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NOAA's Alaska Ocean Acidification Research Plan for FY15-FY17

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Overview

Coastal regions around Alaska are experiencing the most rapid and extensive onset of ocean acidification (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 Alaskan 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, providing over $3 billion annually to the U.S. gross domestic product (GDP). 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 Alaskan species most likely to be affected by OA, especially larval and juvenile stages. Commercially important calcareous species (crab) are our first priority because of their economic value and because these species are likely to suffer direct effects of reduced $CaCO_3$ availability. Our second priority is commercially important fish species; this research will screen for early life history effects and effects mediated by prey. Third priority is coldwater corals whose ecological importance includes sheltering marine organisms (e.g., rockfish), providing focal areas for foraging, and increasing the biodiversity of seafloor habitats.

In FY15-FY17, studies that continue the crab, fish, modeling, coldwater coral, and ocean monitoring research are proposed (Table 1). The proposed crab research will continue evaluating commercially important crab species with different life histories and habitats, which may affect their susceptibility to OA (some inhabit corrosive water, others do not). Results of the crab experiments will be incorporated into bioeconomic models to forecast the effect of OA on future crab abundance. The proposed fish research also will continue to evaluate fish species with different life history strategies and habitats. Like crab, differences in life history may affect susceptibility to OA. The finfish proposal will focus on the behavioral and sensory effects of OA. A letter of intent (LOI) proposes to expand finfish to study the interactive and cumulative effects of OA on recruitment of walleye pollock. The coral research will shift gears from a mineralogy catalog and risk assessment of Alaska corals and sponges (nearly complete) to (in a LOI) studying physiological effects of OA on corals held in the laboratory. The modeling research will expand from bioeconomic models of crab species to begin population dynamic models of finfish species starting with walleye pollock. The ocean monitoring is proposed to continue with funding support requested by NOAA OAP through an LOI. The deliverables and requested budget for FY15-FY17 OA research are listed in Table 1. 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.

Table 1. -- Budget by project and taxa.

Sustained Investment Budget					
Theme	**Product**	**Description**	**FY15**	**FY16**	**FY17**
1. OA monitoring network	Ocean monitoring	PMEL will measure carbon cycles in coastal Alaskan waters	$0	$0	$0
2. Ecosystem impacts of OA	Crab	We will conduct experiments on the effect of CO_2 and temperature on early life-stage development of crab, including water and tissue chemistry	$231,250	$232,225	$233,205
	Finfishes	We will conduct experiments on OA-induced behavioral deficits and changes in prey quality	$139,740	$90,620	$86,504
	Coral		$0	$0	$0

Theme	Product	Description			
3. Biogeochemical and ecosystem models and 4. Human dimensions	Modeling	Socioeconomic forecasting using bioeconomic model for Alaskan crab species	$0	$50,000	$55,000
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	We will produce outreach materials (posters, handouts)	In-house staff time		
Sustained Investment Totals			**$370,990**	**$372,845**	**$374,709**

Letters of Intent for Build-out Investments					
Theme	**Product**	**Description**	**FY15**	**FY16**	**FY17**
1. OA monitoring network	Ocean monitoring	PMEL will measure carbon cycles in coastal Alaskan waters	$200,000	$200,000	$200,000
2. Ecosystem impacts of OA	Crab genetics	We will develop transcriptome for snow crab and use biomarkers for red king crab	$121,559	$130,159	$100,781

				$141,200	$124,100
	Finfishes	We will conduct interaction experiments and pre-recruit modeling		$141,200	$124,100
	Coral	We will conduct experiments on the effect of CO_2 and temperature on physiology of corals.	$84,200	$15,000	$0
Build-out Initiatives Total			**$405,759**	**$486,359**	**$424,881**

Workplan Vision

<u>Working across disciplines</u>
Ocean acidification (OA) research by the Alaska Fisheries Science Center (AFSC) and the Pacific Marine Environmental Laboratory (PMEL) follows the priorities established by the NOAA OA implementation team (Feely et al. 2010). Research is directed towards conducting studies to investigate the impacts of OA on living marine resources. Studies supported by Sustained Initiative (SI) funding focus on assessing the physiological effects on living marine resources and the resulting ecosystem impacts of these effects 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.

New OA data have been collected over the past 3 years by leveraging an initial 2011 investment from the Alaska State Legislature with funds from Federal agencies, private industry, and non-governmental organizations. Unfortunately, these data show that the 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 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, providing over $3 billion annually to the U.S. gross domestic product (GDP). 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 United States.

To date, studies monitoring OA in Alaskan waters have been supported by temporary funding from mostly outside sources. In 2014, a joint PMEL-University of Alaska Fairbanks OA glider study was conducted in Prince William Sound in the northern Gulf of Alaska. In 2015, a joint PMEL-University of Alaska Fairbanks OA cruise is scheduled on the NOAA ship *Ronald Brown* in the Gulf of Alaska. However, there is no dedicated or sustained funding for OA observations in coastal Alaska. Current levels of SI funding directed toward Alaskan studies are insufficient for NOAA to continue these observations, potentially jeopardizing the continuity of these studies.

<u>Priority topics</u>
Lacking basic knowledge of the species-specific physiological response to OA for most Alaskan marine species, a broad research effort is directed toward several taxa including shellfish, coldwater corals, and fish and prioritization of taxa more likely to be affected by OA (Sigler et al. 2008).

<u>Focal species groups</u>
- Crab
- Coldwater corals
- Fish

The assessment focuses on commercially and ecologically important Alaskan species most likely to be affected by OA, especially larval and juvenile stages. Commercially important calcareous species (crab) are first priority because of their economic value and because these species are likely to suffer direct effects of reduced $CaCO_3$ availability. Second priority is commercially important fish species; this research will screen for early life history effects and effects mediated by prey. Third priority is coldwater corals whose ecological importance includes sheltering marine organisms (e.g., rockfish), providing focal areas for foraging, and increasing the biodiversity of seafloor habitats.

Build-out plans

Crab: To augment crab physiological effects experiments in FY15 through FY17, we will also propose continued funding of genetic research to identify molecular organismal response to future changes in regional CO_2 concentrations as a Build-out Investment. Results of current research on red king crab suggest that modest increases in pCO_2 increase the production of proteins related to cuticle development in crab. In addition, proteins related to system organism stress are expressed at a higher rate in crab exposed to lower pH. It is likely that the physiological response of crab to a change in *in situ* pCO_2 will change markedly between early and later developmental stages. Understanding these molecular dynamics is critical to determining how an organism may adapt to future ocean conditions. In addition, it is likely that the molecular response of *Chionoecetes opilio* (one of the largest shellfish fisheries in the United States) will differ from that of red king crab (*Paralithodes camtschaticus*) so we propose to expand the Generation II sequencing to *Chionoecetes* spp. as well. This will allow us to compare the response of multiple commercially important shellfish species from the eastern Bering Sea.

Fish: Two expansions of research on the effects of OA on Alaskan fishes are planned as Build-out Initiatives. Both of these are aimed at refining our understanding of the cumulative and interactive effects of OA on walleye pollock which supports the Nation's largest single-species fishery. First, we will expand the scope of experiments from single factor to examine the interaction between direct (high CO_2) and indirect (reduced prey quality) effects of OA on walleye pollock larvae. We will also develop a bioenergetics-based model of the early life history of walleye pollock to quantitatively evaluate the multiple aspects of OA effects on growth and survival. The model will include the direct physiological effects of high CO_2, OA-induced declines in prey quality, and OA-induced behavioral disruptions. In addition to identifying the pathway of primary action, the model will be used to improve predictions of the cumulative OA impacts on the recruitment and population productivity of walleye pollock in the Gulf of Alaska.

Coral: An expansion of coldwater coral work is proposed through an LOI as a laboratory study of OA-effects on growth, survival, skeletal development, and reproduction of red tree corals (*Primnoa pacifica*). Evidence from the field indicates that these corals, and many others, are somehow thriving well below the present saturation horizons throughout their geographical ranges in Alaska. We anticipate that the results from the laboratory study will provide insights into whether 1) corals are actually compensating for low-pH waters through physiological processes or 2) corals are indeed experiencing effects to low-pH waters in the field but we are as yet unable to measure or detect those effects. In the case of 1) we may pursue additional laboratory work on the physiology of the corals to better understand the mechanisms of compensation. Results from that work, coupled with results from the present work, would provide additional information to help us determine which taxa may be at the highest risk to the effects of OA in the future. In the case of 2) we may undertake additional sampling of corals from above and below the calcite horizons specifically to examine fine-scale differences in skeletal mineralogy (content and structure) and reproductive biology. Red tree corals will continue to be the focal species of study since they are the most ecologically important species in Alaskan waters and other regions of the North Pacific Ocean.

Modeling: A separate LOI to the OAP for funding an expansion of modeling capabilities is not necessary. Leveraged support from the Alaska Fisheries Science Center in 2015-17 will expand modeling capabilities by linking bioeconomic models for Alaska crab and walleye pollock fisheries to a regional economic model of the Alaska economy. This linked regional economic model will be used to simulate economy-wide impacts from effects of OA over the coming decades.

Ocean monitoring: Monitoring the ocean environment will be a critical aspect of the Alaska OA program. As part of the LOI process, we propose to continue and expand the coastal Alaska OA monitoring effort by maintaining at least two OA moorings sites (more if OAP can secure additional ship time) in critical fishing areas and deploying autonomous gliders on an annual basis in OA-vulnerable coastal regions to develop a 4-D understanding of the OA conditions around Alaska. The current OA monitoring network installed, in part, with 2011 state funding has been instrumental in establishing and tracking current conditions; from synoptic "weather" events, to the progressing "climate" of the chemical sea state. While these funds were critical in developing an OA instrumentation pool and infrastructure assets, they have been exhausted.

As part of this OAP build-out initiative we would integrate surface and subsurface pCO_2, pH, temperature, salinity and dissolved oxygen data from moorings with similar data from PMEL-owned carbon wave gliders and Slocum gliders to understand the spatial and temporal dynamics of carbonate mineral saturation throughout the water column. We will continue to improve upon empirical algorithms developed for the Alaska coastal regions to fully utilize data from profiling gliders and conductivity-temperature-depth (CTD) casts that are conducted on a number of NOAA

Fisheries vessels as well as vessels of opportunity. We are requesting $200,000 annually to partially support this effort that will be part of a larger consortium with leveraged funds from the Alaska Ocean Observing System ($95,000 annually), the North Pacific Research Board ($100,000 annually) and the Alaska OA Research Center (all mooring equipment and hardware).

Ideas for out-year partnerships/collaborations

Crab: Research on Alaskan 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 have collaborated 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) collaborated on cellular responses of crab by measuring hemocyte condition and functional change as a result of OA. In addition, Jeremy Mathis (NOAA PMEL) and Andrew Dickson (Scripps Institution of Oceanography, UC San Diego) have been instrumental collaborators in development of our analytical chemistry infrastructure. Academic partners included Gary Dickinson at the College of New Jersey who measured micromechanical properties of the mineralized cuticle in juvenile blue and red king crab. Also, 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.

