DRAFT

A climate science regional action plan for the Gulf of Alaska

by

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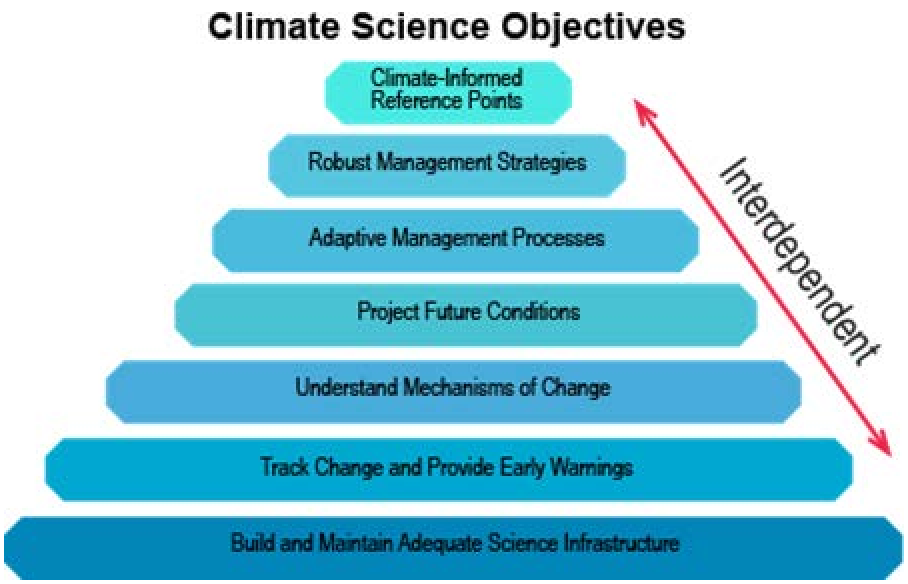
EXECUTIVE SUMMARY

Relatively large changes in climate are expected in the U.S. Gulf of Alaska (GOA) in the coming decades. Projected changes include warming of ocean waters, decreases in ocean pH, sea level rise, changes in ocean circulation and stratification, and potential concomitant changes in species distributions, ecosystem productivity, and food-web structure. While the nature of physical changes is clear, such as warming and ocean acidification, ecosystem responses to changing physical conditions are uncertain because it is unknown which of several forcing factors will be dominant. Directed research is needed to assess the degree of climate-driven change to critical ecosystem components, evaluate potential effects on marine species, and to determine risks to the ecosystem and fishing communities. This research will guide policies to reduce climate impacts, to manage human involvement in changed ecosystems, and to capitalize on any novel opportunities that may arise for marine resource-dependent human communities. This Regional Action Plan (RAP) outlines a framework to initiate this process.

NOAA Fisheries recently developed a Climate Science Strategy (NCCS, Link et al. 2015; Busch et al. 2017) to meet the demand for scientific information to prepare for and respond to climate impacts on the Nation's living marine resources and resource-dependent communities. One requirement of the NCSS is that each region shall develop a RAP that identifies actions needed to make progress in implementing seven objectives in the NCSS in each region over the next 5 years. The RAPs are also intended to increase awareness and support for these efforts, both internally and externally with partners and stakeholders. The objectives are arrayed hierarchically, and build from science infrastructure and monitoring activities (objectives 6 and 7), to process studies (objective 5), to projection of future conditions (objectives 4), and finally to management strategy evaluations (objectives 1-3) (Fig. 1).

Many of the monitoring, assessment, and process-oriented research activities at the NOAA's Alaska Fisheries Science Center (AFSC) can be framed in the context of climate science. These activities are fundamental to meeting AFSC's legislative mandates to provide scientific advice to manage and protect marine resources and dependent human communities, through monitoring changes in the marine ecosystems. The AFSC provides scientific data and analysis and technical advice to the North Pacific Fishery Management Council, the NMFS's Alaska Regional Office, the State of Alaska, Alaska coastal communities, as well as the fishing industry to support appropriate responses to ecological- and human-driven changes in the ecosystem. The enabling legislation for this mission is found in the Magnuson-Stevens Fishery Conservation and Management Act (MSA), the Marine Mammal Protection Act (MMPA), the National Environmental Policy Act (NEPA) and the U.S. Endangered Species Act (ESA). To continue to fulfill this mission in the face of climate change, the AFSC seeks to conduct research and develop science-based strategies for sustaining fisheries, healthy ecosystems, protected species, and coastal communities in a changing climate.



Level 1. How can climate-related effects be incorporated into living marine resource (LMR) reference points?

Level 2. What are robust LMR management strategies in the face of climate change?

Level 3. How can climate-related effects be incorporated into adaptive LMR management processes?

Level 4. How will the abundance and distribution of LMRs and marine ecosystems change in the future, and how will these changes affect LMR-dependent communities?

Level 5. How does climate change alter LMRs, ecosystems, and LMR-dependent human communities?

Level 6. What are the observed trends in climate, LMRs and LMR-dependent communities?

Level 7. What science infrastructure is needed to produce and deliver this information?

Figure 1.--Seven questions are described in the NOAA Fisheries Climate Science Strategy and motivate the Strategy's seven objectives.

The North Pacific Fishery Management Council (NPFMC) has recently adopted a policy of using an ecosystem approach to management, including a proactive approach to managing impacts of climate change on Alaska's fish and fisheries. Specifically, the Council's intent is that fishery management should take into account environmental variability and uncertainty, changes and trends in climate and oceanographic conditions, fluctuations in productivity for managed species and associated ecosystem components, such as habitats and non-managed species, and relationships between marine species. NOAA Fisheries recently produced an Ecosystem-Based Fisheries Management (EBFM) policy statement (NMFS 2016a) and a document called the EBFM roadmap (NMFS 2016b) to assist in implementing EBFM, which will require close coordination between NOAA Fisheries and the regional Councils.

The responses of ecosystems to climate change are complex and occur over multiple temporal and spatial scales (IPCC 2014a,b). To understand these responses and anticipate future change, climate-oriented research needs to occur along multiple lines of inquiry. Four broad areas of research are considered essential to AFSC's comprehensive climate science strategy. These activities are highly complementary, and research activities should be integrated to the extent possible.

1. Long-term monitoring. Ecological responses to environmental change can be rapid, as with ecosystem reorganization in response to regime shifts, or take decades to manifest, as with genetic and population-scale shifts in response to altered conditions. However, marine ecosystems are characterized by short-term variability that can mask long-term change. Therefore repeated, consistent measurements are essential for understanding patterns of variation, establishing links between physical and biological processes, and for early detection of large-scale ecological changes with broad impacts. Monitoring surveys conducted by AFSC and its partners in the Gulf of Alaska are the foundation for research into impacts of climate change and science-based management of the resources in the region. At present, the set of surveys is reasonably comprehensive, but represents the minimal level of monitoring needed to detect climate-driven changes; maintaining the current frequency and sampling level of ecosystem monitoring surveys is critically important.
2. Process studies. Interpreting environmental observations and predicting future change requires a knowledge of the mechanisms that underlay responses of organisms to environmental variation. AFSC has ongoing research programs in recruitment processes, ocean acidification, life history characteristics, fish and crab behavior, and predator-prey relationships, and is moving forward on other process studies to understand environmental forcing on focal species in the Gulf of Alaska. Increased coordination and integration between projects and programs, and streamlined delivery of results to science and management will help further advance scientific and management tools to reduce climate impacts on marine systems.
3. Risk assessment. Evaluating the risks of a changing climate requires one to consider the magnitude of the change, how sensitive the subject (the population, the ecosystem, the community, etc.) is to that variation, and the uncertainty of both of these factors. Climate change involves multiple stressors, such as ocean warming, changes in pH, and changes in sea level, so a comprehensive approach to risk assessment is necessary. Risk assessments can range from qualitative assessments, such as vulnerability analyses based on scoring, to fully quantitative management strategy evaluations, which are described in the next section. A good approach is often to conduct an initial qualitative risk assessment for a large numbers of subjects (species, communities, etc) to identify which are most likely to be strongly impacted, and then to follow up with a more detailed quantitative evaluations for those identified in the initial analysis.

4. Modeling climate impacts and management scenarios. Forecasting and projecting the impacts of climate change on marine fish production involves several steps: a) identifying and modeling potential links between the environmental variables and biological processes such as reproductive success, growth, and distribution; b) downscaling from GCMs (or GCM/ROMS) to obtain projected future values of the environmental variables under alternative climate scenarios; c) using those environmental variables to drive the population dynamics in a simulation with alternative harvest policies, and d) assessing social and economic impacts under different climate and management scenarios using coupled bioeconomic models.

AFSC and its partners have a considerable number of projects underway in the Gulf of Alaska for each of these broad areas of research to address the seven NOAA Fisheries Climate Science Strategy objectives. The following list includes some of those projects:

Long-term monitoring:

Comprehensive set of assessment surveys for long-term monitoring. AFSC conducts multispecies groundfish surveys, mid-water acoustic surveys, longline surveys, ichthyoplankton surveys, juvenile fish surveys, ecosystem process surveys, and marine mammal surveys.

Northern Gulf of Alaska Long-Term Ecological Research (LTER) Site. Recently a group of researchers led by scientists from University of Alaska Fairbanks (UAF) were awarded a grant to establish a LTER site in the Northern Gulf of Alaska. This is an integrated research program that builds upon and enhances the Seward Line time series begun in 1998. It includes a spring-to-fall field cruise and mooring-based observational program. NSF-supported monitoring associated with this new LTER will start in 2017.

Gulf of Alaska Ecosystem Considerations. The AFSC Ecosystem Considerations report is produced annually to summarize information about the Alaska marine ecosystem for the North Pacific Fishery Management Council, the scientific community and the public. This report summarizes ecosystem status and trends for many different biotic and abiotic indices.

Community vulnerability indicators and snapshots. Economic and social conditions in Gulf of Alaska fishing communities will be tracked by updating susceptibility and exposure indices for the community vulnerability analysis, and by collecting and reporting the information in the community snapshots.

Process studies:

Recruitment Processes Alliance. This ongoing, multi-faceted research program attempts to understand recruitment variability, focusing on mechanisms that mediate growth and survival of egg, larval and juvenile stages of focal Gulf of Alaska fish species.

Northern fur seal tracking. This project tracks the migration of northern fur seas in the Gulf of Alaska and relates fur seal distribution to environmental conditions.

Ocean acidification research. This project will involve a series of laboratory experiments to describe the effect of ocean acidification on the growth and development of walleye pollock and northern rock sole. This research will expand the scope of our understanding through the inclusion of more sensitive response metrics (development and energy status), and expand the use of multiple stressor experimental designs (temperature).

Sablefish electronic tagging. This project uses data from internally-implanted archival tags and pop-off satellite tags to provide insights into the optimal thermal envelopes for sablefish and other species, and thus provides information about the potential changes in behavior and spatial distribution under future temperature patterns.

Genetic adaptation to temperature for walleye pollock. The project includes rearing experiments, genomic analysis of wild larval cohorts from different years with contrasting environmental conditions, and a management strategy evaluation to understand how rapid adaptation affects population dynamics under climate change

Spatial response of northeast Pacific groundfish to anomalous warming in 2015. This project examines the role of extreme environmental conditions on the spatial distribution patterns of northeast Pacific groundfish throughout their range in an anomalously warm year (2015), utilizing the alignment of summer multiple survey efforts encompassing stations from U.S. west coast, Canada, and the Gulf of Alaska.

Risk assessment:

Climate vulnerability analysis for the Gulf of Alaska. This project will qualitatively assess species vulnerabilities to climate change and provide guidance on research prioritization. This project will rely on standard NOAA Fisheries approach that has been used in the eastern Bering Sea and elsewhere (Hare et al. 2016). Vulnerability to climate change refers to the potential for the abundance or productivity of a species to be affected by climate change. The method uses a multi-attribute scoring procedure based on expert judgment to rank species according to their vulnerability to climate change (Morrison et al. 2015).

Ecosystem-Socioeconomic Profile (ESP). This project creates a framework for integrating ecosystem and socioeconomic considerations within the existing SAFE chapters. It uses national initiative guidelines to set stock-assessment driven research priorities and generate a set of standardized products to identify important factors affecting each life history stage for a given stock. A profile and conceptual model are used to identify a set of indicators for monitoring which can be used for early warning of changes in stock productivity or in future projections. This project was initialized in parallel with the Gulf of Alaska Integrated Ecosystem Research Program (IERP) and the first set of ESPs will likely be developed for the focal species of the GOA IERP (walleye pollock, Pacific cod, sablefish, Pacific ocean perch, and arrowtooth flounder).

Modeling climate impacts and management scenarios:

CEATTLE multispecies model. This project will apply the CEATTLE multispecies model to characterize interactions between walleye pollock, Pacific cod, arrowtooth flounder, and halibut in the Gulf of Alaska. This project will evaluate future fisheries productivity and climate-specific reference points under a variety of climate projections and harvest strategies.

Northern rock sole bioeconomic model. This project develops a bioeconomic model of northern role sole in the Gulf of Alaska to evaluate the effect of ocean acidification and increased temperature on the population dynamics and fishery yield.

Computable general equilibrium (CGE) regional economic models for southwest Alaska. This project develops computable general equilibrium models for six borough and census areas in southwest Alaska to evaluate impacts of climate change at the local scale.

The RAP team identified two projects that will require additional funding, but were viewed as being critical to meeting National Climate Science Strategy objectives. These projects will allow AFSC to conduct quantitative risk assessments and management strategy evaluations for commercially important species, and assess potential changes in ecosystem productivity:

Bristol to Baja ROM/NPZ model. A high priority should be placed on developing a high-resolution ocean modeling framework for the Gulf of Alaska. A proposal has been developed to upgrade and adjust the NEP-10K grid to 3 km resolution (NEP-3K) and utilize a seamless Nutrient-Phytoplankton-Zooplankton (NPZ) modeling framework (COBALT).

Atlantis ecosystem model (Fulton et al. 2011) . A high priority should be placed on developing an Atlantis ecosystem model for the Gulf of Alaska. The Atlantis model is a spatially explicit, physical-biological oceanographic model that can be coupled to the ROMS model proposed for the Gulf of Alaska, and can therefore be used to simulate ecosystem properties under projected climate change.

AFSC has already submitted a proposal for external funding with several partners for the ROMS/NPZ project, and plans to submit a proposal for external funding for the Atlantis model project in the next year. Nevertheless, supporting these projects with external funding should be regarded as an interim solution since there is a continuing need for both for ROMS and ecosystem modeling capacity at AFSC, both to assess climate change impacts and to address other ecosystem-based fisheries management issues. AFSC provides continuing support for an ecosystem modeling effort in the Bering Sea, however, limited annual support has precluded similar development and operationalization of modeling capacity for the GOA. This shortfall in capacity ideally would be addressed by creating dedicated positions within AFSC or PMEL staff.

Access to and support for additional computing and storage capacity will be required to run and archive these computationally intensive models.

It is important to recognize that at the time of writing of this RAP, Federal funding levels are uncertain. Funding to support research operations at the AFSC in FY18, more likely than not, will be less than in FY17. Therefore, activities described under both level and increased funding scenarios should be viewed as proposals, and not commitments from AFSC. Under a level funding scenario, the projects currently underway and planned for the next 5 years will be substantive step forward in evaluating impacts of projected climate change on living marine resources, ecosystem components, and fishing communities in the Gulf of Alaska. Several gaps were identified in the current suite of projects that make the AFSC research effort in the Gulf of Alaska less than a fully integrated approach. Given the current budget situation, any increase in funding for climate science in Gulf of Alaska would likely have to come from re-prioritizing projects within the AFSC.

This RAP intends to make progress towards addressing several key fisheries management issues for federally-managed groundfish associated with climate change. These are the Optimum Yield (OY) range for the Gulf of Alaska, biological reference points for status determination, and a focus on community-level social and economic impacts of climate change.

An important management application of ecosystem models will be to evaluate the OY range (140,000–800,000 t) for the Gulf of Alaska, which provides both lower and upper limits on total groundfish removals (with the expectation that catches will be at least as high as the lower limit). Unlike the Bering Sea-Aleutian Island upper limit (2 million t cap), which has served as an effective constraint on removals, the upper limit in the Gulf of Alaska has never been constraining, suggesting that the original estimate was inaccurate. Improved ecosystem and socio-economic models would allow the OY range to be re-evaluated, and would allow consideration of whether adjusting the OY range to reflect changes in ecosystem productivity over time is warranted.

Determining stock status relative to biomass reference points in an important element of Gulf of Alaska groundfish harvest policies, but may become increasingly problematic due to climate change. Reference points are used to calculate target fishing mortality rates, and to determine whether a stock is overfished and needs rebuilding. Reference points used in the North Pacific recognize the regime shift that occurred in 1977 by using mean recruitment since 1977 to calculate the biomass reference point. This approach recognizes that an ecosystem-wide climatic change occurred in 1977 that affected the productivity of many groundfish populations in the Gulf of Alaska. Long-term changes in stock productivity due to climate change may require revising the procedures used to determine stock status. The framework developed for modeling climate impacts using tools such as the ESP and climate-enhanced assessment models (e.g., CEATTLE) will allow testing and critical evaluation of different approaches for status determination, climate-specific reference points, and use of early warning indicators.

Impacts of climate change on people can be effectively evaluated by the social and economic conditions of human communities the Gulf of Alaska. At present, however, only qualitative methods to assess impacts are available at the community scale, and so more effort should be directed towards quantitative approaches that can be coupled with aforementioned models. Communities in the Gulf of Alaska are isolated geographically, and have simple yet distinct economies, with differing roles, primarily, of commercial fishing, recreational fishing, and tourism. All of these economic activities are potentially affected by climate change. Projections based on coupled bioeconomic models may provide sufficiently long planning horizons for these communities to prepare for projected changes and formulate adaptive strategies. In addition, consideration should be given to ways in which fisheries management policies can foster or impede the adaptive capacity of communities.

