Crab life history.

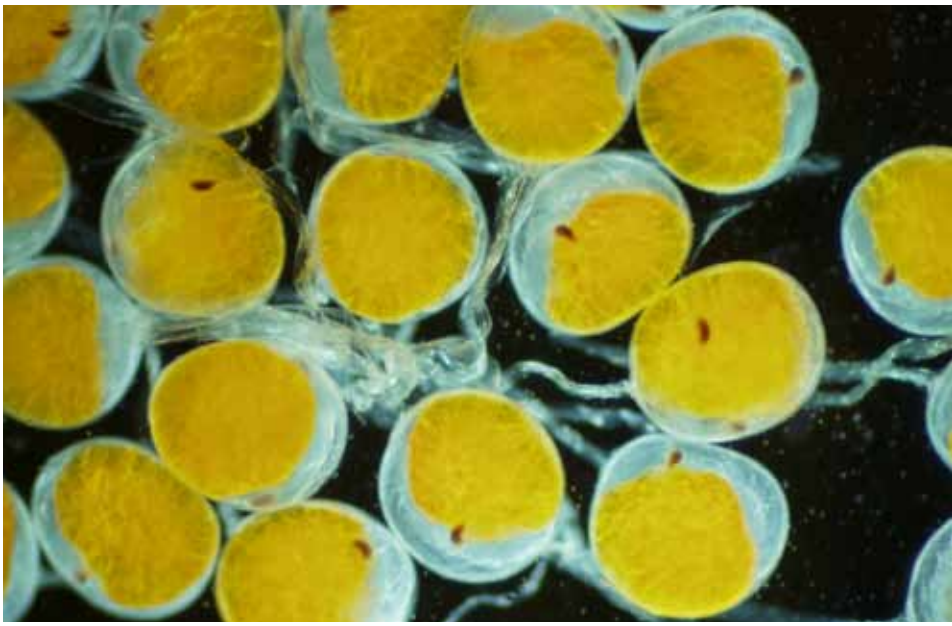
Ocean Acidification: Monitoring and Measuring the Physiological and Population Response of Living Marine Resources in Alaska

Robert J. Foy, Mark Carls, Michael Dalton, Tom Hurst, W. Christopher Long, Michael F. Sigler, Robert P. Stone, Katherine M. Swiney

In the United States and other coastal nations, ocean acidification has quickly become a common topic of scientific research. Ocean acidification also has become a public concern as news headlines warn of this potentially threatening byproduct of global climate change. In March 2009, the U.S. Congress passed the Federal Ocean Acidification Research Monitoring Act, a bill to establish an interagency committee to develop an ocean acidification research and monitoring plan and to establish an ocean acidification program within NOAA. NOAA accordingly developed the NOAA Ocean and Great Lakes Acidification Research Plan in 2010, a plan to improve monitoring capacity, assess organismal response, forecast biogeochemical and ecological responses, provide data synthesis, develop management tools, and provide public outreach and education about ocean acidification in the open and coastal oceans and the Great Lakes.

What Is Ocean Acidification?

Global climate change studies have revealed that the rate of increase in atmospheric carbon dioxide (CO_2) concentration has increased substantially since the industrial revolution (mid-1700s). The world's oceans have absorbed between 30% and 50% of that new CO_2. The increase in oceanic CO_2, when incorporated into the carbonate system, has resulted in an average decrease of surface ocean pH by 0.1 units, the equivalent of a 30% increase in acidity. The increased acidity reduces the saturation of calcium carbonate, making it more difficult for some calcifying organisms to sequester calcium and carbonate to build shells. In the North Pacific Ocean, the saturation depth of calcium carbonate is already shallow (<200 m) relative to the North Atlantic (~2,000 m). Therefore, the marine organisms in Alaska are particularly at risk to effects associated with ocean acidification. In addition, some species such as golden king crab (*Lithodes aequispinus*) in Alaska already inhabit undersaturated environments; understanding how they cope with this environment will help us evaluate the effects of ocean acidification on Alaska species.



Crab embryos.

The Alaska Fisheries Science Center Plan

Scientists at the Alaska Fisheries Science Center (AFSC) have worked locally, nationally, and internationally since 2007 to address the potential impacts of ocean acidification on scales from individual organisms to ecosystems. In 2008, AFSC scientists developed a research plan to test the hypotheses that reduced ocean pH and the resultant reduction in availability of calcium carbonate would have wide-ranging effects, including reduced growth, survival, and reproduction of commercially important fish and shellfish,

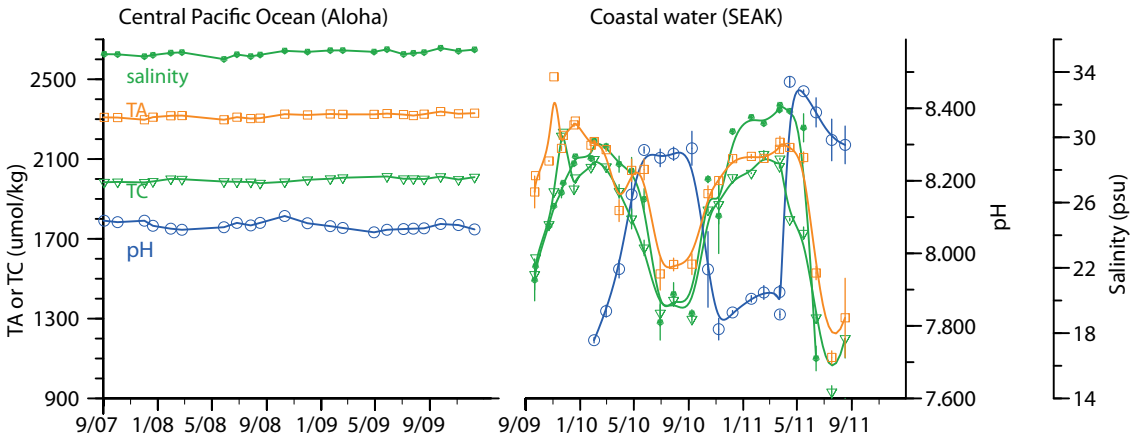


Figure 1. Annual carbon and salinity cycling in surface coastal waters (0 to 0.5 m) of Southeast Alaska and surface open ocean conditions (0 to 10 m) in the central Pacific Ocean at station Aloha. Data are salinity (practical salinity units, psu), total alkalinity (TA), total dissolved inorganic carbon (TC), and pH. Open ocean data were limited to the most recent 2 years of available data.

