 2008; Ianelli et al. 2011; Boughton and Pike 2013; Nye et al. 2013; Szuwalski and Punt 2013; Wilderbuer et al. 2013). Such management strategy evaluations (MSE) will assist in the design and evaluation of management options and adaptive management strategies for LMRs, and should help identify management options that are robust to a wide range of predicted future conditions. Additionally, they could be used to identify the time scale of change and adaptation, allowing us to better focus resources and emphasis. Similar models for cultivated LMRs exist for aquaculture and can be used to predict changes in production due to changing ocean conditions and consumptive and non-consumptive uses (Shelton 2014). Conversely, models of shellfish and seaweed physiology could be used to evaluate the potential for aquaculture systems to provide refuge to LMRs from changing climate and to remove carbon from the coastal ocean.

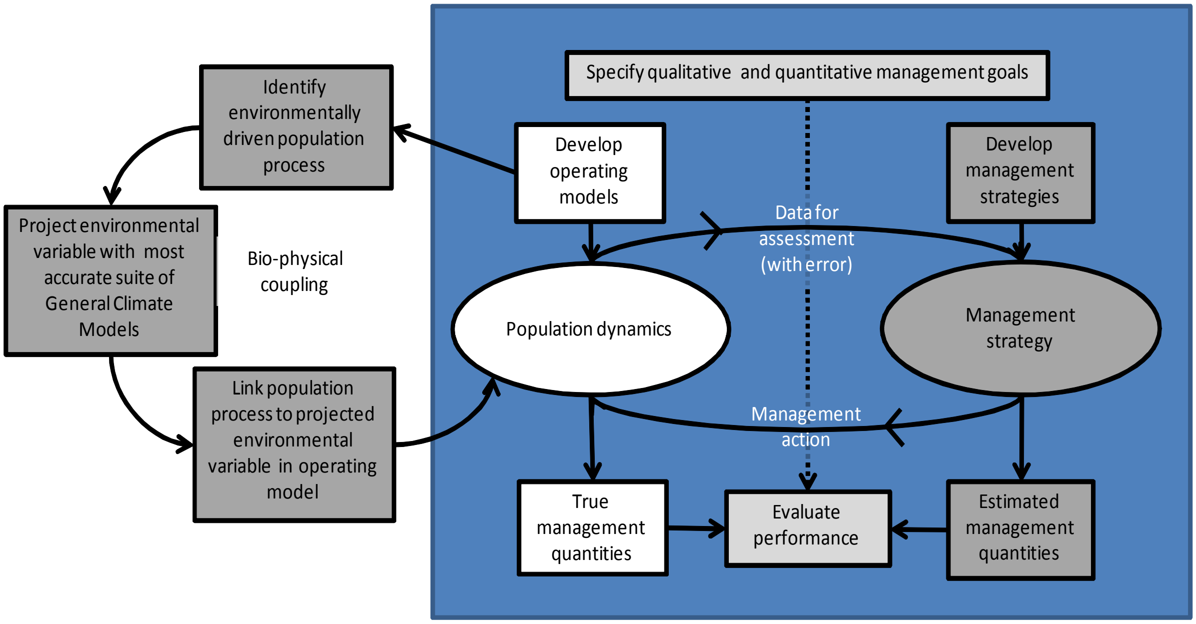
NOAA Fisheries has considerable experience in designing and evaluating strategies for sustainable management of LMRs. Incorporation of expected climate-related changes to marine, coastal, and freshwater ecosystems, as well as human uses of those ecosystems, will help identify management practices and mitigation strategies that may be necessary in the future. Fulfilling NOAA Fisheries' various mandates have specific timelines and processes for providing scientific information to managers and other stakeholders. Through these processes, NOAA Fisheries can provide information on the effectiveness of current management practices and the design and performance of alternative management practices that may be superior. For example, management strategy evaluations for fisheries management practices, recovery plans for ESA-listed species, management practices for aquaculture, use of aquaculture as mitigation, and designation of essential or critical habitat should incorporate understanding of the impacts of climate change into the design of effective management strategies. Such management strategy evaluations would support development of sound adaptive management practices.

A number of products could be routinely created to meet this objective. Reports of such management strategy evaluation efforts that cover the full range of climate, harvest, mitigation, and adaptation scenarios are needed. Within these reports, documented

Management Strategy Evaluations

There are many forms of management strategy evaluations. They range from qualitative assessments of the implications of a proposed change in management to highly technical simulations of the performance of a proposed strategy relative to a suite of performance metrics (e.g., maintaining a stock above a suite of biological reference points). In the context of climate change, the full range of management strategy evaluations is relevant. For example, in the near term, considerable insight can be derived from a qualitative assessment of the vulnerability of a suite of stocks to the combined impacts of climate change and fishing. NOAA Fisheries can use these vulnerability assessments to prioritize research on adaptation strategies for the most vulnerable resources.

Schematic of a typical stock-focused MSE. Taken, with permission, from Punt et al. (in press), and adapted from Smith et al. (1999), Schnute et al. (2007), and Szuwalski and Punt (2012).



The more formal simulation modeling approach is emerging as a primary tool for delivery of adaptation strategies for the sustainable management of LMRs. Management strategy evaluations vary in complexity and biological realism, ranging from fully coupled bio-physical models of regional ecosystem responses to climate forcing, to climate-enhanced single- or multi-species projection models. These approaches incorporate bottom-up and top-down forcing through time.

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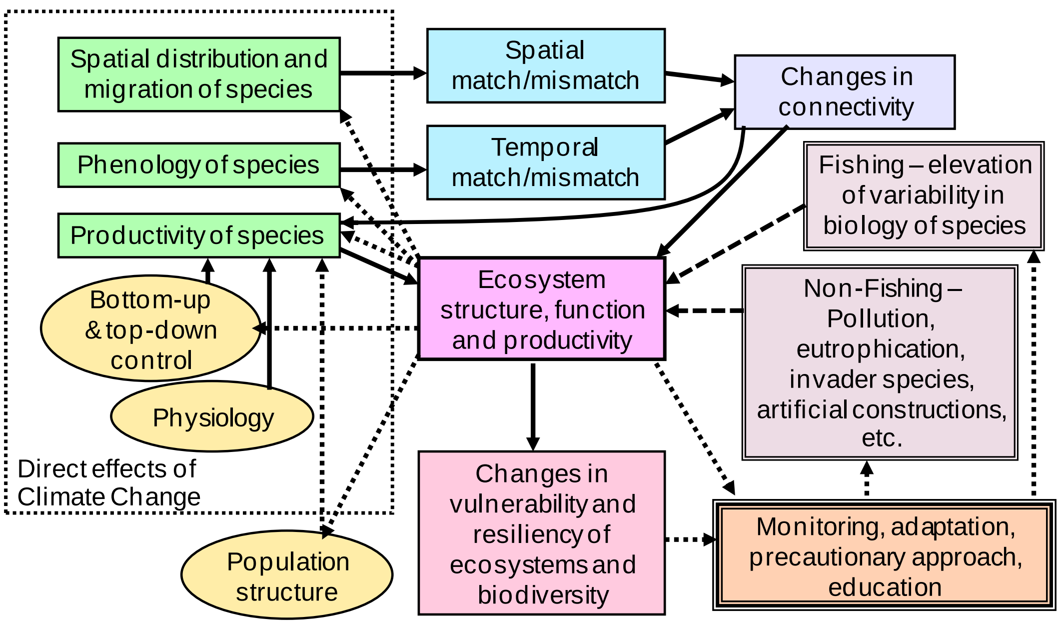
__Management Strategy Evaluations continued__

The fully coupled ecosystem models formally capture species interactions in space and time through first principles of bio-energetics, predation, and probability of encounter with prey. Examples include size spectrum models, food-web models, full life-cycle individual-based models, and gradient tracking spatial models that incorporate predator-prey interactions and bio-energetics. Climate-enhanced single- or multi-species projection models use time trajectories of physics (reproductive success), prey availability (growth and survival), predation (mortality), and bioenergetics (growth and maturation) to inform functional responses, model parameterizations, model structure, and even covariates for modeled stocks into the future.

Schematic of many factors that can go into ecosystem-level management strategy evaluations. Adapted from Smith et al. 1999, Fulton et al. 2013.



changes to biological reference points across a range of scenarios warrants examination, including a catalog of associated LMR and socio-economic responses. Reports generated from these management strategy evaluations need to clearly and simply identify the most robust strategies that will not weaken LMR sustainability. Management strategy evaluations 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 systems. Specific consideration should be given to fisheries prosecuted by fishermen and vessels that originate from multiple regions (e.g., multiple North Pacific fisheries are prosecuted by both West Coast and Alaska fishermen and vessels) because disruptions of these fisheries have the potential for broad-reaching socio-economic and management implications. The best levels of these biological reference points, reflective of a range of possible risk tolerances, need to be examined to better inform risk-based policies.

Many LMRs and ecosystems are experiencing changes in realized production or shifting distributions (Pinsky and Fogarty 2012). Exploration of these situations warrants particular attention. Some LMRs will move into ecosystems with more favorable environmental conditions. Management strategy evaluations to determine how to handle these opportunities also warrant exploration.

Important strategies to bolster and better deliver climate-smart management strategies include:

- Conduct management strategy evaluations and generate other information to allow risk-based policies to be re-evaluated under a changing climate.
- Establish science-based approaches and policies for determining biological reference points and LMR and ecosystem productivities with changing climate and ecosystem conditions.
- Establish science-based thresholds and policies for dealing with the immigration and emigration of LMRs to/from ecosystems.
- Conduct more routine and regular LMR management strategy evaluations with NOAA Fisheries partners and constituents to provide science-based assessments of management options in a changing climate.
- Examine efficacy of proposed mitigation strategies.
- Include human behavioral response or motivations into management design.

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

The procedures used to examine, vet, and provide scientific advice to support management strategies and decisions can be as important as the management advice itself. As depicted simply in Figure 2, the science and information delivery process for any of the main NOAA Fisheries mandates (Table 1) follows a similar sequence: synthesizing available data, reviewing outputs, and providing information to determine the status of LMRs, habitats, or ecosystems. The resulting management advice 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 management advice process, decisions based on it may not result in sustainable management (e.g., Beechie et al. 2013; McClure et al. 2013).

Copious works have documented, described, and evaluated management systems for LMRs and natural resources, in general (Holling 1978; Walters 1986; Hilborn and Mangel 1998). We do not repeat that work here; rather we build on it and note one key point: climate-related information may need to be incorporated into the management process to effectively achieve management and conservation goals. Doing so would require a number of steps. Clearly an openness to incorporate considerations of climate-related information is a huge first step. Second, knowing where the best insertion points are for 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 information related to the rate of environmental change.

