Alaska Regional Action Plan for Southeastern Bering Sea Climate Science

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EXECUTIVE SUMMARY

Alaska is on the front lines of climate change. While temperatures are anticipated to increase globally, the largest anticipated increases and changes are expected for the Arctic including the Bering Sea, Alaska (Larsen et al., 2014). Such changes may have cascading impacts on regional food-webs that are structured by climate-driven changes to biophysical processes (Stabeno et al. 2013a). The southeastern Bering Sea supports some of the most valuable commercial fisheries in the world. Large numbers of seabirds and marine mammals also are found in the region and subsistence harvests are a critical resource for coastal communities. Climate-related changes in ocean and coastal ecosystems likely will impact the fish, seabirds, and marine mammals of the southeastern Bering Sea, as well as the people, businesses, and human communities that depend on them. Actionable information on how, why and when climate change will impact Alaska is needed.

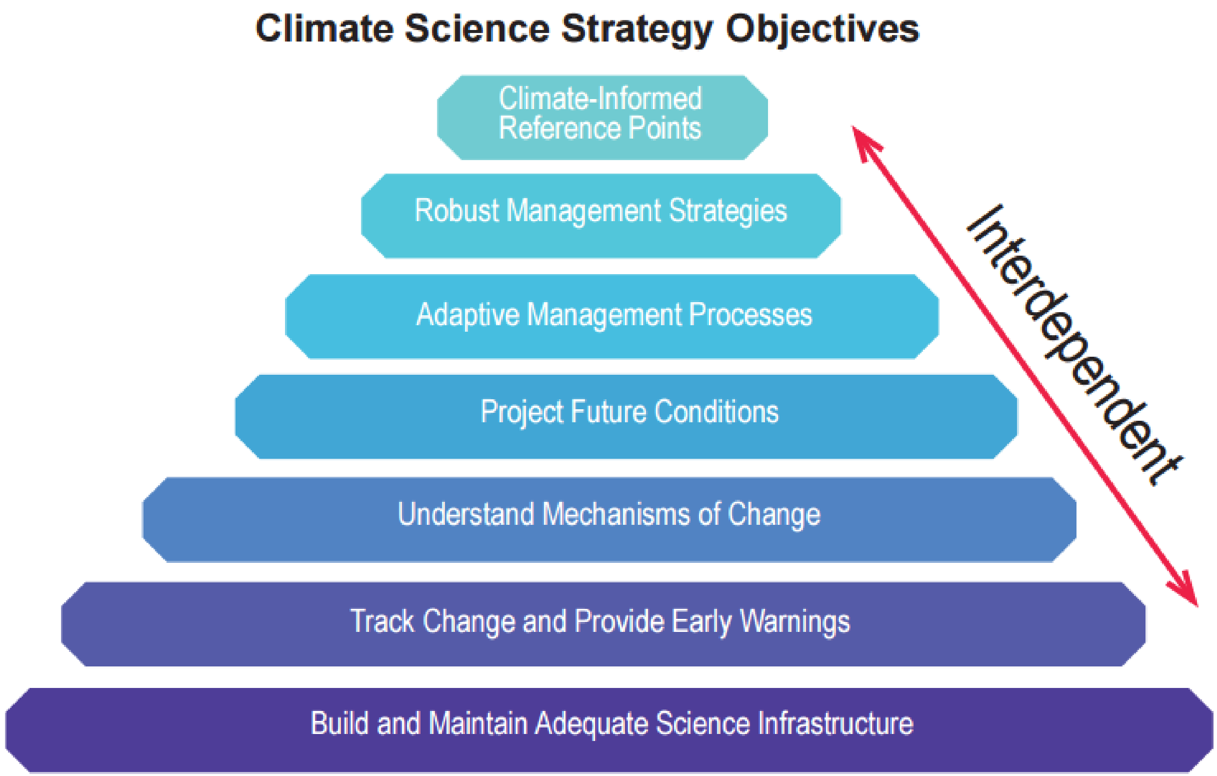
The Alaska Fisheries Science Center (AFSC) acquires and distributes the scientific information necessary to fulfill the mission of the National Marine Fisheries Service (NOAA Fisheries) to sustain fish, seabirds and marine mammals and their ecosystems for the benefit of the Nation. To continue to fulfill the mission in the face of climate change, the AFSC seeks to acquire and develop information needed to understand, prepare for, and respond to climate change impacts on fish, shellfish, marine mammals, and people. The ultimate purpose is to use the information to explore and develop science-based strategies for sustaining fisheries, healthy ecosystems, protected species, and resource-dependent communities in a changing climate.

The Alaska Regional Action Plan (ARAP) for southeastern Bering Sea climate science explains efforts underway to increase the production, delivery, and use of the climate-related information required to fulfill the NOAA Fisheries mission. The goal of the ARAP is to build a portfolio of integrated, "climate-ready" management actions, based on ecosystem-based fisheries management (EBFM; Link and Bowman 2014, Link et al. 2015) tools and approaches. EBFM provides tools for addressing climate-driven changes to the Bering Sea, reducing unintended outcomes of management actions, and balancing newly emerging tradeoffs under climate-change. Some EBFM tools have already been utilized for some time in the Bering Sea to help manage fisheries under variable conditions; continued development and expansion of EBFM approaches will be needed for regional climate-ready fisheries management.

"Climate-ready" management will need to continue to be precautionary, preemptive, and flexible enough to respond rapidly to changing conditions. Specifically, NOAA Fisheries will need to provide information in a timely and efficient manner to the North Pacific Fisheries Management Council (Council) regarding both short-term changes and long-term shifts in the abundance and distribution of federally managed species (Holsman et al. submitted). To do this, NOAA

Fisheries should first rapidly scope the vulnerability and adaptive capacity of species, fisheries, and fishing communities to changing conditions. Such rapid assessments can help identify potential "winners" and "losers" of climate change and should be repeated as new data and projections become available (e.g., on a 5-10 year cycle). Following this rapid assessment, NOAA Fisheries should further evaluate climate impacts on species and fisheries, including socioeconomic impacts, as well as explore management approaches that might attenuate or amplify climate impacts. Management strategy evaluations should be broad enough to test a range of potential conditions against a range of potential management and species responses, and should be explicit in evaluation of various sources of uncertainty (e.g., process, observation, model parameterization; sensu Payne et al. 2016). Such climate change "stress-test" evaluations will be most successful if conducted in collaboration with the Council and regional stakeholders, who can help inform the range of potential management adaptive responses. Finally, both the rapid scoping and management strategy evaluations will depend on regular projections of climate change impacts on the physical and lower trophic conditions in the Bering Sea (i.e., PMEL-AFSC collaboration on the ROMS/NPZ regional model), ecosystem process studies and ecosystem monitoring to understand the effect of climate on fish, crab, and marine mammal populations, as well as on-going ship-based surveys to monitor changes in biomass, age-structure, and distribution of commercially important groundfish species in the Bering Sea and Gulf of Alaska.

As part of the NOAA Fisheries Climate Science Strategy, the ARAP conforms to a nationally consistent blue-print that guides efforts by NOAA Fisheries and partners to address information needs organized into seven science objectives that represent the process of managing the nation's fisheries in the face of changing conditions. The ARAP identifies strengths, weaknesses, priorities, and actions to implement the Strategy in Alaska over the next 3-5 years, and contributes to implementation of the Strategy by focusing on building regional capacity and partnerships to address the seven science objectives illustrated by the pyramid figure below.



As illustrated in the seven levels of the pyramid of objectives (above),the ideal elements of managing living marine resources (LMRs) under changing conditions is the same throughout the Nation. The seven science objectives generate seven questions that are described in the *NOAA Fisheries Climate Science Strategy* and are addressed in the ARAP:

1. How can climate-related effects be incorporated into ***LMR reference points***?

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

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

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

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

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

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

(Bold faced numbers in parentheses identify the number of the objective and question to which the preceding text refers.)

In the process NOAA Fisheries follows to implement the Magnuson-Stevens Act (MSA), scientific observations are made and processed into information (**7**) that can be analyzed (**6, 5, 4,**

2) to produce benchmarks of overfishing and other national standards (**1**) that inform the management (regulatory) processes (**3**). How well each of these elements is attained under the scenario of climate change in the eastern Bering Sea is the subject of this report.

The scientific infrastructure (**7**) needed by AFSC to produce the analyses and deliver the benchmarks is reasonably well developed within AFSC and its NOAA partners (OAR, NESDIS) for the eastern Bering Sea. AFSC has survey projects in place that are maintaining the long time series of physical and biological observations sufficient to identify independent trends in climate, LMRs and LMR-dependent communities (**6**). Making connections among the trends to identify the mechanisms of climate impacts (**5**) and to develop climate-informed reference points (**1**) is at times made problematic by the mismatch between biological, human dimensions and physical data sets with regard to the times and localities of the observations. The older survey projects were put in place some time before concerns about the impacts of climate change became evident, and hence physical survey platforms did not originally incorporate synoptic biology and *vice versa*. As resources permit, existing projects are being modified and new projects developed in order to integrate physical and biological observations. For example, the Recruitment Processes Alliance (RPA) combined historically independent survey efforts with field surveys to provide the improved synoptic data sets that are essential to develop climate-informed reference points (**1)**, develop harvest strategies that are robust to climate induced change (**2**), inform models of future conditions (**4**), and to identify climate driven mechanisms of change (**5)**. As our scientific infrastructure (**7**) and institutional experience increases and the skill of our models improves, AFSC will provide climate-informed reference points to the adaptive management processes (**3**) of the Council.

INTRODUCTION

Alaska is on the front lines of climate change. While temperatures are anticipated to increase globally, the largest anticipated increases and changes are expected for the Arctic including the Bering Sea, Alaska (Larsen et al., 2014). Anticipated changes depend on future global carbon emission and sequestration practices but range from an increase in summer ocean temperatures of 3º C (Hermann et al. 2016) to 8º C (IPCC 2014; Figure 1). Reductions in sea ice and sea ice driven productivity is also anticipated, especially for the southeastern Bering sea where warming may be greatest (Hermann et al. 2016). Such changes may have cascading impacts on regional food-webs that are structured by climate-driven changes to biophysical processes (Stabeno et al. 2013a).

Regional catches represent more than 60% of federal catches annually, and the Alaska Fisheries Science Center (AFSC) supports management of walleye pollock, the largest fishery in the United States exclusive economic zone (EEZ) and in many years the largest fishery globally. It is well known that ecosystem productivity in the region is shaped by thermal conditions that can oscillate in successive years between warm and cold conditions. Most fish and marine species in the region have evolved physiological and behavioral adaptations that capitalize on cold water conditions and strong seasonally-driven productivity. The strength of seasonal productivity, especially during spring months, is in turn structured by physical conditions and global wind patterns that influence the duration and extent of sea ice and the timing of ice-melt driven phytoplankton blooms (Brown and Arrigo, 2011, 2013; Sigler et al., 2014). Such conditions are expected to change markedly over the next 50-100 years as warming alters regional wind-driven circulation, sea ice extent, ocean acidity, and the structure and location of thermal refugia.

While annual climate variation has been observed to impact fisheries in Alaska, the overall impact of climate change on Bering Sea fisheries is unclear. For example, the ecological effects of reduced sea ice has previously impacted southeastern Bering Sea walleye pollock, but this fishery recovered in subsequent years when sea ice again was more widespread. These responses to annual climate variation, while temporary, allow us to understand potential impacts of future climate change. For the eastern Bering Sea pollock example, data from integrated ecosystem surveys conducted by AFSC (e.g., EcoFOCI, BASIS), provided a mechanistic understanding of the impact of stanzas (continued back to back years) of reduced/increased sea ice in spring on the food web for young of the year gadids (e.g., walleye pollock) via the interchange of lipids (i.e., fats), fish fitness during critical periods of life, and survival to older age classes (Coyle et al., 2011; Hunt et al., 2011; Heintz et al., 2013; Sigler et al., 2016). Our current understanding is sufficient to project climate change impacts for a small subset of the 21 quantitatively assessed Fish Stock Sustainability Index (FSSI) stocks in the southeastern Bering Sea; climate change is predicted to lead to reduced abundances of walleye pollock (through loss of sea ice) (Mueter et al., 2011; Ianelli et al. in press), red king crab (Long et al., 2013; Punt et al., 2014) and snow crab (both through reduced calcium carbonate) (Long et al., 2013, 2015; Punt et al., 2015; Swiney et al., 2015) and unchanged abundance of northern rock sole (Wilderbuer et al., 2013).

The Alaska Regional Action Plan (ARAP) for southeastern Bering Sea climate science is part of a national effort to explain how NOAA Fisheries works to understand the impact of climate change on fisheries. This first ARAP focuses on the southeastern Bering Sea Large Marine Ecosystem (LME). The waters of the southeastern Bering Sea support large marine mammal and bird populations and some of the most profitable and sustainable commercial fisheries in the country. Our understanding of climate effects on southeastern Bering Sea fisheries, while incomplete, is greatest among the five LMEs of Alaska. Subsequent Strategies will focus on the other LMEs (Gulf of Alaska, Aleutian Islands, northern Bering and Chukchi seas, Beaufort Sea), if funding allows. The primary customers for this information are the Council and the NOAA Fisheries Alaska Regional Office. Climate science by the AFSC is conducted collaboratively with the NOAA Pacific Marine Environmental Laboratory (PMEL). This climate science informs the ecosystem-based fisheries management (EBFM) approach implemented by NOAA Fisheries, which utilizes ecosystem monitoring to predict changes to ecological interactions and employs food-web based management tools to quantify both direct and indirect impacts of management actions on target and non-target species (Link and Bowman 2014). The multi-species approach at the core of EBFM is of particular utility for addressing compound impacts of multiple pressures and for evaluating trade-offs in conflicting mandates and objectives. Dynamic EBFM approaches can also reduce bycatch and improve efficiency for fisheries under variable and changing conditions like those expected under climate change (e.g., Hobday et al. 2016).

Climate change is expected to alter biophysical processes that structure the productivity, phenology, and distribution of many fish and invertebrate species in the Bering Sea in a way that may be deleterious for some fish stocks and favorable for others (Mueter and Litzow, 2008; Hollowed et al., 2013). Divergent responses to changing conditions may occur slowly over multiple decades (i.e., ecological drift) or as conditions approach historical extremes and species cross ecological tipping points, rapid food-web reorganization and regime shifts could result in sudden changes in abundance (< 5 years). Climate-ready management for the region will need to be flexible enough to address both short- and long-term changes, be responsive to emerging information and science, and be precautionary in order to lessen cascading impacts to biological and socioeconomic systems (Holsman et al. submitted).

Biological marine communities and regional fisheries management in the region are already adapted to succeed under variable conditions; continued advancement of "in-hand" dynamic management tools (e.g., short-term forecasts, flexible seasons, bycatch reduction measures based on thermal envelops, climate-specific biomass reference points, etc.) can help reduce near-term impacts and increase fishery efficiency. Long-term static structures (e.g., 2 million metric ton cap on southeastern Bering Sea groundfish total catch, marine protected areas, northern Bering Sea closed area) could be evaluated with management strategy evaluations to identify the need for and frequency of updating under changing conditions (Holsman et al. submitted). Thus, ensuring resilience through climate-ready management approaches will entail expanding the scope of current research and management to consider climate-driven changes.

