

Ocean Acidification Effects on Shellfish Workshop: Findings and Recommendations

July 7–8, 2010
Workshop Proceedings



The workshop to investigate ocean acidification impacts on West Coast shellfish. Report #624. Southern California Coastal Water Research Project, Costa Mesa, CA.

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Ocean Acidification Impacts on Shellfish Workshop: Findings and Recommendations

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Executive Summary

Overview

For at least the past six years, the West Coast Shellfish industry has observed larval mortality in hatcheries and poor larval recruitment success for some species in the wild, especially during periods of high upwelling. One hypothesis is that these dramatic declines in productivity may be related to increasing ocean acidity and the corresponding decrease in the saturation state of carbonate minerals which shellfish use to create their shells. The West Coast shellfish industry sought help from scientists to explore the causes of the shellfish losses, what role ocean acidification and other factors might be playing, and how to adapt to sustain West Coast shellfish resources. Addressing questions about ocean acidification requires integration of ocean observing measurements, laboratory exposure studies, shellfish recruitment and production data, and field studies of organism performance in relation to ocean conditions. However, these data are collected by different sectors that, to date, have had limited interaction. To stimulate collaborations among these sectors, and at the request of the shellfish farming and wild harvest communities, the Integrated Ocean Observing Systems, California Sea Grant, USC Sea Grant, Oregon Sea Grant, Washington Sea Grant, and California Ocean Science Trust convened a workshop. Fifty-one participants were invited, including state and federal managers, industry representatives, and leading academic researchers and oceanographers with expertise in larval recruitment, laboratory studies, and ocean chemistry.

The workshop consisted of 8 plenary talks and three breakout sessions. The plenary presentations provided information summarizing OA research as related to impacts on the west coast shellfish industry including: monitoring programs, laboratory exposure studies, and industry observations. In the first breakout session, participants separated into three groups to outline existing and ongoing data sets, as well as what is needed to answer questions on OA impacts on the West Coast in three areas: oceanographic data, recruitment data, and exposure study data. In the second breakout session participants discussed how existing data sets can be better integrated to clarify impacts of OA and discuss what is needed for future studies both in the near-shore and open-ocean. In the third breakout session, three working groups discussed how to integrate existing research programs and develop future programs to better address impacts of OA on the West Coast. The workshop concluded with a summary of findings and recommendations for next steps.

Significant Workshop Findings

Workshop participants generally agreed that existing datasets cannot be used to explain impacts of OA on shellfish productivity. These datasets are physically and spatially dissociated and standardized protocols for data collection have not been applied. Consequently, interpreting patterns and relationships with existing data sets is difficult. In order to resolve these problems, there is a need to:

- Develop standardized data collection methodology.
- Coordinate chemical data collection at the best biological monitoring sites, leveraging long-term data sets and employing standardized methods.
- Supplement correlative data with an understanding of biological processes.
- Develop predictive models at smaller scales.

Different communities must work collaboratively to address concerns of OA impacts on the West Coast. The momentum generated at this workshop should be maintained.

Recommendations

West Coast Ocean Acidification–Shellfish Workshop participants reviewed existing research, identified information gaps, and proposed modifications and potential solutions to improve the state of knowledge of ocean acidification on the West Coast and to address problems faced by shellfish hatcheries, growers and harvesters. Recommendations included:

- 1) A West Coast Ocean Acidification Research Coordination Working Group should be established to provide recommendations on best practices and standardized research methods to achieve a coordinated network of ocean observations and experimental studies, in order to observe, understand and quantify the evolving threats posed by ocean acidification along the West Coast of the United States.
- 2) A West Coast Ocean Acidification Data Exchange, integrated with IOOS, and consisting of a single website that serves as an entry portal to data and information, should be established to provide easy access to available data sets and information regarding ocean acidification processes affecting West Coast fish and shellfish.
- 3) The proposed NOAA West Coast Ocean Acidification Observing Network should be enhanced and expanded to include sites on the West Coast where in-field biological response studies are conducted.

All workshop materials, including video of presentations and slides are posted online at: www.sccwrp.org/Meetings/Workshops/OceanAcidificationWorkshop.aspx.

Introduction

Shellfish Productivity Declines

West Coast shellfish (wild-harvest and aquaculture) provide significant socioeconomic and recreational benefits to coastal communities in Washington, Oregon and California. Equally important, problems with larval mortality and shellfish recruitment failure portend potentially significant changes in marine ecosystems. Shellfish industry representatives have been observing shellfish recruitment failures and severe larval mortalities within West Coast shellfish hatcheries, and poor larval recruitment has been documented for some shellfish in wild ecosystems as well, correlated with upwelling events. The problems challenging West Coast growers and harvesters may be associated with ocean acidification, *Vibrio tubiashii* infections, low-oxygen “dead zones,” or a combination of factors. More research is clearly needed to identify the relative impacts of each of these factors and seek possible solutions.

Potential Effects of Ocean Acidification on Shellfish

Since the beginning of the industrial revolution about one-third of anthropogenic carbon dioxide (CO₂) has been absorbed by the oceans. When CO₂ dissolves in seawater, it lowers seawater pH and reduces the concentration of carbonate ions, a process termed ocean acidification (OA). Oceanographic monitoring programs have measured significant changes in ocean chemistry related to OA occurring at a rate much greater than predicted and continuing to accelerate. When waters are under-saturated with respect to carbonates (high-magnesium calcite, aragonite and calcite) they become corrosive to organisms that produce calcium carbonate exoskeletons such as shellfish, corals, and some species of plankton. Consequently, certain shellfish, such as Pacific oyster, may represent the “canary in the coal mine” for longer term impacts of OA (e.g., impairment to ecosystem structure and function and loss of beneficial uses, such as shellfish resources).

