Alaska
Fisheries Science
Center

National Marine
Fisheries Service

U.S DEPARTMENT OF COMMERCE

AFSC PROCESSED REPORT 2017-10
doi:10.7289/V5/AFSC-PR-2017-10

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July 2017

This document should be cited as follows:

Sigler, M. F., J. N. Cross, M. G. Dalton, R. J. Foy, T. P. Hurst, W.C. Long, K. Nichols, I. Spies, and R. P. Stone. 2017. NOAA's Alaska Ocean Acidification Research Plan for FY18-FY20. AFSC Processed Rep. 2017-10, 71 p. Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle WA 98115.

Available at http://www.afsc.noaa.gov/Publications/ProcRpt/PR2017-10.pdf.

NOAA's Alaska Ocean Acidification Research Plan for FY18-FY20

by

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July 2017

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Executive Summary

Overview: The National Oceanic and Atmospheric Administration's (NOAA) Alaska Fisheries Science Center and the Pacific Marine Environmental Laboratory collaborate to form the Alaska Ocean Acidification (OA) Enterprise. This collaboration combines the scientific disciplines of chemical and biological oceanography, fish and crab physiology, and population and bioeconomic modeling. This report describes proposed research pending support from the NOAA Ocean Acidification Program (http://oceanacidification.noaa.gov/).

Abstract: Coastal regions around Alaska are experiencing the most rapid and extensive onset of OA compared to anywhere else in the United States. By integrating observational data with species response studies, OA forecast models, and human impact assessments, it has been determined that Alaska coastal communities and the vast fisheries that support them have varying degrees of vulnerability to OA, ranging from moderate to severe. Areas that are most vulnerable are located in regions where fisheries are vital for the state and national economy. The average processed value of Alaska fisheries was $4.5 billion per year from 2011 to 2015 (Fissel et al. 2016, tables 30-31). Even a relatively small decline in one or more of the fisheries in the Gulf of Alaska or Bering Sea could have cascading economic impacts that could dwarf the combined impacts of other regions around the Nation.

Our research focuses on commercially and ecologically important Alaska species most likely to be affected by OA and monitoring ocean conditions in their habitats (Sigler et al. 2008, 2015). We prioritize commercially important calcareous species (crab) because of their economic value and because initial studies have shown that these species are likely to suffer direct effects of decreased pH and reduced $CaCO_3$ availability. We also study commercially important fish species to screen for early life history effects and ecosystem effects mediated by prey availability. Coldwater corals are our third research priority because of the role they play as biogenic habitat for marine organisms such as commercially important rockfish species. Population modeling research is critical to put our experimental results in the context of stock and ecosystem level vulnerability to inform us about the economic impacts to coastal communities. Lastly, to inform our experimental and predictive modeling research, it is necessary to monitor carbonate chemistry in Alaska at informative spatial and temporal scales.

Summary of Work Plan Outcomes: In FY18-FY20, studies that continue the crab, fish, modeling, coldwater coral, and ocean monitoring research are proposed (Table 1). The proposed crab research will increase the complexity of previous physiological response studies to consider the effects of temporally variable exposure and the potential for commercially important crab species to acclimate to ocean acidification. We will continue to contrast commercial species that live in deep, naturally corrosive and stable waters (e.g., golden king crab (*Lithodes aequispinus*)) with those that live in more shallow variable environments (e.g., red king crab (*Paralithodes camtschaticus*), southern Tanner crab (*Chionoecetes bairdi*)).

The finfish proposal will include a follow-up examination of the effects of OA on walleye pollock (*Gadus chalcogrammus*) using a suite of more sensitive response variables (histology and lipid composition) on fish from the Gulf of Alaska population. Other experiments will further explore the interactive effects of OA with temperature and prey composition and OA-induced behavioral sensitivities. In addition to continuing work on Alaska gadids, this proposal will expand work on commercially important flatfishes and include studies of Arctic cod (*Boreogadus saida*), a keystone species in the Alaska Arctic.

The coral research will shift gears from a mineralogy catalog and risk assessment of Alaska corals and sponges (nearly complete) to analyzing the results for a study on physiological effects of OA on red tree corals held in the laboratory. The results of that study will dictate whether additional work is warranted for corals.

The proposed modeling research will continue to extend bioeconomic models of crab fisheries in the eastern Bering Sea. Results of the crab experiments will be incorporated into population and bioeconomic models to forecast the effect of OA on future crab abundance. These models will also be expanded to initiate population dynamic models of finfish species starting with northern rock sole (*Lepidopsetta polyxystra*) in the eastern Bering Sea and Gulf of Alaska.

The proposed ocean monitoring is directly informed by these species response studies and vulnerabilities identified in bioeconomic models. While OA research in Alaska was built on a foundation of chemical observing, we are now able to use laboratory and modeling studies to optimize the chemical observing system for OA in Alaska. The end goal is to monitor chemical conditions in key habitat areas identified for their vulnerability or ecological importance, and to reduce uncertainty in future projections of ecological and economic impacts to best support decision-makers. One example of this effort is our letter of intent to build out chemical monitoring in the Bering Sea to better observe OA conditions in vulnerable shellfish habitat, and to support the creation of an ecosystem indicator for OA that could be used by fisheries managers. Additionally, the most critical continuing monitoring priority for the Alaska OA enterprise is the moored system at the M2 site located in the Bering Sea crab fishery, and build-out funds are requested to support this work.

Table 1. -- Work plan for sustained investment budget. Summary table by project and taxa. The deliverables and requested budget for FY18-FY20 OA research are listed below. All deliverable products will be prepared for publication. All studies address themes highlighted in the NOAA regional OA implementation plans that have been developed by the NOAA OA implementation team.

Sustained Investment Budget				
Theme	**Product:** Description	**FY18**	**FY19**	**FY20**
1. OA monitoring network	**Ocean monitoring:** PMEL will measure carbon cycles in coastal Alaskan waters	$264,175	$550,317	$285,507
2. Ecosystem impacts of OA	**Crab:** We will conduct experiments and inform models on the effect of pH and $CaCO_3$ saturation on early life-stage development of crab, including response variables to assess potential acclimation.	$253,000	$253,000	$253,000
	Finfishes: We will conduct experiments on OA-induced developmental and behavioral deficits	$156,514	$100,526	$83,960
	Coral: No funds are requested for planned analysis of laboratory experiment on OA effects on coral	$0	$0	$0
3. Biogeochemical and ecosystem models, and 4. Human dimensions	**Modeling:** Socioeconomic forecasting using bioeconomic model for Alaskan crab species and northern rock sole	$52,500	$52,500	$0
5. Synthesis of data and information products	**OA workshops**: AFSC scientists will participate in workshops on OA research	Travel incorporated into each project costs		
6. Public outreach	**Print and display materials**:	In-house staff time		

	We will produce outreach materials (posters, handouts) for public information and education. **Stakeholder Support**: We support GOA-ON and IOOS outreach and communication activities in Alaska focused on commercial and community resilience (e.g., Alaska Ocean Acidification Network).			
Sustained Investment Totals		**$726,189**	**$956,343**	**$622,467**

Supported Letters of Intent for Sustained Investments				
Theme	**Product**: Description	**FY18**	**FY19**	**FY20**
1. Crab molecular response	Assessing potential acclimation of commercially valuable crustaceans to ocean acidification based on molecular response	$38,000	$38,000	$38,000
2. Fish Histopathology	Assess the potential for OA-induced developmental anomalies in walleye pollock and northern rock sole.	$47,214	$5,786	$0
Supported SI LOI Totals		**$85,214**	**$43,786**	**$38,000**
Letters of Intent for Build-out Investments				
Theme	**Product**: Description	**FY18**	**FY19**	**FY20**
1. OA monitoring network - infrastructure	**Ocean monitoring:** Building a permanent observing system for Ocean Acidification in Alaska	$99,977	$99,980	$99,982
2. OA monitoring network - expanded surveys	**Ocean monitoring:** Ocean Acidification and anthropogenic food web impacts to fisheries recruitment dynamics in the eastern Bering Sea	$99,516	$97,243	$87,207
3. Finfishes	**Gadid modeling:** We will develop model of gadid recruitment incorporating OA's Multiple Action Pathways (MAPs)	$0	$100,354	$104,095
Build-out Initiatives Total		**$199,493**	**$297,577**	**$291,284**

Vision Statement

Working Across Disciplines: Ocean acidification (OA) research at the Alaska Fisheries Science Center (AFSC) and the Pacific Marine Environmental Laboratory (PMEL) follows the priorities established by NOAA's Ocean Acidification Program (OAP) implementation team (Feely et al. 2010). Research is directed towards investigation of the impacts of OA on living marine resources and address the three NOAA OA Research Plan hypotheses. In addition, the three northern NMFS Science Centers (Alaska, Northwest, and Northeast), which are responsible for coldwater regions, have been collaborating closely since 2009 due to similarities in ecology, research priorities, and approaches.

The long-term OA research approach of the AFSC and PMEL is composed of three parts (Fig. 1):

1. Ocean acidification monitoring (oceanographic moorings, ocean acidification surveys);
2. Directed research toward understanding how ocean acidification affects life history processes of finfish and crab species (primarily laboratory research); and
3. Modeling (e.g., recruitment and bioeconomic models to project future conditions).

These three parts (chemical monitoring, research on life history processes, and projection modeling) are the three legs of the stool on which our understanding of long-term OA impacts is seated. All three parts are necessary to forecast effects of ocean acidification on living marine resources and communities in Alaska. Additionally, the results from each of these research areas actively and directly inform the others, resulting in an adaptive, efficient research portfolio that addresses key stakeholder needs as understanding of Alaska OA processes evolves.

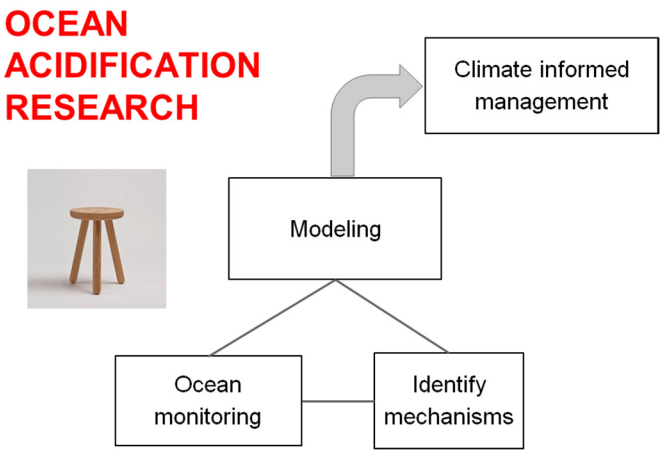

Figure 1. -- The long-term ocean acidification research approach of the Alaska OA Enterprise is composed of three parts: monitoring, identification of mechanisms, and modeling, which together provide for climate-informed management.

Augmentation Priorities

Ocean Monitoring*:* The Alaska OA Enterprise already explores the potential human impacts of OA in the Alaska region through a three-tiered portfolio of ocean chemistry monitoring, laboratory studies of fish, groundfish, and shellfish responses to OA, and population and bioeconomic modeling. This efficient research approach coordinates all of these different perspectives from the outset, and models based on these studies have identified the potential for extreme reductions in some fisheries. The next step in this process is to resolve uncertainty in future forecasting and support decision makers by optimizing the coastal OA observing system.

For example, recent work suggests that OA represents a serious threat to the Bering Sea crab fishery as it currently exists (Punt et al. 2014, Seung et al. 2015, Punt et al. 2016). As a result, the most critical continuing monitoring priority for the Alaska OA Enterprise is the M2 mooring located in this commercially and culturally important fishery. Currently, the OAP supports turnover costs associated with a moored system owned by the Ocean Acidification Research Center at the University of Alaska Fairbanks (OARC). The OARC was founded in large part due to funding provided by the State of Alaska. These funds have now been exhausted. As activities at the facility scale back, this could jeopardize current OAP monitoring activities, especially at the M2 mooring site. In one buildout plan, we request funds that would replace this infrastructure and continue these critical monitoring activities.

A critical opportunity also exists to build out survey monitoring in the Bering Sea by partnering with the NMFS Recruitment Processes Alliance ecosystem monitoring program. We propose to join the biannual Recruitment Processes Alliance (RPA) surveys to collect OA data in the Bering Sea. A record of chemical conditions co-located with important ecosystem information could additionally help create important ecosystem indicators for a variety of fish and shellfish populations, and to improve the understanding of present-day and future OA impacts and Bering Sea ecosystem resilience.

Fish: One expansion of research on the effects of OA on Alaska fishes is planned as a Build-out Initiative. This work will refine our understanding of the cumulative and interactive effects of OA on walleye pollock and Pacific cod which together support one of the Nation's largest fisheries. We will also develop an individually-based bioenergetics model of the early life history of walleye pollock and Pacific cod to quantitatively evaluate the multiple action pathways of OA effects on early life stage growth and survival (Fig. 2). The model will include the direct physiological effects of high CO_2, OA-induced declines in prey quality, and OA-induced behavioral disruptions. The model will be structured such that the results, explicitly accounting for OA, can be integrated into existing model frameworks that are being used to evaluate regional effects of climate change on fisheries (Alaska Climate Integrated Modeling Project, ACLIM), and socioeconomic dynamics of these fisheries.

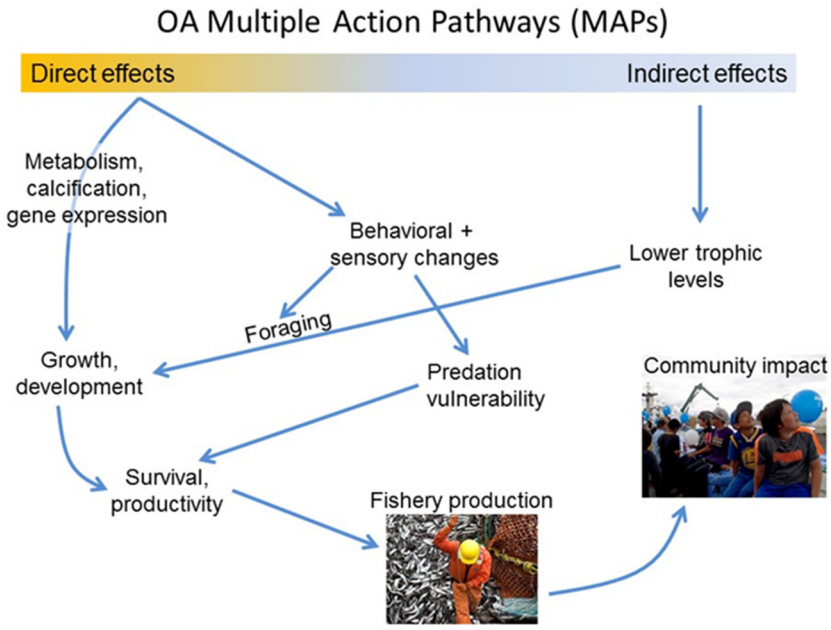

Figure 2. -- OA has multiple pathways to act on the early life stage growth and survival of marine organisms.

Modeling: A separate LOI to the OAP for funding an expansion of modeling capabilities is not necessary. Leveraged support from the AFSC in 2018-20 will expand modeling capabilities by integrating bioeconomic models for Alaska crab and groundfish fisheries into an economic growth model of Alaska's economy.

Priority Science Gaps: Early research into the effects of ocean acidification focused on the potential for depressed oceanic pH levels to lead to reduced calcification and direct mortality of calcifying marine invertebrates. However, as the field has evolved, a number of critical findings have emerged that require a broader and more mechanistic understanding of the effects of OA impacts across multiple levels of biological organization.

1). While it is critical to understand the direct effects of OA on commercially important fishery species, their productivity is dependent upon a wide range of food web interactions. OA-induced changes in the productivity of lower trophic levels can have significant impacts on upper trophic level resource species. Beyond altering the abundance of critical prey species, high CO_2 can also alter the nutritional value of those prey items through alterations in energy density or essential fatty acid composition. Experiments with commercially important northern rock sole and Pacific cod have examined, respectively, the potential role of prey abundance (Hurst et al. 2017) and prey nutritional quality (Hurst et al. in prep).

2). Empirical studies have found that juvenile and adult fishes are, in fact, generally robust to the energetic effects of OA (consistent with theoretical expectations; e.g., Pörtner et al. 2004). However, in addition to negative effects on growth and survival of larvae, high CO_2 has been shown to disrupt the sensory and behavioral ecology of fishes with important implications for recruitment, foraging, and survival. Among Alaskan fishes, these effects have been observed in both juvenile walleye pollock (Hurst unpub. data) and larval Pacific cod (Hurst et al. in prep).

3). It is recognized that changes in the prevailing climate will lead to simultaneous changes in multiple aspects of the environment, such that acidification will occur along with warming temperatures, deoxygenation, and changes in food web dynamics. While most "multi-stressor" experiments have paired CO_2 with temperature stress (e.g., Munday et al. 2009, Ko et al. 2015), a number of studies have demonstrated interactive effects of OA with other environmental stressors (e.g., Hettinger et al. 2013, DePasquale et al. 2015). The AFSC was the first to directly examine the interactive effects of OA and prey field variation in finfishes (Hurst et al. 2016). This interaction is likely to be a critical driver of fisheries recruitment in high-latitude ecosystems.