Long-term climate science approach of the AFSC and PMEL

The long-term climate science approach of the AFSC and PMEL is composed of three parts (Figure 2): ecosystem monitoring (standard fisheries oceanographic surveys which sample from "physics to fish", to track change and provide early warnings), directed research toward understanding ecological processes (fieldwork, laboratory research, and retrospective analyses of ecosystem monitoring, to understand mechanisms of climate change), and modeling (e.g., individual-based models, food-web models, bio-economic models, management strategy evaluations, to project future conditions). The three parts-- monitoring, research on ecological processes, and projection modeling-- are the three legs of the stool on which our understanding of climate effects is seated and all three parts are necessary to meet objectives 5 and 6 of the Strategy.

Process studies are heuristic shorter term studies directed toward understanding ecological relationships (e.g., primary production rates, predator-prey relationships) or coupled biological socioeconomic relationships (e.g., fishery market responses to changes in harvest; fisher responses to management actions or climate conditions). Ecosystem monitoring consists of standard oceanographic surveys which sample "physics-to-fish" (i.e., ocean conditions, phytoplankton, zooplankton larval fish abundances, adult fish, birds,and marine mammal populations), as well as socio-economic monitoring of fish harvest, ex-vessel profits, costs and benefits of fisheries processing, and socio-economic conditions of fishery-dependent human communities. Both the ecosystem monitoring and the biological process studies typically are supported by laboratory studies (e.g., growth response to temperature) and laboratory analyses (e.g., lipid content of sampled zooplankton and fish).

Retrospective analyses are typically conducted in concert with process studies and aim to evaluate the effect of sampling method, climate and species interactions, and biological and socio-economic processes on observed relationships and patterns in the ecosystem. Retrospective analyses of data from long-term ecosystem monitoring often are conducted to detect climate effects on ecological processes. Results of retrospective analyses provide the foundation for mechanistic hypotheses of coupled climate-biological-socioeconomic systems which in-turn are tested and evaluated through conceptual and projection ecosystem modeling. Retrospective studies provide a framework for jointly understanding the results of the ecosystem monitoring and process studies. Ecosystem and bioeconomic modeling can be complex (ecosystem models that are computationally intensive) or simple (Qualitative Network Models; Puccia 1985). Dynamic models can be projected under various climate, biological, and socioeconomic conditions in order to evaluate management impacts on biological and human communities (i.e., 'Management Strategy Evaluations'). Modeling, including management strategy evaluations, are necessary to meet objectives 1 through 5 of the Strategy.

The Alaska Fisheries Science Center makes a significant investment (~$11M per year) in ecosystem and socio-economic monitoring, process studies, modeling, retrospective analyses, and management strategy evaluations in order to understand climate effects on fisheries and fishery dependent-human communities, protected species, and ecosystems. Typically this research work is part climate and part ecosystems, fish, or marine mammals; the climate part is about $4.5M, the ecosystem part is about $4.5M, and the socio-economic part is about $2M.

The long-term approach of the AFSC has led to substantial advances in our understanding of climate effects on the southeastern Bering Sea ecosystem. Some recent research topics with a climate science aspect include annual variation in oceanographic conditions (Stabeno et al., 2012a), ecological distinctiveness of the northern southeastern Bering seas (Stabeno et al., 2012b; Sigler et al., 2011), spring and fall bloom timing (Sigler et al., 2014), the relationship of juvenile fish energy density, recruitment success, and annual climate conditions (Heintz et al., 2013; Siddon et al., 2013a, b), forage fish zoogeography (Hollowed et al., 2012; Parker-Stetter et al., 2013), fish distributions and annual climate conditions (Baker and Hollowed, 2014; Smart et al., 2012a, b, 2013), marine mammal, seabirds and their prey (Sigler et al., 2012; Benoit-Bird et al., 2011, 2013a, b, c), fisheries spatial distributions (Pfeiffer and Haynie, 2012; Haynie and Pfeiffer, 20123), and Alaska coastal communities (Huntington et al., 2013a, b).

ARAP Approach

The goal of the ARAP for Southeastern Bering Sea Climate Science is to build a portfolio of integrated, "climate-ready" management actions. "Climate-ready" managment will need to be continue precautionary, preemptive, and flexible enough to predict and respond rapidly to changing conditions (Holsman et al. submitted). Specifically, NOAA Fisheries will need to provide information in a timely and efficient manner to the Council regarding both short-term changes and long-term shifts in the abundance and distribution of federally managed species (Holsman et al. submitted). For example, in December 2015, the North Pacific Fishery Management Council decided to develop a Bering Sea Fisheries Ecosystem Plan. One of the priority action modules of this plan would address climate change.

In order to develop management relevant advice on climate change, NOAA Fisheries should first

1) rapidly scope the vulnerability and adaptive capacity of species, fisheries, and fishing communities to changing conditions. Such rapid assessments can help identify potential "winners" and "losers" of climate change and should be repeated as new data and projections become available (e.g., on a 5- 10 year cycle). Following this rapid assessment, NOAA Fisheries should 2) further evaluate climate impacts on species and fisheries, as well as explore management approaches that might attenuate or amplify climate impacts. Finally, both the rapid scoping and management strategy evaluations will depend on 3) regular projections of climate change impacts on the physical and lower trophic conditions in the Bering Sea (i.e., PMEL-AFSC collaboration on a physical oceanography-nutrients-phytoplankton-zooplankton (ROMS/NPZ) regional model (Hermann et al. 2016), ecosystem process studies and ecosystem monitoring to understand the effect of climate on fish, crab, and marine mammal populations, as well as on-going ship-based surveys to monitor changes in biomass, age-structure, and distribution of commercially important groundfish species in the Bering Sea and Gulf of Alaska.

The first step of rapid scoping consists of a qualitative assessment currently underway for the southeastern Bering Sea. This climate vulnerability assessment will qualitatively assess species vulnerabilities to climate change and also provide guidance on research prioritization. The vulnerability assessment uses expert elicitation methods to quantify a species' exposure and sensitivity to expected climate change (Hare et al. 2016). Vulnerability, as used here, refers to a reduction in a species' productivity or abundance associated with an expected change in climate. In addition, an ocean acidification risk assessment (Mathis et al., 2015) was conducted by scientists at the NOAA Pacific Marine Environmental Laboratory and Alaska Fisheries Science Center. This assessment predicted that the intensity, extent and duration of ocean acidification in the coastal areas around Alaska will increase with the highest socio-economic risk accruing to regions in southeast and southwest Alaska that are highly reliant on fishery harvests and have relatively lower incomes and employment alternatives. Rapid scoping is a qualitative assessment of climate effects on fisheries (Morrison et al. 2016). Rapid scoping is a good first step for identifying "species of climate-concern" that might be the focus of future field research programs (if more data or mechanistic understanding is needed) or more quantitative analyses (if data is sufficient). For many species, our present ability to project future impacts is limited by our understanding of ecological processes, but for a small subset of the 21 FSSI stocks in the southeastern Bering Sea, quantitative projection may be possible immediately.

The second step of the climate strategy is management strategy evaluations for those species identified as species of climate-concern by the rapid assessment and for which there is also sufficient mechanistic understanding of climate-biological-socioeconomic interactions. Management strategy evaluations should be broad enough to test a range of potential conditions against a range of potential management and species responses, and should be explicit in evaluation of various sources of uncertainty (e.g., process, observation, model parameterization;

sensu Payne et al. 2016). Such climate change “stress-test” evaluations will be most successful if conducted in collaboration with the Council and regional stakeholders, who can help inform the range of potential management adaptive responses.

Finally, the third approach of the region’s climate strategy will be to produce regular short (.e.g, 9 mo), medium (e.g., decadal), and long-term (e.g., 100 year) projections of climate conditions and biological and socioeconomic responses. Such information can help inform monitoring efforts in the upcoming year (as was the case for intensified studies in 2015 to help understand impacts of anomalously warm spring conditions forecasted 9 months prior), provide context for harvest recommendations (e.g., if warm conditions are anticipated to intensify over the decade), or eventually climate-specific harvest reference points and limits (i.e., through climate-enhanced stock assessments or climate-specific management actions). The latter will need to be vetted through management strategy evaluations and modeling efforts, and revisited when rapid assessments are updated periodically.

The independent steps described above are taking place as part of the integrated climate strategy of the AFSC. Scientists working on each step are working as cross-cutting teams to ensure that knowledge and new insights gained through research is transferred in an efficient manner.

Challenges for management

Challenge 1: Improved detection.

For management to be most effective under rapidly changing conditions, we will need to expand our suite of methods for detecting latent changes, --i.e., climate-change driven shifts in the ecosystem that may be masked as climate variability or hidden by lags between monitoring and impacts. Climate-enhanced and EBFM approaches hold promise for shifting management focus from retrospective to preemptive detection of climate-driven changes. Explicitly considering the impacts of shifting conditions on production through a combination of short-term forecasts and climate-enhanced models may help also prevent unintentional overfishing (sensu Szuwalski and Punt 2012, Perishing et al. 2016) or reduce bycatch loss of non-target species (e.g., Hobday et al. 2016).

Challenge 2: Representative fishing pathways.

Scientists at the AFSC recognize that just as global climate modelers required representative concentration pathways for greenhouse gas accumulations in the atmosphere, that representative fishing pathways (RFPs) are needed for implementation of the ARAP. These pathways are meant to represent the collection of possible future directions for fisheries management in the Bering Sea. Identifying representative fishing pathways that provide sustainable options for fishery management under climate change is a complex endeavour. However, if climate change impacts are projected using a suite of management strategies that do not realistically represent the expected responses of managers, fishers and fish dependent communities, they will not provide realistic representations of the future.

The ARAP plans to project the performance of RFPs by identifying the suites of management strategies (mathematically represented as a series of control rules and constraints within an optimization) that collectively result in advancing towards a particular overarching suite of pathways for management. The Council has some experience with this exercise. In preparation for the 2001 Programmatic Supplemental Environmental Impact Statement, the Council was challenged to identify a suite of fishery pathways and the associated management strategies to achieve that pathway. The ARAP recognizes that identifying the RFPs for management of fisheries under changing climate conditions will also require an iterative approach where public engagement is a key element in identifying alternatives.

The NOAA Fisheries Climate Science Strategy is designed to provide simulation tools to depict, to the extent possible, the expected outcome of the integrated processes of global climate change, marine ecosystem responses, fisher's choices, shifting public policy viewpoints in the face of the global demands for marine protein under increasing population growth, shifting public policy opinions, and shifting international markets. These are uncertain processes and therefore as noted above, techniques to represent the full suite of scenario uncertainty, process uncertainty, and structural uncertainty will be critical. Characterizing the full range of fishery pathways in this document would be premature. Therefore, we review a subset of the issues that managers may face and hypothetical management tools that could be considered when forming a RFP.

Challenge 3: Reference biomass levels.

From a single species view-point the flexibility of existing standards is likely to remain, especially the provisions that address options to cope with environmental change. The MSA and associated national standards provide clear guidelines for building sustainable fisheries within the US. These guidelines are built on fundamental rules of population dynamics and control rules identify biological reference points to prevent overfishing and rebuild depleted stocks. Under changing climate conditions these fundamental rules of population dynamics which are founded on principles of growth, reproductive potential, and longevity, will continue to be relevant. However, under some RFPs, the concepts of equilibrium states of nature will be violated for stocks that are affected by climate change (Szuwalski and Hollowed 2016). In particular, reference biomass levels are a key part of the harvest control rules followed by the Council. If population productivity (governed by reproductive success, growth, maturation schedule, mortality rate) is affected by climate change, then first this change has to be detected and identified as distinct from a fisheries effect, and the reference biomass adjusted. Detecting this change can be challenging. Eastern Bering Sea snow crab biomass oscillated dramatically during

1988-2000; differentiating the climate and fisheries signals was controversial (Oresanz et al., 2007; Parada et al., 2010). The challenge will be to develop sufficient understanding of the ecosystem to reasonably project the implications of changing climate on the population dynamics of vulnerable species. One approach is to consider the implications of plausible broad forecasts related to how biological parameters may change in the future as a way to assess the robustness of management strategies, rather than attempting specific predictions *per se* (Punt et al., 2013). Another approach is to consider fixed exploitation rate strategies to cope with the effects of climate change (Walters and Parma, 1996).

Challenge 4: Shifts in ecosystem dynamics.

From an ecosystem view-point, shifts in the carrying capacity, changes in energy pathways, changing growth and maturity schedules, altered species compositions, and different levels of species interactions (competition and predation) are all expected to alter the processes governing species co-existence and productivity within the Bering Sea (Wilson 2011, Hollowed and Sundby 2014). Projecting these shifting processes using models of different levels of ecosystem complexity will provide a landscape for anticipating possible futures. Understanding interaction strengths between species will be a critical element of the ARAP. Multi-species assessments provide insights into the complex decisions that emerge from shifting predator prey interactions. Managers can select from surfaces of theoretically sustainable harvest strategies, but these surfaces may change if historical interaction strengths are no longer representative of encounter probabilities or diet preferences. At the whole ecosystem level, shifting climate may provide new environmental gateways for species from different zoogeographic provinces. These changes may necessitate revisiting the system level caps on groundfish fisheries.

The challenge for fisheries management will be to identify critical thresholds for when or if current management should be altered to sustain fish and fisheries, and to develop alternatives that will mitigate climate change impacts. In the North Pacific, NOAA has considerable experience with abrupt shifts in marine production. While recognition of a long-term shift in production can be recognized retrospectively, the framework needed to correctly anticipate a pending shift remains elusive. Furthermore a high level of ecosystem understanding is necessary to correctly adjust a harvest control rule to the productivity regime that emerges after a shift. With this in mind, defining harvest control rules that adjust to changing productivity will be particularly desirable. In the case of the Bering Sea, the sloping control rules used in crab and groundfish management are good examples of an adaptive harvest strategy.

Under some emission scenarios, environmental conditions could be altered to such an extent that the Bering Sea becomes uninhabitable for some presently abundant populations. While the Endangered Species Act provides protections for species at risk of extinction, such as prohibition of take, it may not be adequate to conserve species whose required habitat is irreversibly altered.

This limitation highlights the need for rapid vulnerability assessments followed by RFPs that identify management provisions and mitigation strategies to sustain the vulnerable species. Projection models that address population viability will be needed to evaluate the performance of mitigation strategies that dampen the rate of declines of populations stressed by changing climate.

Challenge 5: Fishers' choices.

The current ecosystem approach to fisheries management adopted by the Council is far more complicated that the collective suite of single species control rules and system level caps. This complex suite of management strategies includes catch share programs, marine spatial provisions and incentives to comply with bycatch controls and other constraints. The Bering Sea ARAP is designed to evaluate how these provisions will perform under changing species compositions, shifting spatial distributions, changing vital rates and phenology of target and non-target species. A key element of this study will be to model fisher's choices as well as fish responses to climate change. The Bering Sea ARAP will utilize multispecies technical interaction models that simulate how fisheries interact as part of its evaluation of the performance of alternative harvest strategies

Catch share programs may limit fisher's choices when climate change affects fish and crab populations. Typically these programs have some limits on tradeability. Fishing companies may be faced with difficult financial choices when their shares occur for a population declining due to climate change. One goal of the ARAP is to provide long-term predictions as a basis of rational business decisions. Another goal is to motivate providing some flexibility in future regulation writing to promote rules that can be adaptive in the face of climate change and effects on fish and crab populations.