Fish: Research on the OA effects on Alaskan 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 Sustaining and Build-out initiatives. Initial work on walleye pollock was initiated through collaborations with Jeremy Mathis and UAF graduate student Elena Fernandez. Jessica Miller from OSU examined the effects of OA on walleye pollock otoliths. In future planned projects we will be collaborating with Louise Copeman on the effects of OA-induced reductions in prey quality on growth of walleye pollock; Michael Kent on the potential for OA-induced developmental abnormalities in larval fishes; and Lorenzo Ciannelli on modeling the cumulative and interactive effects of OA on recruitment of walleye pollock.

Models: The development of 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 Punt to link effects from experiments to population dynamics for Alaska crab and walleye pollock.

Coral: We are currently collaborating with scientists from the Woods Hole Oceanographic Institution (Department of Geology and Geophysics), the Marine Conservation Institute, and the National Museum of Natural History – Smithsonian Institution (Department of Invertebrate Zoology) on the mineralogy work. Some of the analyses are being conducted in collaboration with staff at the Shared Experimental Facility at the MIT Center for Materials Science and Engineering

through an NSF grant. The proposed laboratory work would be in collaboration with the National Museum of Natural History – Smithsonian Institution (Department of Invertebrate Zoology) and the University of Maine (School of Marine Sciences).

Ocean monitoring: We are collaborating with the Alaska Ocean Observing System, the North Pacific Research Board and the Alaska OA Research Center.

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: [1]UAF-Pollock Conservation Cooperative; [2]North Pacific Research Board.

Narrative timeline: In FY10, OA laboratories were established in Newport, OR and Juneau and Kodiak, AK, and an OA chemistry laboratory was established in Juneau (Table 2). 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 (Table 2).

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 Northwest Fisheries Science Center where collections were successful).

In FY12-14, 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 finfish proposal also adds response variables for behavior. 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.

Table 2. -- History and accomplishments of ocean acidification (OA) research at the Alaska Fisheries Science Center (AFSC).

Project	PIs	Timeframe	Status
AFSC Research Plan on OA	Sigler et al.	2008	Served as framework for NOAA-wide plan in 2010
Initial mineral assessments on crab.	Foy, Swiney, Persselin	2008	Holling scholar supported to develop initial study design for physiological experiments on crab.
Develop Newport OA system	Hurst, Mathis	2009	Basic design in 2009; improved pH control in 2013
Develop Kodiak OA system	Foy, Long, Swiney	2009	Basic design in 2009; improved pH control 2011-12.
Establish water chemistry laboratory	Carls	2010-2011	Transition to UAF for analysis in 2012
Develop Juneau OA system	Carls	2010	Ended in 2012, focus investment in Kodiak and Newport systems
Establish partial water chemistry capability in Kodiak	Foy	2011-12	Capability for pH and alkalinity supporting current projects.
Walleye pollock response expts.	Hurst	2009-2012	Completed - 2 papers published on larval and juvenile walleye pollock
Red king crab response expts.	Long, Swiney, Foy	2009-2011	Data published.
Tanner crab response expts.	Long, Swiney, Foy	2009-2010	Data published.
Euphausiid response expts.	Carls	2010	Unable to collect required animals, ended project - euphausiid work continues at NWFSC

NOAA-Norway Institute of Marine Research (IMR) workshop	Foy, Hurst	2011	Participated in research scoping and coordination workshop
Mineralogy of Alaskan crabs	Carls	2011	Analyses completed.
King crab genomics	Foy	2011-pres.	Incorporated into lab experiments. Publication in review.
Mineralogy of Alaskan corals	Stone	2011	Initial work on mineralogy completed.
Red king crab response with temperature covariate.	Long, Swiney, Foy	2011-2012	Publication in preparation.
Alaska king crab abundance forecasts	Dalton, Punt	2011-2014	Data and model published in 2014.
Alaska Tanner crab abundance forecasts	Dalton, Punt	2012-2014	Joint Tanner-snow crab bioeconomic model development in progress.
Water chemistry QA/QC	Foy, Mathis	2011-2013	Completed inter-laboratory validation study.
Rock sole response	Hurst	2012-pres.	Completed egg and larval expts, MS in preparation; Second experiment underway.
Preliminary walleye pollock behavior	Hurst	2012	Tested experimental design and conducted prelim. trials - foundation for 2015-2017 studies
Partner with UAF for water chemistry	Mathis	2012-pres.	Established partnership with UAF to improve efficiency in water chemistry analyses
Coastal monitoring in SE AK	Carls	2012	Analyses completed, MS in preparation.
Golden king crab response	Long, Swiney, Foy	2013	Experiments underway.

Mineralogy of Alaskan coral	Stone	2014	All analyses completed. Two manuscripts in preparation on mineralogy and new analytical methods.

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 annually since 2010. In 2010, a NMFS-organized workshop was held in Seattle, WA, for NMFS and academic researchers to communicate research results and plans and for NOAA oceanographers to present results from related OA research. In 2011, a side meeting was held for NOAA OA researchers participating in an OA session at the national American Fisheries Society meeting in Seattle, WA. In 2012, a side meeting was held for NOAA OA researchers participating in the Oceans in a High CO^2 World meeting in Monterey, CA. In 2013, the NOAA OA Program Office organized a meeting for NOAA OA researchers in Washington, DC.

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 quarterly 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. These comparisons give the researchers a standard frame of reference, verify measurement accuracy and assure measurement quality. These results were reported at the 2013 meeting by Andrew Dixon with recommendation for lab QA/QC in the future and metrics captured as part of the metadata set being organized by NODC and populated by the NOAA scientists. In 2012 and 2013 researchers from the Northeast Fisheries Science Center provided their expertise on measuring cellular condition to researchers measuring crab response at the Alaska Fisheries Science Center in Kodiak, AK. This collaboration resulted in a publication (in review) and will lead to additional collaborations highlighting the expertise at each location to assess the effects of OA on commercially important species. Researchers from the three northern Science Centers met with Norwegian colleagues in Norway during October 25-27, 2011 because of their common interest in research on potential OA effects on northern ecosystems. This meeting was a follow up to a one held 2 years previously in Seattle. Mike Sigler of the Alaska Fisheries Science Center (AFSC), Paul McElhany of the Northwest Fisheries Science Center (NWFSC) and Beth Phelan of the Northeast Fisheries Science Center (NEFSC) are members of the NOAA OA Working Group. This collaboration also benefits education and outreach. Education and outreach activities were developed and shared among the three centers beginning with an OA education cart at the

Seattle Aquarium replicated and used at Ocean Fun Days Open House at the Sandy Hook Marine Laboratory in New Jersey.

These three northern Science Centers once again are collaborating in proposal development so as to guide, coordinate and integrate OA research that will continue and expand during 2015-2017. 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. The principals on the AFSC, NWFSC, and NEFSC proposals met approximately monthly to coordinate development of their research plans for FY15-17. We will continue to coordinate the three northern Science Centers research as we have done in the past (e.g., quarterly calls). This set of proposals from the three northern Science Centers also includes collaborative research among the three. A joint LOI proposal was developed for FY15-17 as a collaborative project among NWFSC, SWFSC, and AFSC for experiments on regional variation in the response of Dungeness crabs and pteropods to OA. Collaboration between NEFSC and AFSC will continue using blood hemocytes to measure levels of stress in crustaceans.

Citations

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Project Title

Physiological response of commercially important crab species to predicted increases in pCO$_2$

Project Scientists

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Abstract

Dissolution of anthropogenic CO$_2$ has reduced global mean surface water 0.1 pH units below preindustrial levels, a change of about 26% (Caldeira and Wickett 2003, Orr et al. 2005). In addition, deep oceanic waters are depleted in carbonate due to respiration resulting in a saturation depth below which calcium carbonate dissolves. Thus, decreased carbonate ion concentration hinders the formation of shells and support structures by some calcifying organisms (Caldeira and Wickett 2003, Feely et al. 2004, Orr et al. 2005). 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*), Tanner crab (*Chionoecetes bairdi*), and red king crab (*Paralithodes camtschaticus*) are ecologically and economically important crustaceans. The influence of lower pH and decreased carbonate ion concentration in seawater on the condition, survival, and shell calcium carbonate content of snow crabs in Alaska are unknown. Acidified waters can have a significant effect on the development (Findlay et al. 2009, Parker et al. 2009), development time (Findlay et al. 2009), viability (Kurihara et al. 2004a), and even behavior (Ellis et al. 2009) of the embryos of marine invertebrates (though see Arnold et al. 2009). Further, acidified waters can reduce fertilization success (Parker et al. 2009), the hatching success of embryos (Kurihara et al. 2004a), and the fecundity of females (Kurihara et al. 2004b).

We propose to conduct experimental research on golden king crab juveniles, which are currently available from previous experimental treatments on embryological development and larval survival. Next we propose to initiate studies on snow crab. Snow crab culturing is more difficult than the other species, however, the important role of snow crab ecologically and economically to Alaska coastal communities necessitates that we test the effects of OA on this species. Snow crab adults (ovigerous females) will be included in experiments in the summer of 2014 so that embryological studies can be conducted in FY15. Further, snow crab will be treated similarly to its congener, Tanner crab, so that direct comparisons can be made to the physiological response of

this species. Lastly, the results of the previous research and advances in *in situ* monitoring have made it clear that to better understand the physiological response in crustaceans we need to include diurnal and seasonal variability environmental conditions. As such we propose to modify our existing CO_2 dosing system to provide a diurnal and seasonal variability in pCO_2 and temperature consistent with new data currently being collected in Chiniak Bay, Kodiak and in the eastern Bering Sea to simulate more accurate conditions experienced by crabs *in situ*.

Research on the effects of OA on commercial crab species from 2012-2014 focused on experimentally testing the static effects of decreased pH (by increasing pCO_2) on red king crab, golden king crab, and Tanner crab. Response variables assessed at the Kodiak Lab included survival, condition, fecundity, morphology, development timing, and growth. In addition, collaborations with other agencies and academic partners broadened the response variables measured to include intracellular pH, shell mineralization and mechanics, and gene expression on crab from the same experiments. To assess intracellular pH hemocytes can be assessed to detect stressors according to shape, size, staining intensity of nuclei, presence or absence of nucleoli, and nature of cytoplasmic granules (Galtsoff 1964, Feng et al., 1971). All experiments consisted of a static control (ambient which averaged pH 8.0) and treatments
~ pH 7.8 and pH 7.5. For red king crab, embryos reared in acidified water were larger, but had smaller yolks; females in acidified seawater had longer hatch duration, but similar fecundity. Larval survival was reduced by acidified water at both embryo and larval stages, with additive effects giving lowest survival for larvae in acidified water at both stages. Juvenile survival decreased with pH, producing 100% mortality after 95 days at pH 7.5. Acidification did not affect morphology of juvenile red king crab, but growth was slower at pH 7.8. For Tanner crab, larvae died slightly faster at pH 7.5 than in pH 7.8 or control treatments, while survival decreased and growth was slower at lower pH. Variability in condition among species and life history stages revealed different physiological responses to increased dissolved inorganic carbon concentration. Regardless, increased physiological costs are likely the cause for the higher mortality rates observed across these experiments. More research on other life history stages and the molecular response is necessary to fully understand the effects OA will have on golden king crab and snow crab. In addition, dosing experiments are needed that accurately mimic the *in situ* conditions encountered by crab at different life stages and the effects of other co-occurring environmental stressors such as temperature.