1.0 INTRODUCTION

1.1 Why do a climate science plan for the Gulf of Alaska?

The Gulf of Alaska is a large and geographically complex region of the North Pacific Ocean. The geography has been shaped by plate tectonics, glaciation, atmospheric circulation, and ocean currents. The marine ecosystem of the Gulf of Alaska is highly productive, supporting large and diverse fisheries, in addition to large populations of seabirds and marine mammals (Weingartner et al. 2002). The ecosystem is structured by both bottom-up drivers affecting primary production and top-down drivers such as predation and fishing (Bailey 2000). The Gulf of Alaska ecosystem has undergone regime shifts with persistent changes in environmental forcing leading to ecosystem reorganization (Anderson and Piatt 1999). It is an area where relatively strong climate changes are expected. Some of the projected changes include warming of the surface water, ocean acidification, changes in sea level, and potentially an overall reduction in ecosystem productivity (Gattuso et al. 2015,Feely et al. 2008, Beamish 2008). Directed research is needed to assess the impact of climate change on important ecosystem components and to evaluate associated risk of marine resource-dependent human communities to climate change. This RAP outlines a plan to begin this process.

NOAA fisheries recently developed a Climate Science Strategy (Link et al. 2015) to meet the demand for scientific information to prepare for and respond to climate impacts on the Nation's living marine resources and resource-dependent communities. One requirement of the NOAA Fisheries Climate Science Strategy is that each region shall develop a RAP. The Alaska Fisheries Science Center (AFSC) has taken the approach to develop separate RAPS for each of the five Large Marine Ecosystems (LME) under its purview, and a plan was recently completed for southeastern Bering Sea (Sigler et al. 2016). The Gulf of Alaska RAP addresses this near-term action for the Gulf of Alaska, and it is anticipated that similar plans will be developed for the Aleutian Islands and the Arctic regions.

Regional Action Plans are intended to identify actions needed to make progress in implementing seven objectives identified in the NOAA Fisheries Climate Science Strategy for each region over the next 5 years. The RAPs are designed to increase awareness and support for these efforts, both internally and externally with stakeholders and partners. The objectives are arrayed hierarchically, and build from science infrastructure and monitoring activities (objectives 6 and

7), to process studies (objective 5), to projection of future conditions (objectives 4), and finally to management strategy evaluations (objectives 1-3).

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The NPFMC recently adopted a policy of using an ecosystem approach to management, including a proactive approach to managing impacts of climate change on Alaska's fish and fisheries. Specifically, the Council's intent is that fishery management take into account environmental variability and uncertainty, changes and trends in climate and oceanographic conditions, fluctuations in productivity for managed species and associated ecosystem components, such as habitats and non-managed species, and relationships between marine species. NOAA Fisheries recently produced an Ecosystem-Based Fisheries Management policy statement (NMFS 2016a) and a document called the EBFM roadmap (NMFS 2016b) to assist in implementing EBFM, which will require close coordination between NOAA Fisheries and the regional Councils.

1.2 Brief description of the Gulf of Alaska Ecosystem

The Gulf of Alaska is semi-enclosed basin in the North Pacific Ocean, delineated by the curve of the southern coast of Alaska extending from Alexander Archipelago in the east to the Alaska Peninsula in the west (Stabeno et al. 2004). From end to end, the U.S. Gulf of Alaska extends 1,500 miles, which is approximately the same length as the entire Atlantic seaboard. The region that is the primary focus of the document corresponds to the U.S. EEZ, which is also the area defined in the NPFMC FMP for the Gulf of Alaska (NPFMC 2016a). The Gulf of Alaska LME includes Canadian waters and the western boundary extends into the Aleutian Islands (Sherman et al. 1990). The region is the most seismically active region in North America, as a result of a very dynamic plate boundary where Pacific Plate is being subducted under the North American Plate. The Good Friday Earthquake of 1964, a magnitude 9.2 earthquake centered in Prince William Sound, was North America's largest recorded earthquake and the second largest ever recorded (West et al. 2014). The active tectonic boundary has produced series of mountain ranges bounding the Gulf of Alaska that include some of the world's highest coastal mountains, such as Mount Saint Elias at 18,008 feet, which is only 11 miles from tidewater. Many of the mountains in the coastal ranges are volcanic in origin, and some have been active during the historical period. The eruption of Mt. Katmai in 1912 was the 20th Century's largest volcanic eruption (Hildreth and Fierstein 2012).

The landscape and continental shelf of the Gulf of Alaska has been heavily modified by Pleistocene glaciation, and icefield and glaciers remain an important part of the Gulf of Alaska landscape, unlike other regions of the United States. The extensive icefields in the coastal ranges bounding the Gulf of Alaska represent the third largest glaciated area on earth, after Antarctica and Greenland (Meier 1984). Many glaciers descend from icefields to tidewater and calve into the ocean, creating a unique habitat important to some marine mammals (e.g., harbor seals) (Mathews and Pendleton 2000). The glaciers in the region have high turnover, and thus are sensitive to changes in climate. The area is experiencing rapid ice loss (Arendt et al. 2002), leading to glacier retreat, grounding of tidewater glaciers, and increased freshwater discharge into the Gulf of Alaska (Royer and Grosch 2006).

Atmospheric circulation in the Gulf of Alaska is dominated by strong cyclonic winds that extend from fall through spring (Weingartner 2005). The mean storm track in the northeast Pacific Ocean crosses the Gulf of Alaska from west to east, and weather systems are often trapped by the coastal mountain ranges (Mesquita et al. 2010). Substantial freshwater runoff occurs from late spring through fall with a peak in the fall peak, and secondary snowmelt peak in spring. The annual freshwater discharge for the northern Gulf of Alaska is greater than that of the Mississippi River (Royer and Grosch 2006). Southeast Alaska is densely forested and is part of the Pacific temperate rainforest ecoregion (Gallant et al. 1995). West of Kodiak Island, the Alaska Peninsula is treeless and covered by subarctic tundra. The coastline of the Gulf of Alaska is heavily indented and there are numerous fjords and offshore islands. Cook Inlet and Prince William Sound are the two largest embayments, while major island groups include the Alexander Archipelago, Kodiak Island, and the Shumagin Islands.

The Alaska Coastal current (ACC), driven by alongshore winds and freshwater input, dominates the oceanography of the shelf (Stabeno et al. 2004). The ACC extends from Icy Bay to Unimak Pass, a distance of over 1500 km and has the potential to strongly influence the heat and salt balances of the the eastern Bering Sea and the Arctic. Over this distance, the ACC is a nearly continuous feature with a marked freshwater core. Even though the coastal GOA is a predominantly downwelling system, the GOA shelf is comparable to other high latitude, highly productive ecosystems, with high primary productivity ~300 g C m-2 yr-1 (i.e., Grand Banks of Newfoundland, North Sea; Sambrotto and Lorenzen 1986). Macro nutrients from the basin are provided to the coastal system through a number of processes including topographic steering, eddies, upwelling in response to horizontal shear in the barrier jets, and during winter the on-shelf flux in the surface Ekman layer (Mordy et al. in prep). Micronutrients (e.g., iron) are supplied from mechanisms such as resuspension of shelf sediments and river discharge. While strong seasonal cycles and interannual variability are dominant scales in atmospheric forcing and the oceanic response, there is also forcing on El Niño-Southern Oscillation (ENSO) and decadal time scales.

All marine ecosystems are complex, but the GOA is unusual in both the degree and nature of its spatial heterogeneity. An analysis of the physical and biological characteristics of large marine ecosystems (LMEs) in Alaska identified 25 ecoregions at smaller spatial scales than the LME (Piatt and Springer 2007). The GOA comprised 14 of these areas, more than twice the number in any other Alaskan LME. In addition, the GOA ecoregions were divided along multiple axes (e.g., along-shelf and cross-shelf) and varied substantially in size.

Spatial complexity in the GOA occurs at multiple scales. At a regional scale, the western and eastern GOA display different patterns of seasonal and annual variation in sea surface temperature as determined by satellite imagery, available solar radiation for photosynthesis, and chlorophyll-a (Waite and Mueter 2013). Groundfish density is higher in the western GOA, while species diversity is greater in the eastern GOA (Mueter and Norcross 2002). The transition between the eastern and western GOA occurs at the approximate longitude of Prince William Sound. While clearly there are some major physical differences between the two regions (e.g., the continental shelf is generally much wider in the west, and the eastern GOA is influenced by events to the south), the basis for other east/west differences in ecosystem properties is unclear.

In contrast to variation at the regional scale, the GOA ecosystem is also shaped by local processes (i.e., phenomena that occur at scales of 10-100 km). Eddies that form in the eastern GOA propagate to the west, potentially transporting nutrients and organisms. The many canyons that intersect the GOA shelf transport nutrients and possibly fish larvae from deeper waters onto the shelf (Bailey et al. 2008), and interactions between canyons and banks structure the distribution of fishes. Gap winds are highly localized high-wind events that can affect circulation and initiate eddy formation (Ladd and Cheng 2016). The many embayments of various size, and most importantly the larger inland seas (e.g., Prince William Sound and Cook Inlet), provide a great diversity of habitats for marine organisms. All of these local processes affect their immediate surroundings but also greatly influence the function of the larger GOA ecosystem.

Accounting for the heterogeneity of the GOA is important for understanding how climate variation affects the ecosystem. For example, the North Pacific Fishery Management Council divided their GOA ecosystem indicator report card into separate reports for the eastern and western GOA to better understand how the ecosystem changes in each region (Zador and Yasumiishi 2016). Research in the GOA should be spatially comprehensive; because this is often difficult to achieve, studies at limited spatial scales should be conducted with the awareness that the results may not be applicable to the entire ecosystem.

Human habitation of this region dates from approximately 12,000 years BP. A coastal migration pathway along the Gulf of Alaska is now considered a plausible route of human migration to the Americas, but since this would have occurred during a glacial maxima when sea level was much lower than present, archaeological evidence is scarce (Mandryk et al. 2001). Pre-European Native Alaskans in the region were vibrant sea-going cultures, highly dependent on marine resources, including marine mammals, salmon, and halibut, both for food and material aspects of their culture (Dunne et al. 2016). European contact came in the form of Russian fur traders and later missionaries in the 1700s, who gradually spread eastward (Vinkovetsky 2011). As in other parts of North America, European contact resulted high mortality of Native Alaskans due to the lack of immunity to common European illnesses such as smallpox (Fortuine 1989). Some areas of the Gulf of Alaska are even now depopulated relative to the pre-contact period. Within a few decades after the U.S. purchase of Alaska in 1867, there was immigration into area from Scandinavian and other European countries (Hassen 1978).

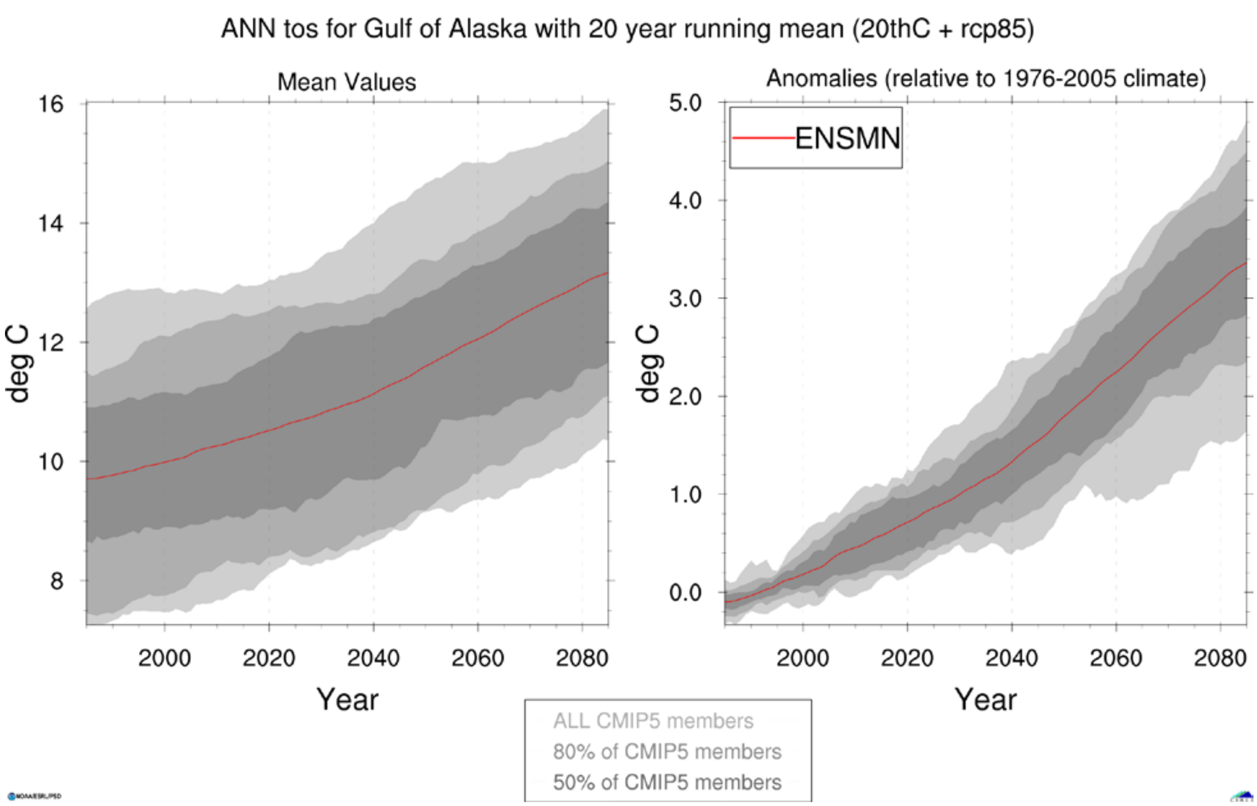
Aside from a few areas where mineral and fossil fuel extraction and logging were significant, the primary economic activity of the area has always been the harvest of living marine resources. In a review of historical marine resource utilization, Gaichas (2006) distinguished three periods: a Russian colonial period (1741-1867), a U.S. colonial period (1868-1958), and an Alaska statehood period (1959-present). In the Russian colonial period, species harvested included sea otters, northern fur seals, and certain species of cetaceans. The harvest of sea otters resulted in a sequential depletion of populations throughout the Aleutian Islands and the Gulf of Alaska. During the U.S. colonial period, fisheries for salmon, herring, and halibut developed. The beginning of the Alaska statehood period saw a rapid expansion and collapse of crab and shrimp fisheries in the Gulf of Alaska, and large removals of remaining whale populations from pelagic whaling operations. Major fisheries for groundfish started in the 1960s, first by foreign fleets, followed by the development and eventual displacement by a domestic fleet after the passing of Magnuson-Stevens Act.

There have been some notable successes in management of fisheries in the Gulf of Alaska. For example, Pacific halibut fishery managed by International Pacific Halibut Commission, salmon fisheries managed by the State of Alaska, and groundfish fisheries managed by the Council and NOAA fisheries are all wide-regarded as examples successful fisheries management. At the same time, there have been several examples of boom and bust fisheries, where overharvesting was followed by population collapse and commercial extinction, most notably, the red king crab fishery.

The communities of the Gulf of Alaska are often reliant on commercial exploitation of living marine resources to support their economies (Himes-Cornell et al. 2013). Except for Anchorage, the only metropolitan area in the Gulf of Alaska, and Juneau, the state capital, these communities are relatively small (population less than 10,000). Many of these communities are not connected to the transcontinental road system, and are accessible only by water or air. For example, Kodiak, which is routinely ranked as the Nation’s third most valuable fishing port, is located on Kodiak Island, in the midst of highly productive fishing areas, but remote from other population centers. The extremely rugged topography, the lack of a well-developed road system, and large distances between communities by necessity make these communities highly self-reliant. There is strong contrast between eastern Gulf of Alaska, where tourism occupies a much greater share of the economy, largely in the form of cruise ship tourism, and the western Gulf of Alaska where tourism is of little importance (Cerveny 2005). Recreational fishing is a common form of recreation throughout the area and is an important part of the economy for some communities with charter fishing businesses, such as Homer and Seward. Subsistence harvest of living marine resources is also important throughout the area (Himes-Cornell et al. 2013). The lack of readily available economic alternatives to commercial fishing make these remote communities extremely vulnerable to changes in the availability of marine resources.

1.3 Projected climate change in the Gulf of Alaska

Current climate models predict strong shifts in the climate of Gulf of Alaska over the coming decades. Two of the most important changes, the warming of the upper ocean and a shift toward a more acidic ocean, are already occurring according to observational evidence, and are very likely to continue into the future, with the magnitude of increase depending on CO_2 concentration pathways (Gattuso et al. 2015). Other process that may potentially be important in the Gulf of Alaska include changes in ocean circulation and stratification, changes in precipitation and attendant changes in the timing and magnitude of freshwater input into the ocean, and changes in sea level height. The mean sea surface temperature is expected to gradually increase until at some point it will exceed the range that has been experienced historically, while the same pattern of decadal variation characteristic of the Pacific Decadal Oscillation will likely persist into the future (Overland and Wang 2007). Model projections indicate that by 2050 most of the North Pacific will have warmed by an average of 1.2-1.8° C



(Fig. 2)

Figure 2.--Projected increases in sea surface temperature for the Gulf of Alaska (left) and future temperatures relative to historic means (right). The simulations are forced

using historical emissions (1976 to 2005) and future projections (2006 to 2099) is under the RCP8.5 emission scenario. Red lines represent CMIP5 ensemble mean annual projections. Dark gray shading represents estimates from 80% of all models; light gray shading represents estimates from 50% of model projections. Data and figure courtesy of the ESRL climate change portal: www.esrl. noaa.gov/psd/ipcc/.

Coastal regions around Alaska are experiencing the most rapid and extensive onset of ocean acidification compared to anywhere else in the United States (Feely et al. 2008, Mathis et al. 2015). Changes in pH affect the ability of organisms to form shells and skeletons from minerals in seawater. They may also have other effects on the physiology and sensory ecology of marine organisms. One way that the effect of shell or skeleton formation can be quantified is by the aragonite saturation state. Aragonite is a form of calcium carbonate found in mollusk shells and corals. Shell and skeleton formation is favored when aragonite saturation is greater than one, while saturation less than one indicates that the water is corrosive to calcium carbonate, and will tend to dissolve shell and skeletons that are not protected. Maps of aragonite saturation indicate that at present the shoaling of undersaturation levels occurs at depths of 90-150 m in the GOA coastal waters. Projections of aragonite saturation indicate that the entire water column in parts of the Gulf of Alaska will become undersaturated by end of this century.