The Council has a long history of developing novel strategies to address management challenges. The NOAA Bering Sea ARAP is designed to work within this innovative, iterative, and transparent management process. The public, government, academic and fisheries constituents will all play a role in formulating representative fishery pathways. As has been the case throughout the history of the Council, this management landscape is expected to evolve over time as our knowledge of the system improves. Developing scenarios that depict this evolution will be critical to the success of the ARAP.

Challenge 6: Balancing process research and ongoing ecosystem monitoring.

Understanding climate-change impacts on marine ecosystems requires bottom-to-top understanding of biophysical, trophodynamic, and socioeconomic processes structuring coupled human-biological systems like the Bering Sea. Thus, integration and coordination of various field sampling programs that provide data on changes in multiple levels of the biological or social system is important for modeling climate-change impacts on fish and fishery-dependent communities. As a result, conducting the research necessary to understand species' responses to climate variability is challenging. Field, lab, and model-based research are necessary to gain this understanding. This process research focuses on providing mechanistic explanations for species' response to climate variability and is strengthened when structured by clear, testable hypotheses. In addition, process research depends on an integrated approach, bringing together scientists from multiple disciplines. While usually fruitful, integrated ecosystem research is complex, time consuming and can be costly. As a result, we cannot quickly determine species' responses to climate variability and instead must conduct the research over several years and must prioritize the research objectives.

The AFSC is challenged by its responsibility for scientific research in five large marine ecosystems (LME) including southeastern Bering Sea, Aleutian Islands, Gulf of Alaska, northern Bering/Chukchi seas, and Beaufort Sea. LMEs are relatively large areas of ocean space of approximately 200,000 km^2 or greater, adjacent to the continents in coastal waters where primary productivity is generally higher than in open ocean areas. Unlike geographical ocean boundaries, LMEs are defined by ecological, rather than political or economic, criteria. Funding is insufficient to study all 5 LMEs in Alaska to the extent required to fully understand climate effects. Consequently, research and monitoring efforts need to be prioritized. This prioritization will affect the balance of process research and ongoing ecosystem monitoring as well as the tempo of each (e.g., annual versus biennial surveys).

The Scientific and Statistical Committee of the Council has addressed this prioritization by expressing strong support for fisheries oceanographic surveys to occur on a yearly basis "while we are trying to identify the effects of climate change and develop the means of making "long-term" predictions of its impacts". However, ongoing review of the balance of scientific activity is necessary to ensure that all research priorities are adequately addressed. This may require greater focus on some components over others in any particular year, while not compromising the integrity of long-term data-sets. In this, management strategy evaluations can be used to evaluate the strengths of different sampling strategies and prioritization scenarios under climate change.

One way these challenges are met is to leverage process research from ongoing monitoring seasonal fisheries surveys. For example, oceanographic sampling and cross-trophic sampling is conducted on all fisheries surveys to provide holistic ecosystem information. Surveys are conducted in all LMEs, adopting a biennial approach to efficiently allocate resources and preserve an ongoing presence in all of Alaska's marine ecosystems. Biennial surveys permit extended spatial sampling beyond that which was available in prior years due to increases in day at sea allocation for individual projects. Examples of this success include a comprehensive gridded spring survey that fully encompasses the known shelf spawning areas of walleye pollock in the Bering Sea and an extension of the Gulf of Alaska spring survey for larval walleye pollock from Prince William Sound to Unimak Island to fully examine the contribution of spawning stocks beyond the Shelikof Strait spawning aggregation to the western Gulf population. Likewise upward looking acoustics in Shelikof Strait provide knowledge of climate impacts on timing of spawning.

Both process research and ecosystem monitoring are necessary as they represent different facets of understanding climate impacts. For example, process studies allow for ground-truthing of mechanistic linkages in between the physical environment, biological processes, and socio-economic components of the system and to check that oceanographic and ecosystem models successfully mimic observations, such as temperature, salinity, etc. Ongoing, regular ecosystem monitoring depends on ship-based fishery independent surveys and fisheries oceanography research and are the backbone that provides baseline information. Additional data is acquired through new technologies such as sail drones, as well as, citizen science, ships of opportunity, underway oceanography (Chla, oxygen, nutrients) and acoustics (zooplankton); and tagging (acoustic, archival, traditional). Finally partnerships with PMEL and other research institutions contribute critical parts to the process research and ecosystem monitoring.

Integrated ecosystem research in the southeastern Bering Sea has focused on walleye pollock, Pacific cod, and arrowtooth flounder, as well as some other flatfish species such as northern rock sole. The most has been learned about walleye pollock, in particular uncovering the explanation for why walleye pollock recruitment declined during the warm years of the early 2000s, and then recovered during subsequent cold years (Hunt et al., 2011; Sigler et al., 2016). This research identified late summer energy density of age-0 walleye pollock as a key characteristic of successful recruitment and linked high energy densities to abundant large crustacean zooplankton (Heintz et al., 2013). These steps are reasonably documented, but the factors leading to abundant large crustacean zooplankton, while hypothesized, have only limited documentation. Thus the question arises to decide: what research is next? Should research focus on completing the walleye pollock story by focusing on processes affecting zooplankton production? Alternately, should research focus on fish or crab species other than walleye pollock? In addition, the story may be more complex. For example, there is some evidence that in the summers of warm years, micro-zooplankton play a major role in the transfer to upper trophic levels, adding an additional trophic level, and thus reducing the biomass of trophic levels above them by roughly 90%, including juvenile walleye pollock (Coyle et al., 2011).

In general, the AFSC addresses research prioritization through cross-Divisional and cross-Program planning. Typically groups of scientific staff meet to discuss, write new research plans, which then are reviewed and approved by the science managers at the AFSC. These plans often are published as technical reports and posted on the AFSC website. As part of the ARAP, we envision research prioritization also occurring through a three-tiered approach that can guide research prioritization (as described earlier): 1) rapid climate vulnerability assessment (CVA) to prioritize research and highlight gaps in knowledge, 2) short-term forecasts will test our predictive capacity and highlight research/process oriented gaps in knowledge about physical-biological-human system couplings, 3) long-term MSEs can be used to evaluate different sampling strategies. In this approach the following questions should be addressed.

Outreach

Outreach for the ARAP has occurred through an organized effort that began with a news release announcing the first ARAP draft. A web page serves as a central point for distributing information and soliciting input on the draft. As of March 16, 2016, the draft ARAP has been downloaded 100 times. A presentation has been made several times, including to the North Pacific Fishery Management Council, the Council Scientific and Statistical Committee, and in University and web-based seminars. Letters seeking written comments have been sent to Alaska Native organizations, Community Development Quota (CDQ) corporations, environmental groups, fishing industry groups, and the State of Alaska. In addition, most of these groups hear presentations and have a chance to comment at Council meetings.

Climate science information is brought forward to the North Pacific Fisheries Management Council. A primary outlet is the Ecosystem Considerations chapter of the Stock Assessment and Fisheries Evaluation report, which has been produced annually for 20 years. This report includes both ecosystem information as well as climate indicators such as average bottom temperature and krill biomass. The climate and ecosystem information also are applied to explain recruitment variation in individual species, which is available for some species with sufficient research and understanding. The latter information is particularly useful to justify catch quota adjustments for the high-volume, high-value fisheries of the southeastern Bering Sea.

ASSESSMENT

The NOAA Fisheries Climate Science Strategy calls for assessment of progress on seven objectives. Efforts are underway (i.e., relatively new), or ongoing (i.e., well-established) for the southeastern Bering Sea, however progress and the rate of progress varies substantially among objectives. For example, implementing the development of decision processes that can incorporate and respond to changing climate conditions (Objective 3) awaits the more precise information and improved tools now being developed under other objectives. The Council has an adaptive management process that has occasionally incorporated climate change information into its decisions in the past on an *ad hoc* basis. Routine incorporation of climate-informed reference points under the formal mathematical criteria of accepted stock assessment models awaits future developments. This Climate Science Strategy will complement a Fisheries Ecosystem Plan currently being developed for the southeastern Bering Sea.

In this section, we assess the status of progress on the seven objectives for the southeastern Bering Sea. An action plan for the next 3-5 years follows in the next section. For each objective, the status of progress is followed by brief descriptions, in bullet form, of specific projects. Initiation or completion of some objectives depends on other work. As noted above, initiating development of an adaptive decision process (Objective 3) depends on making more progress on several other objectives (1, 2, 4 and 5). For further example, the identification of robust management strategies (Objective 2) depends on identification of future states of marine and coastal ecosystems (Objective 4).

Objective 1: Identify appropriate, climate-informed reference points for managing living marine resources (LMRs).

Status: Underway.

- **Single and multi-species models with climate forcing.** The purpose of this project is to incorporate climate effects into single and multi-species models (Figure 3), which are then used to derive climate-informed reference points. The general approach is: 1) statistically fitting population-dynamics models to historical survey and fishery biomass data in order to estimate recruitment, historical harvest rates, selectivity, and annually varying natural mortality; 2) subsequent fitting of the recruitment estimates from each model to spawning biomass and environmental covariates (e.g., cold-pool area, bottom temperature, cross-shelf transport, zooplankton biomass) from a hindcast of a coupled physical-biological oceanography model (Regional Ocean Modeling System-Nutrient Phytoplankton Zooplankton Detritus model, ROMS-NPZD); 3) use model-selection criteria (AIC) to select the subset of climate indices that best fit each model-specific set of recruitments; and 4) project the model forward in operating mode for each climate scenario to derive recommended harvest rates to meet management objectives under future climate conditions.

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

Status: Underway.

The identification of robust strategies depends on identifying future states of marine and coastal systems, as described in Objective 4.

- **Council Bering Sea Fishery Ecosystem Plan.** The development of a Fishery Ecosystem Plan (FEP) for the Bering Sea Management Area was approved by the Council in December 2015. The FEP is expected to include a climate module that would: 1) synthesize current climate change project outcomes; 2) prioritize species for management strategy evaluation (MSE); and 3) run MSEs on specific species and scenarios identified by the Council. The climate module also would include predictions of the future spatial distributions of most commercial fish and crab species (i.e., predictions of future essential fish habitat). This will take place on a 5-7 year cycle and will be summarized in an eastern Bering Sea Climate Change and Fisheries Assessment Report.

- **Management strategy evaluations (MSEs).** The purpose of this project is to identify harvest control rules that remain effective as climate changes. This approach relies heavily on retrospective studies and process oriented research to identify the mechanisms underlying recruitment variability (see the Recruitment Process Alliance; RPA) or other responses (e.g., shifts in spatial distribution, growth, or phenology) to changing climate conditions. These studies inform the response surface and projection using the estimated relationship (see Obj. 1), except in each simulation year of the projection, the harvest strategy for each species in the model is determined from a recommended harvest control rule and "realized harvest" is modeled as a function of fisher behavior, spatial distribution of fish, and economic pressures using socio-economic models. These models track the "true" and "perceived" (including sampling/measurement and process error) biomasses of the population, wherein, the harvest control rule is applied to the "perceived"population. The realized harvest is then fed into the starting conditions for the next year of the simulation along with "sampled" survey biomass (e.g., index of biomass with error). Management strategies will be evaluated relative to agreed upon benchmarks for sustainable fisheries management within an ecosystem context.

- **Alaska CLIMate Project (ACLIM).** This project involves a suite of models designed to provide scenarios of future fish production under a variety of climate and fishing scenarios. The project is the U.S. Bering Sea node of the ICES/PICES Strategic Initiative on Climate Change effects on Marine Ecosystems (SICCME). The SICCME effort is coordinating research nodes in China, Japan, Korea, Russia, the California Current, the Gulf of Alaska, the Pacific Islands, the Barents Sea, Georges Bank/Gulf of Maine, the Gulf of Mexico, the Norwegian Sea, the North Sea, the Baltic and possibly the high Arctic. The goal of ACLIM / SICCME is to provide quantitative scenarios for future distribution and abundance of fish and fisheries by 2019/2020. The ACLIM Bering Sea node features a suite of models that represent a full range of structural complexity ranging from single species projection models (see above) to fully coupled end-to-end models (FEAST) (Figure 4), which allows tracking of different sources of uncertainty in the projection modelling effort. Projected scenarios will be presented to regional fishery management councils, industry and other non-governmental organizations to seek input and advice on the realism of the harvest strategies. The planned outcome is the identification of the most realistic representation of future responses of fishers and fish to changing climate with the expressed goal of identifying strategies that are robust to changing ocean conditions.

- **Multispecies technical interaction model.** The Council adopted a management approach that incorporates an ecosystem approach to fishery management as its goal. Within this management framework the Council includes protocols that explicitly consider the implications of mixed stock fisheries relative to single species management targets. In addition, the Council imposes several protocols to address species interactions including: prohibited species caps, ecosystem level caps on total groundfish removals, and catch deterrents for forage species. The Multispecies technical interaction modelling effort simulates these interacting constraints on future catch and serves as a tool for evaluating the implications of proposed management changes on catch. The model dynamically projects future fish responses to climate variability and change and estimates future catch within existing or proposed constraints. As such this tool provides the best expectation of future biological reference points used to estimate future catch within the Bering Sea under changing climate conditions. This model is used to inform the multi-model stock projection models used in ACLIM by generating future representative fishing pathways.

- **Belmont Forum project.** This project will synthesize information from completed and ongoing regional studies conducted by Japan, the USA and Norway to examine how climate impacts in the Subarctic to Arctic transition zone may affect future marine ecosystems of the Atlantic and Pacific Arctic (including the southeastern Bering Sea), their resource management, and the socio-economic status of human communities in the regions. Natural and social scientists will meet with stakeholders from the fishing industry, regional management bodies, governments and coastal communities in three workshops to assess whether the biological, management and socio-economic systems have the resilience and adaptive capacity to cope with anticipated changes. These workshops will: 1) review and synthesize impacts of climate change on components of Arctic marine ecosystems; 2) compare and contrast the impacts in the Atlantic and Pacific sectors of the Arctic; 3) identify major issues of concern, including biological and socio-economic threats and opportunities, from both biological and socio-economic perspectives; 4) review the ability of current management frameworks to adapt to likely changes; and 5) assess the resilience and adaptive capacity of fish, fisheries, other living resources, resource-dependent human communities, and resource management institutions to future climate change.

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

Status: A work in progress.

The Council currently has a process that adapts harvest actions to changing measurements from fishery independent surveys. Changes in fishery independent surveys and other direct observations are used to adapt fishing mortality to estimates of biomass for those stocks on which such information is available. What is not well worked out is how and when the North Pacific Fishery Management Council should react to climate-informed reference point changes. Information on changes in the ecosystem, including climate change, for the area of this ARAP are presented annually to the Council. Implementing Objective 3 is an area that needs considerable attention, discussion, and education. See the earlier "Challenges for management" section. This discussion should engage all subsidiary bodies of the North Pacific Fishery Management Council, as well as the Alaska Regional Office. The two phase approach developed by ACLIM to involve the Plan Teams, Scientific and Statistical Committee, and Ecosystem Committee should provide a starting point for these discussions.

