NEFSC, NWFSC and AFSC Ocean Acidification FY10 Implementation Plan

February 24, 2010

An integrated, regionally based research program focused on building infrastructure, conducting experimental analyses, and developing predictive models is recommended for year 1 (or FY 10) of the National Marine Fisheries Service (NMFS) response to increasing carbon dioxide (CO_2) absorption by oceans and subsequent interactions with local and regional ocean chemistry and effects on living marine resources. The goals of this research program are to assess the sensitivities of species to ocean acidification and to develop the tools necessary to forecast the effects of altered carbon dioxide concentrations in the marine environment. Specific objectives are to:

- identify priority species based on their vulnerabilities to ocean acidification,
- develop and implement experimental and modeling protocols, and
- create inventories of the current state of knowledge that would be used in species-specific risk assessments.

The development of coordinated infrastructure and methodology across regions is necessary to increase the effectiveness of experimental, monitoring, and modeling outputs among laboratories and regions. This coordination includes an assessment of current capabilities and requirements within NMFS that will be needed to conduct sustained and collaborative research across the agency. Research will evolve from an ocean acidification response model to a potential mitigation tool for management strategies in an environment of increased ocean acidification in the future. Individual regional (NEFSC, NWFSC, and AFSC) plans (see Appendices 1-3) reflect the regional distinctiveness of the biota and ocean chemistry variability but are integrated within the general infrastructure and methodology developed in this implementation plan. It is expected that this plan will be informative to and require expertise from other NMFS regional, U.S. federal and state government, university, and private research programs, as well as follow the national NOAA implementation plan for 2011 and beyond. A summary of FY10 products and budget is provided in Tables 2-4.

Priority Species for Experimental Study

Focal species groups

- Shellfish
- Planktonic prey
- Corals
- Fish

The species-specific physiological response to ocean acidification is unknown for most marine species. Lacking basic knowledge, we recommend a broad research effort directed toward a range of taxa including shellfish, planktonic prey, corals and fish. We also recommend prioritization within this research effort, with earlier and/or larger investments directed towards taxa more likely to be affected by ocean acidification. Collaboration by utilizing specialized taxa-specific expertise at each Science Center and collectively providing understanding among Science Centers strengthens this strategy for a spectrum of taxa. We describe both a general research prioritization strategy for physiological experiments and also identify specific species for study. The specific species identified represent only those research projects that will be

initiated in FY10 – in subsequent years we expect to expand the species and ecological scope of experimental studies to address the full spectrum of NMFS research needs.

Evaluations of species response to high-CO_2 ocean conditions will focus on commercially and ecologically important species most likely to be affected by ocean acidification, especially larval and juvenile stages which are considered most vulnerable to acidification impacts. Commercially important shellfish species are our first priority because of their economic value and because these species are likely to suffer direct effects of altered ocean chemistry due to reduced calcium carbonate ($CaCO_3$) availability and the species limited capacity to regulate internal pH and tissue chemistry. The second priority is planktonic species because of their ecological importance as prey to commercially important species and the likelihood that increased CO_2 will affect their growth and physiology. It is essential to understand how acidification will affect plankton if we are to make accurate predictive models of how commercially important or vulnerable species like harvested fish or endangered marine mammals will be impacted by the indirect effects of elevated carbon dioxide in the ocean. Among the plankton, calcareous zooplankton (e.g., pteropods) are an especially high priority because they are likely especially susceptible to acidification effects. Calcareous phytoplankton (e.g., coccolithophores) are also a priority because they are the basis of most marine productivity, and effects of increased carbon dioxide on these species will ripple throughout the food web. Indeed, suppression of calcifying phytoplankton, coupled with higher carbon availability for remaining phytoplankton, is likely to open niches for proliferation of phytoplankton species that may be relatively rare under current conditions. Thus, identification of phytoplankton taxa that are likely to be "winners" under projected OA scenarios and how these taxa can be expected to modify trophic structure is a secondary effect with fundamental implications to fishery production. The third priority in FY 10 is coldwater corals, whose ecological importance includes sheltering marine organisms (e.g., rockfish). Commercially important fish species are fourth priority. Direct effects of ocean acidification on fish seem less likely because their calcareous tissues are internal. Nevertheless, some research will screen for early life history effects on species from high-value fisheries and we will begin work in FY 10 on olfactory effects in species that rely on chemical cues in the water for navigation and homing (e.g., rockfish and salmonids). We also will assess protected species and species of concern that may be at risk from acidification (e.g., pinto abalone) based on regional management priorities. Feasibility and institutional capability will influence the choice of focal species choice and experimental design.