ecologically important prey of those species, and cold water corals. Species-specific physiological responses to ocean acidification were not well understood, so a broad research effort was considered for several taxa including shellfish, calcareous plankton, coldwater corals, and fish. Prioritization was given to the larval and juvenile stages of commercially and ecologically important taxa more likely to be directly affected by ocean acidification in Alaska. Calcareous invertebrates such as shellfish are likely to suffer direct effects of reduced calcium carbonate availability and have a commercial importance in Alaska. Calcareous invertebrates such as pteropods and euphausiids are likely to be directly affected and are important prey items of commercially important fish species and of marine mammals. Coldwater corals are sensitive to ocean carbonate chemistry and are important habitat for commercially important species such as rockfish. The early life stages of commercially important fish species may be affected by direct and indirect effects of ocean acidification.

While still a relatively new research direction for AFSC scientists, significant progress has been made identifying appropriate research foci, developing accurate and repeatable methodologies, measuring baseline parameters important for understanding ocean carbonate chemistry, testing the physiological response of key marine organisms, and finally, estimating the impacts at population scales. Infrastructure was developed at the AFSC's Juneau, Kodiak, and Newport seawater laboratories including CO_2 delivery systems, pH monitoring systems, CO_2 monitoring systems, and carbonate chemistry analytical instruments.

Monitoring in Alaska

Although monitoring coastal and oceanic carbon chemistry is one goal of the AFSC research plan, funding restrictions have resulted in a limited effort in Alaska. Collaborative efforts to support the Ocean Acidification Research Center at the University of Alaska Fairbanks have led to increased capacity to measure the carbonate chemistry of the Gulf of Alaska and Bering Sea. Local coastal monitoring of carbonate has occurred only in Southeast Alaska.

Carbonate seasonal patterns in eastern Gulf of Alaska coastal water have been monitored by Mark Carls and Lawra Vanderhoof at the AFSC's Auke Bay Laboratories in Juneau. Initial results from their studies conducted in 2009-11 were compared to 2007-09 data from the open

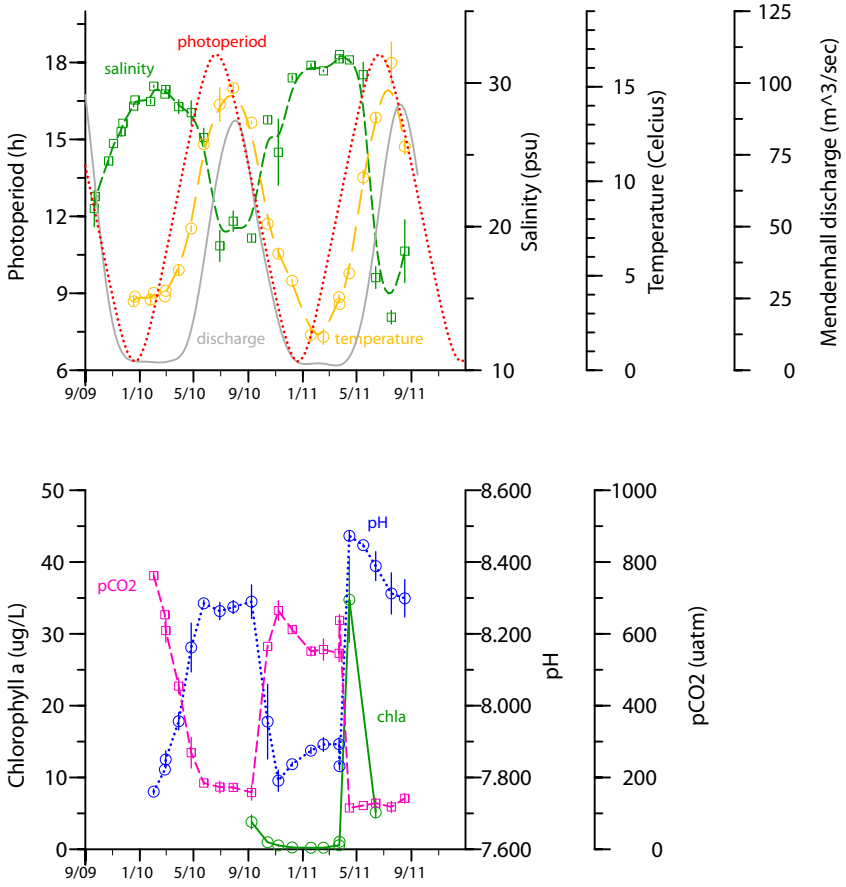


Figure 2. Relationship among photoperiod, water temperature, salinity, and terrestrial discharge in surface water (top panel) and pH, pCO_2, and chlorophyll a in surface water (bottom panel). Data were averaged among three inside water sites (Auke Bay, Favorite Channel, and Lena Cove).

ocean in the North Central Pacific near Hawaii (Fig. 1). Although the data sets were not collected during the exact same time period, seasonal trends and annual averages were compared. Those comparisons showed that mean pH was similar in the open ocean and coastal waters, while mean total alkalinity (TA) was substantially greater in the open ocean (2,320 µmol/kg) than in the coastal water (1,725 µmol/kg) due to salinity differences. The mean total dissolved inorganic carbon (TC) was somewhat greater in the open ocean (1,978 µmol/kg between 2008 and 2010) than in the coastal waters (1,576 µmol/kg). Annual changes in pH, TA, and TC were about ten times greater in the Southeast Alaska waters than in the North

Figure 3. Experimental CO_2 dosing systems at the Kodiak and Newport Laboratories.