These processes are not well worked out because management targets for fishing mortality and spawning biomass are often calculated by assuming stationary population processes, but under climate change this assumption may be violated. Frameworks for incorporating non-stationary responses of exploited populations under the changing influence of the environment are needed. For example, climate-enhanced single- and multi-species assessment models, conditioned on variable trophic and environmental conditions, can be projected to derive climate-specific harvest reference points (Moffitt et al. 2015, Holsman et al. 2015).

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

Status: Underway.

- **Ocean model projections.** Coupled physical/biological models (ROMS-NPZD) are used to downscale global climate change to the ecology of subarctic regions, 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 vs. small zooplankton in relation to ice cover. Environmental indices are derived from these ocean models. A multivariate statistical approach is used to extract the emergent properties of a coupled physical/biological hindcast (ROMS-NPZD) of the Bering Sea for years 1970–2009, which includes multiple episodes of warming and cooling (e.g. the recent cooling of 2005–2009), and a multidecadal regional projections of the coupled models, driven by an IPCC global model forecast of 2010–2040. The ocean models were developed with funding from outside the AFSC and continue to be improved and developed with both AFSC and non-AFSC funding. All projections are based on a suite of selected IPCC models, the IPCC (CMIP3 and CMIP5) model evaluations, which were conducted and funded by PMEL exclusively. The importance of this step cannot be overstated as a poor choice of global models to downscale can render poor and highly uncertain regional forecasts (e.g. multiple global IPCC fail to capture sea ice on the EBS shelf).

- **Incorporate ocean acidification effects into existing ocean models.** An ocean acidification module is being added to the coupled physical biological model (ROMS-NPZD). The addition of an ocean acidification component (and nitrogen, carbon cycles, etc.) is reliant on chemical oceanographers from PMEL and the University of Washington, and their role will increase as this model is developed.

- **Climate-enhanced single species projection models.** Climate-enhanced single species projection models have been completed for walleye pollock, Pacific cod, arrowtooth flounder, and Bristol Bay red king crab and northern rock sole and provide 20- to 50-year forecasts of their abundance, including a measure of the uncertainty of these forecasts. Extensions of these models that include shifting overlap of predators and prey have been tested for the Bering Sea. These projection models, while based on functional relationships, depend on a detailed understanding of ecological processes affecting population productivity and thus benefit from process studies. See objective 1 for more information on the approach of these models.

- **Climate-enhanced multi-species projection models.** The climate enhanced multispecies statistical catch-at-age model (CEATTLE) estimated population dynamics of walleye pollock, Pacific cod, and Arrowtooth flounder under future climate and trophic conditions. The model uses inputs of temperature and climate indices from downscaled climate hindcasts and projections to produce biological reference points (e.g., $F_{40\%}$) conditioned on future climate scenarios, trophic interactions, and predator harvest rates. See objective 1 for more information on the approach of these models.

- **Climate vulnerability assessment for the southeastern Bering Sea.** A climate vulnerability assessment for the southeastern Bering Sea, which will qualitatively assess species vulnerabilities to climate change and provide guidance on research prioritization, currently is underway. The vulnerability assessment uses expert elicitation methods to quantify a species' exposure and sensitivity to expected climate change. Vulnerability, as used here, refers to a reduction in a species' productivity and or abundance associated with a changing climate, both climate change and multidecadal climate variability. This vulnerability assessment will be expanded in the future as the species vulnerability relates to LMR dependent human community vulnerability.

- **Identify human community dependence on LMRs and effects of climate change.** A set of social and fisheries engagement indices were developed using data for human communities throughout Alaska in an attempt to better understand how dependent individual communities are on LMRs, how those communities may be differentially affected by changes in resource management and other external perturbations, and how well each community may be able to adapt to such impacts. In addition, work has been done to develop similar indices focusing on how much communities may be affected by the physical effects of climate change (e.g., sea level rise, melting permafrost, changes in sea ice distribution). Combined, these indices are intended to be used to better understand the overall impact that climate change might be expected to have on communities across a broad spectrum, both geographically and socio-economically. These indices will ultimately be linked to the climate vulnerability assessment for the southeastern Bering Sea that is described above.

- **Arctic Council, AMAP, impacts on coastal communities.** The Arctic Monitoring and Assessment Programme (AMAP) of the Arctic Council is preparing a report entitled, Adaptation Actions for a Changing Arctic (AACA) at the request of the Arctic Council. The AFSC is developing Chapter 6 of AACA on the impacts of development in the Bering/Chukchi/Beaufort area, which focuses on the consequences of environmental, economic, and cultural/social changes on people in the Arctic at present and as may be anticipated in the next 10-30 years. The orientation of this chapter is on the consequences of such changes for the people of the Arctic. The report is expected to be released during the second half of 2016. Loss of sea ice is projected to increase both the number and volume of ship-based oil spills. The acute and cumulative impacts of increasing rate of introduction of hydrocarbons into the coastal environment is expected to threaten food security of subsistence cultures and it may also lead to the disintegration of subsistence dependent coastal communities based on case studies now in the literature.

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

Status: Ongoing.

- **Bering Sea Project.** The Bering Sea has been the focus of a 40-year history of studies on processes underlying recruitment of walleye pollock, as well as, biological and physical oceanography. The region has been the beneficiary of a suite of integrated interdisciplinary research efforts including Bering FOCI, the Southeast Bering Sea Carrying Capacity Program, and the Inner Front Study. An integrated ecosystem research program recently was completed in the eastern Bering Sea (Bering Sea Project, 2007-2014) (Figure 5). The most comprehensive integrated ecosystem assessment ever conducted was completed, revealing how climate cycles affect the Nation's largest fishery. This research has been continued at a smaller scale and has focused on understanding recruitment processes of important southeastern Bering Sea fish species (Recruitment Processes Alliance).

- **Southeastern Bering Sea Ecosystem Assessment research program.** Research goals are to identify and quantify the major ecosystem processes in the southeastern Bering Sea that regulate recruitment strength of key groundfish species. In particular, timing and location of spawning of adult gadids over the southeast Bering Sea shelf, as inferred by observations of egg and larval concentrations and distributions, is important to management of the fishery, and data on relative abundance, distribution, and condition of age-0 pollock are critical to predicting year class recruitment to age-1. We focus on recruitment success of groundfish species because large swings in the abundance have occurred, mitigated by climate, despite precautionary fishing levels. Research emphasizes processes and events that occur during the first year of life. This is a critical period in their life history where climate change and variability have the greatest impact on marine survival. The survey components of this research includes biennial seasonal surveys of the southeastern Bering Sea for groundfish larvae, age 0 and 1 groundfish as well as other biotic and abiotic variables (e.g. bottom temperature, zooplankton) that are used in the Ecosystems Considerations chapter as part of the Integrated Ecosystem Assessment approach.

  Process studies and retrospective studies are core tools for the development and testing of conceptual models and identifying functional responses linking fish distribution, abundance, growth and phenology of fish. In prior years, collections of demersal species (flatfish, crab) had been included but those collections have ceased in an effort to focus resources on understanding midwater species, in particular age-0 walleye pollock. In the case of the Bering Sea there is a 40 year history of recruitment studies on processes underlying recruitment of walleye pollock, biological and physical oceanography. These projects have provided an integrated understanding of several ecosystem processes within the region. Scientists within the AFSC continue to conduct retrospective studies to update time series with new observations to evaluate the skill of past relationships in predicting fish responses. The AFSC places a high priority on incorporating these proposed relationships into stock assessments, short-term stock projections, and long-term stock projections.

- **Ocean Acidification research.** Research focuses on commercially important fish and shellfish species and coldwater corals. The AFSC conducts studies on king and tanner crabs, coldwater corals, pollock, cod and northern rock sole. These experiments are conducted in Kodiak, Alaska, and Newport, Oregon, where species-specific culture facilities and experience are available. Bioeconomic models of Alaskan crab fisheries are being used to forecast fishery performance for a range of climate and ocean acidification scenarios.

- **Fur seal research.** The most recent estimate of northern fur seal pup production on the Pribilof Islands indicated that the overall production had decreased by approximately 45% (annual rate of 3.7%, SE = 0.48%) since 1998. The reason for this steady decline is unknown, but may include direct and indirect effects of fishery competition as well as climate (e.g., mediated by prey availability and distribution). This trend is in contrast to the growing population of northern fur seals on Bogoslof Island to the south in the eastern Aleutian Islands. Possible demographic mechanisms are being assessed by collecting detailed life-history information in longitudinal studies of individually tagged animals. In summer and fall of 2015, the Marine Mammal Laboratory deployed 50 satellite tags on adult females and pups at St. George Island (20 adult females, 20 pups) and Bogoslof Island (10 adult females) to help understand potential behavioral and demographic responses of northern fur seals to environmental perturbations experienced during the winter migration as a result of ongoing El Nino conditions. In the summer of 2016 another project will use satellite telemetry to measure summer foraging behavior in relation to prey availability measured from the mid-water acoustic survey. This project will link fine-scale changes in fur seal foraging behavior with measures of pollock distribution and abundance in real time.

- **Economic effects of climate change.** Past research has focused on Bering sea pollock and cod and has shown that abundance, the size of the cold pool, and the age structure of the population interact with management actions (e.g., salmon bycatch measures) to determine the spatial and temporal distribution of fisheries. Current work is also underway on the Amendment 80 fishery, composed of bottom trawl vessels fishing for yellowfin sole, flathead sole, rock sole, Atka mackerel, and Pacific Ocean Perch. More work is needed on other species and to consider how to minimize the negative economic impacts on different stakeholders and LMR dependent communities.

- **Social and human community effects of climate change.** To date, research on the effects of climate change on fisheries dependent communities has been limited to the development of indices related to community exposure to the bio-physical effects of climate change, community dependence on fisheries, and adaptive capacity for responding to the effects of climate change. Further research is needed to extend this higher level methodology to specific climate change impact projection scenarios so that AFSC can better understand how changes in recruitment and abundance will ultimately affect fisheries dependent communities.

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

Status: Ongoing.

- **Alaska Marine Ecosystem Considerations and Integrated Ecosystem Assessment**. The Ecosystem Considerations report is produced annually to summarize information about the Alaska Marine Ecosystem for the North Pacific Fishery Management Council, the scientific community and the public. The report includes ecosystem report cards (Figure 6), ecosystem assessments, and detailed ecosystem status and ecosystem-based management indicators for the Bering Sea, Aleutian Islands, Gulf of Alaska, and Arctic ecosystems. The report includes current climatic conditions as well as projections (e.g., 9 months) of physical and biological conditions that may impact fish and fishery productivity (e.g., cold-pool area). First developed in 1995, the report has a long history as a vehicle for presenting current ecosystem status to the Council. The annual review by the Council influences each subsequent iteration of the report, creating an adaptive product that can be flexible as issues and scientific knowledge develops

  The integrated ecosystem assessment (IEA) program builds on the Ecosystem Considerations report to synthesize ecosystem information, including climate impacts, on multiple marine sectors including fishing. IEAs provide a framework for incorporating indicator-based ecosystem assessments, risk assessments and management strategy evaluations. Amongst other things, the Alaska IEA program provides support for modelling efforts to project short and long term effects of climate impacts on fish and fisheries in the southeastern Bering Sea and to assess the cumulative impacts and risk of long-term climate change on the Bering Sea ecosystem and dependent human communities.

- **Standard ecosystem monitoring.** Ecosystem trends are monitored through a combination of standardized groundfish and crab resource assessment surveys, fisheries oceanography, seabird, and marine mammal surveys, including ships of opportunity, diet collections, and fisheries observer collections. The standard set of fisheries oceanography surveys are spring and late summer cruises, occupied on a biennial basis, which cover much of the southeastern Bering Sea (Figure 7). In addition, four oceanographic moorings are located along the 70-m isobath. Seabird surveys often are conducted, usually aboard vessels of opportunity, including NOAA surveys. Marine mammal surveys are less common and typically are independent surveys (e.g., northern Bering Sea ice seal survey during 2012-2013). The surveys typically also monitor other aspects such as the food web (via diet collections) and bioenergetics.

- **Loss of Sea Ice research.** Northern Bering Sea surveys will enumerate commercially important shelf species such as snow crab, yellowfin sole, and juvenile salmon which have distributions extending beyond the current area of the southeastern Bering Sea surveys. The resulting survey effort will cover most of the eastern Bering Sea shelf and will be repeated biennially.

- **Coastal assessments.** Nearshore habitats are essential to the functioning of marine ecosystems and LMR-dependent communities in Alaska. Climate change is accelerating the pace of coastal erosion, which determines the ability of coastal habitats to support LMR. AFSC coastal assessments are quantifying and identifying fish habitats in the eastern Bering Sea and elsewhere in Alaska through nearshore fish surveys and coastal habitat mapping.

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

Status: Ongoing.

- **Existing "Science Enterprise" including standard surveys and stock assessments.** The mission of the Alaska Fisheries Science Center is to generate the scientific information and analysis necessary for the conservation, management, and utilization of the region's living marine resources. To meet this mission, the AFSC devotes more than 80% of its resources toward standard surveys, stock assessments of fish, crab and marine mammal populations, and the observer program. Our climate science strategy builds on this effort, which includes standard surveys for fish and crab species (bottom trawl, longline, midwater trawl/acoustics) as well as standard surveys for marine mammal species (most often aerial). Standard data collections occur for age, size, diet, and genetics. A large observer program monitors fisheries. These information sources are incorporated into fish, crab, and marine mammal stock assessments, which are used to provide quantitative advice for management of these species.

- **Recruitment Processes Alliance (RPA).** Research is conducted to understand processes affecting recruitment strength, including effects of climate. The research includes fieldwork, laboratory analysis of field sample collections (e.g., feeding, growth, bioenergetics), laboratory studies, and modeling. A significant fraction of AFSC resources are invested in this effort (e.g., ~15% of labor). The Alliance 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.

- **Laboratory infrastructure.** Laboratories located in Juneau, Kodiak, Newport (OR), Seattle and on research vessels have a wide range of capabilities that help us to understand the mechanisms and effects of climate change. Changes in water temperature and chemistry can directly impact the growth rate and distribution of fish and shellfish in marine environments (Figure 8). Differential thermal preferences can additionally lead to increases or decreases in species overlap and concomitant predator-prey interactions. Laboratory experiments are conducted to parameterize bioenergetic models of fish growth and energetic demand at the core of climate-enhanced models and to understand direct and indirect impacts of changing pH levels on fish and crab species. Laboratory studies and field surveys of fish thermal preferences are conducted to project future species distributions and overlap. Salt water wet labs support process studies on the effects of temperature, ocean acidification, and contaminants on growth and survival of all life stages of fish and crabs. Insights into food web structure and function (trophic dynamics) are made possible by laboratory observations of lipids, stable isotopes, hydrocarbons, molecular genetics, primary productivity, taxonomic identification of ichthyoplankton and other types of zooplankton. Laboratories that measure the caloric content, growth, age and food habits of individual organisms make models of stock abundance, management strategy evaluations and ecosystem models possible.

- **Predator prey food habits studies.** AFSC scientists had the foresight to acknowledge the importance of the collection and analysis of food habits information. This foresight provided one of the world's largest collection and longest time series of food habits of fish and crabs. This time series allows analysts to develop spatial and non-spatial models of predator prey interactions for use in stock assessments and short-term and long-term projection models.

