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DRAFT

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CLIMATE SCIENCE

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STRATEGY

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NATIONAL MARINE FISHERIES SERVICE

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**NATIONAL OCEANIC AND ATMOSPHERIC
ADMINISTRATION**

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U.S. DEPARTMENT OF COMMERCE

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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

1 help achieve the Objective. The Strategy also identifies a set of priority recommendations that
2 are common across mandates, regions, LMRs, and objectives that have high and immediate
3 return on investment. The cross-cutting priority actions include:

4

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

9

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

13

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

22

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

LIST OF ACRONYMS

- 1
- 2
- 3
- 4 BRP – Biological Reference Point
- 5 EBM – Ecosystem-Based Management
- 6 ESA – Endangered Species Act
- 7 ESR – Ecosystem Status Report
- 8 FATE - Fisheries and the Environment
- 9 FMP – Fisheries Management Plan
- 10 FTE – Full-Time Employee
- 11 IEA – Integrated Ecosystem Assessment
- 12 LME – Large Marine Ecosystem
- 13 LMR – Living Marine Resource
- 14 MMPA – Marine Mammal Protection Act
- 15 MSE – Management Strategy Evaluation
- 16 MSA – Magnuson-Stevens Fishery Conservation and Management Act
- 17 NEPA – National Environmental Policy Act
- 18 NOAA Fisheries – National Marine Fisheries Service
- 19 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 LMRs¹). 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.

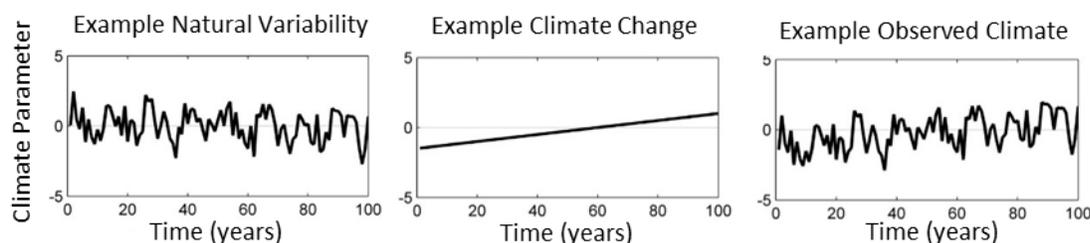
¹ Living marine resources are defined as species (and their habitats) under NOAA Fisheries’ responsibility, including species that spend part of their life cycle in estuarine or freshwater, such as diadromous fishes.

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 °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.



1 **Impacts of a Changing Climate on Marine and Coastal Ecosystems**

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

- 9 • Warmer ocean temperature.
- 10 • Reduced sea-ice thickness and extent.
- 11 • Altered storm tracks and intensity.
- 12 • Precipitation changes.
- 13 • Altered freshwater input.
- 14 • Sea level rise.
- 15 • Reduced ocean pH (i.e., acidification).
- 16 • Reduced dissolved oxygen.

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

- 20 • Salinity.
- 21 • Ocean circulation.
- 22 • Mixed layer depth.
- 23 • Upper-ocean stratification.
- 24 • Wind mixing.
- 25 • Intensity of upwelling and downwelling.
- 26 • Ecosystem connectivity.
- 27 • Nutrient availability.

28 These changes to the marine and coastal physical and chemical environments are known to be
29 occurring, and their cascading effects on species, habitats, and biodiversity in these systems are
30 expected to increase with continued changes in the climate system (Figure 1). The variety of
31 observed or expected effects include changes to ecosystem productivity (Polovina et al. 2008;
32 Polovina et al. 2011; Hollowed et al. 2013); the timing and magnitude of phytoplankton blooms
33 (Steinacher et al. 2010; Behrenfeld 2011; Sigler et al. In press); thermal tolerance and habitat
34 volumes available for LMRs (Baker et al. 2007; Nye et al. 2009b; Baker et al. 2012; Hazen et al.
35 2013; Pinsky et al. 2013; Lynch et al. In press); and vital rates [reproductive rate, emigration,

1 immigration] and life history characteristics (Hare et al. 2010; Saba et al. 2012). These effects
2 can have direct or indirect impacts on species' survival, abundance, distribution, fecundity,
3 reproductive success, and function in an ecosystem, and thereby modify the provision of
4 ecosystem goods and services (Ruckelshaus et al. 2013). These factors may influence the
5 frequency, intensity, and duration of interactions among species, species phenology,
6 distributions and abundance, and the dynamics of invasive and endangered species. We are
7 already witnessing species range shifts (Nye et al. 2009a; Nye et al. 2009b; Cheung et al. 2010;
8 Kotwicky and Lauth 2013; Pinsky et al. 2013), and these shifts are expected to continue, posing
9 challenges and perhaps opportunities for resident and shifting species as they enter or leave an
10 ecosystem.

11
12 Climate-related alterations to freshwater and estuarine systems—such as changes in the
13 amount, location, and timing of precipitation or changes to air or sea temperatures—can affect
14 riverine-dependent diadromous species and the many species that use estuarine habitats
15 (Intergovernmental Panel on Climate Change 2013; Intergovernmental Panel on Climate
16 Change 2014; Melillo et al. 2014). For example, along the U.S. West Coast, the combination of
17 more extreme events coupled with higher temperatures causes more precipitation to fall as
18 rain rather than as snow, which significantly changes the hydrology for listed salmon and
19 steelhead in the region, including (Mote et al 2014):

- 20
- 21 • More flooding and scouring flows in winter (increasing sedimentation, erosion, and
22 potentially washing out deposited eggs).
 - 23 • Earlier spring freshet (likely to change juvenile migration timing with potential mismatch to
24 estuarine and ocean conditions).
 - 25 • Higher water temperatures and lower stream flows in summer and fall (reducing juvenile
26 rearing habitat quality and quantity, potentially increasing predation and disease
27 transmission).
 - 28 • More frequent exceedance of lethal/sublethal temperature thresholds for juveniles and
29 adults.
 - 30 • Modified riparian vegetation (contributing to higher stream temperatures) by factors
31 including greater fire frequency and insect infestation..
- 32

33 In many coastal areas, transformation of shorelines and estuarine habitats with sea level rise
34 and coastal inundation can also impact coastal-dependent species. Threats also arise from
35 ocean acidification, with particular concern for species with calcareous shells [composed of
36 calcium carbonate] or exoskeletons (Cooley and Doney 2009; Bednaršek et al. 2014), which

1 currently comprise about two-thirds of U.S. marine aquaculture production² and more than half
2 of U.S. domestic fishery landings by value (National Marine Fisheries Service 2014) and provide
3 habitat for many species (e.g., coral and oyster reefs).

4
5 Climate-related changes will also interact with other stressors, such as pollution, fishing,
6 bycatch, and changes in human use of these systems (e.g., rapid increase in human use of the
7 Arctic) to affect LMRs. Some examples of climate-related impacts on LMRs and the people who
8 depend on them are included as case studies throughout this document. In some
9 circumstances, mitigating other stressors that are under local or regional control (e.g., fishing
10 impacts and pollution) may help increase the persistence of species sensitive to climate change,
11 by increasing overall resilience and reducing synergistic impacts between climate-related and
12 non-climate-related stressors.

13
14 Climate-related changes in physical and chemical conditions are expected to have a variety of
15 impacts on LMRs across a range of spatial and temporal scales (Stock et al. 2011; Melillo et al.
16 2014). To assume that the effects of climate change will be uniform and consistent across
17 species and ecosystems is imprudent and inconsistent with our scientific understanding. Several
18 studies (e.g., Mueter et al. 2011; Howella and Austerb 2012; Wilderbuer et al. 2013) suggest
19 that in any one region, some species will experience improving environmental conditions that
20 may result in increased species productivity and increased available habitat, while other species
21 will experience the opposite and perhaps decline in abundance. Furthermore, the sensitivity of
22 species to climate change and the nature of the effect may vary with life stage. Understanding
23 how climate change will affect wide-ranging species is challenging, as they may experience
24 positive effects of climate change in one habitat during one life stage and negative effects in
25 another distantly located habitat in another life stage. Because not all climate changes will
26 affect LMR species in the same way, there is an urgent need for careful evaluation of the
27 impacts of climate as well as non-climate stressors in the design, implementation, and
28 evaluation of LMR management efforts. For example, changes in species' abundance,
29 productivity, distribution, and diversity due to a changing environment may require changes to
30 the biological reference points and socio-economic benchmarks used in LMR management.

31
32 The combined physical, chemical, and biological effects of climate change on LMRs will modify
33 the products and services people derive from marine ecosystems, including food, jobs,
34 recreation, medicinal products, aesthetics, tourism, and even health benefits (Ruckelshaus et al.
35 2013). For example, the species available for harvest or culture in a given region could change
36 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

1 their target species and gear types) or developing strategies for reducing bycatch of species
2 new to their fishing grounds (Heenan et al. 2013). Shifts in the distribution and/or abundance
3 of species may affect where fishermen target fish, the location of fishing industries, working
4 waterfronts, supply chains, and the social and economic dynamics of LMR-dependent coastal
5 communities, cultures, and industries. Changes in target species and fishing methods will likely
6 pose challenges for shore-side support services from ports to processing plants, which will also
7 be significantly influenced by climate-related factors such as sea level rise, coastal storms, and
8 inundation (e.g. flooding). Shifts in aquaculture practices may be needed, including rethinking
9 what species may be best suited to meet societal demands under changing climate and ocean
10 conditions. These and many other climate-related effects will impact NOAA Fisheries’
11 stewardship of LMRs (e.g., for ESA-related issues see special section on climate change and
12 NOAA Fisheries ESA work in December 2013 issue of *Conservation Biology*: Boughton and Pike
13 2013; Brainard et al. 2013; Busch et al. 2013; Gregory et al. 2013; Jorgensen et al. 2013;
14 McClure et al. 2013; Seney et al. 2013; Snover et al. 2013; Wainwright and Weitkamp 2013;
15 Walters et al. 2013) .

16

17 **NOAA Fisheries Stewardship Mandates**

18

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

27

- 28 • Under the MSA, NOAA Fisheries assesses and predicts the past, current, and future status of
29 fishery stocks and harvest rates; evaluates the implications of proposed catch on the
30 sustainability of marine resources; and analyzes impacts on essential fish habitat. This
31 information is used to maintain, conserve, and rebuild fishery resources. A primary
32 objective of the MSA is to use the best scientific information available to optimize yield on a
33 continuing basis.
- 34 • The MMPA directs NOAA Fisheries to assess marine mammal stocks, reduce fisheries
35 bycatch of marine mammals, protect key habitats, and conduct stranding response and
36 other activities. This includes the estimation of abundance, distribution, and mortality.
- 37 • Under the ESA, NOAA Fisheries works to identify, protect, and recover threatened and
38 endangered species, including marine mammals, sea turtles, marine and anadromous

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

11

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

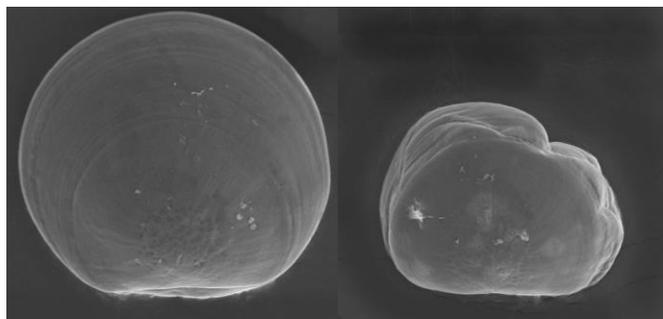
13 is required under many of the mandates (and others) to consider how these decisions may

14 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.



1 Fulfilling these mandates requires a range of science-based information and services to provide
2 the foundation for management action. NOAA Fisheries' responsibilities under the MSA, ESA,
3 MMPA, NEPA, and other mandates include a set of common science activities such as
4 documenting, assessing, and projecting past, present, and future abundance, distribution,
5 production, mortality, and utilization of LMRs. Briefly, this sequence can be described as
6 follows (Figure 2):

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

17
18 Science is essential for effective LMR management, and it becomes even more important as
19 climate change alters the historical characteristics of marine ecosystems. Currently, we lack key
20 scientific information needed to inform LMR management decisions in a changing climate.

21
22 With changing climate and LMR conditions, there are a variety of increasing information needs
23 to inform and fulfill NOAA Fisheries LMR stewardship mandates (Osgood 2008). Some of the
24 major climate-related information needs (Figure 2) for effective LMR management in a
25 changing climate are:

- 26 • Standardized data on past and current changes in marine, coastal, and freshwater
27 ecosystems.
- 28 • Studies to develop a mechanistic understanding of contemporary and historical climate
29 impacts on LMRs.
- 30 • Assimilation and synthesis of climate information into models used to determine stock
31 and ecosystem status and monitoring systems.
- 32 • Future projections of the state and expected human use of marine, coastal, and
33 freshwater ecosystems (based on contemporary and historical climate sensitivities).
- 34 • Evaluation of alternative management strategies to reduce current and future impacts
35 of climate change on LMRs, the goods and services they provide, and the communities
36 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.



1
2 Meeting these changing science requirements will be challenging given the scale and scope of
3 NOAA Fisheries' mission and expected climate-related impacts in marine, coastal, and
4 freshwater ecosystems. For example, NOAA Fisheries is responsible for providing a range of
5 science-based assessments and management advice for the stewardship of more than 449
6 regulated stocks/stock complexes,³ 102 threatened or endangered species, and 117 marine
7 mammal species.⁴ In addition, NOAA Fisheries provides science-based information to conduct
8 more than 2,000 habitat restoration projects nationwide⁵ and protect hundreds of thousands of
9 square kilometers of habitat. NOAA Fisheries also oversees research and siting for a growing
10 number of sustainable marine aquaculture activities, including some designed to mitigate for
11 climate change. To meet NEPA requirements, in 2012 alone, NOAA Fisheries conducted 106
12 environmental assessments, wrote 12 environmental impacts statements, and issued hundreds
13 of categorical exclusions.⁶ Under the MSA, in 2011, NOAA Fisheries provided conservation
14 recommendations to federal and state agencies on over 4,500 individual projects.

15
16 Overall, NOAA Fisheries has direct stewardship responsibilities for LMRs in 11 Large Marine
17 Ecosystems, comprising 16.5 million km², an area 1.7 times the land area of the continental
18 United States and roughly 5 percent of the world ocean's surface area,⁷ plus other stewardship
19 responsibilities of the ESA-listed species that occur in all of the world's Large Marine
20 Ecosystems. NOAA Fisheries also has stewardship responsibilities on the high seas and for
21 operation of U.S. fishing vessel in other countries' EEZs through international treaties and
22 regional fishery management organizations. Due to complex trophic interactions of marine
23 ecosystems, climate change will likely affect marine ecosystems, including all of the managed
24 species. In addition, climate change will likely affect consumptive and recreational human use
25 as well as conservation of managed species. Effective stewardship of LMRs will require
26 information related to climate change for use in the design and execution of a broad range of
27 management actions. In addition, effective stewardship will require an understanding of how
28 fisheries, ocean industries (e.g., shipping, military activities, shoreline development), and other
29 human activities might modify their use of LMRs in the face of projected and actual climate-
30 related changes in marine, coastal, and freshwater ecosystems over time.