4). The AFSC, along with our academic partners, has been a leader in developing models that apply the emerging science on species-specific OA responses to socioeconomics of fisheries (Punt et al. 2014, Punt et al. 2016, Seung et al. 2015) and fishery-dependent communities (Mathis et al. 2015). It is critical to recognize that understanding the impacts of OA will require the development of a broad suite of models because of distinct scales, foci, and response predictions. However, a key goal in improving models across the range of applications will be the development of mutually-applicable input and output parameters. A key aspect of modeling work with the AFSC will be to integrate "OA models" into larger, regional models of ecosystem dynamics and socioeconomic responses to climate change. This will allow the broader modeling efforts to take advantage of detailed, mechanistic understanding of OA impacts of key food web and fishery species.

5). Experiments on the effect of OA on coldwater corals were conducted during the last 3-year project period. During FY18-FY20 we plan to complete chemical and physical examinations of the experimental samples and then analyze the results of these experiments. Once complete, we will assess whether and how to continue these experiments. Some possible research extensions for future laboratory research are to examine short-term respiration and lipid content. These would be logical metrics to analyze as physiological responses and could be studied in the laboratory over the course of weeks or a few months rather than many months to a year. Another possible research approach, if interest continues to build in research in the Arctic, north of the Bering Strait, is to work on the dominant soft coral, the sea raspberry (*Gersemia rubiformis*), that does well in the laboratory.

Ideas for Out-year Partnerships/Collaborations

Ocean Monitoring: The coastal Alaska OA observing system supported by OAP actively shares data and collaborates with several partners, including the Alaska Ocean Observing System, the International Ocean Observing System, the Alaska Ocean Acidification Observing Network, the North Pacific Research Board, and the OARC. These partners help distribute data products generated by OAP to diverse stakeholders.

Crab: Research on Alaska crab species has focused on experimental research conducted at the Kodiak Laboratory with limited data collections *in situ*. Primary response variables measures at the lab included survival, growth, and morphology. We continue to collaborate with numerous NOAA and academic partners to increase the resolution of measured response to the laboratory experiments. NOAA partners at the Northeast Fisheries Science Center (S. Meseck) collaborate on cellular responses of crab by measuring hemocyte condition and functional change as a result of OA. Jeremy Mathis (NOAA Arctic Program), Natalie Monacci (UAF OARC), and Andrew Dickson (Scripps Institution of Oceanography, UC San Diego) have been instrumental collaborators in development of our analytical chemistry infrastructure. Future partners include Krista Nichols (Northwest Fisheries Science Center) to assist with genetic sequencing and bioinformatics analyses. Academic partners included Gary Dickinson at the College of New Jersey who measured micromechanical properties of the mineralized cuticle in crab. Jonathon Stillman at the University of California, Berkeley, collaborated with us to develop an RNA transcriptome for red king crab and subsequently identify changes in protein expression associated with pCO_2 exposures. Andre Punt (University of Washington) continues to be an important partner to identify population dynamics modeling needs as crab experiments are developed.

Fish: Research on the OA effects on Alaska finfishes has included collaboration with academic partners at the University of Alaska Fairbanks (UAF) and Oregon State University (OSU). These collaborations will be expanded in the proposed Sustained and Build-Out initiatives. With additional support (from SI LOI), we will collaborate with Michael Kent of OSU's Oregon Veterinary Diagnostic Laboratory to determine if elevated CO_2 levels induce developmental disorders in larval walleye pollock, as has been observed in other species and we will continue to collaborate with Louise Copeman to examine the effects of OA-induced prey quality and quantity on energetic condition of larvae. As described in a Build-Out LOI, we propose to collaborate with Lorenzo Ciannelli to develop a model of the cumulative and interactive effects of OA on recruitment of Alaska gadids that will be incorporated into broader climate impacts and socioeconomics models. Finally, we will collaborate on a National Science Foundation (NSF)-funded project with Andrij Horodysky of Hampton University on a multi-species comparison of neurobiological impacts of OA on fishes. We will also archive tissue samples of OA-exposed Pacific halibut for potential collaborative analyses with Josep Planas of the International Pacific Halibut Commission.

Coral: The mineralogy work in collaboration with scientists from the Woods Hole Oceanographic Institution (Department of Geology and Geophysics), the Marine Conservation Institute, and the National Museum of Natural History (NMNH) – Smithsonian Institution (Department of Invertebrate Zoology) is near completion. Some of the analyses were conducted in collaboration with staff at the Shared Experimental Facility at the Massachusetts Institute of Technology (MIT) Center for Materials Science and Engineering through an NSF grant. The recent laboratory work is in collaboration with the NMNH – Smithsonian Institution (Department of Invertebrate Zoology), the University of Maine (School of Marine Sciences), and scientists at the University of Miami (Cooperative Institute for Marine and Atlantic Studies)/NOAA's Atlantic Oceanographic and Meteorological Laboratory.

Models: The development of bioeconomic models to forecast effects of OA on Alaska crab has been a partnership with André Punt at the University of Washington. In future planned projects, we will continue to partner with André Punt to develop bioeconomic models that link effects from OA experiments to population dynamics for Alaska crab and groundfish.

Collaboration Among the NMFS Science Centers: NMFS Science Centers work together to ensure that NMFS OA research provides an integrated research program with publishable scientific results. Meetings among OA researchers to communicate research results and plans have been held regularly since 2010. The NOAA OA Program Office organized the most recent meeting for NOAA OA researchers in Seattle, Washington, in January 2017.

The three northern NMFS Science Centers (Alaska, Northwest, and Northeast) which are responsible for coldwater regions have been collaborating since 2009 due to similarities in ecology, research priorities, and approaches. Their research has focused on a range of taxa because the knowledge of biological effects of OA is limited; priority has been placed on species considered most ecologically vulnerable and those of economic importance. The approach consists primarily of species-specific laboratory studies and population and ecosystem modeling. Scientists from the three northern Science Centers teleconference periodically to compare notes on diverse topics such as laboratory setup, experimental challenges and best practices for measuring carbonate chemistry. In 2011, chemists from these three northern Science Centers began testing instruments and comparing their results using certified reference materials from the same source. In 2012, researchers from the Northeast Fisheries Science Center (NEFSC) began providing their expertise on measuring cellular condition to researchers measuring crab response at the AFSC in Kodiak, Alaska. This collaboration has continued and has resulted in publications. Mike Sigler (AFSC), Shallin Busch of the Northwest Fisheries Science Center (NWFSC) and Beth Phelan of the NEFSC are members of the NOAA OA Working Group.

These three northern Science Centers once again have communicated proposal development so as to guide, coordinate and integrate OA research that will continue and expand during 2018-2020. All studies by these three northern Science Centers address themes highlighted in the NOAA regional OA implementation plans that have been developed by the NOAA OA

implementation team. We will continue to coordinate the three northern Science Centers research as we have done in the past (e.g., periodic calls). This set of proposals from the three northern Science Centers also includes collaborative research among the three. Collaboration between NEFSC and AFSC will continue using blood hemocytes to measure levels of stress in crustaceans. Collaboration between the NWFSC and AFSC will begin to use next-generation sequencing and bioinformatics to acclimation of crab species. Additionally, the recent laboratory work on the physiological effects of OA on red tree corals has been in collaboration with scientists at NOAA's Southeast Fisheries Science Center (Atlantic Oceanographic and Meteorological Laboratory) and that work will continue as analyses are completed.

History of Past Research Funded by the NOAA Ocean Acidification Program

This history includes projects primarily supported by OAP and AFSC funds as well as those receiving significant external funding support including the following: UAF-Pollock Conservation Cooperative, North Pacific Research Board, and NOAA-Living Marine Resources Cooperative Science Center.

Narrative Timeline: In FY08, an OA research plan was published for the AFSC (Sigler et al. 2008). In FY09, OA systems were designed for Newport, Oregon, and Kodiak, Alaska. In FY10, OA laboratories were established in Newport, Oregon, and Juneau and Kodiak, Alaska, and an OA chemistry laboratory was established in Juneau. Multiple laboratories were established in order to match expertise resident at each laboratory (e.g., the ability to culture walleye pollock larvae at the Newport Laboratory). In addition, experimental studies were initiated on king crab, euphausiids, coldwater corals, and walleye pollock.

In FY11, studies were conducted on king crab, walleye pollock, and coldwater coral. The king crab research was expanded to include a genomics approach which has the potential to better understand how OA affects king crab. The euphausiid work was discontinued because the Principal Investigators were unsuccessful in obtaining sufficient gravid individuals (euphausiid research continues at the NWFSC where collections were successful). The current OA monitoring network was installed in part with funding from the State of Alaska in 2011. This funding has been instrumental in establishing and tracking current conditions.

In FY12-FY14, crab, fish, and coldwater coral research continued. The crab research expanded the number of commercially important crab species studied. Their life history and habitat differences may affect their susceptibility to OA (some inhabit corrosive water, others do not). Results of the crab experiments were incorporated into bioeconomic models to forecast the effect of OA on future crab abundance. The proposed fish research expanded the fish species studied to include flatfish. Like crab, differences in life history may affect susceptibility to OA. The study on the mineralogy and risk assessment of Alaska corals and sponges will be completed in 2014. A small-scale coastal monitoring study was completed in FY12. At the same time, the OA chemistry laboratory in Juneau was closed and chemistry laboratory processing of water samples was transferred to the University of Alaska Fairbanks OA Research Center as a cost-saving measure.

In FY15-FY17, crab, fish and coldwater coral research continued. The crab research expanded to examine effects of OA on bioenergetics and mineralization. Work on the effects of OA on finfishes incorporated studies to examine the interactive effects of OA and feeding regimes on the growth and survival of larval fishes. Fish research was also initiated on the behavioral impacts of elevated CO_2 on both gadids and flatfishes. The first experiment on the effects of OA on an Alaska coral species was conducted at the Kodiak Laboratory. During this period, modeling efforts continued on crab species. The OAP began supporting ocean monitoring in coastal Alaska in FY15 through a previous build-out LOI for FY15-FY17 that included maintenance of two OA mooring sites in critical fishing areas, one coastal OA cruise during FY15, and deployments of autonomous vehicles during FY15 and FY16.

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Sustained Investment

Project Title

Observations of Ocean Acidification in Alaska Coastal Seas

Project Scientists

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Abstract

New ocean acidification (OA) data has been collected over the past 3 years by leveraging an initial 2011 investment from the Alaska State Legislature, a build-out proposal through the NOAA Ocean Acidification Program (OAP), and funds from private industry and non-governmental organizations. This data shows that the coastal regions around Alaska are experiencing some of the most rapid and extensive progressions of OA in the United States. By integrating observational data with species response studies, OA forecast models and human impact assessments have determined that Alaska coastal communities have a varying degree of vulnerability to OA, ranging from moderate to severe. Areas that are most vulnerable are located in regions where fisheries are vital for the state and national economy. Therefore, it is critical to sustain observing efforts and proactively deploy OA assets in regions that are experiencing rapid change or providing habitats to species that show acute vulnerability to present or future OA conditions, such as red king crab in the Bering Sea. Here, we propose to continue the coastal OA monitoring effort begun in 2015 through an OAP build out proposal and include it in the portfolio of sustained investments of the Alaska OA Enterprise. This work would include the maintenance of two OA mooring sites in critical fishing areas and conduct a 20-day OA survey cruise along the continental shelf of the Gulf of Alaska in summer 2019. Additional funds are requested to replace equipment losses incurred by an OAP project in the previous funding cycle.

Budget

Total Budget Request: $1,099,966.

Table 1. -- Budget Summary Table.

	FY18	FY19	FY20	Total
Moorings	$198,874	$209,306.78	$219,839	$628,020
OA Coastal Cruise	$46,868	$341,010	$65,668	$453,546
Wave Glider Loss	$18,433	$0	$0	$18,433
TOTAL	**$264,175**	**$550,317**	**$285,507**	**$1,100,000**

Project Description

The work of the Alaska OA Enterprise focuses on a combination of environmental monitoring and laboratory based studies to evaluate how commercially and ecologically important Alaska species will likely be affected by OA, especially larval and juvenile stages. To support the species studies, robust monitoring of environmental conditions in Alaska coastal waters is necessary to constrain the intensity, duration and extent of OA events, particularly in sensitive habitats. Ocean acidification monitoring activities began in 2008 and have been part of the NOAA OAP portfolio since 2015.

This work has highlighted the vulnerability of coastal Alaska waters to ocean acidification. The cold waters of high-latitude regions are naturally low in carbonate ion concentration due to the increased solubility of CO_2 at low temperatures, ocean mixing patterns and unique riverine and glacial inputs (Mathis et al. 2011a). Consequently, seawater saturation states with respect to aragonite and calcite are typically lower in sub-polar areas than in temperate and tropical regions. In most areas, the surface waters of high-latitude oceans are presently supersaturated with respect to aragonite, a mineral form of calcium carbonate that is about 50% more soluble than calcite. However, some models project that under current rates of CO_2 emissions surface waters of the subarctic Pacific will become undersaturated with respect to aragonite by the end of this century and in some regions as early as 2023 (Mathis et al. 2014).

Recent field observations (Mathis et al. 2011a, b; Mathis et al. 2012; Cross et al. 2013; Mathis and Questel 2013; Mathis et al. 2013; Cross et al. 2014, Evans et al. 2014; Reisdorph and Mathis 2014, Cross et al. 2017) have also shown that the continental shelves of the North Pacific are currently experiencing seasonal manifestations of OA, including decreased pH, as well as suppressed carbonate mineral saturation states (Ω) in response to CO_2 and non-CO_2 related effects. Modeling studies incorporating these data have indicated that these changes could have major consequences for marine life, including commercially and culturally important fisheries (Punt et al. 2014, 2016; Seung et al. 2015). These rapid rates of change underscore the urgent need for increased efforts in OA research.

To monitor these ongoing changes and support the other parts of the Alaska OA Enterprise portfolio that constrain and model the potential impacts of these changes, we propose to continue the coastal OA monitoring effort begun in 2015. This work would include the maintenance of two OA mooring sites in critical fishing areas and conduct a 20-day OA survey cruise along the continental shelf of the Gulf of Alaska in summer 2019. Additionally, funds are requested to replace equipment losses incurred by an OAP project in the previous funding cycle.

Statement of Project Hypotheses and Relevance to OAP Objectives

Sustained investments in the OAP portfolio form a foundational understanding of OA pursuant to the OAP's mission to fulfill Federal Ocean Acidification Research and Monitoring Act of 2009 and the Strategic Plan for Federal Research and Monitoring Requirements of Ocean Acidification and its Implementation Plan requirements. Specifically, this project addresses objective 2, monitoring of ocean chemistry and biological impacts. In the Alaska OA Enterprise vision, these monitoring activities form one of the three critical legs of understanding OA and its impacts in Alaska. These measurements are used to guide laboratory based species response studies, and help set boundary conditions and guide projections in bioeconomic models. Our project-specified hypotheses are as follows:

[Hypothesis 1] The accumulation of remineralization products in the bottom waters of the Gulf of Alaska and Bering Sea shelves, coupled with moderate seasonal upwelling, creates an environment where carbonate mineral saturation states are sharply reduced, leading to seasonal aragonite undersaturations in important benthic and pelagic habitats.

[*Hypothesis 2*] These seasonal sub-surface aragonite undersaturations are linked both to anthropogenic CO_2 intrusion and natural biogeochemical cycles, such that neither anthropogenic CO_2 nor natural variability results in aragonite undersaturations alone, but do result in aragonite undersaturations when combined.

[Hypothesis 3] Unique biogeochemical processes such as seasonally high rates of glacial discharge create conditions favorable to aragonite undersaturations in surface waters both on the continental shelves and adjacent Gulf of Alaska that are distinctly different from other ocean basins.

[Hypothesis 4] Considerable variability in key biogeochemical processes within the region will cause different responses of the biological community (particularly calcifiers) and inorganic carbon system to coupled climate/OA perturbations.

These hypotheses are related to the three hypotheses set forth in the NOAA OA Research Plan, which suggest regional differences in rates and magnitude of ocean acidification and its impacts.

Project Objectives

To test these hypotheses, we propose to complete the following objectives during 3 years of observation (OA survey cruise in summer of 2015 and two continuous mooring sites in 2015-2017) from January 2015 to December 2017:

[*Objective 1*] Better constrain the impacts of glacial discharge, the remineralization of organic matter and the upwelling of deep Gulf of Alaska basin waters on saturation states of calcite and aragonite throughout the water column and relate these observations to the distributions and stocks of keystone organisms.

[*Objective 2*] Constrain the biogeochemical feedbacks on saturation states by determining how gradients in physical forcing (upwelling, river and glacial discharge, major currents) affect the seasonal biological CO_2 uptake and export, and how primary production/export in turn influences surface/subsurface saturation states.

[*Objective 3*] Synthesize this data with that collected by other projects conducted by the Alaska OA Enterprise and partners to address the present and potential future impacts of OA on Alaska Ecosystems.

As these project hypotheses address key aspects of the NOAA OA Research Plan, our proposed objectives testing these hypotheses also conform to the six sustained investment activity themes. Specifically, monitoring activities relate most directly to Theme 1, support of the U.S. National OA Observing Network (Executive Summary, Table 1). Collectively, the Alaska OA Enterprise also uses this data to address the other five objectives. Most directly, these data are used scale research in Theme 3, targeted, OA species-response studies, and Theme 5, Development of models. We also participate actively in Theme 4, data management, and Theme 6, outreach and education as we denote in the sections below.

Technical Approach and Methodology

There are two components of the observational work plan, the 2015 ocean acidification survey cruise and two ocean acidification moorings.