- **Ecosystem modeling, ecosystem synthesis, and risk assessment.** Projecting future physical and biological conditions in the Bering Sea is a multi-institutional, collaborative effort. It requires coordination between physical modelers at PMEL and UW and fishery biologists at AFSC and UW who can couple biological and physical models through bioenergetic, habitat use, and food-web models of interactions. This requires additional personnel support to analyze data, parameterize models, and evaluate model results. It also requires ample access across facilities to core computers and data. Additionally, fundamental computing infrastructure needs to be maintained in order to run ROMS/NPZ and FEAST models for climate projections. This includes maintenance of the high performance computing infrastructure located at the AFSC (or funds for some cloud-based alternative), as well as ample storage for archived completed model runs.

- **Assess economic impacts.** A critical element of an effective response to a changing climate is an understanding of the economic mechanisms through which fisheries develop, allocate effort, and target different species and sizes of fish. In addition, management, markets, and the environment will all impact where processors and other fishing-related businesses grow or decline. By developing standing economic behavioral and regional economic models of all Alaska fisheries, we are evaluating how changing abundances and spatial distributions of different species impact communities and how management actions can best shape those impacts in the face of the uncertainties that we face. While some of this work occurs strictly within the economic discipline, some also requires ongoing interdisciplinary interaction among economics, other social scientists, biologists, fishery managers, and other stakeholders.

- **Assess community impacts.** There is a great need to link the projected and ultimate bio-physical effects of climate change and related them to impacts on LMR dependent human communities. While AFSC has started in this endeavor with the first iteration of an index of climate change exposure at the human community level, the analysis would greatly benefit from being updated and improved. Updating and improving this index would allow AFSC to better understand the effects of climate change on LMR-dependent human communities and develop management strategies to mitigate expected future impacts.

- **International coordination.** International scientific organizations such as PICES and ICES and bi-lateral partnerships such as Norway-US and Korea-US remain a key part of progress on climate science research. Activities include regional comparisons and climate and ecosystem model collaborations.

- **Critical partnerships.** The fisheries oceanography surveys of the AFSC in the eastern Bering Sea which are collectively known as the Recruitment Processes Alliance (RPA) leverage AFSC resources through partnerships in research programs active in the Alaska region such as those funded by the National Science Foundation (BEST), NOAA Fisheries Office of Science and Technology (FATE ,EFH), the North Pacific Anadromous Fish Commission (BASIS) Alaska Department of Fish and Game (Region III), Pacific Marine Environmental Lab (NOAA), North Pacific Research Board, North Slope Borough, the Bering Sea Fisherman's Association, the Alaska Sustainable Salmon Fund, and the Arctic Yukon Kuskokwim Sustainable Salmon Fund. Critical partnerships also include the University of Alaska, University of Washington, Oregon State University, and the associated joint institutes, and the Alaska Department of Fish and Game. The AFSC and the NOAA Fisheries Alaska Region rely on a large number of data sources on fish landings, stocks, and prices that are collected by the State of Alaska. Current fiscal challenges faced by the State of Alaska may lead to changes in data collection and analysis that have the potential to present new and significant data gaps that may require additional NOAA Fisheries resources in the future. It is very difficult to predict what changes may occur and when they are likely to happen.

ACTION PLAN

NOAA Fisheries and the Council can take three important steps to improve efforts to identify and adapt to climate change impacts on federally managed fisheries in our region. 1) NOAA Fisheries needs to be able to inform the North Pacific Fishery Management Council and industry with about a 10 year lead time, as to which commercially important species are likely to be “winners” and “losers” in regard to climate change in Alaska. These forecasts need to incorporate uncertainty. Such forecasts would assist the Council in adjusting management programs (i.e., catch share programs) as necessary, and allow the industry to “tune” their capacity (e.g., number of fishing vessels) to match productivity, 2) NOAA Fisheries and the Council need to identify and monitor thresholds in ecosystem parameters that signal the need to adjust management strategies, and 3) NOAA Fisheries needs to continue on-going ship-based surveys to monitor changes in biomass, age-structure, and distribution of commercially important groundfish species in the Bering Sea and Gulf of Alaska.

In this section, we describe climate science activities planned for the next 3-5 years. The major actions are to: 1) continue research to identify the mechanisms of climate impacts on fisheries; 2) continue to track trends in ecosystems; 3) continue to identify future states of marine and coastal ecosystems; and 4) continue to identify robust strategies for fisheries management under changing climate conditions. The extent of progress will depend on funding levels. We will make some progress with level funding. Approximately $5M per year is spent to implement the Climate Science Strategy in our region as part of about $9M per year spent on process studies. The funding sources include the NOAA and NOAA Fisheries programs of North Pacific Climate Regimes and Ecosystem Productivity (NPCREP), Integrated Ecosystem Assessment (IEA), Fisheries and the Environment (FATE), Stock Assessment Analysis and Modeling (SAAM), Loss of Sea Ice (LOSI), and Ocean Acidification (OA), as well as external funding from the North Pacific Research Board. The funding amount is approximate because more than one objective usually is supported (e.g., climate and ecosystems); project funds were partitioned to reflect support of multiple objectives. Progress on other Action Plans for other Large Marine Ecosystems in waters off Alaska will follow, as funding allows. This plan assumes two possible funding scenarios: 1) level funding; and 2) an increase of 10% (~$1M) above current funding.

Level funding

The extent of progress will depend on funding level. We will make some progress with level funding, though progress will mostly occur in areas such as monitoring trends, which are less expensive, than in the major, more expensive, challenge of gaining an understanding of the ecological processes that connect climate change to the productivity of fished populations. This understanding is required for quantitative forecasts of the impacts of climate change, which currently is limited to only 3 of 21 comprehensively assessed stocks in our region. With level funding, several projects will continue as described in the assessment. For example, the Ecosystems Considerations report will be produced annually and standard ecosystem monitoring, ocean acidification research, and climate-enhanced single-species projection modeling will continue. Here we list major projects identified in the assessment section which will continue with level funding in future years. Not all projects that will occur are listed here because of their number, but these unlisted projects can be found in the assessment section (e.g., Derive environmental indices from ocean models).

- **Council Bering Sea Fisheries Ecosystem Plan.** Approved for development by the North Pacific Fishery Management Council in December 2015.
- **Alaska CLIMate Project (ACLIM).** This project involves a suite of models designed to provide scenarios of future fish production under a variety of climate and fishing scenarios. This project is currently funded by FATE (Fisheries And The Environment), SAAM (Stock Assessment Analytical Methods), and NPCREP (North Pacific Climate Regimes and Ecosystem Productivity). This project will end with AR5/CMIP5 (IPCC Assessment Report/Climate Model Inter-comparison Project) projections in FY17 without more funding support.
- **Climate vulnerability assessment for the southeastern Bering Sea.** A climate vulnerability assessment for the southeastern Bering Sea, which will qualitatively assess species vulnerabilities to climate change and provide guidance on research prioritization, will be completed during 2016.
- **Belmont Forum project.** This project will synthesize information from regional studies to examine climate impacts in the marine ecosystems of the Pacific and Atlantic Arctic, which will be completed during 2017.
- **Recruitment Processes Alliance (RPA).** This ongoing research focuses on understanding recruitment processes of important southeastern Bering Sea fish species
- **Loss of Sea Ice research.** This effort extends standard surveys of the southeastern Bering Sea into the northern Bering Sea.
- **Ocean Acidification research.** This ongoing research focuses on commercially important fish and shellfish species and coldwater corals.
- **Fur seal research.** This project will link fine-scale changes in fur seal foraging behavior

with measures of pollock distribution and abundance in real time.

- **Assess economic and human community impacts.** Modeling of the climate effects on fisheries and the related economic and human community impacts will continue.
- **Alaska Marine Ecosystem Considerations and Integrated Ecosystem Assessment.**The Ecosystem Considerations report is produced annually to summarize information about the Alaska Marine Ecosystem for the North Pacific Fishery Management Council, the scientific community and the public.
- **Standard ecosystem monitoring.** Ecosystem trends are monitored through a combination of ongoing standardized resource assessment surveys, fisheries oceanography, seabird, and marine mammal surveys, including ships of opportunity, diet collections, and observations collected by fisheries observers.
- **Advanced technology.** New technologies are opening windows and time periods unavailable to conventional methods for understanding prey fields and lower trophic level processes. A recent addition was acoustic estimates of euphausiid abundance. The newest technologies deployed in the last 1-2 years include upward-looking acoustics and sail drones

Obvious limitations will occur with level funding. Funds are insufficient to pay for analysts and computing time on high-performance computers to model the ecological processes that connect climate change to the productivity of managed populations. As a result, new models will be delayed and some existing models may not be updated to present day. Computing senescence may also limit future modeling capacity without additional investment in replacement core processors. Existing model projections will stop with IPCC scenario AR5. A specific lapse is that ACLIM will end in FY17 without more funds.

Our climate science research program depends on continued funding of specific programs. Much of the current work is supported by the IEA program, NOAA Fisheries S&T Economics, Social Sciences, Fisheries and the Environment (FATE), Stock Assessment and Analysis Methods (SAAM), and the North Pacific Climate Regimes, Ecosystem Productivity (NPCREP), and Loss of Sea Ice (LOSI). For example, economic and social science efforts are largely funded on a project-level basis so are highly dependent on annual S&T Economics and Social Science funds. We also will continue to need to write proposals to support project-specific investigations. With some additional funding, we would be able to provide a more integrated approach. In addition, such funding would support the permanent labor required to complete this work.

While climate-related impacts will continue to be an integral component of future research regardless of the level of funding, significant advancements in understanding of climate impacts on marine ecosystems in Alaska depend on integrated evaluations. For example, funding has supported major programs in the Bering Sea every 5-10 years. The most recent major integrated ecosystem research programs have been funded by the North Pacific Research Board and

National Science Foundation for the Bering Sea and the Gulf of Alaska. Follow on research (the Recruitment Processes Alliance) is occurring for the Bering Sea Project. Under level funding, progress will likely continue to be project-based, opportunistic, and periodic around project-specific funds. Further, major program funding is necessary on the same tempo (every 5-10 years) to continue making substantial progress in understanding the ecosystem as a whole.

Diet data, needed to understand predator-prey interactions, is regularly collected and analyzed for four core species (walleye pollock, Pacific cod, arrowtooth flounder, and Pacific halibut), and sampling will likely continue for these species under level funding. A frustration with the current funding level has been that predator-prey interactions, which can be influenced by climate, have only been funded on an ad hoc basis for most species (beyond the core species), rather than receiving continuous funding.

Research on responses of fish and fisheries to changing climate conditions will continue to be an important aspect of AFSC's research enterprise. However, level funding limits proactive responses and pushes research and management into reactive responses. For example, research on climate and oceanographic factors influencing Prohibited Species Catch (PSC) in groundfish fisheries addresses a growing management issue, especially with respect to Pacific halibut and Pacific salmon bycatch, and may not be fully addressed with level funding.

Some additional funds

Expanded funds for both rapid response and systematic climate assessments are needed in order to reduce (potentially damaging) lags in management response to changing conditions. In particular, continued and additional funding is needed to support both (1) rapid assessments of sudden climate and ecological shifts and (2) periodic climate change -risk assessments.

(1) Rapid response to climate driven-shifts beyond ecosystem or species thresholds.

- Facilitate the ability to triage sudden shifts in oceanographic conditions and evaluate ecosystem response. Rapid response, in the form of immediate surveys and field investigations, provides near real-time data to inform forecast models which provide immediate feedback on the repercussions of changes in progress. Managers and stakeholders have an opportunity to develop a dynamic management strategy that changes in response to fluctuating ecosystem conditions. A successful example was the FY14 request to OST to follow up on a sudden, dramatic return of warm conditions in the Southeastern Bering Sea. Concern for a pronounced decline in walleye pollock in the event of a multi-year warm phase prompted funding and execution of a series of field surveys to monitor ecosystem response to oceanographic shifts. A supplemental survey in

2015 was funded and executed, data collected and analyzed, and results made available within a year's time. The capacity to mount a rapid, strategic response to changing environmental conditions requires adequate funding and infrastructure. Enhancement of these resources provides a path to future successful rapid response efforts.

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(2) Comprehensive climate assessment completed every five years.

Operationalize the ACLIM projection modeling framework to facilitate the rapid uptake of the most recent IPCC global climate projections under a range of carbon emission scenarios, application of global projections into regional coupled physical-biological-economic models for the EBS, and coordination of iterative review with regional management councils and fishery stakeholders to evaluate the performance and implications of current and alternative "climate-ready" harvest strategies under future climate scenarios. The proposed iterative ACLIM framework conducted on a ~5 year cycle is modeled after the highly successful annual stock assessment cycle in the region; the approach will ensure that fisheries management decisions account for climate-driven changes to fish production and distribution and that climate-ready fisheries management in the region reflects the most recent global climate and carbon emission projections and best available ecosystem and socioeconomic science.

Both rapid and period climate assessments in turn depend on d**evelopment and maintenance of monitoring, research, and climate-enhanced modelling programs.** With some additional funds, depending on the amount,the following research areas should advance:

Modeling and predictive forecasts

- **Invest in modeling infrastructure.** Invest in computing time and storage on high-speed computers to model ecological processes and projections, as well as the analysts necessary to construct and operate these models, and analyze model outputs. Doing so will provide for new projections based on IPCC scenario AR6 and new management strategy evaluations based on Council input. In particular, enhancing the existing high resolution ROMS/NPZ model to include freshwater inputs and refined nearshore dynamics in order to couple terrestrial and marine systems will provide foundation for near- and long-term projections of climate change driven changes to physical conditions in both offshore and nearshore areas. Investments related to the ROMS-NPZ would include: 1) the elaboration of software which can directly access the stored output from global models; 2) periodic tuning and refinement of the ROMS-NPZ model; 3) bias correction of the regional forcing and boundary terms, based on ROMS hindcasts; 4) exploration and testing of alternative parameterization and structural aspects of the zooplankton components; 5) maintenance of a searchable online system to query model output, e.g. to generate time series of relevant indices.

- **Integrate the evolving tools and data-integration work completed by AFSC and PMEL.** The synthesis and modeling of climate science and process research is data intensive. More investment is needed for data assimilation and repositories for model outputs. Some possibilities are to work with the Alaska Ocean Observing System to identify community-specific climate data that can be used to improve human community climate change vulnerability indices. Create a central repository for climate data, including geographic-based climate data.

- **Integrate biological, management technical interaction, and socio-economic modeling tools into climate-enhanced models** in order to evaluate climate-to-fisheries impacts of climate-change on the coupled human-natural system of the EBS.

Research to understand climate-change impacts

- **Focused effort on identifying ecosystem thresholds and mechanisms driving potential regime shifts.** Changes in climate forcing may influence energy flow through the ecosystem. How will potential changes in ecosystem structure and function (e.g., benthic v. pelagic pathways) affect resilience to changes in climate? In order to answer these types of questions, focused efforts to identify ecosystem or species-specific thresholds to climate drivers and to identify mechanisms of regime shift are needed.