31
32 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

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

7
8 EBM is a national priority and leading business practice within NOAA Fisheries, NOAA, U.S.
9 natural resource management agencies, and many leading international natural resource
10 management organizations (MacLeod and Leslie 2009; Executive Order 13547 of July 19th
11 2010; National Ocean Council 2013; Ocean Research Advisory Panel 2013; U.S. Office of Science
12 and Technology Policy 2013). It is an idea that has existed for decades in the literature
13 (Slocombe 1993), but has only more recently begun to be implemented in practice. Within each
14 of NOAA Fisheries' mandates, the need and benefits of considering a wide range of factors that
15 can influence LMRs is clear. But even more so, across all of these mandates, the need to
16 implement EBM is apparent; NOAA Fisheries will be unable to consider the full range of trade-
17 offs, interactions, and cumulative effects required across all of the mandates under a changing
18 climate if it proceeds otherwise (MacLeod and Leslie 2009; Link 2010). Climate and ocean
19 change impacts are a critical part of this discussion, and adopting common approaches to
20 climate change science that are applicable across all NOAA Fisheries LMR mandates is an
21 important area to leverage resources and gain efficiencies via this Strategy.

22
23 Without adequately incorporating climate change, NOAA Fisheries' conservation and
24 management efforts are likely to be ineffective, produce negative results, or miss positive
25 opportunities. Any of these could have a variety of environmental, social, economic, cultural,
26 and legal consequences. For example, the commercial and recreational fishing industry is
27 important to the U.S. economy (added \$199 billion to the U.S. economy in 2012) and to social
28 systems (generated 1.7 million jobs in 2012) (NMFS 2014). The recreational fishing industry
29 alone contributes \$56 billion a year to the U.S. economy and 364,000 jobs (NMFS 2014).
30 Furthermore, subsistence and personal use fisheries are known to be vital to families and
31 households across the nation, including tribal communities. Beyond fisheries, LMRs help
32 protect coastal communities from storm waves and tsunamis, support the existence of
33 imperiled and charismatic species [charming and widely known], regulate climate, and mitigate
34 climate change effects (e.g., carbon sequestration and storage by coastal habitats).

35
36 Although the value of these services is challenging to quantify, they are vital and impossible to
37 replace (Ruckelshaus et al. 2013). The social, cultural, and economic consequences are vast.
38 Given the pace and scope of expected climate impacts on marine, coastal, and freshwater

1 ecosystems, the ability to understand, plan for, and respond to climate impacts on the nation's
2 valuable LMRs and the people that depend on them is fundamental to fulfilling NOAA Fisheries
3 mandates in a changing climate.

4 5 **The Need for a NOAA Fisheries Climate Science Strategy**

6
7 The demand for more information related to climate change is great and increasing among
8 managers and stakeholders as evidence continues to mount of climate-related impacts on
9 marine and coastal ecosystems, fish, protected species, aquaculture, and habitats. Many
10 sectors are taking significant action to better understand, plan for, and respond to climate
11 impacts (e.g., defense, transportation, land management, water management, public health,
12 and others). This includes natural resource agencies such as the U.S. Forest Service (Solomon et
13 al. 2009), U.S. Fish and Wildlife Service (U.S. Fish and Wildlife Service 2010), National Park
14 Service (National Park Service 2010; National Park Service 2012), U.S. Department of
15 Agriculture (USDA 2011), and the U.S. Geological Survey (Burkett et al. 2013). Increasing the
16 production, delivery, and use of climate-related information in LMR advisory and regulatory
17 documents (e.g., assessments, decisions, and opinions) produced each year in fulfilling NOAA
18 Fisheries stewardship responsibilities is a significant challenge. Moving forward, NOAA
19 Fisheries must include climate-related information in their decision-making and management
20 advice. To do so, NOAA Fisheries should develop new types of information products and new
21 approaches to advise managers, policymakers, and stakeholders (e.g., U.S. Army Corps of
22 Engineers 2009).

23
24 Fortunately, many quantitative tools needed to incorporate climate change into NOAA Fisheries
25 scientific advice already exist, though improvements are needed in the use and application of
26 these tools. Other needed tools remain undeveloped. NOAA Fisheries has a network of internal
27 and external partnerships that could be better mobilized to help address many of these needs
28 (in fact, partners are critical to fill some of the science and information needs; Table 2).
29 However, many challenges remain. For example, many of the data sets needed to
30 parameterize coupled climate-LMR or ecosystem models are not available; additional efforts
31 are needed to collect relevant climate-related data as a regular part of the information base
32 supporting LMR management (Osgood 2008; Hollowed et al. 2009; Stock et al. 2011). Additional
33 action is needed to effectively structure and employ models and tools that utilize climate,
34 biological, and ecological information. Research to better understand key mechanisms and
35 processes linking climate-induced changes to LMRs is also needed. There is a need to identify
36 and test how to effectively insert climate-related information into LMR management processes
37 (Figure 2). Given that many of NOAA Fisheries' LMR mandates have common needs for climate-
38 related information, identifying these common products and responses that can be used across

1 all mandated needs should be a top priority. Finally, all these endeavors require adequate
2 science infrastructure, coordination, and financial support in both the near term and the long
3 term.

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

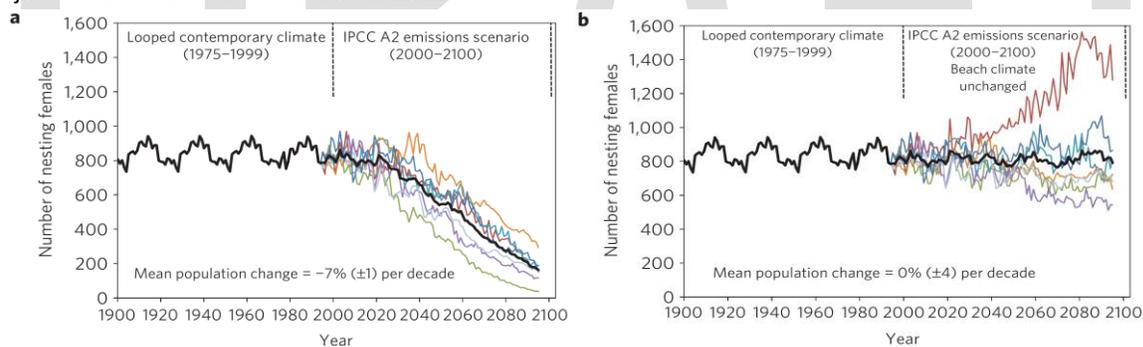
- 11
- 12 1. How can climate-related effects be incorporated into LMR reference points?
 - 13 2. What are robust LMR management strategies in the face of climate change?
 - 14 3. How can climate-related effects be incorporated into adaptive LMR management
15 processes?
 - 16 4. How will the abundance and distribution of LMRs and marine ecosystems change in
17 the future, and how will these changes affect LMR-dependent communities?
 - 18 5. How and why does climate change alter LMRs, ecosystems, and LMR-dependent
19 human communities?
 - 20 6. What are the observed trends in climate and LMRs?
 - 21 7. What science infrastructure is needed to produce and deliver this information?

1

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° 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 competition 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.

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

5
6 Objective 1: Identify appropriate, climate-informed reference points for managing LMRs.

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

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

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

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

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

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

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

24
25 Each of the seven objectives is described in the following pages. Each objective begins with a
26 description of the LMR management objectives and/or the type of science-based information
27 or advice needed in the form of decision criteria. The objectives are highly interdependent; the
28 science and information from any one objective contributes to or is essential to one or more of
29 the other objectives.

30
31 These objectives were ordered according to the main mandated responsibility areas (Table 1),
32 deriving known management needs, generalizing across mandates, identifying analytical
33 products and the science enterprise to support those management needs, and finally noting the
34 infrastructure needed to support that science (Figure 4). Thus, all subsequent objectives
35 support the objectives above it (Figure 4). Building this nested and interdependent science
36 foundation is the core of this Strategy.

37

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

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

20
21 A number of products can be routinely created to meet this objective. Novel or updated LMR
22 management plans and documents are typically produced for each management action.
23 Usually, documents such as Fishery Management Plans, Fishery Ecosystem Plans, Biological
24 Opinions, Species Recovery Plans, Environmental Impact Assessments, and Social Impact
25 Assessments inform Ecosystem Assessments, ESA Status Assessments, MMPA and MSA Stock
26 Assessment Reports, habitat assessments, restoration reports, and EFH designations. These
27 plans and documents provide the scientific basis for the management of LMRs (Table 1). They
28 are regularly used by NOAA Fisheries, Regional Fishery Management Councils; Regional Ocean
29 Councils; Regional Planning Boards; State Fishery Commissions; Regional Fishery Management
30 Organizations; many federal, state, and local agencies and organizations; and other managers in
31 decision making.

32
33 Most current assessments, and the reference points produced by them and included in
34 management plans, assume that natural variability will reflect the range of conditions observed
35 in the past. Such reference points often do not account for the fact that ecosystems and the
36 LMRs in them will change with the directional forcing of climate change. Therefore, stock
37 assessments, biological reference points, and fisheries management plans based on these
38 assessments may not adequately capture the future population dynamics in a changing ocean.
39 In other situations, mandates allow managers to shift their reference points in response to
40 shifts in the environment, such as regime shifts [large, abrupt, persistent changes in the
41 structure and function of an eco-system. A regime is a characteristic behavior of a system which
42 is maintained by mutually reinforced processes or feedbacks]. However, unlike regime shifts—
43 for which estimates of past and current conditions exist—climate change is expected to create

1 novel conditions not captured by past datasets, making identification of baseline conditions and
2 reference points more difficult. In these circumstances, the key is to establish reference points
3 that are robust to shifting status of managed species (Punt et al. In press) and associated
4 ecosystems.

5
6 Moving forward, LMR management plans (e.g., Fishery Management Plans, Fishery Ecosystem
7 Plans, Species Recovery Plans) need to document that decision criteria explicitly include
8 climate-related considerations. Accounting for and, where appropriate, including the best
9 available climate-related science to inform reference points is a necessity to avoid misaligned
10 management targets. Additionally, many of these plans need to include socio-economic
11 analyses that show the consequences of neglecting climate change in establishing biological
12 reference points. Such analyses are challenging but feasible. Moreover, they are critical to
13 demonstrating the value (both biologically and socio-economically) of managing LMRs using
14 reference points that consider the effects of climate change. Misaligned reference points may
15 result in foregone revenue or missed opportunities (e.g., biological, social, economic, cultural)
16 due to climate-induced changes in production, distribution, or other dynamics of LMRs that
17 have been unaccounted for.

18
19 Finally, a reporting tool, accessible to all stakeholders, that simultaneously tracks the status of
20 stocks, ecosystems, and social and economic conditions over time would provide useful
21 products for adequately achieving this objective. NOAA Fisheries has the building blocks for
22 developing such a reporting tool, but does not currently collect information in such a
23 comprehensive way.

24
25 Important strategies to bolster and better deliver climate-smart reference points include:

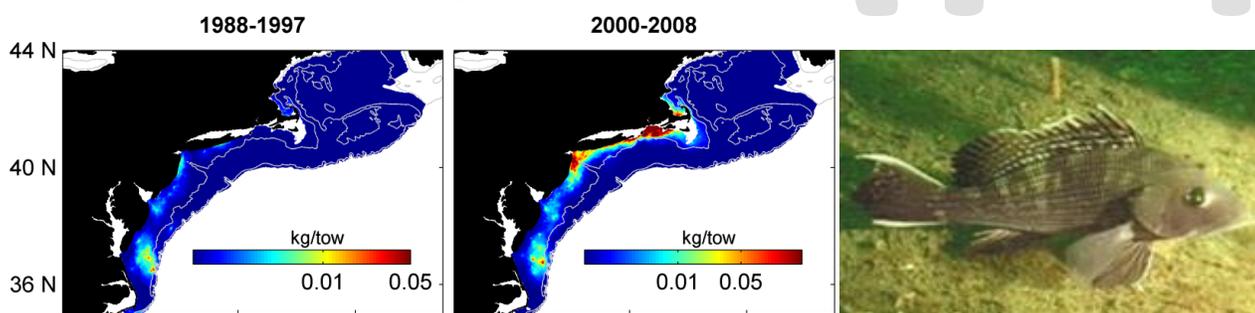
- 26 ● Identify ecosystem-based reference points that include climate change and ecosystem
27 information for all LMR management plans and strategies.
- 28 ● Modify existing biological reference points that fail to include ecosystem considerations
29 and assume that environmental conditions of the past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

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

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.