The overall goal of this multiyear research plan is to determine the effects of OA as reproduced in the laboratory on the early life history of golden king crab, snow crab, and red king crab at appropriate scales so that ecosystem and population modeling can be considered in the future. The specific objectives are 1) to assess the effects of OA on golden king crab juvenile survival and condition, 2) to assess the effects of OA on ovigerous and larval snow crab, and 3) to assess long term effects of OA on red king crab survival, growth, condition, and calcification under diurnal and seasonal variability in pCO_2 and temperature.

The intended benefits of this project are to provide accurate estimates of population responses of OA through effective tests of individual physiological responses of commercially important shell building organisms to expected changes in pCO$_2$. In addition, consideration of multiple stressors (pCO$_2$, pH, and temperature) appropriately scaled diurnally and seasonally will inform researchers about the potential for species acclimation under reasonable environmental conditions.

The FY15-FY17 budget request for this project is: $693,680 (FY15: $230,250; FY16: $231,225; FY17: $232,205)

Project Description
i. Statement of the Project Hypothesis and Relevance to OAP Objectives

This project addresses the following NOAA OAP objectives: Theme 1) Research to understand Responses to OA; Theme 3) Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms; Theme 5) Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems; and Theme 6) Education, outreach, and engagement on OA. The overall hypotheses of this project is that shell forming organisms will be directly affected by OA through the reduction in pH and due to a lower carbonate saturation state. Based on previous NOAA OA funded research it is expected that early life history stages of crab will experience higher mortality with mixed effects on growth and calcification.

ii. Project Goals and Objectives

The overall goal of this multiyear research plan is to determine the effects of OA as reproduced in the laboratory on the early life history of red king crab, golden king crab, and snow crab at appropriate scales so that ecosystem and population modeling can be considered in the future. The specific objectives are as follows:

1. To assess the effects of OA on golden king crab juvenile survival and condition (FY15). As with other crab species, OA is likely to impose an energetic cost on these animals, therefore we hypothesize that OA will have the following effects on juvenile golden king crab: decrease survival, decrease condition, decrease growth, and reduce calcification.

2. To assess the effects of OA on ovigerous and larval snow crab (FY15 and 16). We will compare the early life history response of snow crab to previous results on a shallower more warm water congener Tanner crab. We will include hemocyte condition as a response variable in this study.

3. To assess the long-term effects of OA on red king crab survival, growth, condition, and calcification under diurnal and seasonal variability in pCO$_2$ and temperature (FY16 and 17).

iii. Technical Approach and Methodology

Effects of OA on Golden King Crab Juvenile Survival and Condition (FY15)

Our goal is to expand upon early life history research on golden king crab examining the embryo and larval stages (FY14) to examine juvenile growth, condition, calcification and survival. Further, we will compare the effects of OA on juvenile golden king crab with the effects it has on juvenile *Paralithodes* spp.

Juvenile golden king crab will be raised in the Kodiak Laboratory to the newly settled first or second crab stage. The experiment will be run for 200 days. The 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 walleye 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. Weekly water samples will be taken from each treatment, poisoned with mercuric chloride, and sent to the laboratory 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 condition index for each crab will be calculated as above. Crab morphometrics will be normalized and analyzed with a PCA analysis. Principle components explaining 90% of the cumulative variance will be retained and analyzed with an ANOVA with treatment fully crossed with crab stage and crab number nested within treatments as factors. Crab size after each molt and at the end of the experiment will be analyzed with a one-way ANOVA with treatment as the factor. Percent calcium and condition index will be analyzed with a one-way ANOVA with treatment as the factor.

Effects of OA on Ovigerous and Larval Snow Crab (FY15 and 16)

Healthy, multiparous snow crab with newly extruded eggs will be collected from the eastern Bering Sea during the Alaska Fisheries Science Center bottom trawl survey in June and July 2014 and 2015. Females will be returned to the Kodiak Laboratory, where they will be held in individual 455 L containers with flow-through sand-filtered seawater. Crabs will be reared in

temperatures that do not exceed 2 ºC throughout the experiment, females will be fed squid and fish twice a week to excess.

Females will be randomly assigned to one of three acidification treatments based on projected future changes to ocean pH (Caldeira and Wickett 2003): 1) ambient, pH 8.1 (control), 2) pH 7.8 (c. 2100), 3) pH 7.5 (c. 2200), 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). 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.

To measure hemocyte pH_i in crabs we will use molecular probes that stain the hemocyctes with fluorescence ratios that change with pH. Using probes with a flow cytometer allows discrimination between three populations of hemocyctes. To investigate how OA would affect crab hemolymph we would use two common molecular probes SNARF (for pH_i) and Fluo-4 and Fluo-Red (for intracellular calcium, Ca_i). This work will be a collaboration with the Northeast Science Center.

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, Swiney 2008). Un-eyed eggs will be stained for five minutes with Bouin's solution to facilitate observation of the external morphology of the embryos; eyed eggs will not be stained. The stages will be determined under a compound microscope at 50× magnification. Additionally, digital images of ten fresh eggs from each female will be taken with a digital camera attached to a compound microscope at a total magnification of 50×. Using image analysis software, egg area and maximum, minimum and average diameter will be measured. Once embryos are discernable, embryo area and yolk area will also be measured and percent yolk calculated. Lastly, when embryos become eyed, eyespot area and maximum, minimum and average diameter will be measured. All variables will be analyzed with a fully crossed repeated measures analysis of variance (ANOVA) with Time (month), Treatment (pH level), and Female as factors. In this, and with all other ANOVA-type analyses, the assumption of homogeneity of variance will be checked with Levene's test and the assumption of normality with an Anderson-Darling test, and the data will be transformed where necessary.

At hatching, larvae produced by each female from the three treatments will be collected daily. Some zoea will be collected and used for experiments examining the effects of OA on zoea (see experimental design below). Each day, the dry weight of a counted subsample of zoea from each female will be determined, as well as the dry weight of the rest of the zoea; the total number of zoea hatched per day will be calculated. The fecundity of each female will be calculated as the

total number of zoea hatched. When a female has hatched 500 larvae, dried zoea (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.

Females are receptive to breeding less than one to seven days after cleaning their pleopods (Paul 1984). During this time, males will be placed with the females as above and allowed to extrude a second batch of eggs. The viability of a subsample of eggs will be examined under a compound microscope to determine what percentage of the eggs are dividing normally (Paul and Paul 1990), and the average size of eggs will be determined using the image analysis protocols described above. Fecundity of each female will be determined by measuring the dry mass of a counted subsample of eggs and the dry mass of the remaining egg mass. The eggs will be processed for CHN analysis as described above. If any females do not extrude an egg mass they will be sacrificed and dissected to examine the gonads. 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. The condition index for each crab will be calculated as above. The dry mass of each female will be determined and the condition index will be calculated (dry mass divided by the carapace length cubed). Calcification and condition index 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 zoea to acidified waters. Two experiments will be performed on each set of zoea: a survival experiment and a condition experiment. Zoea 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 zoea hatched from each of the pH treatments above, for a total n of 45 for each experiment (3 maternal treatments × 3 zoea treatments × 5 replicates). Results will be analyzed with a fully-crossed two-way ANOVA, with Maternal treatment and Zoea treatment as factors. When multiple measurements of the same variable are made in each insert, Insert will be included as a nested factor.

Twenty zoea 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 zoea will not be fed. The experiments will be run at 2 ℃. The zoea will be checked daily for molts and mortality, and percent survival will be calculated. Survival in each beaker will be fit to the following model using least-squares fitting techniques:

$$Survival = \frac{1}{1 + (\frac{T}{LT_{50}})^b} \quad ,$$

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 beaker will be analyzed with an ANOVA model as specified above.

Baseline condition (morphology, dry mass, calcification, and CHN content—see details below) of the zoea will be measured from each of the original pools of zoea prior to the start of the experiment. Three hundred zoea will be reared in a 2L insert (as above). Each insert will be assigned to one of the above three pH treatments (as above). Zoea will not be fed. The experiment will be conducted at 2 ℃ for 7 days. A sub-sample of 5 individuals from each beaker will be dried and massed and the average zoeal mass determined. The remaining zoea 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.

Long-term Effects of OA on Red King Crab Under Diurnal and Seasonal Variability in pCO$_2$ and Temperature (FY16 and 17)
Our goal is to expand on work conducted in FY10 – FY11 by examining the effects of OA on red king crab 1) embryo development, 2) larval condition and survival, and 3) calcification in both the mothers and larvae. However, a new CO_2 dosing system will be designed to simulate a diurnal and seasonal variability in pCO_2 expected *in situ*.

Ovigerous Bristol Bay red king crab females will be collected during the NMFS eastern Bering Sea summer bottom survey summer 2015, and shipped live to the AFSC's Kodiak Seawater Laboratory where they will be held in a 2,479 L tank supplied with flow-through ambient sand-filtered seawater until the experiment begins. Crab will be fed twice weekly a diet of squid and fish to excess.

To examine the effects of different pH levels on embryogenesis, females will be transferred to individual 68 L containers and randomly assigned to one of 3 pH levels: ambient ~ 8.0 ($N = 12$), 7.8 ($N = 13$) and 7.5 ($N = 12$) pH levels. All pH levels will be equally varied diurnally and

monthly. Water is flow-through sand-filtered seawater at ambient temperature and a rate of 2L/min. The pH in the treatment tanks will be adjusted by adding CO_2 to the water. Females will be held until larval hatching in the early spring 2016. Females will be fed squid and fish twice a week to excess. pH and temperature will be measured daily. Once every other week water samples will be taken from each treatment, poisoned with mercuric chloride and sent to the University of Alaska laboratory for dissolved inorganic carbon (DIC) and total alkalinity analysis.

To determine if OA affects red king crab embryology, a small clump of approximately 20 eggs will be randomly sampled from each female monthly until hatching. The embryo developmental stages are determined using Moriyasu and Lanteigne's (1998) methods and digital images of ten fresh eggs from each female are taken with a digital camera attached to a compound microscope. Using image analysis software, total egg, embryo, eyespot, and yolk areas and maximum, minimum and average diameters 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 principle component analysis (PCA). Data will be normalized prior to analysis. Principle 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 and month as factors.