Central Pacific waters. Seawater pH was highest in spring-summer and lowest in winter, while TA, TC, and salinity have the opposite seasonal trend.

Salinity seasonal patterns (resultant from solar and hydrological cycles) may be the primary driver of seasonal carbon variability in Southeast Alaska coastal water. Annual trends in TC and TA are similar to salinity trends (Fig. 1), suggesting that salinity is either driving carbonate parameters or may be responding to the same underlying driver. Annual pH patterns are about six months out of phase with salinity. Depth profiles of salinity, pH, TC, and TA provide further information to support salinity as a likely factor driving pH variability as each declined with depth.

A seasonal increase in pH coincident with increases in chlorophyll a concentrations in the water suggests that plankton blooms increase pH in coastal or inside water (Fig. 2). In theory, this relationship is expected as removal of dissolved carbon from the water should increase pH. Several more seasonal observations will be necessary to more rigorously substantiate (or refute) the hypothesis that phytoplankton blooms influence the pH in Southeast Alaska waters.

Shoaling of corrosive deep Pacific water is not likely the explanation for seasonal variation in Southeast Alaska coastal waters because pH cycles are about six months out of phase from when corrosive water is likely to be shoaling in Alaska. The Central Gulf of Alaska is predominantly a downwelling region in the winter with weak upwelling in the summer. Higher pH values in Southeast Alaska during the winter suggest that upwelling is not a major factor in acidifying waters in this region.

Crab Research

King and Tanner crab experimental studies have been conducted by Chris Long, Katherine Swiney, and Robert Foy at the AFSC's Kodiak Laboratory. The effects of increased CO_2 on the survival, condition, and growth of king and Tanner crab species were investigated from 2009 to 2011. At the same time, infrastructure was developed to support a multi-year program capable of assessing both direct and indirect effects of ocean acidification on shell building in commercial crab species in Alaska (Fig. 3). The results of this research program will not only provide empirical data specific to the physiological response of crabs, but will also support modeling efforts on the indirect impacts of ocean acidification associated with food webs and fisheries interactions.

Red King Crab Experimental Studies

Initial experiments tested the effects of ocean acidification on late-stage embryos and larvae of red king crab (*Paralithodes camtschaticus*) at average ocean pH levels expected within the next 50 years. Ovigerous red king crab from the Bering Sea were held in seawater at an ambient pH of 8.0 (control) and a treatment pH of 7.7 in CO_2-acidified seawater. Embryos were photographed throughout the experiment under a microscope and measured using image analysis software (Fig. 4). Embryos reared in acidified water were larger in total length, but were similar in weight and had smaller yolks than those in control water. Females in acidified seawater had longer hatch duration, though there was no difference in fecundity.

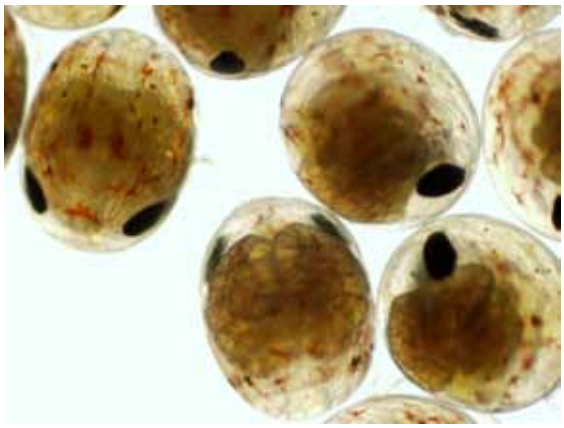


Figure 4. Late stage red king crab embryos photographed under a microscope.

Figure 5. Newly hatched red king crab larvae.

At hatching, larvae (Fig. 5) were collected and pooled from multiple females within the same treatment. A series of fully crossed experiments was performed in which embryo treatment was crossed with larval treatment; larvae that had been exposed to control water as embryos were held in both acidified and control water, as were larvae that had been exposed to acidified water as embryos. Larval survival was reduced by exposure to acidified water at both the embryo and the larval stages, and the effect was additive, such that larvae exposed to acidified water at both stages had the lowest survival rate of all (Fig. 6). Larvae held in acidified water were more calcified than those held in control water (Fig. 7).

Throughout the experiment, carapace samples from mature females were taken from molted shells and from new shells 2 weeks after molting. The samples were analyzed for calcium content. Females held in acidified water had higher calcium content in their shells than females held in control water, especially in their new shells 2 weeks after molting.

To assess juvenile survival, growth, and calcification, juvenile red king crab were placed in three pH treatments. Juvenile survival decreased with pH, with 100% mortality occurring after 95 days in pH 7.5 water (Fig. 8). Although the morphology of juvenile red king crab (Fig. 9) was not affected by acidification, they exhibited slower growth in water acidified to a pH of 7.8. Ocean acidification did not affect the calcium content of red king crab, but the condition index decreased.