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

3 Identifying LMR management approaches and options that will remain biologically and socio-
4 economically sustainable in the face of a changing climate is a critical need. In addition, we
5 need to acknowledge and affirm that the best management practices for LMRs today may not
6 be the best management practices in the future with changing climate and ocean conditions.
7

8 To identify management strategies that are robust to future change, various ecosystem, socio-
9 economic, and LMR models can be coupled with scenarios of climate change to test the
10 performance of current and alternate management practices under future conditions (Battin et
11 al. 2007; Crozier et al. 2008; Ianelli et al. 2011; Boughton and Pike 2013; Nye et al. 2013;
12 Szuwalski and Punt 2013; Wilderbuer et al. 2013). Such management strategy evaluations
13 (MSE) will assist in the design and evaluation of management options and adaptive
14 management strategies for LMRs, and should help identify management options that are robust
15 to a wide range of predicted future conditions. Additionally, they could be used to identify the
16 time scale of change and adaptation, allowing us to better focus resources and emphasis.
17 Similar models for cultivated LMRs exist for aquaculture and can be used to predict changes in
18 production due to changing ocean conditions and consumptive and non-consumptive uses
19 (Shelton 2014). Conversely, models of shellfish and seaweed physiology could be used to
20 evaluate the potential for aquaculture systems to provide refuge to LMRs from changing
21 climate and to remove carbon from the coastal ocean.
22

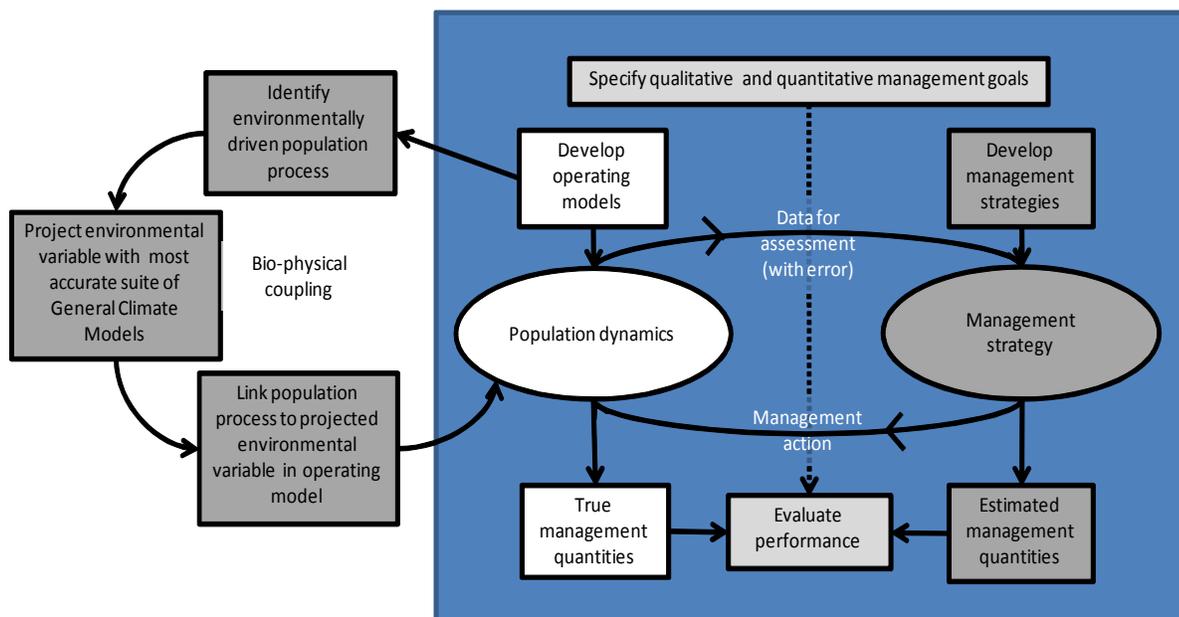
23 NOAA Fisheries has considerable experience in designing and evaluating strategies for
24 sustainable management of LMRs. Incorporation of expected climate-related changes
25 to marine, coastal, and freshwater ecosystems, as well as human uses of those
26 ecosystems, will help identify management practices and mitigation strategies that may
27 be necessary in the future. Fulfilling NOAA Fisheries' various mandates have specific
28 timelines and processes for providing scientific information to managers and other
29 stakeholders. Through these processes, NOAA Fisheries can provide information on the
30 effectiveness of current management practices and the design and performance of
31 alternative management practices that may be superior. For example, management
32 strategy evaluations for fisheries management practices, recovery plans for ESA-listed
33 species, management practices for aquaculture, use of aquaculture as mitigation, and
34 designation of essential or critical habitat should incorporate understanding of the
35 impacts of climate change into the design of effective management strategies. Such
36 management strategy evaluations would support development of sound adaptive
37 management practices.
38

39 A number of products could be routinely created to meet this objective. Reports of such
40 management strategy evaluation efforts that cover the full range of climate, harvest,
41 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).

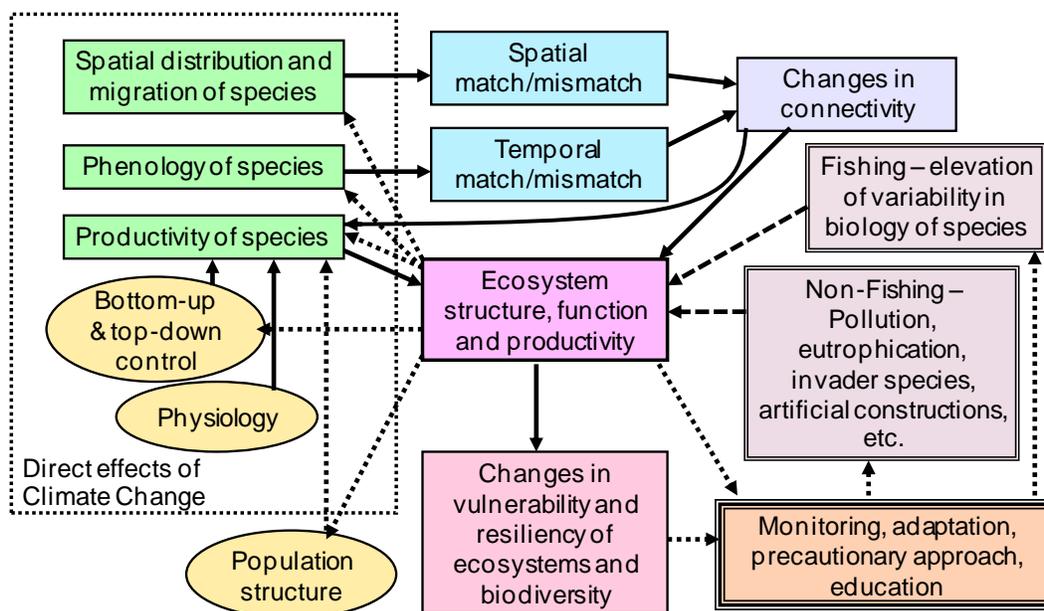


The more formal simulation modeling approach is emerging as a primary tool for delivery of adaptation strategies for the sustainable management of LMRs. Management strategy evaluations vary in complexity and biological realism, ranging from fully coupled bio-physical models of regional ecosystem responses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

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.



1
2
3 changes to biological reference points across a range of scenarios warrants examination,
4 including a catalog of associated LMR and socio-economic responses. Reports generated from
5 these management strategy evaluations need to clearly and simply identify the most robust
6 strategies that will not weaken LMR sustainability. Management strategy evaluations reports
7 should also identify protection and mitigation measures, harvest control rules, and related
8 management options that are compulsory to best manage across a suite of LMRs or systems.
9 Specific consideration should be given to fisheries prosecuted by fishermen and vessels that
10 originate from multiple regions (e.g., multiple North Pacific fisheries are prosecuted by both
11 West Coast and Alaska fishermen and vessels) because disruptions of these fisheries have the
12 potential for broad-reaching socio-economic and management implications. The best levels of

1 these biological reference points, reflective of a range of possible risk tolerances, need to be
2 examined to better inform risk-based policies.

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

8
9 Important strategies to bolster and better deliver climate-smart management strategies
10 include:

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

23

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

3 The procedures used to examine, vet, and provide scientific advice to support management
4 strategies and decisions can be as important as the management advice itself. As depicted
5 simply in Figure 2, the science and information delivery process for any of the main NOAA
6 Fisheries mandates (Table 1) follows a similar sequence: synthesizing available data, reviewing
7 outputs, and providing information to determine the status of LMRs, habitats, or ecosystems.
8 The resulting management advice provided at the end of the process is only as good as the
9 weakest link in that process. If climate-related information is not included in this management
10 advice process, decisions based on it may not result in sustainable management (e.g., Beechie
11 et al. 2013; McClure et al. 2013).

12
13 Copious works have documented, described, and evaluated management systems for LMRs and
14 natural resources, in general (Holling 1978; Walters 1986; Hilborn and Mangel 1998). We do not
15 repeat that work here; rather we build on it and note one key point: climate-related
16 information may need to be incorporated into the management process to effectively achieve
17 management and conservation goals. Doing so would require a number of steps. Clearly an
18 openness to incorporate considerations of climate-related information is a huge first step.
19 Second, knowing where the best insertion points are for specific types of climate-related
20 information is critical. Third, building adaptability into the management process is necessary to
21 allow inclusion of new understanding related to climate change and information related to the
22 rate of environmental change.

23
24 Easing the integration of climate science into the management process may necessitate some
25 changes to the management process itself, requiring close collaboration between managers
26 and scientists. For example, robust strategies for managing LMRs under climate change may
27 require both regular updates in the short term based on performance tracking and periodic
28 evaluation against rigorous management strategy evaluations that employ fully coupled sets of
29 system models. In this example, both the close interaction between managers and scientists
30 and the need for managers to be able to adapt on a routine basis (without scientists having to
31 execute detailed analyses each time) are highlighted. Recent scientific inquiry suggests that
32 detailed analyses are needed to assess whether current management strategies are robust to
33 climate change. Research also suggests that LMR management strategies that are successful
34 under climate change include adaptive management cycles with control rules for changing
35 conditions and monitoring programs to develop and track necessary status indicators.

36
37 The primary output for this objective would be scientific support for management processes
38 that are adaptive and flexible in both the short and long term under the various NOAA Fisheries
39 mandates. These processes would need to be measured by key performance metrics related to
40 their timeliness and accuracy with respect to the ecosystem, LMR, and socio-economic impacts
41 of climate change.

42
43 Further, identification of where in the management process climate-smart information could

1 best be incorporated is needed, recognizing that there may be multiple insertion points (e.g.,
2 Sutton-Grier et al. 2014). This could be established under different management strategy
3 evaluations (Figure 4).

4
5 Important strategies to bolster and better deliver climate-smart, adaptive management
6 processes include:

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

DRAFT

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.

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

5 Simulation of LMR dynamics using climate forecasts are needed to develop management
6 protocols that can adapt to climate change. Forward-looking management of LMRs depends on
7 robust projections of future ocean conditions; marine, coastal, and freshwater ecosystems and
8 LMR responses; and human socio-economic systems and their responses to changing climatic
9 conditions and related LMR responses. Linking changes in the physio-chemical system to
10 marine resources and ecosystems represents a major challenge. Making additional linkages to
11 climate effects on human communities and economies is a second major challenge.
12

13 Robust, model-based projections of the effects of climate change on marine, coastal, and
14 freshwater ecosystems, LMRs, and human communities have the potential to provide useful
15 information for natural-resource decision-making on appropriate temporal and spatial scales.
16 However, coupling across these models is not trivial.
17

18 Key projection considerations include:
19

- 20 1. A capability to downscale and bias-adjust global climate and earth system models to
21 better resolve regional responses of marine and coastal ecosystems to large-scale
22 climate changes.
- 23 2. Different climate scenarios to examine the effect of management choices
24 on population dynamics, population viability, bioenergetics, multispecies
25 interactions, biodiversity, and species distributions, as well as primary and secondary
26 production, habitat structure, energy budgets, and ecosystems. This requires
27 coupling for a full suite of models.
- 28 3. Social and economic models can predict how future change in LMRs may affect
29 working waterfronts; commercial, recreational, and subsistence fishermen; anglers;
30 aquaculture operations; the seafood industry; seafood consumers; and preferences
31 for consumptive and non-consumptive uses of LMRs, but warrant further
32 development and coupling with other LMR and ecosystem models. Coupling these
33 suites of models is also needed.
- 34 4. Hotspots for change in marine, coastal, and freshwater physical condition and
35 biogeochemistry, LMRs, and habitat, including aquaculture mitigation
36 considerations, can be identified from data as well as via projections with coupled
37 models.
- 38 5. Indicators that provide early warnings of rapid or impending change to LMRs, marine
39 habitats, and ecosystems (e.g., large shifts in species phenology and distribution)
40 need to be developed, and routinely monitored and projected as outputs of models.
41

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.

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.

1

2

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

14

15 In addition to these model-based needs, other important products can be routinely created to
 16 meet this objective. One of the key outputs from these projections should be the identification

1 of realistic future scenarios and feasible management strategies. These can set the stage for
2 management actions by bounding future ranges of probable climate conditions. Doing so can
3 minimize exploration of unrealistic scenarios and, thus, ineffective strategies.

4
5 NOAA Fisheries should work with researchers in academia and in the Office of Oceanic and
6 Atmospheric Research to enhance its climate modeling capacity by establishing regional and
7 national modeling teams focused on impacts to ecosystems and management of LMRs,
8 specifically in the context of climate change scenarios. Regional modeling teams could, for
9 example, develop and refine models, linkages among models, and scenarios that allow end-to-
10 end modeling exercises to project the impacts of changes to climate condition on LMRs and
11 ultimately how human communities then modify and adapt their uses of LMRs and ecosystems.
12 They could also provide technical advice on the quality and applicability of modeling output.
13 National teams of NOAA Fisheries experts could develop best practices for integrating changing
14 climate conditions into modeling exercises (e.g., ensemble approach) and help the regions
15 tackle climate change-related efforts in a coordinated and consistent way. These teams would
16 also serve as the experts for linking new research and understanding into the development of
17 advice.

18
19 Important strategies to bolster and better deliver climate-smart projections include:

- 20 • Develop a standard modeling toolbox (or at least documented best practices) to link
21 future ocean and freshwater states and LMRs, with ability to couple models across
22 types.
- 23 • Establish best practices for modeling under uncertainty (e.g., multi-model inference).
- 24 • Research socio-economic consequences of future climate scenarios and LMR, and
25 explore range of probable human LMR-use responses.
- 26 • 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 CO₂ 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.

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

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

12
13 Filling key gaps in the understanding of these underlying processes will improve both NOAA
14 Fisheries science and management, including the models used to develop projections of the
15 future. Vulnerability assessments, improved using newly obtained knowledge of LMR sensitivity
16 to climate change, can help identify focal areas for NOAA Fisheries scientific and management
17 efforts. Process research informs the design of observing systems and underlies the models that
18 project future states. Finally, process research provides the foundational knowledge for
19 developing mitigation strategies to increase species' adaptive capacity and resilience to
20 environmental change and/or to selectively breed climate-adapted stocks for aquaculture.

21
22 In short, climate change can affect LMRs via changes in:

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

28
29 These changes can result in a variety of subsequent changes such as:

- 30 ● Mortality.
- 31 ● Productivity.
- 32 ● Species distribution.
- 33 ● Nutritional value of prey.
- 34 ● Movement of migratory species.
- 35 ● Habitat structure and location.

36
37 And those changes can in turn impact other parameters such as:

- 38 ● Species relative abundance.
- 39 ● Community composition and predator-prey overlaps.
- 40 ● Food web structure.
- 41 ● Energy and matter fluxes.
- 42 ● Invasive species.
- 43 ● Life history.

1 Because of the sensitivity of species physiology to environmental conditions, changing
2 environmental conditions may affect the distribution, migration, depth, and behavior of some
3 species (see text boxes). Improving our understanding of how and why this change may occur
4 provides mechanistic understandings needed for development and implementation of robust
5 NOAA Fisheries management strategies. Laboratory and field investigations can be targeted to
6 reduce uncertainty about species tolerance, response, and adaptive capacity to changing
7 climate conditions and to the rate of change of environmental conditions. Laboratory
8 experiments can examine the direct effects of single climate factors, the direct combined effect
9 of multiple climate factors, and the indirect effects of changing climate conditions on species
10 interactions, energetics, and resilience. Field studies on the response of managed and
11 ecologically important species to different environmental conditions can range from targeted,
12 hypothesis-driven work to analysis of long-term survey data with relevant environmental
13 parameters. Studies of ecological communities build knowledge on the functional role of
14 biodiversity in maintaining ecological and ecosystem resilience. Likewise, ethnographic
15 fieldwork can be done to capture the processes that fishing-dependent communities use to
16 respond and adapt to changing environmental conditions. Additionally, socio-economic analysis
17 of LMR-user behavior over time can help explain historical patterns in resource use and how
18 that use may change given future conditions.