At hatching, live larvae will be collected from each female for CHN analysis (Carbon, Hydrogen, Nitrogen elemental analysis) and calcification analysis. At the end of the experiment, all of the adult females will be sacrificed. In addition the wet mass of each female will be determined. The condition index, wet mass divided by the carapace length cubed, will be calculated (Long et al., 2008). 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.

In order 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. Newly hatched larvae from multiple females within each of the pH treatments (ambient, 7.8, 7.5) will be pooled for this experiment. Five replicate 1 L containers will be established at each of the three pH treatments from larvae hatched from each of the pH treatments, for a total n of 45 (3 maternal treatments x 3 larval treatments x 5 replicates). Fifty larvae will be placed inside each 1L container which are open at the top and have nylon mesh on the bottom. Each 1 L container will be placed inside a tank with water at the appropriate pH. Larvae will be fed enriched Artemia each day. The pH and temperature in each small container will be recorded daily. Additionally mortalities and molts will be recorded and removed daily. We will stop feeding when all the larvae have reached

the non-feeding glaucothoe stage. At this point a small piece of macroalgae mimic will be placed in the container to encourage settlement. The experiment will end when all of the larvae reach the first crab stage and percent survival at each stage will be calculated. Percent survival to each stage will be analyzed with an ANOVA with maternal treatment fully crossed with larval treatment as factors. The average molting date will be defined for each container and the molt to each new stage as the date when 50% of the total molts had been removed. The intermolt period will be defined as the time in degree days between each consecutive set of molting dates. The intermolt period and the variance of the period will be compared among the treatments with an ANOVA with maternal treatment fully crossed with larval treatment as factors.

To determine if OA affects larval condition a second experiment will be conducted. Newly hatched larvae from mothers reared in ambient waters will be pooled and the larvae will be reared in ambient, 7.8 and 7.5 pH waters. Baseline condition (calcification and CHN content) of the larvae will be measured from each pool of larvae. Five replicate 12 L containers will be established for each of the three pH treatments for a total of 15 containers. Similar to above, the containers will be open at the top with nylon mesh on the bottom and placed in tanks with water at the appropriate pH. Each 12 L container will be stocked at 50 larvae/L. The large containers will be randomly placed in the tank and maintained at 8°C. Feeding will occur daily as describe above. Temperature and pH will be recorded daily for each container and mortalities and molts will be removed daily. The goal is to run the experiment until all of the larvae reach the glaucothoe stage, but if mortality is too high, the experiment will be ended early to ensure there is enough mass for mass measurements, calcification and CHN analysis. At the end of the experiment twenty larvae will be removed from each container, rinsed in deionized water, and have the mass determined as above. The average mass of a larvae will be calculated. The remaining larvae will be dried to a constant mass at 60 °C, divided, and sent away for calcification and CHN analysis. The mass, CHN, and percent calcium will be compared among treatments with a one-way ANOVA.

iv. Benefits/Deliverables

The benefits of this project will be

1. Publication on juvenile golden king crab response to OA.
2. Data and publication on snow crab embryo and larval OA response to inform population dynamics/bioeconomic model.
3. Publication on the physiological response of red king to expected temporal variability in OA.

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. This research will inform the fishing industry and coastal Alaskan communities about potential effects of climate change. In addition to presentations to the North Pacific Fishery Management Council 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 AFSC's Kodiak Laboratory.

v. Project Management and Timeline, with Milestones

Robert Foy will be the lead Principal Investigator on this project and be responsible for the overall project management and execution. Foy will oversee chemistry data collection and analysis. William Christopher Long will be responsible for the experimental design and data analysis and will work closely with Katherine M. Swiney to conduct the experiments. Swiney will be responsible for overseeing the OA system and managing the reproductive aspects of this project including monitory embryo development and female fecundity.

Item	FY2015		FY2016		FY2017	
	Fa/Win	Sp/Sum	Fa/Win	Sp/Sum	Fa/Win	Sp/Sum
Golden king crab juvenile experiments	▓					
Golden king crab data analysis and publication			▓			
Snow crab adult collection and culturing	▓		▓			
Snow crab larval experiments		▓				
Provision of initial data for population dynamics mode		▓	▓			
Red king crab experimental setup		▓				
Red king crab adult collection and culturing		▓	▓			
Red king crab juvenile experiments				▓	▓	
Data analysis and publication						▓

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Project Title

Effects of OA on Alaskan gadids: sensitivity to variation in prey quality and behavioral responses

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Abstract

Ocean acidification (OA) has the potential to significantly affect the production of valuable fishery resources. Walleye pollock (*Gadus chalcogramus*) and Pacific cod (*Gadus macrocephalus*) are the central components of North Pacific and Bering Sea food webs and fisheries. With annual harvests of over 1.5 million metric tons (t), they support two of the Nation's largest and most valuable finfish fisheries. Accurate predictions of the effects of OA on the productivity of these and other critical marine resource species is dependent upon an improved understanding of the full range of ecological pathways by which OA will affect individual species and their interactions with predators and prey.

To date, experimental examination of the responses of commercially important marine fishes to OA have focused on the direct growth and survival responses of early life stages. Negative effects of OA have been identified in some species but not others. Work on Alaskan commercial fisheries species has suggested a general resiliency of walleye pollock to elevated CO_2 levels, but work on northern rock sole (*Lepidopsetta polyxystra*) suggests higher mortality and poorer nutritional condition of larvae at elevated CO_2 levels. More importantly, it is recognized that these "direct effects" may not be the primary mechanisms by which OA will impact the productivity of these fishery resources. Two alternative pathways by which OA is predicted to impact fishery production are disruption of sensory and behavioral systems and indirect, food web effects altering species composition and productivity lower trophic levels.

Recent work on other species groups has demonstrated that exposure to high CO_2 can disrupt the sensory and behavioral responses of marine fishes. Demonstrated effects include disruption of homing ability and interference in recognition of prey and predator scent cues (among others). Although the mechanisms are not completely resolved, these effects are believed to occur as a result of physiological adjustment of extracellular acid-base balance at high environmental CO_2 levels. This change in acid-base balance interferes with a key neurotransmitter. The resulting

behavioral changes will have a significant impact on the survival of marine fishes in future high CO_2 seas. Laboratory experiments will describe potential behavioral deficits induced by OA that will affect foraging and growth of larval and juvenile walleye pollock and Pacific cod.

OA also has the potential to alter the production and species composition of the lower trophic levels that support the growth and development of early life stages of fishes. Unable to synthesize certain fatty acids, fishes are dependent upon obtaining these "essential" fatty acids (EFAs) from their diets, although specific requirements vary among species and the requirements of walleye pollock are not yet known. OA can impact the availability of EFAs for marine fishes through changes in the composition and nutritional value of lower trophic levels. Best predictions, based on food web theory and phytoplankton physiology, indicate a reduction of essential nutrients (EFAs) available at higher levels of the food web. In a laboratory experiment, we will determine the sensitivity of walleye pollock growth to nutritional stress (reduced availability of EFAs). Future work would examine the interaction between this nutritional stress and elevated CO_2 levels.

By exploring the two primary ecological pathways by which OA is expected to impact marine fishes we will provide a more comprehensive understanding of OA impacts on marine fisheries. The results from these experiments will be incorporated into a bioenergetically-based model of early life history which will quantitatively evaluate the cumulative consequences of these behavioral, nutritional, and physiological effects (and their interactions) for growth and survival of walleye pollock through the first year of life. The results of the early life history model will be used in conjunction with stock assessments and forecasting models to describe the long-term consequences of OA on walleye pollock population productivity and the socioeconomics of the fishery.

The FY15-FY17 budget request for this project is: $305,577 (FY15: $139,740; FY16: $90,620; FY17: $86,504)

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). 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). While some studies have demonstrated significant negative effects on development or survival (Baumann et al. 2012, Frommel et al. 2012, Chambers et al. 2014), 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) with several studies finding minor or negligible effects on marine fishes (Munday et al. 2011, Bignami et al. 2013, Hurst et al. 2013). More importantly, recent research indicates that sensory and behavioral systems appear to be more sensitive than bioenergetic processes and may be the primary action pathway for OA effects on marine fishes (Leduc et al. 2013). A range of OA-induced effects including disruption of predator recognition and response behaviors 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). This disruption can lead to abnormal, or even polar opposite, behavioral responses to environmental stimuli (Munday et al. 2009). 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).

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. 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. *in press*). 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 *Gadus chalcogrammus*; Hurst et al. 2012 and 2013) and did not include the potential for OA-induced changes in sensory and behavioral ecology which could impact population productivity.

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 (Dalsgaard et al. 2003, 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 (Sargent et al. 1989). Specifically, essential fatty acids (EFAs) which originate in primary production, can limit growth, survival and metamorphosis in larval fish when they are not sufficient in their diet. Further, recently Copeman and Laurel (2010) showed that variation in dietary EFA ratios cause changes in growth and condition in larval Pacific cod (*Gadus macrocephalus*). At a large scale, the availability of certain dietary lipids/EFAs in marine food

webs have been correlated with large scale population regime shifts in marine fish ("Essential Fatty Acid Limitation Hypothesis", Litzow et al. 2008), seabirds and marine mammals ("Junk-Food hypothesis", Osterblom et al. 2008). OA has the potential to impact the availabity 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 on productivity of critical marine resource species must include consideration of these "in-direct" effects which will alter the nutritional environment of sensitive ealry life stages.

i. Statement of the Project Hypothesis and Relevance to OAP Objectives

The project hypothesis is that the effects of OA on productivity of marine fishes will be primarily through the indirect effects on sensory and behavioral systems and changes in lower trophic levels than through direct physiological effects on growth and survival.

Research priorities to address the implications of OA on marine ecosystems have been identified by several different groups (The Royal Society 2005, Fabry et al. 2008). Specific to the Gulf of Alaska and Bering Sea, the Alaska Fisheries Science Center (AFSC) has developed a research plan, identifying the areas of concern (NOAA 2010). This plan focuses on the core areas of:

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

ii. Project Goals and Objectives

We propose to conduct new laboratory experiments to evaluate the effects of OA on the behavior of walleye pollock and Pacific cod relative to foraging and predation cues. Study objective are:

1. Describe the effects of OA on behavioral responses of larval walleye pollock to light and prey cues.

2. Describe the effects of OA on the recognition and behavioral response of juvenile walleye pollock and Pacific cod to prey scent cues.

3. Describe sensitivity of larval walleye pollock growth and survival to essential fatty acid composition of prey.

4. Incorporate CO_2 stripping to increase range of experimental conditions and improve control of experimental CO_2 system.

iii. Technical Approach and Methodology

Behavioral responses to OA

Walleye pollock and Pacific cod are abundant over shelf and slope areas of the North Pacific Ocean and Bering Sea. In addition to being primary trophic linkages in the foodweb (Livingston 1993), walleye pollock support the largest single-species fishery in the United States, with harvests averaging over 1.1 million t over the last decade; and along the West Coast of the United States, landings of Pacific cod trail only those of walleye pollock. Previous work has shown that elevated CO_2 levels did not negatively affect the growth potential of larval (Hurst et al. 2013) or juvenile (Hurst et al. 2012) walleye pollock. However, the latter study did reveal that walleye pollock responded to elevated CO_2 levels with expected increases in internal buffering (E.R. Fernandez, unpublished data). This change is believed to be responsible for the hypercalcification observed in walleye pollock otoliths (Hurst et al. 2012), suggesting the potential for other physiological effects related to changing internal conditions, including disruption of sensory and behavioral responses (Nilsson et al. 2012).

