DRAFT Gulf of Alaska Regional Action Plan to Implement the NOAA Fisheries Climate Science Strategy in 2022-2024

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About this document
This is a draft plan for public review and comment. Comments submitted will be considered when drafting the final document. Implementation of the plan is contingent on available resources.

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EXECUTIVE SUMMARY

Changing climate and oceans are affecting the nation's valuable living marine resources and the many people, businesses and communities that depend on them. Warming oceans, loss of sea ice, rising seas, extreme events, and acidification are impacting the distribution and abundance of species and the structure of marine and coastal ecosystems in many regions. These impacts are expected to increase and there is much at risk.

To prepare for and respond to climate impacts on marine and coastal resources, the 2015 NOAA Fisheries Climate Science Strategy (NCSS) identified seven key objectives to increase the production, delivery, and use of climate-related information needed to fulfill the agency's mandates (e.g., fisheries management, protected resources conservation) in a changing climate. Beginning in 2016, NOAA Fisheries developed Regional Action Plans (RAPs) to implement the NCSS in each region based on regional needs and capabilities. This draft Gulf of Alaska Regional Action Plan (GOARAP) builds on previous efforts and describes proposed actions to implement the NCSS in this region in 2022-2024.

As with many other parts of the world, relatively large changes in climate and ocean conditions are expected in the U.S. Gulf of Alaska (GOA) in the coming decades. While physical and chemical changes are clear and quantifiable, ecosystem responses are more uncertain because there are multiple interacting factors. Directed research is needed to assess climate-driven changes to critical ecosystem components, evaluate potential effects on marine species, and determine which populations, fisheries, and communities are most at risk. AFSC provides scientific data and analysis and technical advice to the North Pacific Fisheries Management Council, the NOAA Fisheries regional office, the state of Alaska, Alaskan coastal communities, as well as the fishing industry and its constituents to support appropriate responses to ecological- and human-driven changes in the ecosystem. To continue to fulfill this mission in the face of climate change, the Alaska Fisheries Science Center (AFSC) seeks to conduct research and develop science-based strategies for sustaining fisheries, healthy ecosystems, protected species, and coastal communities in a changing climate. This research will inform policies to reduce climate impacts and help identify novel opportunities for marine-dependent human communities in the GOA.

This draft GOARAP highlights on-going and planned research by the AFSC and partners to continue to implement the NCSS and other priorities in 2022-24. This effort complements a variety of AFSC efforts including Ecosystem Status Reports (ESRs) that have been produced annually for over 20 years, and the Ecosystem Socio-Economic Profiles (ESPs) and risk tables now being produced to provide context for fish stock assessment development. These products support the work of the North Pacific Fishery Management Council's Bering Sea Fishery Ecosystem Plan, the Council's Climate and LKTK Task Forces, and other activities.

To position AFSC to take advantage of new funding opportunities, this document describes both existing efforts and a number of new initiatives and projects that would require additional resources, such as a new cross-NOAA Climate, Ecosytem and Fisheries Initiative. These new efforts could be started quickly, and would build on the portfolio of climate-related research currently underway at AFSC.

This draft 2022-2024 GOARAP is structured similarly to the previous GOARAP. There are sections that correspond to each of three broad areas of research considered essential to AFSC's comprehensive climate science strategy. These include 1) monitoring, 2) process research, and 3) modeling and management synthesis. It also includes two additional subject-matter sections focused on 4) marine mammal research and 5) socio-economic impacts on fishing communities. A final section was added regarding the 6) communication and engagement strategy to support the co-production of science with Gulf of Alaska communities.

There is a growing list of entities that are doing research on climate change-related issues in the Gulf of Alaska, including local, regional, tribal, federal, state, and university bodies. To improve information sharing and ensure that efforts are building upon each other and moving forward, AFSC intends to foster the development of collaborative networks across these entities. Such collaborations will also be important for limiting the burden on stakeholders of providing input into research processes, and finding information relevant to climate change outcomes and local risks.

Highlights of the RAP for 2022-2024. AFSC and its partners intend to conduct activities that will help make progress in the six key areas of research. Each of these areas include actions that address one or more of the seven objectives of the NCSS as listed below.

Long-Term Monitoring and Assessments (NCSS Objective 6):

- **Maintaining a full suite of surveys in the GOA.** Maintain or, if feasible, increase the current frequency and scope of ecosystem monitoring.
- **Expanding the scope of monitoring.** Leverage external collaborators to expand the scope of surveys, e.g. tracking harmful algae blooms and food web impacts.
- **Rapid assessment methodologies.** Develop new methodologies for assessment of key metrics for use in fishery management.
- **Additional survey-derived indicators.** Add key survey-derived indicators to ESRs, ESPs, and risk tables.

Process-oriented research projects (NCSS Objective 5):

- **Thermal effects on age-0 Pacific cod.** Conduct directed field and laboratory work, and analysis of archived samples, to understand recruitment in a warmer GOA.
- **Experimental studies on temperature and ocean acidification.** Study the influence of temperature and ocean acidification on commercially and ecologically important fishery resources of Alaska.
- **Changes in zooplankton size due to warming.** Examine the relationship between zooplankton size and climate variability in the western Gulf of Alaska.

Modeling and management-oriented synthesis (NCSS Objectives 6, 5, 4, 3, 2):

- **Climate vulnerability analysis for the Gulf of Alaska.** Assess species vulnerabilities to climate change and provide guidance on research prioritization.
- **Ecosystem and socio-economic Profiles (ESPs).** Develop a framework that

facilitates the integration of ecosystem and socio-economic information within the stock assessment process.
- **GOA-CLIM.** Integrate earth system models and biological models, including single species, multi-species, and ecosystem models.

Marine Mammals (NCSS Objectives 6, 5, 4):

- **Harbor seal abundance estimates.** Update estimates of abundance for harbor seal stocks and evaluation of trends.
- **Heatwave impacts on Steller sea lions.** Evaluate impacts of major environmental anomalies to Steller sea lion populations.
- **Impact of environmental variation on Cook Inlet beluga whales.** Evaluate impacts of major environmental anomalies to Cook Inlet beluga whales.

Socio-economic impacts on fishing communities (NCSS Objectives 5, 4, 3, 2) :

- **Coupled fleet-community-adaptation model.** Examine how climate change impacts may reverberate across Gulf of Alaska communities.
- **Bio-economic model of Pacific cod in the Gulf of Alaska.** Develop a bio-economic model of Pacific cod in the Gulf of Alaska to evaluate the effect of ocean acidification on abundance, yields, and fishery income.
- **Decision support tools for ocean acidification.** Develop decision support tools that incorporate the risks of ocean acidification into localized, coupled, socio-ecological systems to support coastal communities.

Communications and engagement strategy (NCSS Objectives 3, 2)

- **Communications and engagement strategy to support co-producing science with Gulf of Alaska communities.** Facilitate bi-directional knowledge exchange to increase trust and inform NOAA Fisheries' mission.

Key gaps. This draft RAP also includes a number of priority projects that would be considered if additional funding were available. These projects are important for addressing key gaps in implementation of the NCSS objectives in the region. Some of the key gaps are:

- Improve the efficiency of the AFSC survey enterprise.
- Increase survey focus on forage fishes.
- Increase spatial coverage of new autonomous sampling platforms and moorings.
- Study climate effects on Euphausiid dynamics.
- Investigate climate-driven changes in maturation and reproductive potential.
- Incorporate recruitment processes into life-cycle models for walleye pollock and Pacific cod.
- Develop dynamic species distribution models for identifying changes to Essential Fish Habitat.
- Support annual harbor seal survey in Gulf of Alaska glacial fjord habitats.
- Complete cetacean abundance, distribution, and density surveys in the GOA.
- Expand socio-economic research on adaptive strategies.

- Study resilience and transformative capacity of fishing communities.
- Collect social data on fishing communities.
- Improve community decision support tools.

Emerging Research Opportunities. This draft GOARAP is designed to also include activities to (1) begin developing the integrated ocean modeling and decision support system called for in the **NOAA Climate, Ecosystem and Fisheries Initiative** (CEFI) and (2) expand existing monitoring of changing fish stock and ecosystem conditions to provide advice for climate-informed management decisions. The NOAA Fisheries FY22 budget includes funding requests for these efforts, and implementation is dependent on available funds.

1. INTRODUCTION

In 2015, NOAA fisheries developed a Climate Science Strategy (NCSS, 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. A requirement of the NOAA Fisheries Climate Science Strategy is for each region to develop a Regional Action Plan. The Alaska Fisheries Science Center (AFSC) has taken the approach to develop separate regional action plans for each Large Marine Ecosystem under its purview. Regional Action Plans have been completed for Eastern Bering Sea (Sigler et al. 2016) and the Gulf of Alaska (Dorn et al. 2018), and a regional action plan is under development for the Arctic.

Regional Action Plans are intended to identify actions needed to make progress in implementing seven objectives identified in the Climate Science Strategy in each region. 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). The RAPs are designed to increase awareness and support for these efforts, both internally and externally with stakeholders and partners.

The initial regional action plan for the Gulf of Alaska was intended as a five-year research plan. Although the end of this five-year period for the Gulf of Alaska has not yet been reached, a process was initiated at the national level to synthesize the accomplishments from the different regions, and to update the RAPs in each region to continue to implement the NCSS to meet the increased demand for scientific information on the impacts of climate change on marine ecosystems. The purpose of this document is to identify and describe planned and proposed climate-science research activities at AFSC during the years 2022-2024. To position AFSC to take advantage of new funding opportunities, this document also describes a number of new initiatives and projects that would require additional resources, but which could be started quickly, and would build on the portfolio of climate-related research currently underway at AFSC.

There has been good progress to date on the activities laid out under the initial GOA RAP, as outlined in the NCSS five year progress report (Peterson et al. 2021). Perhaps the most notable achievement was that AFSC and the University of Washington received awards from the North Pacific Research Board (NPRB) and NOAA's Coastal and Ocean Climate Applications (COCA) program to move forward with a robust modeling effort in the GOA to address NCSS objectives 1-3. This project is modeled on the ACLIM project in the EBS and will involve a multi-model approach including the development of regional ECOPATH models, multispecies models, and an Atlantis ecosystem model for the GOA. The project includes a fleet dynamics component, a marine mammal project looking at heatwave impacts on Steller sea lions, a sociological study of adaptive capacity in fishing communities in the GOA, and coupled regional economic models for southwest Alaska. This research will be conducted over three years, and is an important element in this updated RAP.

Other climate-science accomplishments in the Gulf of Alaska region since development of the Climate Science Strategy include:

- Preparation of annual ecosystem status reports for the North Pacific Fisheries Management Council and its advisory bodies.
- Implementation of Spring PEEC workshops to report on early warnings of ecosystem and economic conditions in the Gulf of Alaska.
- Development of Ecosystem and socio-economic Profiles (ESP), and application to Gulf of Alaska pollock, Pacific cod, and sablefish to inform management decisions.
- Completion of research projects to understand the impact of marine heatwaves on northeast Pacific groundfish, and Pacific cod in particular.
- Development of the initial phase of a place-based Integrated Ecosystem Assessment for Sitka, AK, including conceptual models and ecosystem indicators.
- Conducting a full set of ecosystem surveys to monitor trends of different ecosystem components, though many planned surveys during 2020 were cancelled or curtailed due to the COVID-19 pandemic.
- Expansion of oceanographic sampling capacities to track climate change, both with additional moorings deployed and additional oceanographic sensors.

This update is structured similarly to the previous RAP. There are sections that correspond to each of three broad areas of research considered essential to AFSC's comprehensive climate science strategy. These include 1) monitoring, 2) process research, 3) modeling and management synthesis. While these lines of inquiry are presented independently, they are also highly complementary and research activities should be directly integrated to the extent possible. Additional subject-matter sections deal with marine mammal research, most of which is focused on monitoring and process research needed for management purposes, and socio-economic impacts on fishing communities. A final section was added on the AFSC's communication and engagement strategy to support the co-production of science with Gulf of Alaska communities.

The working group that drafted this update to the RAP was organized in a way similar to the document, with an overall lead (Martin Dorn), and sub-leads for monitoring (Rob Suryan), process research (Lauren Rogers), modeling and management (Olav Ormseth), marine mammals (Brian Fadely), and socio-economics (Marysia Szymkowiak). This structure was adopted to ensure balanced representation from the diverse research programs at AFSC, and also to ensure that monitoring and process research be given increased emphasis to provide the necessary support for modeling and management-oriented synthesis.

1.1 Gulf of Alaska Large Marine Ecosystem

The Gulf of Alaska is an arm of the 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. From end to end the Gulf of Alaska extends 1500 miles, which is approximately the same length as the entire Atlantic seaboard. The landscape and continental shelf of the Gulf of Alaska has been heavily modified by Pleistocene glaciation, and glaciers remain an important part of the Gulf of Alaska landscape, unlike other regions of the U.S. There are extensive icefields in the mountain ranges bounding the Gulf of Alaska, and numerous large glaciers, many of which descend to tidewater. The largest glaciers of continental North America are located in the St. Elias Mountains.

The oceanography of the Gulf of Alaska shelf is dominated by the Alaska Coastal current (ACC), which is forced by coastal freshwater discharge and alongshore winds (Stabeno et al. 2004, Weingartner et al. 2005). Strong cyclonic winds dominate from fall through spring, and substantial runoff occurs from late spring through fall with annual distributed freshwater discharge greater than that of the Mississippi River. The ACC extends from Icy Bay to Unimak Pass, a distance of over 1500 km. Over this distance, the ACC is a nearly continuous feature with a marked freshwater core. Advection in the ACC is a critical process affecting larval survival for a number of commercially-important fishes (Doyle et al. 2009, Doyle and Mier 2016). The GOA is also a downwelling-favorable system, and eddies and topographic disturbances in the ACC are important sources of deep-water nutrients, while freshwater discharge is an important source of terrigenous nutrients (Stabeno et al. 2004). Freshwater discharge, coastal salinity, and the seasonal relaxation of wind mixing are all critical processes affecting the timing of the spring bloom (Henson 2007), which exerts bottom-up control on fisheries production and may be a critical mechanism linking larval survival of commercial fishes to climate change (Laurel et al. 2021). While strong seasonal cycles and interannual variability are dominant scales in atmospheric forcing and the oceanic response, there is also forcing on ENSO and decadal time scales.

The communities of the Gulf of Alaska are often reliant on commercial use of living marine resources to support their economies. 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 important fishing port, is located on Kodiak Island, in the midst of highly productive fishing areas, but remote from other population centers. 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. Marine resources are of particular importance to Alaska Natives living in the Gulf of Alaska region, both for subsistence use, and as a vital element in their cultural heritage. The lack of readily available alternatives to commercial fishing makes these remote communities extremely vulnerable to changes in the availability of marine resources.

1.2 Projected climate change in the Gulf of Alaska

Climate models predict significant changes in the climate of the Gulf of Alaska. Two of the most important changes, the warming of the upper ocean and a shift toward a more acidic ocean, are already happening 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). Changes in oxygen conditions and temperature-dependent critical oxygen levels are also projected. Other processes 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, and changes in sea level height. The mean sea surface temperature is expected to gradually increase until it exceeds 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). Earth system model projections indicate that by 2050 most of the North Pacific will have warmed by 1.2-1.8° C, and by 2.5-3.6° C by the end of the century (www.esrl.noaa.gov/psd/ipcc/ocn/timeseries.html)

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. One way that this 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 Gulf of Alaska coastal waters. Projections of aragonite saturation indicate that the entire water column in parts of the Gulf of Alaska will become undersaturated by the end of this century.

A critical insight for understanding climate change in the GOA is that individual oceanographic processes are strongly responsive to basin-scale modes of atmosphere and ocean variability. The core of the West Wind Drift is likely to shift northward, and with it there will be a northward shift in the bifurcation of the West Wind Drift into the California Current and the Alaska Current. In particular, the GOA is in quadrature to the Aleutian Low, an area of average low surface pressure anomalies that is an important driver of North Pacific climate variability at temporal scales that are critical to fisheries management (i.e., years to decades). In addition to driving large-scale heat fluxes that contribute to coastal temperature anomalies in the GOA (Newman et al. 2016), the Aleutian Low also drives cyclonic winds that affect freshwater discharge, wind mixing, advection, and downwelling, and so drives coherent variability across a suite of physical drivers that are critical for process research (Stabeno et al. 2004, Weingartner et al. 2005, Litzow et al. 2018).

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. Coastal systems may also experience oxygen declines due to increased nutrient loading due to changes in land use and increased precipitation (Breitburg et al., 2018). 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.

Since northerly areas are warming the most, the temperature gradient between north and south latitudes will decrease, leading to less energetic atmospheric circulation, and a reduction in winter storm intensity (Beamish 2008). Projections of warmer and wetter conditions (McAfee et al., 2014) are expected to drive changes in the timing and magnitude of river discharge and system shifts towards winter rainfall dominance from snowmelt dominance (Beamer et al., 2017). Additional precipitation and glacier ice melting would add additional freshwater to coastal areas. Increased freshwater input would add to baroclinic structure on the continental shelf, but overall the decrease in wind stress would weaken the confinement of relatively fresh, buoyant water along the coast, thereby reducing the baroclinic gradient and weakening the Alaska Coast Current. A reduction 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, resulting in an earlier spring bloom. Greater understanding of how the interactions between freshwater discharge and the seasonal wind relaxation impacts advection in the ACC, eddy formation, coastal mixing, and the distribution of terrigenous nutrients will be important for climate-change research in this region.