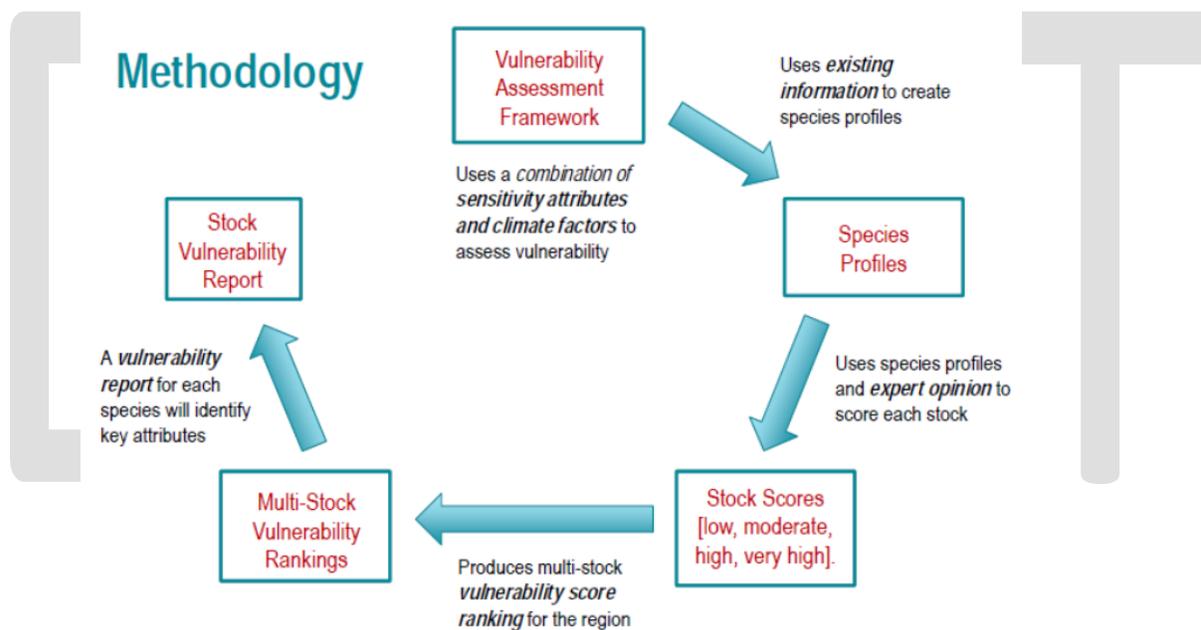
19
20 NOAA Fisheries' current capacity to conduct process-based research will not meet the demand
21 for understanding how aquatic species, ecosystems, and LMR-dependent human communities
22 may respond, acclimate, or adapt to climate change. Developing this capacity will require
23 significant financial investment in state-of-the-art experimental facilities for rearing organisms
24 under expected future conditions, the equipment needed to conduct research in field settings,
25 and the up-to-date laboratory equipment required to process samples rapidly. In some cases,
26 NOAA Fisheries has the needed assets, but needs the support and change in priority to apply
27 these assets to process studies related to climate change. NOAA Fisheries needs to articulate
28 the need for process-based research throughout the organization and beyond, then incorporate
29 new understanding from this research into management advice. Strong partnerships with
30 research institutions and funding agencies (e.g., National Science Foundation, National
31 Aeronautics and Space Administration, Environmental Protection Agency, Department of
32 Energy, Department of the Interior, and other NOAA line offices; Table 2) are also critical.

33
34 Further, process research that is integrated at the level of the ecosystem links ocean dynamics,
35 biodiversity, and trophic interactions with managed species and the human communities using
36 LMRs, and provide a comprehensive understanding of species response to changing climate
37 conditions. For example, it is not enough to simply understand the temperature preferences of
38 a species if warming also affects the abundance or distribution of their prey, predators, and
39 competitors. Within NOAA Fisheries' current portfolio of research activities, observation-based
40 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.



- 1
- 2 laboratory and field investigations of life history traits, genetics, and other physiological
- 3 consequences of climate change. While these types of research are touched upon in some
- 4 programs, NOAA Fisheries would need to build capacity to create the volume of targeted
- 5 research necessary to achieve results commensurate with this aspect of NOAA Fisheries’
- 6 science mission and the mechanisms for integrating this knowledge into ecosystem-level
- 7 understanding.
- 8
- 9 A number of products could be routinely created to meet this objective. One of the key items in
- 10 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.

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

7
 8 Research undertaken to meet this objective can be used to develop updated parameters for
 9 LMR and ecosystem models. Providing revisions to model functional form, structure, and
 10 parameterization will afford better predictive capabilities of LMR responses to a changing
 11 climate and ocean. Additionally, targeted process research can be used to develop mitigation
 12 strategies for either reducing climate impacts on LMRs or providing for lost value and services
 13 to human communities due to climate change. For example, development and/or restoration
 14 of kelp forests and eel grass beds may provide some protection from ocean acidification and
 15 low oxygen. Similarly, researchers are testing whether seaweed and shellfish farms may
 16 provide similar ecosystem services important in a change climate if expanded over a larger area
 17 of the ocean than natural beds (e.g., Chung et al. 2013). Aquaculture provides an opportunity
 18 to explore human intervention to reduce
 19 climate change impacts to vulnerable life stages
 20 and species.

21
 22 Important strategies to bolster and better
 23 deliver climate-smart process research include:

- 24 • Identify process research gaps in each
 25 region.
- 26 • Develop additional NOAA process
 27 research capacity internally and through
 28 competitive funding opportunities.
- 29 • Develop and maintain partnerships to
 30 conduct climate-LMR-related research.
- 31 • Organize and host regular national
 32 climate workshops with LMR emphasis
 33 for NOAA employees across line-office
 34 and external partners to advance
 35 research efforts and promote
 36 collaboration.
- 37 • Develop and maintain partnerships with international and other organizations to
 38 conduct LMR-climate workshops.
- 39 • Organize and host regional thematic workshops related to LMR response to climate
 40 change (regime shift, distribution shift, vital rates, etc.).
- 41 • Conduct research to identify a suite of proposed mitigation strategies, including those
 42 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.

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

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

10
11

DRAFT

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)

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

3 Information on the status and trends of marine, coastal, and freshwater ecosystems, resources,
4 and LMR-dependent human communities is essential to tracking and providing early warning of
5 the impacts of climate change. This information is the foundation of sound science advice and
6 sustainable management of LMRs under changing conditions. NOAA Fisheries has excelled at
7 producing data-based assessments of LMR status and trends for science-based management.
8 Some of these assessments explicitly incorporate climate change data, but most do not. NOAA
9 Fisheries has three main needs related to this objective:

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

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

24
25 An important and regular product should be ecosystem status reports (ESRs and related
26 ecosystem advisories, chapters, etc.). ESRs provide multi-dimensional examination of the
27 ecosystem from physical and habitat condition to trends in LMR abundance and resource use
28 by fleets and communities.⁹ Typically they include brief narratives describing trends within the
29 numerous time series analyses presented. Even apart from formal modeling through to specific
30 biological reference points, the information provided in these ESR has been useful for providing
31 broader context and leading indicators to inform LMR management. Future ecosystem status
32 reports could be enhanced by interpreting detected changes within the current understanding
33 of ecological processes of each large marine ecosystem. Adding climate change projections to
34 these status reports is an important need and will provide information about the projected
35 future states of the ecosystem. Integrating data sets of climate change that are current, are
36 specific to the management tasks, and represent state-of-the-art understanding requires that
37 synthesis products be developed and regularly updated. Such products are designed to serve
38 multiple NOAA Fisheries management requirements, and do so because of shared information
39 needs on climate-change-related impacts on the physical, chemical, biological, and socio-

⁹ <http://www.noaa.gov/iea/>

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

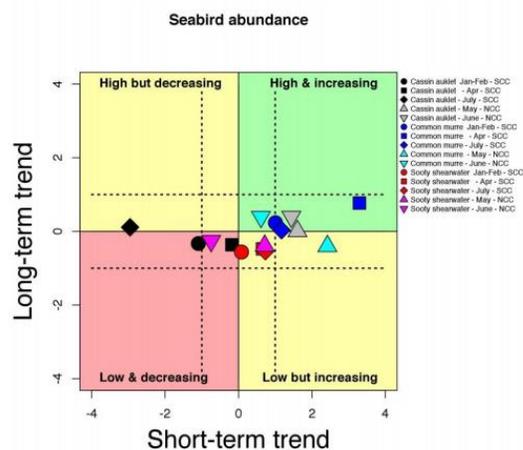
11
 12 Deciding on which indicators to include
 13 in an ecosystem status report requires
 14 knowledge of ecosystem structure and
 15 function, the biogeochemical processes
 16 that influence the ecosystem, human use
 17 of and impacts on the ecosystem, and
 18 vulnerability of the ecosystem to climate
 19 change. Investing time and resources
 20 into the evaluation and development of
 21 useful indicators is an important task to
 22 undertake when designing ecosystem-
 23 climate observing systems and
 24 ecosystem status reports (Peterson et al.
 25 2013). Necessary new indicators of
 26 change could be identified as the impacts
 27 of climate change develop.

28
 29 Further, the biological and physical
 30 indicators developed from ESRs can be
 31 used to establish future thresholds and
 32 decision criteria (Samhoury et al. 2010;
 33 Fay et al. 2013; Large et al. 2013). This
 34 empirical exploration of ecosystem,
 35 habitat, and aggregate groups of LMR
 36 BRPs has been solidly rooted in such
 37 indicators. The full suite of
 38 multidimensional data can be noisy and
 39 typically incorporate multiple patterns
 40 (e.g., warming trend overlaid on El Niño-
 41 Southern Oscillation and Pacific Decadal
 42 Oscillation). Complex statistical techniques can distinguish the multiple drivers of change
 43 through time series analysis and are used to isolate signals in the data. Such statistical and
 44 analytical exercises are relatively novel, and technique development could also advance NOAA

Ecosystem Status Reports

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]



1 Fisheries' understanding of ecosystem state.

2

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

7

8 Important strategies to bolster current status estimates include:

- 9
- 10 • Utilize climate vulnerability risk analyses to conduct triage and prioritization for climate
change science related to LMR management.
 - 11 • Develop and maintain standard climate-LMR report cards to communicate data and
12 understanding available to all stakeholders.
 - 13 • Conduct regional assessments of strengths, weakness, opportunities, and challenges
14 related to LMR science and management in the face of climate change.
 - 15 • Emphasize the critical need of ongoing monitoring in science planning and budgeting
16 processes.
 - 17 • Train staff in time-series analyses.
 - 18 • Engage in scoping exercises related to LMR science and management in the face of
19 climate change with partners and constituents.

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

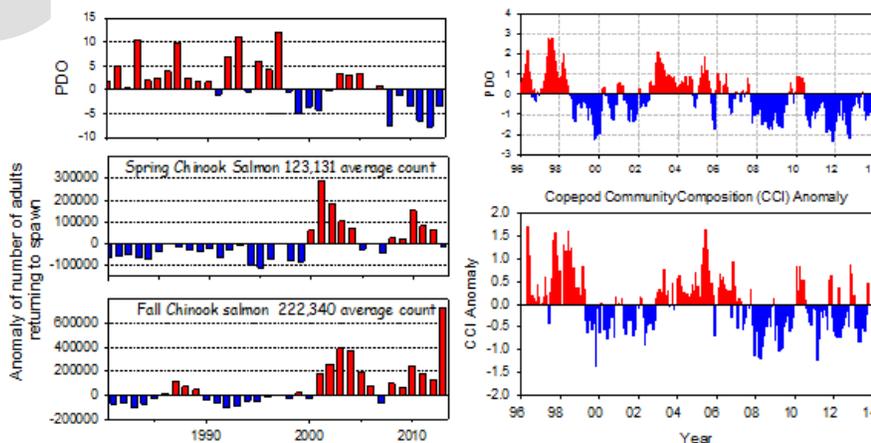
Mantua et al. (1997) showed that changes in the sign of the Pacific Decadal Oscillation (PDO, a basin scale climate indicator) translate into changes in salmon returns (a local response) throughout the North Pacific. When the PDO is in a warm phase, returns are relatively low for salmon that spawn in 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).



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

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

9
10 Observational data on the physical and chemical conditions that freshwater, coastal, and
11 marine organisms experience in their environment are a fundamental part of understanding
12 species response to ocean and climate change. While NOAA Fisheries supports a variety of
13 biological, physical, and human system monitoring efforts that inform fisheries and ecosystem
14 management (e.g, North Pacific Climate Regimes and Ecosystem Productivity, Integrated
15 Ecosystem Assessments, etc.), these efforts fall short of what is need to adequately track the
16 impacts of climate change. An enhanced system that inventories current observing efforts,
17 identifies gaps in these efforts, fills gaps with new observations, makes data readily available to
18 scientists and stakeholders, and allows integration across data types collected in the system is
19 required to meet NOAA Fisheries' needs today and in the future. Doing so would provide the
20 data needed to deliver core information on the status and trends of marine, coastal, and
21 freshwater ecosystems and human systems under climate change, and could provide early
22 warnings of rapid or impending changes.

23
24 Building and maintaining an adequate physical, chemical, and biological observing system will
25 require a variety of critical science infrastructure, including ship time, remote observing assets,
26 establishment of key partnerships, and personnel to collect and process samples. Ideally, a
27 large component of the modified observing system would be ongoing fisheries oceanography
28 and LMR monitoring time series, but paired with simultaneous physical-chemical observations
29 in both marine and freshwater systems. Building and maintaining an adequate observation
30 system for fishing- and LMR-dependent community resource use and overall well-being will
31 require a similar amount of effort given the sheer amount of time required to collect and
32 analyze socio-economic data. Where gaps exist between projected needs and ongoing time
33 series, NOAA Fisheries should increase support for existing activities and initiate, to the extent
34 feasible, new observational time series to generate data relevant to managing LMRs and human
35 communities over the coming decades. Ideally, observing efforts would include concurrent,
36 integrated, interdisciplinary collection of physical, chemical, biological, and socio-economic
37 data.