Ocean Acidification Survey Cruise

Given the pace of ocean acidification in the North Pacific, it is now critical to gain a better understanding of the controls and extent of OA in a region where data is severely limited. To address the considerable data gaps in the Gulf of Alaska, we propose to collect a suite of biogeochemical and carbon measurements during a 20-25 day cruise in May 2019 to better constrain coastal ocean acidification processes in the Gulf of Alaska and to determine the controls and potential impacts of ocean acidification on calcifying organisms in the region.

Due to the strong spatial variability and migrating frontal structure of the water column in the Gulf of Alaska we will collect water samples at 130 conductivity-temperature-depth (CTD) hydro-stations at approximately 10 km spacing along 15 transects, following the same grid established during a similar OAP coastal survey in 2015 (Fig. 1). A list of all the measurements that will be made during the project are shown in Table 2 as well as the anticipated application of the data. Water samples will be taken from a Sea-Bird 911+ CTD package that will be calibrated before and after the cruise and will have dual temperature and salinity sensors. The CTD package will also have a SBE-DO sensor that will be calibrated using discrete Winkler DO measurements.

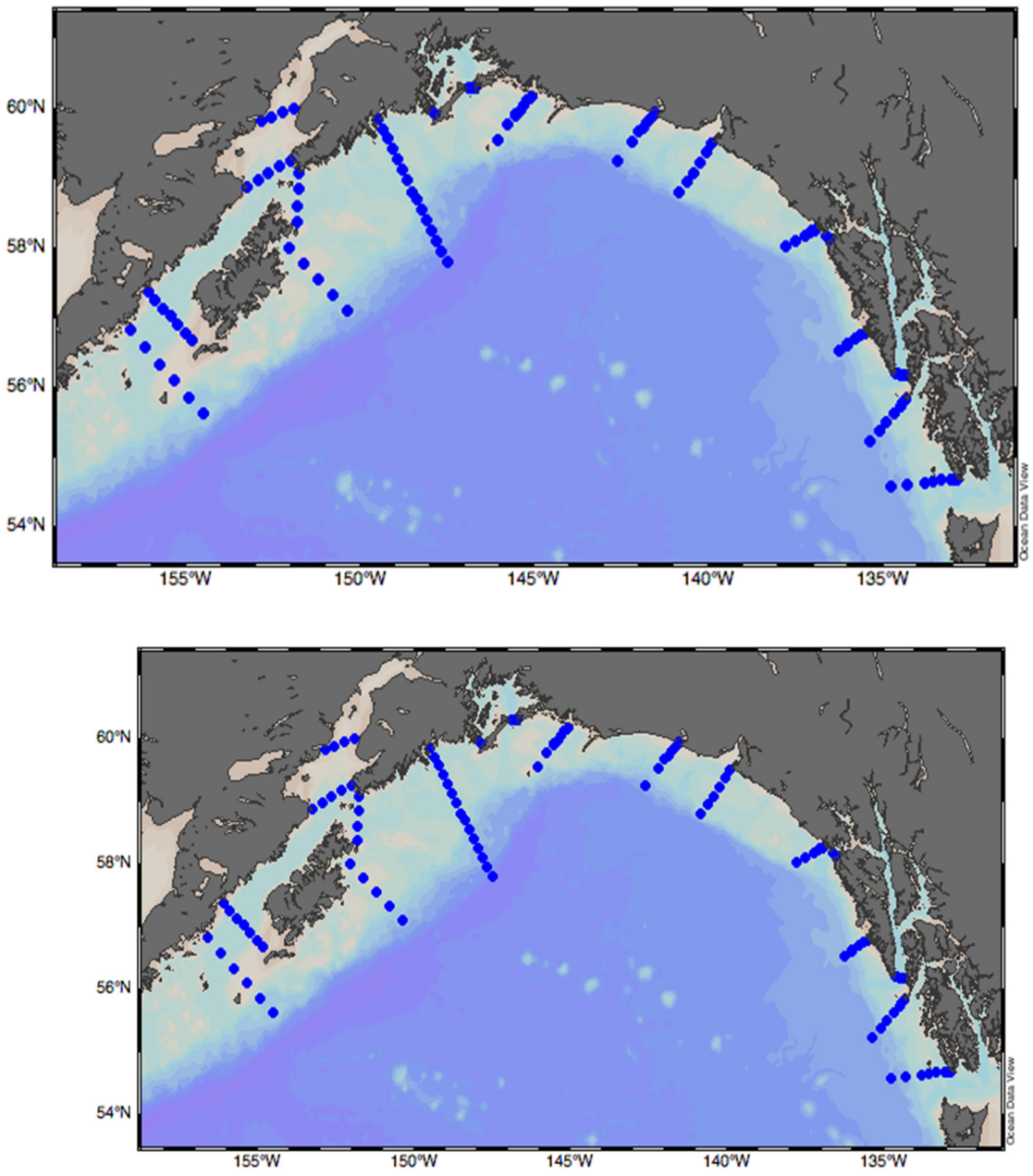

Figure 1. -- Map of the 2015 coastal Alaska OA survey, which will be used as a template for the 2019 coastal Alaska survey for continuity.

Inorganic Nutrients: Samples for nitrate + nitrite, soluble reactive phosphate (SRP), silicic acid and ammonium will be filtered through 0.8 µm Nucleopore filters using in-line polycarbonate filter holders, then frozen (-20 °C) in high-density polyethylene (HDPE) bottles until analysis. Tests of frozen versus refrigerated samples have indicated no significant difference between storage methods. All nutrient samples will be analyzed within several months on a system similar to the Alpkem Flow Solution IV. Analytical precision for triplicate nutrient measurements is approximately 0.03-0.05 µmoles kg^{-1}.

Dissolved Oxygen and $\delta^{18}O$: The OA program has recently identified dissolved oxygen (DO) samples as a high priority, given that significant errors in oxygen concentration can result from the use of profiling sensors of the type commonly used on CTD rosettes. Relative to 2015, DO will be sampled as frequently as possible, rather than to calibrate the profiling sensor on the CTD. DO will be sampled and processed before all other measurements to avoid compromising the samples by atmospheric gas exchange. Dissolved oxygen samples will be drawn into individual 115 mL BOD flasks, rinsed with 4-5 volumes of sample, and analyzed using an automated Winkler titration method. Samples will be analyzed within 12 hours of collection. The use of the UV endpoint detector will allow for increased precision (< 0.08%; < 0.3 μmoles kg^{-1}). Samples for $\delta^{18}O$ will be collected in 5 mL scintillation vials, sealed and returned to the laboratory for analysis. Standard error is ± 0.05 per mL for seawater samples.

DIC and TA: DIC and TA samples will be fixed with a saturated mercuric chloride solution (200 μL), and analyzed using a highly precise (0.05% or1.0 μmoles kg^{-1} for DIC) VINDTA 3C-coulometer system. TA is determined by potentiometric titration with a precision of ~1 μmoles kg^{-1}. Highly accurate DIC and TA samples are calibrated by routine analysis of seawater certified reference materials (prepared and distributed by Andrew Dickson, UCSD), thereby providing the highest possible accuracy. The remaining carbonate parameters (pH, carbonate mineral saturation states, etc.) will be calculated from DIC and TA.

Underway Sampling: Underway data for both surface water and atmospheric pCO_2 will be collected using the NOAA ship *Ronald H. Brown's* underway system. This robust instrument provides pCO_2 precision/accuracy of ±1 μatm/±1 μatm and temperature precision/accuracy of ± 0.01 °C/ ± 0.1 °C. Additionally, discrete underway samples will be collected every 4 hours for $\delta 1^8O$, DIC and TA to increase spatial resolution.

Zooplankton Sampling: In addition to discrete biogeochemical measurements, zooplankton community composition and biomass will be collected at approximately half of the CTD stations. These samples will be processed to determine the relationship between zooplankton stock and health and carbonate chemistry. Along the U.S. West Coast, instances of pteropod dissolution have been observed in waters that are undersaturated in aragonite and this is likely the case in the Gulf of Alaska, as well.

Table 2. -- List of parameters and data usage suggested for the survey.

Parameter	Primary Use of Data
Water-column measurements	
CTD	Water-mass physical properties and characterization
Salinity	Water-mass tracer
Inorganic nutrients	Water-mass tracer; biological response;
Dissolved Oxygen	Biological response
Dissolved Inorganic Carbon	Calculation of carbonate parameters, sea-air CO_2 fluxes
Total Alkalinity	Calculation of carbonate parameters, water mass tracer
$\delta^{18}O$	Water-mass tracer; determination of freshwater, saltwater, and glacial melt components
Underway measurements	
Meteorological Variables	Sea-air CO_2 flux estimates
Temperature and Salinity	Surface water physical properties and characterization
Dissolved Oxygen	Biological Response
Underway pCO_2	Continuous sea-air CO_2 flux, effect on saturation state

Ocean Acidification Moorings

Here, we propose to maintain at least two of the Alaska moorings beyond 2018, which will be critical in constraining the long-term trends in ocean acidification around coastal Alaska. One mooring in the Gulf of Alaska (GAKOA), which is located outside Prince William Sounds, is impacted by a number of processes like high rates of primary production and inundation from glacial melt waters in summer. The site also has the longest record to date, going back to 2011 and is located in an area that supports an extensive salmon fishery. The GAKOA mooring also sits just outside Resurrection Bay, where a "Burkolator" was installed in a shellfish hatchery in 2014. The data from the mooring will be compared to data from the hatchery to determine the impacts that near-shore waters may have on commercial industries that rely on saltwater intakes, such as shellfish hatcheries and the growing mariculture industry, which is projected to grow into a billion dollar industry over the next decade.

We will continue to deploy surface and bottom sensor suites at GAKOA. Surface observations will include a MAPCO$_2$ system for measuring pCO_2, a SeaFET pH sensor, a Seabird system for temperature, salinity, dissolved oxygen and fluorescence, and an ISUS nitrate sensor. The bottom package will consist of a SAMI pCO_2 sensor, a SeaFET pH sensor, a Seabird system for

temperature, salinity, and dissolved oxygen, and an ISUS nitrate sensor. The surface data will be transmitted to PMEL in real-time and the data from the bottom package will be collected during mooring servicing.

The second site that we are proposing to maintain as part of this work plan is M2, due to its ideal location in the Bering Sea. The Bering Sea is a marginally ice-covered sea that has some of the highest rates of biomass production in the global ocean and supports the largest fishery in the U.S. exclusive economic zone (EEZ). The three largest fisheries, which are crab, pollock and salmon all will likely experience either direct or indirect effects from ocean acidification. The M2 mooring has already provided four years of data that have demonstrated how important it is to monitor this location.

Observations of bottom waters at the M2 site (Mathis et al. 2014) have shown a much more immediate threat to the benthic fisheries in the Bering Sea, particularly for crabs. Winter observations have shown that pCO_2 in bottom waters can exceed 1,500 µatm (Fig. 2) and that both aragonite and calcite can become undersaturated for at least 4 months. Excess total alkalinity concentrations have been observed in these locations, which indicates that carbonate mineral dissolution is already occurring to some degree in the shallow waters (<60 m) of this commercially important continental shelf (Cross et al. 2013).

We will continue to deploy surface and bottom sensor suites at the M2 mooring, but because of wintertime ice cover, the surface mooring will only be in the water from May until October each year. Surface observations will include a MAPCO_2 system for measuring pCO_2, a SeaFET pH sensor, a Seabird system for temperature, salinity, dissolved oxygen and florescence, and an ISUS nitrate sensor. The bottom package, which will remain in the water year-round, will consist of a SAMI pCO_2 sensors, a SeaFET pH sensor, a Seabird system for temperature, salinity, and dissolved oxygen, and an ISUS nitrate sensor. The surface data will be transmitted to PMEL in real-time and the data from the bottom package will be collected during mooring servicing.

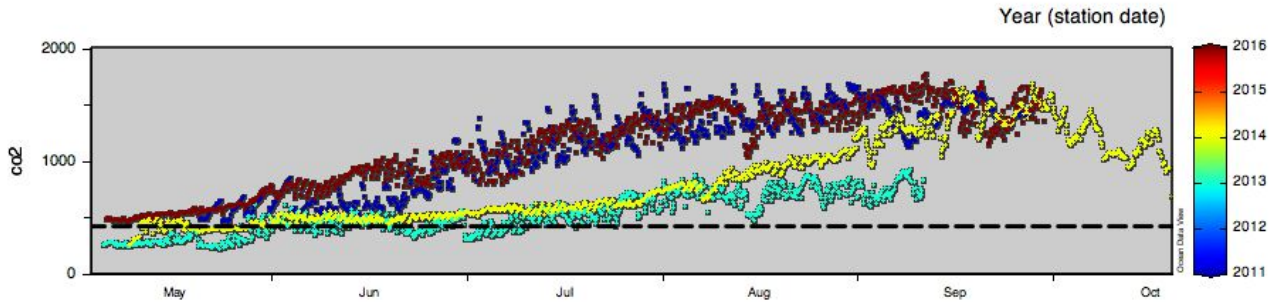

Figure 2. -- Time-series record of sub-surface pCO_2 values (uatm) at the M2 mooring site.

Benefits/Deliverables

We expect a number of cross-cutting products to come from these monitoring activities. Data from the moorings can be used as an early warning system for stakeholders around the state and to provide information for OA species manipulation experiments. Observational data can also be used to validate new OA models that are currently being developed for the Gulf of Alaska and Bering Sea by our partners. These data will also be applied in bioeconomic models of crab and walleye pollock and forecasts of their future abundance. Finally, the data itself will provide new

insights into the seasonal progression of carbonate mineral saturation states as well as the intensity, duration, and extent of aragonite undersaturation events caused by the progressive accumulation of anthropogenic CO_2.

Project Management, Timeline, and Milestones

Jessica Cross [PI] will be the project leader and overall coordinator/point of contact. She has expertise in the connections between the surface ocean and the lower atmosphere, and especially in the cycle of carbon through inorganic and organic pools in high-latitude regions. He will supervise the other project participants, who will assist in cruise preparation, sample analysis, data submission, and publication efforts. The project timeline and milestones are given in Table 3 below.

Table 3. -- Timeline and Deliverables. Deliverables indicated by italicized text.

2018	
January	GOA OA mooring serviced
May	Surface mooring at M2 deployed and overwinter data (bottom) is retrieved
October	Surface mooring at M2 recovered, bottom sensors for overwinter deployed
2019	
January	GOA OA mooring serviced *2018 GOA and M2 mooring data submitted to NCEI*
May	Surface mooring at M2 deployed and overwinter data (bottom) is retrieved Coastal OA survey cruise in the Gulf of Alaska
October	Surface mooring at M2 recovered, bottom sensors for overwinter deployed
2020	
January	GOA OA mooring serviced *2019 GOA and M2 mooring data submitted to NCEI*
March	*2019 Data from coastal OA survey cruise in the GOA submitted to NCEI*
May	Surface mooring at M2 deployed and overwinter data (bottom) is retrieved
October	Surface mooring at M2 recovered, bottom sensors for overwinter deployed
2021	
January	*2020 GOA and M2 mooring data submitted to NCEI* *Publication from coastal OA survey cruise in the GOA submitted* *Publication from ocean acidification moorings completed*

Budget Justification

Funds in this work plan will be used for mooring and cruise activities in all three years. For mooring activities, salary support is requested in all 3 years for PI Cross (6 weeks per year) and technicians Maenner and Musielewscz (1 week per year) and Monacci (10 weeks per year) for deployments and data processing support. Other mooring expenses include annual instrument refurbishment ($23,320 per mooring per year), mooring hardware ($1,500 per year), data transmission fees ($2,000 per year), and ship time (2 days per year). Travel support is requested in all years for fieldwork ($7,500 / year) and national and/or OAPI meetings ($2,500 per year).

For survey activities, salary support is requested in Year 1 for cruise planning and preparation activities (Cross, Monacci, TBD Technician, $32,367). Salary support is requested in Year 2 for cruise personnel to collect ocean acidification and other biogeochemically relevant samples (see Table 2; $119,834 in Year 2) and for sample analysis ($91,899). Additional Year 2 cruise expenses include field travel for 14 people ($35,000) and supplies ($3,250), such as instrument gases, reagents, and certified reference materials. In Year 3, salary support is requested for cruise data processing and submission (Cross, Monacci, TBD technician, $41,404) and travel to national meetings ($5,000).

Lastly, funds are also requested to replace instruments lost in conjunction with a damaged Liquid Robotics SV2 wave glider platform during the previous budget cycle. At 7:30 PM ADT on 23 September, near the end of the joint OAP-Arctic Research Program (ARP) mission, the wave glider lost navigational control south of its scheduled recovery point and began to drift. At this point, the glider's primary GPS continued to function, and we were able to follow the drift pattern. At 4:30 PM ADT 25 September, we lost contact with the glider's primary GPS. The following morning, at approximately 6 AM ADT 26 September, we lost contact with the glider's emergency GPS system. Intermittent contact was regained after this point, but communication consistency was too low to enable a successful recovery. Research vessels in the area were instructed on several occasions to look for the wave glider, but never sighted it.

The platform was never recovered. PMEL self-insures oceanographic platforms, but lost sensors are considered programmatic responsibilities. The total cost of lost sensors and search ship time was $41,893, including two SBE PRAWLER CTDs ($9,800 / each), five SBE56 temperature loggers ($655 / each), and one Eco-FLS Fluorometer ($7,300), and ship time (totaling $11,718). Since this project was jointly supported by OAP and ARP, programs are being asked to proportionally pay for sensor replacement. OAP funded ~44% of the project; resultantly, the OAP replacement cost totals $18,433. We have divided this portion to fund replacement the five SBE56 temperature loggers (total $3,275) one PRAWLER CTD (total $9,800) and the remainder in ship time ($5,333). This project has not been renewed, and therefore information about this project does not appear in the work plan vision, hypotheses, or objectives sections listed above.