Easing the integration of climate science into the management process may necessitate some changes to the management process itself, requiring close collaboration between managers and scientists. For example, robust strategies for managing LMRs under climate change may require both regular updates in the short term based on performance tracking and periodic evaluation against rigorous management strategy evaluations that employ fully coupled sets of system models. In this example, both the close interaction between managers and scientists and the need for managers to be able to adapt on a routine basis (without scientists having to execute detailed analyses each time) are highlighted. Recent scientific inquiry suggests that detailed analyses are needed to assess whether current management strategies are robust to climate change. Research also suggests that LMR management strategies that are successful under climate change include adaptive management cycles with control rules for changing conditions and monitoring programs to develop and track necessary status indicators.

The primary output for this objective would be scientific support for management processes that are adaptive and flexible in both the short and long term under the various NOAA Fisheries mandates. These processes would need to be measured by key performance metrics related to their timeliness and accuracy with respect to the ecosystem, LMR, and socio-economic impacts of climate change.

Further, identification of where in the management process climate-smart information could best be incorporated is needed, recognizing that there may be multiple insertion points (e.g, Sutton-Grier et al. 2014). This could be established under different management strategy evaluations (Figure 4).

Important strategies to bolster and better deliver climate-smart, adaptive management processes include:

- Design scientifically sound review-evaluation protocols that could ensure consideration of climate change as a standard part of LMR management advice.[8]
- Develop and document the scientific basis for the need for climate change considerations in legislation or technical guidance.
- Identify the many ways that information and understanding related to climate change can be inserted into the management process.
- Establish climate-ecosystem criteria that could become a standard part of review of LMR advice.

[8] Developing review-evaluation protocols that ensure consideration of climate change could be quite involved, but initially could take the form of changing the standing terms of reference in the management process to include consideration of a dynamic climate. Making this change for stock assessments, recovery plans, biological opinions, and other NOAA Fisheries management contexts would ensure that any resultant biological reference points include considerations of climate change. This change in criteria would also hold for external review panels, such as Scientific and Statistical Committees and Scientific Review Groups; for permitting, siting and review of essential fish and critical habitat, aquaculture, and NEPA consultations; and for Integrated Ecosystem Assessment scoping and reviews.

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

Simulation of LMR dynamics using climate forecasts are needed to develop management protocols that can adapt to climate change. Forward-looking management of LMRs depends on robust projections of future ocean conditions; marine, coastal, and freshwater ecosystems and LMR responses; and human socio-economic systems and their responses to changing climatic conditions and related LMR responses. Linking changes in the physio-chemical system to marine resources and ecosystems represents a major challenge. Making additional linkages to climate effects on human communities and economies is a second major challenge.

Robust, model-based projections of the effects of climate change on marine, coastal, and freshwater ecosystems, LMRs, and human communities have the potential to provide useful information for natural-resource decision-making on appropriate temporal and spatial scales. However, coupling across these models is not trivial.

Key projection considerations include:

1. A capability to downscale and bias-adjust global climate and earth system models to better resolve regional responses of marine and coastal ecosystems to large-scale climate changes.
2. Different climate scenarios to examine the effect of management choices on population dynamics, population viability, bioenergetics, multispecies interactions, biodiversity, and species distributions, as well as primary and secondary production, habitat structure, energy budgets, and ecosystems. This requires coupling for a full suite of models.
3. Social and economic models can predict how future change in LMRs may affect working waterfronts; commercial, recreational, and subsistence fishermen; anglers; aquaculture operations; the seafood industry; seafood consumers; and preferences for consumptive and non-consumptive uses of LMRs, but warrant further development and coupling with other LMR and ecosystem models. Coupling these suites of models is also needed.
4. Hotspots for change in marine, coastal, and freshwater physical condition and biogeochemistry, LMRs, and habitat, including aquaculture mitigation considerations, can be identified from data as well as via projections with coupled models.
5. Indicators that provide early warnings of rapid or impending change to LMRs, marine habitats, and ecosystems (e.g., large shifts in species phenology and distribution) need to be developed, and routinely monitored and projected as outputs of models.

Arctic seals and the ESA

In 2007–2008, NOAA Fisheries was petitioned to list ribbon, spotted, bearded, and ringed seals under the Endangered Species Act (ESA), based primarily on concerns about loss of sea ice in a disrupted, warming Arctic climate. All four of these seal species are strongly associated with sea ice as habitat for critical functions such as whelping and nursing of pups, and annual molting.

- In 2008 and 2013, NOAA Fisheries determined that the ribbon seal did not warrant listing under the ESA.
- In 2010, NOAA Fisheries determined that listing spotted seals in the Distinct Population Segments (DPSs) of the Bering Sea and the Sea of Okhotsk was not warranted. However, the Southern DPS of spotted seals (in the Yellow Sea and Sea of Japan) was listed as threatened under the ESA.
- In 2012, NOAA Fisheries determined that the bearded seal subspecies *E. b barbatus*, which occupies the Atlantic sector of the Arctic, did not warrant ESA listing. The subspecies *E. b. nauticus*, which occupies the Pacific sector, was further divided into the Okhotsk DPS (Sea of Okhotsk) and the Beringia DPS (Bering, Chukchi, Beaufort, and East Siberian Seas), both of which were listed as threatened because sea ice is projected to decline dramatically during this century in substantial areas of shallow water that are important for benthic foraging. However, these listings were vacated by a federal judge in Alaska in July 2014 (*Alaska Oil and Gas Association v. Pritzker*, 13-18-RRB, D. Alaska).
- Also in 2012, NOAA Fisheries determined that the ringed seal subspecies *P. h. saimensis* (Lake Saimaa, Finland) should retain its 1993 listing as endangered under the ESA and that *P. h. ladogensis* (Lake Ladoga, Russia) should also be listed as endangered. Ringed seal subspecies *P. h. botnica* (Baltic Sea), *P. h. ochotensis* (Sea of Okhotsk), and *P. h. hispida* (Arctic Ocean and surrounding seas) were listed as threatened. In addition to a loss of sea-ice habitat, these subspecies were listed because snow depth on sea ice during the early spring is projected to diminish during this century below the critical depth required for birthing and nursing lairs that shelter ringed seal pups from polar bear predation and hypothermia.

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Arctic seals and the ESA continued

ESA decisions such as these depend heavily on observations and projections of climate-driven change in sea ice, snow, ocean chemistry, and other key environmental factors. Too often, the best available scientific information is sufficient to support only qualitative assessments of extinction risk. Improvements in our ability to quantify the environmental factors, their variability, and their influence on survival and reproduction of living marine resources are paramount for rational ESA decision-making.

These examples show how climate change effects are being considered in an ESA context, how such effects are going to differ across species and locations, and the challenges of incorporating climate change for such arctic species in future years.

Bearded seal, ring seal pup, ribbon seal. Photo credit: Michael Cameron, NOAA Fisheries.

This list provides a sense of the magnitude, scope, and types of data-driven modeling efforts required to better understand projections of LMRs under future conditions. Any such projections need to be downscaled appropriately and temporally resolved to achieve robust projections of the state of future marine ecosystems. These projections should focus on short-, medium-, and longer-term time scales. Many NOAA Fisheries mandates require projections of population status, and working with climate scientists to provide the climate-related projections is increasingly needed to help fill these needs.   Earth system models and global climate models do not project best at scales of days to weeks, but rather at scales of multiple decades to centuries (Stock et al. 2011). The 3– to 10-year projections often needed for LMR management fall between the time scales that climate models predict well, and this poses a challenge for the future.

In addition to these model-based needs, other important products can be routinely created to meet this objective. One of the key outputs from these projections should be the identification of realistic future scenarios and feasible management strategies. These can set the stage for management actions by bounding future ranges of probable climate conditions. Doing so can minimize exploration of unrealistic scenarios and, thus, ineffective strategies.

NOAA Fisheries should work with researchers in academia and in the Office of Oceanic and Atmospheric Research to enhance its climate modeling capacity by establishing regional and national modeling teams focused on impacts to ecosystems and management of LMRs, specifically in the context of climate change scenarios. Regional modeling teams could, for example, develop and refine models, linkages among models, and scenarios that allow end-to-end modeling exercises to project the impacts of changes to climate condition on LMRs and ultimately how human communities then modify and adapt their uses of LMRs and ecosystems. They could also provide technical advice on the quality and applicability of modeling output. National teams of NOAA Fisheries experts could develop best practices for integrating changing climate conditions into modeling exercises (e.g., ensemble approach) and help the regions tackle climate change-related efforts in a coordinated and consistent way. These teams would also serve as the experts for linking new research and understanding into the development of advice.

Important strategies to bolster and better deliver climate-smart projections include:

- Develop a standard modeling toolbox (or at least documented best practices) to link future ocean and freshwater states and LMRs, with ability to couple models across types.
- Establish best practices for modeling under uncertainty (e.g., multi-model inference).
- Research socio-economic consequences of future climate scenarios and LMR, and explore range of probable human LMR-use responses.
- Build on past National Ecosystem Modeling Workshops (NEMoWs).

Collaborations on modeling are necessary for developing projections of the future

Models play an important role in understanding climate change and projecting future climate conditions given different scenarios of human behavior (e.g., different trajectories of CO_2 emissions). NOAA, through the Office of Oceanic and Atmospheric Research (OAR), is a global leader in climate modeling and provides advice to the United States and the international community in the form of understanding, attribution, and the consequences of climate change to various aspects of the Earth's system. NOAA, through NOAA Fisheries, is responsible for providing advice regarding the management of the nation's LMRs. Much of this advice is based on assessments of current status and then the forecasting of future status given different scenarios of human behavior (e.g., fishing levels). This advice is then used to set catch levels, to develop species recovery plans, or to determine the effect of a specific action on LMRs (e.g., fishing effort impacts on sea turtles). The challenge is to couple these two operational infrastructures to incorporate climate information into the advice that NOAA Fisheries is legally mandated to provide to numerous partners and stakeholders.

NOAA Fisheries and OAR researchers have worked closely together for the past decade to develop and demonstrate potential links. Climate effects have been coupled into single-species models (Fogarty et al. 2008; Hollowed et al. 2009; Hare et al. 2010); these studies show that climate will affect the reference points used in management. Climate models themselves have moved into simulating basic biological components of the Earth system (Stock et al. 2014); these models suggest that ocean biomes may shift and change in size, with potential implications for many LMRs (Polovina et al. 2011). These examples show paths forward for greater linkages between climate models and fisheries advice.