38
39 To succeed in implementing the Strategy, NOAA Fisheries will need to evaluate and possibly
40 adopt novel and advanced sampling approaches and invest in enhanced computing
41 technologies and laboratory assets. Many of the advances made for the next generation of
42 remote and unmanned sampling and ocean observation systems will be operational in the next
43 few years, and others are ready now. Taking advantage of the efficiencies and precision these

1 devices can provide will open up new data sets requisite for tracking climate change (e.g.,
2 underwater gliders to measure physical and chemistry conditions, accurate and precise ocean
3 carbon chemistry sensors, acoustic monitoring of fish populations).
4

5 Many of the observing systems and modeling exercises described above, especially future
6 projections and hind-casting, require computing systems that can store large data sets and are
7 fast enough to complete scenarios in a reasonable amount of time. Expansion of computing
8 systems is required to meet these needs. Collection of high-quality, species-response data will
9 require laboratories with specialized equipment and animal holding facilities to elucidate
10 physiological and genetic responses of LMR's to future conditions (e.g., Northwest Fisheries
11 Science Center's ocean acidification experimental system).
12

13 Improved data access and data visualization tools are necessary for fully sustaining and
14 supporting the science enterprise outlined in the Strategy and implementing the Strategy
15 successfully over time. Maintaining data archives accessible inside and outside of NOAA
16 Fisheries, as appropriate, with appropriate database infrastructural elements is one step for
17 doing so. Additionally, improving access to data, meta-data, and data servers will likely
18 increase the utility of the data collected, and make it more palatable for use in other facets of
19 the Strategy. Development of data visualization tools would facilitate uptake and understanding
20 data related to climate change.
21

22 Staffing considerations are key for addressing this strategy. Dedicated LMR-climate staff are
23 needed in the science centers and regional offices to help produce, deliver, and use climate-
24 related information in fulfilling NOAA Fisheries' mission activities. There is also a need for
25 training and development of analytical capacity for NOAA Fisheries personnel. Research and
26 provision of climate-smart management advice is predicated upon a workforce with the vision,
27 understanding, and capability to analytically address the needs described throughout this
28 Strategy. Additional analytical billets, quantitative training, and increased awareness of
29 climate-change needs are warranted to increase the production, delivery, and use of climate-
30 related information in fulfilling NOAA Fisheries' mission activities.
31

32 Many entities outside of NOAA Fisheries collect data, conduct research, build models, and
33 develop predictions that are useful for projecting future states of LMRs, habitats, ecosystems,
34 human communities, and their use of LMRs under climate change (Table 2). Communication of
35 the utility of these resources and their contribution to NOAA Fisheries' LMR mandates should
36 be highlighted by NOAA Fisheries. NOAA Fisheries has a foundation of partnerships within
37 NOAA (e.g., Office of Oceanic and Atmospheric Research, National Ocean Service) and with
38 other entities (e.g., state and other federal agencies, academia, industry etc.; Table 2). Building
39 on and strengthening these internal and external foundations are a critical component of
40 developing an efficient and comprehensive capacity for modeling future states. Gaps in scope
41 and capacity of NOAA Fisheries programs will necessarily need to be filled by expanding existing
42 and establishing new partnerships with programs outside the agency.
43

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

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

DRAFT

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

1 to help launch and make major strides toward implementation over the next 5 years.
 2 Implementing these recommendations will efficiently and effectively increase the production,
 3 delivery, and use of climate-related information in NOAA Fisheries LMR management and
 4 thereby reduce impacts and increase resilience of LMRs and the people that depend on them in
 5 a changing climate.

6

7 **PRIORITY ACTIONS:**

8

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

14

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

19

20 **PRIORITY NEAR-TERM ACTIONS:**

21

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

24

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

- 1 c. Major climate-related data and information gaps in the region.
- 2 d. Existing strengths, weaknesses, opportunities, and challenges to implement the
- 3 Strategy.
- 4 3. Ensure that adequate resources are dedicated to climate-related, process-oriented
- 5 research.
- 6 a. Initiate or expand partnerships with key science providers (e.g., OAR, NASA,
- 7 USGS, NSF, IMR) to leverage and attract resources to help meet NOAA Fisheries
- 8 climate-related science and information needs.
- 9 b. Leverage planned and new initiatives.
- 10 4. Establish standard, climate-smart terms of reference to apply to all of NOAA Fisheries
- 11 LMR management, environmental compliance requirements, and other processes that
- 12 cross multiple mandates and core policy areas.
- 13

14 **PRIORITY MEDIUM-TERM ACTIONS:**

15
16 The following are key medium-term recommendations to advance implementation of this
17 Strategy. These are intended to be ongoing with significant progress (e.g., first phase
18 completed) within 2-5 years after the release of this report:

19 Workshops and training

- 20 1. Establish regular, NOAA-wide, national, climate-science workshops with LMR
- 21 emphasis, with a focus on climate-ready BRPs and science for setting Harvest
- 22 Control Rules, ESA evaluations (section 7 and section 10), essential fish habitat
- 23 consultations, aquaculture, and NEPA analyses in a changing climate.
- 24 2. Increase awareness of and training for NOAA Fisheries science and management
- 25 staff on the impacts of climate change on LMRs and climate-informed LMR
- 26 management practices.
- 27 3. Organize and conduct regime-shift detection workshops for each region.
- 28 4. Organize and conduct distribution shift workshops, with implications for stock and
- 29 population identification and unit area across all LMRs in each region.
- 30 5. Organize and conduct vital rate workshops, with implications for LMR life-history
- 31 parameters across all LMRs in each region.
- 32 6. Organize and conduct workshops aimed at identifying regional data gaps (biological,
- 33 physical, and socio-economic) related to climate variability and change and devising
- 34 data collection programs aimed at filling those gaps, especially socio-economic gaps.
- 35
- 36

37 Engagement and outreach

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

- 1 informed biological reference points, climate-smart Harvest Control Rules,
2 management strategy evaluations for climate-ready LMR management, climate-
3 smart protected species and habitat consultations, and management strategy
4 evaluations for climate-ready species and habitat recovery.
- 5 9. Continue and expand NOAA Fisheries' participation in cross-governmental, national
6 efforts to advance climate-related science LMRs.
7

8 Science to inform policy

- 9 10. Work with partners to re-evaluate risk policies under a changing climate and ocean.
10 11. Establish science-based approaches for shifting biological reference points to
11 account for changing productivities, distributions, and diversities.
12 12. Conduct management strategy evaluations on climate scenarios in extant ecosystem
13 and population models in conjunction with NOAA IEA program, NOAA Fisheries
14 Stock Assessment Improvement Plan Update/Next Generation Stock Assessment,
15 NOAA Fisheries Protected Resources Stock Assessment Improvement Plan, and
16 development of ESA Five-Year Status Reviews.
17 13. Establish science-based thresholds for exiting and entering fisheries.
18 14. Establish and implement clear policies and practices for incorporating climate
19 change into all NEPA and ESA (i.e., listing, recovery planning, interagency
20 consultations, and permitting) activities.
21 15. Establish and implement standards and guidelines for incorporating climate change
22 information into Fisheries Management Plans and Fisheries Ecosystem Plans.
23 16. Develop and implement standards and practices to promote climate resilience and
24 climate mitigation in NOAA Fisheries habitat conservation activities.
25 17. Develop climate-driven regional ocean models for use in projecting climate impacts
26 on LMRs.
27

28 Science planning and management

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

1 SUMMARY

2
3 In summary, changes in the planet's climate system are already affecting the nation's valuable
4 marine, coastal, and freshwater LMRs. These impacts will affect the services these LMRs
5 provide; the many people, businesses, and communities that depend on LMRs (Osgood 2008;
6 Doney et al. 2012; Melillo et al. 2014); and NOAA Fisheries' LMR management efforts.

7
8 This Strategy outlines seven key parts of the operational framework needed to incorporate
9 climate change into the management of LMRs and their associated habitats, ecosystems, and
10 human systems. It is clear that addressing the information and management challenges of
11 climate change will require a cross-cutting effort that spans NOAA Fisheries LMR stewardship
12 mandates (Figure 3) and many partners (Table 2). Thus, in many respects the need to adopt
13 ecosystem-based management is crucial as we move to implement this strategy (MacLeod and
14 Leslie 2009; Link 2010). From the seven objectives of the Strategy, several common items with
15 high utility are identified as priorities with high return for investment. These are approaches
16 that are valuable across mandates, regions, LMRs, and priority areas. The commonality of
17 information needed across mandates should be useful to gain efficiencies in how that material
18 is produced and delivered.

19
20 The main recommendations of the Strategy emphasize facets of climate-related LMR science
21 and management that address critical needs and will have a high return on investment. With
22 adequate resources (people, funding, technology), implementation of the Strategy will provide
23 resource managers with the information they need to sustain the nation's valuable LMRs and
24 the people that depend on them in a changing climate.
25

GLOSSARY

1
2
3 **Adaptation:** (1) An adjustment in natural or human systems to a new or changed environment
4 that exploits beneficial opportunities or moderates negative effects (Melillo et al. 2014); (2)
5 Minimizing the impact of climate change on fish and wildlife through the application of cutting-
6 edge science in managing species and habitats (U.S. Fish and Wildlife Service 2010).
7

8 **Biological Reference Point(s):** A biological benchmark against which the abundance of the stock
9 or the fishing mortality rate can be measured in order to determine its status. These reference
10 points can be used as limits or targets, depending on their intended usage (Blackhart et al.
11 2006).
12

13 **Climate Change:** Refers to a change in the state of the climate that can be identified (e.g., by
14 using statistical tests) by changes in the mean and/or the variability of its properties, and that
15 persists for an extended period, typically decades or longer (Intergovernmental Panel on
16 Climate Change 2007).
17

18 **Climate System:** The climate system is the highly complex system consisting of five major
19 components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and
20 the biosphere, and the interactions between them. The climate system evolves in time under
21 the influence of its own internal dynamics and because of external forcings such as volcanic
22 eruptions, solar variations and anthropogenic forcings such as the changing composition of the
23 atmosphere and land use change (Intergovernmental Panel on Climate Change 2013).
24

25 **Climate Variability:** Refers to variations in the mean state and other statistics of the climate on
26 all temporal and spatial scales beyond that of individual weather events (Intergovernmental
27 Panel on Climate Change 2007).
28

29 **Diadromous:** Diadromous species spend part of their life-cycle in fresh water and other part in
30 salt water. Diadromous is the term used to refer to anadromous, catadromous, or
31 amphidromous species.
32

33 **Ecosystem connectivity:** Ecosystem connectivity is the degree in which the marine ecosystem
34 facilitates or impedes movement among different habitats. Connectivity includes both
35 structural connectivity (the physical arrangements of habitats) and functional connectivity (the
36 movement of individuals among habitats). The degree to which an ecosystem is connected
37 determines the amount of dispersal there is among habitats, which influences gene flow, local
38 adaptation, extinction risk, colonization probability, and the potential for organisms to move as
39 they cope with climate change.
40

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

8
9 **Fisheries Management Plan:** A document prepared under supervision of the appropriate
10 fishery management council for management of stocks of fish judged to be in need of
11 management. The plan must generally be formally approved. A Fisheries Management Plan
12 includes data, analyses, and management measures. A plan containing conservation and
13 management measures for fishery resources, and other provisions required by the Magnuson-
14 Stevens Act, developed by fishery management councils or the Secretary of Commerce
15 (Blackhart et al. 2006).

16
17 **Greenhouse Gases:** A gas in the atmosphere of natural or human origin that absorbs and emits
18 thermal infrared radiation. Water vapour, carbon dioxide, nitrous oxide, methane and ozone
19 are the main greenhouse gases in the Earth's atmosphere. Their net impacts is to trap heat
20 within the climate system (Intergovernmental Panel on Climate Change 2013).

21
22 **Integrated Ecosystem Assessment:** An Integrated Ecosystem Assessment is a formal synthesis
23 and quantitative analysis of information on relevant natural and socioeconomic factors in
24 relation to specified ecosystem management goals. It involves and informs citizens, industry
25 representatives, scientists, resource managers, and policy makers through formal processes to
26 contribute to attaining the goals of an ecosystem approach to management (Levin et al. 2008).

27
28 **Intensity of upwelling and downwelling:** Upwelling intensity depends on wind strength and
29 seasonal variability, as well as the vertical structure of the water, variations in the bottom
30 bathymetry, and instabilities in the currents. Upwelling is the upward motion of cold, nutrient
31 rich deep water along the coast. Downwelling involves the downward motion of warm waters
32 along the coast. (NOAA: <http://oceanservice.noaa.gov/facts/upwelling.html>)

33
34 **Large Marine Ecosystem:** Large Marine Ecosystems are large areas of ocean space,
35 approximately 200,000 km² or greater, that have been identified for conservation purposes.
36 They are located in coastal waters characterized by unique species, levels of productivity,
37 bathymetry, and hydrography (Blackhart et al. 2006).

38
39 **Management Strategy Evaluation:** The evaluation of a strategy adopted by the management
40 authority to reach established management goals. In addition to the objectives, it includes
41 choices regarding all or some of the following: access rights and allocation of resources to
42 stakeholders, controls on inputs (e.g., fishing capacity, gear regulations), outputs (e.g., quotas,

1 minimum size at landing), and fishing operations (e.g., calendar, closed areas, and seasons)
2 (Blackhart et al. 2006).

3
4 **Mitigation:** Implementing actions to reduce greenhouse gas emissions or increase the amount
5 of carbon dioxide absorbed and stored by natural and man-made carbon sinks (Melillo et al.
6 2014).

7
8 **Mixed layer depth:** The surface layer of the ocean that is mixed by the action of waves and
9 tides so that the waters are nearly isothermal and isohaline; underlain by a pycnocline

10
11 **Nutrient availability:** Chemicals (such as nitrogen and phosphorus) that plants and animals
12 need to live and grow. At high concentrations, particularly in water, nutrients can become
13 pollutants.

14
15 **Ocean acidification:** Ocean acidification refers to a reduction in the pH of the ocean over an
16 extended period, typically decades or longer, which is caused primarily by uptake of carbon
17 dioxide from the atmosphere, but can also be caused by other chemical additions or
18 subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH
19 reduction that is caused by human activity (Intergovernmental Panel on Climate Change 2013).

20
21 **Ocean Circulation:** The large scale movement of waters in the ocean basins. Winds drive
22 surface circulation, and the cooling and sinking of waters in the Polar Regions drive deep
23 circulation.

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

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

36
37 **Resilience:** Capacity of a natural system (fisheries community or ecosystem) to recover from
38 heavy disturbance such as intensive fishing (Blackhart et al. 2006).

39
40 **Salinity:** ‘Salinity’ refers to the weight of dissolved salts in a kilogram of seawater. Because the
41 total amount of salt in the ocean does not change, the salinity of seawater can be changed only

1 by addition or removal of fresh water. (IPCC, 2013 pg. 265)

2

3 **Scenario:** A plausible and often simplified description of how the future may develop based on
4 a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of
5 technology change, prices) and relationships. Scenarios are neither predictions nor projections
6 and sometimes may be based on a “narrative storyline.” Scenarios may be derived from
7 projections but are often based on additional information from other sources (Blackhart et al.
8 2006).