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Sustained Investment

Project Title

Physiological Response and Acclimation Potential of Commercially Important Crab Species to Predicted Changes in Marine Chemistry Due to Ocean Acidification in Alaska

Project Scientists

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Abstract

Dissolution of anthropogenic CO_2 has reduced global mean seawater surface water 0.1 pH units below pre-industrial levels and subsequently reduced the availability of carbonate ions. Decreased pH has the potential to affect the acid-base balance of an organism while decreased carbonate ion concentration may hinder the formation of shells and support structures by some calcifying organisms. Crustaceans are calcifying organisms that are critical to marine food webs and support important commercial fisheries. In the North Pacific Ocean, where the saturation depth is relatively shallow due to the cold temperature and age of advected deep water masses, golden king crab (*Lithodes aequispinus*), snow crab (*Chionoecetes opilio*), southern Tanner crab (*Chionoecetes bairdi*), and red king crab (*Paralithodes camtschaticus*) are ecologically and economically important crustaceans. Since 2007, researchers at NOAA's Kodiak Laboratory have assessed the effects of ocean acidification on these Alaska commercial crustacean species with a total ex-vessel value over $275M. At pH and $CaCO_3$ saturation state levels expected to occur in the Bering Sea within the next 100 years, embryos and larvae of red king crab had changed morphology and decreased survival while juveniles had decreased survival and growth. These individual effects, when scaled to the population level, suggest that stock recruitment will be constrained by future levels of ocean acidification leading to dramatic reductions in commercial fishery catch and potential economic welfare loss of $500M to $1B to Alaska communities. To make matters more complicated, increases in temperature synergistically decreased juvenile red king crab survival concurrently exposed to ocean acidification conditions.

To build on the understanding of the potential effects of ocean acidification on commercial crab species in Alaska, our goal is to continue to assess the physiological response of early life history stages while considering the potential for acclimation of crab species. To better understand the potential for crab to acclimate to such environmental perturbations, we must consider additional response variables to assess the whole-organism molecular dynamics that lead to a systemic physiological response. We propose to incorporate such molecular techniques into the short and long term experimentation being proposed for the FY18-FY20 Sustained-Investment studies on commercial crab species in the Alaska Ocean Acidification Enterprise. Our objectives will be to conduct experiments based on complex *in situ*-based exposures on crab species currently living in a stable deep environment and contrast with crab species currently living in a shallow more dynamic environment likely to experience water

chemistry changes due to ocean acidification within the next 10 generations. Our response variables will continue to address macro-scale physiological responses that can be scaled to population level effects while increasing our focus on cellular and molecular responses to better understand mechanism of response and potential for acclimation or adaptation. These variables will include a quantitative estimate of genetic response to further expand upon previous results. Molecular tools will be used to explore potential phenotypic buffering and/or tolerance to future ocean acidification conditions.

To date, research on commercial crab species in Alaska demonstrates that the potential for ocean acidification to negatively affect commercial resources in Alaska is high. These data were from exposure experiments based on globally averaged predictions for changes in surface seawater pH in the next 100 years. Research proposed for FY18 to FY20 will start to provide the public and fisheries communities with more realistic expectations of ocean acidification effects that, when scaled to stock specific population dynamics and socioeconomics, will provide better estimates of community vulnerability to ocean acidification.

Project Budget
The FY18-FY20 budget request for this proposal is $759,000 (sustained investment on crab) and $114,000 (additional sustained investment request for genetics research) for a total budget request of $873,000 distributed evenly over three years (FY18: $291,000; FY19: $291,000; FY20: $291,000).

Project Description
Previous studies on commercially important crab species in Alaska have found that ocean acidification may lead to changes in morphology, decreased growth and condition, and increased mortality (Long et al. 2013a, b; Long et al. 2017a; Long et al. 2016, Swiney et al. 2016). Effects were also found on energetic expenditures associated with intracellular pH maintenance (Meseck et al. 2016) and mineralization in crab chela (Coffey et al. in press) have been found. Interactive effects related to increased temperature were also found with red king crab (Swiney et al. 2017). The effects of these individual physiological effects of decreased pH and carbonate availability will likely lead to population level decreases (Punt et al. 2014, 2016) and subsequent commercial fishery and coastal community effects (Seung et al. 2015, Mathis et al. 2015) if these crab species do not acclimate as ocean acidification persists.

Project Hypotheses and Relevance
The overall hypothesis of this project is that crabs will be directly affected by ocean acidification through the reduction in pH affecting acid-base processes and due to a lower carbonate saturation state affecting the ability of crab to grow and maintain shells. It is expected that early life history stages of crab will experience higher mortality with species and stage-specific effects on growth and calcification. The specific hypotheses of the proposed research program on commercial crab species in FY18-FY20 are that 1) physiological responses of marine crab species in controlled laboratory experiments will represent effects predicted to occur in the sub-arctic and arctic waters of Alaska; 2) cellular and molecular responses of crab to decreased pH and carbonate availability scale to whole organism responses and will provide for acclimation assessment; and 3) scaling of individual response data to population dynamic or ecosystem levels is necessary to quantitatively predict vulnerability of multi-species systems including coastal communities. This project addresses the objectives of the NOAA OAP to research species responses to ocean acidification, to predict effects of ocean carbon cycle changes on marine ecosystems and organisms, to assess

socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems, and to engage in education and outreach on ocean acidification.

Project Objectives

The overall goal of this multi-year research plan is to continue to assess the physiological response of early life history stages of commercial crab species (red king crab *Paralithodes camtschaticus*, snow crab *Chionoecetes opilio*, southern Tanner crab *Chionoecetes bairdi,* and golden king crab *Lithodes aequispinus* while estimating the potential for acclimation to the marine chemistry changes expected with ocean acidification. The specific objectives are as follows:

1. Assess the potential for red king crab to acclimate to lower pH and carbonate availability (FY 18 and FY19). It is likely that there is a genetically variable buffering capacity relative to the dynamic range of pH and carbonate exposure. Red king crab live in a variable environment where photosynthesis and respiration alter the carbonate balance on short and long term temporal and spatial scales. In addition, the different life stages of red king crab are exposed to different magnitudes of change in these environmental conditions. Exposure experiments coupled with molecular tools will be used to assess the propensity for crab that survive multiple exposure experiments to acclimate.

2. Assess the effects of the life history timing of pH and carbonate availability exposure on subsequent physiological response of golden king crab (FY19 and FY20). In previous experiments, golden king crab juveniles had negative response to low pH and carbonate availability. However, these crab naturally live in a stable corrosive environment below the calcium carbonate saturation depth. This suggests that either the phenotypic response to acidified conditions is "set" at early life stages based on exposure or inherent genetic plasticity allows for selection of individuals adapted to particular ocean chemistry.

3. Assess the mechanisms of physiological response to lower pH and carbonate availability by comparing ion transport and energetics of congeneric crab species living in two different yet overlapping thermal environments (FY20). Southern Tanner crab are at the northern edge of their range in the eastern Bering Sea while snow crab are at the southern edge of their range which extends throughout the arctic. Surveys in FY17 and FY19 will make snow crab from the northern areas available for collection to assess spatial variability in ion transport mechanisms while identifying the potential for acclimation.

Technical Approach and Methodology

Red king crab to acclimation potential to lower pH and carbonate availability (FY18-FY19)

Ovigerous Bristol Bay red king crab females were collected during the red king crab commercial fishery in the eastern Bering Sea in the fall of 2016 and shipped live to the AFSC's Kodiak Seawater Laboratory. Crab were held in 2,479 L tanks supplied with flow-through ambient sand-filtered seawater until larvae hatched and females molted. Experiments are currently underway to assess the effects of seasonal variability in pH on physiological response. The juveniles and adults from this experiment will be used for experiments in the FY18-FY20 proposed research.

Red king crab oocyte and larval development study

After mating, females were transferred to individual 68 L containers and randomly assigned to one of four pH levels: ambient, constant 7.8, ambient -0.2 and ambient – 0.4. Ambient pH levels will be varied seasonally based on *in situ* observations. Ambient pH levels will be varied seasonally based on *in situ* observations. Water is flow-through sand-filtered seawater at ambient temperature and a rate of 2L/min. The pH in the treatment tanks is adjusted by adding CO_2 to the water. Once every two weeks water samples will be taken from each treatment, poisoned with mercuric chloride and sent to the University of Alaska Fairbanks laboratory for dissolved inorganic carbon (DIC) and total alkalinity analysis. Crab are fed twice weekly a diet of squid and fish to excess. Females will be held until larval hatching in the early spring 2017.

Monthly, a small clump of approximately 20 eggs will be randomly sampled from each female. The embryo developmental stages are determined from digital images of ten fresh eggs from each female are taken with a digital camera attached to a compound microscope (Moriyasu and Lanteigne 1998). Using image analysis software, the egg, embryo, eyespot will be measured. The embryo developmental stage will be analyzed with an analysis of variance (ANOVA) with pH fully crossed with month as factors. Homogeneity of variance and normality will be verified with Levene's and Anderson-Darling tests. If necessary the data will be transformed to meet these assumptions prior to analysis. Embryo morphometry will be analyzed with a principal component analysis (PCA). Data will be normalized prior to analysis. Principal components explaining 90% of the cumulative variance will be retained and analyzed with an ANOVA with pH fully crossed with month and female nested with pH as factors.

At hatching, larvae produced by each female from the three treatments will be collected daily. Some larvae will be collected and used for experiments examining the effects of OA on larvae. Each day, the dry weight of a counted subsample of larvae from each female will be determined, as well as the dry weight of the rest of the larvae; the total number of larvae hatched per day will be calculated. The fecundity of each female will be calculated as the total number of larvae hatched. When a female has hatched 500 larvae, dried larvae (10 mg) from each female will be prepared and shipped to an analytical laboratory for CHN analysis (carbon, hydrogen, nitrogen elemental analysis). Incubation time will be calculated for each female as the number of days between extrusion and the last day of hatching. During the late stages of larval hatching and prior to extrusion of a new clutch, females clean their pleopods, removing all or nearly all of the empty egg cases over the course of several days (Donaldson and Adams 1989). A subsample of the debris will be collected and examined under a microscope. Hatching success will be calculated as the number of hatched eggs (empty egg cases), divided by the total number of eggs (empty egg cases plus unhatched eggs). All variables will be analyzed with a one-way ANOVA, with Treatment (pH level) as the factor.

At the end of the experiment, all of the adult females will be sacrificed. Samples of the crab carapace and chelas will be sent to the College of New Jersey laboratory for calcification and exoskeleton microstructure analysis. Larval CHN and calcification and adult female calcification and condition index will be analyzed with an ANOVA with pH as the factor.

To assess the linkages between gene expression and response to ocean acidification in red king crab larvae the transcriptome of larval crab exposed to differing pH will be sequenced. RNA libraries will be prepared and sequenced (RNAseq) at the University of Oregon's Genomics and Cell Characterization Core Facility. Data will be processed and analyzed in collaboration

with the Northwest Fisheries Science Center, which has both the bioinformatics resources and expertise in RNAseq data analysis. Data processing and analysis will include the building of a *de novo* red king crab transcriptome from the data using Trinity software (https://github.com/trinityrnaseq/trinityrnaseq/wiki), alignment of samples reads to the *de novo* transcriptome for gene expression quantification, statistical analyses for differential expression between treatments, and annotation of the *de novo* transcriptome. Interpretation of the biochemical and physiological pathways differentially regulated under ocean acidification will be facilitated by pathway analysis in Ingenuity Pathway Analysis (Qiagen). Libraries for 45 larvae (15 individuals per treatment) will be developed and sequenced on an Illumina HiSeq4000 (PE100), with 6-8 samples per library.

To differentiate between the effects of exposure to low pH at the embryo and larval stages, a fully crossed experiment will be conducted examining larval development and survival, and condition. Newly hatched larvae from multiple females within each of the pH treatments will be pooled for this experiment. Five replicate 180 L tanks will be established at each of three pH treatments (ambient, ambient -0.2, and ambient -0.4) from larvae hatched from each of the pH treatments, for a total. Larvae will be stocked at 50 larvae/L. Tanks will be flow through with water at the appropriate pH and ambient temperature. Larvae will be fed enriched Artemia each day until they reach the non-feeding glaucothoe stage. The pH and temperature in each tank will be recorded daily and water samples taken for DIC and alkalinity. Additionally mortalities and molts will be recorded and removed daily. Five larvae will be staged from each tank each day. At the approximate mid-point of each stage, samples of larvae will be taken and the average dry mass, CHN content, and calcium content will be determined. In addition, the density of larvae will be determined and used to calculate percent survival. The experiment will end when all of the larvae reach the first crab stage. Larval development will be with a discrete stage transition model (Long et al. 2016). Percent survival to each stage will be analyzed with an ANOVA with maternal treatment fully crossed with larval treatment as factors. The dry mass, CHN, and percent calcium will be compared among treatments with a one-way ANOVA.

At the end of the adult exposure period, in collaboration with the NEFSC, internal hemocyte pH will be measured with molecular probes that stain the hemocytes with fluorescence ratios that change with pH (Meseck et al. 2016). A flow cytometer will be use to discriminate between three populations of hemocytes. To investigate how ocean acidification would affect crab hemolymph we would use two common molecular probes SNARF (for internal pH) and Fluo-4 and Fluo-Red (for intracellular calcium).

Juvenile red king crab study

Juvenile red king crab from the 2018 larval study will be treated in a fully crossed design by including three pH treatments for each treatment group of larvae exposed during the 2018 study. An approximately 200-day experiment will take place in three tanks (120 (L) × 60 (W) × 60 (H) cm), each of which will be randomly assigned a treatment of ambient ~8.0, 7.8, or 7.5 pH levels. Thirty crabs will be randomly assigned to each of three treatments (90 crabs total). Each crab will be placed in an individual holding cell made of a piece of PVC pipe (diameter 5.1 cm) with mesh glued on the bottom. Ambient temperature flow-through treatment water will be provided to each cell. Crabs will be fed to excess on a commercial gel diet of Gelly Belly enhanced with Cyclop-eeze powder and pollock bone powder. Crabs will be fed three times a week and old food will be removed just prior to feeding. pH and

temperature of five randomly selected cells per treatment will be recorded daily. Water samples will be taken from each treatment every 2 weeks for DIC and alkalinity analysis.

Crabs will be checked daily for mortality or molts. Dead crabs and exuvia will be removed from the tanks for morphometric analysis. The carapace from each exuvia and dead crab will be carefully removed and photographed under a stereomicroscope. Using image analysis software, the carapace width, carapace length, carapace length to the rostrum, carapace length to the eye orbit, rostrum base width, rostrum length, orbital spine width, and orbital spine length will be measured. At the end of the experiment, all crabs will be sacrificed by freezing. The crabs will be imaged for morphometric analysis as above. The crab will be sent to the College of New Jersey laboratory for calcification and carapace microstructure analysis. The crabs will be sent to the College of New Jersey laboratory for calcification and carapace microstructure analysis. Crab morphometrics will be normalized and analyzed with a PCA analysis. Principal components explaining 90% of the cumulative variance will be retained and analyzed with an ANOVA with larval treatment fully crossed with juvenile treatment and crab stage and crab number nested within treatments as factors. Crab size after each molt and at the end of the experiment as well as calcium content in the same way.

To assess the linkages between gene expression and response to ocean acidification in red king crab juveniles the transcriptome of juvenile crab exposed to differing pH will be sequenced. RNA library preparation, sequencing, and data analysis using bioinformatics will be similar to that for the larval experiment above.

Effects of the life history timing of acidification exposure of golden king crab (FY19)
Ovigerous golden crab with eyed eggs will be collected from the Aleutian Islands during the Department of Fish and Game pot surveys or during commercial fisheries in the fall of 2019. Crab will be returned to the Kodiak Laboratory, where they will be held in individual 68 L tanks with flow-through sand-filtered seawater. Crabs will be reared in temperatures that do not exceed 2º C. Throughout the experiment, females will be fed squid and fish twice a week to excess. Once larvae hatch and adults molt the females will be mated by adult male crabs also collected from the Aleutian Islands. Since golden king crab molt and mate asynchronously, this experiment will necessarily occur at separate times for each adult crab.

Females will be randomly assigned to one of three acidification treatments: 1) ambient, pH 8.1 (control), 2) pH 7.8, 3) pH 7.5, for a total of 16 females per treatment. A well-mixed head tank will be established for each treatment. The head tanks for the experimental treatments will have their pH adjusted by bubbling pure CO_2 into them, which will be controlled by a pH probe linked to a computer-controlled gas valve (e.g.. Munday et al. 2009). The pH and temperature will be monitored continuously in each of the head tanks, and measured daily in each of the experimental containers. Weekly water samples will be taken from the head tanks and analyzed for total alkalinity and dissolved inorganic carbon.

In collaboration with the NEFSC, we will measure internal hemocyte pH in crabs using molecular probes that stain the hemocytes with fluorescence ratios that change with pH (Meseck et al. 2016). Using probes with a flow cytometer allows discrimination between three populations of hemocytes. To investigate how ocean acidification would affect crab hemolymph we would use two common molecular probes SNARF (for internal cellular pH) and Fluo-4 and Fluo-Red (for intracellular calcium).