The ratio of available dissolved oxygen and metabolic demand has been shown to influence marine species distributions spatially and at depth (Deutsch et al. 2015). This critical oxygen level (O_{crit}) is a function of dissolved oxygen and temperature-specific metabolic rates of marine organisms. A recent evaluation postulated that significant declines in oxygen and increased temperatures would result in significant declines in O_{crit} levels in the GOA, especially at depth (Deutsch et al. 2015). The resulting metabolic constraints may limit adaptive scope for species that would otherwise seek thermal refuge at depth. Changes in oxygen conditions associated with climate change therefore represent a potentially significant, yet poorly understood impact of climate change on the GOA marine ecosystem.

Changes in ocean circulation and stratification are difficult to predict because they are forced by multiple drivers and is unclear which driver will have the strongest effect. Potential changes include a northward shift in the core of the West Wind Drift, and with it a northward shift in the bifurcation of the West Wind Drift into the California Current and the Alaska Current (Beamish 2008). Precipitation is likely to increase, with more rain rather than snow, because of the increase in temperature. Additional precipitation and glacier ice melting would add additional freshwater to coastal areas, which would enhance the baroclinic structure on the continental shelf (Royer and Grosch 2006). The strength of the Alaska Coastal Current is likely to change, but at this point the direction of the change is unclear. Changes in strength of the Alaska Coastal Current could affect the transport of nutrients along the shelf, and affect the cross-self flux of nutrients. The formation of the thermocline and the surface mixed layer would likely be earlier in the year because of the increase in water temperature, potentially changing the timing of spring bloom (Royer and Grosch 2006).

Potential sea level changes present a challenging forecasting problem for the GOA, but may be important due to the reliance on shoreline habitat of some species. Marine mammals have specific habitat requirements for haulouts and rookeries. Herring and capelin spawn in nearshore habitats. The GOA has more miles of shoreline than any other large marine ecosystem in the United States due to its size and complex geography. Although the dominant process is a projected rise in sea level, in some parts of the GOA the rapidly melting glaciers are causing rapid land uplift (isostatic rebound) that is far outpacing sea level rise (Larsen et al. 2004). Also, because the region is seismically active, tectonic process can produce both sudden (i.e., earthquakes) and gradual sea level changes. For example, after the 1964 Good Friday earthquake, some coastal areas were raised 30 feet, while in other areas the land subsidence was 10 feet (West et al. 2014).

1.4 Potential impacts of climate change on marine biota in the GOA

The physical environment of the Gulf of Alaska is characterized by high level of variability (Stabeno et al. 2004). That variability can be either be interannual, periodic, or display patterns of long-term persistent deviations (regime shifts) (Overland et al. 2010). Unlike historical variability, under projections of climate change, environmental conditions in the GOA are expected to exhibit unidirectional change, both in average conditions and also, potentially, in patterns and magnitude of variability (Overland and Wang 2007). The study of how the environment affects marine populations is one of the cornerstones of fisheries science, but, of course, that research is necessarily retrospective in nature, deriving relationships from responses to environmental variation observed over a historical period. Prediction of responses to environmental variation outside the range observed historically is more difficult and is the challenge of applied climate science.

There are direct physiological implications of environmental variability and change on marine biota such as the non-linear effect of temperature on metabolism (Holsman and Aydin, 2015), and the effect of ocean acidification on shell formation in crustaceans and mollusks (Long et al. 2013, Barton et al. 2012). Other potential impacts are those that propagate through the ecosystem through the food web. For example, a change in the productivity of the system could lead to changes in the availability of prey, resulting in changes in growth. Or a more favorable environment for a predator species could lead to an increase in predation mortality, as may be the case for arrowtooth flounder preying on walleye pollock (Bailey 2000).

As marine population experience changing environmental conditions, and the resources available to them change, they may show phenotypic changes, such as changes in growth, reproduction, as individuals adjust to the changed environment. Populations may also show behavioral changes, such as changes in spatial distribution, predatory behavior, migratory behavior, or annual timing of the life cycle; that is, phenology (Drinkwater 2005, Nye et al. 2009, Hazen et al. 2013). Populations may be adversely affected by more frequent extreme environmental events such as harmful algal blooms and oxygen depletion episodes, or they may be subject to new diseases and illnesses. Recruitment rates to the population could change due to favorable or unfavorable impacts on egg and larval survival (Clark and Hare 2002). Finally, although genetic adaptation is generally regarded as a slow process, changes in the environment create conditions for genetic selection to occur (Munday et al. 2013). Many marine population are highly fecund (10^5-10^6 offspring per year), the potential for rapid evolution to occur should not be discounted. As each population in the ecosystem is beneficially or unfavorably impacted by changes in its environment, some will become more abundant and others will decline in abundance; that is, there will be winners and losers. A loss or at least a shifting of genetic diversity may result. Generalist species generally fare better than specialists, at least over the short-term in a rapidly changing marine environment (Wilson et al. 2008, Clavel et al. 2011).

Large-scale changes may occur at the level of the ecosystem, such as overall changes in productivity, and shifts in energy flow, such as between demersal and pelagic pathways. These changes may be gradual, or there may be ecosystem flipping points with rapid food-web reorganization and sudden (< 5 years) changes in abundance of many species (Anderson and Piatt 1999). Sudden ecosystem changes may increase the risk of population collapses (Pinsky et al. 2011). There may be species invasions or colonizations, as other species more adapted to the changed environment are able to invade and thrive (Pinsky et al. 2013).

1.5 Relationship of this effort to the EBFM roadmap

Recently, NOAA Fisheries produced an Ecosystem-Based Fisheries Management policy statement (NMFS 2016a), and a document called the EBFM roadmap (NMFS 2016b) that is intended to describe the path to implementing the policy for the NOAA Fisheries science centers and regional offices, and the regional Councils. The EBFM roadmap is organized similarly to the climate science strategy with a set of hierarchical objectives that build from science infrastructure to management strategy evaluation of harvest control rules. The EBFM roadmap has a strong focus on the implementation of EBFM through coordination with the regional management Councils. A major element of the roadmap is the development of Fisheries Ecosystem Plans (FEP). The approach in developing this RAP has been to treat climate science as a component of the broader effort by the agency to implement EBFM. We applied EBFM principles in developing this plan, such as taking a broad perspective rather than relying on a single-species focus, considering environmental forcing and ecological interactions, and regarding humans as part of the ecosystem.

An important element of successful incorporation of climate change science into EBFM will be an ongoing dialog with managers and stakeholders to help focus management strategies for evaluation and to improve communication of risk. The Integrated Ecosystem Assessment (IEA) program is designed to support EBFM in each region, and has been slowly growing in Alaska as the program expands nationally. Most of the work to date has been in the Bering Sea, where the IEA framework (Levin et al. 2009) is being used in the Bering Sea FEP, currently under development, to facilitate a dialog with managers and researchers through focused modules, including a climate change module. The climate module is anticipated to be an important part of the eastern Bering Sea FEP and would result in 5-7 year repeated assessments of climate impacts and management options to address climate change impacts on fisheries- and marine-dependent communities in the Bering Sea.

IEA progress in the Gulf of Alaska is lagged relative to the eastern Bering Sea, but with completion of the GOA Integrated Research Project and the recent expansion of the the IEA to the GOA, we expect to shift to a broader planning effort to implement EBFM, including climate-specific research and management outlined in the climate science strategy RAP. The IEA and EBFM planning process will then be able to build on the climate science RAP because many of the tools used to implement the climate science strategy will be also useful for EBFM. Examples include risk analysis, multi-species and ecosystem models, and the modeling tools to conduct management strategy evaluations.

2. A SHORT HISTORY OF NOAA CLIMATE RESEARCH IN THE GOA

2.1 Fisheries-Oceanography Coordinated Investigations (FOCI)

The Alaska Fisheries Science Center has a long history of working to understand climate variability and its impacts on fisheries resources in the Gulf of Alaska. The Fisheries-Oceanography Coordinated Investigations (FOCI) program was established by NOAA in 1984 as a joint research program between the AFSC and the Pacific Marine Environmental Laboratory (NOAA/PMEL). This long-standing partnership between PMEL and AFSC has been leading fisheries oceanographic research in Alaska waters for over three decades and has contributed greatly to understanding ecosystem dynamics and fisheries recruitment processes as related to climate in the Gulf of Alaska.

The FOCI program started with a focus on walleye pollock in Shelikof Strait, Gulf of Alaska, seeking to understand how environmental conditions, both physical and biological, affected the survival, growth and distribution of early life stages and subsequent recruitment into the fishery. The approach has always been threefold, integrating field studies, laboratory studies, and modeling. A series of spring oceanographic research surveys in the western GOA (April – May) spanning the egg and larval periods, as well as surveys during the late summer to sample young-of-the-year juveniles, allowed the estimation of condition, growth, mortality rates, and distribution, as well the collection of information on predators and prey. These biological observations have been related to physical oceanographic processes and features measured onboard, or with data derived from oceanographic moorings, satellite-tracked drifters, or other technology. Focused process-oriented studies as well as the analysis of time-series measurements over a number of years identified features such as eddies, ocean temperatures, prey densities, and wind mixing to be important to survival of early life stages of walleye pollock (Bailey and Macklin 1994, Kendall et al. 1996, Porter et al. 2005).

The field and laboratory-based work formed the basis for modeling efforts, including biophysical models to examine the effects of currents on larval distributions (e.g., Hermann and Stabeno 1996), statistical models to determine the relative influence of physical and biological conditions on e.g. feeding or mortality rates (Porter et al. 2005, Ciannelli et al. 2005), bioenergetics models (Mazur et al. 2007) and recruitment forecasting models (e.g. Megrey et al. 1996), which were used to supplement the stock assessment for walleye pollock in the Gulf of Alaska. A variety of recruitment forecasting models have been used to generate forecasts for walleye pollock recruitment beginning with the 1992 year class and continuing to the present, providing either quantitative or qualitative forecasts of recruitment strength based on biophysical variables and observations of early life stages.

The FOCI program has since expanded its scope to reflect the increasing focus by NOAA Fisheries on ecosystem science in the context of Ecosystem-Based Fisheries Management. Now called EcoFOCI, the program works in all of Alaska's LMEs, in both the western and eastern portions of the Gulf of Alaska, and across species to improve understanding of ecosystem dynamics and apply that understanding to the management of living marine resources. Since 2013, EcoFOCI and other programs within the AFSC have formed the Recruitment Processes Alliance (RPA), bringing together complementary programs to conduct ecosystem monitoring and recruitment process studies. The RPA integrates the efforts of six AFSC programs from three different Divisions: Recruitment Processes, Ecosystem Monitoring and Assessment, Recruitment Energetics and Coastal Assessment, and Resource Ecology and Ecosystem Modeling, Status of Stocks and Multispecies Assessments, and Marine Ecology and Stock Assessment. The RPA carries out biennial ecosystem surveys in the western Gulf of Alaska and annual surveys in the eastern GOA, collecting data on currents, water chemistry, eddies, phytoplankton, zooplankton, and fishes. Field studies, together with laboratory studies and trophic and biophysical modeling are used to determine the impacts of climate and ecosystem conditions on recruitment of walleye pollock, Pacific cod, sablefish, Pacific ocean perch, arrowtooth flounder, and forage fishes, focusing on factors influencing the first year of life. This ongoing research program builds on 30+ years of process studies and time-series of field observations on oceanography, lower trophic levels, and early life stages of fishes in the Gulf of Alaska.

2.2 GLOBEC

From 1997 to 2004, interdisciplinary marine research was conducted in the northern GOA as part of the international Global Ocean Ecosystem Dynamics (GLOBEC) program jointly supported by NOAA-NOS, NOAA-NMFS, and NSF. The goal of GLOBEC was to understand how global-scale climate variation influences the physical and biological dynamics of ecosystems at regional scales (Weingartner et al. 2002). The Northeast Pacific (NEP) GLOBEC program focused mainly on physical and biological oceanography but the relationship between lower trophic-level processes and fish populations, particularly Pacific salmon species, was an essential component of the program. The NEP GLOBEC program included researchers from multiple disciplines inside and outside of academia. A core feature of the program was the establishment of long-term monitoring along the Seward Line, a line of oceanography stations that extends 170 miles from Resurrection Bay on the Kenai Peninsula out into the GOA basin (http://www.sfos.uaf.edu/sewardline/). Expanded sampling of the Seward Line is a key feature of the recently-funded Northern GOA Long-Term Ecological Research site (see below). The NEP GLOBEC work also involved process studies to measure vital rates for plankton and juvenile salmon.

2.3 IERP

The Gulf of Alaska Integrated Ecosystem Research Program (GOAIERP), funded by the North Pacific Research Board (NPRB) and conducted from 2010 to 2018, followed the interdisciplinary model of GLOBEC but expanded the research to higher trophic levels, including humans. The primary goal of the GOAIERP was to identify and quantify the major ecosystem processes that regulate the first-year survival and ultimately recruitment of five key groundfish species (walleye pollock, Pacific cod, arrowtooth flounder, sablefish, Pacific ocean perch) in the GOA. This was accomplished by creating a team of 40+ scientists organized into four groups: three groups focusing on separate trophic levels (lower, middle, upper) and a group constructing models. Research design, data collection, and analysis and interpretation were closely coordinated among the groups. The project was structured around a comparison of eastern and western regions of the GOA, with additional activities designed to investigate connections between the two. The main field years were 2011 and 2013, with additional limited field work in 2010 and 2012. An essential feature of the GOAIERP was its comprehensive spatial scope: Ecosystem surveys were conducted at inshore sites (including bays and inlets) and offshore on the shelf and out over the slope, and surveys were coordinated to provide a synoptic view of the study regions. The field surveys were complemented by laboratory studies of food habits and energetic condition, physiological experiments, and modeling. Seabird surveys were conducted as part of the offshore work, and seabird tagging and diet research was conducted at colonies.

As the name implies, a key concept in the GOAIERP was the integration of research activities among the oceanographers, the fish and seabird biologists, and the modelers. The coordination of the work began early on during the research design phase and included sharing of vessel platforms. The process of integration was challenging and involved trade-offs for the groups involved, but was essential for ensuring that observations could be combined. As a result of the investigators working together in this way, the groups had a better ability to interpret their results (i.e., the whole was greater than the sum of its parts).

3. CURRENT, PLANNED, AND PROPOSED ACTIVITIES THAT FURTHER CLIMATE RESEARCH IN THE GOA

3.1. A strategy for comprehensive climate research in the GOA

The responses of ecosystems to climate change are complex and occur over multiple temporal and spatial scales (IPCC 2014a,b). To understand these responses and anticipate future change, climate-oriented research needs to occur along multiple lines of inquiry. Four broad areas of research are considered essential to AFSC's comprehensive climate science strategy. These activities are highly complementary, and research activities should be integrated to the extent possible.

5. Long-term monitoring. Ecological responses to environmental change can be rapid, as with ecosystem reorganization in response to regime shifts, or take decades to manifest,

as with genetic and population-scale shifts in response to altered conditions. However, marine ecosystems are characterized by short-term variability that can mask long-term change. Therefore repeated, consistent measurements are essential for understanding patterns of variation, establishing links between physical and biological processes, and for early detection of large-scale ecological changes with broad impacts. Monitoring surveys conducted by AFSC and its partners in the Gulf of Alaska are the foundation for research into impacts of climate change and science-based management of the resources in the region. At present, the set of surveys is reasonably comprehensive, but represents the minimal level of monitoring needed to detect climate-driven changes; maintaining the current frequency and sampling level of ecosystem monitoring surveys is critically important.

6. Process studies. Interpreting environmental observations and predicting future change requires a knowledge of the mechanisms that underlay responses of organisms to environmental variation. AFSC has ongoing research programs in recruitment processes, ocean acidification, life history characteristics, fish and crab behavior, and predator-prey relationships, and is moving forward on other process studies to understand environmental forcing on focal species in the Gulf of Alaska. Increased coordination and integration between projects and programs, and streamlined delivery of results to science and management will help further advance scientific and management tools to reduce climate impacts on marine systems.
7. Risk assessment. Evaluating the risks of a changing climate requires one to consider the magnitude of the change, how sensitive the subject (the population, the ecosystem, the community, etc.) is to that variation, and the uncertainty of both of these factors. Climate change involves multiple stressors, such as ocean warming, changes in pH, and changes in sea level, so a comprehensive approach to risk assessment is necessary. Risk assessments can range from qualitative assessments, such as vulnerability analyses based on scoring, to fully quantitative management strategy evaluations, which are described in the next section. A good approach is often to conduct an initial qualitative risk assessment for a large numbers of subjects (species, communities, etc) to identify which are most likely to be strongly impacted, and then to follow up with a more detailed quantitative evaluations for those identified in the initial analysis.
8. Modeling climate impacts and management scenarios. Forecasting and projecting the impacts of climate change on marine fish production involves several steps: a) identifying and modeling potential links between the environmental variables and biological processes such as reproductive success, growth, and distribution; b) downscaling from GCMs (or GCM/ROMS) to obtain projected future values of the environmental variables under alternative climate scenarios; c) using those environmental variables to drive the population dynamics in a simulation with alternative harvest policies, and d) assessing social and economic impacts under different climate and management scenarios using coupled bioeconomic models.

3.2 Long-term monitoring activities at AFSC

AFSC conducts a comprehensive set of surveys of the Gulf of Alaska using a variety of sampling gears to monitor a broad range of ecosystem components for trends in abundance and distribution. Bottom trawls surveys sample demersal fish and invertebrates, while acoustic-trawl surveys sample the pelagic fish, primarily pollock, but also capelin, herring, rockfish, and krill. Early life history stages are also sampled at different times of the year, using a variety of sampling gears, such as plankton tows and surface and small-mesh midwater trawls. Although many of these surveys provide information used in stock assessments to manage fishery stocks, it is important to recognize that survey data are also used to address broader ecological issues, such as predator-prey interactions, life history characteristics, species distribution, growth, survival and recruitment, the relationship of these biological processes to environmental factors. Surveys conducted by AFSC in the Gulf of Alaska are briefly described below and additional information for each survey is included in Appendix 1.