Potential sea level changes present a challenging forecasting problem for the Gulf of Alaska, but may be important due to some species' reliance on shoreline habitat, as well as potential impacts on infrastructure and other built environments in coastal fishing communities. Marine mammals have specific habitat requirements for haulouts and rookeries. Herring and capelin spawn in nearshore habitats. The Gulf of Alaska may have more miles of shoreline than in 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 Gulf of Alaska the rapidly melting glaciers are causing rapid land uplift that is far outpacing sea level rise. Also, because the region is seismically active, earthquakes can produce sudden 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.

2. CURRENT AND PROPOSED ACTIVITIES THAT FURTHER CLIMATE RESEARCH IN THE GOA

2.1. A comprehensive strategy for climate research in the GOA

The responses of ecosystems to climate change are complex and occur over multiple temporal and spatial scales. To understand these responses and anticipate future change, climate-oriented research needs to occur along multiple lines of inquiry. Three broad areas of research are considered essential to AFSC's comprehensive climate science strategy. While they are presented independently, they are also highly complementary and research activities should be directly integrated to the extent possible. Marine mammal and socio-economic research is treated separately in this document in the recognition that these disciplines use different methodologies, but the same three areas of research are just as applicable.

1. *Long-term monitoring*: Ecological response to environmental change can be rapid, as observed during the recent northeast Pacific marine heatwave, or take decades to manifest, as with genetic and population-scale shifts. At the same time, 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, fishery surveys are reasonably comprehensive for portions of the Gulf of Alaska, but are lacking in eastern and coastal areas and during winter periods, and are limited in what observations they can routinely make. Steller sea lion and harbor seal surveys are a core component of AFSC's long-term monitoring of marine mammals. But, the scope of the monitoring is limited to stock abundance and trends with just a few studies of seasonal fluctuations. Long-term monitoring of cetaceans is sorely lacking with only opportunistic studies or survey efforts limited to specific species or certain regions. In all cases, the scope and the frequency of these surveys is increasingly at issue in an era of level or decreasing budgets.
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 robust research programs in recruitment processes, ocean acidification, life history characteristics, and predator-prey relationships, and is moving forward on other process studies to understand environmental forcing on focal species in the Gulf of Alaska. Process studies involving marine mammals (e.g. movement, habitat use, dive behavior) in the Gulf of Alaska are limited and are not funded with enough frequency to truly evaluate responses to short-term climatic perturbations.
3. *Modeling and management-oriented synthesis*: Annual reports, such as ecosystem status reports and ecosystem and socio-economic profiles, provide ongoing tracking of indicators of environmental and ecosystem conditions. These reports also provide synthesis of this information to inform the managers whether additional precaution is warranted in the harvest specification process. Risk assessments, which can range from qualitative assessments based on expert opinion to more quantitative approaches, are used to identify which populations, fisheries, or communities are most vulnerable to climate change. Evaluation of the risks of climate change requires consideration of 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 assessment can motivate additional research to model climate impacts and evaluate management scenarios. Forecasts and projections of the impacts of climate change on production of marine fish involves several steps: identifying and modeling potential links between the environmental variables and biological processes such as reproductive success, growth, and distribution, downscaling from GCMs (or GCM/ROMS) to obtain projected future values of the environmental variables under alternative climate scenarios, using those environmental variables to drive the population dynamics in a simulation with alternative harvest policies.

4. *Marine mammals*: As sentinel species of ecosystem change in the marine environment, long-term and regular monitoring of the abundance and distribution of marine mammal populations are fundamental to understanding consequences of environmental change. While some populations have been consistently monitored, others have little or no data upon which to evaluate potential effects of climatic changes in the Gulf of Alaska. Additional integrated studies of abundance, distribution, vital rates, prey distribution, foraging behavior, and health status must be expanded or added to understand effects of environmentally-driven changes to their prey base and potentially-intertwined direct anthropogenic factors. Ultimately, predictive models should be developed to explore causative mechanisms underlying population changes as a response to environmental variability.
5. *Socio-economic impacts on fishing communities*: The primary elements of socio-economic research to understand fisher responses to changing systems and community resilience in the face of climate change include (1) ongoing monitoring to establish conditions for a socio-economic baseline, (2) the development of economic models that account for the dynamic nature of fisher responsiveness to future climate change, as well as linkages between fishing sectors and the Alaska economy, and (3) socioecological system modeling efforts in collaboration with other modelers developing biological system models. AFSC also intends to advance a two-way dialogue to strengthen working relationships and build partnerships in coastal and Alaska Native communities.

2.2 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; these surveys are focused almost exclusively on commercially important fish and their prey. Although this information is 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, lower trophic level processes, the relationship between species distribution and environmental factors, and many other topics.

The ability of AFSC to execute the full set of surveys in the Gulf of Alaska is increasingly jeopardized by 1) inadequate funding to carry out all surveys in their intended scope, 2) insufficient personnel to conduct surveys, and 3) increasing personnel costs during a period of level funding. Finding opportunities to maintain or, if feasible, increase the current frequency and scope of ecosystem monitoring is of critical importance, as an increased rate of change requires increased sampling frequency to detect and respond. Discussions are underway at AFSC to reduce the frequency and scope of acoustic surveys in the Gulf of Alaska due to insufficient staffing and rebalancing of priorities. Primary surveys conducted by AFSC and collaborators in the Gulf of Alaska are briefly described below.

- **Biennial Shelf and Slope Bottom Trawl Groundfish Survey.** Multi-species 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.** 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 an ecosystem focus and produces estimates of Pacific ocean perch, capelin, 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 aggregations of walleye pollock.
- **Alaska Longline Survey.** Monitor and assess the status of sablefish and other groundfish resources in Alaska.
- **ADFG 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.
- **Spring Larval Survey.** Assess the abundance, distribution, size structure, and survival of larvae of key economic and ecological species, with a focus on pollock. Ecosystem data, including zooplankton, are collected.
- **Young-of-the-Year Pollock and Forage Fish Survey.** Assess the abundance, distribution, condition, food habits, and prey availability of age-0 walleye pollock, capelin, and other forage fishes prior to the onset of the first winter.
- **Age-0 nearshore seine/camera survey.** Assess abundance, condition, age and size of age-0 Pacific cod and other key species in nearshore nursery areas during the summer.
- **Gulf Watch Alaska – Environmental Drivers.** Physical and biological oceanographic sampling from vessels and moorings along the Seward Line, in Prince William Sound, Lower Cook Inlet, and continuous plankton recorder on ships transiting the Gulf of Alaska.
- **Gulf Watch Alaska – Nearshore Ecosystems.** Monitoring of algae and invertebrate populations in rocky and soft bottom intertidal habitats and select predators in four focal study areas from Prince William Sound to the Alaska Peninsula
- **Gulf Watch Alaska – Pelagic Ecosystems.** Integrated predator-prey studies of forage fish and krill populations and their predators - seabirds and cetaceans - in Prince William Sound and the northeastern Gulf of Alaska.
- **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.

- **Juvenile Sablefish Tagging.** Tag and release juvenile sablefish with 1,000 numerical spaghetti tags and 80 surgically implanted electronic archival tags.
- **Nearshore Juvenile Groundfish Assessment.** Assess the abundance, size, mortality, growth, diet and condition of age-0 and age-1 gadids and flatfish in nearshore nurseries during summer
- **Harbor Seal Aerial Surveys and Stock Assessment.** Assess the abundance and trends of harbor seals across six stocks in the Gulf of Alaska from aerial surveys conducted every 3-5 years during the August and September molting period. Limited funding and availability of NOAA aircraft precludes annual surveys.
- **Steller Sea Lion Aerial Surveys and Stock Assessment.** Assess the abundance trends of Steller sea lions in the Gulf of Alaska from aerial surveys conducted every other year. Surveys are conducted in July and correspond with the peak timing of pupping.
- **Cook Inlet Beluga Whale Aerial Surveys and Stock Assessment**. Assess the abundance and trends of beluga whales from aerial surveys conducted every other year (originally conducted annually until 2012). Surveys are conducted in June and correspond with whales aggregating at river mouths to forage on anadromous fish runs.

Monitoring activities by the AFSC are complemented by oceanographic monitoring from PMEL. Currently the EcoFOCI group maintains three long-term moorings in the Gulf of Alaska at Unimak Pass (since 1995), Kodiak Harbor (since 1999), and in Cross Sound (since 2005). While these are the longest records with instruments deployed most years, none of these time series is continuous. It is a priority to continue these deployments as well as a more recent mooring off the Shumagin Islands to generate another long-term record. For over 20 years mooring observations from these long-term sites, additional mooring deployments, drifter releases, and CTD transects across Line 8 (since 1980) in partnership with AFSC have provided metrics to understand seasonal and annual climate variability. AFSC collaborators also maintain moorings in regions that compliment those of EcoFOCI: the GAK1 mooring and monthly CTD casts (University of Alaska, Fairbanks - UAF, since 1970) at the start of the Seward Line off Resurrection Bay has a 50-year continuous time series, the Gulf of Alaska Ecosystem Observatory (UAF, since 2019) located mid-shelf along the Seward Line is the newest with advanced instrumentation similar to GEO moorings in the Bering Sea and Arctic, Prince William Sound CTD casts and moorings (Prince William Sound Science Center, since 1974), and the Kachemak Bay mooring (NOAA National Estuarine Research Reserve, since 2001). These data provide an oceanographic context for the ecosystem surveys and are used for validation of climate models.

New technology for fisheries and oceanographic research - BOX

NOAA is a leader in the development and deployment of advanced technologies that provide effective and efficient collection of physical, chemical, biological, and vessel movement data. AFSC is developing and testing new technologies to extend and augment existing survey capabilities for monitoring marine ecosystems (Figure 1). Moorings with extended observational capacity are being used to provide information on the seasonality of ecological processes. For example, an array of upward facing acoustic moorings was used to assess seasonal fish movement onto spawning grounds in Shelikof Strait (De Robertis et al. 2017). Oceanographic moorings are being equipped with additional sensors and sampling devices, such as nitrate sensors, eDNA samplers and sediment traps, as well as passive acoustic sensors to assess seasonal occurrences of marine mammals. The capacity of both wind-powered and self-propelled uncrewed surface vessels (USVs) to conduct acoustic surveys is being evaluated. Wind-powered USVs have been used to survey fish distributions around tagged marine mammals (Kuhn et al. 2020), and in 2020 a fleet of three wind-powered USVs was used to conduct a survey of pollock in the eastern Bering Sea, replacing a survey cancelled due to the COVID-19 pandemic (De Robertis et al., accepted). In 2023, the capabilities of a diesel-powered USV to run acoustic transects in support of a NOAA research vessel will be evaluated in the Gulf of Alaska. Mid-water sampling methods using broadband acoustics (Bassett et al. 2018) and stereo-optical systems are being refined, as are artificial intelligence and machine learning approaches for automated species identification and size measurements from video imagery (Baker et al. 2021, Williams et al. 2016, Williams et al. 2018). Uncrewed aerial systems (UAS) are integrated into survey designs for several marine mammal populations, and are being tested for surveying other populations, as well as for biological sampling (e.g., stress hormones from whale breath), and mapping nearshore fish habitat. Novel visual, infrared, and multispectral imaging sensors are being tested on UAS and crewed aircraft platforms to improve marine mammal detection and coastal habitat classification. To efficiently analyze the millions of collected images from marine mammal surveys, new software programming utilizing artificial intelligence and neural network designs are being developed. More efficient ways to extract information from ecological samples are being developed, such as on-board rapid assessments that allow for field observations to be provided in near real-time, automated analysis of acoustic imagery, and new physiological fish condition metrics and food web markers are being developed and evaluated

While considerable progress has been made on these issues, primarily using temporary funds from NMFS or from OAR, full transition to operations requires substantial and sustained support. Staff with new types of expertise, such as data scientists and programmers are needed to provide a technical interface between data collection and the new advanced tools used by the agency. In addition, continual investments in equipment, such as new uncrewed systems and passive acoustics recorders, are needed because existing equipment is dated and needs to be replaced on a rotating cycle or risk failure during deployment and subsequent loss of data. Advanced technology also offers excellent opportunities to address key information gaps for marine mammals and help to modernize marine mammal assessments in Alaska.

Figure 1. Schematic of advanced technology being used or under development by AFSC and our partners.

Additional funding is needed to support and enhance monitoring activities at AFSC and PMEL. The projects described below were identified based on scientific merit and their ability to make progress on the NCSS objectives.

2.2.1. Climate-driven changes in species' availability to surveys

Climate-driven changes in species distributions, behavior, migratory patterns, and reproductive timing may impact the availability of fish to AFSC surveys in the Gulf of Alaska. An improved understanding of the mechanisms underlying these changes is needed to account for potential biases in survey estimates and assess modifications to existing survey designs. While the Gulf of Alaska's geography may prevent a large-scale northward shift in species distributions in response to warmer temperatures (Barbeaux *et al.*, 2020), local horizontal shifts across the shelf (e.g. to deeper, cooler waters) or vertically in the water column will have varying impacts on the availability of groundfish species to different surveys, particularly for semi-demersal species such as walleye pollock and Pacific ocean perch. AFSC scientists have previously shown that changes in vertical distributions of pollock associated with environmental and demographic factors determines the proportion of pollock available to bottom trawl and acoustic sampling gear (i.e. vertical availability) in the eastern Bering Sea (Kotwicki *et al.*, 2009, 2015, 2018). Index standardization models for eastern Bering Sea pollock abundance have recently been developed by AFSC scientists that include vertical distribution data to account for spatial and temporal changes in availability to each gear type (Monnahan *et al.*, 2021). Additional process and modeling work is needed to better understand which processes determine vertical availability of pollock and other semi-demersal species in the Gulf of Alaska, as well as mechanisms that impact catchability (i.e., catch efficiency) of demersal species to bottom trawl gear.

There is uncertainty regarding how climate-driven changes in physical and biological oceanographic properties and circulation patterns in the Gulf of Alaska will impact habitat suitability. Climate-driven shifts in species distributions outside the spatial extent of surveys (i.e. horizontal availability) will bias abundance indices if the unsampled proportion of a population varies from year-to-year. The large spatial extent of summer abundance surveys minimizes this potential bias, but future work including retrospective and field process studies are needed to assess surveys that sample relatively smaller areas.

Climate-driven changes in reproductive timing or migration patterns may also impact surveys that are timed to sample spawning aggregations or larval fish, or species undergoing migrations to summer feeding grounds (i.e., temporal availability). Dorn *et al.* (2020) reported mismatches between pollock spawning and the timing of the Shelikof Strait winter acoustic survey were correlated with residuals in the stock assessment model, where surveys conducted earlier relative to inferred time of spawning resulted in lower abundance estimates compared to model estimates. Pollock spawn timing inferred from modeled larval development is primarily driven by sea surface temperature in March and the population's age structure (Rogers and Dougherty 2019), and ongoing work aims to develop a catchability covariate for the winter acoustic survey based on the timing mismatch between the survey and time of spawning. Additional funding is needed to support retrospective analyses and field process studies that identify mechanisms underlying climate-driven changes in geographic, vertical, and temporal availability to surveys, and to develop tools that account for those changes.

2.2.2. Development of satellite-based indicators for tracking changing ecosystems

Remote sensing or satellite data products have multiple applications within our fisheries management system. They have been used directly as indicators to monitor within our Ecosystem and socio-economic Profiles (ESPs) and as covariates within the stock assessment models to inform the quota. We have also used satellite data indirectly to inform survey sampling and to validate ocean models such as ROMS/NPZ and MOM6. The high spatial and temporal resolution of satellite data make it optimal for creating a multitude of stock-specific indicators as well as providing invaluable information on the seasonal timing and spatial patterns of important ecosystem properties, such as primary productions. However, access to the many different satellite products is quite variable and often confusing for users. In addition, the high latitude and cloudiness of the Alaska region renders the interpretation of satellite products quite difficult and very few Alaska specific algorithms have been developed for training the satellite products to observational data (e.g., particularly true for ocean color data).

We propose a two-pronged approach to improving satellite data use and continued access. First, a new staff member will organize satellite information for the AFSC and to coordinate with PMEL staff that are also accessing satellite data. Second, funds will be dedicated to developing Alaska specific algorithms for translating different satellite products. These projects should be coordinated with proposed process studies in the CEFI that would validate the ROMS/NPZ and MOM6 models.

2.2.3. Inter-survey calibration studies with DFO and NWFSC

Climate change can affect species distributions (Pinsky et al. 2013) and other climate responses on a broad scale (Yang et al. 2018, Li et al. 2019), and coordinated sampling across LMEs would be desirable. Along the West Coast of North America, NMFS and DFO conduct bottom trawl and other surveys across the Gulf of Alaska and California Current Ecosystems that straddle the two nations. Attempts have been made to standardize and analyze bottom trawl survey data (Li et al. 2019) but these studies were hampered by the fact that three different bottom trawl survey nets were used in separate regional surveys. Similar challenges occur but have not been evaluated for comparing sampling programs that target other components of the ecosystems (plankton, juveniles, pelagic) and other processes (feeding). Models that forecast fish and shellfish responses to changing ocean conditions depend upon reliable information from synoptic surveys that validate predicted responses and help understand the factors underlying climate change impacts.