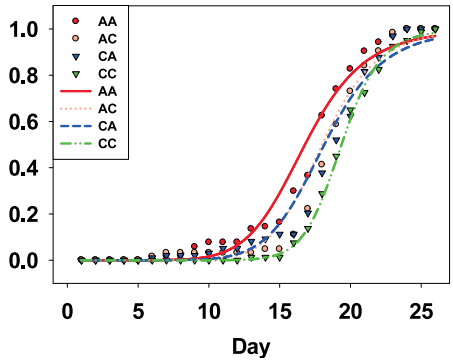


Figure 6. Proportional mortality of starved larvae held in control (C) and acidified (A) water. In the legend, the first letter designates the embryonic treatment and the second the larval treatment. Points represent the proportional mortality in all replicates during the experiment, and lines the predicted mortality based on the best fit model.

Tanner Crab Experimental Studies

The goal for the Tanner crab (*Chionoecetes bairdi*) research was to examine the effects of ocean acidification on aspects of the reproduction and larval development of Tanner crabs. Our objectives were to test the effects of ocean acidification on 1) fecundity, embryo viability, embryo development, and hatching success; 2) larval condition and survival; 3) calcification in both the mothers and the larvae; and 4) juvenile growth, condition, calcification, and survival.

The initial experiments were done on Tanner crab juveniles with similar methods as for juvenile red king crab. Juveniles were held in ambient pH = ~8.0, pH = 7.8, and pH = 7.5 seawater for nearly 200 days at ambient temperatures. Juvenile survival decreased at the lower pH (Fig. 8), growth rate was lower in the pH 7.5 treatment, and calcium content was lower. Morphology (Fig. 9) and condition did not differ among the treatments.

Subsequent experiments were done on adult females with embryos and on larvae. Adult female Tanner crab and their larvae were exposed to increased CO_2 at two treatments (pH 7.8 and 7.5) and a control pH (pH 8.0). The embryo developmental stage was determined and embryo morphology was observed. Embryological development data is currently being analyzed. The best fitting model for larval survival showed that larvae died slightly faster at pH 7.5 than larvae in pH 7.8 or in control treatments (Fig. 10).

Conclusions on King and Tanner Crab Experimental Research

The results of the experimental red king and Tanner crab studies thus far indicate that ocean acidification may have a substantial negative effect on red king and Tanner crab stocks. Reduced survival at the larval and juvenile stages is likely to reduce recruitment and subsequently affect the number of mature male crabs available for commercial fisheries. Variability in calcification and condition between species and life history stages suggests that there are different physiological responses to increased dissolved inorganic carbon concentration. Regardless, increased physiological costs are likely to lead to the higher mortality rates observed across these experiments. More research on the effects of ocean acidification on other life history stages and the molecular response is necessary to fully understand the effects it will have on red king crab, Tanner crab, and other federally managed crab species. Particular attention will be needed to dosing experiments that accurately mimic the *in situ* conditions encountered by crab at different life stages and to concurrent effects of other environmental stressors such as temperature.

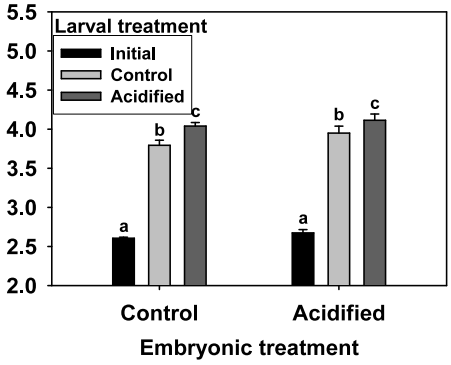


Figure 7. The effect of ocean acidification at the embryonic and larval stage on percent calcium content (m/m, dry mass) in larvae. Initial treatment represents larvae sampled the day after hatching. Bars represent the mean +1 standard error. Bars with different letters above them differ statistically.

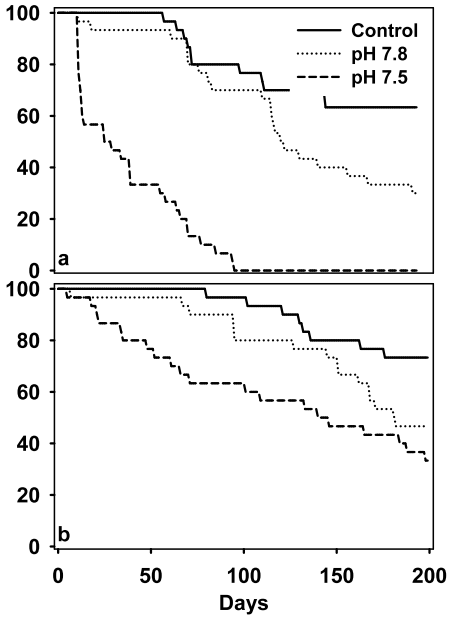


Figure 8. Survival of red king crab (a), and Tanner crabs (b) in control and treatment tanks over the duration of the experiment.

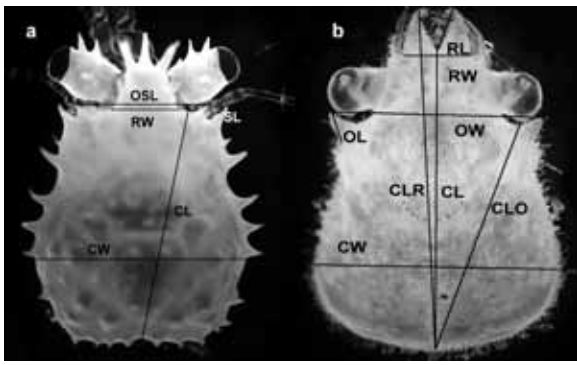


Figure 9. Measurement taken for morphometric analysis for a) red king crabs, and b) Tanner crabs. Measurement on red king crabs included carapace width (CW), carapace length (CL), rostrum base width (RW), orbital spine width (OW), and the first spine length (SL). Measurements on Tanner crab included carapace width (CW), carapace length (CL), carapace length to the rostrum (CLR), carapace length to the eye orbit (CLO), rostrum base width (RW), rostrum length (RL), orbital spine width (OW), and orbital spine length (OL).