The West Coast is vulnerable to the enhanced ocean acidification associated with seasonal upwelling, potentially causing serious impacts to ecosystems and some recreationally and commercially important shellfish. Deep ocean waters are naturally under-saturated with respect to calcium carbonate and thus corrosive to shelled organisms; however, the depth at which waters become under-saturated has been shoaling with continued inputs of anthropogenic CO₂. These corrosive waters are expanding toward the ocean surface at the rate of 1 to 2 meters/year in the North Pacific. Studies have demonstrated the effects of ocean acidification on some species including reduced tolerance to temperature increases, impaired reproduction, inefficient cell function, impaired growth, larval shell dissolution, disease susceptibility, and higher mortality rates at early life stages. Generally, there is a higher “cost of living” for many organisms subjected to a high CO₂ marine environment. Some of the most vulnerable species may be tiny, shell-forming animals at the base of the food web, which provide food for many larger species. However, some shellfish commonly grown or harvested for human consumption, including oysters and sea urchins, are also at risk. Scientists are now conducting laboratory studies to “stress test” marine larvae (including oysters, abalone, sea urchins and other shellfish) at different CO₂ levels. Options for an organism faced with environmental stress, such as ocean acidification, include migration, acclimatization (tolerance), adaptation (which may take generations if possible at all), and extinction.

Response to a Growing Problem

The industry's concern about impacts of OA on shellfish production launched an initiative to expand cooperative research on OA among scientists, shellfish growers, and fishermen, seeking ways to forecast future problems and facilitate adaptive solutions. To determine how monitoring and research can be better coordinated, the Integrated Ocean Observing Systems, California Sea Grant, USC Sea Grant, Oregon Sea Grant, Washington Sea Grant, and California Ocean Science Trust convened a workshop that included 51 invited participants from the three West Coast states and beyond. Participants included state and federal managers, industry representatives, and leading academic researchers and oceanographers with expertise in larval recruitment, laboratory studies, and ocean chemistry.

The workshop was held at the Southern California Coastal Water Research Project (SCCWRP) offices in Costa Mesa, California on July 7 – 8, 2010. There were 51 invited participants, with balanced participation between industry, government, and academia. The goal of the workshop was to initiate collaboration among disparate research groups working to understand the impacts of ocean acidification on the shellfish industry. These proceedings include summaries of the breakout group discussions, including significant findings and recommendations for next steps.

Workshop Objectives

The primary objective of this workshop was to bring together stakeholders from the US West Coast who are working to understand and address ocean acidification. The extent of ocean acidification effects is unknown at present, though it could potentially threaten valuable west coast fisheries for oysters, mussels, clams, sea urchins and other shellfish. Along the Pacific coast, evidence of acidified seawater was found in 2007 during an oceanic survey conducted by the National Oceanic and Atmospheric Administration (NOAA). Hatcheries in Oregon and Washington have separately reported recruitment failure that may be linked to changing ocean chemistry. Climate change and ocean acidification were identified as serious threats in the West Coast Governor's Agreement (among California, Oregon, and Washington), and as high priority research need in the "West Coast Regional Marine Research and Information Needs" report prepared by Oregon Sea Grant, in partnership with other west coast Sea Grant agencies and the South Slough National Estuarine Research Reserve. To date, such studies have largely been conducted independently and would benefit from increased interstate and intrastate coordination.

In order to initiate collaboration among disparate research groups working to understand the impacts of ocean acidification, the Integrated Ocean Observing Systems, California Sea Grant, USC Sea Grant, Oregon Sea Grant, Washington Sea Grant, and California Ocean Science Trust sponsored a workshop involving state and federal managers, and industry representatives, and leading academic researchers and oceanographers. The objectives of this workshop were to:

- Encourage cooperation between scientists, shellfish growers, fishermen, and environmental managers.
- Review and determine how to better integrate currently available shellfish recruitment studies (mostly collected by the shellfish industry), ocean observing system measurements (mostly collected by academia and government), and laboratory exposure studies (mostly collected by academia).
- Identify what future studies are needed.
- Plan for future cross-disciplinary interaction.

The organizing committee intended this workshop to be the first in a series aimed to integrate near-shore and off-shore monitoring programs and coordinate field and laboratory research to improve understanding of the biological sensitivity and response to observed changes in ocean chemistry.

Workshop Structure

The workshop was held at the Southern California Coastal Water Research Project (SCCWRP) offices in Costa Mesa, California on July 7 – 8, 2010. There were 51 invited participants, balanced between industry, government, and academia (Appendix D). Participants included leading researchers and oceanographers with expertise in larval recruitment, laboratory studies, and ocean chemistry. State and federal resource managers, a representative from the Integrated Ocean Observing System and the four West Coast Sea Grant offices also attended, along with shellfish growers and wild harvest shellfish fishery representatives.

The workshop consisted of eight plenary talks and three breakout sessions. The plenary talks consisted of a series of presentations summarizing OA research as related to impacts on the west coast shellfish industry including: monitoring programs, laboratory exposure studies, and industry observations (Appendix B). Plenary presentations set the stage for the workshop by providing the industry's perspective on impacts of OA, the status of current understanding of OA based on oceanographic measurements from ships and moorings, inter-annual patterns in shellfish recruitment, laboratory and field studies of vulnerability of different species to changes in seawater chemistry, and how West Coast efforts to understand OA relate to national efforts.

In the first breakout session, participants outlined existing, on-going, and upcoming data sets related to ocean acidification impacts on the West Coast. The three breakout groups each discussed a particular type of data: oceanographic monitoring data, recruitment data, and exposure study data. They discussed what data was readily available and how this data could be made accessible on the web. In the second breakout session participants discussed how existing data sets can be integrated to clarify impacts of OA and what is needed for future studies to fill in the existing data gaps. Four small groups were formed to discuss hydrographic and biological data for each habitat type: near-shore and open-ocean (two groups for each habitat). In the third breakout session, three working groups discussed how to integrate existing research programs and develop future programs to better address impacts of OA on the West Coast. The first group focused on how monitoring/research programs can be altered to enhance cross-discipline analyses. The second group focused on how cross-discipline data systems can be synchronized. The third group focused on the approaches that should be used to enhance cross-discipline interaction. All participants reconvened at the conclusion of each of the breakout sessions to summarize the discussion and conclusions from each group.

The workshop ended with a plenary discussion to identify the group's primary findings and recommendations. The discussion included major research needs to fill in data gaps, protocol standardization, how cross-discipline interactions can be promoted, and what forums can be used to maintain these interactions into the future. A subset of the group volunteered to serve as a steering committee to facilitate development of a West Coast Coordination/Working Group to enhance future research and outreach.

Summary of Breakout Group Discussions

The workshop consisted of three breakout sessions during which participants discussed existing data and how these data can be integrated, identified data gaps, and developed recommendations for cross-disciplinary interaction to fill these data gaps and improve data accessibility. What follows is a summary of those discussions.