Each type of net or sampling apparatus has innate selectivity for catching animals that can lead to bias in interpreting the results between studies. We propose to use one or more approaches to estimate the relative selectivity between sampling gears. We propose to work with partner organizations to conduct "calibration" events to compare sampling gears. Possible approaches include conducting surveys with different gears in overlapping zones either during the same time period, or preferably in side-by-side sampling between different platforms and gears. These could be conducted in transboundary areas such as Dixon Entrance and the Strait of Juan de Fuca or in special focused areas that will be required to compare US West Coast and GOA bottom trawls. As a secondary, less preferred alternative, study data from nearby adjacent sampling can be examined to estimate sampling correction factors (O'Leary et al. 2021).
As study results are examined, partners can also evaluate the question of whether adopting one sampling gear across agencies and surveys could provide for a robust and cohesive tool for evaluating climate related changes across LMEs and to improve the Fisheries and Climate Decision Support Systems' ability to model fish and shellfish responses to changing ecosystem conditions. In all cases, field work will result in a better understanding of factors underlying climate change impacts on spatial shifts in migratory corridors, feeding distributions and spawning distributions.

2.2.4. Increased Forage Fish Monitoring.

Research is needed on forage fishes (e.g. capelin, eulachon, sand lances, juvenile gadids) to better monitor climate-mediated changes in population dynamics, and to understand how links and energy transfer processes between the lower trophic level (plankton) and the upper trophic level (piscivorous fishes) are affected by climate variability. This project will give increased emphasis to estimating the abundance and distribution of forage species during trawl and acoustic-trawl surveys, and expand survey footprints to areas where forage species are distributed. Algorithms will be developed to improve the identification of acoustic backscatter using broadband and multifrequency approaches. Additional targeted and random mid-water sampling will be done with a range of existing and modified sampling equipment, including stereo-optical systems. Artificial intelligence and machine learning approaches for automated species identification and size measurements with video imagery will be further developed.

2.2.4. Increased focus on surveying nearshore juvenile fish-rearing habitat..

Nearshore habitat may be important rearing areas for juvenile fish of a number of species, particularly forage species, but is not comprehensively surveyed in the Gulf of Alaska. Changes to ocean chemistry, hydrodynamics, and coastal food webs impact juvenile growth and survival; however, these drivers are understudied using traditional oceanographic methods, and are often impacted by boundary conditions and not well constrained in ecosystem models, despite their importance. Additional resources are needed to conduct field and lab studies to better understand what processes and bottlenecks are taking place during the early life stage transition from offshore to inshore rearing (or freshwater to nearshore in the case of salmon) for core commercial species. Information for FMP species with life history stages in nearshore habitats is a critical Essential Fish Habitat information gap.

2.3 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 species habitat models and 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, protected resources, habitat, and ecosystems.

2.3.1. Large-scale climate forcing

Climate change is expected to drive atmosphere-ocean interactions, such as the Aleutian Low effect on the GOA, to novel states (Deser et al. 2010). Better understanding of novel patterns of atmosphere-ocean variability affecting the GOA is therefore needed as an important step towards improving predictive skill for process-oriented research that attempts to elucidate mechanistic effects of physical variability on fisheries production. The GOA is a well-studied system, with established long-term process research on oceanographic variability. Assessing the effects of novel patterns of Aleutian Low variability as they arise therefore requires little new data collection, but would provide a critical framework for understanding novel system configurations that would otherwise be poorly constrained by existing understanding (Wolkovich et al. 2014).

2.3.2 Regional Oceanography

Oceanographic responses to large-scale climate forcing can vary considerably across the Gulf of Alaska. Interactions between river discharge, gap winds, bathymetric steering, coastal mixing, and eddies impact the transport and distribution of water properties such as temperature and salinity as well as of terrigenous nutrients. Sub-seasonal and local dynamics play an important role in ecosystem processes. In situ observations are a critical tool for deriving relationships between physical and biological patterns to forecast and identify shifts in habitat conditions, and for validating ocean models. Research priorities for the next 3-5 years include understanding the dominant mechanisms or interactions that perturb the large-scale circulation patterns in order to improve forecasts from immediate to climatological time scales. Additional support is needed to enhance regular ecosystem and fisheries oceanographic surveys in the Gulf of Alaska that provide a basis for additional opportunistic sampling such as capturing intermittent eddies.

2.3.3. Lower trophic-level dynamics

(a) Phytoplankton community composition and fatty acids

Phytoplankton communities are the primary source of energy and biomass at the base of the marine food web. Energy required by juvenile fish is supported by phytoplankton through the production of energy storage compounds and essential nutrients. Diatoms are particularly important in supporting diverse fisheries in the GOA (Strom et al., 2007). Large *Calanus* copepods, which support favorable growth of age-0 pollock (Sigler et al., 2016), feed on lipid-rich diatoms while laying down energy stores in the form of wax esters and triacylglycerols (TAGs). Some microalgae manufacture large amounts of TAG, which are consumed and stored by these copepod species, representing an important source of energy for age-0 pollock. Moreover, essential lipid compounds such as polyunsaturated fatty acids (PUFAs) are almost exclusively synthesized by primary producers (Brett and Muller-Navarra, 1997).
Samples for preserved phytoplankton have been collected since 2019 to assess phytoplankton community composition and investigate environmentally driven taxonomic changes. The goal of this work is to create a diatom index for the western Gulf of Alaska which will help characterize the favorability of growing conditions for fish. Additional funding would be required to increase sampling of phytoplankton and to characterize the community composition and fatty acid profiles relative to the fatty acid profiles of key co-occurring zooplankton and forage fish. This would enable the tracing of essential fatty acids and PUFAs as they move up the food chain. Understanding this mechanistic process that translates environmental conditions to beneficial nutrients for growing fish could ultimately help to improve fisheries forecast models and management of fish stocks in the GOA.

(b) Zooplankton dynamics

Field and laboratory research to understand climate-related spatial and temporal variation in zooplankton community structure, biomass, energetic content, and suitability as prey continues at AFSC. An NPRB-funded project will examine the relationship between zooplankton size and climate variability in the western Gulf of Alaska. A hypothesized response to climate warming is a reduction in the size of zooplankton; however, little empirical evidence exists to support this hypothesis. A historical time-series of zooplankton size will be constructed and compared to environmental variability to determine if zooplankton size has changed historically. If the hypothesis of size reduction is supported, the finding has implications for the energy transfer from primary producers to higher trophic levels under climate change

AFSC continues to explore the application of new technologies to zooplankton research. In particular, shipboard and in situ imaging is being used to develop image libraries of the zooplankton community. These image libraries will be used to develop artificial intelligence algorithms aimed at identifying plankton to coarse taxonomic categories. The end goal is to deploy imaging platforms to sample the zooplankton community independent of ship net sampling. The use of images will allow more information about the zooplankton community to be extracted throughout the year to better understand how environmental variability impacts this community.

(c) Euphausiid dynamics

Climate effects on euphausiid dynamics across all of Alaska's Large Marine Ecosystems are critically understudied, yet euphausiids comprise probably the single largest food source for zooplanktivorous marine species. Directed field and laboratory efforts that focus on how climate variation influences rates of production, euphausiid community composition, and spatial dynamics are critical to informing and increasing the predictive capacity of our ecosystem models. Additional funding is needed for work focused on refining at-sea acoustic measurements of the zooplankton community to resolve euphausiids, field studies to characterize climate-mediated changes in euphausiid phenology and life-history, and a suite of laboratory studies that examine climate-forced shifts in euphausiid lipid availability.

2.3.4 Recruitment processes and first year of life

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, together with the Fisheries Behavioral Ecology Program. 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. Ongoing studies focused on walleye pollock, Pacific cod and sablefish are described below, as well as an effort to synthesize changes in spring phenology that are important for recruitment success. 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, and is used to identify critical periods and indicators for Ecosystem-socio-economic Profiles.

(a) Walleye pollock

Walleye pollock has long been a focal species in the Gulf of Alaska, building on historical work by EcoFOCI. Currently the RPA is examining how wind-driven advection affects the spatial distribution of juvenile pollock, their delivery to nursery areas with high prey quality, and eventual recruitment success. 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 and indicators for incorporation into the pollock ESP.

(b) Pacific cod

Pacific cod recently emerged as one of the most pressing fisheries management issues in Alaska following very weak recruitment and stock collapse coinciding with the 2014-16 marine heatwave - the largest warm anomaly ever observed in the North Pacific. A leading research priority for the Pacific cod stock is better understanding of climate-driven processes regulating spawning output, larval mortality, and age-0 post-settlement growth and survival. Currently, incoming age classes are observed prior to settlement by the EcoFOCI spring larval survey and then again after settlement in coastal nurseries by seine and camera surveys conducted by the Fisheries Behavioral Ecology Program (FBEP) in the Kodiak region. Seine and camera surveys were spatially expanded in the Central and Western GOA during 2018-21 to determine whether historical localized observations reflect abundance, demographic and process trends over larger spatial scales in the GOA. Additional funding support would help expand these efforts to the eastern GOA for Pacific cod and other species, including juvenile rockfishes. Archived samples from these surveys are being used to understand the thermal effects on Pacific Cod. Analyses include structural examinations of otoliths to determine spawning phenology, early growth, and patterns of mortality following changing climate conditions. Additional analyses include tissue dissections and trophic biomarkers (lipid/fatty acids, stable isotopes, stomach, liver to muscle ratios) to determine whether the prey field and thermal environment are supporting the new metabolic demands of early life stages of cod. These data are being combined with temperature-dependent models of developmental and growth rates from the FBEP laboratory to address key hypotheses regarding how early life history processes influence subsequent recruitment in a warmer GOA.

(c) Sablefish

Sablefish in the Gulf of Alaska have recently exhibited multiple years of strong recruitment after a long-term decline in abundance. 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, Shotwell et al. 2014). 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 also tag and release sablefish to better understand movement and spatial distribution. 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 is analyzed using RNA/DNA analysis, and 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.

(d) Changing spring phenology

Changes in phenology, or the seasonal timing of events, are a wide-spread response to climate change, and have already been documented in the GOA, including changes in spawn timing (Rogers and Dougherty 2019) and zooplankton production (Kimmel and Duffy-Anderson 2020). However, comprehensive work is needed to understand how climate change will affect spring phenology in the GOA, and the consequences of those changes for commercially important species. Ongoing work will analyze available data to synthesize historical changes in the timing of phytoplankton production, spawn timing of fishes, larval first feeding and transition, and match-mismatch of larvae with zooplankton prey. Additional funding is needed for additional survey days and sample processing to target key uncertainties in the relative timing of events and underlying mechanisms.

2.3.5. Climate effects on nutritional ecology

Studies on the effects of climate on nutritional ecology, energy allocation, and food web dynamics continue with the support of long-term fisheries oceanographic surveys acting as sample collection platforms. New directions for these studies include evaluating thiamine deficiency and other nutritional health concerns of commercially important species and food web components, increasing capacity for compound-specific stable isotope analyses to evaluate trophic relationships and energy transfer under changing climate regimes, and identifying energy and thermal thresholds affecting health, survival, and reproductive output of juvenile and adult fishes.

2.3.6. Tracking, understanding, and predicting changes in life history: maturation, spawning, reproductive potential, and size-at-age

Climate change is expected to alter population demographics, including growth rates, maturation schedules, and fecundity of marine fishes. Combined the traits describe a species reproductive potential (RP). Understanding how RP responds to past environmental variability is important for predicting the effects of future climate change. Changes in traits such as size-at-age and 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. However, increased knowledge of maturation processes, spawning strategies (including location and timing), and reproductive potential is needed.

Additional funding is needed to support directed examination of maturity stage (preferably histological) and fecundity, which can be coupled with stock sex ratio to provide a reproductive potential measure of total egg production. As this measure is more nuanced than spawning stock biomass it can provide a means for exploring processes that influence recruitment (via maturation and fecundity), such as thermal effects. Further this type of analysis can be coupled with long-standing EcoFOCI survey information (egg and larval abundance) to delineate areas of mortality from egg to juvenile and the associated environmental conditions. Temporal and spatial variability in maturation has been observed between and within stocks (Williams et al. 2016, Zheng et al. 2020), and an understanding of the mechanisms underlying that variability is increasingly important as the climate changes.

Additional funding is also needed to evaluate the effects of climate change on the growth of important marine resources in the Gulf of Alaska. Large historical changes in growth have been documented for pollock (Dorn et al. 2020) and Pacific halibut (Sullivan 2016). For example, the average weight of a 20-year-old female Pacific halibut declined from 55 kg in 1988 to 20 kg in 2014 (Sullivan 2016). Analysis of extensive collections of length and weight at age data from surveys and the fishery is needed to identify important environmental drivers, while controlling for inter-species and density-dependent effects. Both basin-scale forcing, i.e., Pacific Decadal Oscillation, and more local forcing should be evaluated. Relationships identified by these analyses can then be included in climate-forced population models to project stock dynamics and projected fishery yields. Reductions in weight at age can strongly affect fisheries yields, causing substantial economic impacts. Priority species in the Gulf of Alaska include commercially important species such as pollock, Pacific cod, and sablefish.

2.3.7. Trophic interactions

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. The AFSC Food Habits database currently contains diet data from nearly 400,000 individuals representing 200 distinct predator species. This time series allows analysts to develop models of predator prey interactions for use in stock assessments and ecosystem models such as Atlantis and Ecopath. 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.

Decreased funding resources have reduced sample collection and processing at a time when improved data collections for core species are required to assess impacts of climate change. Stabilizing funding for this lab and archival database will provide a permanent repository for sample data collected in the field and add value to our long-term ecosystem monitoring and modeling efforts.

2.3.8. Experimental studies on temperature and ocean acidification

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). 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 combined effects of OA and co-occurring rapid warming will be stronger than the effects of each considered in isolation. 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.

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 Pacific cod, walleye pollock, and northern rock sole and efforts will be expanded to examine effects on yellowfin sole. This research will expand the scope of our understanding through the inclusion of more sensitive response metrics (development, physiology, and energy status), and will focus on examining the interaction between OA and temperature stress. Experimentally-determined biological sensitivities will be incorporated into models to evaluate the impacts of OA on recruitment potential of commercial fisheries. In addition, a collaborative project will perform community-specific analysis of the sociological and economic vulnerability of southeast and south-central Alaska communities to OA.

2.3.9. Shifting habitat boundaries: Climate and Essential Fish Habitat (EFH)

Spatiotemporal variation in temperature and food are primary drivers of potential growth and survival of many fishes, and climate models are predicting these optimal habitats will shift deeper and more poleward with regional warming. While it is assumed that spatial shifts will be a potential way marine species can adapt to warming, the behavioral and physiological capacity of species may limit exploitation of these new habitats. These include both the energetic cost of transport to new habitats as well as the sensory ability of fish to locate and navigate to new areas previously unoccupied. Understanding how habitat is dynamically shifting under climate change is a research gap to be addressed with implications for effectively implementing EBFM. AFSC scientists are developing and applying a suite of advanced behavioral and physiological tools to determine the historical and future potential of fish occupying new thermal habitats in Alaskan waters. Dynamic habitat modeling methods are also in development that apply information from process studies (see modeling section). These new tools will contribute to redefining boundaries of species distribution and habitat to establish new climate-informed definitions of essential fish habitat (EFH) and improved stock assessment models. These include:

(a) Advanced acoustic telemetry and bio-logging technology

New tagging technology offers the capability to record an animal's location while simultaneously recording the environmental conditions to which it is exposed. 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 move across spatial and depth gradients both within and among years, and how ontogeny affects habitat use (Rodgveller et al. 2017). Vertical movement behaviors and depth distribution provide key information about the potential capacity for a 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. The new work builds on a history of long-term tagging studies conducted by AFSC for a range of species in the GOA.

(b) Temperature-dependent behavior and physiology

Marine species in the Gulf of Alaska must adjust their physiological and behavioral traits to adapt to temporal and spatial fluctuations in ambient temperature. Key physiological functions (growth, metabolic rate) have species-specific temperature optima and important temperature-dependent behaviors (swimming performance, sensory ability) allow fish to exploit those optimal habitats. Parameterizing fish physiology and behavior is accomplished in the laboratory using combinations of respiration, swim tunnels, shuttle box, to evaluate species ability and transport costs for exploiting habitats of the future.

(c) Field metabolic rate models

Improved measurements of physiology in free-ranging fish can determine how fish are performing in their current and historical environment. 'Field Metabolic Rate' (FMR) models based on otolith isotopic signatures offer a new way to recreate true thermal histories and metabolic stress experienced over the lifetime of the fish (Chung et al. 2019).

These new tools are being integrated and focused on Pacific cod, but will be applied to a diverse range of marine species in the GOA to test assumptions and better integrate behavior and physiology limitations in response to climate-driven changes in thermal habitats. Given past changes in marine temperature conditions within the Gulf of Alaska and the potential for future change, improved understanding of species thermal requirements and ability to adapt to new habitats is increasingly important.

2.3.10. 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 highly 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.

2.4 Modeling and management-oriented synthesis

2.4.1. Risk assessments of climate change in the Gulf of Alaska

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 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 capture both direct and indirect effects of climate driven changes and multiple interacting pressures as indirect pathways can greatly alter trajectories of change. 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.

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 has been completed (Spencer et al. 2019). A similar analysis is planned for the Gulf of Alaska, and will be an important element of the regional action plan. 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.

2.4.2. Gulf of Alaska Integrated Ecosystem Assessment

An additional risk assessment project that is ongoing is the Gulf of Alaska Integrated Ecosystem

Assessment (GOA IEA). A place-based IEA was established in Sitka, Alaska, to identify information needs and empower coastal community members in addressing management concerns. The first stage of the IEA loop was completed including the following steps: (1) scoping of the project (definition of a spatiotemporal scale and focal species), (2) identification of local ecosystem components and threats, and (3) conceptualization of the local ecosystem. Public workshops focused on ecosystem processes, ecosystem services, and local ecological knowledge were held to identify user-defined products and co-develop indicators for the IEA. This effort will ultimately link ongoing research and monitoring efforts to products requested by natural resource users.