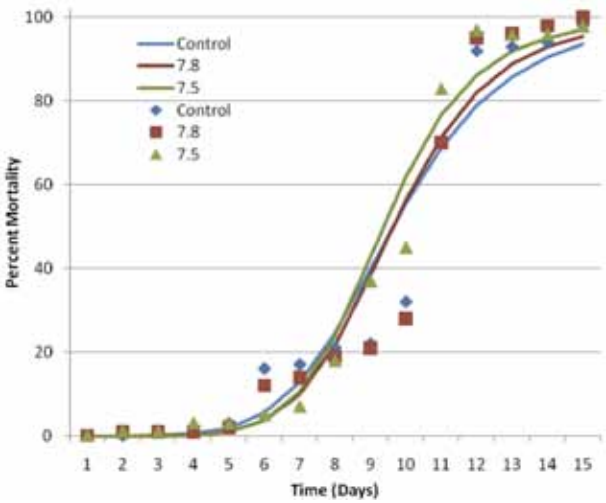


Figure 10. Survival of starved Tanner crab larvae in three treatments. Points represent the average survival at each day and lines represent the best fit mortality models.

King Crab Genetics Research

Genetic studies utilizing the samples from Kodiak Laboratory experimental research have been contracted to Jonathon Stillman at the University of California, Berkeley. Functional genomics can assess how an organism responds to environmental change by studying how genomes are regulated under specific environmental conditions. Gene expression products (mRNA) will be monitored as indicators of stress level, condition, health, and other physiological parameters in larval and juvenile red crab to determine sublethal effects of increased CO_2. Utilizing these methods as response variables in a controlled laboratory CO_2 dosing study will provide a powerful tool for assessing the physiological response of crabs to ocean acidification.

In 2008-10 larval and adult red king crab samples were tested to see if gene expression could be assessed using cDNA microarrays that have been developed for porcelain crabs, (*Petrolisthes* spp.). Results suggested that there was sufficient sequence homology for a large number of genes that the porcelain crab microarray would work to analyze a wide diversity of transcripts and gene expression patterns in red king crab. The initial results also suggested that there may be a set of genes commonly expressed across all crab larvae.

To support the crab genomics project, juvenile red king crab were exposed to three temperature treatments (ambient, ambient +2°C, and ambient +4°C) and three pH treatments (7.5, 7.8 and ambient) to test the effects of increased CO_2 and temperature on juvenile survival. The objectives of this project were to use microarray analysis to fully characterize the manner in which red king crab transcripts bind to the array, characterize the transcriptome of red king crab, compare the red king crab transcriptome to sequences in porcelain crabs, and to compare genetic data to data on mortality and growth as a result of previous experimental studies. Initial funding was secured in late 2011, the initial experiments for juvenile crab were completed in June 2012, and analyses are currently under way.

King Crab Bioeconomics

The bioeconomic modeling research has been conducted by AFSC economist Michael Dalton in collaboration with André Punt and Dusanka Poljak at the University of Washington School of Aquatic and Fishery Sciences. Existing models that estimate future impacts of ocean acidification have been applied mainly to corals and mollusks, and for the latter, these estimates have been fairly modest. However, existing models do not typically differentiate ocean acidification effects among life-history stages that vary in their degree of vulnerability and have been limited in their comparisons at the population level with other stressors such as commercial fishing. By coupling a pre-recruitment component with post-recruitment dynamics, the Bristol Bay red king crab bioeconomic model incorporates effects of ocean acidification on vulnerable juvenile crabs in combination with effects of commercial fishing on the Bristol Bay red king crab population as a whole. The Bristol Bay red king crab pre-recruitment component is a stage-structured model that includes effects of ocean acidification as a stressor via its impact on survival and the time to grow from one stage to the next. Survival rates in the pre-recruitment model were tuned to match the results of the survival experiments for Bristol Bay red king crab conducted at the Kodiak Laboratory for the sizes of crab to which those experiments pertain (see Fig. 11). Post-recruitment dynamics in the bioeconomic model are based on a simplified version of the full Bristol Bay red king crab stock assessment model that was fitted to the existing data for the Bristol Bay red king crab commercial fishery.

Many types of projections under management strategies can be made using the coupled bioeconomic model, and preliminary results suggest that ocean acidification could have substantial effects on the Bristol Bay red king crab fishery. For example, the proxy for fishing mortality at the maximum sustained yield (F_{MSY}), the value of fishing mortality leaving 35% of the spawning biomass per recruit ($F_{35\%}$), is projected to be much lower if effects of ocean acidification on the survival of