- **Invest in understanding biological and human community adaptations to climate change.** Funding is currently limited and only sporadically available through temporary funds and research proposals. To more fully assess the adaptive capacities of managed resources and dependent human communities, additional funds are needed to understand biological and socio-economic responses to changing conditions in order to gain knowledge of the functional relationships governing fish and shellfish responses to changing climate. This includes research funds to help:

    - **Understand the direct impact of changing conditions on growth and survival of fish and shellfish species.** This might include (but is not limited to) studies of the impacts of climate drivers (ocean and OA) on phenologies of life cycle attributes, research to address how OA alters maturation rates of core species, and research to evaluate temperature-dependent reproductive, growth and mortality rates of core species.

- ○ **Improve understanding of the effect of climate change on seabird and marine mammal species of concern.** For example, direct and indirect (i.e., mediated by prey) effects of climate may affect fur seal foraging, their reproductive success, and thus their population trends, which have been declining in the eastern Bering Sea.

- ○ **Expand research to understand how climate change will impact fishery-dependent human communities and evaluate socio-economic scope for adaptation.** For example, changes in the distribution of target and prohibited species (e.g., salmon and halibut) might impact future fishery catches, changes in ex-vessel value might help offset climate-driven changes in harvest, and alternative management structures may differentially impact fisheries and dependent human communities.

Monitoring and surveys

- **Discretionary funds for rapid / emergency (< 1yr) surveys to evaluate potential impacts of sudden changes in climate or ecological conditions.** Presently there are no funds held in reserve to execute field work in response to rapidly changing climate and ocean conditions. Funds available for assessing ecosystem change in progress, and associated effects on fisheries populations, would permit rapid response field work that can be used to inform managers and permit a dynamic management framework.

- **Fully support ongoing NOAA oceanographic moorings to monitor the ecosystem.** Currently, four oceanographic moorings are located along the 70-m isobath of the southeastern Bering Sea, but NOAA covers only part of the funds required to continue this time series. Additional funds would fully support these existing moorings essential for providing valuable data for validating the ROMS/NPZ models.

Coordination and Communication

- I**nvest in regional and international coordination.** Invest in coordination of AFSC climate research and fisheries projections with regional, national, and global efforts.

- **Improve communication of the risks of climate change to fishing dependent communities** (e.g., expected and known changes to important LMR food sources and economically important LMRs), the Council and other fisheries managers (e.g., where management will have to adapt as climate impacts to LMRs occur or are predicted), and other stakeholder groups. Communication products could involve informational interactive websites, glossy brochures and other products that could disseminate the impacts of climate change on LMRs and the expected follow on impact to LMR users.

- **Invest in training, education, and outreach.** There is an overall paucity of scientists who are trained in interdisciplinary science that bridges meteorology, oceanography, fisheries oceanography and fisheries management. Providing public access to data is challenging and requires additional IT and web-based data server support.

A long-term challenge

A long-term challenge is to design adaptive decision processes that can incorporate and respond to changing climate conditions. Preparing to address this long-term challenge will likely occur during the next 3-5 years. What is not well worked out is how and when does the North Pacific Fishery Management Council (Council) react to climate-induced reference point changes, an area that needs considerable attention, discussion, and education. This discussion should involve the Plan Teams, Science and Statistical Committee, and Ecosystem Committee, all subsidiary bodies of the Council, as well as the Alaska Regional Office.In December 2015, the Council decided to go forward with a Bering Sea Fisheries Ecosystem Plan, which includes a climate module. Identify short-term management approaches that should be preserved going forward (e.g., EBFM policies, adaptive management approaches), long-term (i.e., multi-decadal) management measures should be systematically reevaluated for continued performance (e.g., MPA effectiveness, upper or lower biomass thresholds), and EIS studies should be conducted for growing or novel fisheries of species expected to thrive under future conditions.

ARAP action item table

Action Name (short title; add rows as needed for Actions)	Funding Scenario (Level or Increase)	Time Frame (years)	Action Description (short description of who, what, key products and expected outcomes)	POC (name)	Partners
Objective 1 – Climate Informed Reference Points					
Single and multi-species models with climate forcing	Level	2016-2019	The purpose of this project is to incorporate climate effects into single and multi-species models, which are then used to derive climate-informed reference points.	Holsman, Ianelli	AFSC
Objective 2 – Robust Management Strategies					
Council Fisheries Ecosystem Plan, climate module	Level	2016-2018	The climate module would: 1) synthesize current climate change project outcomes; 2) prioritize species for MSE evaluation; and 3) run MSEs on specific species and scenarios identified by the Council.	Aydin, Hollowed	AFSC, PMEL, Council
Management Strategy Evaluations	Level	2016-2019	Identify harvest control rules that remain effective as climate changes.	Hollowed, Heifetz	AFSC
Alaska CLIMate Project (ACLIM)	Level	2016-2018	Scenarios of future fish production and distribution under a variety of climate and fishing scenarios.	Hollowed, Holsman, Haynie	AFSC, PMEL
Multispecies technical interaction model	Level	2016-2019	This model simulates interactions of management rules (e.g., bycatch caps) on catch.	Ianelli, McGilliard	AFSC
Belmont Forum project	Level	2016-2018	1) Review impacts of climate change; 2) compare impacts in the Atlantic and Pacific sectors of the Arctic; 3) review the ability of current management frameworks to adapt.	Mueter, U. Alaska; Haynie, Sigler	AFSC, PMEL, U. Alaska

Objective 3 – Adaptive Management Processes

Design adaptive decision processes	Level	2016-2019	What is not well worked out is how and when the Council should react to climate-informed reference point changes. Information on changes in the ecosystem, including climate change, are presented annually to the Council.	Holsman, Hollowed, Aydin, Zador	AFSC, Alaska Regional Office, Council
Identify ecosystem thresholds and mechanisms driving regime shifts	Increase	2016-2019	How will potential changes in ecosystem structure and function (e.g., benthic v. pelagic pathways) affect resilience to changes in climate? In order to answer these types of questions, focused efforts to identify ecosystem or species-specific thresholds to climate drivers and to identify mechanisms of regime shift are needed.	Holsman, Zador	AFSC

Objective 4 – Project Future Conditions

Ocean model projections	Level	2016-2019	Coupled physical/biological regional models that downscale global climate change to the ecology of subarctic regions.	Hermann	AFSC, PMEL
Incorporate ocean acidification effects into existing ocean models	Level	2016-2017	An ocean acidification module is being added to the coupled physical/biological regional model.	Cross	PMEL
Climate-enhanced single species projection models	Level	2016-2019	These single species models provide 20- to 50-year forecasts of fish and crab abundance, including uncertainty estimates for these forecasts.	Ianelli, Mueter, Punt, Dalton; Wilderbuer; Stockhausen	AFSC, U. Washington, U. Alaska
Climate-enhanced multi-species	Level	2016-2019	These multi-species models add species interactions.	Holsman; Ianelli	AFSC

projection models					
Climate vulnerability assessment for the southeastern Bering Sea	Level	2016	Qualitative assessment of species vulnerabilities to climate change and guidance on research prioritization.	Spencer	AFSC, PMEL, U. Washington, U. Alaska
Identify human community dependence on LMRs and effects of climate change	Level	2016-2019	Monitor indices developed to track effects of climate change on human communities	Kasperski	AFSC
Arctic Council, AMAP, impacts on coastal communities	Level	2016-2017	Prepare report Adaption Actions for a Changing Arctic	Mundy	AFSC
Invest in modeling infrastructure	Increase		Invest in computing time and storage on high-speed computers to provide new projections based on IPCC scenario AR6.	Aydin	AFSC
Comprehensive climate assessment completed every 5 years	Increase		Operationalize the ACLIM projection modeling framework.	Hollowed	AFSC
Integrate tools and data	Increase		More investment is needed for data assimilation and for repositories for model outputs.	Aydin	AFSC, PMEL
Integrate models	Increase	2016-2019	Integrate biological, management technical interaction and socio-economic modeling tools into climate-enhanced models	Holsman, Hollowed, Aydin, Hermann, Haynie	AFSC, PMEL

Objective 5 – Understand the Mechanisms of Change

Bering Sea Project	Level	2007-2016	Integrated ecosystem research project of the eastern Bering Sea.	Sigler	AFSC, PMEL, USFWS, U. Washington, U. Alaska,

					several other academic institutions
Southeastern Bering Sea Ecosystem Assessment	Level	2016-2019	Identify the major processes regulating fish recruitment.	Farley, Duffy-Anderson	AFSC, PMEL
Ocean Acidification research	Level	2016-2019	Understand ocean acidification effects on king and tanner crabs, coldwater corals, pollock, cod and northern rock sole.	Foy, Hurst	AFSC, PMEL
Fur seal research	Level	2016-2019	Understand differing fur seal population trends at the Pribilof Islands and Bogoslof Island.	Sterling	AFSC
Economic impacts of climate change	Level	2016-2019	Understand economic and impacts of climate change.	Haynie	AFSC
Social and human community impacts of climate change	Level	2016-2019	Understand social and human community impacts of climate change.	Kasperski	AFSC
Rapid response to climate driven shifts beyond ecosystem or species thresholds	Increase		Facilitate the ability to triage sudden shifts in oceanographic conditions and evaluate ecosystem response.	Duffy-Anderson, Farley, Stabeno	AFSC, PMEL
Understand the direct impact of changing conditions on growth and survival of fish and shellfish species	Increase		Studies of the impacts of climate drivers (ocean and ocean acidification) on phenologies of life cycle attributes.	Lauth, Heintz,Hollowed, Duffy-Anderson, Farley, Foy, Hurst, Laurel	AFSC
Understand effect of climate on	Increase		For example, direct and indirect (i.e., mediated by prey) effects of climate may affect fur seal foraging, their reproductive	Gelatt, Boveng, Clapham	AFSC

seabirds and marine mammal species of concern			success, and thus their population trends, which have been declining in the eastern Bering Sea.		
Expand research to understand climate change effects on human communities	Increase				

Objective 6 – Track Change and Provide Early warnings

Alaska Integrated Ecosystem Assessments and Alaska Marine Ecosystems Considerations	Level	2016-2019	Annually produce Ecosystem Considerations report including report cards, assessments and detailed ecosystem status and ecosystem-based management indicators.	Zador	AFSC, PMEL
Standard ecosystem monitoring	Level	2016-2019	Conduct biennial spring and late summer cruises. Maintain four oceanographic moorings located along the 70-m isobath.	Duffy-Anderson, Farley	AFSC, PMEL
Loss of Sea Ice research	Level	2016-2019	Biennial surveys of the northern Bering Sea.	Lauth	AFSC
Coastal Assessments	Level	2016-2019	Quantify and assess fish habitats in coastal areas.	Heintz	AFSC
Rapid response	Increase		Rapid research response to evaluate impacts of sudden changes in climate or ecological conditions		
Fully support NOAA oceanographic moorings	Increase		Currently four oceanographic moorings monitor the southeastern Bering Sea, but are only partially supported by NOAA funding.	Stabeno	PMEL

Objective 7 – Science Infrastructure to Deliver Actionable Information

Existing science	Level	2016-2019	Standard surveys and data collections (e.g., age, diet,	various	AFSC

enterprise including standard surveys and stock assessments			genetics)		
Recruitment Processes Alliance	Level	2016-2019	Understand processes affecting recruitment strength, including effects of climate, on selected gadid, and salmon species.	Farley, Duffy-Anderson	AFSC, PMEL
Laboratory infrastructure	Level	2016-2019	Salt water wet labs; laboratory analyses (e.g., lipids, diet, stable isotopes)	various	AFSC
Predator-prey food habits studies	Level	2016-2019	Continue adding to one of the world's largest food habits data collections.	Aydin	AFSC
Ecosystem modeling	Level	2016-2019	Ecosystem modeling, ecosystem synthesis, and risk assessment	Aydin	AFSC
Assess economic impacts	Level	2016-2019	Understand economic impacts of climate change.	Haynie	AFSC
Assess community impacts	Level	2016-2019	Understand human community impacts of climate change.	Kasperski	AFSC
International coordination	Level	2016-2019	International collaborations are a key part of understanding climate effects on fisheries and marine mammals.	various	AFSC
Critical partnerships	Level	2016-2019	Partnerships are a key part of understanding climate effects on fisheries and marine mammals.	various	AFSC
Improve communication of risks of climate change to fishing dependent communities	Increase		Communication products include websites, brochures, Council presentations, and media outreach.	Mooney-Seus	AFSC
Invest in training, education, and outreach	Increase		More scientists with training in interdisciplinary sciences are needed.		

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FIGURES

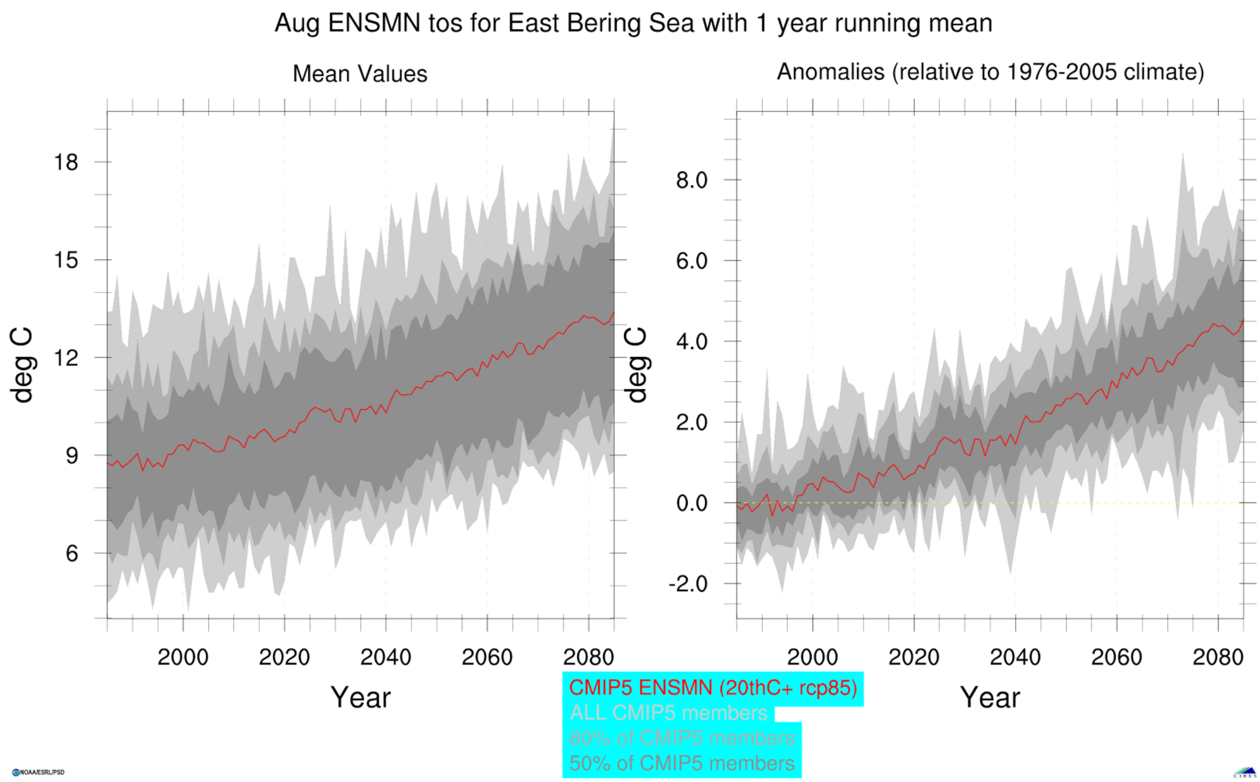

Figure 1. Projected changes in temperature for the Eastern Bering Sea (AK).