- **Gulf of Alaska Biennial Shelf and Slope Bottom Trawl Groundfish Survey.** Multi-species summer bottom trawl surveys are conducted to monitor trends in abundance and distribution of demersal components of the ecosystem, including fish and invertebrates.
- **Pollock Summer Acoustic-Trawl Survey-Gulf of Alaska.** Pelagic populations are surveyed using acoustic methods. Mid-water trawls are used for species identification. The primary target of this survey is pollock, but the survey has a broader focus and produces estimates of capelin, cod, herring, rockfish, and krill abundance.
- **Pollock Winter Acoustic-Trawl Survey - Shelikof Strait and Shumagin/Sanak Islands.** Collect acoustic and trawl data to estimate mid-water abundance and distribution of pre-spawning aggregation walleye pollock.
- **Alaska Longline Survey.** Monitor and assess the status of sablefish and other upper continental slope species during the summer.
- **ADF&G Large-mesh Trawl Survey of Gulf of Alaska and Eastern Aleutian Islands.** This summer survey covers areas inshore of the AFSC biennial bottom trawl survey and estimates the abundance of groundfish and crab and populations.
- **EcoFOCI/EMA Larval Walleye Pollock Assessment Survey and Ecosystem Observations in the Gulf of Alaska.** Assesses the abundance, distribution, size structure, and survival of larvae of key economic and ecological species during the spring. Target species are pollock, cod, sablefish, rockfishes, and arrowtooth flounder.
- **Recruitment Processes Alliance Young-of-the-Year Walleye Pollock Assessment Survey and Ecosystem Observations in the Gulf of Alaska.** Assess the abundance and condition of age-0 walleye pollock and other key economic and ecological species prior to the onset of the first winter.
- **Recruitment Processes Alliance Age-1 Walleye Pollock Assessment Survey and Ecosystem Observations in the Gulf of Alaska (Proposed).** Assess the distribution and condition of age-1 walleye pollock immediately after the first winter.

- **EVOSTC Long-term Monitoring - Apex Predators.** Evaluate the impact by humpback whales and other apex predators on forage fish populations.
- **Southeast Alaska Coastal Monitoring (SECM).** Identify processes or factors that influence growth and survival of salmon in different marine habitats along seaward migration corridors and in the Gulf of Alaska.
- **Recruitment Processes Alliance GOA Assessment.** Identify and quantify major ecosystem processes for key groundfish species in Gulf of Alaska.
- **Juvenile Sablefish Tagging.** Tag and release juvenile sablefish with 1,000 numerical spaghetti tags and 80 surgically implanted electronic archival tags.

3.3 Process-oriented research

Process-oriented research provides the understanding of ecosystem processes that is critical for forecasting how species and ecosystems will respond to climate change. Process-based studies are used to understand ecological relationships and underlying mechanisms of change, for instance by testing hypotheses regarding links between environmental conditions and species vital rates (e.g., survival, fecundity), or identifying predator-prey relationships. Cumulatively, process-based work provides the mechanistic understanding of how changes in the marine environment translate into impacts on fish stocks, protected resources, and fisheries-dependent communities. Findings are used to inform stock assessment models, determine the vulnerability of species to climate change, develop and test indices that inform management, parameterize ecosystem models, and develop scenarios for testing management strategies under climate change. At the AFSC, process-based research is combined with retrospective analyses (e.g., of ecosystem data), ecosystem monitoring, and modeling studies to provide an understanding of climate effects on fisheries and ecosystems.

3.3.1 Recruitment processes

The first year of life is a critical period in the life history of marine fishes where climate change and variability have the greatest impact on survival and subsequent year-class strength. Process studies focused on early life stages of marine fishes are conducted by the Recruitment Processes Alliance (RPA), a cross-Divisional research team focused on understanding bottom-up and top-down mechanisms regulating fish recruitment. Process studies of the mechanisms that mediate survival during the vulnerable egg, larval, and juvenile stages are being used to provide a mechanistic understanding of recruitment success over a range of environmental conditions. Five focal groundfish species (walleye pollock, Pacific cod, sablefish, Pacific ocean perch, and arrowtooth flounder), selected midwater forage fishes (capelin, eulachon, herring), and Pacific salmon (Chinook, chum) constitute the focus of RPA efforts. Ongoing studies focused on walleye pollock and sablefish are described below. An understanding of processes during the critical first year of life, including the physical and biological influences on growth and survival, forms the basis for population- and ecosystem-level modeling efforts which can be used to forecast the effects of climate change.

Walleye pollock: Walleye pollock is important economically and ecologically in the Gulf of Alaska. Current work on recruitment dynamics of walleye pollock focuses on factors responsible for recent weak recruitment. For example, the RPA is examining recruitment processes during the 2015 warm anomaly to better understand how warm ocean conditions affect pollock year-class strength through effects on spawn timing, egg development and survival rates, larval growth, and match/mismatch with zooplankton prey. Further work investigates climate-driven shifts in the zooplankton community and subsequent impacts on juvenile pollock condition and overwinter survival. Observations are related to historical time series maintained by EcoFOCI to develop forecasts of climate-mediated changes in pollock recruitment dynamics as well as the impacts on upper trophic level species (e.g., birds and mammals).

Sablefish: Sablefish are a valuable commercial species in the Gulf of Alaska that have been in declining in abundance since the 1980s. Recruitment is episodic and does not appear to be related to density-dependent factors. This suggests that year-class strength is likely determined during the first year of life and affected by environmental conditions experienced during the larval and free swimming age-0 life stages (Wing 1997, McFarlane and Beamish 1992, Sigler et al. 2001, Shotwell et al. 2014). To better understand inter-annual variability in recruitment strength a collaborative, cross-Divisional research team is conducting research on sablefish during the first year of life to determine underlying mechanisms influencing recruitment variability. Larvae and post-metamorphic juveniles are collected from ecosystem monitoring surveys during spring while larger, free swimming age-0 fish are captured during summer ecosystem surveys to measure growth, diet composition, and energetic health. In addition to monitoring the condition, distribution, and abundance of sablefish, summer surveys will also tag and release sablefish to better understand movement and spatial distribution. Seasonally-deployed moorings will provide thermal experience data. A series of physiological experiments are performed on larval sablefish in the laboratory to model the effect of prey quality and water temperature on the amount of somatic growth and lipid reserves that may be acquired by an individual fish experiencing a range of biophysical conditions. Growth will be analyzed using RNA/DNA analysis, energetic status and reserves will be measured by calorimetry and lipid extraction, respectively. Changes in foraging behavior will be assessed using stable isotope analyses. These data will provide a complete record of a fish condition from larvae to post-settlement that can be related to recruitment and environmental conditions.

3.3.2 Life history characteristics

Climate change is expected to alter population demographics, including growth rates, maturation schedules, and fecundity of marine fishes. Understanding how these life history traits have responded to past environmental variability is important for predicting the effects of future climate change. Changes in traits such as size-at-age or age-at-maturation can have wide-ranging impacts on population productivity, survey and fisheries catchability, ecosystem interactions, and can lead to biases in stock assessments if not properly accounted for. The AFSC conducts age, growth and maturation studies, and maintains an extensive collection of data on size at age that are critical for informing age-structured assessment models. These data can be used to track shifts in species life history with climate change, and allow stock assessments to be responsive to such changes.

3.3.3 Predator-prey relationships

An understanding of predator-prey interactions is necessary for determining the importance of top-down and bottom-up impacts on marine ecosystems. The AFSC maintains one of the world's largest collections and longest time series of food habits of fish and crabs. This time series allows analysts to develop spatial and non-spatial models of predator prey interactions for use in stock assessments and short-term and long-term projection models. Climate change is expected to alter trophic interactions through spatial shifts in species distributions and temperature-driven changes in physiological rates (Holsman and Aydin 2015). Maintaining the collection of food-habits data is necessary to track and be responsive to these changes.

3.3.4 Experimental studies (temperature and OA)

Ocean acidification (OA) has the potential to significantly affect the production of valuable fishery resources. OA is known to have a variety of impacts on organisms through "Multiple Action Pathways" (MAPs) (Fig. 3). Among fishes, these impacts include reduced growth and survival of early life stages and disruptions of sensory and behavioral systems. In addition, fishes will be impacted by OA-induced changes in lower trophic levels that alter the availability of their primary prey species. There is further concern that the effects of OA will interact with those of co-occurring rapid warming. Understanding and predicting the impacts of OA on Alaskan fisheries communities will require a comprehensive examination of these MAPs climate interactions across a diverse species assemblage.

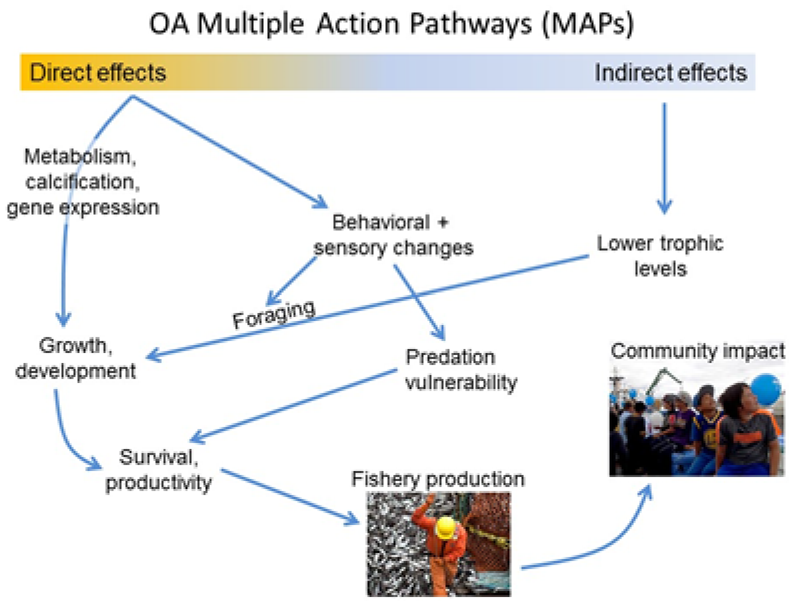


Figure 3.--OA has multiple pathways to act on the early life stage growth and survival of marine organisms.

Process studies on OA will involve a series of laboratory experiments to describe the influence of MAPs of OA on commercially and ecologically important fishery resources of Alaska. There will be continued examination of the effect of OA on the growth and development of walleye pollock and northern rock sole. This research will expand the scope of our understanding through the inclusion of more sensitive response metrics (development and energy status), and expand the use of multiple stressor experimental designs (temperature). A new species, Pacific halibut, will be added to the study plan. In addition, collaborative work in a NSF-funded project will examine the underlying physiological mechanisms of OA impacts through neurobiological studies of walleye pollock.

3.3.5 Use of archival and satellite tags for defining species niche

The Alaska Fisheries Science Center, Marine Ecology and Stock Assessment Program, has conducted long-term tagging studies for a range of species in the Gulf of Alaska, Bering Sea, and Aleutian Islands regions, including: sablefish (*Anoplopoma fimbria*), spiny dogfish (*Squalus acanthias*), Pacific sleeper shark (*Somniosus pacificus*), salmon shark (*Lamna ditropis*), shortspine thornyhead (*Sebastolobus alascanus*), Greenland turbot (*Reinhardtius hippoglossoides*), and lingcod (*Ophiodon elongatus*). Data from internally-implanted archival tags and pop-off satellite tags provide unique insights into the optimal thermal envelopes for these species, how these species are distributed and move across spatial and depth gradients both within and among years, and how ontogeny affects habitat use (Rodgveller et al. 2017). Information on vertical movement behavior and distribution have also been used to assess the availability of species to survey gear within the Gulf of Alaska (Hulson et al. 2016). Given past changes in marine temperature conditions within the Gulf of Alaska and the potential for future change, improved understanding of species thermal niches as well as vertical movement behaviors and depth distribution provide key insights about the potential capacity for species to adapt their behavior and distribution, vertically and spatially, to future marine temperature patterns. Knowledge of actual temperatures experienced by target species can be combined with laboratory physiological studies to better model growth and predict climate change impacts.

3.3.6 Genetic adaptation

Scientists at AFSC and the University of Washington are collaborating on a study to evaluate whether rapid genetic adaptation occurs in response to temperature variation in pollock populations in the Gulf of Alaska. Genetic adaptation has generally been thought to be very slow, certainly much slower than the pace of current anthropogenic environmental change. However, recent evidence suggests that adaptation may occur on much shorter time scales, and that such evolutionary responses may be instrumental for species persistence in variable environments (Carvalho et al. 1996, Conover and Munch 2002). There is evidence that selective mortality may be sufficiently large to change the genotypic composition of a population within a single generation (Mork and Sundnes 1985, Planes and Romans 2004, Pespeni et al. 2013). If so, the genotypic composition of the spawning stock would depend on genetic variation of dominant year classes, and may thus be very dynamic over time. Such temporal variation in adaptive genetic variability in the spawning stock may be an important factor in stock dynamics in a changing climate.

The project includes rearing experiments under controlled conditions to test whether selective changes are detectable at the molecular level within larval cohorts reared under different temperatures. In addition, a genomic analysis of wild larval cohorts from different years with contrasting environmental conditions using archived larval collections will test whether similar changes are observable in the wild. A management strategy evaluation will be performed to understand how rapid adaptation affects population dynamics, and to evaluate performance of current assessment and harvest policies under climate change.

3.3.7 Spatial response of northeast Pacific groundfish to anomalous warming in 2015

A 3-year research project, funded by NPRB, is examining the role of extreme environmental conditions on the spatial distribution patterns of northeast Pacific groundfish throughout their range in an anonymously warm year (2015). In the winter of 2013-14 an anomalously warm ocean feature ("the Blob") formed in the northeast Pacific Ocean and persisted through the summer of 2015 (Bond et al. 2015). These unusual conditions provide an opportunity to evaluate relationships between environmental conditions and species distribution that may be representative of future climate regimes. Pinsky et al. (2013) found that local differences in the spatial extent of range shifts of several species could be explained by climate velocity, which is the rate and direction at which climate is changing in the habitat of the species. However, behavioral responses by marine organisms to environmental variability suggests that other factors may impede or buffer the direct response of species to shifts in oceanographic conditions.

This project utilizes the alignment of summer multiple survey efforts encompassing stations along the U.S. west coast (West Coast Bottom Trawl Survey), the Canadian Coast, and the western Gulf of Alaska (GOA Bottom Trawl Survey and GOA Acoustic-Trawl Survey) to compare groundfish fish responses to warming ocean conditions. A collaborative approach is required to explore climate impacts on distributional shifts when the biological population span jurisdictional boundaries. The project compares fish responses at the leading and trailing edges, and middle of their distributions. The data will be used to evaluate leading hypotheses regarding the implications of climate on the spatial distribution of fish and fisheries. In addition, a modeling project has been funded though FATE that will attempt to "stitch" various surveys together using advanced spatio-temporal modeling methods (Thorson and Barnett, 2017) and to evaluate relationships between satellite-based sea surface temperature and species distribution.

3.4 Risk assessment of climate change

Long-term climate change has the potential to both amplify and attenuate existing pressures on marine ecosystems as well as introduce novel interactions that may result in partial or complete ecosystem reorganization. To evaluate climate change risk on a marine system it is therefore important to include evaluations of both probable or well understood events and interactions, as well as events and interactions that may be relatively rare under historical conditions but may manifest more frequently under future climate change (e.g., low DO events or HABs). It is also important to try to capture both direct and indirect effects of climate driven changes and multiple interacting pressures as indirect pathways can greatly alter trajectories of change (Levin et al. 2013, Tommasi et al. 2017; Woodworth-Jefcoats et al. 2015). This poses a challenge for evaluating climate change risk across ecosystems where data availability, mechanistic understanding, and conceptual frameworks for the ecosystem vary across species, sub-regions, and human communities.

Risk assessments are used to evaluate the probability of occurrence and characterize the consequences of a natural or human-mediated event. A central objective of most risk assessments for conservation and management is to characterize uncertainty and impacts associated with one or more pressures of interest, including management actions. Risk assessments have been used in marine resource management to help evaluate the risk of environmental, ecological, and anthropogenic pressures on species or habitats including for fisheries management.

Holsman et al. (2017) describe a conceptual framework for ecosystem risk assessment (ERA), highlighting its role in operationalizing EBFM, with specific attention to ocean management considerations. Their framework builds on the ecotoxicological and conservation literature on risk assessment and includes recent advances that focus on risks posed by fishing to marine ecosystems. Holsman et al. (2017) categorize risk assessments in two dimensions, the first relating to whether or not the assessment is quantitative, and the second relating to the complexity of the stressor-subject relationship (Fig. 4).

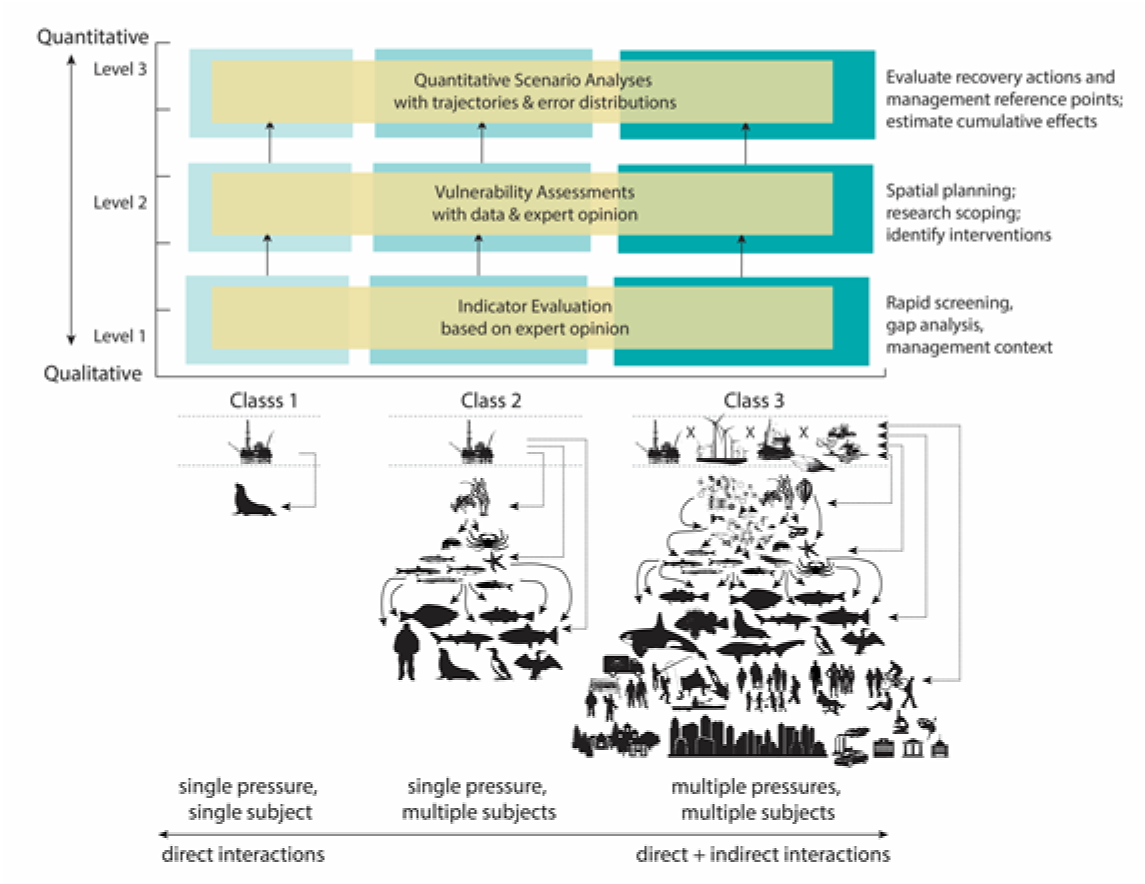


Figure 4.--Hierarchical conceptual framework for ecosystem risk assessment from Holsman et al. (2017). Scoping and stakeholder engagement increases left to right, and data requirements and computational costs increase diagonally from lower left to upper right. Far right column highlights example applications of each level of ecosystem risk assessment. Class 1 represents evaluations of a single pressure on a single focal subject, Class 2 analyses consider impacts of a single pressure on multiple ecosystem subjects or multiple pressures on a single subject, and Class 3 analyses considerer the reciprocal and cumulative interactions among multiple (interacting) pressures and multiple interacting subjects.