This work is continuing with the development of an ECOPATH model for the eastern Gulf of Alaska to evaluate alternative management strategies as the next step in the IEA cycle. There are also plans to extend the place-based IEA approach to Kodiak or another fishing community in the central or western GOA and to increase stakeholder engagement to better define the most relevant temporal and spatial scales of importance.

2.4.3 Annual Ecosystem Status Report

Evaluation of 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 Status Report (ESR) for the Gulf of Alaska. This document is intended to provide the North Pacific Fishery Management Council, its advisory groups, and NOAA's Alaska Regional Office with broader information on ecosystem status and trends, and provides context for the Science and Statistical Committee's (SSC) acceptable biological catch (ABC) and overfishing limit (OFL) recommendations. It follows the same annual schedule and review process by the Groundfish Plan Team and the SSC as groundfish stock assessments, and is made available to the Council at the December meeting when groundfish harvest recommendations are developed. ESRs include assessments based on ecosystem indicators that reflect the current status and trends of ecosystem components, which range from physical oceanography to biology and human dimensions. Many indicators are based on data collected from AFSC surveys. All are developed by and include contributions from scientists and fishery managers at NOAA, other U.S. federal and state agencies, academic institutions, tribes, nonprofits, and other sources. Many indicators are presented separately 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 detects major changes in the ecosystem as they occur.

2.4.4 Spring Preview of Ecosystem and Economic Conditions

Beginning in 2019, the AFSC has convened an annual "Spring Preview of Ecosystem and Economic Conditions" (PEEC) to provide "early warnings" of ecosystem conditions as they develop. The meeting includes presentations of survey results, model outputs, and observations by community and industry members of current environmental conditions in Alaska marine waters. Development of on-board rapid assessments (e.g. for zooplankton and larval fish) has allowed for field observations to be provided in near real-time, documenting ecological responses to changes in the environment. The information shared during this meeting contributes to the development of the annual Ecosystem Status Reports, and unusual physical and biological observations are presented to the SSC and the Council in October, as “Early Warnings” ahead of the TAC-setting process for groundfish. This represents a significant advancement in the speed and efficiency with which ecosystem information is available for informing management advice, and lays the groundwork for not only monitoring, but also responding to rapid changes in climate. The positive reception of the PEEC resulted in this workshop becoming an annual meeting (with support from the Alaska IEA Program) in the North Pacific assessment and management process.

2.4.5 Ecosystem and socio-economic Profiles (ESPs)

We have a century-long legacy of qualitative reviews, conceptual modeling, and retrospective studies that have been focused on detecting mechanisms underlying ecosystem responses to improve stock assessments. Over the past several decades we have also built up the capacity for including additional pieces of information through major advances in ecosystem modeling. However, there remained a communication gap between the ecosystem and stock assessment disciplines. The ecosystem and socio-economic profile or ESP is a standardized framework that facilitates the integration of ecosystem and socio-economic information within the stock assessment process and acts as a pathway for use in management advice. The ESP process was initiated in 2014 through the Alaska groundfish Plan Teams and the first formal ESP report appeared as an appendix in the Alaska sablefish stock assessment and fishery evaluation (SAFE) report in 2017. In the last EBS and GOA RAPs, we discussed the initiation and formal development of the ESPs for the groundfish and crab stocks in Alaska. As of 2020, we have six ESPs (four groundfish, two crab stocks). We will continue to create new and update current ESPs over the next three years and plan to implement an indicator submission system for ESPs that is linked to the stock assessment cycle for both groundfish and crab stocks.

2.4.6 Risk tables

Risk tables are sections within AFSC groundfish stock assessments that summarize factors that may influence a stock’s true Acceptable Biological Catch (ABC), but that are not addressed within the stock assessment model and therefore not accounted for in the model-estimated maximum ABC. Factors are categorized as related to the assessment model, the stock’s population dynamics, ecosystem conditions, and fisheries performance. Ecosystem Status Reports (ESRs) and Ecosystem and socio-economic Profiles (ESPs) are used primarily to inform the ecosystem conditions factors, but also population dynamics and fisheries performance. Risk tables were introduced as a pilot project in five groundfish assessments in 2018. Since 2019 they have been included in all full assessments. Risk tables for groundfish will continue to be refined based on guidance from the SSC. Pilot risk tables are planned for two crab stocks in 2021. Risk tables are an important tool for enabling a rapid management response to sudden and unexpected events that are likely to become more frequent in a changing climate.

2.4.7 Dynamic species distribution models for identifying changes to Essential Fish Habitat

Species distribution models (SDMs) of essential fish habitat (EFH) have been used to describe and map the habitat-related distribution (EFH Level 1), density or abundance (EFH Level 2), and vital rates (EFH Level 3) of groundfishes in the Gulf of Alaska as is required by EFH regulations for life stages of species in fishery management plans. SDMs of EFH Levels 1 and 2 were first developed in 2017. Currently, new SDMs are in development for 2022, where significant advances in methods and data will result in the first comprehensive set of EFH Level 2 maps and a smaller set of Level 3 maps incorporating SDM and vital rates for the first time. In addition to supporting EFH mandates, this new stock-specific habitat information has been extended to stock assessment in the Ecosystem and socio-economic Profiles and to other ecosystem-based fisheries management (EBFM) information needs for our region, such as projecting these SDMs using Global Climate Models in the Bering Sea to inform species distribution shifts with a changing environment, and including these SDMs in individual-based biophysical models to study population connectivity and recruitment informed by spawning locations and spawning stock biomass in other regions over time. Moving to a more temporally dynamic definition of EFH for our regions is prudent given recent and rapid changes in the environment and species distributions. Dynamic SDMs are currently in development for species in the Bering Sea, an approach which should be extended to the Gulf of Alaska. Looking ahead, integrating spatially-explicit ecosystem models such as Atlantis with SDMs has the potential to describe and identify production rates by habitat (EFH Level 4), which can be extended to inform understanding of the influence of habitat on population dynamics and to evaluate different management strategies under a changing marine environment.

2.4.8 Incorporating recruitment processes into life-cycle models for walleye pollock and Pacific cod

Knowledge of early life stage processes should be incorporated into a state-space stage-structured population model to identify extrinsic (e.g. climate, prey, predators) and intrinsic (e.g. density-dependence, both inter- and intra-cohort) effects on recruitment and adult biomass. By fitting to early life stage data, including larval and age-0 abundance, such an approach can be used to test the relative importance of identified recruitment drivers and their population consequences. Future climate scenarios can be run in this dynamic framework and used to evaluate harvest policy performance in a changing environment.

2.4.9 Regional climate projections (GCM, ROMS, NPZ)

The US GLOBEC Northeast Pacific program originally provided funds 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).

Continued development and support for a high-resolution ocean modeling framework for the Gulf of Alaska is a high priority. The GOA-CLIM project, described in further detail below, provides support to collect and make accessible ROMS hindcasts from 1996 to present for both the high resolution 3K model and lower resolution NEP-10K model. Model runs for 1996-2013 are available from the substantial modeling effort associated with the GOAIERP (Coyle et al. 2012, 2013). The NPRB-funded Miller et al. project, "Pacific Cod Individual Based Model Enhancement and Validation" will update the GOA ROMS/NPZ model from 2013 through the present. This will provide high resolution model output during the 2013-2016 marine heat wave, as well as before and after this phenomenon, which will be extremely valuable in elucidating potential mechanisms for recent ecosystem impacts (e.g., the striking decline in Pacific cod abundance).

The Hollowed et al. project, "Projecting climate impacts on shifts in distribution and abundance of GOA groundfish using a 3km Regional Ocean Model with biogeochemistry", funded by the AFSC regional work plan, plus the additional funding from GOA-CLIM, will provide projections to end-of-century using a 3km grid ROMS/NPZ model nested within the NEP 10K model. Boundary and forcing data will be derived from output from three GCMS including the GFDL model developed for CMIP6 under two future scenarios (SSP and RCP combinations). In the GOA, limitation by both nitrogen and dissolved iron affects the spatial and temporal patterns of primary production, and dissolved iron from river runoff is a significant source term (Crusius et al. 2017) which will need to be modeled accurately.

The ocean modeling framework will be directly useful to drive spatial ecosystem models, such as the Atlantis model under development for the Gulf of Alaska. In addition, ROMS/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 for 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.

2.4.10 GOA-CLIM. From climate to communities in the Gulf of Alaska: using an integrated modeling approach to evaluate drivers of present and future system-level productivity and assess climate impacts on fishing-dependent communities

GOA-CLIM is an integrated research program that 1) leverages ongoing research at the Alaska Fisheries Science Center, 2) is closely aligned with the successful eastern Bering Sea ALCIM project, and 3) represents a substantial step towards meeting the objectives of GOA Climate

Science Regional Action Plan (Dorn et al. 2018) and the NMFS climate science strategy (Link et al. 2015). The overarching research questions of this integrated program concern the drivers of system-level productivity under climate change, the ways that fisheries management can promote resilient fisheries in a changing climate, and development of a coupled modeling approach that extends from climate to communities to evaluate economic and social impacts of climate change on resource-dependent communities in the GOA.

The integrated program includes oceanographic modeling driven by climate projections of earth system models (ESM), an ensemble of biological models including single species, multi-species, and ecosystem models. The models being developed include 1) an Atlantis ecosystem model, 2) regional ECOPATH models for the eastern GOA and the central and western GOA, 3) size-spectrum models, 4) a multispecies statistical model of pollock, arrowtooth flounder, Pacific cod, and Pacific halibut, and 5) climate-enhanced single species models for sablefish and Pacific cod. A generalized projection modeling framework being developed should make it easier to conduct climate-forced stock projections for other stocks. A marine mammal component will use the 2013-2016 marine heatwave as a natural experiment to evaluate and predict the impacts of major environmental anomalies on an endangered population of Steller sea lions.

A major focus of this research is to evaluate the impacts of a changing climate on resource-dependent communities in the Gulf of Alaska. Surveys will be conducted and predictive models will be developed of decision-making by individual fishermen as they respond to changing management structures and fishing opportunities in the GOA. A fleet dynamics model for different fleets in the GOA developed, which will provide the capacity to link the models in the multi-model ensemble, including the Atlantis model, to computable general equilibrium (CGE) regional economic models that separately model the economies of six fishing communities in Southwest Alaska within a larger economic model of Alaska.

The suite of ecosystem models will be valuable for studying how energy flow and overall ecosystem productivity changes 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 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). The OY range was derived early in the history of the GOA Fisheries Management Plan by arbitrarily reducing the sum of single-species MSY proxies available at that time to account for ecosystem considerations, as well as for model and estimation uncertainties. 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 models would allow the OY range to be re-evaluated. Consideration also could be given to the possibility of adjusting the OY range to reflect changes in ecosystem productivity over time.

Stock status relative to biomass reference points is another 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 Gulf of Alaska. 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.

2.4.11 Climate, Ecosystem and Fisheries Initiative (CEFI)

In response to the clear and emerging threat to fish and fisheries in the US, NOAA launched the Climate, Ecosystem and Fisheries Initiative (CEFI). The CEFI enlists all branches of NOAA to provide Fisheries and Climate Decision Support Systems (FACSS) in at least five US Large Marine Ecosystems (LMEs). The CEFI provides the critical infrastructure changes to establish a permanent climate change research element to the science portfolio of NOAA. The CEFI builds on regional pilot projects like GOA-CLIM. The CEFI provides:

- Critically needed high spatial and temporal resolution ocean model products (including pH, nutrients, phytoplankton, and zooplankton) at multiple time scales (sub-seasonal, seasonal, decadal and multidecadal);
- Research and development to ensure the fish or fishery specific products derived from these models provide the best available scientific information on evolving ocean conditions; and
- The interdisciplinary analysts and information support specialists (multiple FTEs per LME within NOS, OAR and NMFS) necessary to implement and sustain fisheries and climate change impact assessments, fishery dependent adaptation response assessments, and scientific decision support products for Fishery Management Councils and NMFS fishery managers.

It is anticipated that CEFI will provide substantial support for GOA-CLIM modeling effort beginning in 2022 (details on how new FTEs will be assigned to different LMEs are under discussion). One goal of the CEFI is to transition the ROMS models to the sixth generation of the Modular Ocean Model (MOM6). This will align high resolution ocean modeling in the Gulf of Alaska with the state-of-the-art ocean modeling system developed by NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). MOM6 coupled physical/biological models will be used to downscale global climate change to the ecology of subarctic ecosystems, and to explore the bottom-up and top-down effects of that change on the spatial structure of subarctic ecosystems; for example, the relative dominance of large versus small zooplankton.

The specific needs that the CEFI could address in GOA-CLIM project include:

- Adding an economist FTE dedicated to GOA-specific issues related to fleet dynamics, fisher choice, and fishery participation.
- Setting up database servers to provide access to ROMS/MOM6 hindcast and projections to analysts at appropriate spatial and temporal scales.
- Operationalize GOA freshwater runoff hindcasts and projections for use in ocean modeling
- Advanced statistical modeling expertise to deal with multi-model ensembles and management strategy evaluations
- Expanding outreach activities to fishing communities in the GOA.

By 2025, it is anticipated that the CEFI will build on the advances derived from GOA-CLIM projects to launch a new era of climate change research within NMFS within the next 3 years providing major advancements in levels 1-4 of the NCSS. The availability of accessible, reliable and verifiable model derived physical and biogeochemical ocean products will allow analysts to design and test ecosystem linkages at the appropriate temporal and spatial scales for managed species.

2.5 Marine mammals

The Gulf of Alaska is used year-round or seasonally by at least 16 species of cetaceans, seven 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, belugas, gray whales) to pelagic (whales, pinnipeds) 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.

2.5.1. Status of marine mammal populations in a changing environment

Changes in the distribution and abundance of marine mammal populations in the Gulf of Alaska 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). To develop models that can track changes in marine mammal abundance and distribution, priority should be given to monitoring species where modeling capability is high and the management need is great (Silber et al. 2016). Initial 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 whales, Cook Inlet beluga whales, Steller sea lions, and harbor seals. 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 Gulf of Alaska ecosystems are 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 (for example, 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. North Pacific 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). Long-term abundance monitoring provides the fundamental basis upon which to build hypotheses for climate change impacts. Unfortunately, many of the marine mammal stocks in Alaska do not benefit from regular abundance assessments that lead to tracking trends.

Cetacean distribution and abundance - 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). However, information from these surveys is rapidly becoming outdated and provides no information on trends in abundance; in fact, only ~50% of Alaska cetacean stocks have current information on abundance and only 15% of Alaska cetacean stocks have current information on trends in abundance. Without such information, managers will not know whether cetacean stocks are increasing, decreasing, or stable, and have very limited time series information to advise protected species managers or fisheries scientists on impacts of climate change on endangered and threatened species. The limited existing information on density, abundance, and distribution of Alaska cetaceans is likely inaccurate because the information is dated and because climate change is certainly altering cetacean distribution and could be impacting abundance. Increased funding and days at sea are needed to complete GOA surveys and acoustics through the Pacific Marine Assessment Program for Protected Species (PacMAPPS).

Year-round passive acoustic monitoring of cetaceans - To study potential effects of climate change on year-round 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 and there are numerous examples of their effectiveness in obtaining time series data on cetacean seasonal presence and changes in occurrence in the Bering Sea and Arctic (Berchok et al. 2019, Thode et al. 2021, Wright et al, 2018, 2019). This option spans relatively inexpensive acoustic recorder redeployments piggy-backed on vessels used for other projects, to expanded deployments of new moorings with broader spatial coverage in the GOA.

Long-term monitoring of humpback whales in Prince William Sound - The long-term monitoring of humpback whales in Prince William Sound (PWS) is part of the Gulf Watch Alaska (GWA) long-term research and monitoring (LTRM) program's Pelagic Component. Five projects focused on species that play a pivotal role in the pelagic ecosystem as trophic indicators for short and long-term ecosystem change: killer whales, marine birds, humpback whales, and forage fish. The overall goals of the Pelagic Component are to (1) determine the population trends of key pelagic species groups in Prince William Sound (PWS) and their abundance in adjacent shelf waters, and (2) improve our understanding of predator – prey relationships and their response to ecosystem changes.

Monitoring humpback whales and their diets is important to understanding predator prey interactions in the pelagic waters of PWS. Because humpback whales are significant predators in the ecosystem (Straley et al. 2018, Moran et al. 2018), they may have the potential to control the distribution and abundance of forage fish. The humpback whale population in the North Pacific has rebounded from near extinction in the late 1960s to over 22,000 individuals (Barlow et al. 2011). Parallel increases in whale abundance have been documented in PWS (Teerlink 2015). This recovery has coincided with major natural and anthropogenic perturbations in the marine ecosystem (regime shift, Pacific Decadal Oscillation, EVOS). Following EVOS and concurrent with the increase in humpback whales, the abundance of the dominant forage fish, Pacific herring, shifted from an abundant state to a diminished state. The lack of a commercial fishery has not restored this population to their former abundance. Pacific herring were identified as an injured species following the EVOS. Understanding the mechanisms behind their failed recovery requires a comprehensive understanding of both top-down and bottom-up processes in the context of a changing ecosystem. Our previous work in PWS (EVOS Trustee Council [EVOSTC] project PJ090804) estimates that humpback whales are consuming 15% to 20% of the pre-spawning biomass of adult herring, roughly equivalent to the percentage of herring removed during the final years of the commercial herring fishery (Rice et al. 2011). In PWS humpback whales during 2007 to 2015 had a higher percentage of herring in their diet during the winter months and foraged longer on wintering herring shoals than their counterparts in Southeast Alaska, suggesting that top-down forcing may be limiting the recovery of herring in PWS. There is a need to continue evaluating predation pressure on herring stocks in PWS and to understand the ecosystem impacts of a humpback whale population that has been functionally absent from the Gulf of Alaska for over 50 years.