Projected increases in sea surface temperature for the Eastern Bering Sea (left) and future temperatures relative to historic means (right). Red lines represent CMIP5 ensemble mean annual projections. Dark gray shading represents estimates from 80% of all models; light gray shading represents estimates from 50% of model projections. Data and figure courtesy of the ESRL climate change portal: www.esrl.noaa.gov/psd/ipcc/ .

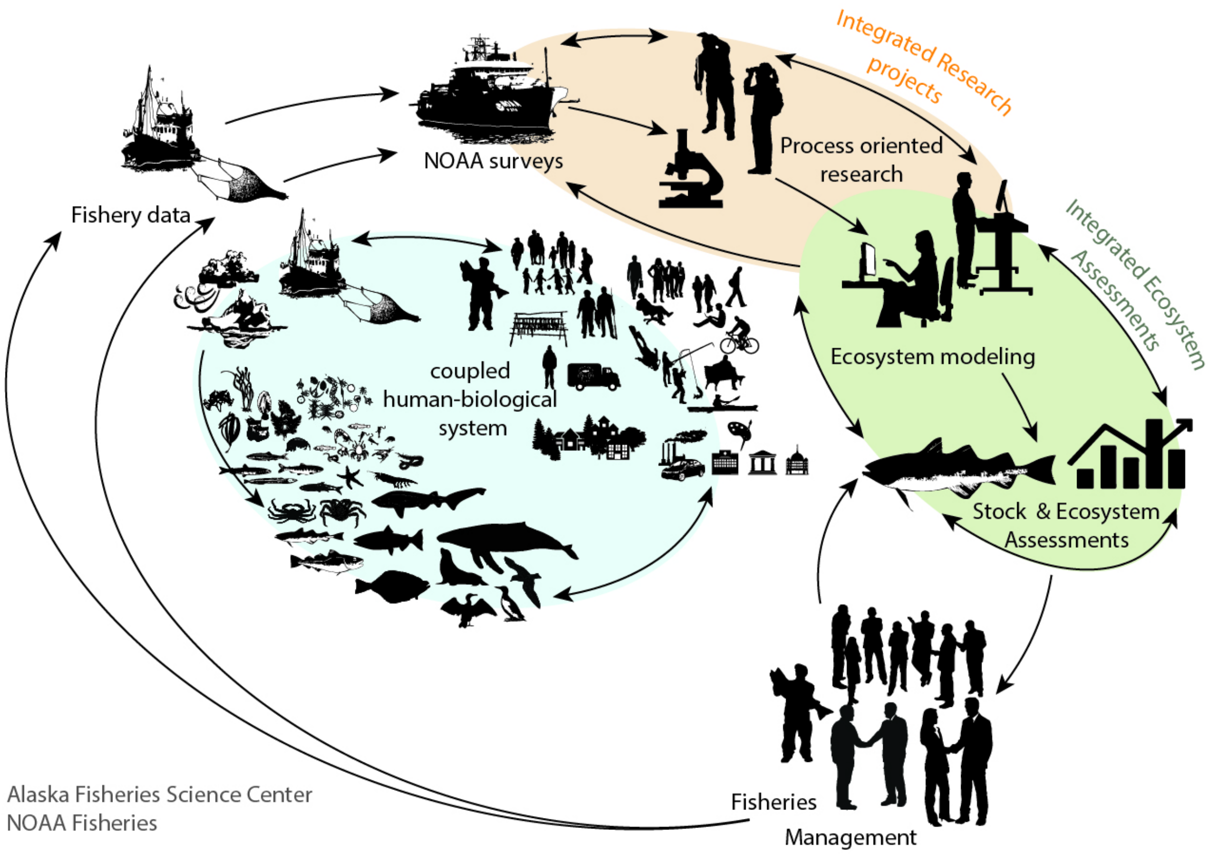

Figure 2. The AFSC integrated research approach.

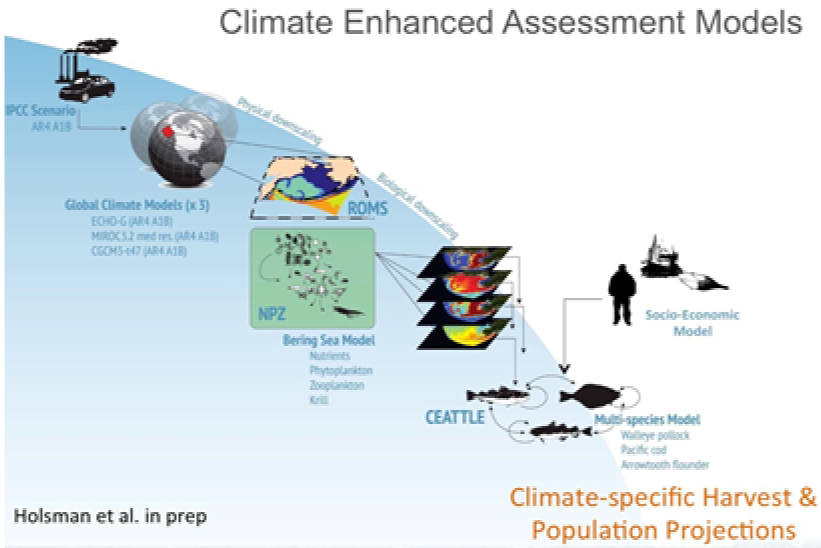

Figure 3. Example of climate-enhanced multi-species model with socio-economic module.

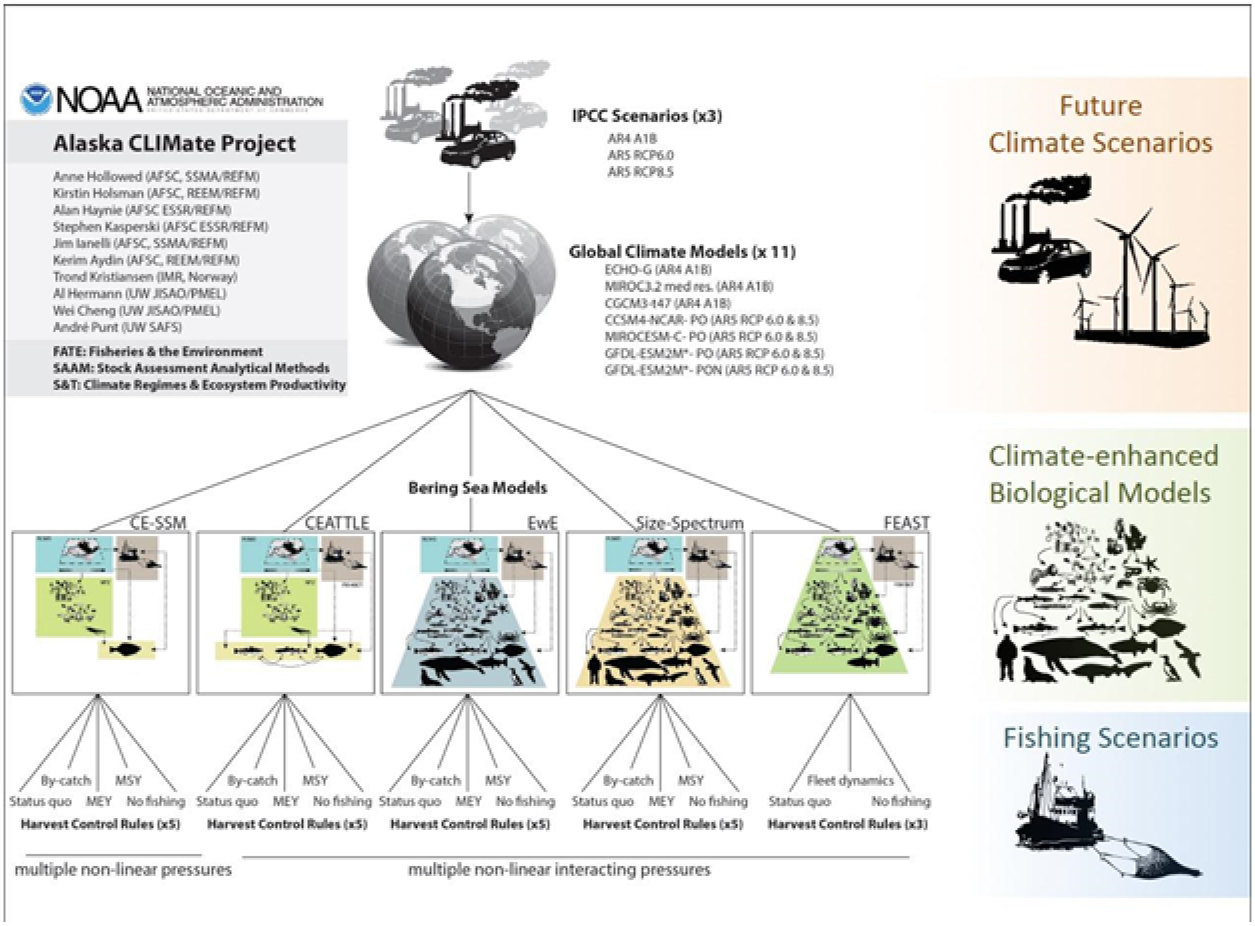

Figure 4. Illustration of the multiple models and climate and fishing scenarios in the ACLIM project.

A suite of models represent a full range of structural complexity ranging from single species projection models (see above) to fully coupled end-to-end models (FEAST), which allows tracking of different sources of uncertainty in the projection modelling effort. In phase 1, the multi-model projections will be run to provide a suite of potential fish distributions and fishers responses to a suite of climate change scenarios. The climate change scenarios will include projected climate conditions under 2 Representative Concentration Pathways (RCPs) using at least 3 global climate models from the CMIP5 suite. Output from downscaled projected ocean conditions will be used to project the future distribution and abundance of fish and fisheries. The projected scenarios will be presented to regional fishery management councils, industry and other non-governmental organizations to seek input and advice on the realism of the harvest strategies.

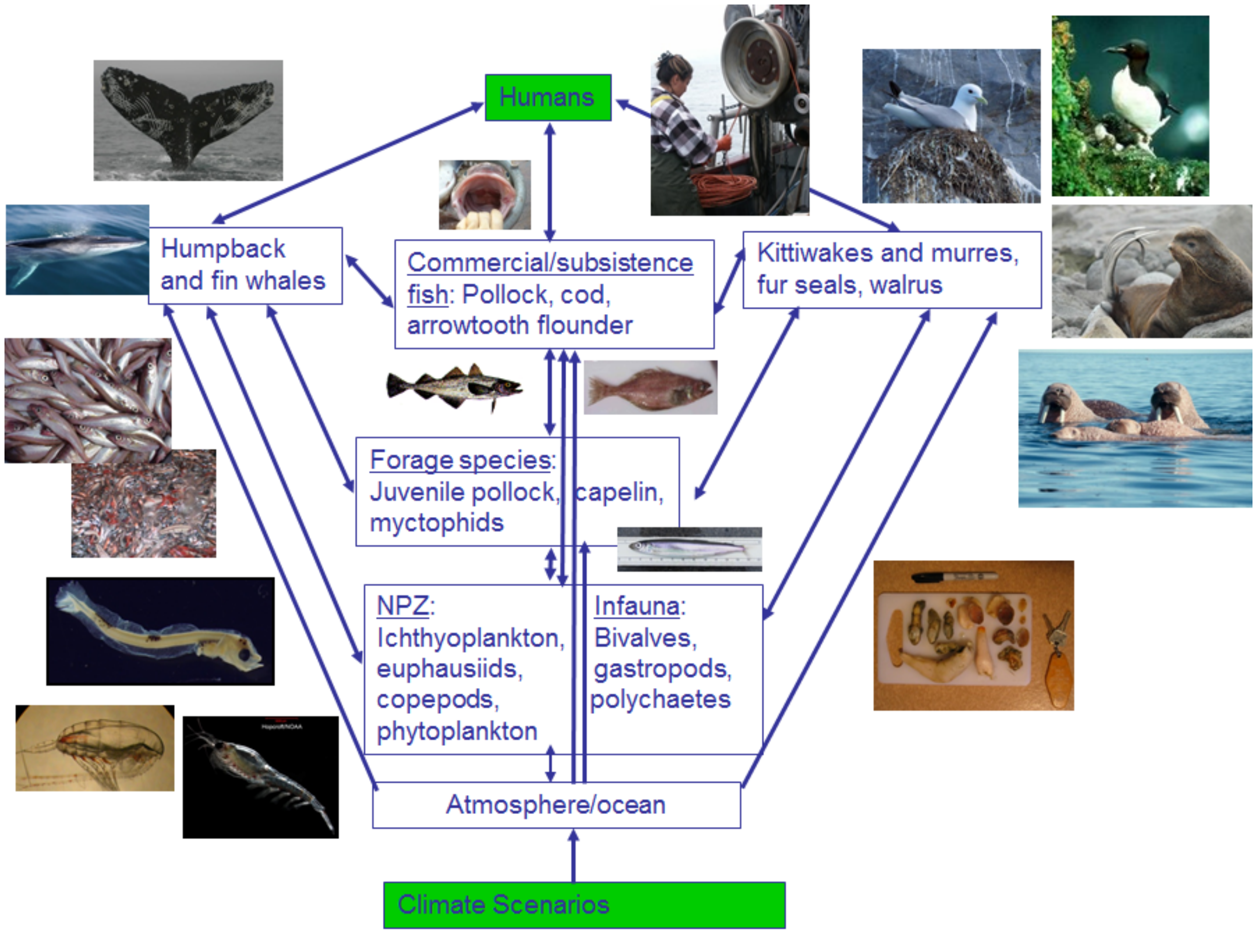

Figure 5. Scientific scope of the Bering Sea Project.

The links and species shown here were studied in this project.