Once a month, a small clump of approximately 20 eggs will randomly be sampled from each female. The embryo developmental stage will be determined for ten eggs (Moriyasu and Lanteigne 1998). Additionally, digital images of ten fresh eggs from each female will be taken with a digital camera attached to a compound microscope, measured, and analyzed as above.

At hatching, larvae produced by each female from the three treatments will be collected daily. Some larvae will be collected and used for experiments examining the effects of OA on larvae. Each day, the dry weight of a counted subsample of larvae from each female will be determined, as well as the dry weight of the rest of the larvae; the total number of larvae hatched per day will be calculated. The fecundity of each female will be calculated as the total number of larvae hatched. When a female has hatched 500 larvae, dried larvae (10 mg) from each female will be prepared and shipped to an analytical laboratory for CHN analysis. Incubation time will be calculated for each female as the number of days between extrusion and the last day of hatching. During the late stages of larval hatching and prior to extrusion of a new clutch, females clean their pleopods, removing all or nearly all of the empty egg cases over the course of several days (Donaldson and Adams 1989). A subsample of the debris will be collected and examined under a microscope. Hatching success will be calculated as the number of hatched eggs (empty egg cases), divided by the total number of eggs (empty egg cases plus unhatched eggs). All variables will be analyzed with a one-way ANOVA, with Treatment (pH level) as the factor.

At the end of the experiment, all females will be sacrificed. Samples of the crab carapace and chelas will be sent to the College of New Jersey laboratory for calcification and exoskeleton microstructure analysis. Calcification and microstructure will be analyzed with a one-way ANOVA, with Treatment (pH level) as the factor.

Larval experiments will be conducted to examine whether embryos that developed in acidified water exhibit phenotypic plasticity such that they are better adapted as larvae to acidified waters. Two experiments will be performed on each set of larvae: a survival experiment and a condition experiment. Larvae hatched from multiple females from within each of the pH treatments (pH 8.1, 7.8, 7.5) will be used. Five replicate beakers will be established at each of the three pH treatments (pH 8.1, 7.8, 7.5) from larvae hatched from each of the pH treatments above, for a total n of 45 for each experiment (3 maternal treatments × 3 larvae treatments × 5 replicates). Results will be analyzed with a fully-crossed two-way ANOVA, with Maternal treatment and Larval treatment as factors. When multiple measurements of the same variable are made in each insert, Insert will be included as a nested factor.

Twenty larvae will be placed inside a PVC insert. The PVC insert will be open on the top and have a nylon mesh on the bottom. Each insert will be randomly assigned to one of the three pH treatments, and will receive water from the head tanks as described above. The larvae are lecithotrophic so will not be fed. The experiments will be run at 2º C. The larvae will be checked daily for molts and mortality, and percent survival will be calculated. Survival in each insert will be fit to the following model using least-squares fitting techniques:
where T is the time in days, LT_{50} is the time to 50% survival, and b is a slope parameter that indicates how steep the decline in survival is. The LT_{50} from each insert will be analyzed with an ANOVA model as specified above.

Baseline condition (morphology, dry mass, calcification, and CHN content) of the larvae will be measured from each of the original pools of larvae prior to the start of the experiment.

Three-hundred larvae will be reared in a 2L insert. Each insert will be assigned to one of the above three pH treatments. Larvae will not be fed. The experiment will be run at 2º C for 7 days. A sub-sample of 50 individuals from each beaker will be dried and massed and the average larval mass determined. The remaining larvae will be dried and samples taken for calcification (25 mg wet weight) and CHN analysis as above. All variables will be analyzed with an ANOVA model as specified above.

Juvenile snow crab study (FY20)

Juvenile snow crab will be obtained from one of the NMFS surveys in the Bering Sea or Arctic, and shipped live to Kodiak via air. An approximately one-year experiment will take place in three tanks (120 (L) × 60 (W) × 60 (H) cm), each of which will be randomly assigned a treatment of ambient ~8.0, 7.8, or 7.5 pH levels. Thirty crabs will be randomly assigned to each of three treatments (90 crabs total). Water will be chilled to 2º C throughout the experiment. Crabs will be fed and mortality, morphology, and growth quantified and analyzed as in the above red king crab juvenile experiment. At the end of the experiment the crabs will be sent to the College of New Jersey laboratory for calcification and carapace microstructure analysis.

Physiological response mechanisms of congeneric crab species (FY20)

These experiments will determine the specific mechanisms by which these species regulate their hemolymph pH, and will directly complement and help interpret the information on gene expression in these crabs. Previous experiments show that after long-term exposure to pH, Tanner crabs are able to regulate the pH of their hemolymph to the same level as in ambient crabs (Meseck et al. 2016). Further, initial results suggest that snow crab are less sensitive to OA than are Tanner crabs (Long, unpublished data). We will determine how these crabs are able to regulate their hemolymph pH, the time scale over which that occurs, and the energetic costs of that regulation. By combining this data with information on gene expression, we will pinpoint not only the mechanism of the response, but also the genes involved allowing for a holistic understanding of their response. By comparing the two closely related species, we will be able to better understand why they differ in their sensitivity to OA. Crabs for this experiment will be obtained from the fisheries and transported to Kodiak in the live holds. We will use only morphometrically mature males in this experiment to ensure that we can draw multiple hemolymph samples without causing additional stress to the crabs. Crabs will be held in flowing, ambient seawater and fed three times a week until used in the experiments. Preliminary experiments will be performed to determine the timescales over which measurements need to be made as the physiological responses can vary with species.

Crabs will be exposed to three pHs: ambient, pH 7.8, and pH 7.5 at a constant temperature, 2º C for snow crabs, and 7 °C for Tanner crabs. At regular intervals (determined by preliminary experiments), hemolymph samples will be taken with an air-tight syringe. The hemolymph pH will be measured using a microelectrode immediately after the sample is taken. The sample will be kept in a water bath held at the same temperatures as the crabs. The TCO_2 will be measured using a blood gas analyzer and the bicarbonate concentration calculated from the pH and TCO_2 using the Henderson-Hasselbalch equation. Serum lactate and protein concentrations will be measured with standard L-lactate reagent and Commassie Brilliant Blue methods. Hemolymph ion concentrations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and Cu^{2+}) will be measured using inductively coupled plasma-optical emission spectrometer. Samples will continue to be take until the hemolymph pH values in the acidified treatments return to the same value as those in ambient water.

Energetics of the crabs will be investigated through feeding and respiration experiments. Again, these will measured at regular intervals as determined by preliminary experiments. Crabs will be starved for 48 hours prior to taking these measurements to standardize hunger levels. Crab O_2 consumption will be measured with standard, intermittent flow respirometry methods. Feeding ration will be measured by offering the crabs a pre-weight portion of squid-mantle. The remaining food will be collected after 24 hours and weighted and the feeding ration, normalized to crab mass, will be calculated. At the end of the experiment, the crabs will be sacrificed and gill, cardiac, leg muscle, and hepatopancreas tissue will be taken, preserved in RNA later for RNAseq gene expression analysis.

All measured parameters will be analyzed with a repeated measures ANOVA with time fully crossed with pH treatment as factors and individual crab as a blocking factor.

Benefits/Deliverables

The benefits of this project include multiple publications on the physiological responses of commercially important crab species to future ocean conditions mediated by ocean acidification. These data will be used to inform modeling efforts to assess population and coastal community resilience to future ocean changes. The results of this project will be used to inform estimates of mortality for long-term fisheries management through the North Pacific Fishery Management Council (NPFMC). This research will inform the fishing industry and coastal Alaska communities about potential effects of climate change. In addition to presentations to the NPFMC presentations will be given to local community representatives in Kodiak and other coastal cities in Alaska. In addition, outreach materials will be developed to inform the public visiting the Kodiak Laboratory.

Project Management and Timeline

Robert Foy and William Christopher Long will co-lead this project and be responsible for the overall project management and execution, chemical and biological data collection and analysis. Ingrid Spies will be responsible for overseeing the genetics data collection and analyses.

Item	FY18		FY19		FY20	
	Fa/Win	Sp/Sum	Fa/Win	Sp/Sum	Fa/Win	Sp/Sum
Red king crab adult experiment: Embryos and seasonal variability						
Red king crab larval/juvenile experiments						
Golden king crab collection and experiment						

Golden king crab larval experiments						
Provision of initial data for population dynamics models						
Snow crab juvenile collection and experiments						
Adult snow and southern Tanner crab collection and physiological experiments						
Data analysis and publication						

Budget Justification
The proposed budget includes funds for technician (or post-doctoral) salaries, contracts for analysis, and supplies to cover laboratory costs. Because we will be holding multiple life stages of crabs constantly over the entire duration of the project, the costs from year to year remain approximately the same each year.

We request funds to support travel (airfare, per diem, and hotel from Kodiak, AK) for one person in each year to attend a national NOAA OA or other meeting ($2,700/trip) to present the findings of NOAA funded ocean acidification research and to regional collaboration meetings ($3,000/trip) to support communication from the AFSC to other science centers within NMFS and NOAA. In addition, we request travel ($4,000/person/trip to cover airfare from Connecticut to Alaska, per diem, and housing for extended time period) for NEFSC scientists to come to Kodiak to conduct the hemocyte pH experimental monitoring in each year of the study.

We request $3,000 per year to help cover costs of shipping live crab from the Bering Sea and or from the Alutiiq Pride Shellfish Hatchery to support adult female culturing and juvenile dosing experiments.

Printing costs ($1,500/year) will cover average costs associated with publishing peer-review articles in journals to be determined.

Contract requests total $257,967 each year to pay for contract technicians and data analysis for mineral content and chemistry. One full-time contracted technician (Biotech III) and one postdoctoral fellow will work on the multiple experiments daily. This includes, but is not limited to, experimental setup, animal care, tank care, and data collection. Two technicians are required given the density of crabs and number of treatments being considered.

Instrument servicing ($5,000) will support a flow cytometer maintenance for assessing the condition of hemocytes. Mineral quantification ($20,000) includes a contract to support supplies and services to assess physical shell characteristics and mineral content. Seawater chemistry ($28,800) will support approximately 300 samples each year to assess water alkalinity and DIC to ensure consistent carbonate parameters in the experiments. These may be processed at the University of Alaska OARC or onsite using a Burkolator to be installed with NOAA Arctic research funds in fall 2017. Contracts to support the genetics research include $26,667per year to support bioinformatician time to conduct the bioinformatics analysis in collaboration with the NWFSC and $7,500 per year for the RNA library construction and sequencing.

We request funding to support supplies each year which including support for the genetics analysis and software ($3,833); OA dosing and monitoring system in the laboratory ($6,700); crab culturing and animal care including food, cleaning, and holding supplies ($1,200); experimental chambers and water pumps associated with delivering acidified water to the experiments ($4,300); and laboratory supplies for hemocyte collection and analyses ($1,000).

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Sustained Investment

Project Title

Effects of OA on Alaska Groundfishes: Identifying Patterns and Mechanisms of Sensitivity and Resiliency in Physiological and Behavioral Performance

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Abstract

Ocean acidification (OA) has the potential to significantly affect the production of valuable fishery resources. With several of the nation's largest commercial fisheries and a heavy reliance on subsistence use of marine resources, Alaska communities are particularly sensitive to this threat (Mathis et al. 2015). OA-induced changes to ecosystem function and fisheries production would have major impacts on the regional economy and culture. OA is known to have a variety of impacts on organisms through "Multiple Action Pathways" (MAPs). Among fishes, these impacts include reduced growth and survival of early life stages and disruptions of sensory and behavioral systems. In addition, fishes will be impacted by OA-induced changes in lower trophic levels that alter the availability of their primary prey species. There is further concern that the effects of OA will interact with those of co-occurring rapid warming and loss of sea ice in the North Pacific and Arctic Ocean. Understanding and predicting the impacts of OA on Alaska fisheries communities will require a comprehensive examination of these MAPs climate interactions across a diverse species assemblage.

In this project, we will conduct a series of laboratory experiments to describe the influence of MAPs of OA on commercially and ecologically important fishery resources of Alaska. In addition to a continued examination of the effect of OA on walleye pollock (*Gadus chalcogrammus*) and northern rock sole (*Lepidopsetta polyxystra*), this research will expand the scope of our understanding through the inclusion of more sensitive response metrics (development and energy status), expand the use of multiple stressor experimental designs (temperature), and include new species into the study plan (Pacific halibut *Hippoglossus stenolepis* and Arctic cod *Boreogadus saida*). In addition, collaborative work will examine the underlying physiological mechanisms of OA impacts through neurobiological studies of walleye pollock (NSF-funded) and gene expression responses in Pacific halibut (pending support). Finally, we will incorporate the findings of this research into regional analyses of the climate sensitivity of fisheries and ecosystems.

Budget

Total budget request: $ 394,000 ($341,000 SI; $53,000 supported SI-LOI).

Budget Summary Table.

	FY18	FY19	FY20	Total
Laboratory experiments - OA effects on Alaska groundfishes.	$156,514	$100,526	$83,960	$341,000
LOI - Developmental sensitivity of Alaska groundfishes.	$47,214	$5,786	$0	$53,000

Project Description

Ocean acidification (OA) is occurring as anthropogenically-released CO_2 dissolves from the atmosphere into surface waters of the world's oceans reducing the pH and the availability of carbonate ions (Feely et al. 2004, Sabine et al. 2004). Significant concern has arisen that OA will disrupt the functioning of marine ecosystems and reduce the productivity of important fishery resources (Cooley and Doney 2009, Denman et al. 2011) and the communities that rely upon those resources, both economically and nutritionally (Mathis et al. 2015, Ekstron et al. 2015). The Gulf of Alaska and Bering Sea support important fisheries for a wide variety of species including gadids, flatfishes, crabs, as well as salmonids. Walleye pollock (*Gadus chalcogrammus*) supports the world's largest single-species fishery. Reflecting the importance of this issue, NOAA's Five-year Research and Development Plan specifically addresses the need for additional research on OA and "a better understanding of how ecological interactions are affected by environmental change." The high-latitude seas of the North Pacific Ocean are of particular concern because they are predicted to be acutely affected by both acidification and continued warming (Fabry et al. 2009, Mathis et al. 2011).

Experimental studies on marine organisms have demonstrated a range of effects from elevated CO_2 and reduced pH (Fabry et al. 2008, Kroeker et al. 2010). In general, fishes are expected to be more resilient to some of the direct physiological effects of OA than invertebrates with carbonate exoskeletons (Pörtner et al. 2004, Melzner et al. 2009). Most studies have found little effects of OA on the growth energetics of juvenile fishes (Hurst et al. 2013, Perry et al. 2015). In contrast, a number of studies have found sensitivity to elevated CO_2 levels in larval stages of some (e.g., Baumann et al. 2012, Frommel et al. 2012, Hurst et al. 2016), but not all marine fishes (Munday et al. 2011, Bignami et al. 2013, Hurst et al. 2013). Importantly, several studies that have incorporated non-growth metrics such as identification of developmental anomalies have documented negative effects of elevated CO_2 levels (Frommel et al. 2012, Chambers et al. 2014, Pimentel et al. 2016). These observations suggest that studies focused on growth responses may underestimate the potential impacts of OA on early life stages; identification of which may require the incorporation of more sensitive non-growth metrics. Further complicating the evaluation of effects is the potential for pre-experimental (in some cases, transgenerational) acclimation. Comparing across several studies of Atlantic cod (*Gadus morhua*) offspring of wild-caught fish appeared more sensitive to the effects of high CO_2 than offspring of laboratory- or aquaculture- reared fish (Frommel et al. 2012, 2013; Stiasny et al. 2016). As a result of these combined concerns, there is a possibility that initial experiments suggesting the relative robustness of walleye pollock larvae to elevated CO_2 levels (based on

growth responses in laboratory-cultured parents; Hurst et al. 2013) may not have provided a sufficiently sensitive evaluation in this critical resource species.

In addition to the "hidden" developmental abnormalities that can be induced by elevated CO_2 levels, a growing body of research has identified sensory and behavioral systems as more sensitive than bioenergetic processes to the effects of OA, suggesting that such behavioral disruptions may be a primary action pathway for OA effects on marine fishes (Leduc et al. 2013, Clements and Hunt 2015). A range of OA-induced effects including disruption of predator recognition and response have been documented (e.g., Dixson et al. 2010, Ferrari et al. 2012). These sensory and behavioral effects are believed to be caused by interference in the GABA-a neuroreceptor following adjustment of extracellular ion composition to maintain the pH and oxygen binding capacity of the blood (Nilsson et al. 2012, Hamilton et al. 2014). This disruption can lead to abnormal, or even polar opposite, behavioral responses to environmental stimuli (Munday et al. 2009b). Although initially investigated in tropical reef species, recent work has demonstrated that these behavioral disruptions occur in temperate fishes as well (Forsgren et al. 2013, Jutfelt et al. 2013, Hurst et al. in prep.).

Behavior is often overlooked in studies that predict the impacts of climate change on marine communities (Rijnsdorp et al. 2009). However, behavioral interactions between predators and their prey provide the underlying structure of the food web and it is those behavioral interactions that allow, or prevent, physiological processes from scaling up to population and community-level responses (Nagelkerken and Munday 2016). For example, a recent analysis evaluated the vulnerability of Alaskan communities to OA-induced declines in fishery productivity based on the likelihood of negative impacts of OA on population productivity of major resource groups (shellfish, salmon, other marine fishes; Mathis et al. 2015). However, the assumption that marine fishes would be minimally impacted by OA was based on empirical observations of responses in only one of Alaska's harvested fish species (walleye pollock) and did not include the potential for OA-induced changes in sensory and behavioral ecology which could impact population productivity.