NOAA Fisheries scientists have also been working with a group of end-to-end models that link changes in the physical environment to changes in LMRs to changes in the socio-economics of fisheries (Fulton et al. 2011). These models represent the trophic interactions of ecosystems as well as the physics and human pressures. As examples, work on the West Coast demonstrates the potential cascading effects of ocean acidification on groundfish species (Kaplan et al. 2010) and, on the East Coast, the potential effect of warming on large predators (Keister et al. 2011; Nye et al. 2013). These models accommodate the interactive effects of climate change and fishing to be evaluated together and offer a powerful tool for examining the complexity of climate change and LMR dynamics. The next steps are to further improve these models and to develop greater integration between climate models and population and ecosystem models. This integration will allow the impacts of climate change on LMRs to be regularly incorporated into the scientific advice for management practices developed by NOAA Fisheries.

Objective 5: Identify the mechanisms of climate impacts on ecosystems, LMRs, and LMR-dependent human communities.

Information on how and why a changing climate is likely to affect LMRs and LMR-dependent human communities provides the foundation for projecting possible future impacts, and identifying possible strategies to reduce impacts and increase resilience. Process research, conducted both in the laboratory and the field, elucidates the mechanisms underlying how and why species, ecosystems, habitats, and human systems are or may be affected by climate change. Understanding the processes that cause these impacts can help managers identify which LMRs and ecosystems may be most vulnerable climate change and what actions may reduce climate impacts on LMRs, and can provide robust projections of changes to species, habitats, ecosystems, and human systems.

Filling key gaps in the understanding of these underlying processes will improve both NOAA Fisheries science and management, including the models used to develop projections of the future. Vulnerability assessments, improved using newly obtained knowledge of LMR sensitivity to climate change, can help identify focal areas for NOAA Fisheries scientific and management efforts. Process research informs the design of observing systems and underlies the models that project future states. Finally, process research provides the foundational knowledge for developing mitigation strategies to increase species' adaptive capacity and resilience to environmental change and/or to selectively breed climate-adapted stocks for aquaculture.

In short, climate change can affect LMRs via changes in:

- Genotype (natural selection, selective breeding).
- Vital rates (reproductive rate, emigration, immigration).
- Physiology rates (growth, consumption, respiration, metabolism, thermal tolerance).Susceptibility to disease.
- Trophic interactions.

These changes can result in a variety of subsequent changes such as:

- Mortality.
- Productivity.
- Species distribution.
- Nutritional value of prey.
- Movement of migratory species.
- Habitat structure and location.

And those changes can in turn impact other parameters such as:

- Species relative abundance.
- Community composition and predator-prey overlaps.
- Food web structure.
- Energy and matter fluxes.
- Invasive species.
- Life history.

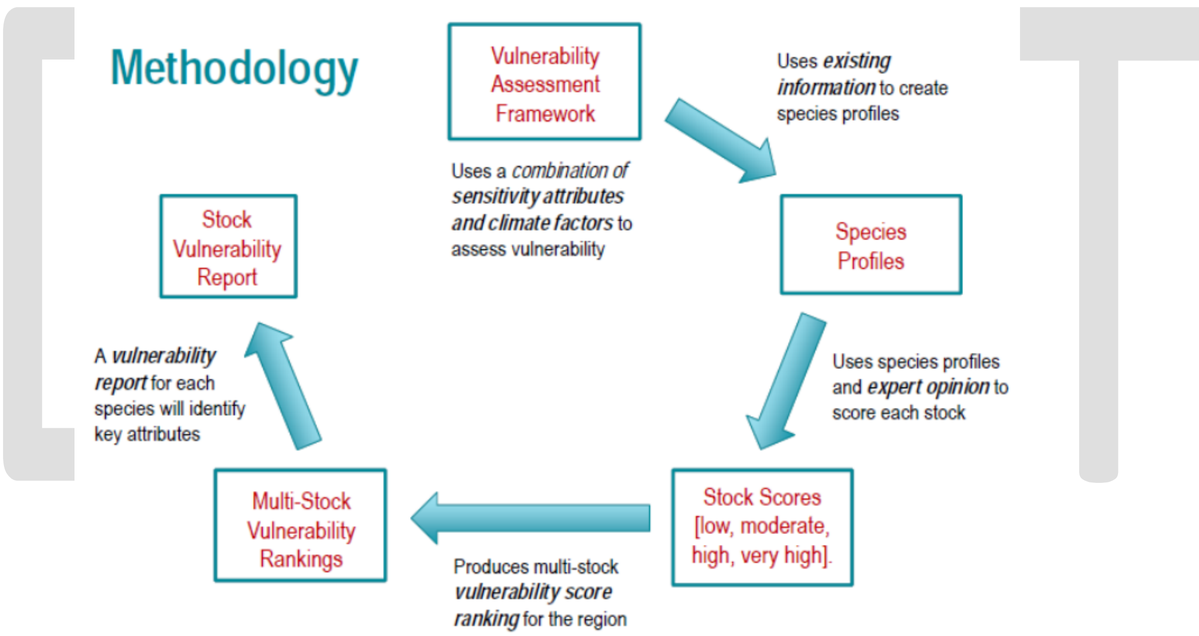
Because of the sensitivity of species physiology to environmental conditions, changing environmental conditions may affect the distribution, migration, depth, and behavior of some species (see text boxes). Improving our understanding of how and why this change may occur provides mechanistic understandings needed for development and implementation of robust NOAA Fisheries management strategies. 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 of environmental conditions. Laboratory experiments can 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 ecological and ecosystem resilience. Likewise, ethnographic fieldwork can be done to 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 given future conditions.

NOAA Fisheries' current capacity to conduct process-based research will not meet the demand for understanding how aquatic species, ecosystems, and LMR-dependent human communities may respond, acclimate, or adapt to climate change. Developing this capacity will require significant financial 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 equipment required to process samples rapidly. In some cases, NOAA Fisheries has the needed assets, but needs the support and change in priority to apply these assets to process studies related to climate change. NOAA Fisheries needs to articulate the need for process-based research throughout the organization and beyond, then incorporate new understanding from this research into management advice. Strong partnerships with research institutions and funding agencies (e.g., National Science Foundation, National Aeronautics and Space Administration, Environmental Protection Agency, Department of Energy, Department of the Interior, and other NOAA line offices; Table 2) are also critical.

Further, 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, and provide 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. Within NOAA Fisheries' current portfolio of research activities, observation-based integrative studies and translations of climate change are handled more comprehensively than

Vulnerability assessments
Vulnerability assessments identify LMRs, habitats, or human communities that are especially sensitive (or especially resilient) to climate change. Such assessments combine exposure to physical conditions with sensitivity to these conditions and aim to identify vulnerability. Vulnerability assessments should be viewed as iterative, with an update frequency linked to the International Panel on Climate Change Assessment Reports (4 to 5 years). They have been developed for fisheries stocks (Mueter et al. 2011; Wainwright and Weitkamp 2013) and communities (Gaichas et al. In press), marine mammals (Boveng et al. 2009), highly migratory species, habitats, ecosystems, and human social and economic systems. These assessments essentially utilize globally established best practices in risk assessment, particularly considering multiple criteria. They are a robust, feasible approach to help "triage" species and habitats in an ecosystem.

Methodology used by the NOAA Fisheries Fish Stock Vulnerability Assessment project, which has been piloted for Northeast fisheries stocks.



laboratory and field investigations of life history traits, genetics, and other physiological consequences of climate change. While these types of research are touched upon in some programs, NOAA Fisheries would need to build capacity to create the volume of targeted research necessary to achieve results commensurate with this aspect of NOAA Fisheries' science mission and the mechanisms for integrating this knowledge into ecosystem-level understanding.

A number of products could be routinely created to meet this objective. One of the key items in targeted research is to know what research is needed. An assessment that identifies the major

Migration of Adult Sockeye Salmon

Sockeye salmon, like other anadromous fishes, lay eggs in freshwater, migrate to the ocean as juveniles, and return to their natal waters to spawn 2 to 4 years later. Like other salmonids, they tend to be highly locally adapted to the combination of conditions in their freshwater and marine environments. The Columbia River basin was historically home to many populations of lake-spawning sockeye salmon; several populations of these remain, with the largest population found in the Okanogan Basin, Canada. Since the Columbia River was dammed, however, these fish have faced changes in temperature and flow that have altered the natural environment. Currently, the Columbia River reaches biologically important temperatures over 2 weeks earlier than it did in the 1950s, and experiences a mean temperature in June and July, when sockeye migrate, that is about 1.5°C warmer. In addition, mean flow during migration periods is over 50 percent lower than it was historically (Quinn and Adams 1996; Quinn et al. 1997). In response, sockeye salmon have changed both the speed and timing of their migration – arriving nearly 11 days earlier at dams along the Columbia than they did in the 1950s. Crozier and colleagues (2011) used a modeling approach to determine that an evolutionary response to thermal selection explained up to two-thirds of this trend in earlier arrival time, translating to a shift of about 0.3 days per generation. Most of the remainder of this trend appears to be due to a plastic response to changes in flow. The increase in temperature in this system is attributable to both impoundments (e.g., dams) and climate change; it is likely to continue as global temperatures increase. Importantly, these fish are subject to selective pressures in all of their environments, which may impose constraints on the species' ability to adapt to ongoing rises in temperature.

Sockeye salmon spawning aggregation. Photo credit: Lisa Crozier, NOAA Fisheries.

gaps in the research useful for generating data to inform management under climate change is needed for each region. The items above should be compiled into a national inventory of data gaps. Any such research pursuit would be in relation to one of the main climate-change-induced pressures on the physio-chemical environment noted in Figure 1. This would need to be followed by research into the socio-economic responses of human communities to such changes.

Research undertaken to meet this objective can be used to develop updated parameters for LMR and ecosystem models. Providing revisions to model functional form, structure, and parameterization will afford better predictive capabilities of LMR responses to a changing climate and ocean. Additionally, targeted process research can be used to develop mitigation strategies for either reducing climate impacts on LMRs or providing for lost value and services to human communities due to climate change. For example, development and/or restoration of kelp forests and eel grass beds may provide some protection from ocean acidification and low oxygen. Similarly, researchers are testing whether seaweed and shellfish farms may provide similar ecosystem services important in a change climate if expanded over a larger area of the ocean than natural beds (e.g., Chung et al. 2013). Aquaculture provides an opportunity to explore human intervention to reduce climate change impacts to vulnerable life stages and species.

Important strategies to bolster and better deliver climate-smart process research include:

- Identify process research gaps in each region.
- Develop additional NOAA process research capacity internally and through competitive funding opportunities.
- Develop and maintain partnerships to conduct climate-LMR-related research.
- Organize and host regular national climate workshops with LMR emphasis for NOAA employees across line-office and external partners to advance research efforts and promote collaboration.
- Develop and maintain partnerships with international and other organizations to conduct LMR-climate workshops.
- Organize and host regional thematic workshops related to LMR response to climate change (regime shift, distribution shift, vital rates, etc.).
- Conduct research to identify a suite of proposed mitigation strategies, including those targeted at LMR-dependent human communities.