Juvenile walleye pollock are known to have considerably plastic behavioral patterns, varying traits such as swim speed and group cohesiveness in response to prey patchiness, nutritional state, predation risk, and temperature (Ryer and Olla 1995, Sogard and Olla 1997, Hurst 2007). Behavioral responsiveness of walleye pollock to prey scent cues develops sometime in the late larval or early juvenile stage. Previous work found that larval walleye pollock (> 25 mm) exhibited no behavioral responsiveness to the introduction of prey scent cues (Colton and Hurst 2010) but that larger juveniles (80-250 mm) responded to prey scent cues with an increase in activity level (Davis et al. 2006). Less work has been conducted on the behavioral patterns of juvenile Pacific cod, however Colton and Hurst (2010) demonstrated that the species showed responses similar to those of larval walleye pollock in gradients of light and prey in the larval stage. Conversely, Ottmar and Hurst (2012) showed that the responses to temperature variation of juvenile stage Pacific cod were distinctly different from those of walleye pollock, reflecting differences in primary habitats.

Walleye pollock and Pacific cod will be reared in the laboratory at ambient and elevated CO_2 levels from eggs produced by a captive broodstock according to the methods of Hurst et al. (2010 and 2013). During the larval phase (until approximately 12 weeks of age) fish will be fed a combination of rotifers (*Brachionus plicatilis*) enriched with Algamac 3050 (Aquafauna, Hawthorne, CA) and microparticulate dry food (Otohime, Marubeni Nisshin Feed Co., Tokyo). During the juvenile phase, fish are fed 3 times per week on thawed krill (*Euphausia pacifica*) and a gelatinized combination of squid, krill, herring, commercial fish food, amino acid supplements, and vitamins). Lights will be maintained on a 12:12 light:dark schedule and temperatures maintained at 7-8 °C throughout rearing and the behavioral trials.

Larval behavior trials

Larval walleye pollock will be reared at 4 environmental pH conditions (ambient pH ~ 8.05; future levels of 7.9 and 7.6; and extreme 7.2) in an existing experimental system. Following rearing, we will evaluate the effects of pH on the ability of larvae and juveniles to detect the presence of prey, locate, and capture prey. The design of these experiments will be based on previously published experiments describing ontogenetic patterns in larval behavior (Colton and Hurst 2010). Prior to each trial, experimental chambers ($20 \times 20 \times 15$ cm) will be filled with pH conditioned water from the culture system. Prior to daily introductions of food, groups of 5 larvae will be captured from rearing tanks and transferred to the experimental chambers. After 30 minutes of acclimation, pre-feeding activity levels will be determined from analysis of overhead video. Prey (rotifer *Brachionus plicatilis*) will be introduced to the chamber at densities of 10/mL. Fish will be continuously video monitored to determine the reaction time from introduction of prey to initiation of foraging. The number of feeding strikes made during the first 15 minutes will be determined from the overhead observations. After 15 minutes, fish will be removed from the experimental chamber and the number of consumed prey will be determined by dissecting out the gut under a microscope. Foraging success will be calculated from the cumulative number of feeding strikes and ingested prey. At least 8 trials will be conducted with larvae from each pH treatment and trials will be conducted at two stages of larval development: "pre-flexion" larvae will be tested at approximately 3 weeks of age and more developed "post-flexion" larvae will be tested at approximately 6 weeks of age.

Juvenile responses to prey scent cue

In a separate series of experiments, we will examine the behavioral responses of juveniles to prey scent cues. Individual fish will be tested in a non-recirculating flume similar to that used in other studies (Munday et al. 2009). All fish will be tested at their acclimation CO_2 level as the header tank for the flume will be continuously supplied with CO_2-conditioned water from the same mixing tanks that supply the rearing and acclimation tanks from which the test fish are drawn. Water flows into the flume from the header tank at 3 L/min, creating a flow speed through the flume of 0.45 cm/sec. Prey scent cues will be introduced by injection from behind an opaque curtain through a small tube into the seawater line connecting the header tank and flume to ensure thorough mixing. A grid was marked on the bottom of the fish chamber will allow an observer to score activity levels of the fish with an overhead camera. All observations and introductions of prey scent cues to the tank will be conducted from behind a "blind" to avoid experimenter interference and introduction of a seawater control ("blank") will be used as a methodological control.

Prey scent cues will be made with 5 g of krill (*E. pacifica*) homogenized into 250 mL of seawater (as described in Davis and Olla 1995). The seawater is filtered of particulates and stored at -80 °C in aliquots of 100 mL prior to use in trials. On the day of the trial, a prey scent cue is thawed and a series of dilutions used to create cues varying in "strength" (concentration of original solution) by

five orders of magnitude (the strongest cue was undiluted). The cues (and a seawater blank) are injected into the flume at 30-minute intervals in a prescribed order. Based on preliminary trials the following order was adopted: undiluted (strongest) cue, seawater blank, weakest cue, followed by three cues of increasing concentration. Presenting the strongest cue first allowed evaluation of basic responsiveness of the fish to a cue which was expected to elicit a response without being affected by potential recognition of previous cues. Prior to injecting each cue, the baseline activity level (line crossings per minute) is observed for three consecutive minutes. 50 mL of the scent cue (or blank) was then injected into the flume, followed by 100 mL of CO_2-conditioned seawater to flush the injection port, and fish activity level observed for the next 8 consecutive minutes.

Sensitivity of walleye pollock to OA-induced changes in prey quality
We will determine the sensitivity of larval walleye pollock growth potential to changes in the EFA content of their prey. Docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) are two essential fatty acids (EFAs) that are found at higher proportions in dinoflagellates and diatoms, respectively. 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). The impact of dietary ratios of these poly-unsaturated FAs on walleye pollock growth, condition and survival remain unknown. Larvae will be hatched and reared using established protocols (Hurst et al. 2010). However, we will modify the enrichment of rotifers to produce a gradient in their EFA ratios. To quantify the dietary DHA/EPA requirements of larval walleye pollock, we will compare larvae reared on rotifers enriched with 3 different experimental emulsions (ICES standardized enrichments, Table 1). Based on our previous experience (Copeman et al. 2002, Copeman and Laurel 2010) we know that cold-water larvae do not survive past 3 weeks on unenriched rotifers, therefore we will not use this treatment. The three experimental emulsions, which have been developed by researchers at the Laboratory of Aquaculture and *Artemia* Reference Center in Ghent, Belgium and the International Council for Exploration of the Sea (ICES) (hereafter called ICES emulsions), have a constant level of total lipid and proportion of total n-3 PUFA (30% of total FAs). ICES emulsions are routinely provided for a small formulation and shipping fee to researchers conducting nutrition work with marine larvae (i.e., Martins et al. 2006, Stottrup and Attramadal 2007). These ICES emulsions will be utilized to determine the optimal supplementation of DHA/EPA for larval walleye pollock. Use of controlled standardized ICES emulsions will allow comparisons of the dietary requirements of walleye pollock to those of other cold water species such as Atlantic cod, *Gadus morhua*. The use of experimental emulsions, rather than commercial emulsions, will provide an explicit test of the effects of the DHA/EPA ratio on larval walleye pollock, while keeping all other nutritional components of the live-food constant (i.e., total lipids, proteins, lipid classes). Sufficient tank space will allow us to culture 4 tanks of larvae on each type of enriched rotifers.

Table 1. -- Experimental emulsions used in determining dietary DHA/EPA requirements of larval walleye pollock (Garcia et al. 2008; ICES reference emulsions).			
Lipid parameters	ICES Emulsion (30/0.6)	ICES Emulsion (30/2.3)	ICES Emulsion (30/4)
Total n-3	30%	30%	30%
DHA/EPA	0.6	2.3	4

Larvae will be assessed for length and weight at weeks 2 and 4 (methods in Copeman and Laurel 2010). Lipid samples of live food enrichments as well as larvae with be taken on a bi-weekly basis and will be analyzed for lipid classes and fatty acids according to methods in Copeman et al. (2008 and 2009). Survival will be assessed at the end of the 4 week feeding trail by counting all remaining larvae.

A second experiment in this theme is proposed in a Letter of Intent for Build-out Investments of the OAP. In that experiment, we will examine the potential interactions between depressed pH and reduced food quality on growth and survival of walleye pollock larvae. This experiment builds on the food quality experiment described above. Larval walleye pollock will be reared at two environmental pH conditions (ambient pH ~8.05 and low 7.5). At both pH levels, fish will be exposed to two prey quality treatments (as defined by the nutritional experiment described above) resulting in four experimental treatments: 1) high quality food and ambient pH, 2) high quality food and extreme pH, 3) low quality food and ambient pH, 4) low quality food and extreme pH. Twelve 100 L larval rearing tanks will be used resulting in three replicate tanks per treatment. Larvae will be sampled on a bi-weekly basis for growth and condition. Lipid samples will be taken for the determination of fatty acids and lipid classes in live food and in larvae at week 3 and week 6.

iv. Benefits/Deliverables

This project will significantly advance our understanding of the mechanisms by which OA impacts commercially important marine fishes.

This project directly addresses NOAA's OAP objective of 1) Understanding Responses to OA and will provide the empirical observations necessary to effectively (3) Model Impacts on Marine Ecosystems and Organisms and 5) Assess Socioeconomic Impacts. In addition, this work is closely aligned with NOAA's Next Generation Strategic Plan (2010) and Five-year Research and Development Plan (2013). Whereas progress is being made on understanding the direct physiological effects of acidification on some resource species (e.g., Long et al. 2012, Hurst et al. 2013, Chambers et al. 2014), it is recognized that such efforts are not sufficient and that

research must also examine the ecology of the organisms in their ecosystem: "A better understanding of how ecological interactions are affected by environmental change and human interactions will enable more certain assessments and forecasts, leading to improved management that ensures sustainable, healthy and productive ecosystems" (NOAA 5-Year Research and Development Plan). By examining the effects of OA on the behavioral ecology of groundfish resource species and the indirect, food web effects of OA on production of these species, this work will complement previous direct-effect studies on these species, and will allow for quantitative evaluation of the importance of the different forms of acidification effects on an important north Pacific groundfish species.

v. Project Management and Timeline, with Milestones

Overall project management will be conducted by Thomas Hurst. Hurst will oversee OA system maintenance and upgrades, fish culture. He will design the behavioral experiments, participate in their execution, conduct statistical analyses and prepare manuscripts for publication. Hurst will partner with Louise Copeman (Oregon State Univ.) 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. Hurst and Copeman will jointly perpare a manuscript describing the results.