Existing Data

A large number of historical and ongoing oceanographic, biological, and exposure data sets exist for the West Coast, although length, sampling frequency, data quality, and available metadata vary among datasets. Some of these data are already available on-line and can easily be linked to a central repository, while others would need to be digitized. This section highlights the discussion of existing data sets and identifies data needs moving forward.

Oceanographic Data

Precise measurements of both off-shore and near-shore changes in ocean chemistry and the complex interactions between the physics and the chemistry will be vital to development of predictive models. As noted above, there are a large number of oceanographic data sets available; however, the group identified at least three issues impeding comparison of these data sets and using this data for predictive models:

- 1) Methods and sensors are not standardized.
- 2) Sampling locations, times, and depths are decoupled from locations of biological significance (e.g., shellfish harvesting grounds and hatcheries).
- 3) Carbon parameters are not available at all locations so precise calculation of ocean acidification is not widely available.

Ocean acidification predictive models will be difficult to achieve in some localities, but more tractable in others where somewhat predictable patterns of ocean circulation occur. In order to forecast when incursions of lower pH water will occur, as well as whether they are likely to persist, enhanced understanding is needed of near-shore ocean circulation, phytoplankton growth and CO₂ uptake, and their consequences for water column geochemistry. This understanding needs to be built into models on the appropriate time and space scales. Therefore, looking forward, the group had several recommendations to improve existing monitoring programs/platforms to improve understanding of ocean acidification:

- 1) Deployment of relevant instruments on moorings, gliders, and other measurement platforms in the vicinity of source waters used by hatcheries, farms, and wild harvest locations. In some cases, appropriately located IOOS sites could be expanded to include carbon variables. Measurements should be made continuously and telemetered in real time, resolving at least diel variations of key variables.
- 2) Development of standard protocols that recommend specific instruments and/or procedures for data collection, analysis and archiving.

- 3) Development of an integrated information management system that delivers real-time data, derived variables, and metadata in an accessible, intuitive manner. Biological, not merely physical/chemical data need to be served. The data from disparate sites should be presented in a coherent, integrated manner as a network of linked observations with appropriate tools for visualizing data and comparing regions. Pre-existing data should also be accessible in the same manner. There must be an open access data policy.
- 4) Detailed ocean surveys that characterize wind, near-shore circulation, and water column chemistry on small spatial scales, in the vicinity of hatcheries and wild harvest locations.

Recruitment Data

“Recruitment data sets” should include more than just recruitment; these data sets should include oyster grow out, urchin growth and roe quality, etc. Historical data sets are important for determining baseline conditions, but the group felt that more emphasis should be placed on additional contemporary biological studies. There are existing data sets that likely meet research and management needs in terms of length, frequency, and quality (useful for looking at relationships between recruitment/ other biological criteria and oceanographic/ exposure data) – including CalCOFI and PISCO data, both of which are accessible online. Some studies and historical data sets may be less useful and should be evaluated before use in modeling/ analysis. Given the scarcity of quality biological data, the breakout group had several recommendations looking forward:

- 1) Review existing data: inventory available “historical” data sets, assess data quality, identify data gaps, and formulate how studies can be improved to address data gaps.
- 2) Prioritize collection of data for long-term, high-quality data sets; add relevant measurements where needed to fill data gaps.
- 3) For contemporary studies, consider range of species that are sensitive, keystone, and/or economically important. Specifically include studies on Pacific oyster; it is a sensitive, commercially valuable species, some long-term recruitment data sets are available.
- 4) Focus new studies on collection of information that supports shellfish growers, sustainable management of fisheries for “wild” invertebrates and fish, predictive modeling, and ecosystem function. Studies of adaptation should be included (e.g., studies of resilience and geonomic variability).

Exposure Study Data

Exposure studies are currently ongoing with the goal of understanding the effect of ocean acidification (e.g., increased pCO₂ and DIC, and decreased pH) on a number of different marine species. Breakout group participants were aware of studies focused on native oysters, littlenecks, abalone, urchins, hard clams, geoducks, crustaceous and calcareous plankton, and squid. However, much of this work is in the incipient stages. Thus, the group viewed the workshop as a timely opportunity to identify guidelines for the development of quality data sets that could be shared among researchers and correlated to appropriate oceanographic and recruitment data. These guidelines include:

- 1) Establish standard operating protocols for chemical analyses and methodologies. For manipulative experiments, the “Guide to Best Practices in Ocean Acidification Research and Data Reporting” should be used (available online <http://www.epoca-project.eu/>).
- 2) To better provide for comparison of results from exposure experiments, coordinate experimental methodologies, such as using a standard source of seawater and biological organisms (e.g., bred populations rather than those collected from the wild).
- 3) Develop improved QA/QC protocols, data analysis, and reporting.

Given these guidelines and the nature of exposure study work, the breakout group had several recommendations looking forward:

- 1) Development of West Coast Chemistry Training and Analysis Facility that would ensure consistent measurements of a known quality among researchers.
- 2) Development of metrics for evaluating the quality of exposure studies.
- 3) Data and methodology sharing including a list serve and website for exchange of ideas and questions.

Data Integration

As noted in the previous section, the primary obstruction to using disparate data sets to assess impacts of ocean acidification on the West Coast is that different programs/ studies use different sampling protocols of varying accuracy and precision. Additionally, sites of high quality physiochemical monitoring are not co-located with sites of high quality biological monitoring, and some industry data (including hatching success, settlement, and grow-out data) are proprietary and may not be available for data sharing. Furthermore, there is currently no system in place for data sharing even if it were collected systematically. This section details the discussion surrounding integration of existing diverse data sets and the needs for a more fully integrated ocean acidification monitoring network.

Integrated Ocean Observing Systems

A successful and fully integrated observing system will include sustained observations that use standardized methods and instrumentation, where the quality of the measurements is known and documented, and data and metadata are made broadly available to the community. In terms of adding biological measurements, both research and funding are needed to define what metrics beyond species abundance would be useful indicators of biological response to, or indicative of, impacts of ocean acidification (e.g., daily increment size, stable isotopic composition of shells, which moored sensors will provide useful information). Linkages between hatchery observations and laboratory follow-up studies would be useful to help resolve these questions and are discussed in the next section. For carbon observations, the community would benefit both from further discussion on the tradeoffs between insights gained through better quality measurements (i.e., higher accuracy and precision) versus a greater abundance of measurements (i.e., with cheaper and easier-to-operate carbon sensors or use of algorithms to convert hydrographic data to saturation state). Both options require further research in terms of either instrument development or empirical studies. The suggestion of a large-scale request for government funding was made that

could be directed at this issue to support increased demand for improved carbon sensors by this community, as well as the broader water quality monitoring community (e.g., EPA, state agencies, etc., that are under increasing pressure to improve their pH measurements).