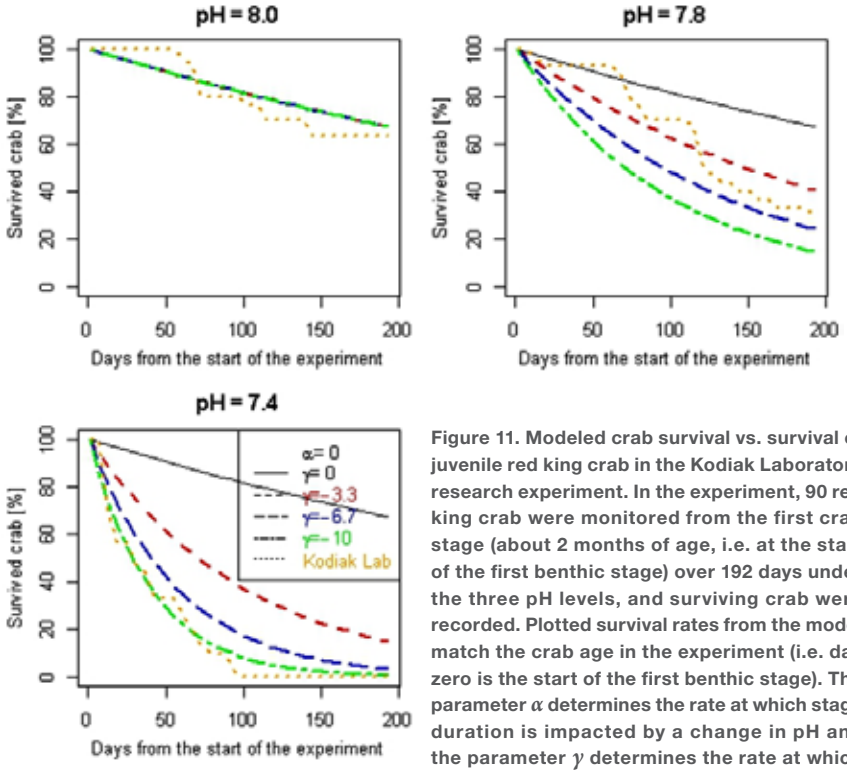


Figure 11. Modeled crab survival vs. survival of juvenile red king crab in the Kodiak Laboratory research experiment. In the experiment, 90 red king crab were monitored from the first crab stage (about 2 months of age, i.e. at the start of the first benthic stage) over 192 days under the three pH levels, and surviving crab were recorded. Plotted survival rates from the model match the crab age in the experiment (i.e. day zero is the start of the first benthic stage). The parameter α determines the rate at which stage duration is impacted by a change in pH and the parameter γ determines the rate at which survival is impacted by a change in pH. The results in the figure are based on the assumption that survival is proportional to the number of molts within a stage.

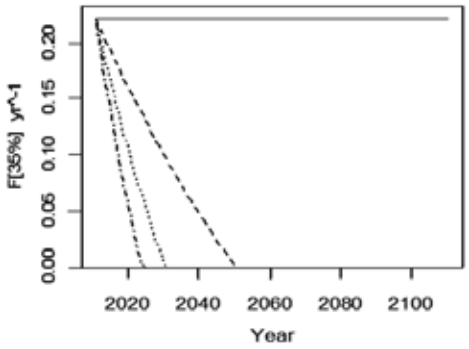


Figure 12. $F_{35\%}$ versus year for the no ocean acidification impact scenario (solid line) and three scenarios in which ocean acidification impacts the survival of pre-recruit Bristol Bay red king crab.

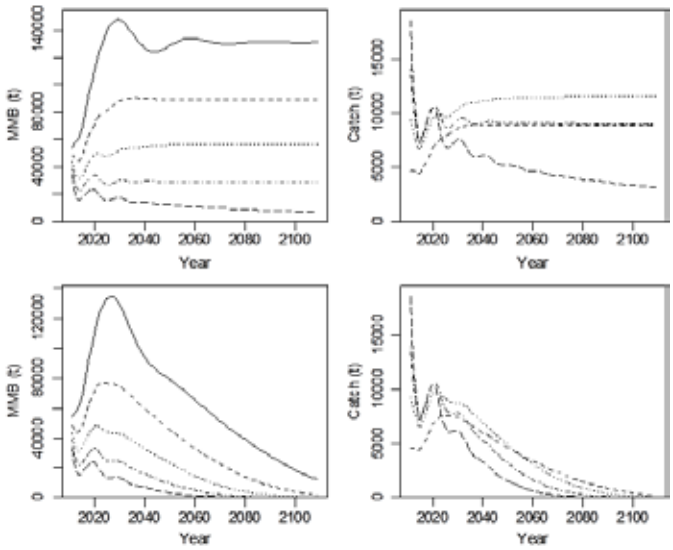


Figure 13. Time-trajectories of mature male biomass (tons) at the time of spawning (left panels), and the catch (right panels) for two of four ocean acidification scenarios (no ocean acidification impact, upper panels; level of ocean acidification impact which best matches the survival rates in the Kodiak experiments based on a pH of 7.8, lower panels). Results are shown for five levels of constant exploitation rate (solid line no future fishing; dotted line $F_{35\%}$ under the assumption of no ocean acidification impact).

juvenile crab are included in the model. Figure 12 shows the impact of ocean acidification on $F_{35\%}$ as a function of time, and hence, the target fishing mortality rate to achieve the current target level of male mature biomass-per-recruit. This fishing mortality rate equals zero just after 2020 for the most extreme scenario, which implies that mortality due to ocean acidification effects alone will be sufficiently high at this time to drop the stock to the target level even without any fishing. Predictions of long-term catch and mature male biomass for a range of constant fishing mortality rates are presented in Figure 13. These plots illustrate the consequences for the fishery if no changes are made to how management operates except to reduce harvests when abundance is lower. As expected, fishing at $F_{35\%}$ (dotted line in the upper panels) leads to the largest long-term catch. However, mature male biomass declines over time irrespective of fishing mortality for the level of ocean acidification impacts which best matches the survival rates in the Kodiak experiments based on a pH of 7.8. The projected impacts of ocean acidification on the Bristol Bay red king crab fishery are summarized in Figure 14 by showing shifts over time in the yield curve that plots mature male biomass versus catch in equilibrium for the scenario which best matches the survival rates in the Kodiak Laboratory experiments based on a pH of 7.8. In particular, the maximum sustainable yield (and associated mature male biomass) drops by ~50% every 20 years.