Warmer water temperatures combined with seabird and marine mammal die-offs and large changes in abundance and quality of krill and forage fish (Arimitsu et al. 2021), emphasize that the Gulf of Alaska is still undergoing major perturbations that impact species at the population level. In PWS, we have failed to see a recovery in humpback whale numbers following the recent marine heatwaves.

This project began monitoring humpback whales in 2006 and will continue through spring of 2022. We have requested funding from the EVOSTC to continue monitoring efforts through 2031.

Cook Inlet beluga whales - 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" (https://www.fisheries.noaa.gov/species/beluga-whale#spotlight), the Cook Inlet beluga whale population is the subject of continuing abundance surveys and studies of habitat use (Shelden et al. 2015, McGuire et al. 2020). Priority actions needed to understand why this population is failing to recover include enhancing stranding response, reducing anthropogenic noise, protecting foraging and reproductive areas, understanding population characteristics, and ensuring prey species are healthy, plentiful, and remain available to the whales. Funding is needed to develop and apply abundance estimation methods based on the aerial survey (currently conducted biennially) and photo-identification data that allow for variation in distribution patterns, and to investigate the role of climate on prey, habitat, and anthropogenic activities within Cook Inlet and the GOA. A re-analysis of the abundance and trend time series (Shelden and Wade 2019) found signs of recovery following implementation of harvest management regulations. However, around 2010 the population began to decline precipitously and the current cause is not known.

Timely stranding response is critical to determining cause of death and for the collection of samples for contaminants and disease analyses. Immunosuppression in this population is of increasing concern with exposure to both natural and anthropogenic sources due to climate change. One key component of the "Species in the Spotlight" priority action plan is to determine prey requirements for Cook Inlet belugas. Studies currently underway include prey collection and eDNA sampling for prey species (by collecting water samples) in rivers used by belugas, and DNA analyses of gut contents from stranded whales. Data on beluga energetics will be collected in partnership with aquaria housing whales. These data will be incorporated into models such as Population Consequences of Disturbance (PCOD) which will also include survival and fecundity parameters and anthropogenic impacts.

Another key piece of data that will help track changes in distribution patterns and investigate possible driving factors is passive acoustic monitoring (e.g., Small et al. 2017, Castellote et al.

2018, 2020). Funding is needed to support development and implementation of a passive acoustic monitoring array program that will enable tracking changes in distribution patterns year-round. In addition to abundance and distribution studies, it is also critical to obtain estimates of calf production, examine health indicators (e.g, microbiomes, contaminant loads, hormones (reproductive/stress)), and calculate survival and fecundity parameters in order to develop a comprehensive Population Viability Analysis to 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. Current efforts include use of UAS platforms to obtain aerial photographs of beluga groups for calf production studies, and biopsy sampling of free-swimming whales to obtain skin samples for genetics and hormone analyses. However, there is also a need for fatty acid and stable isotope studies to examine responses of belugas to potential climate driven shifts in prey availability seasonally, annually, and decadally (e.g., Nelson et al. 2018) .

Steller sea lions - 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 has been completed (Pascual and Adkinson 1994, Trites et al. 2006; Heymans et al. 2007; Guenette et al. 2012), but none have attempted to forecast changes in distribution or abundance in response to environmental variability related to projected climate change scenarios. Steller sea lion populations in the Gulf of Alaska appeared to be significantly affected by the recent marine heatwave (Suryan et al. 2021). Aerial surveys using crewed and uncrewed aircraft will continue to provide abundance and trend data that are used to evaluate potential population consequences of climate change.

To study potential impacts of climate change on Steller sea lion populations, additional funds are needed to add capacity to capture and track sea lions for foraging and condition studies in the Gulf of Alaska to better understand interactions with oceanographic conditions and prey distribution. Recent tracking of adult females by Alaska Department of Fish and Game has added to the scant data collected over 25 years ago, and more is needed to increase seasonal and geographic coverage. This additional capacity would 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 - Harbor seals are an ideal species for exploring local effects of environmental variability on the coastal ecosystems of Alaska. Harbor seals range somewhat widely but are considered non-migratory and have local genetically-distinct stocks (O’Corry-Crowe et al. 2003;

Boveng et al. 2012; Womble and Gende 2013). Harbor seals also comprise an important cultural and subsistence resource for Alaska Native communities throughout the Gulf of Alaska dating back at least 800 years, with present stocks along the northern and southeastern Gulf supporting a high proportion of harbor seal subsistence hunting statewide. Traditional ecological knowledge has complemented recent data on stock structure and population trends, and their ecology has been described through studies on body condition, space use, foraging behavior, and diet. Newer survey designs, imaging systems, and advanced statistical models have maintained the effective temporal and spatial scope of abundance estimates despite reduced funding and limited aircraft availability. Additional funds and resources, however, are needed for harbor seals to provide insight and serve as sentinels of marine ecosystem change during large, episodic oceanographic perturbations (e.g. “the blob”) and localized anthropogenic impacts. The increasing frequency of warm water events in conjunction with reduced abundance of important prey species within regions of the Gulf of Alaska (e.g., salmon and herring in the Central Gulf and Southeast) elevates the need to better understand how seals - opportunistic predators that often target seasonally available prey runs - may adapt to a changing “prey map” influenced by warming conditions. Current survey effort and ecological studies are not funded with the consistency and frequency needed to detect changes at these scales.

One of several concerns related to the effects of climate change on harbor seals in the Gulf of Alaska is the accelerating rate of habitat loss as glaciers recede and the floating ice habitat essential for seals in tidewater glacial fjords disappears. The number of seals currently found at glacial fjord habitats during August surveys comprises about 20% of the Gulf of Alaska population, a relatively small remnant of ice-associated seals projected to have inhabited tidewater glacier fjords prior to the current glacial retreat (Crowell 2016). The tidewater fjord ice habitat is unique in providing a floating substrate irrespective of tides and thus a reliable platform on which seals whelp and nurse pups in the spring and molt in the summer. The increasingly inevitable loss of this habitat due to reduced snowpack, glacial melt, and grounding of tidewater glacier fronts (e.g., Muir, Harriman, and Turner glaciers) could have a substantial impact on Gulf of Alaska harbor seal stocks due to the loss of critical nursing grounds. The majority of tidewater glaciers from the Kenai Peninsula to Southeast have retreated dramatically over the last few decades with their calving faces approaching the point of grounding - and seal counts at historical lows. New funds would be used to scale already planned surveys to an appropriate level of effort to accurately estimate seal abundance and trends at these rapidly changing sites. Expanded surveys would also inform our understanding of ecosystem level impacts of reduced glacial fjord habitat on surrounding populations of coastal harbor seals use and distribution throughout the Gulf of Alaska.

2.5.2. Health consequences of climate change to marine mammals

A concern for all Gulf of Alaska 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 (VanWormer et al. 2019). Current disease surveillance and knowledge of health status is minimal and generally limited to occasional species-specific investigations. 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 Gulf of Alaska 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 have already been detected in Alaskan 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 Gulf of Alaska marine mammal populations and an evaluation of health risk.

2.5.3 Understand, monitor and mitigate anthropogenic sources of direct injury/mortality

Harbor porpoise bycatch - The bycatch of harbor porpoise in Southeast Alaska (SEAK) is an emerging significant conservation and management concern. Recent research indicates the population currently recognized as the SEAK stock is likely composed of multiple stocks. New information on abundance of harbor porpoise in inside waters of SEAK – one of the putative stocks - indicates a population size of approximately 926 animals. A 2-year observer program in a portion of the districts in SEAK documented a level of incidental serious injury and mortality in the salmon drift gillnet fishery in those districts that, if stock structure was changed, would exceed the apparent maximum allowable level under the Marine Mammal Protection Act. Pingers, which make sounds that alert harbor porpoise to the presence of a net, are a broadly-used device that is effective in deterring some marine mammals from some types of commercial fishing gear. However, in some areas pinger use does not appear to reduce marine mammal mortalities in fisheries. The AFSC needs to pursue: 1) an understanding of whether pingers are likely to be an effective way to deter harbor porpoise in SEAK and 2) an expanded observer program in the drift gillnet fishery to understand harbor porpoise bycatch in areas of SEAK that have not yet been observed.

Oil and gas development, spill response, and other anthropogenic activities - Abundance, density and distribution data are lacking for many cetacean species in the GOA (see subheader "Cetacean distribution and abundance" in section 2.5.1). Understanding cetacean presence within and around regions within the GOA proposed for new oil and gas exploration and development is necessary to understand and potentially mitigate impacts from seismic exploration, oil spills, and Navy operations. Such anthropogenic stressors may lead to changes in habitat use which will likely be amplified by climate change. Key areas where data are needed include lower Cook Inlet and eastern Shelikof Strait and the central GOA.

Harbor seals - The broad distribution of Alaska harbor seals along coastal areas creates a significant overlap between their habitats and human activities. Monitoring the potential impact of anthropogenic activities (e.g. shoreline development, resource exploration and extraction, increased vessel activity) on harbor seals is of key interest for NOAA's management and conservation missions. Species' responses to adapt to direct and indirect effects of climate change are likely influenced by anthropogenic stressors emphasizing the importance of understanding human impacts. More recent concerns regarding the potential for anthropogenic disturbance have revolved around a rising interest in establishing aquatic farms in coastal areas of the Gulf of Alaska (e.g., Kodiak Island, Kenai Peninsula, Prince William Sound, and Southeast). Expanding the existing time series of survey data adjacent to current and proposed farming areas would provide a better monitoring of proximate impacts related to construction and seasonal farming operations. New funds would be used to scale existing surveys and plan new surveys to establish seasonal levels of abundance of seals hauled out in areas where active permits are being considered.

Floating ice habitats of glacial seals have for more than a century witnessed dramatic increases in vessel-based tourism in terms of both vessel numbers and capacity. Researchers have documented such increases in vessel presence - and direct effects on seals - in several fjords that are most targeted by ships because of ease in navigation and overall natural aesthetics (e.g., calving tidewater glaciers of Glacier Bay, Tracy Arm, and Disenchantment Bay)(Jansen et al. 2015). But glaciers at most of these sites are retreating and/or thinning which results in less calving and less floating ice - two factors that are making these areas less desirable for both tour vessels and seals. Long established trends suggest that vessel-based glacier tourism will continue to grow in popularity, requiring tour companies to adapt and expand into new glacial areas - where vessel presence has been historically low. New funds would be used to establish baseline visitation levels by ships at lesser-visited tidewater glacier fjords via new data streams from rapidly expanding satellite-based AIS vessel tracking (subscription-based) and newly designed autonomous land-based AIS systems (purchasing and deploying hardware).

2.5.4 Measuring life history parameters to track populations adapting to a changing climate.

Harbor seals - Tracking seal abundance over time provides critical insights about the health and resilience of populations in the changing coastal environment of Alaska. But interpreting different trajectories in abundance across stocks requires context about a species life history, and informed estimates of age and sex-specific productivity and survival. These latter metrics are required as foundation for hypotheses to distinguish sources of a possible decline and in turn formulate a meaningful conservation response. New techniques in aerial remote sensing (piloted and unpiloted) have enabled novel methods for estimating size and growth of individual seals and thus provide opportunities for modelling of age structure and population growth. New funding would be used to establish a new analytical effort using existing 2D aerial photographs taken over the last two decades in glacial ice habitats in the Gulf of Alaska, and expand aerial survey effort during pupping in long-term study areas (i.e., Icy and Disenchantment Bays) to compare to efforts conducted in the early 2000s. New automated methods for estimating seal dimensions and modelling body volumes would be devised in order to establish a new time series of pupping phenology, productivity, and age structure in relation to total abundance. Ice-associated harbor seals - which are currently threatened by degradation of floating pup-rearing habitat - stand to provide unique insights about the adaptations of populations under climate stress.

2.5.5. Environmental drivers of marine mammal populations

Steller sea lions and northern fur seals- The marine heatwave of 2013-2016 had measurable impacts on Steller sea lion populations in the Gulf of Alaska (Sweeney et al. 2017; Suryan et al. 2021). The mechanisms for this are unknown but suspected to be related to large declines in Pacific cod, which are a significant portion of sea lion winter diets (Sinclair et al. 2013). Two modeling approaches will explore this as a natural experiment to predict how climate change will impact their population dynamics. One will use output from the ROMS/NPZ, CEATTLE and Atlantis models to evaluate changes in ecosystem structure and function prior to and during the marine heat wave, and a second will develop bioenergetic models for adult female sea lions to investigate how the marine heatwave affected energy consumption and estimate the level of prey reductions that could have led to the observed reproductive failure.

New funding is needed to apply novel techniques to monitor changes in Steller sea lion and northern fur seal diets that reflect changes in quality, quantity, and type of prey consumed or available based on shifts occurring in response to climate change. Diets can be tracked through biogeochemical tracers (e.g. stable isotopes and fatty acids) using tissue samples collected from northern fur seals and Steller sea lions across the range of Alaskan breeding sites during research studies and subsistence harvest hunts. Concurrent sampling of potential prey species is also necessary to create linkages between predator diets and changes at lower trophic levels.

2.5.6 Modernize Alaska marine mammal assessment surveys

Investments in research, equipment, and personnel with new types of expertise are needed to modernize marine mammal assessments in Alaska. Gaps include the need for AI to streamline processing for image and acoustics data in order to provide data products to managers on a timeline relevant for management decisions and the use of new types of platforms, such as uncrewed vehicles and satellites, to assess marine mammals. While progress has been made on these issues, primarily using temporary funds from NMFS or from OAR, full transition to operations requires additional support. Staff with new types of expertise, such as data scientists and programmers are needed to provide a technical interface between data collection and the new advanced tools used by the agency. In addition, continual investments in equipment, such as new uncrewed systems and passive acoustics recorders, are needed because existing equipment is dated and needs to be replaced on a rotating cycle or risk failure during deployment and subsequent loss of data.

2.6 Socio-economic impacts on fishing communities

Fisheries in the Gulf of Alaska and the fishing communities that depend on them are at risk from ocean acidification and climate change (Mathis et al. 2015; Himes-Cornell and Kasperski 2016; Spencer et al. 2019; Peterson-Williams et al. 2021). A series of marine heatwaves that began in late 2013 triggered a steep and abrupt decline in Pacific cod in the Gulf that led to a closure of the directed federal fishery in 2020, leaving the fishermen that are highly dependent on this fishery in the region without their primary source of income (Barbeaux et al. 2020; Peterson-Williams et al. 2021). These marine heatwaves also led to an unprecedented, large recruitment class of sablefish swarming the directed fishery with small, unmarketable fish and setting off a series of costly avoidance behaviors and ongoing policy discussions at the North Pacific Fisheries Management Council and its advisory committees about how to allow the fleet to maintain their income in the face of this change (Szymkowiak and Rhodes-Reese 2020).

As part of a growing body of research focusing on climate change and Gulf of Alaska fisheries and fishing communities, the AFSC has been working on examining how these marine heatwaves have impacted the region (Szymkowiak and Rhodes-Reese 2020; Seung, Waters, and Barbeaux 2021). AFSC researchers have also undertaken a number of socio-ecological system research efforts over the last several years including a large, interdisciplinary and multi-year study intended to understand fisher responses to changing systems and community resilience in the face of climate change. These efforts are in addition to continued, ongoing socio-economic baseline studies and monitoring tools against which climate change impacts can be evaluated and economic assessments that can be applied to inform trade-offs and economic impacts of climate change.

The following subsections describe these efforts in terms of: (1) ongoing research to establish conditions for a socio-economic baseline, (2) 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, and (3) socio-ecological system modeling efforts. This is followed by a presentation of the challenges to socio-economic studies of climate change in the Gulf of Alaska and an outline of further research that needs to be conducted in this arena.

2.6.1 Socio-Economic Baseline and Monitoring

This section outlines a number of socio-economic baseline and monitoring efforts that exist in the Gulf of Alaska, including the Annual Community Engagement and Participation Overview, Economic Data Reports, and multiple efforts intended to improve data quality and linkages of individuals across multiple modes of fisheries engagement.

The AFSC has developed the Annual Community Engagement and Participation Overview (ACEPO) to provide community-level social and economic information to the NPFMC for those communities substantially engaged in the commercial FMP groundfish and crab fisheries in

Alaska (Wise, Sparks, and Lee 2021). This analysis considers four performance metrics of fisheries participation to help understand the different ways that communities are involved in FMP groundfish and crab fisheries: commercial processing engagement, commercial harvesting engagement, the processing regional quotient which measures the percentage of all FMP groundfish and crab landings occurring in each community, and the harvesting regional quotient that measures the percentage of all FMP groundfish and crab landings revenue attributable to vessels owned by residents of each community. These indicators provide a quantitative measure of community participation in Alaska fisheries and how their participation has changed from 2008 through 2019. These indicators are supplemented with other community-level information about fish landings volumes and values, fisheries taxes, school enrollment, demographics, vessel ownership, crew licenses, and quota share ownership. ACEPO is built on engagement and vulnerability indices that are updated annually as part of a process to provide consistent metrics of fisheries communities across the nation.

Whereas most fisheries in the Gulf of Alaska do not have an economic data collection program associated with them, since 2014 there has been an Economic Data Report (EDR) for the GOA Trawl Fishery that was initiated in anticipation of the potential implementation of a rationalization program. This data collection program is intended to provide the NPFMC and NMFS with baseline economic information on harvesters, crew, processors, and communities active in the GOA trawl fisheries to assess the impacts of changes in management measures, but it can similarly be used to examine the effects of other changes, such as changes to the marine environment as a result of climate change.