Hurst will work with Jeremy Mathis (PMEL) 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, OAP-supported Biological Technician at OSU-CIMRS Eric Hanneman will participate multiple aspects of fish culture and conducting behavioral experiments and Laboratory Technician Karoline Klink will process and analyze samples for lipid composition. Hurst will be responsible for annual progress reporting and archiving data with NODC.

Item	FY2015 Fa/Win	FY2015 Sp/Sum	FY2016 Fa/Win	FY2016 Sp/Sum	FY2017 Fa/Win	FY2017 Sp/Sum
CO_2 stripping installation		■				
Larval pollock behavior	■		■			
Juvenile pollock behavior		■	■			
Larval cod behavior			■		■	
Juvenile cod behavior				■	■	■
Larval cod prey quality expt.			■			
Analysis of prey quality fish				■		

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Sustained Investment

Project Title

Forecast effects of ocean acidification on Alaska crabs and walleye pollock abundance

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Abstract

The increase in atmospheric CO_2 concentrations, caused primarily by fossil fuel emissions, deforestation, and concrete production, has led to a corresponding increase in the CO_2 concentrations in the ocean. This increase is leading to changes in the carbonate chemistry of the oceans and a decrease in pH (IPCC 2011). As CO_2 levels continue to rise over the coming decades, the pH in the ocean will fall even further. This reduction in pH, and increase in pCO_2, can have substantial physiological effects on marine organisms, affecting growth, survival, reproduction, and behavior. The overarching goal of this project is to take estimates from ocean acidification (OA) exposure experiments, scale these estimates to a population level, and forecast biological and economic impacts for commercially important populations. This project builds on past and ongoing NOAA-supported research in this area. In particular, model input will be taken from physiological research for these populations that is being conducted at the Alaska Fisheries Science Center (AFSC) to characterize their susceptibility to effects of OA and from existing modeling work, which shows how OA can be linked with population dynamic processes. This project addresses Hypothesis 3 of the NOAA OA Research Plan, through the Sustained Investment priority for Modeling. In particular, a set of linked bioeconomic models based on estimates from exposure experiments will be used to infer population scale effects for forecasts of abundance, yields, fishery income, and impacts to the Alaska economy over time under a scenario of future OA.

Calcifying organisms may be particularly affected by OA because the reduction in pH makes it more difficult to excrete and sustain a calcified shell or exoskeleton. While the focus of the impacts of OA has been mainly on the biological effects, species such as crabs support valuable fishery resources, and OA may have major consequences for these fisheries, and how they are managed. Punt et al. (2014) based on evidence in Long et al. (2013) developed a linked biological – economic model that forecast severe effects of OA on the fishery for Bristol Bay red king crab (*Paralithodes camtschaticus*). The socio-economic impacts of the Bristol Bay red king crab fishery in decline under a global OA scenario to 2100 include a cumulative loss to all sectors of the Alaska economy of more than $1 billion for some assumptions (Seung et al. 2014). Two objectives in this project will forecast effects of OA on the future abundance of vulnerable

and commercially important North Pacific crab stocks. An assessment of economic impacts of OA on the Eastern Bering Sea snow crab fishery is warranted. This fishery generated $270 million in 2012, compared to $76 million for the Bristol Bay red king crab fishery, and a total for all BSAI crab fisheries of $387 million (Garber-Yonts and Lee 2013). The first objective in this project is to develop a model of OA effects on growth and survival of juvenile snow crab. This "pre-recruit" model for snow crab will be linked to population dynamics of a bioeconomic model for Eastern Bering Sea (EBS) snow crab (*Chionoecetes opilio*) which itself is linked to population dynamics and pre-recruit model with OA effects for EBS Tanner crab (*Chionoecetes bairdi*). The development of the population dynamics and pre-recruit model for EBS Tanner crab was supported in FY12 – FY14. The linked bioeconomic model will be used to evaluate OA effects on EBS snow and Tanner crabs jointly with the additional population stressors of directed fishing mortality and bycatch of Tanner crab in the snow crab fishery.

The current bioeconomic model for Bristol Bay red king crab excludes the effects of future changes in ocean temperatures and restricts spatial heterogeneity of OA effects, which should be considered under Hypothesis 3 in the NOAA OA Research Plan The second objective in this project will continue development of a bioeconomic model for Bristol Bay red king crab with model extensions that incorporate i) joint effects of ocean temperature and OA, and ii) integrate spatial variation in these variables for the nearshore environment inhabited by juvenile crab. The third objective in this project begins development of a linked bioeconomic model for walleye pollock (*Gadus chalcogrammus*) in the eastern Bering Sea. A model of OA effects on juvenile fish will be qualitatively similar to the pre-recruit models for crab that are based on experimentally measured changes in growth and survival rates of juvenile crab. Growth and survival rates are easy to interpret life-history parameters and changes in these rates are considered direct effects of OA that are relatively easy to apply to population dynamics. However, these rates for juvenile walleye pollock were not sensitive to OA in directly exposure experiments under optimal foraging conditions. However, OA is expected to affect prey quality and foraging ability of juvenile walleye pollock. The third objective in this project will develop a model that relates OA effects on prey quality and foraging ability to growth and survival rates of juvenile walleye pollock, and link this new pre-recruit model to a bioeconomic model of the walleye pollock fishery in the eastern Bering Sea. Similar to the linked bioeconomic models for crab stocks, this bioeconomic model for the walleye pollock fishery in the eastern Bering Sea will be used to forecast abundance, yields, fishery income, and economic impacts to the Alaska economy under a scenario of future OA.

The objectives of this project are: 1) to develop a pre-recruit model for the effects of OA on growth and survival of juvenile snow crab and integrate it into the joint Tanner-snow crab model; 2) to extend the pre-recruit model for the effects of OA on juvenile red king crab to integrate joint effects of ocean temperature and spatial heterogeneity in environmental condition; and to develop a pre-recruit model for the effects of OA on growth and survival of juvenile walleye pollock based on changes in foraging ability and prey quality.

The intended benefits of this project are to construct a bioeconomic model to forecast joint effects of OA on snow and Tanner crabs, a bioeconomic model for Bristol Bay red king crab to forecast *in situ* effects of OA and a bioeconomic model to forecast effects of OA on Alaska walleye pollock.

The FY15-FY17 budget request for this project is: $105,000 (FY15: $0; FY16: $50,000; FY17: $55,000).

Project Description

i. 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 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* (p.51). In addition, the methods employed in this project conform to the Short-term goals under Theme 5, 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* (p.55). The AFSC OA research plan also prioritizes work on commercially important species. Research is planned for Alaska's most valuable groundfish, walleye pollock, and the two most valuable crab stocks: Eastern Bering Sea snow crab, and Bristol Bay red king crab.

ii. Project Goals and 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. Develop a model for the effects of OA on growth and survival of juvenile snow crab and integrate this model to an existing joint model of snow crab-Tanner crab population dynamics and fishery.
2. Extend a model for the effects of OA on growth and survival of juvenile red king crab to integrate joint effects of ocean temperature and spatial heterogeneity in environmental conditions.
3. Develop a model for the effects of OA on growth and survival of juvenile walleye pollock based on changes in foraging ability and prey quality.

iii. Technical Approach and Methodology

The previous AFSC Bristol Bay red king crab (BBRKC) OA project will serve as a basic template for the models in this project. The BBRKC template consists of four separate component models, and linking these provides 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 (Punt et al. 2014), and the fourth component is a regional economic model (Seung et al. 2014):

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. Bioeconomic models are used to evaluate impacts.
3. Bioeconomic model with linked population dynamics to forecast changes in abundance, yields and fishery income over time.
4. Regional economic model linked to a bioeconomic model to evaluate cumulative impacts on all sectors of the Alaska economy under an OA scenario.
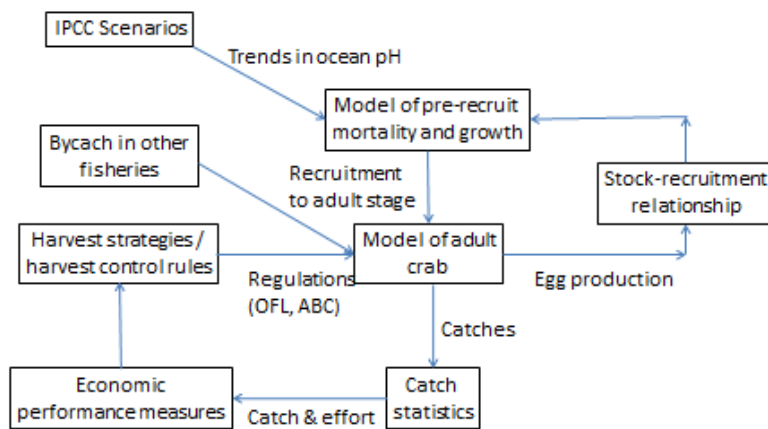

Figure 1. Outline of the linked bio-economic model.

Current research applies to Tanner crab, which follows the BBRKC template except that the Tanner crab model is more complicated because fishing mortality depends on bycatch in the snow crab fishery. Therefore, it was necessary to develop a population dynamics model for snow crab. The first objective in this project is to complete a joint bioeconomic model for snow and Tanner crabs, with OA effects for both species, by developing a pre-recruit model with OA effects on growth and survival of snow crab. The second objective for crab in this project is to extend the

BBRKC pre-recruit model to integrate *in situ* effects of ocean temperatures and pH on juvenile red king crab when they inhabit different areas from adults and experience different environmental conditions. The third objective in this project is to develop a pre-recruit model for walleye pollock, and ultimately, link it to a population dynamics model for walleye pollock in the eastern Bering Sea. In each case, the series of linked models will be used to explore the implications of different rates and trends in future ocean pH to compute:

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, and iii) walleye pollock in the eastern Bering Sea.

iv. Benefits/Deliverables

The benefits of this project will be

1. Bioeconomic model to forecast joint effects of OA on snow and Tanner crabs.
2. Bioeconomic model for Bristol Bay red king crab to forecast *in situ* effects of OA.
3. Bioeconomic model to forecast effects of OA on walleye pollock in the eastern Bering Sea.

The outputs from this project will be

1. A report which [i] documents the models, [ii] 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 [iii] 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 regularly (at least annually) to the North Pacific Fishery Management Council crab and groundfish plan teams.

v. Project Management and Timeline, with Milestones

Punt will develop the mathematical models for recruitment processes and population dynamics, and the bioeconomic models. He will also work with a graduate student to implement these models. The graduate student will obtain the necessary data, implement the models, and work with Punt on the final report.