Linking Oceanographic and Near-Shore Biological Data

In order to appropriately link oceanographic monitoring data and near-shore biological data there must be a partnership between hatcheries and researchers on the physiological and biochemical response of organisms to ocean conditions associated with upwelling events. In particular, the group emphasized the critical need for better analysis of the observed correlation between upwelling events and increased mortality of oyster larvae to determine the causal mechanisms. In addition to changes in carbon chemistry (pH, pCO₂, carbonate saturation states), high concentrations of the bacterial pathogen *Vibrio tubaiashii*, lower oxygen concentrations, and higher concentrations of various other chemical species are associated with upwelled water masses and have not been ruled out as contributors to the observed hatchery failures. A corollary is that whatever is causing the declines in the hatchery populations is also affecting organisms in the wild by imposing physiological stress during exposure to the same upwelled water; however, these effects are more difficult to untangle in natural environments. In this sense, the hatcheries represent large-scale tank experiments that provide an opportunity for biological studies on the physiological and biochemical response of susceptible organisms (e.g., through assays of carbonic anhydrase activity or by seeking to identify markers of stress that could subsequently be applied to wild populations of organisms). Similarly, settlement plates of known genetic stock and uniform developmental stage could be outplanted in the field (e.g., on moorings) to give some standardization to studies of impacts of water in the coastal oceans on organisms *in situ*. This would also be useful for identifying more resilient strains of commercial organisms. Additionally, archived samples in institutional and private collections can be used in conjunction with historical oceanographic data to understand past changes in shell morphology and calcification in relation to ocean variability. Finally, the composition of the upwelled water needs to be fully characterized to determine what factors correlated with high CO₂ and lower pH may also contribute to larval shellfish mortality.

With respect to future needs for open-ocean hydrographic and biological data, the overarching sentiment was that biological and hydrographic (i.e., chemical and physical) data collection must be linked to provide synoptic observations of oceanic conditions and biological response at appropriate temporal and spatial scales. To be able to understand linkages between conditions near-shore and off-shore oceanographic conditions, two things are needed:

- 1) Implementation of an observing system spanning the environmental gradient between near-shore and off-shore environments and including sensors, moorings, gliders, and full water-column measurements.
- 2) Improved understanding of water transport, exchange, and modification processes in the coastal ocean between off-shore and near-shore observational platforms.

Furthermore, locations of oceanographic measurements and recruitment studies must be co-located. Potential sites/regions of interest:

- Puget Sound
- New observations at La Push (tribal participation)
- Columbia, Cape Elizabeth, Willapa Bay
- presently few observations near Tillamook (Whiskey Creek)
- South Slough (Coos Bay)
- Humboldt Bay – observations and oysters (Greg Dale)
- Bodega – BML and Hog Island
- South SF Bay Restoration – Olympia Oyster
- Morro Bay – Two companies there; Drew Alden (Morro Bay Oyster Company), George (new)
- Santa Barbara (Bernard Friedman, offshore)
- Channel Islands
- Carlsbad

To improve linkages between biological data and oceanographic data the group noted several needs:

- 1) Outfit important growing areas/hatcheries with instruments/sensors to support compatibility between hatcheries and off-shore monitoring. Depending upon resources, it may be important to prioritize and select sites for instrumentation that are (1) of high, critical value to the shellfish industry / community (e.g., Taylor and Whiskey Creek) or (2) are of value due to their long-term recruitment datasets.
- 2) Link recruitment and grow-out data on a gradient from high to low success and link to oceanographic data to examine relationship between ocean chemistry and ‘hot spots’ or ‘cold spots’ for growth and physiological success. Exposure studies could also be linked to this activity.
- 3) Laboratory exposure studies to understand the role of water quality in relation to mechanisms of biomineralization, vulnerability of life history stages, and critical developmental phases.
- 4) Studies of natural recruitment areas. Hatchery operators operate with tendencies that may obscure the relationship between water chemistry and recruitment. Studies of natural recruitment areas, particularly those with long histories, could help identify natural variation and OA impacts, where sensors are coupled to recruitment observations (e.g., Willapa Bay).

Formation of a West Coast Ocean Acidification Observing Network

The group proposed the formation of a West Coast Ocean Acidification Observing Network which should include enhanced and expanded moorings which include sites where in-field biological response studies are conducted. The group noted that the ocean monitoring system most relevant to shellfish growers and wild harvest fishermen would provide two essential features: a) nowcasts, reporting in real time the current status of ocean waters with respect to pCO₂, pH, aragonite saturation state, and other key variables; and b) forecasts of the onset of upwelling events and other incursions of offshore waters of altered geochemistry, as well as the anticipated duration and extent of such events. At present, the first goal is within reach while the second will require expanded measurement infrastructure and model development. In addition, forecasts will be more attainable in some specific coastal locations than in others.

The group agreed that with focused efforts, the measurement and display of real-time data so that hatcheries/growers/wild harvest fishermen can make practical decisions is presently achievable with minor modifications to existing programs:

- 1) Upgrade existing moorings, gliders, and other platforms in the vicinity of source waters used by hatcheries, farms, and wild harvest locations with standardized, relevant instruments.
- 2) Development of a best practices guide that recommends specific instruments and procedures for instrument deployment, calibration, and validation. This guide should be accompanied by rigorous, intensive training courses in a centralized laboratory location.
- 3) Develop proxies for pH from more readily measured hydrographic variables.
- 4) Development of an integrated information management system that delivers real-time data, derived variables, and metadata in an accessible, intuitive manner.
- 5) Expand monitoring programs into estuaries where hatcheries are collecting data.