The AFSC is also collaborating with the Alaska Fisheries Information Network (AKFIN), the State of Alaska Department of Fish and Game (ADF&G), and the International Pacific Halibut Commission (IPHC) to improve data and research around the multiple modes of engagement in Gulf of Alaska fisheries, which can improve understanding of adaptive capacity and adaptation strategies in response to climate change impacts. AFSC will be working with AKFIN to develop persistent identifiers for fisheries participants across multiple fisheries datasets allowing researchers to understand how individuals engage across fisheries as crew, permit, vessel, and quota share owners. AFSC will also be working with ADF&G and IPHC to examine the intersection of subsistence, recreational, and commercial fisheries, with a focus on halibut fisheries, in fulfilling household food needs to improve understanding of the economic and social values of non-commercial fisheries. Understanding access and trade-offs in participation across these different fisheries can inform researchers about how individuals may make choices about participation in light of changing conditions associated with climate change.

2.6.2 Economic Assessment

Economic models are used to assess effects of climate change and ocean acidification on fisheries and fishing communities. 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 and vessel-processor interaction models (e.g., Haynie and Layton 2010), b) bioeconomic models with multiple species (e.g., Kasperski 2015), single species with multiple life-history stages (Punt et al. 2014, 2016), and multispecies and multistage population dynamics (Punt et al. 2020), c) computable general equilibrium (CGE) regional economic models (e.g., Seung et al.2015; Seung and Ianelli 2016; Seung, Waters, and Barbeaux 2021), and d) recreational fishing and protected species models (e.g., Lew and Larson 2015, Lew et al. 2010; 2019).

Researchers at the AFSC have created tools and modeling frameworks of fisher behavior that can 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 (e.g., 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, 2017; Kroetz et al. 2019; Szymkowiak and Rhodes-Reese 2020). AFSC researchers and partners are also working 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.

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 and Cook Inlet beluga whales (Lew et al. 2010; Lew 2019). An extension of the protected species models involves integrating a population viability analysis with the species valuation models for the Cook Inlet beluga whale, which is expected to facilitate the evaluation of public economic benefits associated with alternative recovery actions. Over the last several years, AFSC scientists and others have worked to expand economic models from the previous focus on a regional and whole State level to be formulated at the borough and census areas (BCA), which is discussed in more detail under the “Regional CGE Model” section below.

(a) Spatial econometric and fishing fleet models

AFSC researchers are leading the development of the Spatial Economics Toolbox for Fisheries (FishSET), which provides an integrated modeling framework to assess and predict how fishers respond to changing fish distributions and abundance, regulations such as spatial closures, management actions such as IFQ programs, and changes in prices across various fisheries. Spatial modeling is an integral component of GOA-CLIM as well. The fleet dynamics and fisheries management model in GOA-CLIM will predict future fishery catch and ex-vessel revenue in response to projected and potential changes in the ecosystem, regional economy, and management system. The modeling approach utilizes a wide range of fisher location choice models (e.g., Haynie and Layton 2010), models that evaluate fishery responses to changes in environmental changes (e.g., Haynie and Pfeiffer 2013), and multispecies models that simulate how fisheries interact under changing climate conditions and alternative harvest strategies. Spatial econometric models will be coupled with ecological models of stock dynamics described in the preceding sections in order to utilize stock projections as inputs and to inform the spatial and temporal distribution of commercial fishing mortality. The outputs from these models will also be coupled with regional economic models to estimate potential economic impacts on GOA fishing communities.

(b) Bioeconomic models

Biological and economic impacts of ocean acidification (OA) on Pacific cod will be assessed with forecasts of long-term effects of OA on abundance, yields, and fishery income, by applying results from exposure experiments and ocean monitoring/modeling to infer population-scale changes in juvenile growth and survival. The specific objectives are to develop two bioeconomic models for Pacific (i.e. Alaska) cod, one for the Eastern Bering Sea, and the other for the Gulf of Alaska, which will be based on age-structured population dynamics for each area, and a prerecruit function that accounts for long-term effects of OA. Separate bioeconomic models are necessary for each area due to the different population dynamics and present and projected oceanographic conditions for each area. This research focuses on potential effects of OA on a major U.S. fishery, with potentially significant effects on commercial fishing revenue as well as U.S. exports and trade deficits. Current funding levels allow for the incorporation of pH as an environmental driver but not ocean temperatures, thereby leaving a key gap in bioeconomic projections of the fishery.

(c) Regional SAM and CGE models

To address the lack of local-area models, AFSC researchers have developed a set of economic models for Alaska fisheries.

First, they have developed a 10-region multi-regional social accounting matrix (10MRSAM) model for Southwest Alaska fisheries using regional economic information collected from a survey and other supplementary data. The regional economic information (such as employment and expenditures) was collected for six boroughs and census areas (BCAs) in Southwest Alaska from fish harvesting vessels and key informants including seafood processors and local businesses. The 10 regions are (i) the six BCAs which include Aleutians East Borough, Aleutians West Census Area, Bristol Bay Borough, Dillingham Census Area, Lake and Peninsula Borough, and Kodiak Borough, (ii) an at-sea "region", (iii) the rest of Alaska, (iv) West Coast (Washington, Oregon, and California), and (v) the rest of US.

Results from this model 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 (e.g., Seung et al. 2021). The BCA-based 10MRSAM model utilizes a variety of economic data on expenditures and employment by vessels, processors, and marine supply businesses gathered from seafood industry data, surveys, and interviews. 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 the Southwest Alaska region. Currently, communities in Southwest Alaska are part of the aggregated Alaska region, but given the remoteness and reliance on fishing activities in this area, disaggregating their economic outcomes would be valuable.

Second, based upon the data assembled in the 10MRSAM, AFSC researchers are developing a dynamic four-region multi-regional CGE (4MRCGE) model to compute the temporal and cumulative economic impacts from climate change-induced alterations in GOA fisheries. The four regions in the CGE model result from aggregating some of the 10 regions above, and include Aleutians East Borough, Kodiak Island Borough, Other Southwest Alaska region (including At-sea Region), and the rest of US. Thus, this model, once developed, can calculate the economic impacts of an external shock (e.g., climate change) to GOA fisheries on Aleutians East Boroug

2.6.3 Socio-ecological system modeling efforts

Over the last several years AFSC researchers have been working on a number of integrated research and modeling projects intended to holistically examine socio-ecological systems and to predict fishers responses to changing components of fisheries including biological, management, and economic forces. These efforts include a Gulf of Alaska Integrated Ecosystem Assessment (GOA IEA), a Gulf of Alaska Climate Integrated Project (GOA-CLIM), and a Regional Vulnerability Assessment for Gulf of Alaska fishing communities.

AFSC economists and social scientists have been working with natural scientists from AFSC and the University of Alaska Fairbanks to develop the GOA IEA - an integrated, multi-disciplinary effort targeted at understanding management goals and trade-offs. As part of the GOA IEA researchers have developed place-based well-being indicators tied to fisheries uses that could potentially be used to examine system shocks, like climate change (Szymkowiak and Kasperski 2020). The larger GOA IEA team is also now working on the development of an EwE model with the inclusion of Eastern Gulf of Alaska fleets to examine how changes, such as ecosystem shocks associated with climate change, would affect this system.

Economists and social scientists are examining fleet dynamics, community impacts, and adaptation potential in Gulf of Alaska fishing communities associated with climate change as part of a newly funded, multi-year and interdisciplinary project - GOA-CLIM. This project will examine the impacts of shared socio-economic pathways (SSPs) on the Gulf of Alaska ecosystem, target fisheries, and fishing communities. Economists and social scientists in this project are focusing on understanding how fishing fleets will respond to climate change, how those responses will affect fishing communities, and what tools stakeholders have and need to adapt to these new challenges.

Finally, AFSC researchers are also initiating a project focusing on community vulnerability to ocean acidification (OA) in the Gulf of Alaska. This project will develop decision support tools that incorporate the risks of OA into localized, coupled socio-ecological systems to support coastal communities. Producing network models in collaboration with community members and resource industry representatives will improve stakeholder knowledge of system dynamics, interactions, and potential adaptive strategies. A central goal is to create decision support tools that are responsive to stakeholder concerns; reflect regional variation in the priorities of communities and their ecological, social, and management context; and synthesize the best available science.

2.6.4 Challenges to socio-economic research on climate change impacts in the Gulf of Alaska

Scientists face a number of challenges in framing an understanding of how fishermen and fishing communities may respond to, and be affected by, climate change. At the most foundational level, basic data about fishermen and fishing operations is generally not available in Gulf of Alaska fisheries. Economic data on fishing operations gathered through Economic Data Reports (EDRs) have been mandated for some fisheries with the creation of catch shares (e.g., Amendment 80 and crab). However, in the Gulf of Alaska, EDRs have generally not been implemented except in the Gulf of Alaska trawl fishery. The lack of availability of basic economic data for all fisheries that would be provided in EDRs precludes our understanding of how fishing operations make decisions and the distribution of fishing-related expenditures across communities. The development of EDRs for GOA fisheries would provide this kind of information against which to evaluate climate change impacts, in addition to other changes.

In addition to economic information, basic social data is also missing for individuals who participate in GOA fisheries. For example, basic demographic information about participants' gender, ethnicity, Tribal affiliation, educational attainment, marital status, and so on is not available, yet there is ample evidence about the role that these variables play in individual decision making around fisheries participation, with implications for how individual characteristics may frame choices about responding to shocks associated with climate change. Even aggregated at the community level, social data has a number of limitations that make understanding climate change impacts difficult including data confidentiality issues associated with limited observations, missing years of data, and aggregations at levels that are not meaningful towards distinguishing fisheries participants (Szymkowiak and Kasperski 2020).

2.6.5 Building a research portfolio of climate change impacts on Gulf of Alaska communities

Fisheries in the Gulf of Alaska are already experiencing the impacts of climate change (Barbeaux et al. 2019; Peterson-Williams et al. 2021). In the coming years, as anthropogenic change accelerates there is an anticipation that novel combinations of physical variables may emerge that are poorly described by existing ecological understanding (Litzow et al. 2020b). Fishermen will be at the forefront of the unprecedented changes that a reshuffling of environmental variables and their relationships may cause on fisheries in the Gulf.

In order to understand how these potential climate change drivers will impact fisheries participants and fishing communities in the Gulf of Alaska, economists and social scientists at AFSC are looking toward addressing foundational data needs and expanding on understanding relationships between fisheries participants, their adaptive strategies and capacity, and long-term community resilience. At the forefront of these efforts is the necessity of working within and towards addressing the President's recent Executive Orders on climate change and environmental justice, which point to the intersection of climate-related impacts on historically disadvantaged and marginalized populations (E.O. 14008; E.O. 13985; E.O. 13990). AFSC researchers will need to work with Tribes and fishing communities to frame an understanding of resilience that aligns with locally-relevant conceptualizations of community well-being and cumulative impacts from past management practices, ecosystem shocks, and broader socio-cultural and economic effects.

In order to move towards addressing these issues, AFSC researchers will continue and expand upon ongoing research efforts in the Gulf of Alaska. This includes continuing work on the GOA IEA to frame an understanding of community well-being tied to fisheries; expanding research on climate change impacts, adaptation strategies, and community resilience in the face of climate change as part of GOA-CLIM; and, the development of work focusing on community vulnerability to ocean acidification (OA) in the Gulf of Alaska. The following section outlines additional research that is needed in the near term to improve an understanding of potential climate change impacts in the Gulf of Alaska.

Improve collections of economic and social data for Gulf of Alaska fisheries participants and communities - In order to understand how fisheries participants may respond to change and how those responses may affect their and their communities' resilience, basic data gaps need to be addressed about who fishermen are, their other potential sources of income, and the costs of their operations. This would address the overarching challenges to having baseline information about fishermen that would help inform an understanding of the possible choices they have in response to impacts associated with climate change. Such information can then be scaled up to examining impacts on fishing fleets or geographic communities. Similar information should be gathered for subsistence and recreational users, with consideration of how existing data generation in this arena from the Alaska Department of Fish and Game can be facilitated.

Improve baseline information of human relationships with their ecosystems in the Gulf of Alaska - People have highly individualized relationships with fisheries and the local marine ecosystem within which they reside, based on a number of socio-cultural and economic factors. The well-being that people derive from their fisheries and marine ecosystems is in turn also highly individualized. Understanding these relationships and well-being connections is critical for being able to conceptualize how they may be impacted by climate change effects. Therefore, researchers have to gather baseline information about individual relationships with fisheries and local marine ecosystems, inclusive of relationships between types of engagement (commercial, recreational, and subsistence) and how those may flow into larger, community-level issues around access and food security.

Improve understanding of absorptive, adaptive, and transformative capacity across Gulf of Alaska communities - The resilience capacity of socio-ecological systems is increasingly being described in terms of the capacity of the system to absorb and remain stable (absorptive capacity), to adapt with flexibility (adaptive capacity), and to transform through structural change (transformative capacity). Transformative capacity integrates social justice and equity considerations within resilience, focusing on the distribution of risks across populations and away from historical burdens placed on marginalized populations. All three elements are considered critical for resilience, but much of the literature around resilience focuses on absorptive and adaptive capacity. Research needs to be conducted across the Gulf of Alaska on what these three levels of resilience look like for communities with the understanding that they will be fundamentally different based on community values and current baselines.

Develop collaborative networks of fishers and scientists - Fishermen across the Pacific Northwest and Alaska are experiencing changes that are often mechanistically similar in terms of species migrations, fish diseases, etc. Yet experiences of change and adaptation strategies are not shared across, or even very well within, these regions. At the same time such knowledge exchange can inform researchers about local ecological knowledge, observed ecological changes, and behavioral adaptations that may drive changes in fisheries and stock status. Researchers will need to help facilitate building collaborative networks of fishers within Alaska and across the Pacific Northwest to share ecosystem observations and lessons learned around science communication, fisher adaptive strategies, and adaptive management.

Increase collaboration with local, regional, Tribal, Federal, State, and university bodies working on climate change issues and research activities in the Gulf of Alaska - There are a number and growing list of entities that are working on climate change related issues and research in the Gulf of Alaska. In order to improve information sharing and to ensure that efforts are building upon each other and moving forward, researchers will need to increase collaborative networks across these entities. Such collaborations will also be important for limiting the burden on stakeholders in terms of providing input into research processes and finding information relevant to climate change outcomes and local risks.

Continue expanding research targeted at understanding adaptation potential and adaptive strategies across the Gulf of Alaska - Much of the work of GOA-CLIM focuses on the level of the individual to understand adaptation strategies and capacity. This effort should be expanded upon in a variety of ways to conceptualize adaptive capacity at the community level. For example, understanding the role of social networks among fishermen and how information about adaptation passes through these networks can inform expectations about how communities of practice may invoke various adaptive strategies. Researchers should also seek to more comprehensively examine the role of mariculture and hatcheries in fisheries resilience and community adaptation potential. The processing sector also plays a critical role in shaping fishermen's choices and adaptive capacity of communities, which needs to be examined. Other interrelated fishing sector activities, such as support service businesses, need to be considered as part of project extensions as well.

3. COMMUNICATIONS AND ENGAGEMENT STRATEGY TO SUPPORT CO-PRODUCING SCIENCE WITH GULF OF ALASKA COMMUNITIES

Over the next five years to support implementation of the Gulf of Alaska Climate Regional Action Plan for 2020-2024 and lay a foundation for future plans, we will take steps to strengthen existing relationships and continue to expand reciprocal relationships with Alaska Native and fishing communities in the Gulf of Alaska.

Through regular communications, outreach and engagement efforts, we plan to facilitate bi-directional knowledge exchange to increase trust and enable collaborative research that informs NOAA Fisheries mission to manage living marine resources. We hope to work together to identify mutual priorities for research to better inform our understanding of and response to marine ecosystem changes, largely due to Climate Change, that are dramatically affecting these communities' food security and way of life. This approach for co-production of knowledge was recommended in public comments to NOAA on Executive Order 14008 on Climate Change.

To execute its mission to manage fisheries and conserve marine mammals, NOAA Fisheries identifies and prioritizes research that includes climate-driven change in the environment and effects on living marine resources. However, not all communities have equal access during the process of identifying, prioritizing, or executing regionally-specific research needs.

To address these inequalities, NOAA Fisheries will expand opportunities to advance Environmental Justice in research through consistent and sustained engagement and collaboration with Indigenous communities to co-produce marine research to better inform management of living marine resources. This effort will directly support the following U.S. government priorities: EO 14008: Tackling the Climate Crisis at Home and Abroad Section 219-223. Securing Environmental Justice And Spurring Economic Opportunity (Sec 219) (Sec 220); EO 13985: Advancing Racial Equity and Support for Underserved Communities through the Federal Government; EO13990: Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis; and the Presidential Memorandum: Tribal Consultation and Strengthening Nation-to-Nation Relationships (2021) that reinforces the importance of EO13175 (2000): Consultation and Coordination with Indian Tribal Governments.

Our new Tribal Research Coordinator will assist by providing information about the NOAA Fisheries research mission and helping to advance a two-way dialogue to strengthen working relationships and build partnerships in coastal and Alaska Native communities. This work will be done in coordination with Center social scientists and external partners.