Climate change involves multiple changes to the environment, such as ocean warming, changes in pH, and changes in sea level that may impact one or more life history stages, so it cannot be considered a single stressor. Ideally, cumulative effects of the multiple stressors should be evaluated. For example, the combination of increased temperature and lower pH may have synergistic effects on larval survival that would not be evident if the two factors were considered separately. While, marine risk assessments have traditionally focused on singular pressure-response relationships, recent advancements include methods and application of cumulative ecosystem risk to multiple interacting pressures, including climate.

Vulnerability analyses are semi-quantitative methods for risk assessment that have been used in Alaska and elsewhere to evaluate climate change risk (Gaichas et al. 2014). Vulnerability analyses use numerical scoring rubrics to evaluate susceptibility of a population to a stressor and degree to which it is exposed to the stressor. The concept of vulnerability combines the scores of susceptibility and exposure for an overall assessment of risk. Several risk assessments relating to climate change have already been completed in Alaska, with a focus on fishing communities. Himes-Cornell and Kasperski (2015) evaluated vulnerability of Alaska fishing communities by evaluating exposure to the biophysical effects of climate change, the dependence on resources that will be affected by climate change, and the adaptive capacity of the community. Mathis et al. (2015) conducted a similar analysis at the scale of census areas that focused only on the impact of ocean acidification.

A vulnerability analysis of stocks in the eastern Bering Sea using a standard NOAA Fisheries methodology (Morrison et al. 2015) is in progress. A similar analysis is planned for the Gulf of Alaska, and will be an important element of this RAP. These vulnerability analyses should be viewed as intermediate risk assessments that identify highly vulnerable stocks or ecosystem components that are then candidates for more thorough evaluation using management strategy evaluations or other quantitative approaches.

3.4.1. Gulf of Alaska Integrated Ecosystem Assessment

An additional risk assessment project that is just beginning is the Gulf of Alaska Integrated Ecosystem Assessment (GOA IEA). This effort will ultimately link ongoing research and monitoring efforts to products requested by natural resource users. The IEA is a process through which ecosystem-based management goals and targets are defined, indicators are developed, the ecosystem is assessed, uncertainty is assessed, and strategies are evaluated. Specific initial products for the GOA IEA will be a conceptual model and the development of a place-based IEA program for Sitka, Alaska. Current human dimensions and sociological products are the groundfish and crab economic reports in the SAFE, a poverty vulnerability assessment, and fisheries information spatial economics toolbox (FishSET). Future efforts will be focused on developing integrated models that can describe coupled social-ecological systems and increasing stakeholder engagement to better define the most relevant temporal and spatial scales of importance.

3.5 Modeling climate impacts and management scenarios

3.5.1 Regional climate projections (GCM, ROMS, NPZ)

A high priority should be placed on continued development and support for a high-resolution ocean modeling framework for the Gulf of Alaska. The U.S. GLOBEC Northeast Pacific program originally funded for a first-generation regional ocean model (the NEP-10K), which was based on the Regional Ocean Modeling System (ROMS; Haidvogel et al. 2008). Lessons learned from applications of the NEP-10K model to the California Current and Gulf of Alaska revealed that finer resolution was needed to resolve upwelling processes, eddy formation, and topographic steering in regions of complex topography which are all environmental factors important in determining early marine feeding, growth, and survival of salmon (Wells et al.

2016, Bi et al. 2011). Likewise, for buoyancy-driven systems influenced by freshwater inflow, inland extensions of the coastal boundary of the grid are needed to capture critical processes governing the transition to and from the freshwater phases of salmon life histories (Malick et al. 2016, Beamish and Mahnken 2001).

Ideally this high-resolution model should not be limited to Gulf of Alaska but extend to include the large marine ecosystems (LMEs) of the northeast Pacific (California Current System, CCS; Eastern Bering Sea, EBS; and Gulf of Alaska, GOA). A proposal has been developed to upgrade and adjust the NEP-10K grid to 3 km resolution (NEP-3K) and utilize a seamless Nutrient-Phytoplankton-Zooplankton (NPZ) modeling framework (COBALT) that is implemented in both global Earth System Model (ESM) and ROMS applications to project future ocean conditions in the CCS, GOA, and EBS.

The ocean model framework would be directly useful to drive spatial ecosystem models, such as the Atlantis model, which is proposed for Gulf of Alaska in the ecosystem modeling section of this document. In addition, ROM/NPZ ocean models have potential utility in identifying environmental forcing in single-species and multispecies models. ROMS/NPZ models can be queried directly to obtain the environmental variables to use in the correlation analysis with recruitment and growth. This would allow evaluation of the underlying processes affecting recruitment and growth rather than having to use indirect proxies such as SST. Projection under climate change scenarios is also more direct and straightforward. Since ROMS models use GCMs for their boundary conditions, statistical downscaling would not be needed. Other potential applications include risk assessments, Individual-Based Models (IBMs), climate envelope spatial models, and Ecopath-with-Ecosim.

3.5.2 Ecosystems

Evaluating climate change impacts at the ecosystem level is a necessary counterpart to studies that focus on individual species. An ongoing project at AFSC is the annual Ecosystem Considerations Report for the Gulf of Alaska (Zador and Yasumiishi 2016). This document provides the Council and its advisory groups with information on ecosystem status and trend and provides context for the Council's ABC and OFL recommendations. It follows the same annual schedule and review process by the Plan Team and the SSC as groundfish stock assessments and is made available to the Council at their annual December meeting when groundfish harvest recommendation are developed. The report includes an ecosystem status report card with indicators that track the physical and biological characteristics of the ecosystem, with a separate set of indicators for the western and eastern portions of the Gulf of Alaska. Although the report is not explicitly focused on climate change, the ecosystem indicators included in the report are, in aggregate, a monitoring system that can be used to make inferences about any major changes in the ecosystem (climate-mediated or otherwise) as they occur.

Further development of ecosystem models is a priority addressing ecosystem-based fisheries management issues in the Gulf of Alaska. Innovative ecosystem modeling was done for the Gulf of Alaska ecosystem by Gaichas and Francis (2008) and Gaichas et al. (2010, 2011), who used Ecopath and other simple ecosystems models to study ecosystem structure and energy flow in the Gulf of Alaska. An important outcome of this research was the identification of a suite of species that are highly connected by their predator-prey relationships, namely, Pacific cod, walleye pollock, Pacific halibut, and arrowtooth flounder, suggesting that a focus on modeling the dynamics of these species would capture key ecosystem dynamics.

At current resource levels at AFSC, expectations for new ecosystem models for Gulf of Alaska should be limited. The Gulf of Alaska ECOPATH model developed by Gaichas and Francis has not been kept up-to-date. There is ongoing work to revisit the Mueter and Megrey (2006) analysis that fit multi-species surplus production models to aggregate biomass in the Gulf of Alaska. This work is intended to incorporate economic considerations in the estimation of aggregate MSY. The production model can be forced by environmental variation (initial work has used sea temperature), so assessment of climate change impacts is possible.

With additional capacity, we recommend that an Atlantis ecosystem model (Fulton et al. 2011) be developed for the Gulf of Alaska as a first priority. The Atlantis model is a spatially-explicit, coupled physical-biological oceanographic model developed by Elizabeth Fulton (CSIRO, Ocean and Atmosphere Flagship). Atlantis models have been developed for the U.S. West Coast, and this modeling effort is ongoing and well-supported (Kaplan et al. 2010, Kaplan et al. 2012a, Kaplan et al. 2012b, Kaplan and Leonard 2012, Kaplan et al. 2013, Kaplan et al. 2014). Atlantis is similar to the FEAST ecosystem model being used for the eastern Bering Sea but has the advantage of being widely applied and based on a supported modeling package. The Atlantis model can be coupled to the ROMS model under development for the Gulf of Alaska and can therefore be used to simulate ecosystem properties under projected climate change.

Other approaches should be considered if additional funding becomes available since the ACLIM project in the eastern Bering Sea is finding considerable benefit in a comparative multi-model approach. Several possibilities are to 1) develop regional size-spectrum models for different areas of the Gulf of Alaska, and 2) utilize mass-balance modeling techniques under development for the ACLIM project, where an ECOPATH model is being implemented in R and driven by climate forcing.

Ecosystem models will be valuable for studying how energy flow and overall ecosystem productivity is expected to change with a changing climate. An important management application is to evaluate the Optimum Yield range (140,000–800,000 t) for the Gulf of Alaska, which provide both lower and upper limits on total groundfish removals (with the expectation that catches will be at least as high as the lower limit). The OY range was derived early in the history of the GOA Fisheries Management Plan by adding together the single-species MSY proxies available at that time, and then reducing that total by 8% to account for ecosystem considerations, as well as for model and estimation uncertainties. Unlike the Bering Sea-Aleutian Island OY upper limit (2 million t cap), which has served as an effective constraint on removals, the upper limit in the Gulf of Alaska has never been constraining, suggesting that the original estimate was inaccurate, or at least is not relevant currently. Improved ecosystem models would allow the OY range to be re-evaluated. Consideration also could be given an adaptive management approach adjusting the OY range to reflect changes in ecosystem productivity over time.

3.5.3 Fisheries resources

This section focuses on federally-managed groundfish in the Gulf of Alaska. Important species in the groundfish fishery are walleye pollock, Pacific cod, sablefish, flatfish species, such as arrowtooth flounder, and rockfish (*Sebastes*) species, such as Pacific ocean perch (*S. alutus*). Pacific halibut is a groundfish but is managed through an international commission (U.S. and Canada) and not through the federal system.

Hollowed et al. (2009) describe a framework for a unified approach to forecasting the implications of climate change on production of marine fish. The framework involves several steps: a) identifying potential links between the measurable environmental variables and biological processes such as reproductive success, growth, and distribution, b) applying of a modeling approach to quantify these relationships and evaluate significance, c) downscaling from GCMs (or GCM/ROMS) to obtain projected future values of the environmental variables under alternative future climate scenarios, d) using those environmental variable to drive the population dynamics in a simulation with alternative harvest policies, e) evaluating of the mean, variability, and trends in production under a changing ecosystem for each harvest policy.

An early example of this approach is A'mar et al. (2009a, 2009b), who evaluated the effects of climate change and ecological interactions on the performance of the current single-species harvest policy for walleye pollock in the Gulf of Alaska. Their study was a full-feedback management strategy evaluation that evaluated the ability of both the assessment model and the alternative harvest controls rules to achieve a set of performance metrics. An inverse relationship between sea surface temperature and pollock recruitment led to a moderate decline in abundance under plausible climate projections. The current harvest control for pollock performed reasonably well preventing the stock from declining to low abundance, but yield from the fishery substantially declined.

We describe three groundfish projects that are currently in progress or are proposed for the Gulf of Alaska that are related to climate change research. The first of these projects is the ecosystem-socioeconomic profile (ESP) , which has developed in parallel to the GOA IERP. The species involved in the first ESPs are likely the focal species for the GOA IERP: walleye pollock, cod, sablefish, Pacific ocean perch, and arrowtooth flounder. The objective of the ESP project is to create a framework for including ecosystem and socioeconomic linkages within the current stock assessment process so that the products are directly usable within the context of the stock research priorities. The synthesis phase of the GOA IERP allowed for collecting a large amount of dedicated research on the five focal species that can be readily incorporated into the ESP. The IERP research and other information will be used to identify the important environmental and/or ecological factors affecting each life history stage for a given stock, and to develop indicators to track these variables. This represents the first step in the framework identified by Hollowed et al. (2009).

A second project is a FATE funded project to apply the CEATTLE multispecies model (Holsman et al. 2015), currently being used for the eastern Bering Sea, to look at interactions between walleye pollock, Pacific cod, arrowtooth flounder and halibut, which are strongly-interacting focal species in the GOA (Gaichas and Francis 2008). CEATTLE will build on Amar et al. (2009a) and the ESP project to identify environmental variables for each of the species in the model. For arrowtooth flounder, the importance of cross-shelf transport and ENSO events have been identified as potential drivers of recruitment (Bailey and Picquelle 2002, Bailey et al. 2008; Stachura et al. 2014) and indices of cross-shelf transport from the 10-km Regional Ocean Modeling System (ROMS) northeast Pacific model will be evaluated in the upcoming arrowtooth flounder stock assessment. For climate projections, this project will use either environmental variables downscaled from GCMs or output from the ROMS model if available. Since CEATTLE can be run in single-species mode, a comparison between multispecies and single species results will be done. A strength of the CEATTLE model is the ability evaluate physiological effects of temperature change on growth in addition to environmental forcing on recruitment. CEATTLE is a type of MICE model (Models of Intermediate Complexity for Ecosystem assessments) that have been advocated as a tactical approach to EBFM (Hollowed et al. 2013, Link and Browman 2014, Plagányi et al., 2014, Dolan et al. 2016).

While significant progress is possible with the projects underway, additional capacity is needed to accomplish the climate science objectives for groundfish. A third project would apply the Hollowed et al. (2009) framework to other important groundfish species in the GOA. Shotwell et al. (2014) evaluated potential environmental variables influencing sablefish recruitment and developed a population model with environmental forcing, so the first steps in the Hollowed et al. (2009) framework have already been completed for sablefish. Quantitative models to evaluate climate impacts are also needed for several representative rockfish species in the GOA.

Stock status relative to biomass reference points is an important aspect of groundfish harvest policies used in the North Pacific. Reference points are used to calculate target fishing mortality rates, and to determine whether a stock is overfished and needs rebuilding. Unlike approaches used in other regions, reference points used in the North Pacific recognize the regime shift that occurred in 1977 by using mean recruitment since 1977 to calculate the biomass reference point. This approach recognizes that an ecosystem-wide climatic change occurred in 1977 that affected the productivity of many groundfish populations in the GOA. Long-term changes in stock productivity due to climate change may require revision to the procedures used to determine stock status. The modeling framework that we develop in this section will allow testing of different approaches for status determination, which is likely to be an important policy question for fisheries management under climate change.

3.5.4 Marine mammals and other ecosystem components

The GOA is used year-round or seasonally by at least 16 species of cetaceans, 7 pinniped species and one mustelid, the northern sea otter. These populations of marine mammals utilize nearshore, coastal and offshore habitats, and occupy a diverse range of trophic niches from lower trophic levels (baleen whales) to apex predators (toothed whales, Steller sea lions, and harbor seals), benthic foragers (northern sea otters, Steller sea lions, harbor seals) to pelagic (whales, northern fur seals) and deep-sea foragers (beaked whales, sperm whales, northern elephant seals). This diversity in foraging styles and habitat use provides excellent opportunities to study effects of environmental variability and climate change on marine mammal distribution and abundance.

Changes in the distribution and abundance of marine mammal populations in the GOA can be expected as a response to projected environmental conditions attributable to climate change (Hazen et al. 2013, IWC 2014), likely because of changes in prey distribution and abundance rather than directly due to environmental factors (Silber et al. 2016). In contrast to projected climate change-related impacts on Bering Sea ice-associated seal populations (Boveng et al. 2009, Cameron et al. 2010, Kelley et al. 2010, Boveng et al. 2013), impacts of predicted climate change scenarios on Gulf of Alaska marine mammal populations have not yet been modeled, although the influence of climate as a population driver has been explored in several retrospective models (Pascual and Adkison 1994, Trites et al. 2006, Gaichas et al. 2011).

NMFS recently held a workshop to develop best approaches for projecting marine mammal distributions in response to a changing climate (Silber et al. 2016). The workshop recommended that priority for developing models that can track changes in marine mammal distribution should be given to species where modeling capability is high and the management need is great. Predictive modeling efforts should thus focus on species or populations that are depleted or currently declining, represent a high management priority because of anthropogenic threat exposure, and for which aspects of their ecology are already quantified (Silber et al. 2016). Several species meet these criteria, including humpback whale, Cook Inlet beluga whale, Steller sea lion, northern fur seal, and harbor seal. However, understanding future impacts associated with a changing environment, and underlying mechanistic processes will be challenging to quantify given ecosystem complexity and the scope of anthropogenic threats facing marine mammal populations (Clapham 2016, Silber et al. 2016).

Sustained and consistent monitoring of marine mammal population abundance and distribution is a minimum requirement to monitor population trends and detect changes in vital rates that may be the first indication of a response to climate change (Sigler et al. 2016). Studies to build on, develop and validate marine mammal distribution and abundance models at multiple spatial and longer temporal scales (Silber et al. 2016) are needed, and can also be extended to explore climate change effects relative to timing of breeding seasons and migrations (Anderson et al. 2013).