Item	FY2015		FY2016		FY2017	
	Fa/Win	Sp/Sum	Fa/Win	Sp/Sum	Fa/Win	Sp/Sum
Snow crab pre-recruit model			■	■		
Link to joint snow-Tanner bioeconomic model				■		
Red king crab pre-recruit model with *in situ* temp+pH					■	■
Walleye pollock pre-recruit model: behavior+prey quality				■	■	
Link to walleye pollock population dynamics in the eastern Bering Sea					■	■

Citations

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Long W.C., K.M. Swiney, C. Harris, H.N. Page, and R.J. Foy. 2013. Effects of OA on juvenile red king crab (*Paralithodes camtschaticus*) and Tanner crab (*Chionoecetes bairdi*) growth, condition, calcification, and survival. PLos ONE 8(4): e60959. doi:10.1371/journal.pone.0060959.

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Seung, C., M. Dalton, A.E. Punt, D. Poljak, and R.J. Foy. In prep. Economic impacts of changes in an Alaska crab fishery from ocean acidification. Available, C. Seung, AFSC, 7600 Sand Point Way NE, Seattle WA 98115.

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.

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

We are working with the outreach and graphics departments of the Alaska Fisheries Science Center to produce a display describing the basics of OA and the results from ongoing NOAA research on commercial crab species. This display will be fabricated in FY15 and will be 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.

From this template, matching displays will be generated describing NOAA's research on Alaskan finfishes (FY15-16) for display in the Hatfield Marine Science Center's Visitor Center which receives nearly 150,000 annual visitors. Portable versions will be made for use at off-site public outreach events as described above. We anticipate updating these displays to reflect emerging science on a 2-year timeframe.

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 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.

At the AFSC's Newport, OR, 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 4 years, these students, funded by a grant from NSF, have conducted research on the effects of OA on Alaskan groundfishes. Hurst is also mentoring a graduate student (Jessica Andrade) in OSU's Department of Fisheries and Wildlife who is examining the effects of OA on the behavioral responses of northern rock sole, a complementary project to that proposed here on walleye pollock and Pacific cod. Andrade is 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.

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. This work will continue with under the planned SI work plan. Significant examples include "Sea Change", the *Seattle Times* ongoing series on OA and the NOAA Communications Office's coordinated press rollout for "OA Risk Assessment for Alaska's Fishery Sector", which included coordination with academic and non-governmental organizational partners.

Letter of Intent

<u>Sustained Investment Topic</u> -- To focus efforts on gaps in knowledge regarding the molecular response of shellfish to ocean acidification and to enhance the capacity to assess physiological responses of shellfish to ocean acidification at the Kodiak Laboratory, this Build-out Investment supports the <u>Upgrade Enhancement of Existing Ocean Acidification Observational or Experimental Technologies</u> priority area.

Project Title

Gene regulation in Alaskan crab species in response to ocean acidification.

Project Scientists

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Statement of the Problem

Functional genomics approaches can be used to leverage the large amount of gene regulation information that can be collected to assess the molecular response of an organism to environmental change. Gene regulation, whether a gene is expressed or repressed, is commonly indexed by the level of the corresponding mRNA for that gene in a sample. Gene expression products (mRNA) can be monitored as indicators of stress level, condition, health, and other physiological parameters to determine sublethal effects of environmental change. A transcriptome which represents all of the mRNA molecules in a sample can be derived using high throughput sequencing methods and processed using bioinformatics tools.

A transcriptome was been developed for red king crab (*Paralithodes camtschaticus*) from 2012-2014 to assess genome-wide transcriptomic changes in red king crab juveniles exposed to changes in ocean temperature and OA in laboratory experiments. Red king crab held in experiments at the AFSC's Kodiak Laboratory were sampled to generate RNA-seq transcriptomic data. Those data were then used to identify genes that may be biomarkers for changes in ocean temperature and acidification. Gene functions were explored by identifying specific protein expression through gene regulation as a result of experimental conditions.

Results of current research (Stillman, Fay, Swiney, and Foy in prep.) on red king crab suggest that modest increases in $p\mathrm{CO}_2$ increase the production of proteins related to cuticle development in crab. In addition, proteins related to system organism stress are expressed at a higher rate in crab exposed to lower pH. It is likely that the physiological response of crab to a change in *in situ* $p\mathrm{CO}_2$ will change markedly between early and later developmental stages. Understanding

these molecular dynamics is critical to determining how an organism may adapt to future ocean conditions.

Now that a transcriptome has been developed for red king crab, further experimentation can be tested at specific genes without additional sequencing work. In addition, transcriptome libraries should be developed for other commercial shellfish species that are likely to be affected by concomitant environmental stressors such as temperature and acidification. To augment crab physiological effects experiments in FY15 through FY17, we propose continued funding of genetic research to identify molecular organismal response to future changes in regional CO_2 concentrations. It is likely that the molecular response of *Chionoecetes opilio* (one of the largest shellfish fisheries in the United States.) will differ from that of red king crab so we propose to expand the Generation II sequencing to *Chionoecetes* spp. This will allow us to compare the response of multiple commercially important shellfish species from the eastern Bering Sea.

Scope of Work and Project Costs

To assess gene regulation in snow crab, a new RNA-seq transcriptome will need to be developed in J. Stillman's molecular laboratory and will support a graduate student thesis. D*e novo* assembly will be required to generate a reference transcriptome. Using a preliminary *P. camtschaticus* RNA-seq dataset, we will consider the appropriate *de novo* transcriptome assembly program, assess appropriate filters, determine the depth of sequencing required, identify which transcripts will get annotated, and finally analyze how many genes are differentially expressed among OA test libraries. RNA will be extracted from snow crab during experimentation at the Kodiak Laboratory to develop libraries and bioinformatics will be developed to assess differential gene expression.

For red king crab, a suite of genetic biomarkers derived from previous transcriptome building research in 2012-2014 will be used to assess the effects of diurnal and seasonal exposure to pCO_2 of juvenile red king crab with the goal to estimate the potential acclimation red king crab may have to increases in OA conditions in the near future. Samples will be taken and analyzed from laboratory experiments (see above) and processed based on a finite selection of genes.

The FY15-FY17 budget request for this project is: $352,499 (FY15: $121,559; FY16: $130,159; FY17: $100,781).

Expected Outcome(s)

One peer-reviewed publication describing the development of a snow crab transcriptome. One publication assessing the molecular response and acclimation of red king crab to variable pCO_2 exposure (see year 3 red king crab experiment above). Data will also be made available to national transcriptomics databases specific to crustacean biologists.

Letter of Intent

Understand responses to ocean acidification: Modeling to predict impacts on marine ecosystems and organisms.

Project Title

Modeling direct and indirect effects of ocean acidification on walleye pollock recruitment

Project Scientists

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Statement of the Problem

Walleye pollock are a key species in north Pacific and Bering Sea ecosystems where they are a central component of the food web and support the largest single-species fishery in the United States, with harvests averaging over 1.1 million t over the last decade. Previous work on the effects of OA on the growth and development of this species (Hurst et al. 2012 and 2013) and other commercially important marine fish species have focused on the direct effects of high CO_2 which may not the primary pathway by which OA impacts these species. Recent work has suggested that sensory and behavioral disruption and changes in the lower trophic levels of the food web are likely to interact with, and have a greater impact than the direct effects of elevated CO_2 (refs). As part the Sustained Investment (SI) workplan, laboratory experiments will be conducted to examine the effects of OA on foraging behavior and determine the sensitivity to nutritional stress associated with reduced prey quality of larval and juvenile walleye pollock. The application of those experimental results to the prediction of population level responses in recruitment and productivity necessitates testing interactive effects among co-occurring stressors and development of a model which allows the integration of the full suite of OA-induced impacts on the early life stages.

Scope of Work and Project Costs

This project would examine the potential for deleterious interactions in walleye pollock larvae exposed to high CO_2 levels under poor feeding conditions. Unable to synthesize certain fatty acids, fishes are dependent upon obtaining these "essential" fatty acids (EFAs) from their diets. 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.

Walleye pollock larvae will be reared at ambient (~ 350 µatm) and elevated (1500 µatm) CO_2 levels on two diets with high and low ratios of DHA/EPA essential fatty acids (3 replicate tanks within each of the four experimental treatments). Fish will be sampled for length and mass weekly during the first 6 weeks of life. In addition, samples will be drawn for lipid composition and histopathological analysis at 3 and 6 weeks of age (Frommel et al. 2012, Chambers et al. 2013). Total lipids and lipid class composition will be measured at the Oregon State University's Lipid Analysis Laboratory according to Copeman and Laurel (2010). Standard histopathological analyses will be conducted in independent larval samples at OSU's Department of Microbiology. Both lipid and histological analyses will be conducted with the observer blind to the treatment conditions. The integration of measurements of survival, growth, lipid composition, and developmental anomalies will provide a powerful analysis of the range of lethal sub-lethal impacts of the direct (high CO_2) and indirect (change in prey quality) effects of OA as well as their potential interactions.

To evaluate the cumulative impact of direct and indirect effects of OA on walleye pollock, we will adapt an existing mechanistic foraging and growth model to incorporate the experimentally observed physiological, behavioral, and food web impacts. This model, originally developed for Atlantic cod (Kristiansen et al. 2007) has recently 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. Input parameters to the model are the water temperatures, size-distribution and energy density of prey categories.

The effects of OA on walleye pollock will be incorporated into the model through alteration of the parameters that govern intrinsic growth rates and behavior of walleye pollock 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 walleye pollock growth will be modified by a factor representing the availability of EFAs in the diet based on and the experimentally-determined magnitude of EFA-limitation on growth of walleye pollock larvae and interaction with pH. In addition, changes in relative abundances of prey types available to walleye 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).

Output parameters from the model will be the size 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). The cumulative effects of OA on early life stages of

walleye pollock will be evaluated by running the model under multiple scenarios representing near-future, and 100-year forecasts of CO_2 levels in the Bering Sea.

The FY15-FY17 budget request for this project is: $265,300 (FY15: $0; FY16: $141,200; FY17: $124,100).

Expected Products

1. Established collaborations with Academic colleagues with expertise in nutritional biochemistry and fish histopathology to supplement NOAA's expertise in experimental culture of marine resource species.
2. Improved understanding of the range of direct and indirect effects of OA on marine fishery resources and publications in national/international scientific journals.

Applications

1. Improved prediction of effects of OA on walleye pollock fishery.
2. Refinement of analytical approach to identifying OA effects in marine fishes.
3. Improved input for demographic, ecosystem, and socioeconomic models predicting the impacts of OA on Alaskan fisheries and communities.

Citations

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Copeman, L.A., and B.J. Laurel. 2010. Experimental evidence of fatty acid limited growth and survival in Pacific cod larvae. Mar. Ecol. Progr. Ser. 412:259-272.

Frommel, A.Y., R. Maneja, D. Lowe, A.M. Malzahn, A.J. Geffen, A. Folkvord, U. Piatkowski, T.B.H. Reusch, C. Clemmesen. 2012. Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. Natl. Clim. Change 2:42-46.

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Hurst, T.P., E.R. Fernandez, and J.T. Mathis. 2013. Effects of OA on hatch size and larval growth of walleye pollock (*Theragra chalcogramma*). ICES J. Mar. Sci. 70:812-822.