9

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

15

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

23

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

28

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

36

37

38

39

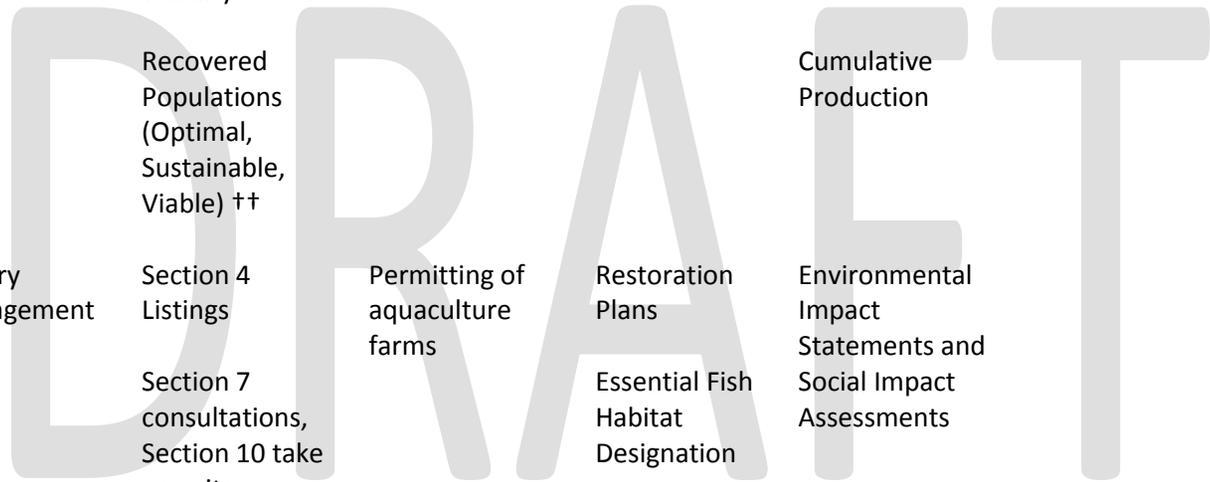
TABLES

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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					
	<i>Fisheries</i>	<i>Protected Species</i>	<i>Aquaculture</i>	<i>Habitat</i>	<i>Ecosystems</i>
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
What are main regulatory or management delivery devices to achieve objectives	Fishery Management Plans	Recovered Populations (Optimal, Sustainable, Viable) †† 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	Cumulative Production 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**

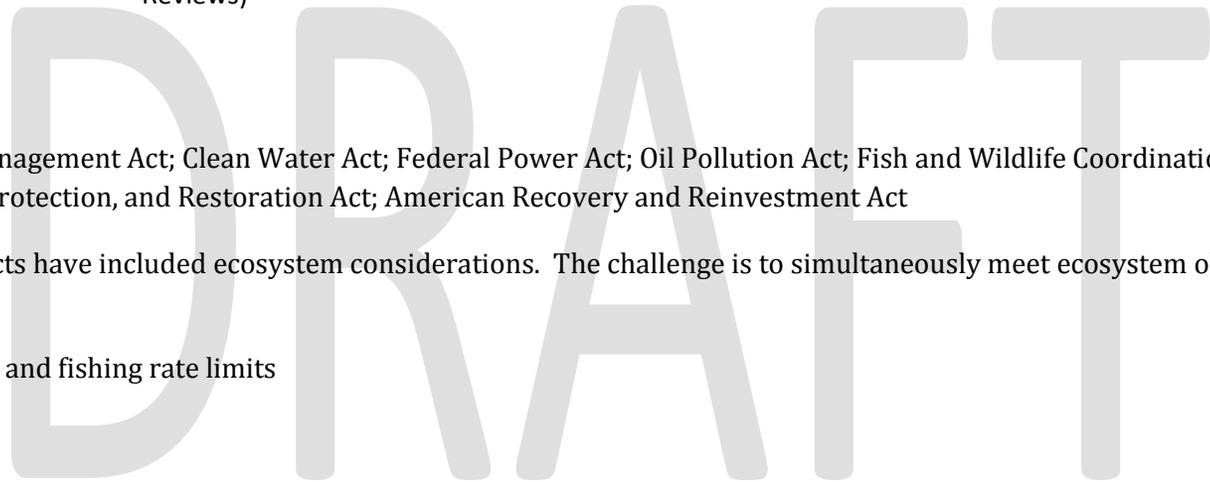
Stock
Assessments

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.

<u>Entity</u>	<u>Information</u>
NOAA	
<i>Oceans and Atmospheric Research</i>	Physical and chemical ocean conditions Physical oceanographic models Coupled bio-physical models Climate monitoring and prediction
<i>National Weather Service</i>	Weather monitoring and prediction Storm monitoring and prediction
<i>National Ocean Service</i>	Shoreline monitoring Estuarine monitoring
<i>National Environmental Satellite, Information, and Data Service</i>	Ocean and coastal monitoring Sea ice monitoring Data management services
<i>Integrated Ocean Observing System</i>	Physical and chemical ocean conditions
Federal agencies	
<i>National Aeronautics and Space Administration</i>	Physical ocean monitoring Ocean productivity monitoring Ocean circulation monitoring
<i>Environmental Protection Agency</i>	Coastal monitoring
<i>US Geological Service</i>	Stream monitoring
<i>US Department of Agriculture</i>	Food/Seafood supply and demand
<i>US Army Corps of Engineers</i>	River monitoring
<i>US Census Bureau</i>	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

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Table 3. Recommended strategies to address each objective.

<p>Objective 1: Identify appropriate, climate-informed reference points for managing LMRs.</p> <ul style="list-style-type: none"> ● 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.
<p>Objective 2: Identify robust strategies for managing LMRs under changing climate conditions.</p> <ul style="list-style-type: none"> ● 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.
<p>Objective 3: Design adaptive decision processes that can incorporate and respond to changing climate conditions.</p> <ul style="list-style-type: none"> ● 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
<p>Objective 4: Identify future states of marine, coastal, and freshwater ecosystems, LMRs, and LMR -dependent human communities in a changing climate.</p> <ul style="list-style-type: none"> ● 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.

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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.

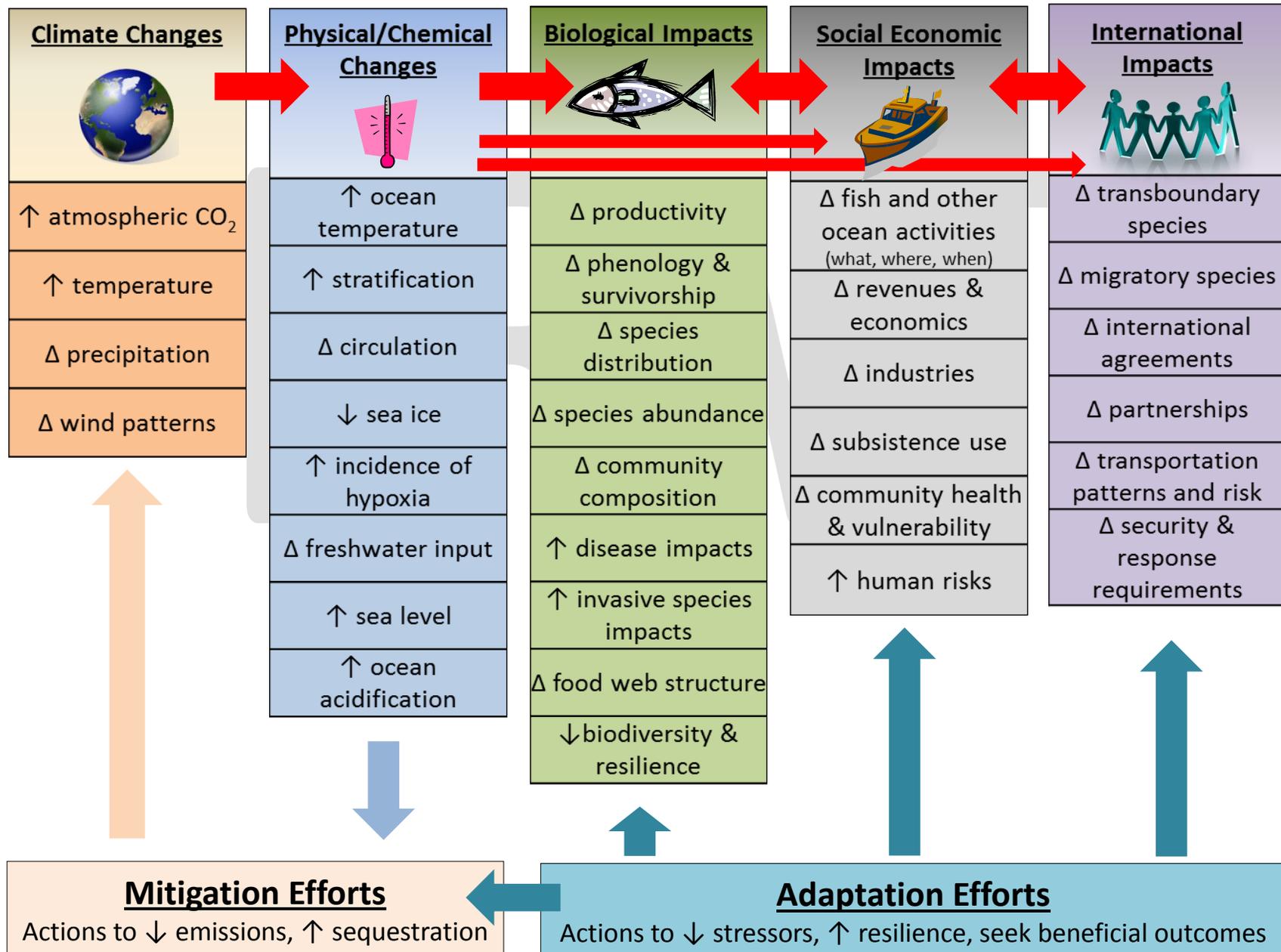


Figure 2. A simplified, generic LMR management process. There are distinctions and caveats across all NOAA Fisheries mandates, but this generalized version depicts the major steps required to produce management (mgt) advice to fulfill NOAA Fisheries mandates. A key point is that climate information can 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.

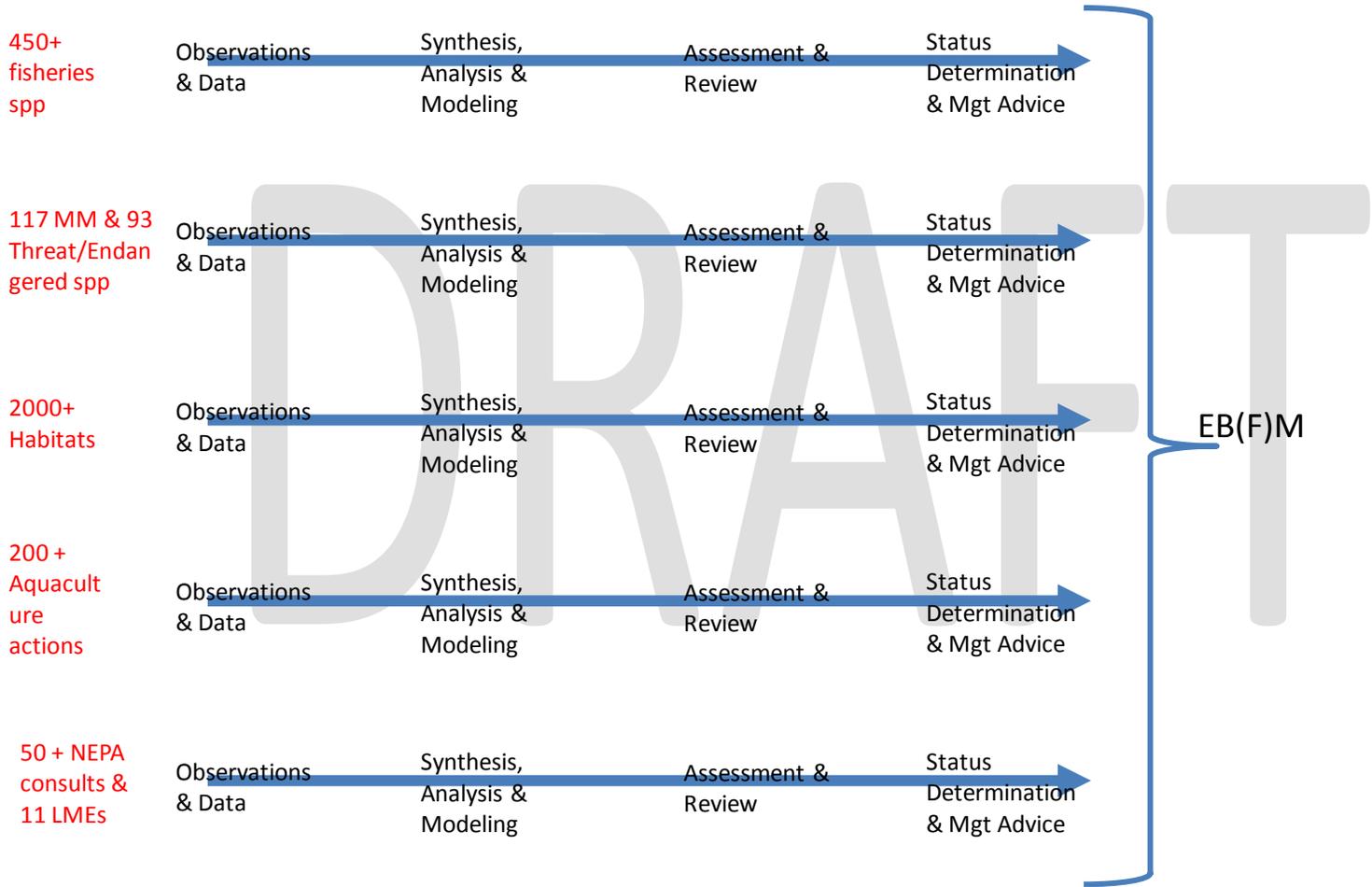
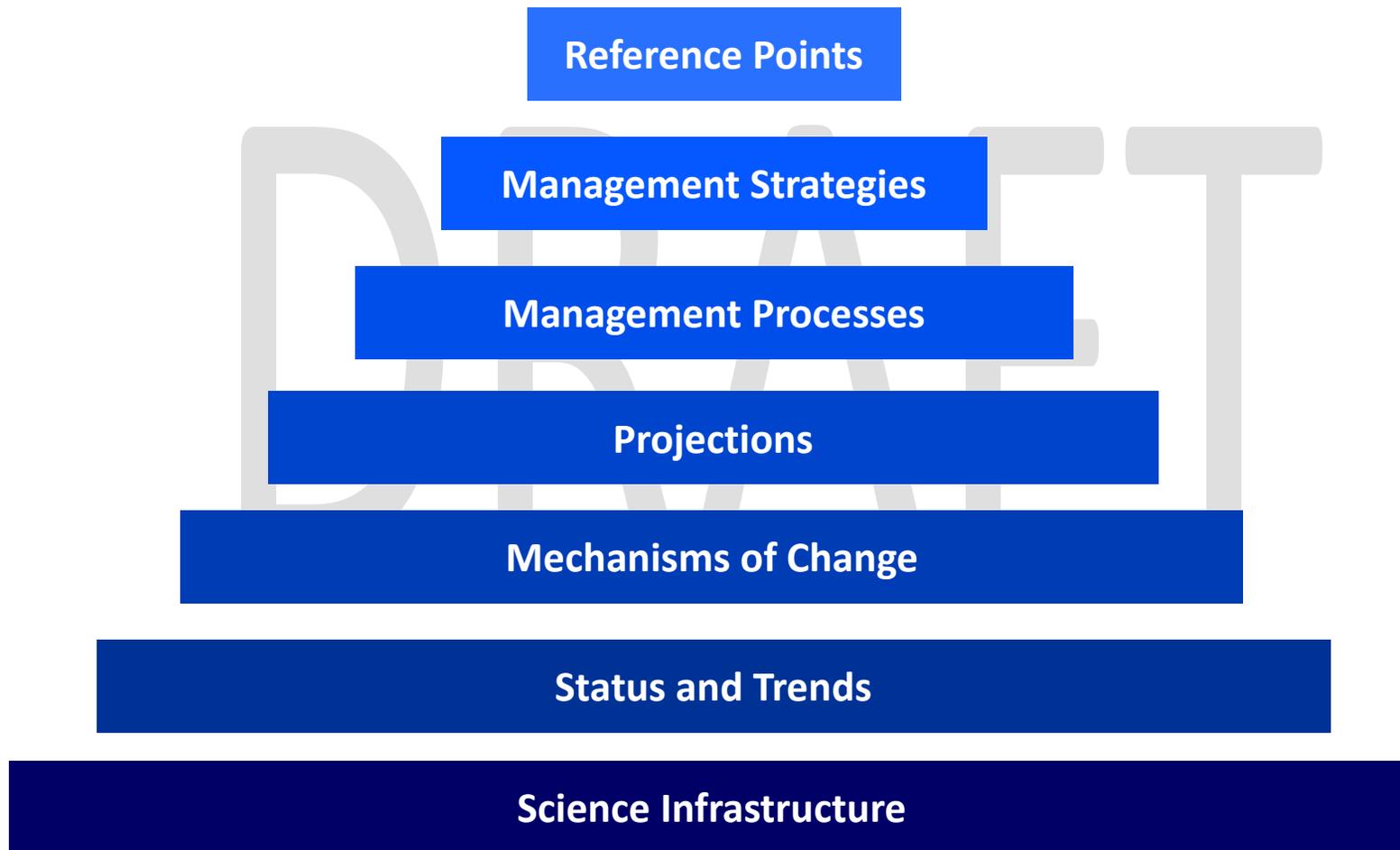