> One of NOAA Fisheries' key partnerships is with NOAA Office of Oceanic and Atmospheric Research. NOAA Fisheries and Oceanic and Atmospheric Research scientists have collaborated successfully for decades. Many of these collaborations are at the individual scientist level, but examples of institutional partnerships exist (e.g., between Pacific Marine Environmental Laboratory and Alaska Fisheries Science Center). Such cross-NOAA partnerships are crucial for moving forward with climate-informed LMR management.

- Strengthen core science partnerships with formal mechanisms, especially with academic institutions, NASA, USGS, NSF, EPA, etc.

Although more process research could be conducted to inform management decisions, and although copious uncertainty about species performance in a changing climate context persists, common themes and consistent patterns related to climate change could provide the basis upon which NOAA Fisheries can act. Not knowing a particular functional form, mechanistic detail, or relationship between LMR responses and climate variables should not preclude NOAA Fisheries from acting in situations that have generally known LMR and ecosystem response trajectories.

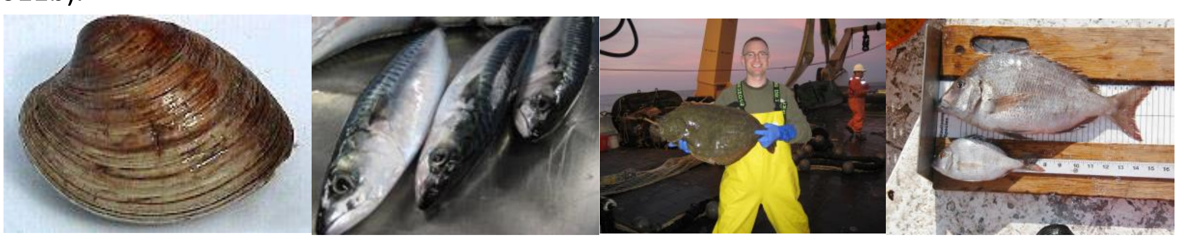
Changing fisheries behavior in response to climate-induced changes to LMRs

Marine fisheries distributions are changing in response to climate change. Pinsky et al. (2013) found that, in general, changes in species distributions around North America tracked changes in environmental conditions. However, they identified important regional differences. For example, species in the Northeast United States shifted northeast on average, but species in the Gulf of Mexico shifted southwest; the Gulf Coast precludes a northward shift. These results demonstrate how regional geomorphology and oceanography influence how a species or stock responds to climate change.

In the Northeast region specifically, Nye et al. (2009) found that approximately two-thirds of the stocks investigated shifted distribution. A majority of observed shifts were northward (~80%) and into deeper water (~85%). However, some stocks moved to the south and some moved into shallow water. These results demonstrate the importance of the interaction between climate change and individual species life history and ecology.

Changes in fishery distributions can result from shifts in individuals or spatial changes in population productivity. For example, the distribution of Atlantic surfclam has changed on the northeast U.S. shelf (Weinberg et al. 2005). Surfclams are sessile as adults, and the changes in distribution have been linked to increased mortality (decreased productivity) at the southern end of the range owing to increasing temperatures. In contrast, the distribution of Atlantic mackerel has changed, and this is at least partially linked to a change in migration and in overwintering habitats as a result of warming (e.g., changes in individual distribution; Overholtz et al. 2011; Radlinski et al. 2013).

Changes in distribution can be caused by any one of several stressors; the two primary stressors are climate change and fishing. Bell et al. (in review) found that the northward movement of summer flounder was related to increasing age-class structure over time, which is likely a result of decreased fishing and stock rebuilding. In contrast, the northward movement of scup and black sea bass was related to warming. These results emphasize the importance of documenting trends in distributions, studying the mechanisms that cause changes in distribution, and then transitioning this information into advice for use by LMR managers (see Link et al. 2011a; Link et al. 2011b).



Atlantic surfclam, Atlantic mackerel, summer flounder, scup (Credit: NOAA)

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, resources, and LMR-dependent human communities is essential to 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. NOAA Fisheries 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, but most do not. NOAA Fisheries has three main needs related to this objective:

- Monitoring programs to track LMRs, ecosystem dynamics, and LMR-dependent human communities.
- Development of good physical, biological, and socio-economic indicators for tracking trends related to climate change and early warning signals of change.
- Regular reports to present and interpret monitoring data while considering the effects of climate change.

Climate-change-related biophysical data—such as observed trends in sea surface temperature, upwelling indices, sea level height, biogeochemistry, food chain structure, or regional hydrology—need to be regularly incorporated into LMR, ecosystem, and habitat assessments. These form the basis from which links between change in physical conditions and biotic variables can be established (Figure 1). Information on the status and trends of ecosystems, LMRs, and resource-dependent communities is needed to modify management reference points for LMRs, habitats, ecosystems, and human communities to incorporate climate change and its impacts (e.g., NOAA Coastal Services Center 2014).

An important and regular product should be ecosystem status reports (ESRs and related ecosystem advisories, chapters, etc.). ESRs provide multi-dimensional examination of the ecosystem from physical and habitat condition to trends in LMR abundance and resource use by fleets and communities.[9] Typically they include brief narratives describing trends within the numerous time series analyses presented. Even apart from formal modeling through to specific biological reference points, the information provided in these ESR has been useful for providing broader context and leading indicators to inform LMR management. Future ecosystem status reports could be enhanced by interpreting detected changes within the current understanding of ecological processes of each large marine ecosystem. Adding climate change projections to these status reports is an important need and will provide information about the projected future states of the ecosystem. Integrating data sets of climate change that are current, are specific to the management tasks, and represent state-of-the-art understanding requires that synthesis products be developed and regularly updated. Such products are designed to serve multiple NOAA Fisheries management requirements, and do so because of shared information needs on climate-change-related impacts on the physical, chemical, biological, and socio-

[9] http://www.noaa.gov/iea/

economic components of marine, coastal, and freshwater ecosystems. The simple presentation of multidimensional information in ESRs is critical in the production and delivery of climate-change-related information for decision-making. One can readily envision compiling all the regional ESRs to form a national report on climate-related LMR status.

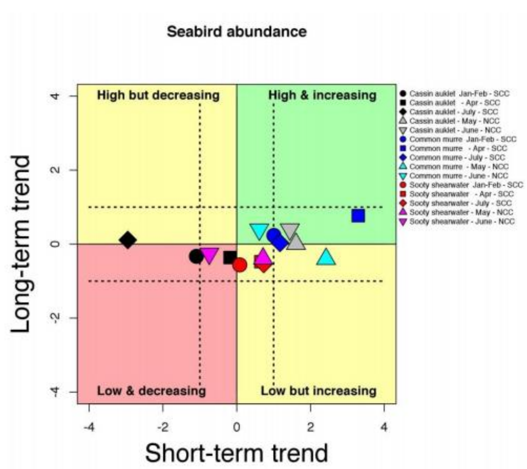
Deciding on which indicators to include in an ecosystem status report requires knowledge of ecosystem structure and function, the biogeochemical processes that influence the ecosystem, human use of and impacts on the ecosystem, and vulnerability of the ecosystem to climate change. Investing time and resources into the evaluation and development of useful indicators is an important task to undertake when designing ecosystem-climate observing systems and ecosystem status reports (Peterson et al. 2013). Necessary new indicators of change could be identified as the impacts of climate change develop.

Further, the biological and physical indicators developed from ESRs can be used to establish future thresholds and decision criteria (Samhouri et al. 2010; Fay et al. 2013; Large et al. 2013). This empirical exploration of ecosystem, habitat, and aggregate groups of LMR BRPs has been solidly rooted in such indicators. The full suite of multidimensional data can be noisy and typically incorporate multiple patterns (e.g., warming trend overlaid on El Niño-Southern Oscillation and Pacific Decadal Oscillation). Complex statistical techniques can distinguish the multiple drivers of change through time series analysis and are used to isolate signals in the data. Such statistical and analytical exercises are relatively novel, and technique development could also advance NOAA

<u>*Ecosystem Status Reports*</u>

Ecosystem status reports (ESRs) have emerged as useful, common reporting tools in the past few years. ESRs track trends in marine, coastal, and aquatic ecosystems and can be incorporated into the stock assessment process. ESRs exist as the Ecosystems Considerations Report for the Alaska Fisheries Science Center and the State of the California Current Report jointly produced by the Northwest and Southwest Fisheries Science Centers. They are produced annually or biennially, with some regions adding short-term updates between report publication dates. Such ESRs are important as compilations of leading indicators of climate change and climate effects on living marine resources.

Quadratic plot of trends in abundance at sea for the two most common piscivorous birds in the California Current large marine ecosystem (common murre, sooty shearwater) and one of the common planktivores (Cassin's auklet). *From Levin et al. (2013)[Please indicate how this graphic relates to the text in this box]*



Fisheries' understanding of ecosystem state.

The detection and reporting of status and trends of physical and biological data could also provide commonly needed climate-related data inputs for LMR and ecosystem models. These data vectors or matrices can serve as direct inputs, covariates, data modifiers, parameter tuning sets, or similar value in a host of LMR and ecosystem models.

Important strategies to bolster current status estimates include:

- Utilize climate vulnerability risk analyses to conduct triage and prioritization for climate change science related to LMR management.
- Develop and maintain standard climate-LMR report cards to communicate data and understanding available to all stakeholders.
- Conduct regional assessments of strengths, weakness, opportunities, and challenges related to LMR science and management in the face of climate change.
- Emphasize the critical need of ongoing monitoring in science planning and budgeting processes.
- Train staff in time-series analyses.
- Engage in scoping exercises related to LMR science and management in the face of climate change with partners and constituents.