It is well recognized that changes in the prevailing climate will lead to simultaneous changes in multiple aspects of the environment, such that acidification will occur along with warming temperatures as well as changes in stratification, deoxygenation, and precipitation patterns. Consequently, studies have started examining the potential for interaction among factors. To date, most of these factorial experiments have paired high CO_2 with elevated temperatures (e.g., Munday et al. 2009a, Ko et al. 2015). However, throughout much of their range, most species are not living near their thermal tolerance limits and may not face a physiological risk from increased temperatures. In these cases, climate effects other than temperature may exert the strongest influences on population dynamics (Rijnsdorp et al. 2009). Because they have limited energetic reserves, the survival of marine fish larvae is especially sensitive to the foraging environment encountered during the first few weeks of life. The idea that interannual variation in prey production can be a significant determinant of year-class success is encapsulated in both the "Critical Period Hypothesis" and the "Match-Mismatch Hypothesis." If elevated CO_2 imposes additional stress on larval fish or disrupts patterns of prey production, ocean acidification could exacerbate the risk of "prey mismatches" during critical periods when fisheries recruitment is determined.

Research on larval fish nutrition, mostly in an aquaculture setting, has demonstrated the importance of prey quality (lipids and fatty acids, FAs) in determining growth and survival in

cold-water marine fish (Sargent et al. 1999, Copeman et al. 2002). FAs play a vital role both as a source of energy and as important structural components of cell membranes. Specifically, essential fatty acids (EFAs) which originate in primary producers, can limit growth, survival and metamorphosis in larval fish when they are not sufficient in the diet. Copeman and Laurel (2010) showed that variation in dietary EFA ratios caused changes in growth and condition in larval Pacific cod (*Gadus macrocephalus*). OA has the potential to impact the availability of EFAs for marine fishes through changes in the composition and nutritional value of lower trophic levels which could compromise production of critical marine resource species. Understanding the cumulative impacts of OA's MAPs and the interactions with co-occurring aspects of climate change on productivity of critical marine resource species must include consideration of these "indirect" effects which will alter the nutritional environment of sensitive early life stages.

Statement of the Project Hypothesis and Relevance to OAP Objectives

The project hypothesis is that the effects of Ocean Acidification on productivity of marine fishes will be characterized through careful experimental examination of "Multiple Action Pathways" ("OA MAPs") including energetics, development, and behavior, as well as the incorporation of a multi-stressor perspective that incorporates other environmental changes expected to occur in conjunction with OA. In addition, the development of models that can integrate the effects of these MAPs will be necessary to accurately predict the cumulative effects of OA on marine populations.

Research priorities to address the implications of OA on marine ecosystems have been identified by several different groups (Fabry et al. 2008). Specific to the Gulf of Alaska and Bering Sea, the AFSC has developed a research plan, identifying the areas of concern. This plan focuses on the core areas of

1. Understanding species-specific physiological response to ocean acidification;
2. Forecasting the population, community and ecosystem responses to OA; and
3. Developing scenarios to forecast socio-economic consequences of these responses.

Project Objectives

We propose to conduct new laboratory experiments to evaluate the effects of OA on walleye pollock, Arctic cod (*Boreogadus saida*), Pacific halibut (*Hippoglossus stenolepis*) and northern rock sole (*Lepidopsetta polyxystra*). These will examine a diversity of responses including energetic, developmental, sensory, and behavioral.

Objective 1. Describe the effects of OA on the growth and development of walleye pollock offspring from wild-caught parents.

Objective 2. Describe the effects of OA on the behavioral responses of juvenile Pacific halibut to predator and prey cues.

Objective 3. Describe the interactive effects of OA and prey quality variation on growth and development of northern rock sole larvae.

Objective 4. Describe the interactive effects of OA and temperature variation on growth and survival of larval Arctic cod

Objective 5. Maintain experimental facility for collaborative studies examining the effects of OA on marine resource species.

Technical Approach and Methodology

Growth and Development of Walleye Pollock Larvae

Previous experiments examined the sensitivity of walleye pollock larvae to the effects of elevated CO_2 levels (Hurst et al. 2013). However, it is important to experimentally revisit this issue, as several aspects of the experiment may have inadvertently underestimated the potential impact of OA on this critical resource species. First, the experiment was conducted with fish from the Puget Sound population of walleye pollock; it is possible that this population which lives in a high CO_2 environment due to naturally and anthropogenically enhanced microbial respiration (Feely et al. 2010) could be less sensitive to elevated CO_2 than the Alaska stocks. Secondly, the eggs for that experiment were obtained from laboratory cultured fish; it is possible that the exposure to high CO_2 during annual upwelling events may have preconditioned offspring to elevated CO_2 levels (Murray et al. 2014). Finally, by focusing on the growth rates of larvae, the experiment may have missed important sub-lethal developmental disorders that have been observed in other species (Frommel et al. 2012, Chambers et al. 2014, Pimentel et al. 2016).

We will address these deficiencies with an experiment examining the growth and development of walleye pollock offspring from wild-caught parents from the Gulf of Alaska stock. Adult walleye pollock will be captured during AFSC's annual acoustic assessment survey in Shelikof Strait. Eggs will be fertilized and maintained aboard ship in the dark before being transported to the AFSC's laboratory, in Newport, Oregon. In the laboratory, eggs will be hatched and distributed to replicate 100-L larval rearing tank. This procedure has been successfully used for experiments on walleye pollock larvae (Porter and Bailey 2007). At 3 days post-hatch, CO_2 levels will be adjusted to four treatment levels (ambient to 2,000 μatm) using our automated CO_2 injection system. During culture, fish will be fed enriched rotifers (*Brachionus plicatilis*) supplemented with microparticulate dry food at 3 weeks post-hatch. Samples of fish will be drawn at hatch, 2 weeks and 5 weeks of age for measurements of body size and histological examination. For body size, fish will be individually measured from digital photographs and pooled (up to n = 5) for determination of dry weight. A separate sample of fish will be preserved for histological examination at the Oregon Veterinary Diagnostic Laboratory, Oregon State University (OVDL). The histology laboratory has extensive experience processing small fish for histology, including marine fish larvae. Two sagittal sections (eye level and midline) will be prepared from fish, to provide complete organ coverage. Each slide would be examined and scored by Co-PI Michael Kent. Michael Kent has extensive experience examining the histopathology of larval fishes, including the effects anthropogenic influences on development. Initially, a subset of known control fish will be examined to establish a baseline of the range of type and severity of anomalies in larval walleye pollock. The presence and severity of lesions in all major organ systems will be scored using a ranking system calibrated to the control group. All samples will then be processed "blind" such that the examiner does not know the experimental treatment that the sample was derived from.

Effects of OA and Prey Quality on the Growth and Development of Larval Northern Rock Sole

We will determine the sensitivity of larval northern rock sole to changes in the EFA content of their prey and the potential interaction with OA. Docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) are two essential fatty acids (EFAs) that are found at higher

proportions in dinoflagellates and diatoms, respectively. The impact of dietary ratios of these poly-unsaturated FAs on rock sole growth, condition and survival remain unknown. But, recent work with other cold-water marine species such as Pacific cod has shown that larvae are sensitive to changes in the dietary ratios of these EFAs (Copeman and Laurel 2010). Further, a recent experiment demonstrated that OA and prey quality had both independent and interactive effects on the growth, lipid storage, and survival of Pacific cod larvae (Hurst et al. in prep.). Northern rock sole larvae will be hatched and reared using established protocols (Hurst et al. 2016). However, we will modify the enrichment of rotifers to produce a gradient in their total lipid content and EFA ratios (Hurst et al. in prep.). Larvae will be assessed for length and weight at 2 and 5 weeks of age. Lipid samples of live food enrichments as well as larvae will be taken on a bi-weekly basis and will be analyzed for lipid classes and fatty acids according to methods in Copeman et al. (2002). Survival will be assessed after 2 and 5 weeks of growth by visual estimation of numbers of fish in each tank (Hurst et al. 2016), and will be determined at the end of the experiment by a complete count of all surviving larvae.

Temperature and CO_2 Effects on Growth of Arctic Cod Larvae

In a separate experiment, we will examine the interactive effects of temperature and high CO_2 on the growth and survival of Arctic cod larvae. Living in the high Arctic, we anticipate that for this species, the interactive effects of OA and warming will have a marked effect on the species, as the most rapidly changing aspects of the environment (Flynn et al. 2015). This experiment will require a modification to our existing experimental setup which would allow for lower overall temperatures (2-5° C) as well as multiple temperature treatments. The experiment will generally follow the design of previous high CO_2 exposures, substituting elevated temperature stress for nutritional stress in the factorial design. Arctic cod eggs will be obtained from spawning fish in a laboratory broodstock maintained at the NOAA laboratory in Newport, Oregon. Eggs will be "strip-spawned" and incubated at two temperatures (2° and 6° C) and three CO_2 levels (ambient, 1,000, and 1,750 μATM) until hatch. Survival, time to hatch, and size at hatch will be measured in multiple independent egg clutches from different parents. For the larval experiment, eggs will be spawned and batch-incubated at 2° C and ambient CO_2 levels. After hatch, pre-feeding larvae will be randomly distributed among the 6 temperature-CO_2 treatments for rearing. Fish will be sampled after 2 and 5 weeks of growth to determine body size and growth rates. Additional samples will be archived for lipid and histological analyses (processed, pending additional resources). Survival will be assessed after 2 and 5 weeks of by visual estimates of numbers of fish in each tank, and will be determined at the end of the experiment by a complete count of all surviving larvae.

Behavioral Responses of Flatfishes to OA

Fishes exhibit a wide range of behaviors and sensitivities to environmental stimuli. In understanding the ecological impacts of OA-induced behavioral disturbances, it is critical to focus examination on well understood, ecologically-relevant behaviors. Flatfishes rely upon their inconspicuousness (burial, sediment mimicry, and reduced activity) to minimize the threat of predation. However, the effectiveness of these anti-predator traits are compromised by foraging activity which entails saltatory movement over or away from the sediment surface, setting up a clear tradeoff between two necessary behaviors (foraging and predator-avoidance). Previous experimental work by the lead PI has described variations on this pattern among Alaska flatfish species (Boersma et al. 2008) with Pacific halibut exhibiting a "risk sensitive" behavioral strategy, in that they are highly reactive to the presence of a potential predation threat. We will examine the effects of OA on the baseline activity and foraging as well as the response to an episodic predation threat. For these experiments, fish will be acclimated to

ambient and two levels of elevated CO_2 conditions for a minimum of 3 weeks and all fish behavior will be characterized at their acclimation CO_2 level. During this time, fish will be acclimated to the food-delivery system that will be used in the behavioral observation trials.

Behavioral observations will be made in custom 0.5 × 0.5 m glass aquaria. Baseline behavior will be examined by measuring body posture on the sediment, activity rate, and the responsiveness and willingness to feed (Boersma et al. 2008, Andrade 2017). Fish will then be briefly exposed to a model predator and their subsequent behavior examined, including the willingness to feed. Fish will be tested one additional time at 1-hour post predator exposure. The experimental setup will be behind a blind, allowing remote introduction of food items and exposure to the model predator. Behavioral metrics of body posture, activity level, willingness to feed and success of feeding strikes will be made from video recordings of the experimental trials and analyzed with repeated-measures ANOVA to identify the effects of elevated CO_2 level on recognition and behavioral response to both foraging opportunities and predation risks.

Although not funded as a part of this project, we will archive samples of muscle, liver, and gill tissues from OA-incubated juvenile halibut. These will be saved for future analysis of gene expression in response to high CO_2 exposure. That work would complement ongoing studies of gene expression in Pacific halibut in response to other aspects of environmental variation. This work is being done through a collaboration of AFSC and the International Pacific Halibut Commission with funding from the North Pacific Research Board. These samples would be analyzed pending the identification of the additional necessary resources.

Benefits/Deliverables

This work will provide critical data necessary for evaluating the ecological and socioeconomic impacts of ocean acidification in Alaska waters.

The project will result in multiple peer-reviewed manuscripts examining the direct, indirect, and interactive effects of ocean acidification on commercially and ecologically important groundfishes. In addition, we will continue to work with staff of the Alaska Ocean Observing Network to communicate the results of this work to community members throughout Alaska.

The data from this work will be directly applied to ongoing analyses of climate risks to regional fisheries. Relevant data and data syntheses (e.g., species-specific sensitivity curves) will be provided to NOAA staff members conducting these climate assessments. These assessments do not currently include explicit modeling of the effects of OA on ecosystem dynamics. We will work directly with these colleagues to ensure that both the qualitative and quantitative aspects of the experimental studies are accurately reproduced in the assessments and models.

Project Management/Timeline

Overall project management will be conducted by Thomas Hurst. Hurst will oversee OA system maintenance and modifications. He will design the physiological and behavioral experiments, participate in their execution, conduct statistical analyses and prepare manuscripts for publication. Hurst will partner with Louise Copeman (OSU) in the design and execution of the prey quality experiment. Copeman will conduct lipid compositional analysis of fish diets and larval fish and analyze the resulting data. Michael Kent (OSU) will perform histological analyses of specimens from the walleye pollock and rock sole experiments and analyze the resulting data. Copeman and Kent will contribute to preparation of manuscripts.

We will work with the OA Research Center at the University of Alaska for analysis of water samples to confirm proper operation of CO_2 dosing systems and characterization of seawater carbonate conditions. We will be assisted in various aspects of these projects by AFSC technicians Chris Magel (OA system operation and experiments), Scott Haines and Michele Ottmar (fish culture). In addition, an OAP-supported temporary Biological Technician will participate multiple aspects of fish culture and conducting behavioral experiments. Hurst will be responsible for annual progress reporting and archiving data with NODC.

Project Timeline

Item	FY2018		FY2019		FY2020	
	Fa/Win	Sp/Sum	Fa/Win	Sp/Sum	Fa/Win	Sp/Sum
Walleye pollock larval experiment						
Walleye pollock histology						
Rock sole OA prey quality experiment						
Rock sole larval histology						
Juvenile flatfish behavior						
Arctic cod egg and larval growth						

Budget Justification

Personnel/Salaries: No support is requested for existing AFSC permanent staff. Overtime costs ($1,200) are requested in FY2018 for collecting walleye pollock during the scheduled research cruise in Shelikof Strait. Funds are requested to support 5 month/year of a temporary biological technician to assist with fish culture and laboratory experiments. Support is requested for Louise Copeman (3 month total) and Michael Kent (1.5 month total) for analysis of fish lipids and histology, respectively.

Travel: $5,000 is requested in each year of the project. This would allow the lead PI to attend one scientific conference per year to present the results of this work, and to participate in regional planning/collaboration/outreach efforts. An additional $10,000 is requested over the 3 years of the project for travel associated with collecting fishes for laboratory experiments.

Supplies: $15,000 is requested in each year of the project for necessary laboratory supplies. These include CO_2 cylinders, sample containers and preservatives, fish food, nets and other husbandry supplies, in addition to plumbing and fish tank materials for custom designed aquaria. An additional $1,786 is requested for supplies specific to fish histological analyses.

Transportation: $8,000 is requested for shipping of fish and water samples.

Rents: $12,185 (total across 3 years) is requested to support the chilling system necessary for conducting, controlled low temperature experiments with Alaska fishes. No other infrastructure costs are requested.

Contracts: Fish larvae will be prepared for histological analyses at the Oregon Veterinary Diagnostic Laboratory ($16,000). Routine water samples from the experimental systems will be analyzed for total alkalinity and dissolved inorganic carbon for carbonate system characterization at the University of Alaska's Ocean Acidification Research Center ($48,000).

Cooperative Institute Grant: Copeman, Kent, and the first year of the temporary technician will be funded through a Cooperative Institute (OSU-CIMRS) grant. This grant will also include the costs of lipid sample processing and travel for Copeman to attend one scientific conference. Total costs over 3 years, including salary, benefits, supplies, travel and overhead: $166,291.

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Sustained Investment

Project Title
Forecast Effects of Ocean Acidification on Alaska crab and Groundfish Fisheries

Project Scientists
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Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle WA 98115
André Punt
University of Washington, 1122 NE Boat St, Seattle, WA 98105

Abstract
This project proposes an extension of past work on Bering Sea crab stocks with the development of a multispecies bioeconomic model to evaluate the combined cumulative effects of ocean acidification on red king (*Paralithodes camtschaticus*), snow (*Chionoecetes bairdi*), and Tanner (*Chionoecetes opilio*), crab fisheries. In addition, this project initiates bioeconomic analysis of OA effects on Alaska finfish through the development of a bioeconomic model for fish stocks, with initial application to northern rock sole (*Lepidopsetta polyxystraa*) in the Bering Sea and Gulf of Alaska.

The FY18-FY20 budget request for this project is: $105,000 (FY18:$52,500; FY19: $52,500; FY20:$0).