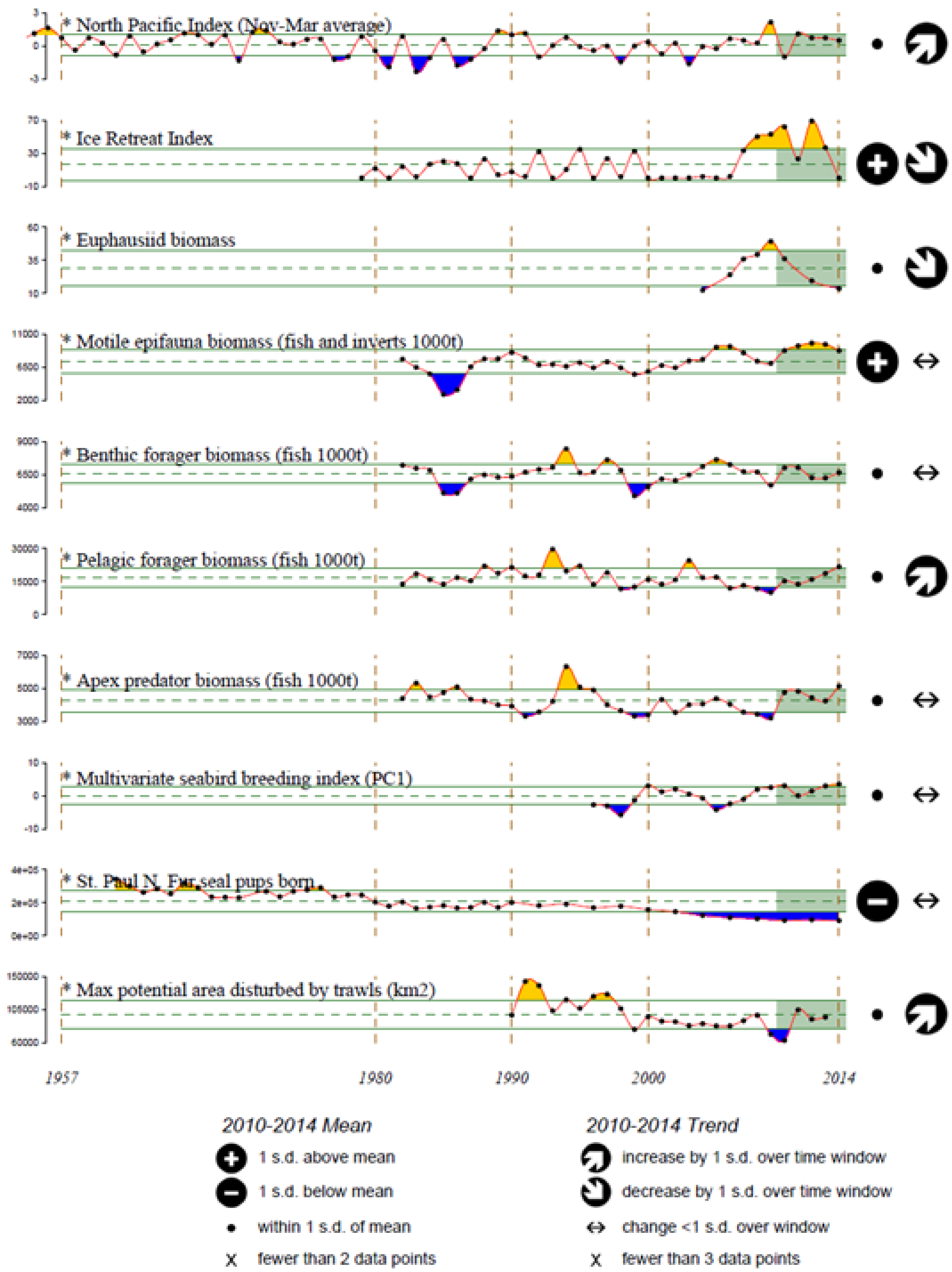

Figure 6. Example of ecosystem report card for the eastern Bering Sea (Zador et al., 2015).

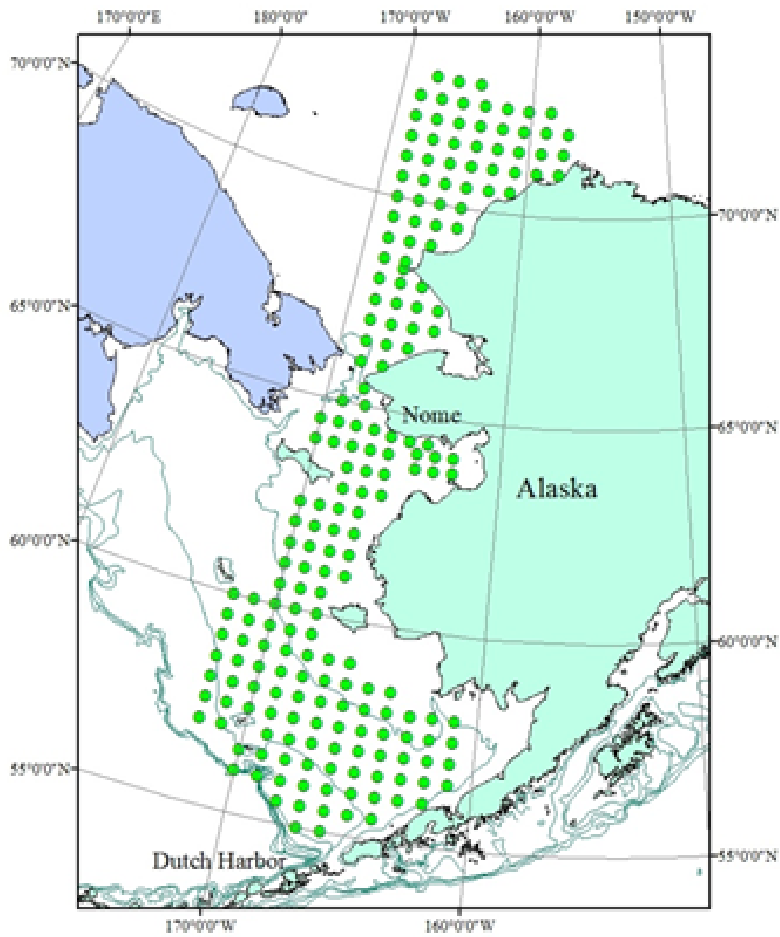

Figure 7. Example of ecosystem monitoring survey.

The example survey (BASIS) occurs biennially during late summer (http://www.afsc.noaa.gov/ABL/EMA/EMA_default.php).

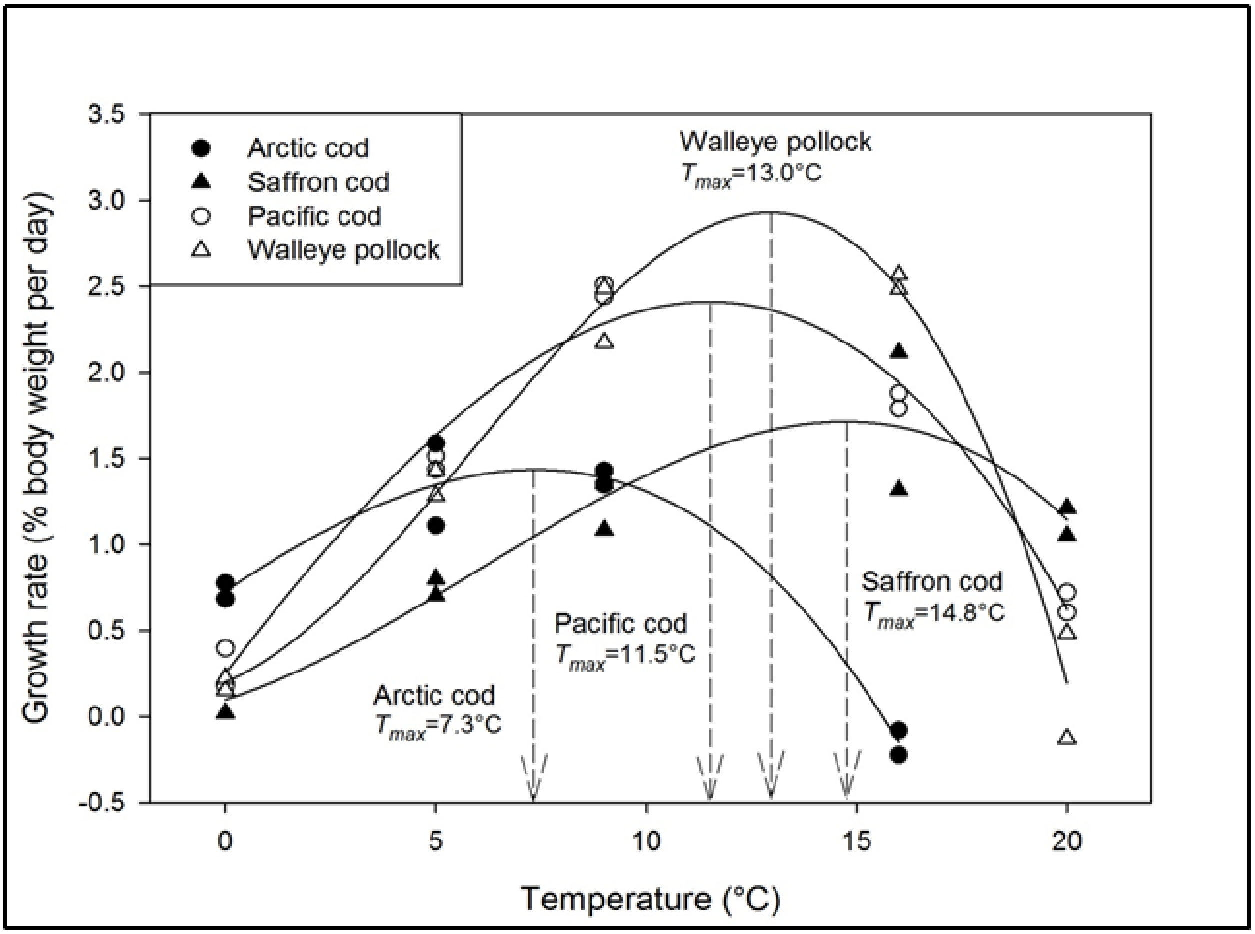

Figure 8. Example of laboratory research related to climate change.
Growth response in relation to temperature of four cod species (Laurel et al., 2015).

Response to SSC comments

Comment: The document seems optimistic in its descriptions of what can be done now, and what we will be able to do about this challenge in the near future. It is not clear that we will be able to make any quantitative predictions about how present-day climate variability will affect any stock in the near future, let alone out to ten years. There are species for which we can make qualitative statements about how current patterns or timing of sea-ice retreat may affect recruitment, but even for these species, the time series are sufficiently short that the observed relationships need to be accepted with caution. However, the SSC also felt that an ambitious timeframe was advantageous and appropriate for the scale of the challenge ahead, and the SSC looks forward to the new information that will be brought forward.

Response: We added text and references to document cases where understanding is sufficient to make quantitative predictions and to be published in the peer-reviewed literature. These include pollock, red king crab, snow crab, and northern rock sole.

Comment: The document outlines three steps that are deemed important for the Council to take in this region. The first is that NFMS needs to be able to inform the Council of the "winners and losers" of climate change on a 10 year time frame. This goal of predicting "winners and losers" ten years out also seems optimistic. It seems feasible to predict two or three years out based on age-0 or age-1 fish of a stock, and we can at least expect to predict trends 20 -30 years out when average temperatures begin to exceed those high temperatures that appear to have negative impacts on stocks. However, within intermediate time spans, inter-annual variability will probably swamp out the underlying, long term climate trends, thereby making predictions difficult.

Response: As in the previous response, we added text and references to document cases where understanding is sufficient to make quantitative predictions and to be published in the peer-reviewed literature. These include pollock, red king crab, snow crab, and northern rock sole. In addition, these are probabilistic predictions that show the range of realizations that we can expect, irrespective of the prediction time frame. It is true that it will take some time for the median prediction value to range outside current variability, but this does not prevent us from making defensible predictions with accompanying estimates of their uncertainty for short, intermediate, and long-term time frames.

Comment: The second step outlined in the document is the need to identify and monitor ecosystem thresholds that signal the need to adjust management, and finally, the need to continue ongoing ship-based surveys.

Response: We agree and have added text on this point.

Comment: The SSC also strongly supports the continuance of all existing ship-based fishery independent surveys and fisheries oceanographic research.

Response: Yes, we agree, but in reality, choices must be made to balance process research and ecosystem monitoring and to balance how much attention is paid to each of the several Large Marine Ecosystems that the AFSC is responsible for. We have added a section to describe this balancing and to justify some of AFSC choices. For example, the AFSC has changed from annual to biennial sampling of the Gulf of Alaska and southeastern Bering Sea. The change has provided more sea days for each region in the year each is sampled so that the area sampled has expanded. For Bering Sea pollock, sampling that occurred only along the Alaska Peninsula now has expanded past the Pribilof Islands; the new area now encompasses the known shelf spawning areas of pollock in the southeastern Bering Sea.

Comment: To identify the effects of climate variability and developing ability to predict the effects of warm or cool periods with impacts on fish stocks requires data that can link climate characteristics in one year with outcomes in that year and subsequent years. BASIS was remarkably successful in demonstrating how conditions in one year affected the survival of age-0 pollock to the next year. The ability to reach this conclusion required several consecutive years of research to develop the necessary insights and to test the resulting hypotheses. If this research had been stretched out over a longer period with surveys every other year, it is not clear that the BASIS scientists would have made the progress that they did. **The SSC strongly recommends that the spring and fall fisheries oceanographic surveys be conducted on a yearly basis while we are trying to identify the effects of climate change and develop the means of making "long-term" predictions of its impacts.**

Response: See our response to the previous SSC comment.

Comment: The research plan says little about focusing research on short-lived prey species that may react very quickly to climate warming (via large copepods and euphausiids on the EBS middle shelf). We need to know more about the prey of species other than pollock, and determine what may limit their prey abundance or availability in the future. It is likely that it is these prey species that will determine the health of stocks that we value.

Response: We have added text to explain this choice. While a final decision has not been made, the AFSC likely will increase focus on zooplankton in coming years.

Comment: An additional area of concern is the possibility that warming conditions will lead to more of the primary production going through micro-zooplankton than has been true in the past. Recent research has shown that in the summers of warm years they play a major role in the transfer to upper trophic levels. By imposing themselves in the food web, they, in essence, add an additional trophic level, and thus reduce the biomass of trophic levels above them by roughly 90%. There is a need to learn about their roles in times past (possibly using stable isotopes), as this may help us understand what they are or will contribute in the future.

Response: A new isotope instrument and isotope chemist recently have arrived at the Auke Bay Laboratories. One question that will be tackled with this new capacity is whether the food web lengthens in warm years.

Comment: The SSC suggests an exercise to prioritize the most valuable research to collect within this action plan might be helpful, and asserts that a focus on mechanistic explanations for species' responses to climate variability that provides clear hypotheses to test should be a high priority. Additionally, the SSC acknowledges the importance of the FEAST model to the regional action plan, and looks forward to the planned improvements that are already in progress.

Response: We agree. The Recruitment Processes Alliance, a cross-program collaboration of the AFSC and PMEL, regularly conducts meetings to prioritize this type of research.

Comment: The regional action plan is deficient in its explanation of how Alaskan communities will be participating in this process. It was clear from the presenter that feedback from communities on theoretical fishing scenarios is vital for continued model development and vetting during this five year plan. However, this was not made clear in the document or the actual presentation.

Response: We agree. We have added text on the outreach strategy for the regional action plan. Projected fishing scenarios will be presented to regional fishery management councils, industry and other non-governmental organizations to seek input and advice on the realism of the harvest strategies. The planned outcome is the identification of the most realistic representation of future responses of fishers and fish to changing climate with the expressed goal of identifying strategies that are robust to changing ocean conditions.

Comment: Finally, there was a general tone in the document that implied that management is a static entity, and that the science and management recommendations that will be brought forward through this action plan will simply allow for a switch to a new management regime that solves the challenges of climate change. However, this is clearly not the Strategy's intent. Both the national strategy and the regional action plan acknowledge that this will be an ongoing and evolving process as our understanding improves and management adapts as necessary to a changing climate. **The SSC would like to see this concept better reflected in the document.**

Response: We agree. We have added a section on how science and management will respond and evolve.