The Pacific Decadal Oscillation, Food Chain Structure, and Salmon Returns to the Columbia River

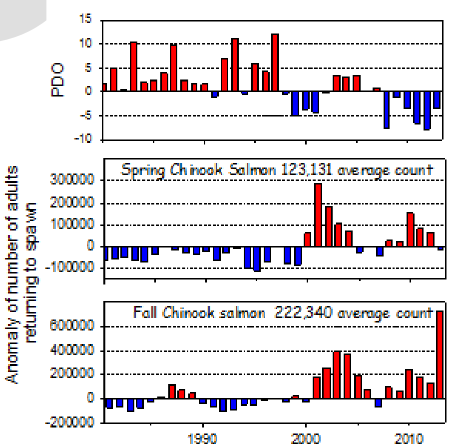
Mantua et al. (1997) showed that changes in the sign of the Pacific Decadal Oscillation (PDO, a basin scale climate indicator) translate into changes in salmon returns (a local response) throughout the North Pacific. When the PDO is in a warm phase, returns are relatively low for salmon that spawn in the Columbia River system and other rivers that discharge into the California Current. The opposite is true during the cool phase of the PDO. This is illustrated below, where it is shown that from 1980 through 1998, the PDO was in warm phase (red bars) and salmon returns were below average (blue bars). When the PDO turned negative (to cool phase) in late 1998, salmon returns rebounded with a 2-year lag for spring Chinook (which spend 2 years at sea) and with a 3-year lag for fall Chinook (which spend 3 years at sea). The PDO changed sign again in 2003 (warm phase) and 2008 (cool phase), and salmon again responded predictably to these changes. (http://www.nwfsc.noaa.gov/ and click on "Salmon Forecasting")

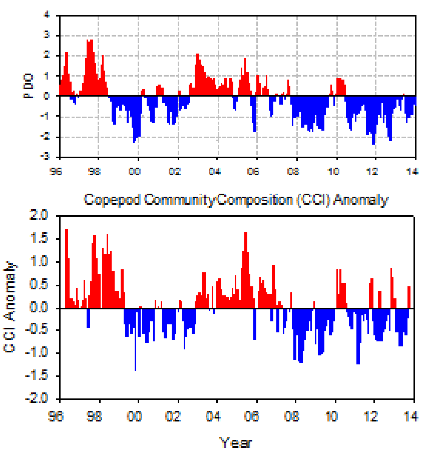
The Pacific Decadal Oscillation, Food Chain Structure, and Salmon Returns continued

A mechanism for these sudden changes in salmon returns was offered recently by Hooff and Peterson (2006) and Keister et al. (2011). They showed that changes in zooplankton (copepod) community composition were closely linked with the PDO. Further, they pointed out that cold-water copepod communities are dominated by species that are relatively large and enriched with lipids, especially omega-3 fatty acids, which are needed and desired by young salmon.

Hooff and Peterson (2006) and Keister et al. (2011) hypothesized that the mechanism linking the PDO with salmon returns is related to the source waters that feed the northern California Current and the species composition of copepods in these source waters. During negative PDO, the bulk of the water entering the northern California Current is from the coastal Gulf of Alaska and the zooplankton are dominated by large lipid-rich copepods; when the PDO is in positive phase, the source waters are from offshore and small subtropical copepods (which lack significant amounts of lipids) are transported to the northern California Current. Salmon returns are high during the cool phase of the PDO because the food chain is bio-energetically enriched with lipids from the cold-water copepods and these lipids are transferred up the food chain, through the krill and forage fish upon which salmon feed.

(Left) PDO and returns of Columbia River spring and fall Chinook over time (NOAA Northwest Fisheries Science Center 2014).(Right) PDO and copepod community composition index anomaly over time (from Keister et al. 2011; Batchelder et al. 2013, with updated data from B. Peterson, NOAA NWFSC).





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Objective 7: Build and maintain the science infrastructure needed to fulfill NOAA Fisheries mandates under changing climate conditions.

Adequate scientific infrastructure is critical to the science enterprise described in this Strategy. However, NOAA Fisheries' existing infrastructure is not adequate to meet those science needs. Here, we identify extant programs that could be built upon, better coordinated, or expanded to meet the needs outlined in the Strategy with minimal disruption to NOAA Fisheries as it fulfills its mandates. Clearly there is a general need for increased capacity to link climate change and LMRs. But what would that entail?

Observational data on the physical and chemical conditions that freshwater, coastal, and marine organisms experience in their environment are a fundamental part of understanding species response to ocean and climate change. While NOAA Fisheries supports a variety of biological, physical, and human system monitoring efforts that inform fisheries and ecosystem management (e.g, North Pacific Climate Regimes and Ecosystem Productivity, Integrated Ecosystem Assessments, etc.), these efforts fall short of what is need to adequately track the impacts of climate change. 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 collected in the system is required to meet NOAA Fisheries' needs today and in the future. Doing so would provide the data needed to deliver core information on the status and trends of marine, coastal, and freshwater ecosystems and human systems under climate change, and could provide early warnings of rapid or impending changes.

Building and maintaining an adequate physical, chemical, and biological observing system will require a variety of critical science infrastructure, including ship time, remote observing assets, establishment of key partnerships, and personnel to collect and process samples. Ideally, a large component of the modified observing system would be ongoing fisheries oceanography and LMR monitoring time series, but paired with simultaneous physical-chemical observations in both marine and freshwater systems. Building and maintaining an adequate observation system for fishing- and LMR-dependent community resource use and overall well-being will require a similar amount of effort given the sheer amount of time required to collect and analyze socio-economic data. Where gaps exist between projected needs and ongoing time series, NOAA Fisheries should increase support for existing activities and initiate, to the extent feasible, new observational time series to generate data relevant to managing LMRs and human communities over the coming decades. Ideally, observing efforts would include concurrent, integrated, interdisciplinary collection of physical, chemical, biological, and socio-economic data.

To succeed in implementing the Strategy, NOAA Fisheries will need to evaluate and possibly adopt novel and advanced sampling approaches and invest in enhanced computing technologies and laboratory assets. Many of the advances made for the next generation of remote and unmanned sampling and ocean observation systems will be operational in the next few years, and others are ready now. Taking advantage of the efficiencies and precision these devices can provide will open up new data sets requisite for tracking climate change (e.g., underwater gliders to measure physical and chemistry conditions, accurate and precise ocean carbon chemistry sensors, acoustic monitoring of fish populations).

Many of the observing systems and modeling exercises described above, especially future projections and hind-casting, require computing systems that can store large data sets and are fast enough to complete scenarios in a reasonable amount of time. Expansion of computing systems is required to meet these needs. Collection of high-quality, species-response data will require laboratories with specialized equipment and animal holding facilities to elucidate physiological and genetic responses of LMR's to future conditions (e.g., Northwest Fisheries Science Center's ocean acidification experimental system).

Improved data access and data visualization tools are necessary for fully sustaining and supporting the science enterprise outlined in the Strategy and implementing the Strategy successfully over time. Maintaining data archives accessible inside and outside of NOAA Fisheries, as appropriate, with appropriate database infrastructural elements is one step for doing so. Additionally, improving access to data, meta-data, and data servers will likely increase the utility of the data collected, and make it more palatable for use in other facets of the Strategy. Development of data visualization tools would facilitate uptake and understanding data related to climate change.

Staffing considerations are key for addressing this strategy. Dedicated LMR-climate staff are needed in the science centers and regional offices to help produce, deliver, and use climate-related information in fulfilling NOAA Fisheries' mission activities. There is also a need for training and development of analytical capacity for NOAA Fisheries personnel. Research and provision of climate-smart management advice is predicated upon a workforce with the vision, understanding, and capability to analytically address the needs described throughout this Strategy. Additional analytical billets, quantitative training, and increased awareness of climate-change needs are warranted to increase the production, delivery, and use of climate-related information in fulfilling NOAA Fisheries' mission activities.

Many entities outside of NOAA Fisheries collect data, conduct research, build models, and develop predictions that are useful for projecting future states of LMRs, habitats, ecosystems, human communities, and their use of LMRs under climate change (Table 2). Communication of the utility of these resources and their contribution to NOAA Fisheries' LMR mandates should be highlighted by NOAA Fisheries. NOAA Fisheries has a foundation of partnerships within NOAA (e.g., Office of Oceanic and Atmospheric Research, National Ocean Service) and with other entities (e.g., state and other federal agencies, academia, industry etc.; Table 2). Building on and strengthening these internal and external foundations are a critical component of developing an efficient and comprehensive capacity for modeling future states. Gaps in scope and capacity of NOAA Fisheries programs will necessarily need to be filled by expanding existing and establishing new partnerships with programs outside the agency.

Important strategies to bolster and better deliver climate-smart science infrastructure include:

- Increase the Fisheries and the Environment (FATE), Fisheries Oceanography, and IEA program budgets, including investment in socio-economic research.
- Maintain 10 percent of overall NOAA Fisheries science budget directed to process-oriented research.
- Establish dedicated climate-LMR FTEs at each fisheries science center with a portion of their time dedicated to coordinating with managers in NOAA Fisheries Regional Offices through regional teams.
- Bolster NOAA Fisheries climate-LMR coordination nationally.
- Continue and expand NOAA Fisheries' participation in cross-governmental efforts related to climate change.

Chapter 3

MOVING FORWARD

Given the scale of U.S. dependence on LMRs, and the expected pace, scale, and scope of climate-related impacts on marine, coastal, and freshwater ecosystems, immediate action is needed to understand, prepare for, and respond to these changes in ways that reduce impacts and increase resilience of LMRs for current and future generations (Osgood 2008; Intergovernmental Panel on Climate Change 2013; Melillo et al. 2014). This Strategy provides a blueprint for strengthening the production, delivery, and use of the climate-related information needed to fulfill NOAA Fisheries mandates in a changing climate. It is intended to provide a national framework that can be regionally tailored and implemented through NOAA Fisheries Science Centers, Regional Offices, and their partners via existing planning processes. Implementation of the Strategy over the next 5 years is critical for effective fulfillment of NOAA Fisheries mission and mandates in a changing climate.

This Strategy identifies seven priority objectives and strategies to address them. Many of the recommendations are designed to address common needs across mandates, regions, and LMRs, so implementation of these items could have especially high utility and return on investment. 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 that will need to be assessed as part of developing Strategy implementation plans for each region. The seven objectives are intended to identify areas that should be addressed by each region, although the specific actions and priorities should be determined by science and management experts in each region.

The Strategy is designed to provide a consistent, national framework that is primarily implemented through regional plans. The regional implementation plans will focus on building regional capacity, products, and services under the seven objectives based on evaluation of regional, climate-related, LMR information needs, and existing strengths, weaknesses, opportunities, and challenges to address them. While the particular timeline for implementation will depend on specific budget realities, regional implementation plans are expected to guide implementation of this Strategy through a variety of means, including adjustments to programs within existing budgets and initiation of additional efforts using new resources.

In developing this Strategy, a variety of science and information needs came up repeatedly as priorities to be addressed because they were common needs across many mandates and regions. Addressing these needs is key to meeting a variety of other requirements and, if filled, would advance climate-ready LMR management over the next 5 years.

The following is a list of recommendations to help implement this Strategy. This list is designed to help launch and make major strides toward implementation over the next 5 years. Implementing these recommendations will efficiently and effectively increase the production, delivery, and use of climate-related information in NOAA Fisheries LMR management and thereby reduce impacts and increase resilience of LMRs and the people that depend on them in a changing climate.