In terms of forecasting, development of models that predict ocean acidification so as to estimate its impact in advance of corrosive waters coming ashore, reaching hatcheries, impacting wild stocks, etc., are necessary. Such models would need to take into account near-shore hydrodynamics where bottom friction and coastal topography may play an important role. Nested models could be developed with appropriate boundary conditions that influence the near-shore circulation, with carbonate chemistry and key elements of planktonic food webs incorporated. Data Management Strategy: A West Coast Ocean Acidification Data Exchange

A West Coast Ocean Acidification Data Exchange, integrated with IOOS, and consisting of a single website that serves as an entry portal to data and information, should be established to provide easy access to available data sets and information regarding ocean acidification processes affecting West Coast fish and shellfish. Proper data management and dissemination is vital to making efficient use of all available and future data. A repository (website and servers) that provides data management services (searchable catalog(s), data discovery, delivery of data and metadata in standardized formats, archival data) for chemical, physical, and biological data needs must be created. The repository should provide visualization tools for the data. The minimal content of metadata needed to describe these datasets and support search capabilities should be agreed upon by the respective communities. For ocean-chemical measurements the CDIAC system (Mercury)

provides community agreed upon metadata standards. For ocean-biological measurements, the OA community needs to decide upon a process that will lead to a metadata content standard – presumably through community workshops (with possible assistance from the future OA Program Office). Ecological Metadata Language (EML) should be considered as a potential structure to organize this content; EML tools could potentially be leveraged to make the creation of metadata simpler for data providers. Assuming the consent of the parties, measurements of water quality from current and upcoming installations of monitoring instrumentation at hatcheries and field sites (e.g., results of “Senator Maria Cantwell” funding) should be integrated into the repository.

Future Ocean Acidification Research Coordination

As noted above, existing monitoring and research programs can potentially be modified and data systems can be synchronized to increase cross-disciplinary interactions, which will aid our understanding of the impacts of ocean acidification on the West Coast Shellfish Industry. Workshop participants were keenly interested in collaborating to bring the expertise of multiple disciplines to bear on this pressing problem.

A West Coast Ocean Acidification Research Coordination Working Group was proposed to provide recommendations on best practices and standardized research methods to achieve a coordinated network of ocean observations and experimental studies, in order to observe, understand and quantify the evolving threats posed by ocean acidification along the West Coast of the United States. Workshop participants suggested that this group should have a broad scope of participation, including fishermen, growers and scientists. This group would have the following goal and objectives:

Goal of Group

To facilitate development of a coordinated research and monitoring system and dissemination of information to academic, state and federal/national agencies and other stakeholders

Objectives of Group

Coordinate/facilitate:

- Collaborative efforts to develop a system including:
 - Standardize research protocol to integrate biological information with IOOS measurements.
 - Identify potential funding sources.
- Processes, including standardized data management system(s) for community to use information.
- Communication within community.
- Information and Outreach to agencies and the public.

Potential activities could include:

- Creation of 3-5 regional centers that could train individuals/groups on development/use of standard protocols, develop standardized sensors and calibration protocols for OA parameters, conduct research on fundamental assumptions, and build cross-interest network across OA community.

- Map existing assets and sites of importance.
- Develop data-sharing capabilities and a centralized database.
- Ensure ocean acidification is considered a research priority among potential funders, and work with funders to include a mandate on funded OA proposals to share data and use standardized techniques.
- Organize the generation of a white paper.
- Conduct outreach and education to increase awareness of ocean acidification as a threat to ecosystems and industry.
- Develop a dedicated conference on the multidisciplinary topic of ocean acidification. Alternatively, session(s) at ongoing, planned conferences.
- Conduct a socio-economic study to examine the potential risk to industry.

Summary of Significant Workshop Findings and Recommendations

Significant Workshop Findings

Mounting evidence suggests that ocean acidification may change the structure, function, and biodiversity of marine ecosystems. However, existing datasets are physically and spatially dissociated and furthermore, standardized protocols for data collection have not been applied. Addressing questions about ocean acidification requires integration of ocean observing measurements, laboratory exposure studies, shellfish recruitment and production data, and field studies of organism performance in relation to ocean conditions. To date, these data have been collected by different sectors with limited interaction. Thus, there is a need to: 1) coordinate chemical data collection at the best biological monitoring sites, leveraging long-term data sets and employing standardized methods, 2) supplement correlative data with an understanding of biological processes, and 3) develop predictive models at smaller scales. Different communities must work collaboratively to resolve these issues. The momentum generated at this workshop needs to be maintained.

Recommendations

Workshop participants reviewed existing research, identified information gaps, and proposed modifications and potential solutions to improve the state of knowledge of ocean acidification on the West Coast and to address problems faced by shellfish hatcheries, growers, and harvesters. Recommendations include:

- 1) A West Coast Ocean Acidification Research Coordination Working Group should be established to provide recommendations on best practices and standardized research methods to achieve a coordinated network of ocean observations and experimental studies, in order to observe, understand and quantify the evolving threats posed by ocean acidification along the West Coast of the United States.
- 2) A West Coast Ocean Acidification Data Exchange, integrated with IOOS, and consisting of a single website that serves as an entry portal to data and information, should be established to provide easy access to available data sets and information regarding ocean acidification processes affecting West Coast fish and shellfish.
- 3) The proposed NOAA West Coast Ocean Acidification Observing Network should be enhanced and expanded to include sites on the West Coast where in-field biological response studies are conducted.

Appendix A. Workshop Agenda

Wednesday, July 7

- 8:00-8:30 Coffee and continental breakfast
- 8:30-8:50 Introductions and goals of the workshop (Steve Weisberg)
Welcome from meeting co-sponsors:
Russ Moll, California Sea Grant
Phyllis Grifman, USC Sea Grant
Teri King, Washington Sea Grant
Rob Emanuel, Oregon Sea Grant
Carl Gouldman, NOAA Integrated Ocean Observing System
Skyli McAfee, California Ocean Science Trust
- 8:50-9:20 Plenary talk: Industry perspective
Robin Downey, Pacific Coast Shellfish Growers Association
Bruce Steele, California Sea Urchin Commission
- 9:20-10:00 Plenary talk: Oceanographic measurements of acidification prevalence and plans for future monitoring and modeling studies – Richard Feely, NOAA
- 10:00-10:20 Break
- 10:20-11:10 Plenary talk: Interannual patterns in shellfish recruitment
Chris Langdon, Oregon State University
Steve Schroeter, University of California Santa Barbara
- 11:10-12:00 Plenary talk: Studies of acidification vulnerability
Gretchen Hofmann, University of California Santa Barbara
Jim Barry, Monterey Bay Aquarium Research Institute
- 12:00-1:00 Lunch on site
- 1:00-1:15 Charge to breakout groups (Steve Weisberg)
- 1:15-4:00 Breakout Session 1.
Questions for breakout groups
1. What data sets are readily available?
 2. What is the quality of the data sets?
 3. Can they be made available on a website?
 4. What projects are coming on-line that will provide important data in the near future?
 5. Are there proper tools available to work with the data sets?
- Breakout by data type (session moderators are in parentheses):
Group 1 Oceanography data (Russ Moll)
Group 2 Recruitment data (Skyli McAfee)
Group 3 Exposure studies (Juliette Hart)
- 4:00-5:00 Groups reconvene; Session moderators summarize discussion and conclusions