Calbet, A., A.F. Sazhin, J.C. Nejstgaard, S.A. Berger, Z.S. Tait, L. Olmos, D. Sousoni, S. Isari, R.A. Martinez, J-M. Bouquet, E.M. Thompson, U. Bamstedt, H.H. Jakobsen. 2014. Future climate scenarios for a coastal productive planktonic food web resulting in microplankton phenology changes and decreased trophic transfer efficiency. Plos One 9 DOI: 10.1371/journal.pone.0094388

Kristiansen, T., O. Fiksen, and A. Folkvord. 2007. Modeling feeding, growth, and habitat selection in larval Atlantic cod (*Gadus morhua*): observations and model predictions in a macrocosm environment. Can. J. Fish. Aquat. Sci. 64:136-151.

Leu, E., M. Daase, K.G. Schulz, A. Stuhr, and U. Riebesell. 2013. Effect of OA on the fatty acid composition of a natural plankton community. Biogeosciences 10:1143-1153.

Siddon, E.C., T. Kristiansen, F.J. Mueter, K.K. Holsman, R.A. Heintz, and E.V. Farley. 2013. Spatial match-mismatch between juvenile fish and prey explains recruitment variability across contrasting climate conditions in the eastern Bering Sea. Plos One 8: e84526.

Letter of Intent

<u>Augmentation of Existing Surveys</u> -- Collection and integration of complementary biological observations and laboratory-manipulated chemistry data to provide a robust suite of OA-relevant physiological observations.

Project Title

Physiological Response of the Red Tree Coral (*Primnoa pacifica*) to low pH scenarios in the laboratory

Project Scientists

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Statement of the Problem

Research on the effects of ocean acidification (OA) on coldwater corals has been quite limited worldwide even though impacts on these important ecosystems are anticipated. Coldwater corals are the focus of only a single project within the portfolio of NOAA's OA Program. Results from that study, even though preliminary, formed the basis for the final ruling issued by NMFS in their Notice of 90-day Finding on a Petition by the Center for Biological Diversity to List 44 Species of Corals as Threatened or Endangered Under the Endangered Species Act. NOAA's study focused on the calcium carbonate mineralogy of Alaskan corals with the expectation that corals composed of high-magnesium calcite and aragonite will be inherently at risk to the corrosive properties expected to be seen in North Pacific waters in the near future. Results to date indicate that most octocorals examined are entirely or principally composed of "low to mid" magnesium calcite ($<$ 12 mol% $MgCO_3$). Only a few species are composed of the most soluble form of calcium carbonate—high-magnesium calcite ($>$ 12 mol% $MgCO_3$). Of those few species, the red tree coral (*Primnoa pacifica*), is an excellent candidate for laboratory study on the physiological effects of decreased pH.

Red tree corals are one of the most ecologically important corals in the North Pacific Ocean. They can grow to be very large (up to 5 m high and wide), are geographically widespread (Washington state to Bering Sea), and form dense thickets in some regions. Thickets provide essential habitat for some life stages of managed species of fish and crabs and are highly vulnerable to disturbance from anthropogenic activities including fishing gear disturbance. Thickets occur below the current

calcite horizon in the North Pacific Ocean so their ability to thrive at those depths is also a good reason to study their physiology.

Red tree corals are bathymetrically widespread (6–899 m depth) but are typically found at depths between 125 and 400 m. They are one of a few species worldwide that have emerged from their typical depth range to thrive in very shallow water in high-latitude glacial fjords. These emerged populations in Southeast Alaska have provided researchers with a living laboratory accessible to scuba divers year-round to study biological processes not possible for deep-water populations.

These populations have provided researchers a unique source of hand-selected specimens for laboratory study. Since March 2014, we have maintained colony snips in unfiltered running seawater at the Kodiak Laboratory and are monitoring their survival and growth. To date all corals are in excellent condition and appear to be growing at rates similar to those expected for the species. With these favorable results, we now intend to move forward with a full study beginning in March 2015. The objectives of this study are to determine if the survival, growth, skeletal development, and reproduction of red tree corals are affected by low pH in the laboratory.

Scope of Work and Project Costs

Specimens will be collected from an established study site in Tracy Arm, Southeast Alaska, in March 2015. We will collect 90 branch tips from 30 healthy colonies. Previously tagged large (> 50 cm length) colonies will be purposely targeted for collection since we already know the gender and reproductive status (i.e., mature vs. immature) of those colonies; otherwise the gender of colonies will be determined on the vessel to ensure that 15 female and 15 male colonies are sampled. At the AFSC's Kodiak Laboratory, each coral snip will be photographed and a volumetric measurement (water displacement) will be made. Each snip will be photographed every 2 months and at the end of the experiment. Volumetric measurements will be made at the beginning and end of the experiment. The growth of all snips will be determined using ImageJ software.

One snip from each colony will be randomly assigned to each of three pH treatments (pH 8.0 -- control, current oceanic conditions; pH 7.8 -- expected global average by the year 2100; and pH 7.5 -- expected by year 2200). This is the same suite of exposures used for recent studies on the effects of OA on Alaskan crabs. Coral snips will be maintained in unfiltered running seawater for one year (~25 March 2015 – 25 March 2016).

We will measure differences in survival and growth (branch tip extension and volumetric displacement as a proxy for mass). Additionally we will examine changes in fecundity and oocyte development (staging) for females and changes in spermatocyst development (staging) for males. Samples ($N = 30$) will be collected at the beginning of the experiment from each parent colony

(tissue sampled adjacent to each snip) and at the end of the experiment from the study snip ($N =$ 90). Samples will be processed using established techniques for this species (Waller et al. 2014).

We will examine differences in coenchymal, body wall, and opercular sclerite morphology for all study specimens via scanning electron microscopy (SEM) and use a scoring technique similar to Gabay et al. (2014). We will subsample 10 coral snips from each treatment before and after the experiment ($N = 60$ total). Sample preparation and SEM analyses will be done at the Smithsonian Institution.

The FY15-FY17 budget request for this project is: $99,200 (FY15: $84,200; FY16: $15,000; FY17: $0).

Expected Outcome(s)

1. At least two peer-reviewed publications describing the physiological responses of the North Pacific's ecologically most important coral to natural and manipulated levels of pH.

Citations

Gabay Y., M. Fine, Z. Barkay, and Y. Benayahu. 2014. Octocoral tissue provides protection from declining oceanic pH. PLoS ONE 9(4): e91553 doi:10.1371/journal.pone.0091553.

Letter of Intent

Project Title

Autonomous Observations of ocean acidification in Alaska Coastal Seas

Project Scientists

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Statement of Problem

New ocean acidification (OA) data have been collected over the past 3 years by leveraging an initial 2011 investment from the Alaska State Legislature with funds from Federal agencies, private industry, and non-governmental organizations. Unfortunately, these data show that the coastal regions around Alaska are experiencing some of the most rapid and extensive progressions of OA in the U.S. exclusive economic zone (EEZ). By integrating observational data with species response studies, OA forecast models and human impact assessments it has been determined that Alaska coastal communities have a varying degree of vulnerability to OA, ranging from moderate to severe (Mathis et al. 2014). Areas that are most vulnerable are located in regions where fisheries are vital for the state and national economy, providing over $3 billion annually to the U.S. gross domestic product (GDP). 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 United States. 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 responses to present or future OA conditions, such as the Alaska red king crab in the Being Sea.

Scope of Work and Project Costs

Here, we propose to continue and expand the coastal Alaska OA monitoring effort by maintaining at least two OA moorings sites (more if OAP can secure additional ship time) in critical fishing areas and deploying autonomous gliders on an annual basis in OA-vulnerable coastal regions to develop a 4-D understanding of the OA conditions (Fig. 1). The current OA monitoring network installed, in part, with 2011 state funding has been instrumental in establishing and tracking current conditions; from synoptic "weather" events, to the progressing "climate" of the chemical sea state. While these funds were critical in developing an OA instrumentation pool and infrastructure assets they have been exhausted.

As part of this OAP build-out initiative we would integrate surface and subsurface pCO_2, pH, temperature, salinity and dissolved oxygen data from moorings with similar data from PMEL-

owned carbon wave gliders and Slocum gliders (Fig. 1) to understand the spatial and temporal dynamics of carbonate mineral saturation states throughout the water column. We will continue to improve upon empirical algorithms developed for the Alaska coastal regions (e.g., Evans et al. 2013) to fully utilize data from profiling gliders and CTD casts that are conducted on a number of NOAA fisheries cruises as well as vessels of opportunity.

We are requesting $200,000 annually to partially support this effort that will be part of a larger consortium with leveraged funds from the Alaska Ocean Observing System ($95,000 annually), the North Pacific Research Board ($100,000 annually) and the Alaska OA Research Center (all mooring equipment and hardware). This work will contribute to all of the
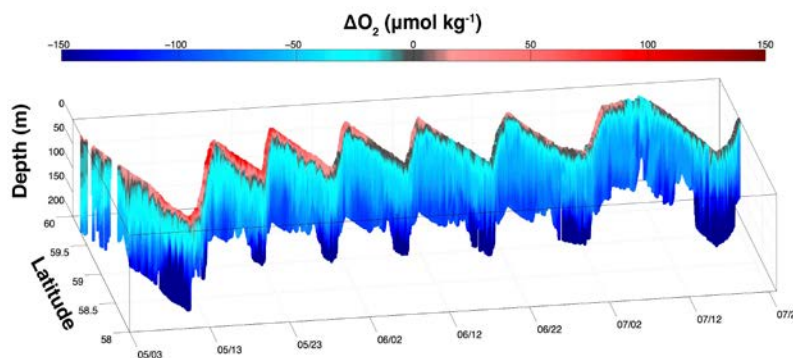

Fig. 1. -- 4-D transect from a Slocum glider of the change in dissolved oxygen concentrations over the Gulf of Alaska shelf. Using empirical algorithms, it is possible to determine carbonate mineral saturation.

NOAA-OAP build-out and investment thematic priorities:

1. By adding at least two additional OA moorings to the NOAA OA mooring network we will increase the number of fixed monitoring sites and geographic coverage through shared monitoring assets in underserved regions (Alaska currently has no OAP funded observing platforms).
2. We will enhance OA observational technologies and augment existing surveys by deploying autonomous gliders that are more cost effective than ship-based surveys.
3. We will enhance and expand synthesis activities by combining dataset from a variety of platforms (moorings and gliders) and other sources (e.g., fishers survey data, OA species response studies) to develop comprehensive OA assessments for Alaska.

Expected Outcomes

We expect a number of crosscutting products to come from these monitoring activities. Data from the moorings and gliders 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 be used to validate new OA models that are currently being developed for the Gulf of Alaska and Bering Sea. These data will be applied in bioeconomic models of crab and walleye pollock and forecasts of their future abundance. Finally, the data itself (Fig. 1) will provide new insights into the seasonal progression of carbonate mineral saturation states as well as the intensity, duration,

and extent of undersaturation events caused by the progressive accumulation of anthropogenic CO_2 in the water.

Citations

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