Inventories

Each region will develop a comprehensive inventory of the potential vulnerabilities of local species to the direct effects of ocean acidification. These inventories will include a literature review of species present in the region with respect to the extent of calcification, calcium carbonate mineralogy (e.g., aragonite vs. calcite), mechanism of calcification, life history, habitat and other factors that likely reflect direct vulnerability to the effects of acidification. The three regions will work together to develop a common vulnerability-classification system. For the many commercially and ecologically important species where information about mineralogy is lacking, a determination of the mineralogy of select species will be obtained using x-ray diffraction.

Laboratory-based experiments

In FY 10, a major focus will be laboratory-based experiments conducted on focal species to measure biological responses to increases in atmospheric CO_2 (which will directly affect pH). Species-specific responses will be applied subsequently in population and ecosystem models in order to forecast population and ecosystem-level effects. Initial studies will likely focus mostly on CO_2 treatments; temperature will be added as a second variable in later experiments with the goal of emulating predicted conditions during this century. The CO_2 treatments will range from pre-industrial conditions, to current atmospheric levels to levels projected for the future (e.g. years 2020, 2050 and 2100). Initial ranges in trial experiments will typically be broad to ensure effects. Ranges in subsequent experiments will be refined according to prior trial results.

In FY10, the Northeast Center (NEFSC) will focus on a number of phytoplankton species, including representatives of both calcifying (prymnesiophytes) and non-calcifying groups, for example a prasinophyte (*Tetraselmis chui)*, a cyanobacterium (*Synechococcus* sp.), a non-calcifying prymnesiophyte (*Isochrysis* sp.), a cryptophyte (*Rhodomonas* sp.), and several diatoms (*Pseudo-nitzschia* spp., *Thalassiosira pseudonana*, and *Chaetoceros neogracile*). Further, the NEFSC will continue the development of micro- and mesocosms designed to study the effects of pH under controlled conditions particularly on early life history stages of commercially important fish and shellfish species. Surf clam research will be initiated in FY11. In FY10, the Northwest Center (NWFSC) will study oysters (in response to current recruitment crisis), geoducks, and euphausiids. Studies may also begin on calcifying communities collected on settling plates. Rockfish studies, including olfactory response, will be initiated in FY10. In FY10, the Alaska Center (AFSC) will study walleye pollock and Pacific cod at the Newport Lab, king crab (golden and red) at the Kodiak Lab, and herring embryos, euphausiids or copepods, and coral at the Auke Bay Laboratories. Future work likely will include calcifying plankton such as pteropods. In future years, all Centers anticipate studying a similar organism such as an oyster or amphipod sp. to check the consistency and quality of CO_2 treatment analyses as part of a regional collaboration among Centers.

Measured responses will include effects on survival, growth, and reproductive output as well as sublethal effects, such as changes in morphology, metabolism and behavioral capabilities. For example, hatching success and metamorphosis will be monitored in flounders, walleye pollock, crabs, euphausiids, and bivalves. Bivalve response to pathogen challenge will also be evaluated because of suspected interactions between acidification and pathogens on the West Coast. Notably such interactions were documented for lobster and pathogens under altered environmental (low oxygen) conditions on the East Coast. Calcium content and the breaking strength of shell, test, or carapace will be measured in calcifying organisms. Protein and lipid composition, energy content, and RNA/DNA ratios will be measured in some embryonic or larval fish; protein microassays for calcifying genes will be examined in crabs; and division rate, photosynthetic performance, carbon uptake nitrate uptake, and phosphate uptake will be examined in phytoplankton.

Modeling and Forecasting

Ultimately, we need to predict how ecosystems will respond to changes brought about by ocean acidification and other stressors and how alternative management actions can affect that response. Of particular interest is whether species at higher trophic levels (e.g., piscivorous fishes) that may not experience significant or lethal effects of acidification may nevertheless be affected indirectly through the food web. In each region, existing ecosystem modeling frameworks will be expanded to consider CO_2 effects. These models generally consider interactions of a species or functional group with physical environmental variables, circulation patterns, nutrient availability, primary productivity rates, diet composition and consumption rates, fecundity, density dependent recruitment relationships, fishing rates, and a host of other ecological and anthropogenic relationships. These models provide predictions of abundance for each of the species or functional groups. We will also develop models to predict the effects of ocean acidification on human communities in terms of economic and other values (i.e., "ecosystem services").