PRIORITY ACTIONS:

Three main products or activities consistently emerge across all seven objectives of the Strategy. We highlight these here as the major, ongoing, prioritized actions that will best help NOAA Fisheries address its mandates in a more climate-ready manner. We recommend these be adopted and executed as soon as is appropriate, given the other, more time-constrained or infrastructural needs subsequently identified below.

1. Conduct climate vulnerability analyses in each region for all LMRs.
2. Establish and strengthen ecosystem indicators and status reports in all regions.
3. Develop capacity to conduct management strategy evaluations regarding climate change impacts on management targets, priorities, and goals.

PRIORITY NEAR-TERM ACTIONS:

The following are key near-term recommendations to advance implementation of this Strategy in the 6 to 24 months after the release of this report:

1. Strengthen climate-related science capacity within each region and nationwide.
    a. Bolster national and region-level capacity for implementing the Strategy and advancing LMR-ecosystem-climate initiatives to support implementation
    b. Establish dedicated LMR-climate leads at Science Centers and Regional Offices to increase coordination, priority setting, evaluation, and implementation of the Strategy at regional levels.
    c. Establish regional climate-LMR teams composed of Science Center, Regional Office, and external partners to help strengthen the production, delivery, use, and evaluation of climate-related information in LMR management.
    d. Strengthen production and delivery of output from climate-driven regional ocean models used for projecting climate impacts on LMRs
    e. Strengthen production and delivery of output from climate-driven regional models of temperature, precipitation, and other factors used for projecting climate impacts on LMRs in coastal and freshwater habitats.
2. Develop regional-level implementation plans to execute this Strategy based on Science Center, Regional Office, and external partners' assessment of:
    a. Specific climate-LMR issues in the region.
    b. Barriers to producing, delivering, and incorporating climate-related information into LMR management.

   c. Major climate-related data and information gaps in the region.
   d. Existing strengths, weaknesses, opportunities, and challenges to implement the Strategy.
3. Ensure that adequate resources are dedicated to climate-related, process-oriented research.
   a. Initiate or expand partnerships with key science providers (e.g., OAR, NASA, USGS, NSF, IMR) to leverage and attract resources to help meet NOAA Fisheries climate-related science and information needs.
   b. Leverage planned and new initiatives.
4. Establish standard, climate-smart terms of reference to apply to all of NOAA Fisheries LMR management, environmental compliance requirements, and other processes that cross multiple mandates and core policy areas.

PRIORITY MEDIUM-TERM ACTIONS:

The following are key medium-term recommendations to advance implementation of this Strategy. These are intended to be ongoing with significant progress (e.g., first phase completed) within 2-5 years after the release of this report:

Workshops and training

1. Establish regular, NOAA-wide, national, climate-science workshops with LMR emphasis, with a focus on climate-ready BRPs and science for setting Harvest Control Rules, ESA evaluations (section 7 and section 10), essential fish habitat consultations, aquaculture, and NEPA analyses in a changing climate.
2. Increase awareness of and training for NOAA Fisheries science and management staff on the impacts of climate change on LMRs and climate-informed LMR management practices.
3. Organize and conduct regime-shift detection workshops for each region.
4. Organize and conduct distribution shift workshops, with implications for stock and population identification and unit area across all LMRs in each region.
5. Organize and conduct vital rate workshops, with implications for LMR life-history parameters across all LMRs in each region.
6. Organize and conduct workshops aimed at identifying regional data gaps (biological, physical, and socio-economic) related to climate variability and change and devising data collection programs aimed at filling those gaps, especially socio-economic gaps.

Engagement and outreach

7. Develop and execute national and regional science communication plans for increasing dissemination of climate-related LMR science and information to technical users and other interested stakeholder audiences.
8. Expand and support engagement with international partners to advance the production, delivery, and use of climate-related information (e.g., Climate-LMR related workshops, symposia, meetings, etc.) with specific focus on climate-

informed biological reference points, climate-smart Harvest Control Rules, management strategy evaluations for climate-ready LMR management, climate-smart protected species and habitat consultations, and management strategy evaluations for climate-ready species and habitat recovery.

9. Continue and expand NOAA Fisheries' participation in cross-governmental, national efforts to advance climate-related science LMRs.

Science to inform policy

10. Work with partners to re-evaluate risk policies under a changing climate and ocean.
11. Establish science-based approaches for shifting biological reference points to account for changing productivities, distributions, and diversities.
12. Conduct management strategy evaluations on climate scenarios in extant ecosystem and population models in conjunction with NOAA IEA program, NOAA Fisheries Stock Assessment Improvement Plan Update/Next Generation Stock Assessment, NOAA Fisheries Protected Resources Stock Assessment Improvement Plan, and development of ESA Five-Year Status Reviews.
13. Establish science-based thresholds for exiting and entering fisheries.
14. Establish and implement clear policies and practices for incorporating climate change into all NEPA and ESA (i.e., listing, recovery planning, interagency consultations, and permitting) activities.
15. Establish and implement standards and guidelines for incorporating climate change information into Fisheries Management Plans and Fisheries Ecosystem Plans.
16. Develop and implement standards and practices to promote climate resilience and climate mitigation in NOAA Fisheries habitat conservation activities.
17. Develop climate-driven regional ocean models for use in projecting climate impacts on LMRs.

Science planning and management

18. Develop a national inventory of key science and information gaps related to NOAA Fisheries LMR and socio-economic responsibilities, building on regional data/information gap assessments.
19. Increase support for existing programs addressing priority needs and objectives identified in this Strategy (e.g., FATE, Fisheries Oceanography, IEA).
20. Establish common climate-smart input data vectors/matrices for inclusion in LMR assessments in conjunction with NOAA Fisheries Stock Assessment Improvement Plan Update/Next Generation Stock Assessment and Protected Resources Stock Assessment Improvement Plan, and development of ESA Five-Year Status Reviews.
21. Identify and support process research linking changing climate and ocean to LMR dynamics.
22. Identify and maintain capability to execute process-oriented oceanographic cruises for climate-smart observations.
23. Increase capability to undertake climate-smart, socio-economic research projects and analyses of human uses of LMRs and their ecosystems.
24. Develop climate-resilient and climate-mitigating aquaculture strategies.

SUMMARY

In summary, changes in the planet’s climate system are already affecting the nation’s valuable marine, coastal, and freshwater LMRs. These impacts will affect the services these LMRs provide; the many people, businesses, and communities that depend on LMRs (Osgood 2008; Doney et al. 2012; Melillo et al. 2014); and NOAA Fisheries’ LMR management efforts.

This Strategy outlines seven key parts of the operational framework needed to incorporate climate change into the management of LMRs and their associated habitats, ecosystems, and human systems. It is clear that addressing the information and management challenges of climate change will require a cross-cutting effort that spans NOAA Fisheries LMR stewardship mandates (Figure 3) and many partners (Table 2). Thus, in many respects the need to adopt ecosystem-based management is crucial as we move to implement this strategy (MacLeod and Leslie 2009; Link 2010). From the seven objectives of the Strategy, several common items with high utility are identified as priorities with high return for investment. These are approaches that are valuable across mandates, regions, LMRs, and priority areas. The commonality of information needed across mandates should be useful to gain efficiencies in how that material is produced and delivered.

The main recommendations of the Strategy emphasize facets of climate-related LMR science and management that address critical needs and will have a high return on investment. With adequate resources (people, funding, technology), implementation of the Strategy will provide resource managers with the information they need to sustain the nation’s valuable LMRs and the people that depend on them in a changing climate.

GLOSSARY

Adaptation: (1) An adjustment in natural or human systems to a new or changed environment that exploits beneficial opportunities or moderates negative effects (Melillo et al. 2014); (2) Minimizing the impact of climate change on fish and wildlife through the application of cutting-edge science in managing species and habitats (U.S. Fish and Wildlife Service 2010).

Biological Reference Point(s): A biological benchmark against which the abundance of the stock or the fishing mortality rate can be measured in order to determine its status. These reference points can be used as limits or targets, depending on their intended usage (Blackhart et al. 2006).

Climate Change: Refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer (Intergovernmental Panel on Climate Change 2007).

Climate System: The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land use change (Intergovernmental Panel on Climate Change 2013).

Climate Variability: Refers to variations in the mean state and other statistics of the climate on all temporal and spatial scales beyond that of individual weather events (Intergovernmental Panel on Climate Change 2007).

Diadromous: Diadromous species spend part of their life-cycle in fresh water and other part in salt water. Diadromous is the term used to refer to anadromous, catadromous, or amphidromous species.

Ecosystem connectivity: Ecosystem connectivity is the degree in which the marine ecosystem facilitates or impedes movement among different habitats. Connectivity includes both structural connectivity (the physical arrangements of habitats) and functional connectivity (the movement of individuals among habitats).The degree to which an ecosystem is connected determines the amount of dispersal there is among habitats, which influences gene flow, local adaptation, extinction risk, colonization probability, and the potential for organisms to move as they cope with climate change.

Ecosystem Based Management: Ecosystem Based Management is an integrated approach to management that drives decisions at the ecosystem level to protect the resilience and ensure the health of the ocean, our coasts and the Great Lakes. Ecosystem Based Management is informed by science and draws heavily on natural and social science to conserve and protect our cultural and natural heritage, sustaining diverse, productive, resilient ecosystems and the services they provide, thereby promoting the long-term health, security, and well-being of our Nation (Ocean Research Advisory Panel 2013).

Fisheries Management Plan: A document prepared under supervision of the appropriate fishery management council for management of stocks of fish judged to be in need of management. The plan must generally be formally approved. A Fisheries Management Plan includes data, analyses, and management measures. A plan containing conservation and management measures for fishery resources, and other provisions required by the Magnuson-Stevens Act, developed by fishery management councils or the Secretary of Commerce (Blackhart et al. 2006).

Greenhouse Gases: A gas in the atmosphere of natural or human origin that absorbs and emits thermal infrared radiation. Water vapour, carbon dioxide, nitrous oxide, methane and ozone are the main greenhouse gases in the Earth's atmosphere. Their net impacts is to trap heat within the climate system (Intergovernmental Panel on Climate Change 2013).

Integrated Ecosystem Assessment: An Integrated Ecosystem Assessment is a formal synthesis and quantitative analysis of information on relevant natural and socioeconomic factors in relation to specified ecosystem management goals. It involves and informs citizens, industry representatives, scientists, resource managers, and policy makers through formal processes to contribute to attaining the goals of an ecosystem approach to management (Levin et al. 2008).