Project Description
Ocean acidification (OA) is inherently a multi-disciplinary problem that requires models to combine methods from oceanography and fisheries science with the necessary linkages to assess socio-economic impacts. By linking multistage population dynamics and bioeconomic models, Punt et al. (2014) made a significant contribution to the multi-disciplinary approach for OA models. According to Cooley et al. (2015): *"detailed policy-relevant information about the relative effects of ocean acidification, rising temperatures, fishing pressure, and socioeconomic factors on specific species has yet to be developed for most species, with a few notable exceptions"* and noted Punt et al. (2014) *"linked population and bioeconomic models to project ocean acidification impacts on the Alaskan king crab fishery, providing both management insight and rationale for future studies."* Cooley et al. (2015) make a major contribution to OA assessment because they formalized the multi-disciplinary approach with a single-species Integrated Assessment Model (IAM). The proposed project will reconfigure, and link, existing crab bioeconomic models for Bristol Bay red king crab (*Paralithodes camtschaticus*), and Eastern Bering Sea snow (*Chionoecetes bairdi*) and Tanner (*Chionoecetes opilio*) crabs, by developing a new multispecies bioeconomic model to simultaneously evaluate the combined cumulative impacts of OA on the crab fisheries off the coast of Alaska. The proposed project will follow the approach of Cooley et al. (2015) by utilizing a one-way linkage for the ocean model component, and by applying current climate scenarios. In addition, a new single-species bioeconomic model with population dynamics for northern rock sole (*Lepidopsetta polyxystraa*)

in the eastern Bering Sea and Gulf of Alaska will be developed based on the experimental results in Hurst et al. (2016).

Statement of the Project Hypothesis and Relevance to OAP Objectives

The project hypothesis is that effects of OA on growth and survival of juvenile marine organisms will be heterogeneous, species-specific, and cause changes in abundance, yields, and economic value of commercially-important populations. This hypothesis addresses elements of Hypothesis 3 in the NOAA OA Research Plan. The linked model framework employed in this project follows Requirements and Recommendations under Theme 5 (p. 51) in the Interagency Working Group on OA Strategic Plan for Federal Research and Monitoring Requirements of OA: *For example, it would be wise for natural scientists to research impacts of OA on species that are economically and culturally significant. Similarly, social scientists should study impacts that can be accurately represented with models of the biophysical system and are feasibly quantifiable*. In addition, the methods employed in this project conform to the Short-term goals under Theme 5 (p. 55), and in particular, the goal to Develop integrated models that link physical, biological, and economic systems in order to estimate the economic and distributional impacts of OA. The AFSC OA research plan also prioritizes work on commercially important species. Research is planned for Alaska's economically valuable crab and groundfish fisheries.

Project Objectives

The goals of this project are to forecast effects of OA on abundance, yields, fishery income, and economic impacts to the state of Alaska by applying results from exposure experiments and ocean monitoring/modeling to infer population-scale changes in juvenile growth and survival. In terms of model development, the specific project objectives are as follows:

1. Extend previous research by developing a multispecies and multistage bioeconomic model to evaluate the combined and cumulative effects of OA on red king, snow, and Tanner, crab fisheries in Alaska.
2. Develop a new single-species multistage bioeconomic model of northern rock sole to begin to evaluate effects of OA on finfish stocks in the Bering Sea and Gulf of Alaska.

Technical Approach and Methodology

The previous Bristol Bay red king crab OA project (Punt et al. 2014) and eastern Bering Sea Tanner crab OA project (Punt et al. 2016) will serve as a basic template for the models in the proposed project. This template consists of developing and parameterizing four separate component models, and linking these to provide a comprehensive framework to forecast the cumulative impacts of OA for a given scenario (Fig. 1). The first two components are biological models, the third is a bioeconomic model, and the fourth component is a regional economic model (Seung et al. 2015):

1. Pre-recruit model for growth and survival of juveniles estimated using data from OA exposure experiments and forecast using future scenario for multi-decadal population projections with OA effects.

2. Population dynamics model linked to pre-recruit model, which include fishery fleets, their selectivity, and discarding practices, with outputs needed to applying the economic component of a bioeconomic model.
3. Bioeconomic model with linked population dynamics to forecast changes in abundance, yields and fishery income over time.
4. Regional economic model for Alaska linked to a bioeconomic model to evaluate cumulative impacts on all sectors of the Alaska economy under an OA scenario.

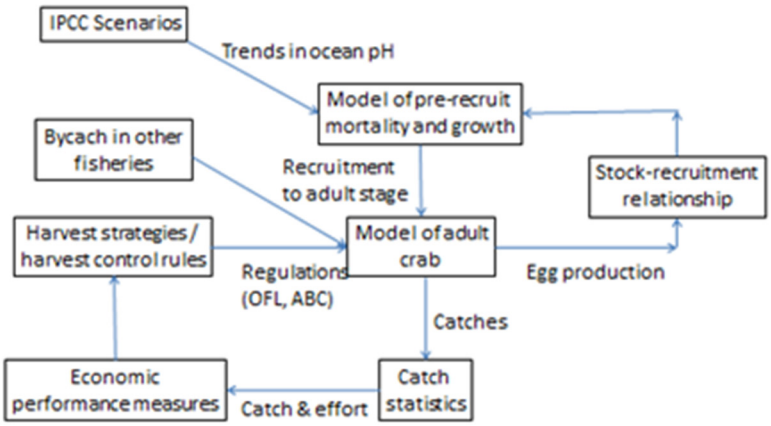

Figure 1. Outline of the linked bio-economic model.

In previous bioeconomic models of Alaska crab fisheries, the linkage to IPCC scenarios was not based directly on an ocean model component, but instead on an interpolated straight-line decrease in ocean pH to a value in 2100 based on the IPCC SRES scenarios. The linkage to IPCC scenarios in the proposed project will be handled using the one-way linkage assumption (Cooley et al. 2015). The proposed bioeconomic models will be applied to time series of ocean pH for Bristol Bay, the eastern Bering Sea, and Gulf of Alaska from scenarios RCP 4.5 and RCP 8.5 in the GFDL CMIP5 database. The proposed bioeconomic models will be used to evaluate effects of OA on:

1. Maximum Sustainable Yield, MSY, and Maximum Economic Yield, MEY, as well as the uncertainty associated with these estimates due to i) observational error associated with the data, ii) the relationship between pH and impacts on juvenile mortality and growth, and iii) other sources of process error such as inter-annual variation in egg production and natural mortality.

2. The consequences of applying the Acceptable Biological Catch, ABC control rule for i) snow and Tanner crab jointly in the eastern Bering Sea, ii) red king crab in Bristol Bay, iii) northern rock sole in the eastern Bering Sea and Gulf of Alaska.

The population dynamics models on which the analyses for Bering Sea crab as based were stage- and size-structured, which limited their use for fish species for which assessment models are typically age-structured. In addition, economic analyses are more tractable when models are based on biomass dynamics (or surplus production). The extension to northern rock sole will lead to age-structured modeling framework that could be applied generally to fish species, while the extension of the crab models will include population dynamics models formulated a surplus production models with delay to better integrate with economic analyses.

Benefits/Deliverables

The benefits of this project will be as follows:

1. Integrated Assessment Model for Alaska crab to forecast combined and cumulative effects of OA on red king, snow, and Tanner crab.

2. Bioeconomic model for northern rock sole to forecast effects of OA on groundfish stocks in the eastern Bering Sea and Gulf of Alaska.

The outputs from this project will be as follows:

1. A report that documents the models, evaluates how well the population dynamics models underlying the bioeconomic models fit the available data compared to the population dynamics models on which management advice is currently based, and provides estimates of the biological and economic consequences of alternative management actions in terms of the relationship between MSY and MEY and average pH, and well as the consequences of alternative rules for setting ABCs given scenarios regarding changes over time in ocean pH as well as the relationship between pH are growth and mortality rates.

2. Software (written in AD Model Builder, FORTRAN and R) for conducting population assessments and estimating the values for the parameters related to animals susceptible to the fishery, which can be used by other scientists who wish to explore alternative management strategies.

The results of this project will be reported to the North Pacific Fishery Management Council crab and groundfish plan teams.

Project Management and Timeline, with Milestones

Dalton and Punt will co-lead the project. Dalton will serve as overall coordinator/point of contact. He is an economist with expertise in bioeconomic models and integrated assessment models. He will prepare economic data for the bioeconomic models. Punt has expertise in population dynamics, and bioeconomic models. Punt will develop the mathematical models for recruitment processes and population dynamics, and the bioeconomic models. He will obtain the necessary data, implement the models, and write the final report. The project timeline and milestones are given in the table below.

Project Timeline

Item	FY2018		FY2019		FY2020	
	Fa/Win	Sp/Sum	Fa/Win	Sp/Sum	Fa/Win	Sp/Sum
Alaska Crab Integrated Assessment Model						
Northern Rock Sole Bioeconomic Model						

Budget Justification

Project Budget

	Rate	Months	Cost (FY18)	Rate	Months	Cost (FY19)	Total
Faculty Salary	**14,744**	**1.75**	**25,802**	**15,334**	**1.70**	**26,067**	**51,869**
Faculty Benefits (24.9%)			**6,425**			**6,491**	**12,916**
Supplies and material			**583**			**252**	**836**
Total direct costs			**32,810**			**32,810**	**65,621**
Amount subject to Indirect Costs			**32,810**			**32,810**	**65,621**
Indirect cost (55.5%)			**18,210**			**18,210**	**35,150**
Total costs (SAFS)			**51,020**			**51,020**	**102,041**
JISAO (Task I fee; 2.9%)			**1,480**			**1,48**	**2,959**
Total costs (UW)			**52,500**			**52,500**	**105,000**

Justification

Personnel/Salaries: The project costs include 3.45 months (2018: 1.75 months; 2019: 1.7 months) of salary for Punt. Punt will develop the mathematical models for recruitment processes and population dynamics, and the bioeconomic models. Punt will obtain the necessary data, implement the models, and write the final report. Personnel/Fringe Benefits: Salary projections are based on an assumed 3% cost of living adjustment on 1 July 2017 and a 4% cost of living

adjustments on 1 July 2018. Faculty salaries are subject to a benefit rate of 24.9%. (www.washington.edu/research/osp/gim/gim3.html). Supplies: $836 is requested to cover the costs of software and computing and to contribute to publication costs. Indirect Costs: UW rate of 55.5% on salaries and benefits. (www.washington.edu/research/osp/gim/gim13a.html).

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Data Management Plan

Environmental data and information collected and/or created under this award will be made visible, accessible, and independently understandable to users in a timely manner, consistent with the requirements of NOAA's OAP.

Temporal Coverage

This plan applies to data collected between FY2018 and FY2020 by AFSC and PMEL PIs and their collaborators working on projects funded wholly or in part NOAA's Ocean Acidification Program.

Summary Description of the Data to be Generated

Data collected for this project will be physical and chemical monitoring data collected by two surface moorings and on one coastal survey, biological measurements made on organisms exposed to ambient and elevated CO_2 levels and descriptions of physical properties of seawater in the experimental treatments. The biological measurements may include information gathered at multiple levels of biological organization: groups of individuals, individuals, organ, cellular and subcellular. Data on seawater characteristics will include temperature, salinity, pH, total alkalinity, and CO_2 concentration. This project will also include the collection of "environmental data" as defined as geospatially-referenced observations reflecting the natural biological, physical, or chemical conditions of the ocean or atmosphere.

Data Types

Data will generally be comprised of digital numeric data.

Quality Assurance

Quality control and assurance procedures will vary markedly depending on the type of measurements being made. These will be applied by the PI for each project, and will conform to community best practices. These may include, but are not limited to instrument calibration at appropriate temporal frequencies, integration of blanks and standards into data collections, and outlier analysis. Depending on the nature of the data, type of QA/QC applied, and available remedies for potential errors in data collection, the data in question may be corrected, censored, or flagged in data sets provided for public dissemination. The type of QA/QC applied and relevant indicators of precision will be incorporated into the data set and/or metadata records as appropriate.

Availability

All oceanographic datasets collected as part of this project will be sent to the National Centers for Environmental Information (NCEI) with associated metadata within 2 years after the end date of the project or followed publication of a peer reviewed paper, whichever is first. While NCEI is the archival backbone for this data, it is also made accessible through other portals, including the

GOA-ON Explorer, the Alaska Ocean Observing System (AOOS) website, the UAF Ocean Acidification Research Center, and previously at CDIAC.

Experimental observations are particularly vulnerable to misapplication and misinterpretation when examined in part or without the proper context of the experimental design. As such, we will adopt policies for public archiving of this data consistent with the nature of these experiments. Data will be considered "collected" when the PI has completed an experiment (or series of integrated/replicated experiments), conducted QA/QC procedures, performed the necessary statistical analyses of the data to determine that additional data collection for this experiment is not warranted, and determination that the data are of sufficient quality to warrant public archiving. The final two steps may include consultation with scientific colleagues as part of the peer-review process of publishing in scientific journals. Data will be made available to the public and scientific communities within 1 year from completion of the collection process. Data and metadata records will be generated and delivered to NODC for permanent archiving and public discovery.

Responsible Parties

Mike Sigler (mike.sigler@noaa.gov) will be the primary point of contact for general questions about overall project initiatives planned under this project.

Individual PI's will be responsible for verifying data collected from their own projects and coordinating the archiving and public dissemination of this data with NODC:

Oceanography: Jessica Cross, jessica.cross@noaa.gov

Crabs: Bob Foy, robert.foy@noaa.gov

Fishes: Tom Hurst, thomas.hurst@noaa.gov

Corals: Bob Stone, bob.stone@noaa.gov

Bioecon models: Mike Dalton, michael.dalton@noaa.gov.

Liqung Jiang (liqing.jiang@noaa.gov) will work with individual AFSC PIs to compile appropriate data sets and ensure adherence to data and metadata standards consistent with NODC requirements and OAP expectations. NODC will be responsible for permanent data archiving and ensuring public availability of the data.

Education and Outreach Plan
As part of this research plan, AFSC will undertake a range of education and outreach activities consistent with the objectives of NOAA's OAP and the FORAM Act.

Alaska Ocean Acidification Network
Enterprise PIs participate in the Alaska Ocean Acidification network, a coordination group in Alaska supported by the Alaska Ocean Observing System (AOOS) program. The main mission of the Network is to connect scientists to stakeholders. The Network was formally established in 2016 after several scoping workshops, in which the Enterprise PIs also participated.

The activities of the Network and participation of the various PIs varies. The Network is organized by an Executive Committee (EC), which includes Enterprise PIs Foy as well as Jeremy Mathis (NOAA Arctic Program) at present. The EC hosts workshops for active participants in the Network. Here, participants a) develop and build consensus around priority knowledge and information gaps on issues surrounding OA in both the physical and social sciences; b) co-develop best practices for research and monitoring; and c) promote data sharing, data synthesis, and provide a resource hub for participants. Lastly, the Network also sponsors open science meetings designed to showcase Network efforts for a wider public audience. These open science meetings are mostly focused on science communication, and to provide a forum for the public to express their interests and concerns in OA.

One key Network activity over the past year has been participation in the Alaska Coastal Resilience program sponsored by the U.S. Fish and Wildlife Service. This program visited communities in four key Alaska regions to discuss the impacts of anthropogenic climate change on their regions and communities, and to build trust between researchers, managers, and Alaska communities. Given that OA may have a substantial impact on many Alaska communities, the Network strongly encouraged participation. The Alaska OA Enterprise voluntarily took on this challenge and supported these workshops by discussing OA as one of many Alaskan concerns. The program has received vocal support from Alaskans, helped create emergency planning strategy documents for some communities, and has earned several award nominations from federal agencies, including DOI and DOC.

Public Outreach
AFSC scientists give numerous presentations to public audiences and routinely participate in outreach events where marine science topics are explained to the general public. Through special arrangement, we also provide more in-depth tours of OA the laboratories to groups when these further the broader outreach goals of NOAA and the OAP. Providing up to date information on the emerging science of OA is a critical component of these activities. Public outreach events include the following:

Seaweek Program @ TSMRI, Juneau, AK
Marine Science Day, Newport, OR
Wild Seafood Weekend, Newport, OR

Alaska CommFish, Kodiak, AK
Kodiak Whale Festival, Kodiak, AK
Kodiak Fisheries Research Center (NOAA) Seawater Facility tours, Kodiak, Alaska.

The AFSC produces displays to describe the basics of OA and the results from ongoing NOAA research on commercial crab species. This display is placed in the public visitors section of the Kodiak Fisheries Research Center which receives 12,000 annual visitors in the 3rd largest fishing port in the United States.

Student Training

High school, undergraduate, and graduate student training are incorporated into multiple aspects of this research plan. These students both benefit from and contribute to AFSC's research initiative on OA, although most are supported through other partner programs and institutions.

Educational opportunities at the NOAA Laboratory in the Kodiak Fisheries Research Center include students at the high school and undergraduate levels. Each semester up to three Kodiak High School students are involved in an internship program to work in the Center's seawater laboratory where they become familiar with research and animal care at the facility. In addition, undergraduate students in the NOAA Hollings Scholarship Program are actively sought to participate in the OA research at the Center. Researchers at the Kodiak Laboratory are also collecting nearshore carbonate data (with other oceanographic variables) in collaboration with K-12 educators in a program that incorporates native cultural values to assess the effect of ocean acidification and environmental variability on coastal communities.

At the AFSC's Newport, Oregon, laboratory, Principal Investigator (PI) Hurst annually hosts a summer undergraduate intern through Oregon State University's Research Experience for Undergraduates (REU) program. For the past 6 years, these students, funded by grants from NSF, have conducted research on the effects of OA on Alaska groundfishes. Hurst also mentored a graduate student (Jessica Andrade) in OSU's Department of Fisheries and Wildlife who examined the effects of OA on the behavioral responses of speckled sanddab which served as a precursor to the complementary work proposed here for Pacific halibut. Andrade was funded through the Living Marine Resources Cooperative Science Center, a NOAA-sponsored consortium of research and teaching universities training under-represented students in NOAA-relevant sciences. Hurst will have a new graduate student starting in 2017.