However, the abundance and distribution of marine mammals in present day GOA ecosystems are very different than in the past. This is due to the long history of whale harvests by humans in the North Pacific Ocean, other sources of anthropogenic mortality (e.g., following the *Exxon Valdez* oil spill) and large population declines of Steller sea lions, harbor seals, and northern sea otters. The scope of some of these events created multi-generational changes in distribution and abundance that are still evident. During the 19th through mid-20th centuries more than 500,000 large whales were removed by commercial whaling from the North Pacific Ocean, with lasting damage to some populations. Northern right whales (Shelden et al. 2005), sperm whales (Clapham 2016), sei whales (Mizroch et al. 2015), and blue whales (Monnahan et al. 2014) still reflect the impact of those removals, while some species, such as humpback whales and fin whales, show signs of recovery (Clapham 2016, Rone et al. 2017).

Several recent vessel-based surveys and passive acoustic monitoring studies provide updated information on whale distributions in the Gulf of Alaska (Wade et al. 2011, Witteveen et al.

2011, Monnahan et al. 2014, Rone et al. 2017). To study potential effects of climate change on cetacean distribution, the addition of cost-effective monitoring that could be sustained into the future is required. Moorings that collect acoustic data in addition to other biological and physical oceanographic data are a high priority. This option for increased funding spans relatively inexpensive acoustic recorder redeployments piggy-backed on vessels used for other projects, to expanded deployments of new moorings with broader spatial coverage.

The endangered Cook Inlet beluga whale could serve as a sentinel species that addresses most of the Silber et al. (2016) criteria: these whales are a small and endangered population with a restricted home range located entirely within a populated area, and this population has long-term distribution and abundance data. As a NMFS “Species in the Spotlight”, the Cook Inlet beluga whale population is the subject of continuing abundance surveys and studies of habitat use. In a currently-funded project, a series of simulation models will be developed in collaboration with Alaska Department of Fish and Game (ADF&G) to support a research strategy analysis to determine what types of data and analysis will be required to answer key management questions, which may include some evaluation of climate change effects. A preliminary re-analysis of distribution patterns observed from summer aerial surveys suggests considerable interannual variation may be linked to changes in the availability of anadromous prey resources (i.e., salmon, smelt). Increased funding will be necessary to develop projects that will increase the utility of abundance and distribution data based on the aerial surveys that will allow for variation in distribution patterns to investigate the role of climate. Another key piece of data that will help track changes in distribution patterns and investigate possible driving factors is passive acoustic monitoring data. Additional funding would be needed to support a sampling design analysis for a passive acoustic monitoring array program that will enable tracking changes in distribution patterns. Development of an individual-based stock assessment model is currently funded, but additional funding will be needed to extend the model to an individual-based population viability analysis that would support recovery planning and management decision-making, integrate with socio-economic studies, and examine how the model can be used in the context of addressing climate change effects.

Because of their endangered status and interaction with commercially-important fisheries, Steller sea lions have had one of the most comprehensive monitoring programs for marine mammals in the Gulf of Alaska, including long-term studies of population abundance, trends, and diet habits. More recent studies monitor survival and reproductive rates, population structure, trophic interactions, health status, and foraging behavior. Considerable modeling of Steller sea lion population trends relative to bottom-up and top-down forcing mechanisms have been completed (Pascual and Adkinson 1994, Trites et al. 2006, Heymans et al. 2007, Guenette et al. 2006), but none have attempted to forecast changes in distribution or abundance in response to environmental variability related to projected climate change scenarios. Current studies assess abundance, vital rates and diet habits through aerial and vessel surveys. To study potential impacts of climate change on Steller sea lion populations, additional funds are needed to capture and track adult female sea lions for health and foraging studies in the Gulf of Alaska to better understand interactions with oceanographic conditions and prey distribution. This is one aspect of Steller sea lion ecology where the few data that exist are now over 25 years old. Additional funding is also needed to provide for the integration of Steller sea lion population, life history, and foraging behavior data with models of mechanistic processes underlying potential effects of altered prey abundance in response to projected climate change scenarios.

Harbor seals are an ideal species for exploring local effects of environmental variability, as they range widely but have local genetically-distinct stocks (O'Corry-Crowe et al. 2003, Boveng et al. 2012, Womble and Gende 2013). There are also long-term data on population abundance, and their ecology has been described through studies on body condition, foraging behavior and diet. With level funding ongoing aerial surveys collect data to update GOA harbor seal abundance estimates. A main concern of climate change impacts on harbor seals in the GOA is the potential for changes in the amount of floating ice habitat in tidewater glacial fjords. The number of seals currently found in this type of habitat during August surveys comprises about 10-15% of the total population in Alaska. The importance of this habitat is even greater during the pupping season, as glacial fjords seem to be prime whelping and pup-rearing habitat. Loss of this habitat due to grounding of tidewater glacier fronts (already observed in some cases) could have a substantial impact on GOA harbor seal stocks. At some of the glaciers, there may be potential for the opposite effect from warming, at least temporarily: surges in glacial flow could perhaps produce transient increases in the production of floating ice. Increased funding would be used to project tidewater glacial ice production (in collaboration with glaciologists), monitor the GOA harbor seal stocks for changes in ice habitat, and monitor harbor seal redistribution between ice and terrestrial haul-out habitats.

Northern fur seals breed outside of the GOA in the Bering Sea and southern California Current ecoregions, but in fall migrate into the GOA and remain there for about 8 months each year. Migration patterns are influenced by oceanographic conditions (Ream et al. 2005), and pup dispersal is affected by storm patterns (Lea et al. 2009). Oceanographic and weather patterns likely affect individual foraging success, with consequences for survival and reproductive success (Lea et al. 2009, Pelland et al. 2014, Sterling et al. 2014). Climate-induced changes in North Pacific storm intensity and frequency (Graham and Diaz 2001) could thus have population-level consequences for northern fur seals. Current research is continuing long-term investigations into interactions between winter migration behavior and weather and ocean patterns with level funding. Increased funding is needed to expand tagging deployments, and to add capacity to determine whether these interactions lead to demographic consequences, and to integrate with other modeling efforts linking climate-mediated changes in prey abundance with fur seal behavior and, ultimately, population trends.

A concern for all GOA marine mammal populations is the potential for an increased risk of exposure to infectious diseases brought to the region by expanding ranges of marine mammals through arctic and temperate areas (Burek et al. 2008). Current disease surveillance and knowledge of health status is minimal and generally limited to occasional species-specific investigations in response to disease outbreaks or mass mortality events. New funding would provide the capacity to create a surveillance program across multiple species, and tracking to detect and better understand the epidemiology of novel infections (Norman 2008). Another major potential threat to GOA marine mammal populations is the ingestion of neurotoxins associated with harmful algal blooms, the range of which are likely to expand as water temperatures increase (Lefebvre et al. 2016). These toxins (e.g., domoic acid and saxitoxin) have already been detected in Alaska cetaceans and pinnipeds, and have the potential to impact individual health and ultimately affect population trends (Lefebvre et al. 2016). Additional capacity will provide for continued and expanded monitoring of neurotoxin presence among GOA marine mammal populations and an evaluation of health risk.

Although U.S. Fish and Wildlife Service has direct trust responsibilities for seabirds, NOAA has established a National Seabird Program that includes participation by AFSC scientists. Two key focus areas for the NOAA program are the mitigation of bycatch and the promotion of seabirds as ecosystem indicators. Seabird abundance, distribution, and productivity can reflect physical and biological properties of marine systems. As seabirds are also relatively easy to detect and observe, they can serve as useful indicators of ecosystem state. NOAA has prioritized promoting seabirds as ecosystem indicators, and as such will continue to develop improved indicators using seabird data, such as diet and reproductive success, that tracks ecological and environmental changes associated with a changing climate.

3.5.5 Fishing communities and other socio-economic constructs

Fisheries off the coast of Alaska, and the fishing communities that depend on them, are at risk from ocean acidification and climate change (Mathis et al. 2015). The AFSC has developed a number of tools that can serve to inform an understanding of current baseline socioeconomic conditions in Alaska communities for potential evaluations of future climate change impacts on these conditions. The following subsections describe (a) ongoing research to establish conditions for a socio-economic baseline, and (b) economic models informed by this baseline that account for the dynamic nature of fisher responsiveness to future climate change, as well as linkages between fishing sectors and the Alaska economy. Hence these models can provide information about climate change impacts on Alaska fishing communities, and quantitative (i.e., dollar value) welfare measures applicable to all Alaska households based on the full range of economic effects (i.e., direct and indirect) from impacts of climate change in fishery-dependent sectors.

(a) Socio-Economic Baseline and Monitoring

A risk assessment for communities throughout Alaska was conducted by developing a set of community vulnerability and fishing engagement indices (Himes-Cornell and Kasperski 2016). These indices use a standardized methodology developed for communities across the country by social scientists working in NOAA Fisheries' Regional Offices and Science Centers (Colburn and Jepson 2012). The vulnerability index utilizes Census data on labor force participation, housing characteristics, poverty, population composition, and personal disruption and represents social factors that can shape a community's resilience or ability to adapt to change. The fishing engagement indices use annual data on the harvesting and processing sectors to portray community dependence on commercial or recreational fishing. These vulnerability and fishing engagement indices have been utilized to examine how these communities may be differentially affected by changes in resource abundance and management and how well each community may be able to adapt to such impacts. The fisheries engagement indices have been incorporated into NPFMC reviews of catch share programs to examine changes in harvesting and processing engagement for individual communities in relation to management changes and over time (NPFMC/NMFS 2016b, NPFMC 2017). The vulnerability and fisheries engagement indices are updated with the availability of data and are expected to continue being updated with level funding.

An additional risk assessment focused specifically on climate change was also conducted for Alaska communities (Himes-Cornell and Kasperski 2015). A set of indices were developed to assess how much communities may be affected by the physical effects of climate change (e.g., sea level rise, melting permafrost, changes in sea-ice distribution). This framework of indicators was developed to examine three constituents of community vulnerability – the biophysical effects of climate change, dependence on resources that will be affected by climate change, and a community's adaptive capacity to offset negative impacts of climate change. These indices were intended to be used to better understand the overall impact that climate change might be expected to have on individual communities and to help develop adaptation strategies. Mathis et al. (2015) conducted a similar risk assessment that evaluated only on the impact of ocean acidification, and used census areas rather than communities as the focus of analysis.

This research could be extended by examining how changes in recruitment and abundance of exploited fish stocks will ultimately affect fisheries-dependent communities using specific climate change impact projection scenarios or species vulnerability assessments. Increased funding would be necessary for these extensions.

The AFSC has also developed community profiles, community snapshots, and the Alaska community survey, which provide detailed information on demographics and fishing involvement for individual Alaska communities (Himes-Cornell et al. 2013, Himes-Cornell and Kent 2014a). All three of these provide important baseline information and data on socioeconomic conditions across Alaska communities and constitute a regular monitoring effort on these conditions. The community profiles provide narratives for 196 communities from around Alaska and include information on location, demographics, history, infrastructure, governance, facilities, and involvement in state and federal fisheries targeting commercial, recreational and subsistence resources. Because developing (in 2005) and updating (in 2010 and 2011) the community profiles was a labor- and time-intensive process, the AFSC created the community snapshots to provide annually updated time series information on communities involved in fishing in the North Pacific. The community snapshots include annual information on commercial and recreational fishery harvest and processing sectors, participation in subsistence activities, and demographic information using the most recent data from the U.S. Census Bureau. The Alaska community survey collects primary socioeconomic data about community demographics (population size and fluctuations), fishery participation and change, available infrastructure, fishery services and businesses, social support services, social networks, and challenges related to fishery policy and management for 208 Alaska communities. The survey has been implemented four times (2011, 2012, 2014, and 2016) and NOAA Fisheries Technical Memorandums have been produced from three iterations of the survey thus far (Himes-Cornell and Kent 2014b, Himes-Cornell and Kent 2014a, Himes-Cornell and Santos 2017). The community snapshots are anticipated to continue under level funding. Updating the Alaska community surveys and community profiles would necessitate additional funding.

(b) Economic Assessment

Economic models are used to assess effects of climate change and ocean acidification on LMRs. Within the AFSC, four distinct classes of economic models have been developed to analyze or estimate these effects. Linked together these economic models have a dual role in representing local behavioral changes, and relating these changes to economy-wide effects on Alaska households using dollar-based welfare-measures. The four classes of models are described as follows: a) Spatial econometric and fishing fleet models (e.g., Haynie and Layton 2010), b) multispecies and multi-stage bioeconomic models (e.g., Kasperski 2015, Punt et al. 2014, respectively), c) computable general equilibrium (CGE) regional economic models (e.g., Seung et al.2015, Seung and Ianelli 2016), and d) recreational fishing and protected species models (e.g., Lew and Larson 2015, Lew et al. 2010, respectively).

Previous AFSC economic modeling efforts have been applied mainly to the top commercially important fisheries in the Bering Sea, including spatial econometric models for BSAI pollock, and bioeconomic models for Bristol Bay red king crab, Eastern Bering Sea snow, and Tanner crabs. However, researchers at the AFSC have created tools and modeling frameworks of fisher behavior that can potentially be adapted to the GOA to inform an understanding of the dynamic nature of climate change adaptations and impacts. These models include fisher responses to ecological and regulatory changes and the factors underlying those decisions (Abbott et al. 2015, Haynie and Pfeiffer 2012, 2013, Haynie and Huntington 2016, Lew and Larson 2015, Szymkowiak and Felthoven, 2016, Szymkowiak and Himes-Cornell 2015, 2016). AFSC researchers are also working with others to develop the Spatial Economics Toolbox for Fisheries (FishSET), which provides an integrated modeling framework to assess and predict how fishers respond to changing fish distributions, regulations, and prices across various fisheries. Effects of ocean acidification on Bering Sea crab fisheries were estimated using size-structured bioeconomic models (Punt et al. 2014, and Punt et al. 2016), and the associated welfare effects on Alaska households were assessed using a regional economic model (Seung et al. 2015).

Improved coverage of economic models for GOA fisheries, and fishing communities, is a priority for ongoing research at the AFSC. Econometric models of the recreational halibut fishery, in particular, apply to the GOA (e.g., Lew and Larson 2015), whereas protected species modeling has primarily focused on Steller sea lions (e.g., Lew et al. 2010). A project to estimate economic values related to the Cook Inlet Beluga whale population is ongoing. Moreover, an important methodological improvement is underway to develop economic models formulated at the borough and census area (BCA) level. Most regional economic models developed for North Pacific fisheries are designed to depict either the whole state (i.e., Alaska) or an administrative region (e.g., the Southeast region). While these models are well suited to calculate the impacts of fishery management actions on relatively large regions, they may not as accurately represent impacts on smaller, fishing-dependent areas such as boroughs, census areas or “fishing communities”. Therefore, results from these large models may be less useful for fishery managers, policy makers, and other parties interested in illustrating impacts on specific communities, especially ones with unique economies. No existing study has yet developed models designed to estimate impacts on individual fishing-dependent communities in Alaska.

(b.1) Regional CGE models

To address the lack of local-area models, AFSC researchers are developing a set of economic models for six BCAs comprising the Southwest Alaska region using regional economic information (such as employment and expenditures) collected for these six BCAs from fish harvesting vessels and key informants including seafood processors and local businesses. The six BCAs include Aleutians East Borough, Aleutians West Census Area, Bristol Bay Borough, Dillingham Census Area, Lake and Peninsula Borough, and Kodiak Borough. These data and other sources are currently being assembled to construct a social accounting matrix (SAM) and develop a CGE model for each BCA. Results from these models will be useful for fishery managers and others who are interested in understanding the economic impacts of fishery management actions or exogenous shocks (such as climate change) on fishing-dependent communities in southwest Alaska region and other regions. The BCA-based models utilize a variety of economic data on expenditures and employment by vessels, processors, and marine supply businesses gathered from seafood industry data, surveys, and interviews. Coupled with basic regional economic structures, these data are the empirical foundation for a set of linked CGE models that can be used to calculate BCA-level impacts of fishery management changes and environmental shocks like climate change. With increased funding it would be possible to model additional BCAs. For example, it may be useful to compare economic impacts on communities in the Southeast Alaska region with those for Southwest Alaska region.

(b.2) Bioeconomic models

Understanding impacts of ocean acidification (OA) requires a multi-disciplinary approach that combines models and methods from oceanography and fisheries science with the necessary linkages to socio-economic systems. By linking multistage population dynamics and bioeconomic models, Punt et al. (2014) made a significant contribution to the multi-disciplinary approach for OA models. According to Cooley et al. (2015): "*detailed policy-relevant information about the relative effects of ocean acidification, rising temperatures, fishing pressure, and socioeconomic factors on specific species has yet to be developed for most species, with a few notable exceptions*" and noted Punt et al. (2014) "*linked population and bioeconomic models to project ocean acidification impacts on the Alaskan king crab fishery, providing both management insight and rationale for future studies.*" Cooley et al. (2015) make a major contribution to OA assessment because they formalized the multi-disciplinary approach with a single-species Integrated Assessment Model (IAM). Future research on effects of OA in the GOA will follow the approach of Cooley et al. (2015) by utilizing a one-way linkage for the ocean model component, and by applying current climate scenarios.

Based on funding in the current AFSC ocean acidification research plan (Sigler et al. 2017), a new single-species bioeconomic model with population dynamics for northern rock sole (*Lepidopsetta polyxystra*) in the GOA will be developed based on the experimental results in Hurst et al. (2016). The working hypothesis is that effects of OA on growth and survival of juvenile marine organisms will be heterogeneous, species-specific, and cause changes in abundance, yields, and economic value of commercially-important populations. The previous Bristol Bay red king crab OA project (Punt et al. 2014) and eastern Bering Sea Tanner crab OA project (Punt et al. 2016) will serve as a basic template for the development of future bioeconomic models applied to the GOA. This template consists of developing and parameterizing four separate component models, and linking these to provide a comprehensive framework to forecast the cumulative impacts of OA for a given scenario (Fig. 1). The first two components are biological models, the third is a bioeconomic model, and the fourth component is a regional economic model (Seung et al. 2015):

- A pre-recruit model for growth and survival of juveniles estimated using data from OA exposure experiments (Long et al. 2013, Meseck et al. 2016, Swiney et al. 2016) and forecast using future scenario for multi-decadal population projections with OA effects.
- A population dynamics model linked to pre-recruit model, which include fishery fleets, their selectivity, and discarding practices, with outputs needed to applying the economic component of a bioeconomic model.
- A bioeconomic model with linked population dynamics to forecast changes in abundance, yields and fishery income over time.
- A regional economic model for Alaska linked to a bioeconomic model to evaluate cumulative impacts on all sectors of the Alaska economy under an OA scenario.