The goals are to promote information sharing, support each other's individual data collection efforts, develop collaborative research projects and identify mutual priorities to co-produce research. The Tribal Research Coordinator will also help RAP team members to coordinate meetings on the Regional Action Plan development and research activities over the next several years. Alaska Fisheries Science Center staff will continue to work with fishing communities throughout Alaska and work to build and strengthen relationships with Alaska Native communities who are involved in commercial, recreational, and subsistence fisheries, and hatchery and aquaculture operations. Some of these communities include: Kodiak (and Kodiak Island villages), Homer, Hoonah, Hydaburg, Kake, King Cove, Metlakatla, Petersburg, Sand Point, Sitka, Yakutat.

To build broader awareness of the Alaska Fisheries Science Center mission, other communications efforts are expected to coincide with this effort including: 1) radio interviews and local newspaper features to introduce the Alaska Fisheries Science Center and highlight any projects that are jointly undertaken; and 2) educational efforts targeting students, teachers and parents in the communities (e.g., regionally-focused interactive seminars for K-8 and internship opportunities for high school and college students). As appropriate, we will also use NOAA Fisheries communications platforms to highlight collaborative efforts (website, Facebook and other social media platforms regionally and nationally).

3.1 Improving community decision support tools

Central to effective implementation of the RAP is a process of constant and robust engagement with fishing-dependent coastal communities. In Alaska, fishing-dependent communities range from some of the Nation's largest commercial fishing ports to small communities where residents have consumed subsistence resources from the sea for millennia. Ecosystem Based Fishery Management (EBFM) recognizes the central role that humans play in marine ecosystems, a role that will continue to evolve as climate change alters the abundance and range of the resources that human communities depend upon.

This project will support three main activities: 1) new staff to develop and coordinate the variety of adaptation activities occurring across spatial scales as well as governance across Federal, State, municipal, and Tribal governments in Alaska, 2) workshops in fishery-dependent communities supporting a plurality of perspectives, including indigenous knowledge and approaches toward improving co-management, and 3) development of public-facing tools to increase awareness of local and regional changes in the environment and help them prepare for the future.

Specifically, this project will provide support for communities and individuals to adapt to climate change at the local level through:

- Informing short-and long-term investments in marine infrastructure.
- Promoting local commercial, recreational, and subsistence fleet adaptation.

- Exploring opportunities in aquaculture/mariculture development to support local economies.

- Understanding the diverse ways in which climate change will provide increased opportunities and challenges for many remote communities in Alaska.

These efforts will also contribute to meeting the Administration's environmental justice goals by addressing the climate-related and other cumulative impacts on disadvantaged communities. (EO 14008 Sec 219, Sec 220). By promoting better adaptation by Native Alaskan communities, this project will also promote racial equity by promoting economic development, sustainability, and adaptation for these communities.

4. BUILDING AND MAINTAINING CRITICAL PARTNERSHIPS

Partnerships are critically important for long-term monitoring in the Gulf of Alaska. AFSC resources are heavily leveraged and provide a catalyst for partnerships with other federal and state agencies, universities, non-profit and private organizations. Leveraged resources range from AFSC vessels providing sample collection opportunities for non-AFSC collaborators and time series data and expertise for modeling of climate effects on fisheries to AFSC personnel providing key leadership of large-scale integrated research programs. Maintaining and building upon these partnerships where AFSC also greatly benefits from sample collection, leveraged resources, and information gained from external partners will likely become increasingly important given current and future funding challenges, in addition to the complexity of understanding mechanisms and future projections of changing marine ecosystems. 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 oceanographic data collections from the GOA, including long-term moorings deployed as part of EcoFOCI, and analysis and interpretation 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.

The Fisheries-Oceanography Coordinated Investigations (FOCI) program was established by NOAA in 1984 as a joint research program between AFSC and PMEL and later expanded as EcoFOCI to a focus on Ecosystem Based Fisheries Management and improve understanding of ecosystem dynamics and management of living marine resources. This long-standing partnership between PMEL and AFSC has been leading fisheries oceanographic research in Alaskan waters for over three decades and has contributed greatly to understanding ecosystem dynamics and recruitment processes of groundfish related to climate variability in the Gulf of Alaska.

4.2 Recruitment Processes Alliance

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 focusing on factors influencing early life stages of groundfish species. The RPA joins the efforts of six AFSC programs: 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 spring and fall ecosystem surveys in the western Gulf of Alaska. 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.

4.3 *Exxon Valdez* Oil Spill Trustee Council/Gulf Watch Alaska

The *Exxon Valdez* Oil Spill Trustee Council has funded research led by AFSC in the Gulf of Alaska for over 30-years, with a major emphasis on ecosystem monitoring to understand limitations to recovery of resources injured by the oil spill. Three initial integrated studies in the decade following the 1989 oil spill focused on oil toxicity and natural environmental drivers of population declines and included the Sound Ecosystem Assessment (salmon and herring populations), the Alaska Predator Ecosystem Experiment (seabirds and forage fishes), the Nearshore Vertebrate Predator project (inter- and sub-tidal predators).

These programs provided a catalyst for longer-term ecosystem monitoring efforts supported by the *Exxon Valdez* Oil Spill Trustee Council, such as Gulf Watch Alaska. Gulf Watch Alaska is a 20-year research and monitoring program that began in 2012 and integrated monitoring efforts from the three initial programs noted above and various other projects the Trustee Council was contributing to, like the Seward Line initiated during GLOBEC, the GAK1 station monitoring initiated in 1970, and seabird and mammal surveys initiated before and after the spill.

Gulf Watch Alaska is entering its second 10-year period, 2022-2031, with over 40 investigators from a dozen institutions and maintaining its three main components of Environmental Drivers, Nearshore Ecosystems, and Pelagic Ecosystems, while adding the Herring Research Program and Synthesis and Modeling as new components. Gulf Watch Alaska also shares investigators and large vessel research platforms with the Northern Gulf of Alaska LTER funded by the National Science Foundation. Collectively, these two programs provide unprecedented annual spring, summer, and fall sampling of four major oceanographic sampling lines from Kodiak Island to Cape Suckling, year-round sampling in Prince William Sound and Kachemak Bay, and intertidal to offshore oceanic sampling of multi-trophic levels from physics to whales.

4.4 North Pacific Research Board (NPRB)

The Board recommends marine research to be funded through a competitive grant program using interest earned from the Environmental Improvement and Restoration Fund (EIRF) that was established from a settlement by the U.S. Supreme Court pertaining to a land dispute in the Arctic known as Dinkum Sands. The funds are used to conduct research in the North Pacific Ocean, Bering Sea, and Arctic Ocean to address pressing fishery, protected resource, and subsistence management issues and marine ecosystem information needs. NPRB has funded large interdisciplinary research projects called Integrated Ecosystem Research Programs in the Gulf of Alaska, eastern Bering Sea and the Arctic. The Gulf of Alaska IERP is in the final synthesis phase, while a new IERP for the Arctic, with plans for additional integrated programs in other Alaska large marine ecosystems.

4.5 Alaska Department of Fish and Game (ADFG)

ADFG manages ecologically and economically important fisheries in the Gulf of Alaska for salmon, crab and nearshore groundfish, such as black rockfish and lingcod. ADFG 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 SSC. ADFG conducts surveys, such as the Gulf of Alaska large mesh survey, that provide information for stock assessments and ecosystem indicators, and ADFG assists in the catch recording system in the Gulf of Alaska. ADFG are also a collaborator in beluga whale, Steller sea lion, and harbor seal studies.

4.6 Fisheries and Oceans Canada

Fisheries and Oceans Canada is a science and management agency that is 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. One example of 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. Another example is the application of machine learning algorithms developed by the Marine Mammal Laboratory to acoustic recordings of cetaceans collected by DFO to identify the seasonal occurrence of critically endangered North Pacific right whales.

4.7 Cooperative Institute for Climate, Ocean, and Ecosystem Studies (UW, OSU, and UAF)

The Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES) is a new partnership between the University of Washington, Oregon State University, and the University of Alaska Fairbanks that fosters research collaboration with the National Oceanic and Atmospheric Administration (NOAA). Under the auspices of CICOES, AFSC collaborates with academic researchers on research topics of mutual interest. Often this collaboration takes the form of funding for graduate students and postdoctoral researchers. CICOES has a strong focus on climate research targeted at societal needs, with the goal of improving predictions of climate variation affecting coastal regions and ecosystems.

4.8 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 Gulf of Alaska. 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 Gulf of Alaska 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. 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, modeling and management-oriented synthesis. Projects relating to marine mammals, most of which would be described as either monitoring or process studies, and socio-economics 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 used the term "increase" for projects that would require additional funding to implement. We have not attempted to estimate the funding that would be required for the projects that were identified under the increased funding scenario, but have 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. Therefore, activities described under the alternative funding scenarios should be viewed as placeholders, and not commitments from the AFSC.

5.1 Table of projects cross-linked to National Climate Science Strategy (NCSS) 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 the demersal component of the ecosystem, including fish and invertebrates. Physical measurements include water temperature and irradiance, with efforts to add dissolved O_2, pH, and *in situ* cholorphyll a concentration	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 has an ecosystem focus and also produces estimates of Pacific ocean perch, capelin 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	ADFG large-mesh trawl survey	Level	Ongoing	Conduct an annual bottom trawl survey in the Gulf of Alaska focusing on Tanner and red king crab	ADFG, RACE
6,7	Oceanographic moorings in the Gulf of Alaska	Level/ Increase	Ongoing	Moorings in the Gulf of Alaska provide continuous monitoring of oceanographic conditions	PMEL, RACE, UAF
6,7	Spring larval survey	Level/ Increase	Ongoing	Assess the abundance, distribution, size structure, and survival of larval fish, with a focus on pollock. Ecosystem data, including zooplankton, are collected.	RACE, ABL
6,7	Young-of-the-year pollock and forage fish 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

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
6,7	Age-0 nearshore seine/camera survey	Level	Ongoing	Assess abundance, condition, age and size of age-0 Pacific cod and other key species in nearshore nursery areas during the summer	RACE
6,7	Gulf Watch Alaska	Level	Ongoing	Long-term ecosystem monitoring in the northeastern Gulf of Alaska, Prince William Sound, and Lower Cook Inlet. Physics to upper trophic levels and intertidal to offshore ecosystems.	ABL lead with many collaborators
6,7	Southeast Coastal Monitoring	Level	Ongoing	Identify processes that influence the growth and survival of salmon in SE Alaska	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	Nearshore juvenile fish-rearing habitat.	Increase	Ongoing	Nearshore habitat is important rearing areas for juvenile fish of a number of species, particularly forage species, but is not comprehensively surveyed in the Gulf of Alaska.	ABL RACE
6,7	Improve the efficiency of the AFSC survey enterprise	Increase	2022-2024	Evaluate the potential for increasing spatial and temporal scope of monitoring by leveraging existing platforms and consolidating survey efforts.	RACE ABL
6,7	Increase spatial coverage of new autonomous sampling platforms and moorings	Increase	Ongoing	Autonomous sampling platforms and moorings offer a potential low-cost opportunity to extend the spatial and temporal footprint of ecosystem monitoring in the Gulf of Alaska.	PMEL RACE UAF
Process studies					
5	Changing Aleutian Low dynamics and ecosystem consequences	Increase		Identify how changing Aleutian Low dynamics change the relationships among advection, stratification, and temperature in the Gulf, and how those changes in turn affect population processes.	RACE, PMEL

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
5	Regional oceanography	Level/ Increase	Ongoing	Research priorities include understanding the dominant mechanisms or interactions that perturb the large-scale circulation patterns in order to improve forecasts from immediate to climatological time scales. Additional support is needed to enhance regular ecosystem surveys in the Gulf of Alaska that provide a basis for additional opportunistic sampling such as capturing intermittent eddies.	PMEL, RACE
5, 6	Phytoplankton community composition and fatty acids	Level/ Increase	2022-2024	Create a diatom index for the western GOA which will help characterize the favorability of growing conditions for fish. Additional funding would be required to increase sampling and to characterize phytoplankton community composition and fatty acid profiles relative to co-occurring zooplankton and forage fish.	ABL, RACE
5, 6	Zooplankton community dynamics	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. An NPRB-funded project will examine the relationship between zooplankton size and climate variability	RACE, ABL
5, 6	Euphausiid dynamics	Increase	2022-2024	Directed field and laboratory efforts that focus on how climate variation influences rates of production, euphausiid community composition, spatial and temporal dynamics, and lipid availability.	RACE, ABL
5	Recruitment processes	Level	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	Thermal effects on age-0 Pacific cod	Level	2019-2023	A suite of projects is examining thermal effects on Pacific cod through their first year of life through directed field and laboratory work, and analysis of archived samples (e.g. for age, growth, food habits, trophic biomarkers), with the aim of understanding how early life history processes influence subsequent recruitment in a warmer GOA.	RACE, ABL, OSU, PMEL

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
5	Sablefish recruitment processes	Level	2019-2024	A collaborative, cross-Divisional research team is conducting research on sablefish during the first year of life to determine mechanisms underlying recruitment variability.	ABL, RACE, REFM
6	Tracking changes in spring phenology	Level/ Increase	2022-2024	Comprehensive work is needed to understand how climate change will affect spring phenology in the GOA, and the consequences of those changes for commercially important species.	RACE, PMEL
5, 6	Climate effects on nutritional ecology	Level	Ongoing	Studies on the effects of climate on nutritional ecology, energy allocation, and food web dynamics.	ABL, RACE
5, 6	Maturation, spawning, and reproductive potential	Level/ Increase	Ongoing	Increased knowledge of how maturation processes, spawning strategies (including location and timing), and reproductive potential are being affected by climate change is needed.	REFM, RACE
5,6	Climate effects on growth and size-at-age	Level/ Increase	Ongoing	The AFSC maintains an extensive collection of data on size at age that are critical for informing age-structured assessment models. Additional funding is needed to evaluate the effects of climate change on the growth of important species in the GOA, including pollock, Pacific cod, and sablefish.	RACE, REFM
5,6	Trophic interactions and food habits	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 models of predator prey interactions for use in stock assessments and short-term and long-term projection models.	REFM

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
5	Experimental studies of ocean acidification and temperature on selected species in the Gulf of Alaska	Level	2018-2023	There will be continued examination of the effect of OA on the growth and development of Pacific cod, walleye pollock, and northern rock sole and efforts will be expanded to examine effects on yellowfin sole. Efforts will focus on the interaction between OA and temperature stress.	RACE
5	Use of telemetry, archival and satellite tags for defining species niche and behavior for sablefish, Pacific cod, and other species	Level	Ongoing	Data from internally-implanted archival tags and pop-off satellite tags provide insights into the optimal thermal envelopes for 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, RACE
5	Temperature-dependent behavior and physiology	Level	2022-2024	AFSC scientists are developing and applying a suite of advanced behavioral and physiological tools to test assumptions and better integrate behavior and physiology limitations in species distribution models and climate-informed definitions of Essential Fish Habitat.	RACE
5	Genetic adaptation to temperature for walleye pollock	Level	2022-2023	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.	REFM, UW
Modeling and management-oriented synthesis					

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
5	Vulnerability analysis of GOA marine fish populations	Level	2022-2024	Conduct a vulnerability analysis of groundfish, salmon, and other stocks to climate change.	REFM, PMEL, ABL
1,2,3,4	Gulf of Alaska IEA	Level	Ongoing	GOA integrated ecosystem assessment projects include the development of an ECOPATH model for the eastern GOA, and extension of the place-based IEA approach to a fishing community in the Central/Western GOA.	ABL, REFM
6	Annual ecosystem status report (ESR) 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, ABL, RACE, PMEL
3, 6	Spring preview of ecosystem and economic conditions (PEEC)	Level	Ongoing	Annual meeting to provide Council and advisory bodies rapid "early warnings" of ecosystem conditions as they develop. Survey, model results, and anecdotal information is presented of current environmental conditions in Alaska marine waters. Development of on-board rapid assessments allows for field observations to be provided in near real-time, documenting ecological responses to changes in the environment.	REFM, ABL, RACE, PMEL, Sea Grant
5,6	Add ecosystem and socio-economic profiles (ESPs) to stock assessments	Level	2022-2024	The ecosystem and socio-economic profile or ESP is a standardized framework that facilitates the integration of ecosystem and socio-economic information within the stock assessment process and acts as a pathway for use in management advice. We will continue to create new and update current ESPs over the next three years and plan to implement an indicator submission system for ESPs that is linked to the stock assessment cycle for both groundfish and crab stocks.	ABL, REFM, RACE

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
3,6	Risk Tables	Level	Ongoing	Risk tables are sections within AFSC groundfish stock assessments that summarize factors that may influence a stock's true Acceptable Biological Catch (ABC), but that are not addressed within the stock assessment model and therefore not accounted for in the model-estimated maximum ABC. Factors are categorized as related to the assessment model, the stock's population dynamics, ecosystem conditions, and fisheries performance.	REFM, ABL, RACE, PMEL
3,6	Dynamic species distribution models for identifying changes to Essential Fish Habitat	Increase	2022-2024	Dynamic SDMs are currently in development for species in the Bering Sea, an approach which should be extended to the Gulf of Alaska. Integrating spatial-explicit ecosystem models such as Atlantis with SDMs has the potential to describe and identify production rates by habitat (EFH Level 4), which can be extended to inform understanding of the influence of habitat on population dynamics and to evaluate different management strategies under a changing marine environment.	RACE, REFM, UW
4, 5	Incorporating recruitment processes into life-cycle models for walleye pollock and Pacific cod	Increase	2022-2024	Knowledge on early life stage processes should be incorporated into a state-space stage-structured population model to identify extrinsic (e.g. climate, prey, predators) and intrinsic (e.g. density-dependence, both inter- and intra-cohort) effects on recruitment and adult biomass. By fitting to early life stage data, including larval and age-0 abundance, such an approach can be used to test the relative importance of identified recruitment drivers and their population consequences.	RACE, UW