Media Outlets

The PIs routinely cooperate with local, regional, and national media to raise public awareness and understanding of OA and the NOAA research addressing the issue. Significant examples include the *Seattle Times* "Sea Change", Fisherman's News articles, local newspaper articles, and regional radio shows which tend to get picked up by national press outlets.

Ship Time Requirements

Ship time requirements are given in the table below as specified by the projects above. We request ship time aboard the NOAA ship *Ronald H. Brown* for the Gulf of Alaska coastal OA survey cruise in 2019. Specifically, we request time in May, when spring conditions provide for optimal ecosystem specimen collection. Alternately, we request ship time in September, when the cruise would be able to observe late-season physical dynamics that could impact carbonate chemistry over the Gulf of Alaska shelf.

Day's at Sea (max/min)							PREFERRED				
#	#	#	Proposal Title	PI/CHIEF SCIENTIST	Fleet Coordinator	AREA	VESSEL OPERATOR	PREFERRED VESSEL	BERTHING	SPECIAL CAPABILITIES	ROV/AUV REQUIREMENTS
0	20-25	0	Observations of Ocean Acidification in Alaska Coastal	J. N. Cross	CDR Peltzer, PMEL	Gulf of Alaska	NOAA	R.H. Brown	20	None	None

Build-out Investment Letter of Intent

Strategic Plan for Federal Research and Monitoring Requirements of OA Directive 2: Monitoring of Ocean Chemistry and Biological Impacts

OAP Buildout Investment FY18-FY20 Thematic Priority Area 1: Service, maintenance, calibration/validation, standardization, staffing and development of more advanced OA observing infrastructure which directly contribute to the U.S. National OA Observing Network in adherence to best-practices and in alignment with Global Ocean Acidification Observing Network requirements.

Project Title
Building a Permanent Observing System for Ocean Acidification in Alaska

Project Scientists
Jessica Cross
Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115

Statement of the Problem
New ocean acidification (OA) data have been collected over the past 6 years by leveraging an initial 2011 investment from the Alaska State Legislature with funds from federal agencies, private industry, and non-governmental organizations. These data show that the coastal regions around Alaska are experiencing rapid and extensive seasonal acidification mediated by the absorption of anthropogenic CO_2 (e.g., Mathis et al. 2013, Cross et al. 2013). Therefore, it is critical to sustain observing efforts and deploy OA assets in regions that are experiencing rapid change or providing habitats to species that show acute responses to present or future OA conditions, such as Bering Sea red king crab.

These observational data have been the bedrock of the Alaska OA Enterprise, providing critical information for species response studies (Punt et al. 2014), OA forecast models (Mathis et al. 2015a), and human impact assessments (Mathis et al. 2015b). The current Alaska OA monitoring network has been instrumental in establishing and tracking current conditions from synoptic weather events to the progression of climate-scale variability. While leveraged funds were critical to initializing this process, they have now been exhausted. In particular, this will limit the support provided by the Ocean Acidification Research Network, including important infrastructure, OA instrumentation, and technical expertise.

In order to continue this integral chemical monitoring and continue to provide information for the other components of Alaska OA Enterprise research, here we request buildout funds that will continue to support the moored observing system and provide critical instrumentation for the coastal OA surveys included in the sustained investment portfolio for the Alaska OA Enterprise.

Scope of Work and Project Costs
Here, we propose to continue and expand the coastal Alaska OA monitoring effort by investing in permanent equipment for two OA mooring sites in critical fishing areas, and the instrumentation necessary to support discrete sampling on coastal cruises. While this project could not cover a complete duplication or replacement of all the infrastructure required for these moored systems, we focus on the most critical portions of the instrumentation that would allow us to continue operations as consistently as possible. In order to hire and train adequate technical

support for these instruments, we also request salary support in all three years (total $73,332). Costs within each fiscal year total $99,977 in Year 1, $99,980 in Year 2, and $99,982 in Year 3.

Mooring Support: Funds in this project are requested to support the Alaska OA moorings in the Bering Sea at the M2 time series site and the Gulf of Alaska GAK1 time series site. The M2 mooring is located in critical crab fishery habitat. Given the recently identified vulnerability of this fishery (Punt et al. 2014, Seung et al. 2016, Punt et al. 2016), it is our highest priority for continuing moored OA observations. To continue time-series observations at each site, funds are requested for a surface $MAPCO_2$ system that monitors sea-air CO_2 exchange and flux rates ($40,000 each), and a supporting SBE PRAWLER CTD ($9,800 each). Additional support for the moorings is provided in our sustained investment plan, including support for turnover costs and other disposable materials, such as anchor weights and chain. One $MAPCO_2$ and PRAWLER will be purchased in Year 1 to support M2 and a second $MAPCO_2$ and PRAWLER will be purchased in Year 2 for GAK1.

Survey Support: In the current proposed sustained investment plan, the Alaska OA Enterprise conducts an ocean acidification research cruise in coastal waters in the Gulf of Alaska once every four years. This cruise helps support maintenance of OA algorithms previously developed and provides an opportunity to scale boundary conditions and monitor ongoing changes throughout the water column. While a variety of recharge centers do provide off-site analysis of OA samples, the most cost-effective way to make these measurements is through on-board analysis. This reduces the cost of shipping between remote field sites in Alaska and recharge centers that provide off-site analysis, reduces overhead costs incurred by off-site analysis, and maximizes the value of cruise participants by concurrently sampling and analyzing. Therefore, rather than requesting additional funds for the use of a recharge center, we request the funds necessary to provide in-house instrumentation. According to the highest industry standards and data quality demands, we recommend the purchase of a MARIANDA AIRICA system for the analysis of dissolved inorganic carbon ($35,000) and a MARIANDA VINDTA 3S for the analysis of total alkalinity ($25,000). These instruments will be purchased in Year 3.

Expected Outcomes

Overall, this work contributes to the NOAA-OAP build out and investment thematic priorities, by supporting the sustained investments of the Alaska OA Enterprise. The data itself will provide new insights into the intensity, duration, and extent of acidification events caused by the progressive accumulation of anthropogenic CO_2. This observational data supports species response studies, bioeconomic modelling, maintenance of previously developed OA algorithms, and validation of newly developed OA models. Continued mooring operations at M2 (highest priority) and GAK1 time series sites support OA assessments of critical fishery areas. Cost-effective discrete sampling will support the coastal OA cruises in the Sustained Investment portfolio. Note that if funded, this instrumentation will also dramatically ease feasibility of opportunistic sampling.

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Build-out Investment Letter of Intent

Strategic Plan for Federal Research and Monitoring Requirements of OA Directive 2:
Monitoring of Ocean Chemistry and Biological Impacts

Project Title

Ocean Acidification and Fisheries Recruitment Dynamics in the Eastern Bering Sea

Project Scientists

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Statement of the Problem

The NOAA Ocean Acidification Program (OAP) Alaska OA Enterprise explores the potential human impacts of ocean acidification (OA) in the Alaska region through a three-tiered portfolio of ocean chemistry monitoring, laboratory studies of fish, groundfish, and shellfish response to OA, and bioeconomic modeling. This efficient research approach coordinates these different disciplinary perspectives from the outset, and models based on these studies have identified the potential for extreme reductions in some fisheries. The next step in this process is to resolve uncertainty in future forecasting by optimizing the OA observing system around coastal Alaska.

Improvements in forecasting OA impacts are a key research goal both for the NOAA OAP and the National Marine Fisheries Service, identified through the 1) OAP Strategic Plan for Federal Research and Monitoring Requirements of OA, 2) the Global Ocean Acidification Network, and 3) the NMFS Integrated Ecosystem Assessment (IEA) program. In recent documentation and reports, these organizations have identified the co-location of chemical monitoring with current fishery and ecosystem monitoring and the development of biological indicators as a critical step forward in this effort. Here, we propose an opportunity to take that next step in the eastern Bering Sea, where recent work suggests that OA represents a serious future threat to the fishery economic sector as it currently exists (Punt et al. 2014, Seung et al. 2015, Punt et al. 2016). This proposal directly addresses Bering Sea vulnerabilities by building on partnerships and expertise from across NOAA to operationalize an ecosystem-based approach to fisheries management of our resources and sustainable community livelihoods. The work outlined here will demonstrate complementary NOAA initiatives in the OAP and NMFS working together.

The key deliverable of this work will be development of an ecosystem indicator for Ocean Acidification incorporated into NOAA's Ecosystem Status Report for the eastern Bering Sea. This indicator would be developed according to statistical procedures already developed by the National Marine Fisheries Service (NMFS) Recruitment Processes Alliance (RPA) ecosystem monitoring program. OA indicators considered during the stock assessment process could mitigate deleterious effects of corrosive waters on commercially important groundfish and shellfish populations.

Scope of Work and Project Costs

Development of this indicator would require additional sampling over the Bering Sea shelf. Currently, Bering Sea OA monitoring is limited to a pair of seasonal moorings over the central shelf. While these moorings effectively resolve temporal variability on the seasonal

scale and represent an important long-term time series asset, a variety of non-anthropogenic drivers result in extreme spatial variability in the extent, duration, and intensity of OA. Better spatial coverage is integral to understanding the present-day, baseline relationship between OA and important ecosystem hotspots.

We propose expanding the spatial footprint of chemical monitoring in the region by partnering with the National Marine Fisheries Service (NMFS) Recruitment Processes Alliance (RPA) ecosystem monitoring program, which conducts biennial ship-based surveys. The RPA surveys collect important ecosystem and trophic information focused on identifying and monitoring important environmental indicators for zooplankton and fish communities with the goal towards understanding statistical relationships between environmental data and population-level variability (e.g., Zador and Siddon 2016). A record of OA conditions co-located with biological samples could help create important indicators for a variety of ecosystem components.

Another way of identifying an OA indicator is by exploring the relationship between chemical conditions and environmental DNA (eDNA). This new metagenomic tool has primarily been used to monitor and assess species composition, population sizes, and genetic diversity of marine community food webs. Here, eDNA samples will focus on collection of mollusk, crustacean, and larval fish presence and abundance to supplement data on juvenile fish already collected by the RPA monitoring program. This helps provide a more robust record of covariance between ocean chemistry and ecosystem variables.

Ocean chemistry and eDNA samples will be collected during two research surveys in the southeastern Bering Sea during FY18. Field costs including sample collection, travel, labor, and shipping are approximately $84,456. These samples will be processed during FY18 and FY19. Processing costs are approximately $61,088 for carbon sampling and $15,089 for high-throughput genetic sequencing of eDNA. Then, the OA data collected during this survey will be statistically analyzed for connections to species distribution and abundance and other ecosystem variables collected during the RPA program and the eDNA comparison with the intention of creating an OA indicator. In addition to publication of this indicator in NOAA's Ecosystem Status Report for the eastern Bering Sea, this work will also result in a peer-reviewed publication. Labor and travel associated with this collaboration is expected to cost $126,528 across FY19 and FY20 for PMEL and approximately $12,000 in travel support for NMFS PI Siddon. Costs within each fiscal year total $99,516 in Year 1, $97,243 in Year 2, and $87,207 in Year 3.

Expected Outcomes

1) Surveys of inorganic carbon system variables and eDNA, high-throughput genetic sequencing, and genomic identifications of molluscs, crustaceans, and larval and juvenile fish during 2018.
2) A statistical ecosystem indicator identifying population-level relationships between OA and the distribution and abundance of important commercial and subsistence species studied by the RPA program.
3) At least one peer-reviewed publication documenting these results.

Citations

Punt, A. E., D. Poljak, M. G. Dalton, and R. J. Foy. 2014. Evaluating the impact of ocean acidification on fishery yields and profits: The example of red king crab in Bristol Bay. Ecol. Model. 285: 39-53. doi: 10.1016/j.ecolmodel.2014.04.017.

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Build-out Investment Letter of Intent

Alaska Ocean Acidification Enterprise – Effects of Ocean Acidification on Alaska Groundfishes

SI Thematic Area: Targeted Ocean Acidification Species-Response Studies

Project Title

Mapping Ocean Acidification Impacts : Modeling the Multiple Action Pathways (MAPs) of Ocean Acidification Effects on Alaska Gadids

Project Scientists

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Statement of the Problem

Walleye pollock (*Gadus chalcogrammus*) and Pacific cod (*Gadus microcephalus*) are key species in north Pacific and Bering Sea ecosystems where they are a central component of the food web and support several of the largest single-species fisheries in the United States. Previous work on the effects of OA on the growth and development of these species (Hurst et al. 2012, 2013, in prep.) and other regionally important fishery species (Hurst et al. 2016, 2017) have demonstrated species-specific differences in the direct physiological sensitivity to OA. OA his also been shown to induce behavioral disruptions in larval and juvenile fishes including Alaska gadids (Hurst et al. in prep.). Fishes will also be markedly affected by OA-induced changes in lower trophic levels that may alter the availability or nutritional value of their primary prey species. The cumulative impacts of OAs independent and interacting Multiple Action Pathways (MAPs) have yet to be clearly resolved for any major fishery species. Finally, OA is not occurring in isolation, it is occurring in conjunction with other aspects of climate change. In the high latitude seas, temperature change the interaction with OA is predicted to be a significant driver of ecosystem function.

As part the Sustained Investment (SI) work plan, laboratory experiments have been conducted (and additional work planned) to examine the direct effects of OA on the growth, survival, and behavior of commercially important fishery species. In addition, two experiments have examined the independent and interactive effects of nutritional stress on fish larvae. While these experiments are effective at characterizing the array of OA effects fishery species, the range of response variables and difference in duration of exposures limits the degree to which they can be directly translated into models of fishery production under future climate scenarios. The application of those experimental results to the prediction of population level responses in recruitment and productivity necessitates the development of a model which allows the integration of the full suite of OA-induced impacts on the early life stages when recruitment to the fishery is established.

Scope of Work

To evaluate the cumulative impact of direct and indirect effects of OA on early life stages of

walleye pollock and Pacific cod, we will adapt an existing mechanistic foraging and growth model to incorporate the experimentally observed physiological, behavioral, and food web impacts of elevated CO_2 levels. This model framework, originally developed for Atlantic cod (Kristiansen et al. 2007) has been adapted for walleye pollock in the Bering Sea (Siddon et al. 2013). The model describes vertical swimming behavior, foraging, and growth based on a bioenergetics submodel. Bioenergetics parameters (Hurst et al. 2010) and behavioral patterns (Colton and Hurst 2010) are known to change through the fish ontogeny, particularly during early life history stages. Therefore, for modeling purposes we will divide the early-life cycle in the following stages: 1) egg and yolk-sac stage, 2) feeding larval stage (May to June), 3) pelagic juvenile stage (July to September), and 4) wintering stage (October to March). Input parameters to the baseline model are the water temperatures, size-distribution and energy density of prey categories.

The effects of OA on will be incorporated into the model through alteration of the parameters that govern intrinsic growth rates and behavior including depth distribution (based on phototaxis), swimming speed, prey encounter rate and capture success rates. Whereas most models of fish growth rely exclusively on the energy content of prey, we will modify the model to include the impacts of variation in EFA composition of the diet. The conversion of prey energy to fish growth will be modified by a factor representing the availability of EFAs in the diet based on the experimentally-determined magnitude of EFA-limitation on growth of fish larvae and interaction with CO_2 level (Copeman et al. 2010).

The cumulative effects of OA on early life stages of walleye pollock and Pacific cod will be evaluated by running the model under multiple scenarios representing current, near-future, and 100-year forecasts of CO_2 levels in the Bering Sea. Changes in relative abundances of prey types available to pollock and their EFA composition due to OA will be based on the most recent available experimental observations (e.g., Leu et al. 2013, Calbet et al. 2014). Ocean acidification scenarios will be based on projections specific to the surface waters of the Bering Sea based on regional calibration of IPCC RCP 8.5 (see Mathis et al. 2015). Similarly, temperature predictions will be RCP 8.5 projections for the Bering Sea. The relative importance of individual OA Action The relative importance of the action pathways will be evaluated, and critical pathway interactions identified through additional simulations including subsets of the MAPs.

Output parameters from the model will be the size, survival, and nutritional condition of age-0 walleye pollock at the end of the summer growing season which has been linked to cohort strength in the eastern Bering Sea (Heintz et al. 2013, Farley et al. 2016). This will allow the model to be directly applicable (incorporated as submodule) into existing model structures being use by the AFSC to evaluate recruitment dynamics (e.g., Mueter et al. 2011), climate-driven ecosystem interactions (Holsman and Aydin 2015), and socioeconomics of fisheries (Punt et al. 2014). We would work directly with researchers on each of these projects (J. Ianelli, K. Holsman, and M. Dalton, respectively) to ensure compatibility of model inputs and conceptual frameworks.

Budget

We are requesting $204,449 for this work. These funds would directly support a full–time graduate student at Oregon State University and Ciannelli (1.5 month/year). We also include $8,000 in travel in each year to organize a workshop of among the collaborators to ensure that

the early life history model is coordinated and compatible other ongoing modeling efforts into which it will be incorporated.

Expected Outcomes

1) Model of the effects direct, indirect, and interactive effects of OA on walleye pollock and Pacific cod early life stages.
2) Refined parameterization of fisheries recruitment module of existing models of fishery recruitment, socioeconomics, and ecosystem dynamics.
3) Peer-reviewed publications in national/international scientific journals.

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