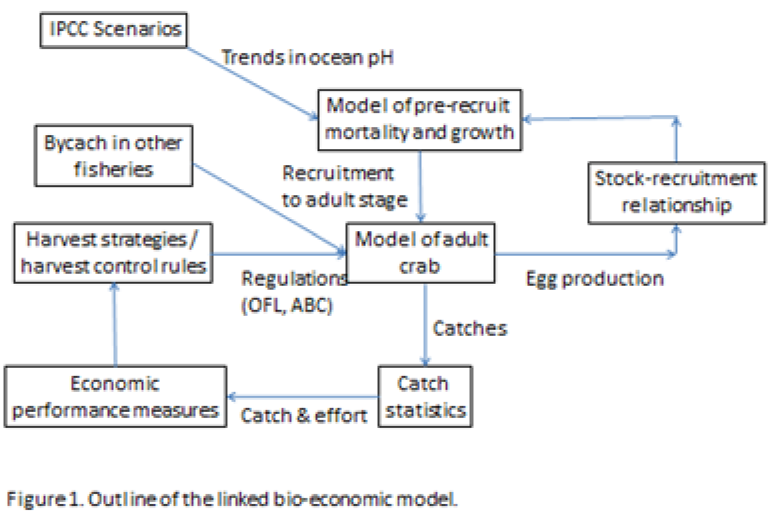


Figure 5.--Outline of the linked bioeconomic model.

Implementation of IPCC scenarios can be handled using the one-way linkage assumption (Cooley et al. 2015). The proposed bioeconomic models will be applied to time series of ocean pH and sea surface temperatures (SSTs) for the Gulf of Alaska from scenarios RCP 4.5 and RCP 8.5 in the GFDL CMIP5 database. The proposed bioeconomic models will be used to evaluate effects of OA on: Maximum Sustainable Yield, MSY, and Maximum Economic Yield, MEY, as well as the uncertainty associated with these estimates due to (i) observational error associated with the data, (ii) the relationship between pH and impacts on juvenile mortality and growth, and (iii) other sources of process error such as inter-annual variation in egg production and natural mortality.

Under increased funding, it is anticipated that the bioeconomic model for northern rock sole in the GOA would serve as a template to facilitate the development of an age-structured bioeconomic modeling framework for the GOA that could be applicable to other GOA stocks, with rockfish considered a priority because of their economic importance and their unique life history that may make them more vulnerable to climate change.

4.0 PARTNERSHIPS

Building and maintaining critical partnerships is an important element of this action plan. AFSC resources are leveraged through partnerships in research programs active in the Alaska region such as those funded by the NOAA Fisheries Office of Science and Technology (FATE, EFH, NPCREP, SAAM), Alaska Department of Fish and Game, Pacific Marine Environmental Laboratory (NOAA), and North Pacific Research Board. The AFSC program collectively known as the Recruitment Processes Alliance (RPA), which conducts fisheries oceanography surveys in the Gulf of Alaska, includes PMEL as a leverage partner. Critical partnerships also include the University of Alaska, University of Washington, and University of Oregon, and the associated joint institutes CIFAR, JISAO, and CIMRS, and other academic institutions. The AFSC and the NOAA Fisheries' Alaska Region rely on the Alaska Department of Fish and Game for collecting data on fish landings, stocks, and prices. Current fiscal challenges faced by the State of Alaska may lead to changes in data collection and analysis that have the potential to present new and significant data gaps. Additional NOAA Fisheries resources may be required to fill those gaps in the future. A brief description of some of AFSC's long-standing partnerships is given below, but this is not intended as an exhaustive list.

4.1 Pacific Marine Environmental Laboratory (PMEL)

Pacific Marine Environmental Laboratory is a federal laboratory that is part of NOAA's Office of Oceanic and Atmospheric Research (OAR). Key research areas at PMEL include ocean acidification, tsunami detection and forecasting, hydrothermal vent systems, fisheries oceanography, and long-term climate monitoring and analysis. AFSC depends on PMEL for both for oceanographic data collections from the GOA, and analysis, interpretation, and modeling of oceanographic and atmospheric data. There is also expertise in developing and running regional ocean models (i.e., ROMs) that are essential for understanding processes affecting ecosystem productivity and dynamics, and for driving various kinds of population and ecosystem models.

4.2 North Pacific Research Board (NPRB)

The Board supports marine research projects through a competitive grant program funded by the interest earned from the Environmental Improvement and Restoration Fund (EIRF) that was part of a large settlement by the U.S. Supreme Court pertaining to a land dispute in the Arctic known as Dinkum Sands. The funds are required to be used to conduct research in the North Pacific Ocean, Bering Sea, and Arctic Ocean to address pressing fishery management issues or marine ecosystem information needs. NPRB has funded large interdisciplinary research projects called Integrated Ecosystem Research Programs (IERPs) in the EBS and the GOA. The GOA IERP is in the final synthesis phase, while a new IERP for the Arctic has just begun. The Board also has an annual call for general proposals that allows scientists to target-specific focused issues.

4.3 Gulf Watch/Exxon Valdez Oil Spill Trustee Council

Gulf Watch Alaska (GWA) is the long-term ecosystem monitoring program of the Exxon Valdez Oil Spill Trustee Council. The 1989 oil spill, the second largest in U.S. history, was a major perturbation to GOA ecosystem with some injured resources still not recovered over 25 years later. GWA is an anticipated 20-year program, initiated in 2012, that includes annual ecosystem sampling in the GOA. GWA has three main research and monitoring components (Fig. 1): 1) environmental drivers (physical and biological oceanography); 2) Pelagic Ecology (prey and upper trophic level species; 3) nearshore ecology (subtidal and intertidal ecosystems). There is also a program management team, a science review panel, a science coordinating committee, and an outreach steering committee. NOAA/AFSC/ABL is the lead for overall program management and science coordination. GWA has five primary objectives: 1) sustain and build upon existing time series in the EVOS-affected regions of the GOA; 2) provide scientific data, data products and outreach to management agencies and a wide variety of users; 3) develop science synthesis products to assist management actions, inform the public and guide monitoring priorities for the next 15 years; 4) continue to build on collaborations between the GWA and Herring Research and Monitoring programs, as well as other Trustee program focus areas including data management and lingering oil; and 5) leverage partnerships with outside agencies and groups to integrate data and expand capacity through collaborative efforts.

A consortium of over 25 researchers from various agencies and organizations comprise 11 field sampling projects within GWA. These projects include many biophysical time series extending decades, with the longest over 40-years (e.g., hydrographic sampling at GAK-1 and in Prince William Sound). All GWA data, including these long-term legacy datasets are publicly available through the Alaska Ocean Observing System data catalogue and DataOne (45 datasets). Three GWA supported time series are included annually in NOAA's ecosystem considerations report to the North Pacific Fishery Management Council and development of additional ecosystem indicators are being investigated.

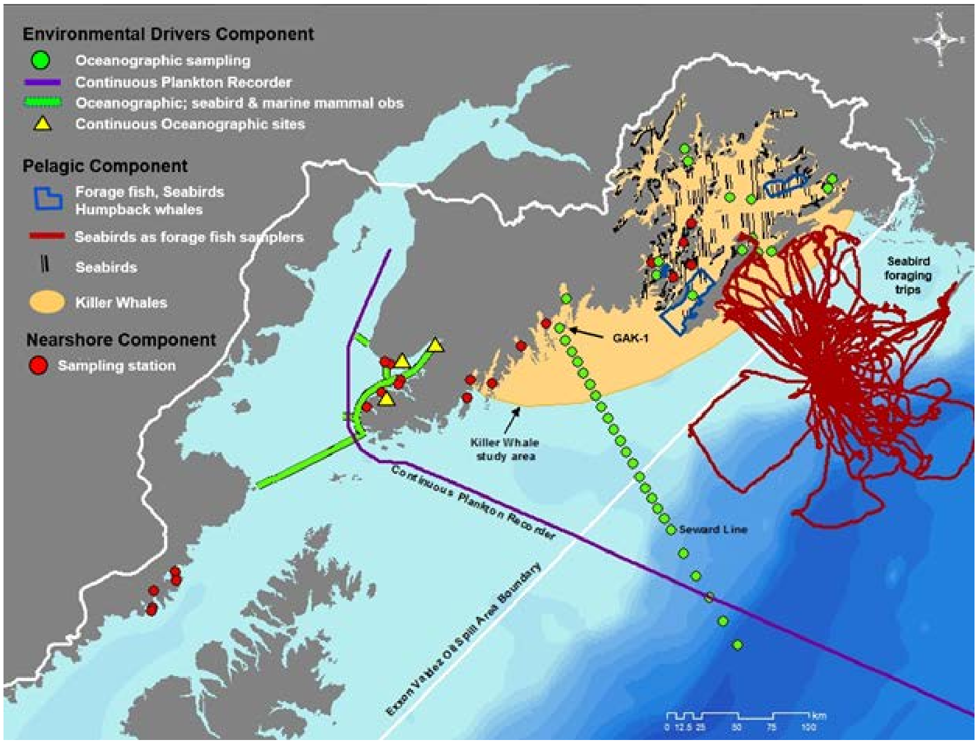


Figure 6.--Gulf Watch Alaska monitoring "footprint" by ecosystem component and project focus. Gulf Watch Alaska is a 20-year research and monitoring program that began in 2012, with annual sampling in the Gulf of Alaska.

4.4 Alaska Department of Fish and Game (ADF&G)

ADF&G manages ecologically and economically important fisheries in the GOA for salmon, crab and nearshore groundfish, such as black rockfish and lingcod. ADF&G participates in the Council's federal management process by conducting stock assessments and providing technical expertise on review committees such as Plan Team and the Scientific and Statistical Committee. ADF&G conducts surveys, such as the GOA large mesh survey, that provide information for stock assessments and ecosystem indicators, and ADF&G assists in the catch recording system in the GOA. ADF&G are also a collaborator in beluga whale, Steller sea lion, and harbor seal studies.

4.5 Fisheries and Oceans Canada

Fisheries and Oceans Canada is a science and management agency responsible for the marine resources of the Pacific coast of Canada. Research to study changing fish distributions on the west coast of North America due to climate change will require a collaborative approach that includes DFO. An example this collaboration is the project to study the spatial response of northeast Pacific groundfish to anomalous warming in 2015, which involves researchers from AFSC, DFO, SWFSC, and NWFSC using survey data collected in each region.

4.6 UAF-CIFAR, UW-JISAO, AND OSU-CIMRS

AFSC collaborates with researchers at the University of Washington, the University of Alaska Fairbanks (UAF), and Oregon State University on research topics of mutual interest. Often this collaboration takes the form of funding for graduate students and postdoctoral researchers. At the University of Washington, the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) fosters research collaboration between the University of Washington (UW) and the National Oceanic and Atmospheric Administration (NOAA), while the University of Alaska Fairbanks, the Cooperative Institute for Alaska Research (CIFAR) performs the same role. At Oregon State University it is the Cooperative Institute for Marine Resource Studies that fills this role. All of the cooperative institutes have a strong focus on climate research targeted at societal needs, with the goal of improving predictions of climate variation affecting coastal regions and ecosystems.

4.7 National Center for Ecological Analysis and Synthesis (NCEAS)

The National Center for Ecological Analysis and Synthesis (NCEAS) is a research center of the University of California, Santa Barbara. NCEAS supports cross-disciplinary research that uses existing data to address major fundamental issues in ecology and allied fields, and encourages the application of science to management and policy. NCEAS recently hosted two working groups concerned with the Gulf of Alaska. The first study, *Applying portfolio effects to the Gulf of Alaska ecosystem: Did multi-scale diversity buffer against the Exxon Valdez oil spill*, used a synthesis approach to study Gulf of Alaska ecosystem responses to various types of environmental forcing. The second study, *Analysis of Past Dynamics to Improve Prediction of Future Response to Natural and Anthropogenic Change*, developed models that examined the interactions among ecosystem components and social structures to better predict how the whole system might respond to different types of forcing in the future. Future NCEAS workshops could address other scientific gaps or overarching research questions related to the GOA that are appropriate for a synthesis approach.

4.8 Northern GOA LTER

The Long-Term Ecological Research (LTER) network was created by the National Science Foundation (NSF) in 1980 to conduct research on ecological issues that can last decades and span huge geographical areas. Recently a group of researchers led by scientists from UAF were awarded a grant to establish an LTER site in the northern GOA. This is an integrated research program that builds upon and enhances the Seward Line time series. It includes a spring-to-fall field cruise and mooring-based observational program. Other components of the program are process studies that focus on mechanisms leading to variability in GOA productivity, and modeling studies to predict ecosystem responses to projected environmental changes. Links to higher trophic levels are not included in the original design, but the lead investigators hope to establish partnerships (e.g,. with the AFSC) to expand the project across the broader ecosystem.

5.0 SYNTHESIS: ACTION PLAN UNDER LEVEL AND INCREASED SUPPORT

The projects described in the table below are abstracted from the discussion in main text, where motivation for the project and additional details are provided. The projects are grouped according to the four broad areas of research in AFSC's comprehensive approach: long-term monitoring, process studies, risk assessment, and modeling of climate impacts. Projects relating to marine mammals and socioeconomic projects are grouped separately. Ongoing projects such as assessment surveys that we identified as requiring "level" funding are those which AFSC would be able to accomplish if support for project continues as it has in the past. Unfortunately, this does not necessarily translate into a level budget since continually increasing personnel costs at AFSC reduces the funding that is available for projects even under a level budget. We used the term "level/increase" for projects that could beneficially be increased in scale (increased sample sizes, additional tags, etc.) without altering the basic design of the project. We have not attempted to estimate the funding that would be required for the projects that were identified under the increased funding scenario, but included projects based their scientific merit and their ability to make progress on the NCSS objectives.

It is important to recognize that at the time of writing of this RAP, Federal funding levels are uncertain. It is more likely than not, that funding to support research operations at the AFSC in FY18 will be less than in FY17. Therefore, activities described under both funding scenarios should be viewed as proposals, and not commitments from AFSC.

5.1 Table of projects crosslinked to National Climate Science Strategy Objectives

NCSS objectives addressed	Action name	Funding scenario	Time frame	Action description	Division/ Partners
Long-term monitoring					
6, 7	Bottom trawl survey	Level	Ongoing	Multi-species bottom trawl surveys are conducted to monitor trends in abundance and distribution of demersal component of the ecosystem, including fish and invertebrates.	RACE
6,7	Summer acoustic survey	Level	Ongoing	Pelagic populations are surveyed using acoustic methods to monitor trends in abundance and distribution.. Mid-water trawls are used for species identification. The primary target of this survey is pollock, but the survey also produces estimates of capelin rockfish, and krill abundance.	RACE

6,7	Winter acoustic survey	Level	Ongoing	Conduct annual acoustic surveys of pre-spawning aggregations of walleye pollock	RACE
6,7	Longline survey	Level	Ongoing	Conduct an annual longline survey of the Gulf of Alaska focusing on sablefish	ABL
6,7	ADF&G large-mesh trawl survey	Level	Ongoing	Conduct an annual bottom trawl survey in the Gulf of Alaska focusing on Tanner and red king crab	ADF&G, RACE
6,7	NOAA oceanographic moorings in the Gulf of Alaska	Level/ Increase	Ongoing	Moorings in the Gulf of Alaska provide continuous monitoring of oceanographic conditions	PMEL, RACE
6,7	Larval survey	Level	Ongoing	Conduct a biennial survey to assess larval fish and ecosystem conditions in the Gulf of Alaska	RACE, ABL
6,7	Young-of-the-year pollock survey	Level	Ongoing	Assess abundance, condition and food habits of age-0 pollock and other key species prior to onset of the first winter, as well as ecosystem conditions	RACE, ABL
6,7	Age-1 pollock survey	Increase		Assess abundance and condition of age-one pollock after the first winter	RACE, ABL
6,7	EVOSTC Monitoring apex predators	Level	Ongoing	Evaluate the impact of humpback whales and other apex predators on forage fish	ABL
6,7	Southeast Coastal Monitoring	Level	Ongoing	Identify processes that influence the growth and survival of salmon in SE Alaska	ABL
6,7	GOA assessment	Level	Ongoing	Identify and measure ecosystem processes for key groundfish	RACE, ABL
6,7	Juvenile sablefish tagging program	Level	Ongoing	Tag and release juvenile sablefish with several tag types. Information from this project will allow evaluation of time-varying growth and relate that variation to environmental factors.	ABL