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
4	GOA-CLIM Regional climate projections (GCM, ROMS, NPZ)	Level/ Increase	2022-2024	Continued development and support for a high-resolution ocean modeling framework for the Gulf of Alaska is a high priority. The GOA-CLIM project, described in further detail below, provides support to collect and make accessible ROMS hindcasts from 1996 to present for both the high resolution 3K model and lower resolution NEP-1. GOA-CLIM will also provide projections to end-of-century using a 3km grid ROMS/NPZ model nested within the NEP 10K model. Boundary and forcing data will be derived from output from three GCMS including the GFDL model developed for CMIP6 under two future scenarios (SSP and RCP combinations).	REFM, PMEL, DFO, NWFSC
1,2,3,4	GOA-CLIM Atlantis ecosystem model	Level		An Atlantis model, which is a spatially explicit, coupled physical-biological oceanographic model, will be developed for the GOA. The model to gain a broader understanding of the drivers of ecosystem productivity in the GOA, and to elucidate how large-scale environmental forcing propagates through the ecosystem to higher trophic levels. The Atlantis model will also be used to evaluate the Optimum Yield (OY) range for the GOA, and to simulate ecosystem properties under projected climate change.	REFM, UW
1,2,3,4	Other ecosystem models	Level/ Increase	2022-2024	Develop regional size-spectrum and mass-balance models driven by environmental forcing for the Gulf of Alaska to complement the Atlantis model	REFM, UW, UAF
1,2,3,4	CEATTLE multispecies model for the GOA	Level	2022-2024	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 to evaluate physiological effects of temperature change on growth in addition to environmental forcing on recruitment.	REFM, UW

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
1,2,3,4	Single-species MSEs for sablefish and several rockfish species	Level/ Increase	2022-2024	Develop management strategy evaluations for sablefish and several flatfish 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
1,2,3,4	Climate, Ecosystem and Fisheries Initiative	Level/ increase	Ongoing	The CEFI provides the critical infrastructure to establish a permanent climate change research element to the science portfolio of NOAA. The CEFI includes high spatial and temporal resolution ocean model products, research and development to ensure the fish or fishery specific products derived from these models provide reliable information on evolving ocean conditions, and interdisciplinary analysts and information support specialist necessary to implement and sustain fisheries and climate change impact assessments, and scientific decision support products for the NPFMC.	
Marine mammals					
6,7	Abundance and trends of Steller sea lions	Level/ Increase	Ongoing	*Status of marine mammal populations in a changing environment*- Aerial surveys of Steller sea lions using occupied and UAS to track population trends.	MML
6,7	Steller sea lion foraging and condition in the Gulf of Alaska	Increase	2022-2024	*Status of marine mammal populations in a changing environment*- To study potential impacts of climate change on Steller sea lion populations, additional funds are required to add the capacity to capture and track sea lions in the GOA for body condition and foraging studies in the Gulf of Alaska to better understand responses to oceanographic conditions and prey distribution.	MML, ADFG
5,6,7	Abundance & Trends of Harbor Seals in Response to Extreme Oceanographic Conditions in GOA	Level/ Increase	2022-2024	*Status of marine mammal populations in a changing environment*- Increasing the spatial coverage and frequency of harbor seal aerial surveys in the Gulf of Alaska. Specific focus on regions that are likely to experience dramatic shifts in oceanographic conditions and prey abundance.	MML

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
5,6,7	Abundance & Trends of Harbor Seals in Glacial Fjords	Increase		*Status of marine mammal populations in a changing environment*- Increased frequency and technological improvements for dedicated aerial surveys of harbor seals in glacial fjord habitats. These harbor seals are dependent upon sea ice in glacial fjords for pupping and resting. Additional technologies and advanced imaging would improve the efficiency and quality of survey results.	MML
5,6,7	Cook Inlet beluga "Species in the Spotlight" monitoring	Level/ increase	2021-2024	*Status of marine mammal populations in a changing environment*- Priority actions needed to understand why this population is failing to recover include enhancing stranding response, reducing anthropogenic noise, protecting foraging and reproductive areas, understanding population characteristics, and ensuring prey species are healthy and plentiful. Increased funding is needed to develop passive acoustic monitoring arrays, to collect data for and develop PCOD and PVA models, and to expand stranding response and photo-identification studies. In particular, acquiring estimates of calf production, examining health indicators (e.g, microbiomes, contaminant loads, hormones (reproductive/stress)), and calculating survival and fecundity parameters. There is also a need for fatty acid and stable isotope studies to examine potential climate driven shifts in prey availability seasonally, annually, and decadally.	MML, AKR, ADFG, CICOES, REFM
4,6,7	Deploy passive acoustic systems on existing and new oceanographic moorings	Increase	2021-2024	*Status of marine mammal populations in a changing environment* - Moorings that collect acoustic data in addition to other biological and physical oceanographic data are a high priority. These data allow the study of potential effects of climate change on cetacean phenology and distribution, providing a time series of information on cetaceans that could inform managers of broad scale ecosystem change., Acoustics processing is done manually and is currently unfunded; in addition, funds are needed to deploy acoustics recorders and to expand deployments of moorings to provide broader spatial coverage.	MML, PMEL, NOAA S&T, UW-CICOES

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
5,6	Long-term monitoring of humpback whale populations throughout northern Southeast Alaska	Level	2022-	*Status of marine mammal populations in a changing environment* - Long-term, agency, university, and private non-profit cooperative effort to study humpback whale populations in Southeast Alaska. Glacier Bay National Park program has continued for over 35 years and is one of the longest continuously running humpback whale population studies.	ABL, NPS, UAS, AWF
5,6	Killer whale population and diet monitoring	Pending	2022-2031	*Status of marine mammal populations in a changing environment* - Photo ID, acoustic, and diet studies to determine distribution, abundance, and diets of killer whales. Primary effort is monitoring pods affected by the 1989 T/V Exxon Valdez oil spill	ABL, NGOS
6,7	PacMAPPS: Pacific Marine Assessment Program for Protected Species	Increase	2021-2024	*Status of marine mammal populations in a changing environment* - -Information on Alaska cetacean distribution, density, and trends using various field techniques including acoustics and vessel or aerial surveys is required to understand the impacts of climate change on several species designated as threatened or endangered under the Endangered Species Act. At this time, NMFS has current information on abundance for only 53% of Alaska cetacean stocks and current information on trends in abundance for only 15% of Alaska cetacean stocks. This information is critical for managers in NMFS and other partner agencies to understand the potential impacts of anthropogenic activities; information on abundance is needed to put impact information into a population-level context; time series information on cetacean distribution and density can be used used by fisheries researchers to understand ecosystem changes impacting federally managed commercial fisheries in the Gulf of Alaska.	MML, CICOES, Navy

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
6,8	Cetacean distribution and abundance surveys and ecology studies	Increase	2022-2024	*Monitor and mitigate anthropogenic sources of direct injury/mortality* - Understanding cetacean presence within and around regions within the GOA proposed for O&G Leases to mitigate potential impacts from spills, sonar, and seismic activities. Projects include proposed spring/summer/fall studies in Lower Cook Inlet /Shelikof (BOEM, MML).	MML, CICOES, BOEM
6,7	Harbor porpoise abundance, trends, bycatch, and bycatch mitigation	Increase	2021-2024	*Monitor and mitigate anthropogenic sources of direct injury/mortality* - Bycatch of harbor porpoise in the Southeast Alaska commercial salmon drift gillnet fisheries is an emerging conservation issue. The AFSC and AKR needs additional information on bycatch in unobserved components of the fishery and on whether pingers successfully deter porpoise from the nets.	MML, AKR, F/PR, UW-CICOES
5,6,7	Remote sensing of phenology and pup growth and health in glacial ice habitats	Increase	2022-2024	*Monitor productivity of ice-associated pinnipeds in relation to climate* - Advances in imaging systems permit regular photogrametric surveys for abundance, but by developing automated techniques age/sex classes can be distinguished and measured thus building a valuable context for understanding long-term anthropogenic climate impacts.	MML, AKR
4,7	Track incidence and overlap of rapidly expanding aquaculture farms with habitats used by harbor seals for pupping and molting, and by cetaceans for foraging.	Increase	2022-2024	Capitalize on both existing surveys and design focused aerial effort to gather more detailed time series of abundance and distribution of seals and cetaceans near proposed farming areas. Better resolution data will enable more detailed analyses to increase power of detected population impacts due to farming construction and ongoing activity.	MML, AKR, ADFG

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
4,5,6,7	Modeling overlap between vessel traffic and habitats traditionally used by marine mammals for migration, feeding, rearing young, molting, and other activities.	Increase	2022-2024	*Environmental drivers of marine mammal populations* - Explore new datasets derived from a rapidly growing array of AIS satellites. Initiate constructing time series of vessel distribution and movement across habitats newly available due to ice loss, and in particular areas targeted by evergrowing marine tourism. Conduct spatial analyses to define potential future hotspots of animal-ship overlap especially in relation to ESA species and Native subsistence activities.	MML, AKR
4,5,6,7	Evaluate impacts of climate-mediated habitat impacts to prey populations and subsequent changes/shifts in prey, such as SE salmon runs, on harbor seal abundance and distribution.	Increase	2022-2024	*Environmental drivers of marine mammal populations* - Long time series of harbor seal abundance and distribution on fine spatial scales, in conjunction with additional contemporary surveys and prey maps, will enable more focused analyses to gain an understanding of how seals are adapting (or not) to dramatic changes in prey availability as indicated by more frequent fishery closures and prey runs that reach new lows every few years following long-term downward trajectories.	MML, AKR
3,4,5,6	Evaluate impacts of major environmental anomalies to Steller sea lions using 2013-2016 marine heatwave as a natural experiment	Level	2021-2024	*Environmental drivers of marine mammal populations* - SSL responses to the 2013-2016 marine heatwave will be modeled to better predict how climate change will impact the population dynamics of this top predator in the GOA	MML, CICOES
5,6	Integrated Predator-Prey Surveys 2022-2031: Humpback Whales, Marine Birds, Forage Fish	Pending	2022-2031	*Environmental drivers of marine mammal populations* - Long -term monitoring of humpback whale abundance, distribution, and prey in Prince William Sound is funded by the EVOSTC. This is a continuation of work that began in 2007. This project integrates with marine bird and forage fish surveys.	ABL, UAS

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
4,5	Monitor changes in northern fur seal and Steller sea lion foraging in response to environmental changes using biogeochemical tracers.	Increase	2021-2024	*Environmental drivers of marine mammal populations* - Tracking of Steller sea lion and northern fur seal diets through stable isotope analysis of tissue samples collected across the range of Alaskan breeding sites and concurrent prey collections will improve quantifying responses to environmental changes.	MML
6,7	Health monitoring of marine mammals	Increase	2022-2024	*Health consequences of climate change to marine mammal*s - Expand health monitoring for neurotoxins caused by harmful algal blooms, for infectious diseases brought by expanding ranges through arctic and temperate areas, and for changes in entanglement rates in fishing gear and other debris such as packing bands.	MML, NWFSC, ADFG, UAF, AKR, NGOs, ANOs
	Modernize marine mammal assessments	Increase	New	The AFSC has been highly successful in receiving support for R&D of multiple	
Socio-economic impacts on fishing communities					
6,7	Maintain community vulnerability tracking indices	Level	Ongoing	Update vulnerability and exposure indices for community vulnerability analysis	REFM
6,7	Annual Community Engagement and Participation Overview (ACEPO)	Level	Ongoing	Continue to collect and report the information provided in the ACEPO.	REFM
4,5	Develop fleet dynamics and fisheries management model for climate change scenarios	Level	Ongoing	Predict future fishery catch and ex-vessel revenue in response to changing ecosystem, economic, and management conditions	REFM

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
4,5	Develop community economic model linking climate change impacts with community economic impacts	Level	Ongoing	Develop a model that links changes in future fishery ex-vessel revenues in response to climate change to the economies of GOA fisheries-dependent regions.	REFM
4,5	Develop community adaptation model for climate change impacts	Level	Ongoing	Collect information about human adaptation to climate change to shape responses that will be incorporated under the fleet dynamics and fisheries management model and the community economic model, above.	REFM
4,5	Develop Ecopath with Ecosim (EwE) model for Eastern Gulf of Alaska	Level	Ongoing	Develop an EwE model of the Eastern Gulf of Alaska including fishing fleets to examine how changes, such as ecosystem shocks associated with climate change	ABL/ REFM
4,5	Develop community vulnerability assessment to OA	Level	Ongoing	Develop decision support tools that incorporate the risks of OA into localized, coupled socio-ecological systems to support coastal communities	REFM/ Newport
6,7	Collect socio-cultural information from fisheries participants and communities	Increase		Collect social data about fishermen and fishing communities including demographics and cultural information about well-being ties to fisheries.	REFM
6,7	Collect economic data for fishing fleets	Increase		Collect economic data for all Gulf of Alaska fishing fleets.	REFM
6,7	Collect information on absorptive, adaptive, and transformative capacity	Increase		Conduct research across Gulf of Alaska communities on what these three levels of resilience look like for communities.	REFM

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
6,7	Collect information on adaptation potential across different levels and fisheries-related sectors	Increase		Expand research targeted at understanding adaptation potential by examining adaptive strategies of processors, marine support service businesses, fishing associations, and the role of mariculture and hatcheries.	REFM
1,2,3,4	Computable general equilibrium (CGE) model for Gulf of Alaska fisheries	Level	2018-2023	Develop a computable general equilibrium model for Gulf of Alaska fisheries to evaluate the economic impacts of climate change at the local scale.	REFM
1,2,3,4	Extend the CGE model to additional communities	Increase	2025-2030	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	Gulf of Alaska Pacific cod bioeconomic model	Level	Ongoing	Develop a bioeconomic model of Pacific cod in the Gulf of Alaska to evaluate the effect of ocean acidification on abundance, yields, and fishery income.	REFM
Communications and engagement strategy					
	Communications and engagement strategy to support co-producing science with Gulf of Alaska communities	Level	2020-2024	Through regular communications, outreach and engagement efforts, we plan to facilitate bi-directional knowledge exchange to increase trust and enable collaborative research that informs NOAA Fisheries mission to manage living marine resources. We hope to work together to identify mutual priorities for research to better inform our understanding of and response to marine ecosystem changes, largely due to climate change, that are dramatically affecting these communities' food security and way of life.	REFM

NCSS objectives addressed	Action name	Funding Scenario	Time frame	Action description	Division/ Partners
	Improving community decision support tools	Increase		This project will support three main activities: 1) new staff to develop and coordinate the variety of adaptation activities occurring across spatial scales as well as governance across Federal, State, municipal, and Tribal governments in Alaska, 2) workshops in fishery-dependent communities supporting a plurality of perspectives, including indigenous knowledge and approaches toward improving co-management, and 3) development of public-facing tools to increase awareness of local and regional changes in the environment and help them prepare for the future.	REFM

6. TRACKING METRICS FOR THE GOA RAP 2020-2024 UPDATE

Monitoring

- Maintain the schedule and scope of existing surveys done by AFSC and our partners to monitor the Gulf of Alaska marine ecosystem.
- Improve monitoring capacity by increasing efficiency, leveraging existing platforms, and through new approaches or technology.
- Add the new measures of environmental or ecosystem properties to monitoring surveys that are identified as important through process studies or modeling efforts.

Process studies

- Published studies or technical reports on how the environment or the ecosystem affects some aspect of recruitment, early life history, growth, maturation, phenology, predator-prey relationships, or temporal and spatial distribution of marine fish stocks the Gulf of Alaska ecosystem.
- New indicators of the above used in the Gulf of Alaska ESR or ESPs.

Modeling and Management-oriented synthesis

- Conduct a vulnerability analysis of groundfish, salmon, and other stocks to climate change.
- Hindcasts and projections of ROMS/MOM6 oceanographic and biological variables under multiple GCMs that are easily accessible to the wider research community.

- Single-species, multispecies, and ecosystem projections of future conditions in the Gulf of Alaska.
- Improved understanding of likely changes in GOA ecosystem structure and function under climate change.
- Hold annual meetings and prepare reports for the PEEC meeting, ecosystem status and ESPs.
- Meaningful engagement with the Council and its advisory bodies on effective management strategies in the face of climate change

Marine Mammals

- Maintain the schedule and scope of existing surveys done by AFSC and our partners to monitor marine mammal populations in the Gulf of Alaska
- Make improvements in monitoring capacity or efficiency due to new approaches or technology.
- Published studies or technical reports on how marine mammals are likely to respond to climate change in the Gulf of Alaska.
- Meaningful engagement with the Office of Protected Resources Alaska region on the management implications of climate change of marine mammal populations in the Gulf of Alaska.

Socio-economic impacts on fishing communities

- Continue and enhance the ability to track economic and sociological characteristics of fishing communities in the Gulf of Alaska
- Develop working socio-economic models that integrate with biological models to support the broader effort of evaluating the impacts of climate change on fishing communities in the Gulf of Alaska.
- Understand the adaptive capabilities of individuals, families, and communities to a changing climate.
- Develop a bioeconomic model of Pacific cod in the Gulf of Alaska to evaluate the effect of ocean acidification on abundance, yields, and fishery income.
- Develop a network of stakeholders across Gulf of Alaska communities to regularly engage in climate change research.

Outreach Communication plan

- Institute regular communications, outreach and engagement with Alaska Native and fishing communities in the Gulf of Alaska.
- Make progress on other communications efforts including: 1) radio interviews and local newspaper features; and 2) educational efforts targeting students, teachers and parents in the communities.

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