NOAA Fisheries' stock assessment modeling is well-developed, and species specific assessment models also will be used to forecast population-level effects. For example, these models provide a useful tool for forecasting direct effects on crab species. These models sometimes are spatially-explicit and include an economic component. When combined with scenarios of future ocean conditions, bioeconomic models will be used to forecast future socioeconomic effects of ocean acidification on crabs.

Ecosystem modeling at NMFS is partially coordinated through the NEMOWs (National Ecosystem Modeling Workshops), which bring together scientists from all of the NMFS science centers to work though problems of common interest. To advance the development of ecosystem models addressing ocean acidification, we will hold a workshop of invited scientists from all Centers focused on this topic in the 4th quarter of FY10. This modeling workshop may be held in conjunction with the general NMFS OA workshop described below, or may be a separate event.

Biological Monitoring for Ocean Acidification

In order to observe whether ocean acidification is causing direct and indirect biological effects in marine systems, we need to have a comprehensive field monitoring program that can detect changes in abundance, physiology or behavior of susceptible species and identify the cause of any change. Existing monitoring programs designed to evaluate specific fisheries, ecological or oceanographic processes can provide much of the information needed to detect changes from acidification. Additional monitoring that targets specific acidification questions, such as changes in the benthic community or plankton composition may be necessary. In FY10, each Center will develop a report that evaluates existing biological monitoring programs with respect to detecting ocean acidification effects. The reports will propose changes to existing monitoring programs or new monitoring efforts that address gaps in current monitoring for ocean acidification. It is expected that the NOAA document, "Marine Fisheries Habitat Assessment Improvement Plan", will be approved in the early part of FY10 and will provide guidance on conducting monitoring and research to study effects such as ocean acidification.

Coordinated infrastructure development

Facilities for exposing target species to waters with altered pH will be developed at Kodiak (AKC), Juneau (AKC), Seattle (NWC), Newport (NWC and AKC shared system), Milford (NEC) and Sandy Hook (NEC). These locations were chosen based on existing infrastructure, proximity to test organisms, and expertise of staff for performing physiological experiments.

Each Science Center will build or expand exposure systems in a coordinated fashion. In addition, carbon chemistry parameters (pCO_2, pH, dissolved inorganic carbon, alkalinity) will be measured using equipment recommended by the OA research community's best practices manual. The systems will be designed to allow for replication of exposures in a 3x3 factorial design at a minimum. Personnel will travel between facilities to exchange expertise and experience and to ensure systems' consistency and harmonize the design specifications of the individual systems. Such exchanges are a critical step to insure comparable data are produced by all systems.

Uniformity trials will be designed to evaluate the ability of each system to produce comparable exposure conditions for specified lengths of time and to reliably reproduce pulse exposure conditions. To further establish that the individual systems are comparable, quality assurance and quality control (QA/QC) tests using a common species (e.g., oysters, sea urchins or amphipods) will be conducted once the systems are stable. These initial QA/QC assessments will provide the foundation for developing a QA/QC program for exposures conducted by NOAA Fisheries, and will facilitate coordination with collaborators and other OA exposure facilities outside of NOAA Fisheries.

Methods evaluation

Exposures with test species selected by each Center (Table 1) will be carried out at CO_2 concentrations from IPCC scenarios. Exposures also will consider local coastal conditions and variability. Large pH changes on relatively short temporal scales can occur in coastal areas. Thus an important design feature will be the ability to determine the effect of pulsed changes in pH on organism fitness and survival. Evaluation experiments will be conducted to determine the ability of the system to reproduce a pulse design experiment. The length of exposure to low pH also will be varied to assess the range of possible experimental design conditions that can be reproduced in future experiments. Recent research shows that interactions between increased temperature and decreased pH can be additive or multiplicative. Thus, screening experiments will be conducted to evaluate the exposure systems to reliably reproduce experimental design that co-varies both pH and temperature.

Recommendations for oceanographic monitoring and modeling

Oceanographic monitoring and forecasting is needed from oceanographers that will provide fisheries scientists the tools needed to evaluate fisheries effects from ocean acidification. This effort will require an understanding of current and future coastal ocean carbon conditions to forecast ocean acidification effects on fisheries. The NMFS Science Centers will not be focusing research in FY10 (or beyond) on

chemical and physical oceanography, although some chemical and physical parameters are measured as part of NMFS biological monitoring programs. We are including discussion of this issue here to highlight the connection between our work and the other research programs in NOAA. Coastal areas within the EEZ account for most commercial fisheries landings in the United States. Geo-referenced measurements of current coastal conditions by moorings and oceanographic cruises are necessary to relate ocean carbon conditions to spatial distributions of fish, shellfish, seals whales and their prey. These ocean measurements combined with results of species-specific physiological experiments provide a means to assess current risks to species managed by NOAA. Spatially explicit forecasts of future coastal conditions from oceanographic models are needed to forecast future abundances of target species and functional groups. These forecasts should be based on climate scenarios (e.g. IPCC) appropriate for regional and finer scales. The forecasts of regional ocean conditions will be incorporated into spatially explicit population and ecosystem models in order to forecast effects on abundances of fish, shellfish, seals, sea lions and whales. Development of harmful algae blooms can also be predicted.