Thursday, July 8

- 8:00-8:30 Coffee and continental breakfast
- 8:30-8:45 Summary of previous day; Charge to breakout groups (Steve Weisberg)
- 8:45-11:00 Breakout Session 2.
Questions for the Breakout Groups:
 1. What analyses integrating these diverse data sets can we conduct?
 2. What additional methods/tools are required from future studies?
Two breakout groups for each habitat:
 Group 1. Open-ocean hydrographic and biological data (Simone Alin)
 Group 2. Open-ocean hydrographic and biological data (Mark Ohman)
 Group 3. Near-shore hydrographic and biological data (Jim Barry)
 Group 4. Near-shore hydrographic and biological data (Phyllis Grifman)
- 11:00-12:00 Groups reconvene; session moderators summarize discussion and conclusions
- 12:00-1:00 Lunch on site
- 1:00-1:30 Plenary talk: Placing west coast efforts into a national context
 Phil Taylor, National Science Foundation and Co-Chair of the Interagency Working Group on Ocean Acidification
- 1:30-3:30 Breakout Session 3:
Planning for the future cross-discipline interaction
Breakout by separate topics:
 Group 1. How should we modify monitoring/research program designs to enhance cross-discipline analyses? (Jan Newton)
 Group 2. How should we synchronize cross-discipline data systems? (Steve Hankin)
 Group 3. What approaches should we use to enhance future cross-discipline interaction? (Skyli McAfee)
- 3:30-4:30 Groups reconvene; session moderators summarize discussion and conclusions
- 4:30 Summary of next steps identified at the meeting (Steve Weisberg)

Appendix B. Presentation Summaries

The Pacific Coast Shellfish Growers Association Oyster Emergency Initiative: What It Can Teach Us About Changing Ocean Conditions – and How to Adapt

Robin Downey

Pacific Shellfish Growers Association

The Pacific Coast Shellfish Growers Association (PCSGA) was formed in 1930 and represents growers from Alaska, Washington, Oregon, California, and Hawaii who sustainably farm oysters, clams, geoduck, mussels, and scallops. This presentation focused on oysters, which appear to be most sensitive to changing ocean conditions. Furthermore, oysters represent the largest portion of shellfish produced on the West Coast (83%) and a majority of the shellfish sales (62%).

Oyster farming has occurred on the Pacific coast since the mid-1800s. Early shellfish management included building dikes to retain seawater on oyster beds to protect against temperature extremes and to increase growth rates. However, populations of the native Olympia Oysters crashed due to overharvesting and pollution from pulp mills, at which point Pacific oyster seed was brought in from Japan to keep farmers in business. Presently, four hatcheries, Taylor, Whiskey Creek, Coast and Lummi, produce oyster seed for West Coast oyster farms.

Recently, growers have experienced serious problems with oyster seed: 1) significant oyster larvae mortalities at 2 of the 3 major hatcheries, and 2) virtually no natural set in Willapa Bay (the largest oyster producing region on the West Coast) for 6 years. This seed shortage has led to a 22% decrease in harvest rates between 2005 and 2009. At first, proliferation of the pathogenic marine bacteria, *Vibrio tubiashii*, was identified as a cause of the mortalities; however, problems continued even as spread of the pathogen was controlled. Ultimately, analysis of ocean chemistry resulted in discovery of a correlation between upwelling of lower pH water and larval mortalities in the hatcheries. However, it is unclear what is actually driving these decreases both in the hatcheries as well as in the wild.

PCSCA identified the oyster seed scarcity as its top priority in 2007, spurring the development of a “The Oyster Emergency Initiative,” and identification of priority areas of study most likely to lead to solutions or adaptive strategies to overcome oyster production problems:

- 1) Development of an easy and rapid assay testing method for *Vibrio tubiashii*,
- 2) Identification of the genetic traits of high performing oyster families that survive in high stress ocean conditions,
- 3) Increased monitoring of the near-shore environment, including the intake water to the hatcheries, as well as water conditions within the hatcheries, so that survival of larvae and seed in hatcheries and the wild can be correlated with environmental conditions.
- 4) Development of tools for adapting to/managing ocean conditions including development and testing of small-scale experimental water treatment systems in the hatcheries (UV Sterilization, de-gassing, biofiltration/protein skimmers, probiotics, CO₂ stripping/buffering).
- 5) Study information from existing and historical research
- 6) Identify gaps in research/understanding
- 7) Raise awareness of problems and engage critical mass of researchers and policy makers in forging solutions.

Ocean Acidification vs. West Coast Shellfish Fisheries: Setting the Context for this Workshop

Bruce Steele

California Sea Urchin Commission

Evidence of corrosive water was found less than 20 miles off of the west coast of North America during in 2007. Upwelling of this water was correlated with recruitment declines in wild fisheries which, in addition to their value to coastal ecosystems, are also economically important to coastal communities. Commercial shellfisheries represent about half of the total value of all fisheries landings on the West Coast and are thus critically important to support harbor infrastructure, jobs, and local businesses. Furthermore, recreational shellfisheries contribute an additional source of income for coastal communities. Up to 30,000 people can come out for a season opening in a day, an event which supports local businesses (hotels, restaurants, etc.), in addition to the income from commercial fishing.