Gadid Research

Research on the effects of ocean acidification on Alaskan marine fishes is being conducted by Tom Hurst at the AFSC's Newport Laboratory, Oregon, in collaboration with Jeremy Mathis at the University of Alaska.

Marine fishes have an internal skeleton composed primarily of calcium phosphate and are generally assumed to be less sensitive to the effects of ocean acidification than those invertebrates which precipitate external skeletons of calcium carbonate. Further, it has been suggested that the high metabolic capacity and ability to increase intercellular buffering capacity provides most marine fishes the physiological capacity to cope with projected levels of ocean acidification. However, there are few studies which have tested those assumptions, and it is possible that early life stages with less developed acid-base regulation may be more susceptible to the effects of ocean acidification. The few studies to date have yielded mixed results, with no clear patterns emerging about which species might be most vulnerable to ocean acidification. While several studies have found that growth was not negatively affected by elevated CO_2, others have documented reduced survival and increased incidence of morphological deformities in early life stages reared in high CO_2 conditions. Further, the potential range of effects that may be induced by ocean acidification are only beginning to be understood. For example, experiments have demonstrated that elevated CO_2 levels alter the growth rates of the otolith (ear bone) and disrupt olfactory and auditory cues in some species. Additional work is needed to study the range of responses to projected ocean acidification in fishes, especially in the temperate and boreal marine species that support much of the world's fishery production.

The first part of the project was to develop a system for the rearing of marine fish eggs, larvae, and juveniles under controlled temperature and CO_2 conditions (Fig. 3). The flow-through system feeds water conditioned to four CO_2 levels to sixteen 100-L rearing tanks. The system also includes UV sterilization of water, allowing fish to be tested under quarantine conditions.

Given the direct links from individual growth rate to survival probability and population productivity, the focus of experiments to date has been to examine the growth responses of early life stages of walleye pollock (*Theragra chalcogramma*) to elevated CO_2 levels (Fig. 15). So far, the results suggest that walleye pollock are relatively robust when exposed to elevated CO_2. In both short-term (6 week) and long-term (6 month) exposures with juveniles, growth rates were not negatively affected by elevated CO_2 levels, even at levels well beyond those predicted for high latitude seas over the next 100 years. In fact, during one phase of the experiment, fish under high CO_2 levels actually grew faster than the ambient controls. In the short-term experiment, elevated CO_2 increased the rate of otolith deposition (Fig. 16) but did not affect otolith elemental composition. Further, measurements of consumption rates indicated that fish were not simply eating more in order to offset increased metabolic demands of hypercapnia (the presence of excessive amounts of CO_2 in the blood), a strategy which would be fine for captive culture fish but might not be available to fish in the wild.

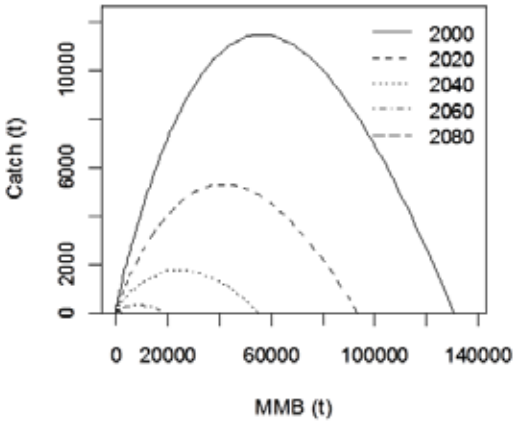


Figure 14. Equilibrium yield (tons) versus for mature male biomass (tons) for 5 years. These results are based on the ocean acidification scenario which best matches the survival rates in the Kodiak experiments based on a pH of 7.8.

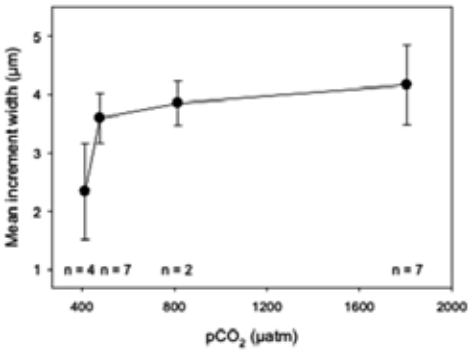


Figure 16. Mean otolith increment width (µm) of yearling walleye pollock reared under elevated CO_2 levels. Points are the mean (± std. dev.) fish pooled across three replicate tanks in each treatment.

Figure 15. Yearling pollock size measurement for growth assessment.

In addition to simply extending the duration of exposure, the long-term experiment also included seasonally-reflective warm (8°C) and cold (2.5°C) phases. Most ocean acidification experiments have been conducted at the upper end of the species' thermal range, and where temperature has been manipulated, tropical fishes have been tested at temperatures near or above current exposure limits. However, it is important to recognize that arctic and sub-arctic fishes will continue to be exposed to low temperatures in winter. It has been hypothesized that ocean acidification may restrict fishes' "thermal window" by reducing physiological performance at low as well as high temperatures. Low temperatures are known to reduce the effectiveness of ion balance at both the cellular and organismal level, a response which may depress feeding ability. The degree to which low temperature responses interact with or exacerbate the effects of other physiochemical stressors is largely unknown. For walleye pollock, it was important to determine if the effects of ocean acidification are more pronounced at the upper or lower end of the thermal range because potential interactions with low temperature stress would disproportionately affect the high latitude populations in the Gulf of Alaska and Bering Sea, which support major commercial fisheries. Fortunately, the resilience displayed by juvenile walleye pollock at high temperatures extended into the lower temperature range.