Figure 4. Seven priority objectives for the NOAA Fisheries National Climate Science Strategy. The ultimate goal is to provide management advice to meet NOAA Fisheries mandated responsibilities, with each prior level required to support that and subsequent objectives





REFERENCES

- Anthony KRN, Kline DI, Diaz-Pulido G, Dove S, Hoegh-Guldberg O (2008) Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences* 105: 17442-17446
- Baker JD, Howell EA, Polovina JJ (2012) Relative influence of climate variability and direct anthropogenic impact on a sub-tropical Pacific top predator, the Hawaiian monk seal. *Marine Ecology Progress Series* 469: 175-189
- Baker JD, Polovina JJ, Howell EA (2007) Effect of variable oceanic productivity on the survival of an upper trophic predator, the Hawaiian monk seal *Monachus schauinslandi*. *Marine Ecology Progress Series* 346: 277-283
- Barton A, Hales B, Waldbusser GG, Langdon C, Feely RA (2012) The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnol Oceanogr* 57: 698-710
- Batchelder HP, Botsford L, Daly K, Davis C, Ji R, Ohman M, Peterson W, Runge J (2013) Climate impacts on animal populations and communities in coastal marine systems: forecasting change through mechanistic understanding of population dynamics. *Oceanography* 26: 34-51
- Battin J, Wiley MW, Ruckelshaus MH, Palmer RN, Korb E, Bartz KK, Imaki H (2007) Projected impacts of climate change on salmon habitat restoration. *Proceedings of the National Academy of Sciences* 104: 6720-6725
- Bednaršek N, Feely RA, Reum JCP, Peterson B, Menkel J, Alin S, Hales B (2014) *Limacina helicina* shell dissolution as an indicator of declining habitat suitability due to ocean acidification in the California Current Ecosystem. *Proceedings of the Royal Society B: Biological Sciences* 281: 20140123
- Beechie T, Imaki H, Greene J, A. Wade2, A., Wu H, Pess G, Roni P, Kimball J, Stanford J, Kiffney P, Mantua N (2013) Restoring salmon habitat for a changing climate. *River Research and Applications* 329: 939-960
- Behrenfeld M (2011) Uncertain future for ocean algae. *Nature Climate Change* 1: 33-34
- Bell RJ, Hare JA, Manderson JP, Richardson DE (In review) Externally driven changes in the abundance of summer and winter flounder. *ICES Journal of Marine Science*
- Blackhart K, Stanton DG, Shimada AM (2006) NOAA Fisheries glossary. US Dept. Commerce, NOAA Technical Memorandum NMFS-F/SPO-69
- Boughton DA, Pike AS (2013) Floodplain rehabilitation as a hedge against hydroclimatic uncertainty in a migration corridor of threatened steelhead. *Conservation Biology* 27: 1158-1168
- Boveng PL, Bengtson JL, Buckley TW, Cameron MF, Dahle SP, Kelly BP, Megrey BA, Overland JE, Williamson NJ (2009) Status review of the spotted seal (*Phoca larga*). NOAA Technical Memorandum. NMFS-AFSC-200
- Brainard R, Birkeland C, Eakin C, McElhany P, Miller M, Patterson M, Piniak G (2011) Status review report of 82 candidate coral species petitioned under the U.S. Endangered Species Act. U.S. Dept. Commerce, NOAA Technical Memorandum, NOAA-TM-NMFS-PIFSC-27
- Brainard RE, Weijerman M, Eakin CM, McElhany P, Miller MW, Patterson M, Piniak GA, Dunlap

- MJ, Birkeland C (2013) Incorporating climate and ocean change into extinction risk assessments for 82 coral species. *Conservation Biology* 27: 1169-1178
- Bruno JF, Selig ER (2007) Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. *PLoS ONE* 2: e711
- Burke L, Reynter K, Spalding M, Perry A (2011) *Reefs at risk revisited*. World Resources Institute, Washington, DC
- Burkett VR, Kirtland DA, Taylor IL, Belnap J, Cronin TM, Dettinger MD, Frazier EL, Haines JW, Loveland TR, Milly PCD, O'Malley R, Thompson RS, Maule AG, McMahon G, Striegl RG (2013) U.S. Geological Survey climate and land use change science strategy — a framework for understanding and responding to global change. U.S. Geological Survey, Circular 1383-A
- Busch DS, Greene CM, Good TP (2013) Estimating effects of tidal power projects and climate change on threatened and endangered marine species and their food web. *Conservation Biology* 27: 1190-1200
- Carpenter KE, Abrar M, Aeby G, Aronson RB, Banks S, Bruckner A, Chiriboga A, Cortes J, Delbeek JC, DeVantier L, Edgar GJ, Edwards AJ, Fenner D, Guzman HM, Hoeksema BW, Hodgson G, Johan O, Licuanan WY, Livingstone SR, Lovell ER, Moore JA, Obura DO, Ochavillo D, Polidoro BA, Precht WF, Quibilan MC, Reboton C, Richards ZT, Rogers AD, Sanciangco J, Sheppard A, Sheppard C, Smith J, Stuart S, Turak E, Veron JEN, Wallace C, Weil E, Wood E (2008) One-third of reef-building corals face elevated extinction risk from climate change and local impacts. *Science* 321: 560-563
- Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson REG, Zeller D, Pauly D (2010) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology* 16: 24-35
- Chung IK, Oak JH, Lee JA, Shin JA, Kim JG, Park K-S (2013) Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean Project Overview. *ICES Journal of Marine Science* 70: 1038-1044
- Cooley SR, Doney SC (2009) Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters* 4: 024007
- Crozier LG, Scheuerell MD, Zabel RW (2011) Using time series analysis to characterize evolutionary and plastic responses to environmental change: a case study of a shift toward earlier migration date in sockeye salmon. *The American Naturalist* 178: 755-773
- Crozier LG, Zabel RW, Hamlet AF (2008) Predicting differential effects of climate change at the population level with life-cycle models of spring Chinook salmon. *Global Change Biology* 14: 236-249
- De'ath G, Fabricius K, Sweatman H, Puotinen M (2012) The 27-year decline of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences* 109: 17995-17999
- Doney SC, Ruckelshaus MH, Duffy JE, Barry JP, Chan F, English C, Galindo HM, Grebmeier JM, Hollowed AB, Knowlton N, Polovina J, Rabalais NN, Sydeman WJ, Talley LD (2012) Climate change impacts on marine ecosystems. *Annual Review of Marine Science* 4: 11-37
- Dumbauld BR, Kauffman BE, Trimble AC, Ruesink JL (2011) The Willapa Bay oyster reserves in Washington State: fishery collapse, creating a sustainable replacement, and the potential for habitat conservation and restoration. *J Shellfish Res* 30: 71-83
- Eakin CM, Lough JM, Heron SF (2009) Climate variability and change: monitoring data and evidence for increased coral bleaching stress. In: van Oppen MJH, Lough JM (eds) *Coral Bleaching*. Springer, Berlin Heidelberg, pp 41-67
- Eakin CM, Morgan JA, Heron SF, Smith TB, Liu G, Alvarez-Filip L, Baca B, Bartels E, Bastidas C, Bouchon C, Brandt M, Bruckner AW, Bunkley-Williams L, Cameron A, Causey BD, Chiappone M, Christensen TRL, Crabbe MJC, Day O, de la Guardia E, Díaz-Pulido G,

- DiResta D, Gil-Agudelo DL, Gilliam DS, N. GR, Gore S, Guzmán HM, Hendee JC, Hernández-Delgado EA, Husain E, Jeffrey CFG, J. JR, Jordán-Dahlgren E, Kaufman LS, Kline DI, Kramer PA, C. LJ, Lirman D, Mallela J, Manfrino C, Maréchal J-P, Marks K, Mihaly J, Miller WJ, Mueller EM, M. ME, Orozco Toro CA, Oxenford HA, Ponce-Taylor D, Quinn N, Ritchie KB, Rodríguez S, Ramírez AR, Romano S, Samhuri JF, Sánchez JA, Schmahl GP, Shank BV, Skirving WJ, Steiner SCC, Villamizar E, Walsh SM, Walter C, Weil E, Williams EH, Roberson KW, Yusuf Y (2010) Caribbean corals in crisis: record thermal stress, bleaching, and mortality in 2005. *PLoS ONE* 5: e13969
- Executive Order 13547 of July 19th (2010) National Policy for the Stewardship of the Ocean, our Coasts, and the Great Lakes. C.F.R. code 75 FR 43021.
- Fay G, Large SI, Link JS, Gamble RJ (2013) Testing systemic fishing responses with ecological indicators: an MSE approach. *Ecological Modelling* 265: 45-55
- Feely RA, Sabine CL, Hernandez-Ayon JM, Ianson D, Hales B (2008) Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science* 320: 1490-1492
- Fogarty M, Incze L, Hayhoe K, Mountain D, Manning J (2008) Potential climate change impacts on Atlantic cod (*Gadus morhua*) off the northeastern USA. *Mitigation and Adaptation Strategies for Global Change* 13: 453-466
- Fulton EA, Link JS, Kaplan IC, Savina-Rolland M, Johnson P, Ainsworth C, Horne P, Gorton R, Gamble RJ, Smith ADM, Smith DC (2011) Lessons in modelling and management of marine ecosystems: the Atlantis experience. *Fish and Fisheries* 12: 171-188
- Gaichas SK, Link JS, Hare JA (In press) Addressing Hjort's "other considerations" with ecological risk assessment: a review of methods and application evaluating Northeast U.S. fish community vulnerability to climate change. *ICES Journal of Marine Science*
- Gardner, T. A., Côté IM, Gill JA, Grant A, Watkinson AR (2003) Long-term region-wide declines in Caribbean corals. *Science* 301: 958-960
- Gregory R, Arvai J, Gerber LR (2013) Structuring decisions for managing threatened and endangered species in a changing climate. *Conservation Biology* 27: 1212-1221
- Griffis R, Howard J (2013) Oceans and marine resources in a changing climate. Technical input to the 2013 National Climate Assessment. Island Press
- Hare JA, Alexander MA, Fogarty MJ, Williams EH, Scott JD (2010) Forecasting the dynamics of a coastal fishery species using a coupled climate–population model. *Ecological Applications* 20: 452-464
- Harvell D, Jordan-Dahlgren E, Merkel S, Rosenberg E, Raymundo L, Smith G, Weil E, Willis B (2007) Coral disease, environmental drivers, and the balance between coral and microbial associates. *Oceanography* 20: 172-195
- Hazen EL, Jorgensen S, Rykaczewski RR, Bograd SJ, Foley DG, Jonsen ID, Shaffer SA, Dunne JP, Costa DP, Crowder LB, Block BA (2013) Predicted habitat shifts of Pacific top predators in a changing climate. *Nature Climate Change* 3: 234-238
- Heenan A, Pomeroy R, Brainard R, Amri A, Alino P, Armada N, Bell J, Cheung W, David L, Guieb R, Green S, Jompa J, Leonardo T, Logan C, Mamauag S, Munday P, Parker B, Shackeroff J, Yasin Z (2013) Incorporating climate change and ocean acidification into an ecosystem approach to fisheries management (EAFM) plan. The USAID Coral Triangle Support Partnership
- Hilborn R, Mangel M (1998) *The Ecological Detective: Confronting Models with Data*. Princeton University Press, Princeton, NJ
- Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A, Hatzitolos ME (2007) Coral reefs under rapid climate change and ocean acidification. *Science* 318
- Hoeke RK, Jokiel PL, Buddemeier RW, Brainard RE (2011) Projected changes to growth and mortality of Hawaiian corals over the next 100 years. *PLoS ONE* 6: e18038