6,7	Annual ecosystem considerations report for the Gulf of Alaska	Level	Ongoing	Annual report that provides the Council and its advisory groups with information on ecosystem status and trend, and provides context for the Council's ABC and OFL recommendations. Includes an ecosystem status report card with indicators that track the physical and biological characteristics of the ecosystem, with a separate set of indicators for the western and eastern portions of the Gulf of Alaska.	REFM
Process studies					
5	Recruitment processes	Level/ Increase	Ongoing	Conduct multi-faceted research to understand recruitment variability focusing on mechanisms that mediate growth and survival of egg, larval and juvenile stages of walleye pollock, sablefish, other focal groundfish, selected midwater forage fish, and Pacific salmon	RACE, ABL
5,6	Lower trophic level processes	Level	Ongoing	Field and laboratory research to understand climate-related spatial and temporal variation in zooplankton community structure, biomass, energetic content, and suitability as prey	RACE, ABL
5	Spatial response of northeast Pacific groundfish to anomalous warming in 2015	Level	2018-2019	Research project to examine the role of extreme environmental conditions on the spatial distribution patterns of northeast Pacific groundfish throughout their range in an anomalous warm year (2015). Important lessons can be learned from analysis of extreme events in nature. Project utilizes the alignment of summer multiple survey efforts encompassing stations along the US west coast (West Coast Bottom Trawl Survey), the Canadian Coast and the western Gulf of Alaska (GOA Bottom Trawl Survey) to compare groundfish fish responses to warming ocean conditions.	REFM, RACE, DFO, NWFSC
5	Climate- driven changes to species and fisheries distribution	Level	2017-2019	Develop species distribution models using VAST spatio-temporal modeling and satellite SST based on the understanding gained from preceding project of the spatial response of groundfish in the northeast Pacific to the warm episode.	REFM, NWFS, Rutgers
5,6	Ichthyoplankton as indicators of ecosystem change, California to Alaska	Level	2017-2019	This project utilizes multi-decadal ichthyoplankton data sets collected from the Gulf of Alaska and California Current ecosystems to develop cross-LME ichthyoplankton indices and metrics for use in	RACE, NWFSC, Scripps

				forecasting and EBFM. Analyses include evaluating spatial-temporal scales of coherence among fish assemblages along the west coast of North America, examining relationships with environmental drivers, and the assessment of ichthyoplankton assemblages as indicators of changing ocean conditions (e.g. deoxygenation, warming).	
5,6	Life history studies	Level/ Increase	Ongoing	The AFSC conducts age, growth and maturation studies, and maintains an extensive collection of data on size at age that are critical for informing age-structured assessment models. These data can be used to track shifts in species life history with climate change, and allow stock assessments to be responsive to such changes.	RACE, REFM
5,6	Predator-prey relationships	Level/ Increase	Ongoing	An understanding of predator-prey interactions is necessary for determining the importance of top-down and bottom-up impacts of climate change. The AFSC maintains one of the world's largest collections and longest time series of food habits of fish and crabs. This time series allows analysts to develop spatial and non-spatial models of predator prey interactions for use in stock assessments and short-term and long-term projection models.	REFM
5	Process studies of ocean acidification and temperature on selected species in the Gulf of Alaska	Level	2018-2023	This project will involve a series of laboratory experiments to describe the effect of ocean acidification on the growth and development of walleye pollock and northern rock sole. This research will expand the scope of our understanding through the inclusion of more sensitive response metrics (development and energy status), and expand the use of multiple stressor experimental designs (temperature).	RACE
5	Use of archival and satellite tags for defining species niche for sablefish and other species	Level	Ongoing	Data from internally-implanted archival tags and pop-off satellite tags provide insights into the optimal thermal envelopes for sablefish and other species, how these species are distributed and move across spatial and depth gradients both within and among years. Improved understanding of species thermal niches as well as vertical movement behaviors and depth distribution provide key insights about the potential capacity for species to adapt their behavior and distribution, vertically and spatially, to future marine temperature patterns.	ABL

2,3,4,5	Genetic adaptation to temperature for walleye pollock	Level	2018-2019	The project includes rearing experiments under controlled conditions to test whether selective changes are detectable at the molecular level within larval cohorts reared under different temperatures. In addition, a genomic analysis of wild larval cohorts from different years with contrasting environmental conditions using archived larval collections will test whether similar changes are observable in the wild. A management strategy evaluation will be performed to understand how rapid adaptation affects population dynamics, and to evaluate performance of current assessment and harvest policies under climate change.	REFM, RACE, UW
Risk assessment					
5	Vulnerability analysis of GOA stocks	Level	2018-2020	Conduct a vulnerability analysis of groundfish, salmon, and other stocks to climate change.	REFM, PMEL, ABL
5,6	Develop Ecosystem-Socio economic Profile (ESP) process and products for stock assessments	Level/ Increase	Ongoing	Create a framework process for linking ecosystem and socioeconomic considerations to stock assessments that is based on stock-assessment driven research priorities. Generate a standardized set of products that identify important factors affecting the stock and allow for monitoring indicators that provide early warning of change that can ultimately be used in future projections.	ABL, REFM, RACE, UAF, UW, HQ
3,4,5,6	Initial phase of the Gulf of Alaska IEA	Level	2018-2019	Products for the initial phase of the GOA integrated ecosystem assessment will be a conceptual model and the development of a place-based IEA program for Sitka, Alaska.	ABL
Modeling climate impacts and management scenarios					

4	Bristol to Baja ROM/NPZ model	Increase	2018-2020	A high priority should be placed on continued development and support for a high-resolution ocean modeling framework for the Gulf of Alaska. Ideally this model should not be limited to Gulf of Alaska but extend to include the large marine ecosystems (LMEs) of the northeast Pacific (California Current System, CCS; Eastern Bering Sea, EBS; and Gulf of Alaska, GOA). A proposal has been developed to upgrade and adjust the NEP-10K grid to 3 km resolution (NEP-3K) and utilize a seamless Nutrient-Phytoplankton-Zooplankton (NPZ) modeling framework (COBALT) that is implemented in both global Earth System Model (ESM) and ROMS applications to project future ocean conditions in the CCS, GOA and EBS.	REFM, RACE, ABL, PMEL, DFO, NWFSC
4	Climate- driven changes to species and fisheries distribution	Increase		Projection of species distribution models using VAST geospatial modeling and Bristol to Baja ROMS projections.	REFM, NWFSC, SWFSC
4	Using individual-based models to predicting future changes in connectivity for fish stocks	Increase		Use IBMs for Pacific cod and sablefish early-life stages to evaluate changes in connectivity between offshore adult spawning areas and nearshore juvenile nursery habitats along the western coast of North America from Baja to the Bering Sea due to future climate change.	REFM, ABL, UAF
1,2,3,4	Climate-forced aggregate surplus production model for the GOA	Increase		Develop aggregate surplus production models that incorporate economic considerations in the estimation of aggregate MSY. Assessment of climate change impacts is possible by forcing the production model by environmental variation.	REFM
1,2,3,4	Atlantis ecosystem model	Increase		The Atlantis model is a spatially explicit, coupled physical-biological oceanographic model. Atlantis models have been developed for the U.S. West Coast, and this modeling effort is ongoing and well-supported. Importantly, the Atlantis model can be coupled to the ROMS model under development for the Gulf of Alaska, and can therefore be used to simulate an ecosystem properties under projected climate change.	REFM, UW

1,2,3,4	Other ecosystem models	Increase		Develop regional size-spectrum and mass-balance models driven by environmental forcing for the Gulf of Alaska to complement the Atlantis model	REFM, UW
1,2,3,4	CEATTLE multispecies model for the GOA	Level	2018-2020	Apply the CEATTLE multispecies model, currently being using for eastern Bering Sea, to look at interactions between walleye pollock, Pacific cod, arrowtooth flounder and halibut in the Gulf of Alaska. For climate projections, this project will use either environmental variable downscaled from GCMs or output from the ROMS model if available. A strength of the CEATTLE model is the ability evaluate physiological effects of temperature change on growth in addition to environmental forcing on recruitment.	REFM, UW
1,2,3,4	Single-species MSEs for sablefish and several rockfish species	Increase		Develop management strategy evaluations for sablefish and several rockfish species. Link recruitment and other biological processes to environment variables. Project future population trends, distribution and movement patterns, under climate change scenarios, and evaluate performance of alternative management strategies for both target and bycatch species.	ABL, REFM
3,4,5,6	First Year Models: Forecasting recruitment dynamics in the Gulf of Alaska using short-term models of fish early life history	Increase		The overall goal of this collaborative, cross-Divisional research is to develop and operationalize near-term (9 mos) biophysical and trophic models that forecast the physical marine environment and age-1 recruitment potential for selected fish species in Alaskan waters.	RACE, ABL, PMEL
Marine mammal and other ecosystem components					
6,7	Marine mammal distribution and abundance surveys and ecology studies	Level/ Increase	Ongoing	Continue to conduct surveys to monitor the abundance trends, distribution and ecology of marine mammal populations in the Gulf of Alaska. Increased funding is required to conduct cetacean surveys.	MML, ADF&G

6,7	Deploy passive acoustic systems on existing and new oceanographic moorings	Level/ Increase	2018-2023	To study potential effects of climate change on cetacean distribution, moorings that collect acoustic data in addition to other biological and physical oceanographic data are a high priority. Some increased funding is needed to use relatively inexpensive acoustic recorder redeployments piggy-backed on vessels used for other projects, more increased funding is necessary to allow expanded deployments of new moorings with broader spatial coverage.	MML
5	Increase capacity to assess climate change risk for Cook Inlet beluga whales	Level/ Increase		Increased funding is needed to develop and apply abundance estimation methods based on aerial survey data that allow for variation in distribution patterns, and investigate the role of climate; to conduct a sampling design analysis for a passive acoustic monitoring array program that will enable tracking changes in distribution pattern, and to extend an individual-based stock assessment model to a population viability analysis integrated with socio-economic studies and explore how model can address climate change effects.	MML, REFM
5	Tag and track adult female sea lions in the GOA	Increase		To study potential impacts of climate change on Steller sea lion populations, additional funds would add the capacity to capture and track adult female sea lions for health and foraging studies in the Gulf of Alaska to better understand interactions with oceanographic conditions and prey distribution, where little data exists and those data are now over 20 years old.	MML
4,5,6	Harbor seals and glacier ice	Level/ Increase		Prime whelping and pup-rearing habitat is being lost due to grounding of tidewater glacier fronts (already observed in some cases). Additional funds are needed to project tidewater glacial ice production (in collaboration with glaciologists), monitor the Gulf of Alaska stocks for changes in ice habitat, and monitor harbor seal redistribution between ice and terrestrial haul-out habitats.	MML

5,6	Track migration of northern fur seas in the North Pacific Ocean and relate to environmental conditions	Level/ increase	Ongoing	Northern fur seals in the fall migrate into Gulf of Alaska and North Pacific Ocean for about eight months each year. Migration patterns are influenced by oceanographic conditions and weather patterns, which likely affect individual foraging success with consequences for survival and reproductive success. Changes in North Pacific storm intensity and frequency could thus have population-level consequences for northern fur seals. Current research is continuing studies into interactions between winter migration patterns and weather and ocean patterns. Increased funding would expand deployments and provide capacity for directed analysis.	MML
4,5	Develop models for northern fur seal and Steller sea lion distribution, abundance and vital rates relative to environmental conditions	Increase		Studies to build-on, develop and validate marine mammal distribution and abundance models at multiple spatial and longer temporal scales are needed. Additional funding is needed develop these to evaluate demographic consequences, and to integrate with other modeling efforts linking climate-mediated changes in prey abundance with pinniped behavior and ultimately population trends.	MML
6,7	Expanded health monitoring of marine mammals, shellfish etc.	Increase		Increased funding is needed to expand health monitoring for neurotoxins caused by harmful algal bloom and for infectious diseases brought by expanding ranges through arctic and temperate areas.	MML, NWFSC
6,7	National Seabird Program	Level	Ongoing	The two key focus areas for NOAA's National Seabird Program are mitigation of bycatch and promotion of seabirds as ecosystem indicators. Bycatch may depend on environmental factors that are affected by climate change. Seabirds, which are relatively easy to observe, may provide early indicators of extreme environmental events	REFM
Socioeconomic surveys and modeling					
6,7	Maintain community vulnerability tracking indices	Level	Ongoing	Update vulnerability and exposure indices for community vulnerability analysis	REFM

4,5	Extend climate vulnerability analysis	Increase		Link community vulnerability analysis to single species and multispecies projection models that are forced by environmental variables under different climate scenarios	REFM
6,7	Maintain community snapshots	Level	Ongoing	Continue to collect and report the information in the community snapshots	REFM
6,7	Update community profiles and community surveys	Increase		Collect information needed to update communities profiles, and conduct surveys to obtain supplementary socioeconomic information on community characteristics.	REFM
1,2,3,4	Computable general equilibrium (CGE) regional economic model for southwest Alaska	Level	2018-2023	Develop a computable general equilibrium models for six borough and census areas in southwest Alaska to evaluate impacts of climate change at the local scale.	REFM
1,2,3,4	Extend the CGE model to additional communities	Increase		Add additional borough and census areas to the CGE model. Compare communities in SW Alaska with those in SE Alaska.	REFM
1,2,3,4	Northern rock sole bioeconomic model	Level	2018-2020	Develop a bioeconomic model of northern rock sole in the Gulf of Alaska to evaluate the effect of ocean acidification and increased temperature of the population dynamics and fishery yield.	REFM, RACE
1,2,3,4	Extend OA and bioenergetics bioeconomic model to other species	Level/ Increase		Apply the methods used for the bioeconomic model for northern rock sole to evaluate the effect of ocean acidification and increased temperature of other species in the Gulf of Alaska. A priority would be a GOA rockfish species.	REFM

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7.0 APPENDIX. AFSC long-term monitoring activities in the Gulf of Alaska

Research Activity Name	Survey Description	Area of Operation	Season, Frequency, Yearly Days at Sea (DAS)	Vessel Used	Gear Used, Number of Samples
Gulf of Alaska Biennial Shelf and Slope Bottom Trawl Groundfish Survey	Multi-species bottom trawl surveys are conducted to monitor trends in abundance and distribution of groundfish populations.	Gulf of Alaska - continental shelf and upper continental slope (out to 1000 m depth) from Islands of Four Mountains to Dixon Entrance	Summer, biennially, 225 DAS; daytime samples only	Three large chartered fishing vessels working collaboratively, 75 DAS each	Bottom trawl with net sounders 820 survey stations, 884 attempted stations, underway plankton pump, temperature depth recorders, underway temperature
Pollock Summer Acoustic Trawl Survey - Gulf of Alaska	Estimate the mid-water abundance and distribution of walleye pollock in the GOA shelf.	Gulf of Alaska shelf/slope from approximately 50 m bottom depth out to 1000 m bottom depth between the Islands of Four Mountains and Yakutat Trough.	Summer, biennially, 60 DAS; daytime trawl sampling only but other listed work occurs at night.	NOAA ship R/V *Oscar Dyson*	Bottom trawl with net sounders 20 trawls Mid-water Trawl with net sounders 100 trawls Small Mid-water Trawl 10 tows Echosounder with five split-beam transducers Continuous CTD 120 casts

Pollock Winter Acoustic Trawl Survey - Shelikof Strait and Shumagin/Sanak Islands	Collect acoustic and trawl data to estimate mid-water abundance and distribution of walleye pollock.	Shelikof Strait, Chirikof Island shelf break, Marmot Bay, Shumagin Islands, Sanak, Prince William Sound, Kenai Bays.	Winter, spring, annually, 7-31 DAS; samples day and night	NOAA ship R/V *Oscar Dyson*	Bottom trawl with net sounders 10 trawls Mid-water Trawl with net sounders 30 trawls Echosounder with five split-beam transducers Continuous CTD 30 casts
Alaska Longline Survey	Monitor and assess the status of sablefish and other groundfish resources in Alaska.	Gulf of Alaska, Aleutian Islands, Bering Sea Slope	Summer, fall, alternates annually between GOA and BSAI, 30-90 DAS; daytime sampling only	Large chartered fishing vessel	Longline 75 stations
ADF&G Large-mesh Trawl Survey of Gulf of Alaska and Eastern Aleutian Islands	Estimate the abundance and condition of Tanner crab and red king crab populations.	Gulf of Alaska - Aleutian Islands	Summer, annually, 30-90 DAS; daytime samples only	ADF&G R/V *Resolution*	Bottom trawl with net sounders ~ 380 trawls
EcoFOCI/EMA Larval Walleye Pollock Assessment Survey and Ecosystem Observations in the Gulf of Alaska	Assesses the abundance, distribution, size structure, and survival of larvae of key economic and ecological species	Gulf of Alaska	Spring, biennially, 7-31 DAS; samples day and night	Large chartered fishing vessel	Bongo Net 150 tows (20 cm bongo net) 150 tows (60 cm bongo net) Multiple-Opening and Closing Net 30 tows Neuston Net 150 tows CTD 150 casts

Recruitment Processes Alliance Young-of-the-Year Walleye Pollock Assessment Survey and Ecosystem Observations in the Gulf of Alaska	Assess the abundance and condition of age-0 walleye pollock prior to the onset of the first winter.	Gulf of Alaska	Fall, biennially, 7-31 DAS; samples day and night	Large chartered fishing vessel or NOAA ship R/V *Oscar Dyson*	Mid-water trawl 50-75 trawls Beam Trawl 50-75 trawls Bongo Net 200 tows with each bongo net CTD 200 casts
Recruitment Processes Alliance Age-1 Walleye Pollock Assessment Survey and Ecosystem Observations in the Gulf of Alaska (Proposed)	Assess the distribution and condition of age-1 walleye pollock immediately after the first winter.	Gulf of Alaska	Winter, biennially, 7-31 DAS; samples day and night	Large chartered fishing vessel	Bottom trawl with net sounders 50 trawls Bongo Net 250 tows with each bongo net CTD 250 casts
EVOSTC Long-term Monitoring - Apex Predators	Evaluate the impact by humpback whales and other apex predators on forage fish populations	Gulf of Alaska and Southeast Alaska	All seasons, monthly, 7-31 DAS; samples day and night	Large chartered fishing vessel, motorized skiff	Mid-water Trawl 10 trawls Surface Trawl 10 trawls Bongo Net 50 tows Tucker Trawl 50 tows Gillnet with pingers 10 sets Cast Net 100 casts Dip Net 50 samples

Southeast Alaska Coastal Monitoring (SECM)	Identify processes or factors that influence growth and survival of salmon in different marine habitats along seaward migration corridors and in the Gulf of Alaska.	Gulf of Alaska, Inland Southeastern Alaska (Icy Strait, Clarence Strait)	Summer, monthly, 1-7 DAS; daytime sampling only	Large chartered fishing vessel	Surface Trawl 96 trawls per year Bongo Net 64 samples per year
Recruitment Processes Alliance GOA	Identify and quantify major ecosystem processes for key groundfish species in Gulf of Alaska (GOA).	Gulf of Alaska, Along the shelf, slope, and basin waters of the southeast GOA from Baranof Island to Cape Yakataga.	July, annually, 25 DAS; samples day	Large chartered fishing vessel	Surface trawl 225 trawls Bongo Net 225 tows CTD with rosette water sampler 225 casts

Juvenile Sablefish Tagging	Tag and release juvenile sablefish with 1,000 numerical spaghetti tags and 80 surgically implanted electronic archival tags.	Gulf of Alaska, Inland Southeastern Alaska - St. John the Baptist Bay, Salisbury Sound	Summer, annually, 14 DAS; daytime sampling only	Chartered vessel	Hook-and-Line/ Depth sounder/ Tags 240 rod-hrs/yr over 5 days.