Changing ocean chemistry represents a major challenge to fisheries managers who must be able to forecast how their fisheries will evolve. Presently, ocean acidification, low dissolved oxygen events, warming waters, and diseases are serious threats both directly to the wild shellfisheries, but may also have effects up the food chain (e.g., salmon). Managers need to be able to predict when changes will occur and understand the effects on the ecosystem so that they can adapt their practices to best support their fisheries. This requires an understanding of baseline conditions so that we can understand how long-term changes in physics and chemistry are related to changes in biological communities (recruitment success or failure). There are presently a precious few long-term (20-years) biological data sets, which can be used to establish such baseline conditions. These need to be linked with near-shore physiochemical monitoring data so that patterns in recruitment success/failure can be correlated with changing environmental conditions. Thus, one of the industry's goals for this workshop is to establish collaborations with oceanographic programs to bring monitoring technology to bear on observed changes in shellfisheries.

Ocean Acidification: Measurements, Modeling and Plans for Future Work

Richard A. Feely

NOAA Pacific Marine Environmental Laboratory

Over the past 250 years, atmospheric carbon dioxide (CO₂) levels have increased by 40% due to human activities such as burning of fossil fuels and land use changes. About 30% of this CO₂ is absorbed by the oceans causing dramatic changes in ocean chemistry including a decrease in surface ocean pH (~0.1), carbonate ion concentrations (~16%), and aragonite and calcite saturation states (~16%). This last point is critical because as the saturation state decreases organisms will have increasing difficulty in precipitating and maintaining calcium carbonate shells and exoskeletons resulting in reduced growth, production, and life span. Additionally, the rate of increase in the partial pressure of carbon dioxide in the oceans ($p\text{CO}_2$) is faster than any time over the past 800,000 years and this rate is likely to increase over the next century, such that surface ocean pH could be reduced a further 0.3 or 0.4 units. Given the rapidity of change, it is questionable whether organisms can adapt to these changes (compounded stressors of increasing temperature and changing ocean chemistry). Furthermore, the absorption of atmospheric CO₂ results in a myriad changes in addition to its effects on carbonate chemistry, including shifts in key nutrient and trace element speciation, ecosystem-level shifts in species composition and loss of biodiversity, reduced tolerance of species to other environmental fluctuations.

A global ocean CO₂ survey indicated that the depth saturation of aragonite and calcite is relatively shallow (within 500 m of the surface) in the north Pacific and West Coast and models predict that depth is shoaling ~1-2 m/yr. The West Coast is susceptible to under-saturated (corrosive) waters during seasonal upwelling. Upwelled water originates in the North Pacific and by the time it reaches the West Coast it is 30-50 years old, contains about 30 μm of anthropogenic CO₂ plus additional CO₂ from the remineralization of organic matter along its flow path, and is thus highly corrosive with a pH of 7.7. A series of cruises along the West Coast in 2007 found corrosive water everywhere they looked from Canada to Mexico. This water was typically 40-80 m below the surface near the shoreline but reached the surface in several locations. Models did not predict corrosive waters at this depth until the end of the century.

In light of these observations, NOAA is developing a plan to bring together efforts to understand ocean acidification to offer science based guidance for developing adaptation strategies to deal with the impacts. These efforts center around several hypothesis: 1) rates and magnitudes of acidification vary across time, space, and depth as a consequence of local and regional geochemical hydrological, and biological mechanisms, 2) ocean acidification will change ecosystem structure, function, and biodiversity via both direct impacts (e.g., altered growth or survival rates) and indirect effects (e.g., food web and/or habitat changes), and 3) heterogeneity in species-specific responses, local environmental, and regional considerations will confer a broad range of vulnerabilities that differ both locally and regionally. The goals of this program are to: 1) develop the monitoring capacity to quantify and track ocean acidification and its impacts in open-ocean, coastal, and Great Lakes systems, 2) assess the response of organisms to ocean and lake acidification, 3) forecast biogeochemical and ecological responses to acidification, 4) develop management strategies for responding and adapting to the consequences of ocean acidification from a socioeconomic perspective, 5) provide a synthesis of ocean and Great Lakes acidification data and information, and 6) provide an engagement strategy for educational and public outreach. The themes will take full

advantage of observational, experimental, and modeling capacities within NOAA and rely on external research partners to complement and augment NOAA's internal expertise.

An observational network for ocean acidification is under development for the West Coast; however, ocean acidification is a global problem and therefore a global monitoring plan must also be instituted with international cooperation. The back bone of this program is adding carbon and pH measurements to existing moorings to look at seasonal trends in pCO₂ and pH and look at changes in saturation state in real time. New technologies are coming on-line to collect these kinds of data with greater precision (submersible and solid state pH sensors). Similarly, systems are being developed to collect high resolution data for large areas such as multi-channel systems to measure pH, DIC, and pCO₂ shipboard while underway and gliders outfit with carbon measurements. Furthermore, algorithms are being developed to calculate saturation state from hydrographic data (temperature and salinity). Such systems can generate high resolution data from lower cost platforms. Together, the new platforms and technology in combination with the algorithms can be used to provide early warning systems for the development of corrosive waters off shore.

Challenges for the West Coast Shellfish Industry with Increasing Local and Global Ocean Acidification

Chris Langdon

Hatfield Marine Science Center, Oregon State University

The West coast shellfish industry has harvests worth about \$111 million a year with oyster harvests making up about 75%. Including services, wholesale sales and supplies, the industry has an annual economic impact of about a quarter billion dollars and employs about 3000 people. Since 2005, two of the three major hatcheries on the West Coast have been having problems with high larval mortality: the Whiskey Creek hatchery in Oregon and Taylor hatchery in Puget Sound. Whiskey Creek alone supplies about 75% of the oyster growers with seed (eyed larvae). The loss of adequate supplies of oyster seed from hatcheries has been compounded by the absence of a natural set of wild oysters in Willapa Bay, WA, the main bay for oyster production on the West coast and a major source of wild seed. Sets of wild oysters have been recorded in Willapa Bay since 1942 and there have been other periods of 4 to 6 years where sets of wild oysters have been poor. It is unknown if the present declines in wild set will end, as other periods have, or if the declines will continue.