Communication towards internal and external integration

We plan periodic workshops and monthly phone calls to ensure internal integration within NOAA Fisheries. To ensure effective coordination of research activities among all three Centers we will hold monthly teleconference meetings to review progress, compare experiences and make any mid-course adjustments if needed. Past experience suggests that holding short monthly calls can be very useful for coordinating research. In particular, we will use these phone calls to harmonize exposure systems and experimental designs. In the 4th quarter of FY 10 we will hold a NOAA Fisheries workshop to evaluate and assess the year's activities and to develop the research implementation plan for FY 11. The workshop will be held at one of the facilities with an exposure system to allow for any hands on joint testing of the exposure system.

We recognize that specialized expertise may be needed to complete the research plans described in the attached regional plans. During FY 10, we will establish collaborative relationships with external researchers as needed and work collaboratively in establishing such relationships. We anticipate that through coordination we can leverage collaborations by, for example, jointly working with academic scientists and sharing post doctoral fellows whose skills will benefit all parties.

Outreach and Education

Outreach and education are not the highest priority for FY10, but we will develop materials for communicating the biological effects of acidification and NMFS research to classrooms and community events. These materials will be shared among the NMFS Science Centers.

Table 1. Species/Center matrix for initial ocean acidification research. An asterisk (*) indicates candidate species studies planned for FY10.

Biological Group	**NEFSC**	**NWFSC**	**AFSC**
Phytoplankton	*Representatives Of major Classes		
Zooplankton		Copepods *Euphausiids	*Copepods *Euphausiids
Crustacean	Atlantic Lobster		*Golden king crabRed king crab
Bivalves	Surf clam Sea scallop	*Oysters *Geoduck	
Gastropods		Pinto Abalone	
Fish	Black sea bass *Summer flounder *Shortnose sturgeon Winter flounder	*Rockfish *sp* *P. herring	*Pacific cod *Walleye pollock *Pacific herring
Coral			*cold water species

Table 2. NWFSC deliverables and budget for FY 10 ocean acidification research.

Theme	Deliverable Product	Description
1. Ocean acidification monitoring network	OA biological monitoring report	Report on current and proposed biological monitoring to detect effects of ocean acidification
2. Ecosystem impacts of ocean acidification	Shared-use facility for OA experiments	A complete experimental system providing water with controlled pH, pCO2, saturation state, temperature and dissolved oxygen for multiple simultaneous factorial experiments on diverse organisms.
	Experiments on zooplankton	We will conduct experiments on the effect of CO_2 and temperature on early life-stage development of *Euphausia pacifica* (Pacific krill) and prepare results for publication. Will initiate experiments on copepods.
	Experiments on mollusks	We will conduct experiments on the effect of CO_2 and temperature on early life-stage development of Pacific oysters, Olympia oysters, geoducks, and pinto abalone (a NOAA "species of concern") and prepare results for publication.
	Olfaction Experiments on Rockfish	We will conduct experiments on the role of olfaction in rockfish behavior and prepare results for publication. This is an initial step for experiments in FY11 on the impact of acidification on the olfaction of rockfish.
	Development experiments on Rockfish	We will conduct experiments on the effect of CO_2 and temperature on early development of several species of rockfish and prepare results for publication.
	Settlement plate experiments	We will place settlement plates in NW habitats to collect benthic organisms (largely calcareous). In FY11, these plates will be retrieved for experiments on OA-induced changes in community structure.
3. Biogeochemical and ecosystem models	Ecosystem models of OA effects in Puget Sound and the California Current	We will build off of three existing modeling frameworks (Ecopath, Atlantis and SLAM) to explore how expected changes from acidification will affect NW food webs, including commercially and ecologically important species. We will distribute both model source code and analysis papers from the projects.
	OA ecosystem modelers workshop	In the 4th quarter of FY10, the NWFSC will host a workshop of NMFS ecosystem modelers (and experimentalists) involved in predicting the indirect effects of OA on ecosystems. We will produce a summary report on the workshop.
4. Human dimensions	Preliminary Plans	Although we will do planning for research on the human dimensions of OA in FY10, significant work on the topic will not begin until FY11.
5. Synthesis of data and information products	Database of species vulnerability estimates	We will create a database that is publically available on the web of the estimated vulnerabilities of NW coast species to the direct effects of ocean acidification.
6. Public outreach	Print and display materials	We will produce educational materials (posters, handouts, 3-d displays and interactive components) that can be used by NWFSC staff to describe the science of ocean acidification to school groups, public fairs, stakeholders groups and others.