Intensity of upwelling and downwelling: Upwelling intensity depends on wind strength and seasonal variability, as well as the vertical structure of the water, variations in the bottom bathymetry, and instabilities in the currents. Upwelling is the upward motion of cold, nutrient rich deep water along the coast. Downwelling involves the downward motion of warm waters along the coast. (NOAA: http://oceanservice.noaa.gov/facts/upwelling.html)

Large Marine Ecosystem: Large Marine Ecosystems are large areas of ocean space, approximately 200,000 km^2 or greater, that have been identified for conservation purposes. They are located in coastal waters characterized by unique species, levels of productivity, bathymetry, and hydrography (Blackhart et al. 2006).

Management Strategy Evaluation: The evaluation of a strategy adopted by the management authority to reach established management goals. In addition to the objectives, it includes choices regarding all or some of the following: access rights and allocation of resources to stakeholders, controls on inputs (e.g., fishing capacity, gear regulations), outputs (e.g., quotas, minimum size at landing), and fishing operations (e.g., calendar, closed areas, and seasons) (Blackhart et al. 2006).

Mitigation: Implementing actions to reduce greenhouse gas emissions or increase the amount of carbon dioxide absorbed and stored by natural and man-made carbon sinks (Melillo et al. 2014).

Mixed layer depth: The surface layer of the ocean that is mixed by the action of waves and tides so that the waters are nearly isothermal and isohaline; underlain by a pycnocline

Nutrient availability: Chemicals (such as nitrogen and phosphorus) that plants and animals need to live and grow. At high concentrations, particularly in water, nutrients can become pollutants.

Ocean acidification: Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity (Intergovernmental Panel on Climate Change 2013).

Ocean Circulation: The large scale movement of waters in the ocean basins. Winds drive surface circulation, and the cooling and sinking of waters in the Polar Regions drive deep circulation.

Potential Biological Removal: Defined by the MMPA as the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population. The Potential Biological Removal level is the product of the following factors: the minimum population estimate of the stock; one-half the maximum theoretical or estimated net productivity rate of the stock at a small population size; and a recovery factor of between 0.1 and 1.0 (NOAA Fisheries Office of Protected Resources 2014).

Projection: The potential evolution of a quality or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasize that projections involve assumptions – concerning, for example, future socio-economic and technological developments, that may or may not be realized – and are therefore subject to substantial uncertainty (Intergovernmental Panel on Climate Change 2007)

Resilience: Capacity of a natural system (fisheries community or ecosystem) to recover from heavy disturbance such as intensive fishing (Blackhart et al. 2006).

Salinity: 'Salinity' refers to the weight of dissolved salts in a kilogram of seawater. Because the total amount of salt in the ocean does not change, the salinity of seawater can be changed only by addition or removal of fresh water. (IPCC, 2013 pg. 265)

Scenario: A plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technology change, prices) and relationships. Scenarios are neither predictions nor projections and sometimes may be based on a “narrative storyline.” Scenarios may be derived from projections but are often based on additional information from other sources (Blackhart et al. 2006).

Sensitivity: The degree to which a system is affected, either adversely or beneficially, by climate variability or climate change. The effect may be direct (e.g., a change in population size in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise) (adapted from Intergovernmental Panel on Climate Change 2007).

Upper Ocean stratification: Water stratification occurs when water masses with different properties - salinity (halocline), oxygenation (chemocline), density (pycnocline), temperature (thermocline) - form layers that act as barriers to water mixing which could lead to anoxia or euxinia. These layers are normally arranged according to density, with the least dense water masses sitting above the more dense layers. The upper ocean term refers to the density difference between 200m and the surface. (Miller, Charles B. (2004). Biological Oceanography. Blackwell Publishing.)

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed and its adaptive capacity (Melillo et al. 2014).

Wind mixing: Wind mixing increases turbulence levels in the water column. It has been shown that turbulent mixing can increase the contact rates between zooplankton and their prey. As turbulence increases, however, the probability of successful prey capture declines. The probability of feeding success therefore is dome-shaped with a maximum at intermediate levels of wind-speed and turbulence. The impact of changes in wind intensity must therefore be evaluated with respect to the optimal wind speeds and levels of turbulence. (http://www.nefsc.noaa.gov/ecosys/ecology/Climate/)

TABLES

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

	NOAA Fisheries 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††	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
		Recovered Populations (Optimal, Sustainable, Viable) ††			Cumulative Production
What are main regulatory or management delivery 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	Fishery Ecosystem Plans

				Site Reviews	
What are 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

** 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 NOAA Fisheries' management of living marine resources under a changing climate.

Entity	**Information**
NOAA	
Oceans 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, Information, and Data 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 Service	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 for on the ground changes
Countries	Data on national fisheries Data on fisheries in international waters

Table 3. Recommended strategies to address each objective.

Objective 1: Identify appropriate, climate-informed reference points for managing LMRs. ● identify ecosystem-based reference points that include climate change and ecosystem information for all LMR management plans and strategies. ● modify existing biological reference points that fail to include ecosystem considerations and assume that environmental conditions of the past will persist into the future; ● communicate that ecosystem-based biological reference points improve accuracy, especially under climate change; ● foster innovation in climate-smart scenario testing; ● elucidate the positive opportunities associated with emerging LMRs; and ● develop scientific underpinning for Environmental Impacts Statements for climate change in each region, including comprehensive socio-economic impact analyses.
Objective 2: Identify robust strategies for managing LMRs under changing climate conditions. ● conduct management strategy evaluations and generate other information to allow risk-based policies to be re-evaluated under a changing climate; establish science-based approaches and policies for determining biological reference points and LMR and ecosystem productivities with changing climate and ecosystem conditions; ● establish science-based thresholds and policies for dealing with the immigration and emigration of LMRs to/from ecosystems; ● conduct more routine and regular LMR management strategy evaluations with NOAA Fisheries partners and constituents to provide science-based assessments of management options in a changing climate; ● examine efficacy of proposed mitigation strategies; and ● include human behavioral response or motivations into management design.
Objective 3: Design adaptive decision processes that can incorporate and respond to changing climate conditions. ● design scientifically sound review-evaluation protocols that could ensure consideration of climate change as a standard part of LMR management advice; ● develop and document the scientific basis for the need for climate change considerations in legislation or technical guidance; ● identify the many ways that information and understanding related to climate change can be inserted into the management process; and ● establish climate-ecosystem criteria that could become a standard part of review of LMR advice
Objective 4: Identify future states of marine, coastal, and freshwater ecosystems, LMRs, and LMR -dependent human communities in a changing climate. • develop a standard modeling toolbox or at least documented best practices to link future ocean and freshwater states and LMRs, with ability to couple models across types; • establish best practices for modeling under uncertainty (e.g., multi-model inference);

- research socio-economic consequences of future climate scenarios and LMR, and explore range of probable human LMR-use responses; and
- build on past National Ecosystem Modeling Workshops (NEMoWs).

Objective 5: Identify the mechanisms of climate impacts on ecosystems, LMRs, and LMR-dependent human communities.

- identify process research gaps in each region
- develop additional NOAA process research capacity internally and through competitive funding opportunities
- develop and maintain partnerships to conduct climate-LMR-related research;
- organize and host regular national climate workshops with LMR emphasis for NOAA employees across line-office and external partners to advance research efforts and promote collaboration;
- develop and maintain partnerships with international and other organizations to conduct LMR-climate workshops;
- organize and host regional thematic workshops related to LMR response to climate change (regime shift, distribution shift, vital rates, etc.);
- conduct research to identify a suite of proposed mitigation strategies, including those targeted at LMR-dependent human communities; and
- strengthen core science partnerships with formal mechanisms, especially with academic institutions, NASA, USGS, NSF, EPA, etc.

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

- utilize climate vulnerability risk analyses to conduct triage and prioritization for climate change science related to LMR management;
- develop and maintain standard climate-LMR report cards to communicate data and understanding available to all stakeholders;
- conduct regional assessments of strengths, weakness, opportunities, and challenges related to LMR science and management in the face of climate change;
- emphasize the critical need of ongoing monitoring in science planning and budgeting processes;
- train staff in time-series analyses; and
- engage in scoping exercises related to LMR science and management in the face of climate change with partners and constituents.

Objective 7: Build and maintain the science infrastructure needed to fulfill NOAA Fisheries mandates under changing climate conditions.

- increase the Fisheries and the Environment (FATE), Fisheries Oceanography, and IEA program budgets, including investment in socio-economic research;
- maintain 10% of overall NOAA Fisheries science budget directed to process-oriented research;

- establish dedicated climate-LMR FTEs at each fisheries science center with a portion of their time dedicated to coordinating with managers in NOAA Fisheries Regional Offices through regional teams;
- bolster NOAA Fisheries climate-LMR coordination nationally; and
- continue and expand NOAA Fisheries participation in cross-governmental efforts related to climate change.

Figure 1: General illustration of possible impacts of climate variability and change on physical/chemical, biological, social, and economic components of marine, coastal, and freshwater ecosystems, along with general avenues of possible human action to promote resilience/adaptation of resources/people, as well as mitigation of emissions and atmospheric changes.