A second series of experiments examined whether eggs and larvae might be more vulnerable to the effects of ocean acidification than the larger juveniles are. Five batches of eggs were collected from laboratory-maintained broodstocks and were incubated until hatch across a range of CO_2 conditions. There was a statistically significant delay in time to hatch at the highest CO_2 level, the average difference was less than 1 day and was less than the difference observed between the different batches of eggs. Body size at hatch did not differ among CO_2 treatments. Experiments with larval walleye pollock will conclude the experimental series on early life stages of walleye pollock. Those experiments are currently being completed, and preliminary results again suggest that growth rates are no worse under elevated CO_2 levels than current conditions. While not exhaustive of potential interactive environmental factors, these experiments demonstrate a general resiliency of growth energetics among juvenile walleye pollock to the direct effects of CO_2 alterations predicted for the Gulf of Alaska and Bering Sea in the next century.

While that resiliency is good news, unfortunately it is not the end of the story. Recent work has demonstrated that exposure to elevated CO_2 levels altered sensory and behavioral responses in some coral reef fishes that did not appear to suffer from depressed growth at high CO_2 levels. Under elevated CO_2 conditions, fish exhibited maladaptive responses to the scent and auditory cues of preferred nursery habitats and exhibited maladaptive responses to predator scents. It is believed that the physiological compensation of increased levels of HCO_3- to buffer against pH changes in the blood (which alters oxygen binding) may alter the function of a critical neurotransmitter. Whether such sensory and behavioral disruptions could also occur in cold water fishes is not yet known. Future experiments are planned to examine the behavioral characteristics of young walleye pollock under ocean acidification conditions.

Coral Research

Coral research has been conducted by Robert Stone at Auke Bay Laboratories in collaboration with John Guinotte (Marine Conservation Institute), Anne Cohen (Woods Hole Oceanographic Institution), and Stephen Cairns (Smithsonian Institution). Corals are widespread throughout Alaska, including the continental shelf and upper slope of the Gulf of Alaska, the Aleutian Islands, the eastern Bering Sea, and as far north as the Beaufort Sea. They are found from the shallow subtidal zone to depths over 6,000 m, and many fish and crab species use them as habitat. Decreases in oceanic pH and resulting decreases in calcium carbonate saturation could have profound effects on corals dependent on the extraction of calcium carbonate from seawater for skeletal building. Corals will be affected differently depending on their skeletal composition (aragonite vs. calcite), geographical location, and depth relative to the already particularly shallow saturation depth in the North Pacific Ocean.

The skeletal composition is unknown for most species of deep-sea corals worldwide and is known for only a handful of the 140 taxa documented from Alaskan waters. Extensive archives at the Auke Bay Laboratory and Smithsonian Institution were sorted, and 130 specimens were selected comprising 61 taxa from all major groups of corals (scleractinians, gorgonians, true soft corals, stoloniferans, pennatulaceans, and hydrocorals) for laboratory analyses. Multiple specimens were selected for taxa of particular ecological importance (i.e. those that form large single-species assemblages). In addition, specimens of the same species were selected from multiple depth and geographic zones.

Laboratory analyses are being performed at the Department of Geology and Geophysics at the Woods Hole Oceanographic Institution. X-ray diffraction was used first to determine the aragonite/calcite ratios and then Inductively Coupled Plasma Mass Spectrometry was used on the high magnesium calcite specimens to determine their Mg content. Corals composed of high Mg calcite are the most soluble and consequently, these corals, particularly those residing at depths deeper than the saturation depth, are most at risk to decreases in oceanic pH unless they have adapted physiological processes to counter the effects.

The mineralogy data will be used in conjunction with species distribution data (depth and geographical) and the present and projected aragonite and calcite saturation horizons in Alaska to predict the effects of ocean acidification on coral resources of the North Pacific Ocean. At the completion of this project a comprehensive risk assessment for all corals in Alaskan waters and recommendations for future research will be provided.

Future Research

Future research on ocean acidification at the Alaska Fisheries Science Center will continue to build on the existing research program focused on nearshore monitoring and physiological response of crabs, fish, and coldwater corals.

King and Tanner crab will continue to be the focus of crab studies at the Kodiak Laboratory, with expanded studies on blue king crab (*Paralithodes platypus*) which live in relatively shallow water and golden king crab which live at such extreme depths that they are likely already adapting to a corrosive environment. Experimental treatments for red king crab will add temperature as a covariate with increased CO_2 to assess the additive effects of these parameters on crab condition. New studies to expand the response variables considered for crab will include determination of hemocyte pH as a potential mechanism affecting the transport of calcium with the hemolymph and respirometry to assess metabolic condition. Bioeconomic models will continue to be developed to include additional species and mortality information from multiple life history stages.

Fish research at the Newport Laboratory will continue to assess the direct effects of oceanic pH on the growth, development, and survival of early life stages. Studies will be expanded to include Pacific cod (*Gadus macrocephalus*) and northern rock sole (*Lepidopsetta polyxystra*). Experimental treatments will include temperature and food limitation. Otolith calcification and behavior will be added as additional response variables.

Large primnoid coral loaded with brittle stars on Dickins Seamount, Gulf of Alaska.
Photo by NOAA Office of Ocean Exploration.

Coral research will continue to explore the mineralogy of Alaskan corals by analyzing additional coral taxa and broadening spatial measurements of the current taxa. Comparisons in mineralogy will be made with coral species found at different saturation states in the North Atlantic Ocean. Methods will be refined to identify variability in skeletal composition and density in coral colonies. Risk assessment models will be developed for Alaskan corals.

Additional Reading

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