Table 3. NEFSC deliverables and budget for FY 10 ocean acidification research.

Theme	Deliverable Product	Description
1. Ocean acidification monitoring network	OA biological monitoring report	Report evaluating past, current and proposed biological monitoring to detect effects of ocean acidification
2. Ecosystem impacts of ocean acidification	Experimental facility for OA experiments	A prototype experimental system providing seawater with controlled pH, pCO2, saturation state and temperature for experiments on diverse organisms will be constructed.
	Experiments on phytoplankton	We will conduct experiments on the effect of CO_2 and temperature on phytoplankton and prepare results for publication.
	Experiments on mollusks	System development will take place to conduct pH experiments on the effect of CO_2 on life-stage development of selected shellfish in culture and prepare a summary report
	Development of experiments on finfish	We will conduct experiments on the effect of CO_2 and temperature on early development of finfishes (winter flounder, summer flounder and/or shortnose sturgeion) and prepare results for publication.
3. Biogeochemical and ecosystem models	Ecosystem models of OA effects on the northeast U.S. continental shelf	We will build off of existing modeling frameworks (EMAX, Atlantis or NEMURO) to explore how expected changes from acidification will affect NE food webs, including commercially and ecologically important resource species.
	OA workshop	In the 4^{th} quarter of FY10, the NWFSC will host a workshop of NMFS ecosystem modelers and experimentalists involved in predicting the effects of OA on ecosystems. NEFSC staff will participate and y a summary report on the workshop will be produced.
4. Human dimensions	Preliminary plans	We will seek partners to conduct work on this topic in FY11
5. Synthesis of data and information products	Database of species vulnerability estimates	We will create a public access web database on the estimated vulnerabilities of NE coast species to the direct effects of ocean acidification.
6. Public outreach	website	We will construct a website to describe the science of ocean acidification and the research effort in the NEFSC.

Table 4. AFSC deliverables and budget for FY 10 ocean acidification research.

Theme	Deliverable Product	Description
1. Ocean acidification monitoring network	OA biological monitoring report	Report on current and proposed biological monitoring to detect effects of ocean acidification
2. Ecosystem impacts of ocean acidification	Experiments on king crab	We will conduct experiments on the effect of CO_2 and temperature on early life-stage development of red king crab and adult golden king crab and prepare results for publication.
	Experiments on zooplankton	We will conduct experiments on the effect of CO_2 and temperature on copepods, euphausiids and pteropods and prepare the results for publication.
	Experiments on cod and pollock	We will conduct experiments on the effect of CO_2 and temperature on early life stage development of Pacific cod and walleye pollock and prepare results for publication.
	Mineralogy of Alaskan corals	We will determine the calcium carbonate mineralogy of several Alaskan corals and prepare results for publication.
	Calcium carbonate measurements	Regional Ocean Acidification Center: Water and tissue chemistry analysis for all AFSC laboratories.
3. Biogeochemical and ecosystem models	OA ecosystem modelers workshop	In the 4th quarter of FY10, AFSC scientists will participate in a workshop of NMFS ecosystem modelers involved in predicting the indirect effects of OA on ecosystems.
4. Human dimensions	Preliminary Plans	Preliminary work on socioeconomic forecasting using bioeconomic models for Alaskan king crab.
5. Synthesis of data and information products	Database of species vulnerability estimates	We will create a database that is publically available on the web of the estimated vulnerabilities of Alaskan marine species to the direct effects of ocean acidification.
	OA researchers workshop	In the 4th quarter of FY10, AFSC scientists will participate in a workshop of OA researchers to evaluate and assess FY 2010 activities and develop a research implementation plan for FY 2011.
6. Public outreach	Print and display materials	We will produce educational materials (posters, handouts) that can be used by AFSC staff to describe the science of ocean acidification to school groups, public fairs, stakeholders groups and others.