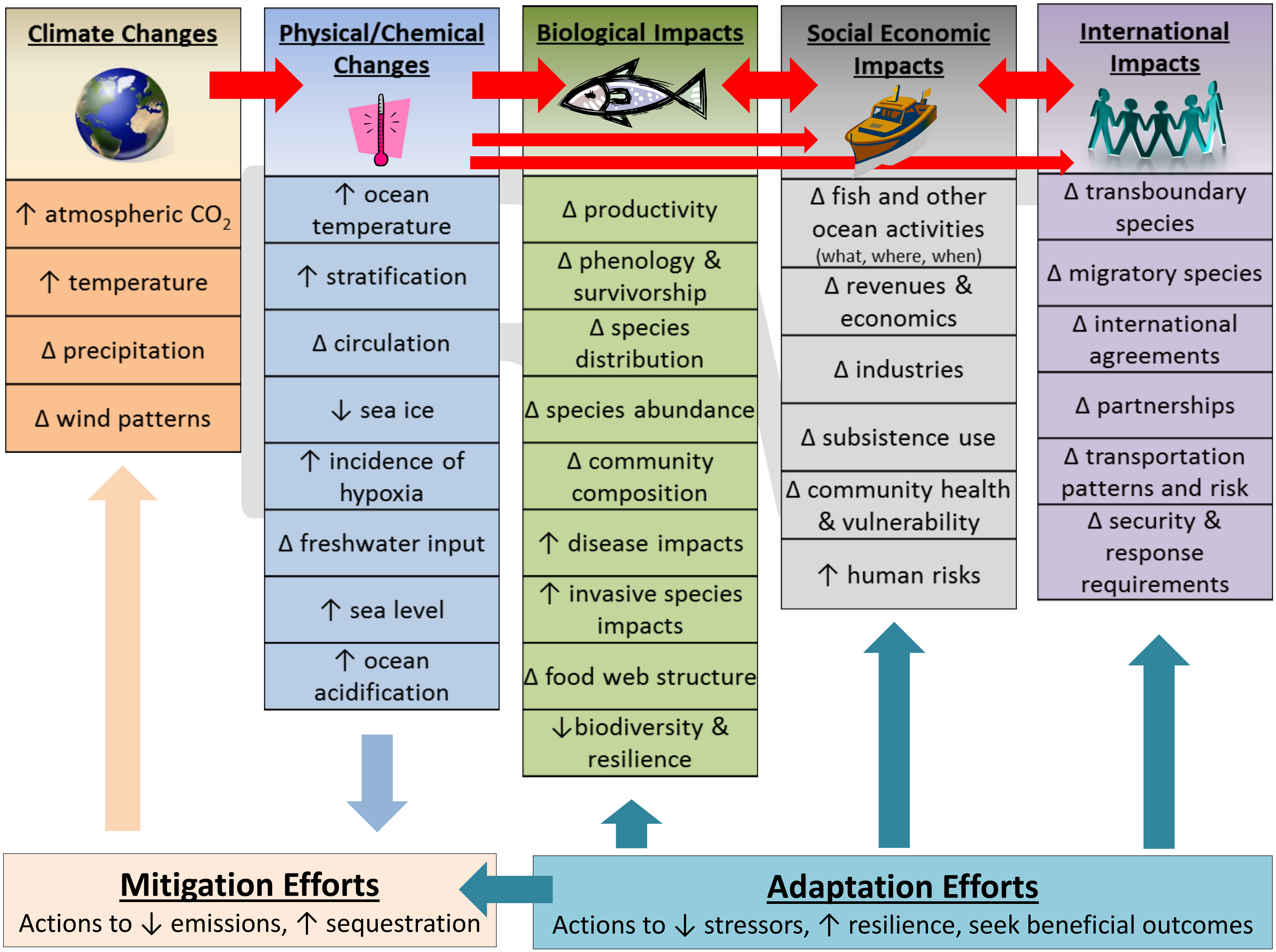


Figure 2. A simplified, generic LMR management process. There are distinctions and caveats across all NOAA Fisheries mandates, but this generalized version depicts the major steps required to produce management (mgt) advice to fulfill NOAA Fisheries mandates. A key point is that climate information can be inserted at each step in the process. It is understood that this process is then iterated to continually improve the information provided to make management decisions.

Figure 3. Meeting NOAA Fisheries mandates in a climate-smart manner requires that climate-related information is produced and inserted into many steps of a generic LMR management process, as well as coordination across them where appropriate. To fully meet all NOAA Fisheries mandates, an ecosystem-based approach to fisheries management (EBFM) is necessary.

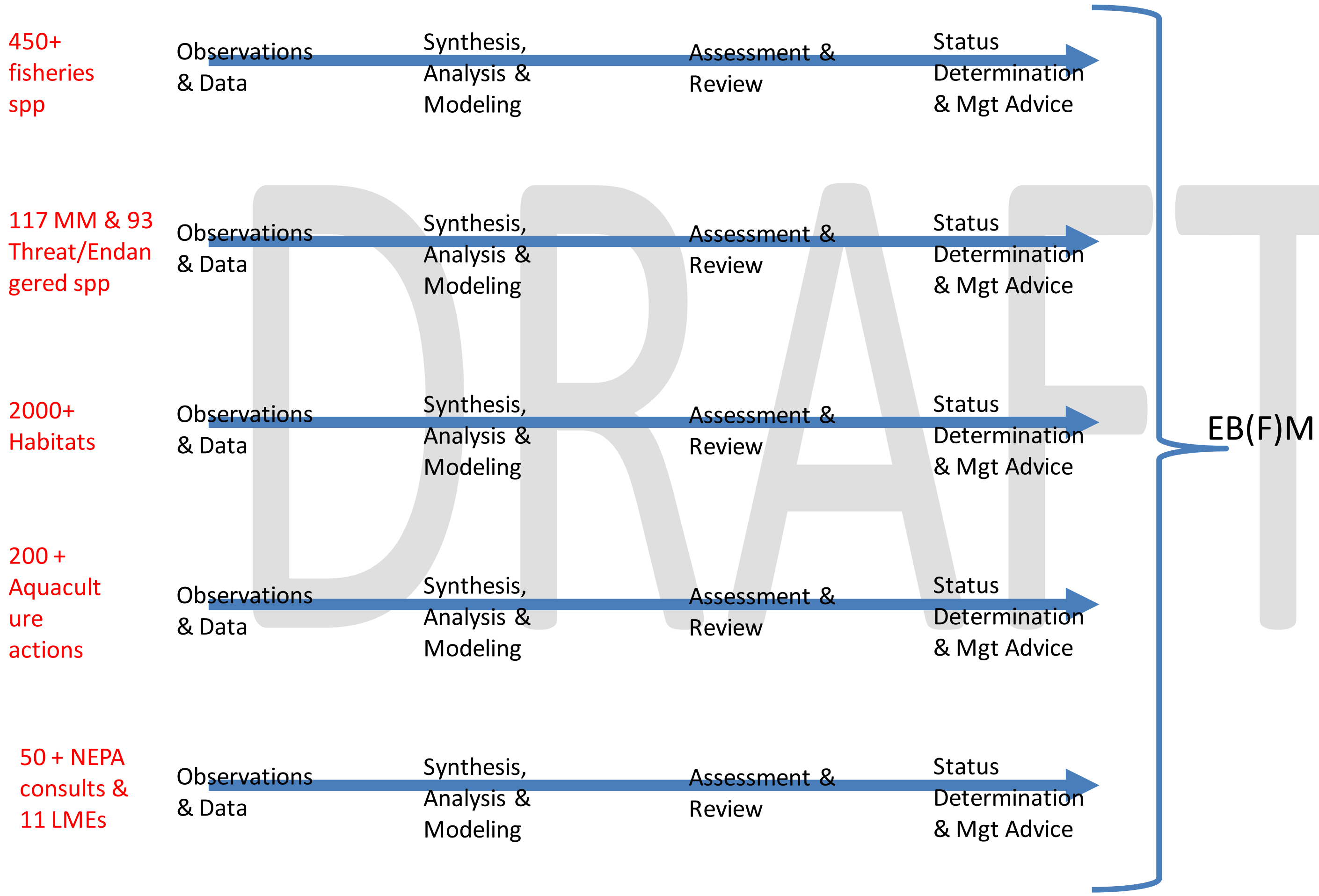
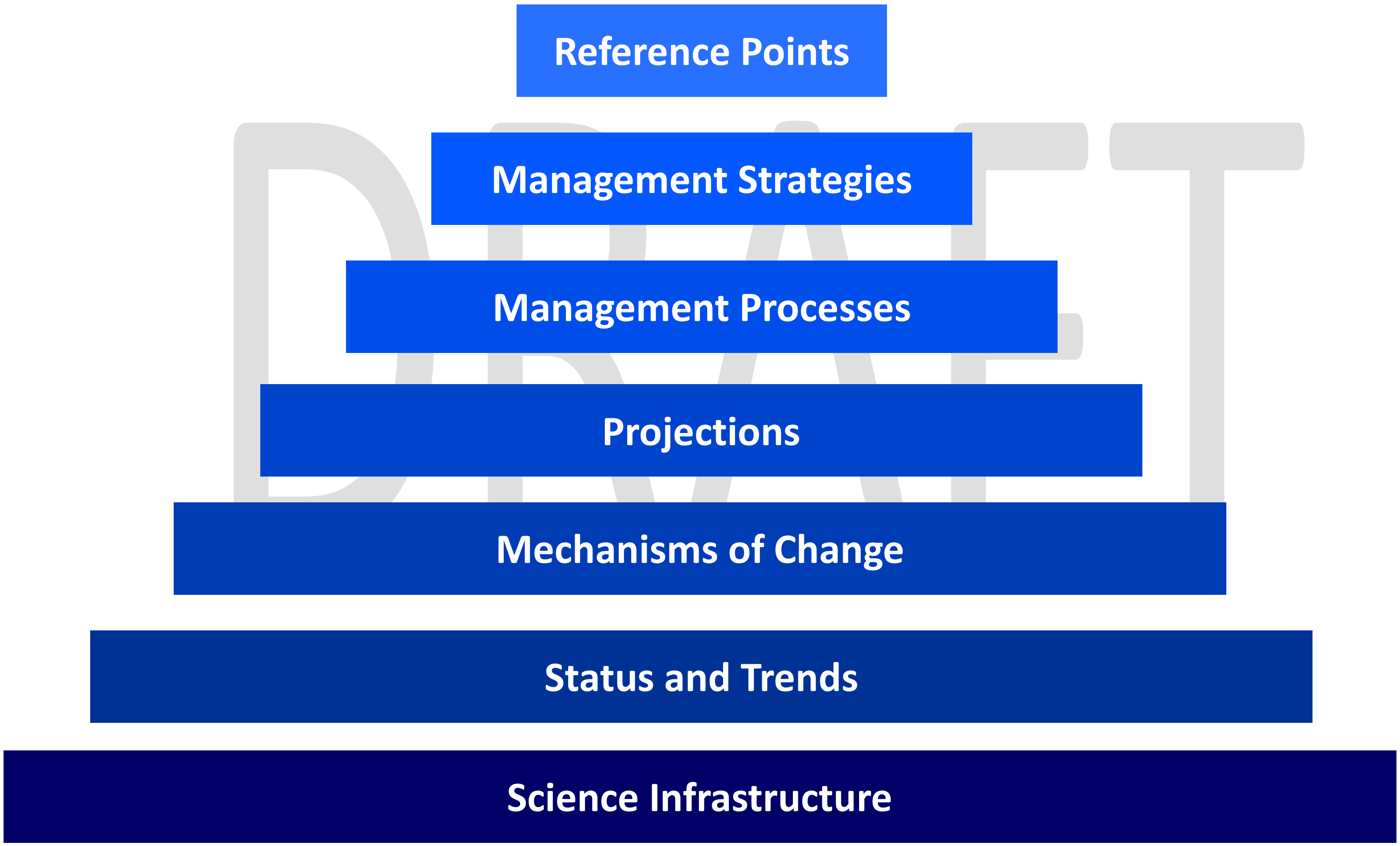


Figure 4. Seven priority objectives for the NOAA Fisheries National Climate Science Strategy. The ultimate goal is to provide management advice to meet NOAA Fisheries mandated responsibilities, with each prior level required to support that and subsequent objectives



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