- Holling CS (1978) Adaptive environmental assessment and management. John Wiley & Sons, Chichester, UK
- Hollowed AB, Barange M, Beamish RJ, Brander K, Cochrane K, Drinkwater K, Foreman MGG, Hare JA, Holt J, Ito S-i, Kim S, King JR, Loeng H, MacKenzie BR, Mueter FJ, Okey TA, Peck MA, Radchenko VI, Rice JC, Schirripa MJ, Yatsu A, Yamanaka Y (2013) Projected impacts of climate change on marine fish and fisheries. *ICES Journal of Marine Science* 70: 1023-1037
- Hollowed AB, Bond NA, Wilderbuer TK, Stockhausen WT, A'mar ZT, Beamish RJ, Overland JE, Schirripa MJ (2009) A framework for modelling fish and shellfish responses to future climate change. *ICES Journal of Marine Science* 66: 1584-1594
- Hooff RC, Peterson WT (2006) Copepod biodiversity as an indicator of changes in ocean and climate conditions of the northern California current ecosystem. *Limnology and Oceanography* 51: 2607-2620
- Howella P, Austerb PJ (2012) Phase shift in an estuarine finfish community associated with warming temperatures. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* 4: 481-495
- Ianelli JN, Hollowed AB, Haynie AC, Mueter FJ, Bond NA (2011) Evaluating management strategies for eastern Bering Sea walleye pollock (*Theragra chalcogramma*) in a changing environment. *ICES Journal of Marine Science* 68: 1297-1304
- Intergovernmental Panel on Climate Change (2007) Climate change 2007: synthesis report. Contribution of work groups I, II and III to the 4th Assessment Report of the Intergovernmental Panel on Climate Change Core writing team
- Intergovernmental Panel on Climate Change (2013) Climate change 2013: the physical science basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY USA, pp 1535
- Intergovernmental Panel on Climate Change (2014) Climate change 2014: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Field C, Barros V, Mach K, Mastrandrea M (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY USA
- Jorgensen JC, McClure MM, Sheer MB, Munn NL (2013) Combined effects of climate change and bank stabilization on shallow water habitats of Chinook salmon. *Conservation Biology* 27: 1201-1211
- Kaplan IC, Levin PS, Burden M, Fulton EA (2010) Fishing catch shares in the face of global change: a framework for integrating cumulative impacts and single species management. *Canadian Journal of Fisheries Science* 67: 1968-1982
- Keister JE, Di Lorenzo E, Morgan CA, Combes V, Peterson WT (2011) Zooplankton species composition is linked to ocean transport in the Northern California Current. *Global Change Biology* 17: 2498-2511
- Kelly RP, Cooley SR, Klinger T (2013) Narratives can motivate environmental action: the Whiskey Creek ocean acidification story. *AMBIO*: 1-8
- Kotwicki S, Lauth RR (2013) Detecting temporal trends and environmentally-driven changes in the spatial distribution of bottom fishes and crabs on the eastern Bering Sea shelf. *Deep Sea Research Part II: Topical Studies in Oceanography* 94: 231-243
- Kuffner IB, Andersson AJ, Jokiel PL, Rodgers KuS, Mackenzie FT (2007) Decreased abundance of crustose coralline algae due to ocean acidification. *Nature Geosci* 1: 114-117
- Langdon C, Atkinson MJ (2005) Effect of elevated pCO₂ on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient

- enrichment. *Journal of Geophysical Research* 110: C09S07
- Large SI, Fay G, Friedland KD, Link JS (2013) Defining trends and thresholds in responses of ecological indicators to fishing and environmental pressures. *ICES Journal of Marine Science* 70
- Levin PS, Fogarty MJ, Matlock GC, Ernst M (2008) Integrated ecosystem assessments. U.S. Dept. of Commerce, NOAA Technical Memorandum NMFS-NWFSC-92
- Levin PS, Wells BK, Sheer MB (2013) California Current Integrated Ecosystem Assessment: Phase II Report.
- Link JS (2010) Ecosystem-based fisheries management: confronting tradeoffs. Cambridge University Press, Cambridge, UK
- Link JS, Brodziak JKT, Edwards SF, Overholtz WJ, Mountain D, Jossi JW, Smith TD, Fogarty MJ (2011a) Marine ecosystem assessment in a fisheries management context. *Canadian Journal of Fisheries and Aquatic Sciences* 59: 1429-1440
- Link JS, Bundy A, Overholtz WJ, Shackell N, Manderson J, Duplisea D, Hare J, Koen-Alonso M, Friedland KD (2011b) Ecosystem-based fisheries management in the Northwest Atlantic. *Fish and Fisheries* 12: 152-170
- Lynch PD, Nye JA, Hare JA, Stock CA, Alexander MA, Scott JD, Curti KL, Drew K (In press) Projected ocean warming creates a conservation challenge for river herring populations. *ICES Journal of Marine Science*
- MacLeod KO, Leslie HM (2009) Ecosystem-based management for the oceans. Island Press, Washington, D.C.
- McClure MM, Alexander M, Borggaard D, Boughton D, Crozier L, Griffis R, Jorgensen JC, Lindley ST, Nye J, Rowland MJ, Seney EE, Snover AMY, Toole C, Van Houtan K (2013) Incorporating climate science in applications of the U.S. Endangered Species Act for aquatic species. *Conservation Biology* 27: 1222-1233
- Melillo JM, Richmond TC, Yohe GW (2014) Climate change impacts in the United States: the third national climate assessment. U.S. Global Change Research Program, pp 841
- Mueter FJ, Bond NA, Ianelli JN, Hollowed AB (2011) Expected declines in recruitment of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea under future climate change. *ICES Journal of Marine Science* 68: 1284-1296
- Murawski SA, Matlock GC (2006) Ecosystem science capabilities required to support NOAA's mission in the year 2020. NOAA Technical Memorandum NMFS-F/SPO-74
- National Marine Fisheries Service (2014) Fisheries economics of the United States, 2012. US Dept. Commerce, NOAA Technical Memorandum NMFS-F/SPO-137
- National Ocean Council (2013) National Ocean Policy implementation plan
- National Park Service (2010) National Park Service climate change response strategy. National Park Service Climate Change Response Program, U.S. Department of the Interior
- National Park Service (2012) Climate Change Action Plan 2012-2014. U.S. Department of the Interior
- NOAA Coastal Services Center (2014) Coastal change analysis program regional land cover
- NOAA Fisheries Office of Protected Resources (2014) Protected Resources Glossary
- NOAA Northwest Fisheries Science Center (2014) Ocean ecosystem indicators: Pacific decadal oscillation
- Nye JA, Gamble RJ, Link JS (2013) The relative impact of warming and removing top predators on the Northeast US large marine biotic community. *Ecological Modelling* 264: 157-168
- Nye JA, Link JS, Hare JA, Overholtz WJ, William J. (2009a) Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology Progress Series* 393: 111-129
- Nye JA, Link JS, Hare JA, Overholtz WJ (2009b) Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology Progress Series* 393: 111-129

- Ocean Research Advisory Panel (2013) Implementing ecosystem-based management: a report to the National Ocean Council
- Osgood KE (2008) Climate impacts on US living marine resources: National Marine Fisheries Service concerns, activities and needs. US Dept. Commerce, NOAA Technical Memorandum NMFS-F/SPO-89
- Overholtz WJ, Hare JA, Keith CM (2011) Distribution of Atlantic mackerel on the U. S. northeast continental shelf. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* 3: 219-232
- Pandolfi JM, Bradbury RH, Sala E, Hughes TP, Bjorndal KA, Cooke RG, McArdle D, McClenachan L, Newman MJH, Paredes G (2003) Global trajectories of the long-term decline of coral reef ecosystems. *Science* 301: 955-958
- Peterson WT, Morgan CA, Peterson JO, Fisher JL, Burke BJ, Fresh K (2013) Ocean ecosystem indicators of salmon marine survival in the northern California Current. NWFSC Web Document
- Pinsky ML, Fogarty MJ (2012) Lagged social-ecological responses to climate and range shifts in fisheries. *Climate Change Letters* 115: 883-891
- Pinsky ML, Worm B, Fogarty MJ, Sarmiento JL, Levin SA (2013) Marine taxa track local climate velocities. *Science* 341: 1239-1242
- Polovina JJ, Dunne JP, Woodworth PA, Howell EA (2011) Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. *ICES Journal of Marine Science* 68: 986-995
- Polovina JJ, Howell EA, Abecassis M (2008) Ocean's least productive waters are expanding. *Geophysical Research Letters* 35: L03618
- Punt AE, A'mar T, Bond NA, Butterworth DS, de Moor CL, De Oliveira JAA, Haltuch MA, Hollowed AB, Szuwalski C (In press) Fisheries management under climate and environmental uncertainty: control rules and performance simulation. *ICES Journal of Marine Science*
- Quentin Grafton R (2010) Adaptation to climate change in marine capture fisheries. *Marine Policy* 34: 606-615
- Quinn TP, Adams DJ (1996) Environmental changes affecting the migratory timing of American shad and sockeye salmon. *Ecology* 77: 1151-1162
- Quinn TP, Hodgson S, Peven C (1997) Temperature, flow, and the migration of adult sockeye salmon (*Oncorhynchus nerka*) in the Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 1349-1360
- Radlinski MK, Sundermeyer MA, Bisagni JJ, Cadrin SX (2013) Spatial and temporal distribution of Atlantic mackerel (*Scomber scombrus*) along the northeast coast of the United States, 1985–1999. *ICES Journal of Marine Science* 70: 1151-1161
- Ruckelshaus M, Doney SC, Galindo HM, Barry JP, Chan F, Duffy JE, English CA, Gaines SD, Grebmeier JM, Hollowed AB, Knowlton N, Polovina J, Rabalais NN, Sydeman WJ, Talley LD (2013) Securing ocean benefits for society in the face of climate change. *Marine Policy* 40: 154-159
- Rykaczewski RR, Dunne JP (2010) Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model. *Geophysical Research Letters* 37: L21606
- Saba VS, Stock CA, Spotila JR, Paladino FV, Tomillo PS (2012) Projected response of an endangered marine turtle population to climate change. *Nature Climate Change* 2: 814-820
- Samhuri J, Levin P, Ainsworth C (2010) Identifying thresholds for ecosystem-based management. *PLoS ONE* 5: e8907
- Schnute JT, Maunder MN, Ianelli JN (2007) Designing tools to evaluate fishery management strategies: can the scientific community deliver? . *ICES Journal of Marine Science* 64:

1077-1084

- Seney EE, Rowland MJ, Lowery RA, Griffis RB, McClure MM (2013) Climate change, marine environments, and the U.S. Endangered Species Act. *Conservation Biology* 27: 1138-1146
- Shelton C (2014) Climate change adaptation in fisheries and aquaculture – compilation of initial examples. *FAO Fisheries and Aquaculture Circular No. 1088*. Rome, FAO. 34 pp.
- Sigler MF, Stabeno PJ, Eisner LB, Napp JM, Mueter FJ (In press) Spring and fall phytoplankton blooms in a productive subarctic ecosystem, the eastern Bering Sea, during 1995-2011. *Deep Sea Res II*
- Slocombe DS (1993) Implementing ecosystem-based management. *BioScience* 43: 612-622
- Smith ADM, Sainsbury KJ, A. SR (1999) Implementing effective fisheries management systems—management strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science* 56: 967-979
- Snover AK, Mantua NJ, Littell JS, Alexander MA, McClure MM, Nye J (2013) Choosing and using climate-change scenarios for ecological-impact assessments and conservation decisions. *Conservation Biology* 27: 1147-1157
- Solomon A, Birdsey R, Joyce L, Hayes J (2009) Forest Service global change research strategy, 2009–2019. US Department of Agriculture, US Forest Service, Research and Development, FS-917a
- Steinacher M, Joos F, Frölicher TL, Bopp L, Cadule P, Cocco V, Doney SC, Gehlen M, Lindsay K, Moore JK, Schneider B, Segschneider J (2010) Projected 21st century decrease in marine productivity: a multi-model analysis. *Biogeosciences* 7: 979-1005
- Stock CA, Alexander MA, Bond NA, Brander KM, Cheung WWL, Curchitser EN, Delworth TL, Dunne JP, Griffies SM, Haltuch MA, Hare JA, Hollowed AB, Lehodey P, Levin SA, Link JS, Rose KA, Rykaczewski RR, Sarmiento JL, Stouffer RJ, Schwing FB, Vecchi GA, Werner FE (2011) On the use of IPCC-class models to assess the impact of climate on Living Marine Resources. *Progress in Oceanography* 88: 1-27
- Stock CA, Dunne JP, John JG (2014) Global-scale carbon and energy flows through the marine planktonic food web: An analysis with a coupled physical–biological model. *Progress in Oceanography* 120: 1-28
- Sutton-Grier AE, Moore AK, Wiley PC, Edwards PET (2014) Incorporating ecosystem services into the implementation of existing U.S. natural resource management regulations: Operationalizing carbon sequestration and storage. *Marine Policy* 43: 246-253
- Szuwalski CS, Punt AE (2012) Fisheries management for regime-based ecosystems: a management strategy evaluation for the snow crab fishery in the eastern Bering Sea. *ICES Journal of Marine Science*
- Szuwalski CS, Punt AE (2013) Fisheries management for regime-based ecosystems: a management strategy evaluation for the snow crab fishery in the eastern Bering Sea. *ICES Journal of Marine Science* 70: 955-967
- U.S. Army Corps of Engineers (2009) Water resource policies and authorities: Incorporating sea-level change considerations in civil works programs Department of the Army, EC 1165-2-211.
- U.S. Fish and Wildlife Service (2010) Rising to the urgent challenge: strategic plan for responding to accelerating climate change. U.S. Department of Agriculture
- U.S. Office of Science and Technology Policy (2013) Science for an ocean nation: update of the ocean research priorities plan
- USDA (2011) USDA Climate Change Science Plan. U.S. Department of Agriculture
- Wainwright TC, Weitkamp LA (2013) Effects of climate change on Oregon Coast coho salmon: habitat and life-cycle interactions. *Northwest Science* 87: 219-242
- Walters AW, Bartz KK, McClure MM (2013) Interactive effects of water diversion and climate change for juvenile Chinook salmon in the Lemhi River basin (U.S.A.). *Conservation*

Biology 27: 1179-1189

Walters CJ (1986) Adaptive management of renewable resources. McGraw Hill, New York, NY

Weinberg JR, Powell EN, Pickett C, Nordahl J, V.A. , Jacobson LD (2005) Results from the 2004 cooperative survey of Atlantic surfclams. Northeast Fisheries Science Center Reference Document 05-01

Wilderbuer T, Stockhausen W, Bond N (2013) Updated analysis of flatfish recruitment response to climate variability and ocean conditions in the Eastern Bering Sea. Deep Sea Research Part II: Topical Studies in Oceanography 94: 157-164

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