In 2005, the first larval rearing problems (poor larval survival and growth and high spat mortalities in the nursery) were observed at the Hatfield Marine Science Center with no obvious cause. Seawater treatment systems were installed to mitigate these declines. In 2007, very high concentrations of *Vibrio tubiashii* (*Vt*) were associated with larval mortalities at Whiskey Creek. *Vibrio tubiashii* is a pathogenic bacteria that causes rapid reduction in larval motility and necrosis of soft tissues, leading to high mortality rates. This *Vt* outbreak led to the development of new molecular tools for the detection of *Vt* and the installation of seawater systems to kill *Vt* and remove its extracellular toxins. While this treatment initially improved oyster larval growth and survival, it did not help from mid-July to mid-September when larval production collapsed. This collapse coincided with lower-pH water (7.6) upwelling along the coast. Operators were sometimes able to improve larvae growth and survival by increasing pH to 8.1 - 8.3 with sodium carbonate. In 2008, acidic water was found in Dabob Bay, the source of seawater for Taylor Hatchery and they began adjusting seawater pH. Hatchery biologists suspect that because larval oyster shells are composed of amorphous and aragonite forms of calcium carbonate they are particularly susceptible to dissolution. In 2009, larval problems at the hatcheries continued, sometimes associated with *Vt*, although Whiskey Creek noted a strong correlation with upwelling events. Currently, the hatcheries have implemented continuous pCO₂ and water quality monitoring and are developing adaptive strategies to avoid using acidified deep water for larval culture.

The characteristics of upwelled water (low pH, high pCO₂, DIC, DOM, reduced compounds, or a combination of these factors) that are harmful to oyster productivity are currently unknown. Furthermore, development and expansion of hypoxic zones off shore and in the bays may be compounding the problem. In addition the interaction of hypoxia and the spread of *Vt* with upwelling confound our ability to assign causes to the observed declines in productivity. Some possible remedies for hatcheries have been proposed including: installation of water quality monitoring systems, restricting oyster larvae culturing to periods without upwelling, pumping seawater into hatcheries only during periods with low pCO₂, install water treatment systems to remove high pCO₂, develop strains of oysters that are tolerant of high pCO₂.

Role of Long-Term Data Sets on Settlement of Marine Invertebrates in Understanding Effects of Ocean Acidification

Steve Schroeter

Marine Science Institute, University of California, Santa Barbara

Long-term studies on larval settlement can provide the opportunity to distinguish signals of shifting oceanographic regimes (e.g., El Niño/La Niña and the Pacific Decadal Oscillation) from the effects of ocean acidification on the early and most vulnerable life stages of range of invertebrate species. Such studies are cost effective and sustainable over the long term and providing baseline data on recruitment and settlement patterns over a wide geographic range and varying oceanographic conditions. This presentation described such a study (begun in 1990 and continuing to the present) looking at settlement of sea urchins and other invertebrates at 30 sites from Cape Mendocino to the Mexican Border using high frequency sampling (weekly to bi-weekly). Invertebrates were enumerated from artificial substrates (scrub brushes) and preserved in alcohol for future analysis.

Results indicate regional differences in settlement and recruitment of sea urchins. In northern California, there was a positive correlation between settlement and El Niño conditions but in southern California settlement was correlated with upwelling conditions. There was typically one major settlement event at the southern California sites in late winter/early spring, while in northern California, there were two settlement events, one in winter and one in late summer. Settlement in southern California is typically higher than in northern California; furthermore, there is a declining trend in settlement in northern California, but not in southern California. There were similar patterns in settlement on the mainland and island sites in southern California; however, settlement at the island sites was significantly larger than on the mainland. These results indicate that settlement events are episodic and are strongly influenced by a few, large events.

In order to draw conclusions between settlement and recruitment and ocean acidification, these data sets must be linked to physical and chemical monitoring offshore. Time series measurements and/or hindcasts of temperature, salinity, pH and pCO₂ at different depths in the water column during settlement events are critical to understanding how settlement is related to environmental conditions. Furthermore, archival samples can be used to measure morphological changes related to changing environmental conditions. Such studies would compliment controlled laboratory exposure studies and can be used to select sites for field studies by establishing an environmental gradient over which a biological response was observed.

Organismal Perspective on Effects of Ocean Acidification

Gretchen Hofmann

University of California, Santa Barbara

Current research efforts have been focused on looking at how organisms respond to environmental changes, particularly those related to increasing temperature and $p\text{CO}_2$ and decreasing pH, in a controlled laboratory environment that mimics conditions in the field. Studies are designed to look at the vulnerability of different organisms, specifically the early life-stages, to variable environmental conditions; both present conditions as well as predicted changes in the future. This presentation looked at the effects of elevated $p\text{CO}_2$ on purple sea urchins, abalone, and oysters. The goal of this research is to determine how plastic critical species are to environmental stressors and when their tolerances are exceeded.

Purple sea urchins do continue to develop under elevated $p\text{CO}_2$ conditions; however, the size of the larval endoskeleton is significantly reduced. Furthermore, even if these larvae are placed back in lower $p\text{CO}_2$ waters, they never catch up to the larvae that never experienced the stress and the impacts of larval stress were felt over the entire lifespan of the organism. Additionally, thermal stress can act synergistically with stress from elevated $p\text{CO}_2$ and lowered pH, such that increasing temperature increases the vulnerability to higher $p\text{CO}_2$. However, there was a wide range of variability in response such that some genotypes were more resilient than others under the same conditions. Preliminary studies of the offspring from different maternal lines fertilized with the same sperm donor indicate that there is a strong maternal effect on response to elevated $p\text{CO}_2$ conditions. Off-shore monitoring indicates that $p\text{CO}_2$ conditions are highly variable both spatially and temporally, thus some organisms will be more used to seasonally high $p\text{CO}_2$ conditions and may have experienced local adaptation to such stressors. Such areas could be a source for more resilient strains.

Similar to the sea-urchins, oyster larvae and juveniles (*Ostrea lurida*) also show less growth under elevated CO_2 and were never able to catch up to un-stressed oysters after removal to lower $p\text{CO}_2$ tanks. The effects of elevated $p\text{CO}_2$ were not as dramatic for abalone. Temperature was the main abiotic driver of survivorship for all 4 stages of the abalone lifecycle. However, high $p\text{CO}_2$ did alter larval response at two stages and within a given stage, the effect $p\text{CO}_2$ had on survival was not consistent. This goes to show that this is a dynamic system and the sensitivity of larval stages is different. These differences are important because we cannot make general assumptions about how a specific species or even a given larval stage will be affected by $p\text{CO}_2$.

In terms of future research directions, more information needs to be made available for existing conditions along the coast so that laboratory studies can be better tailored to what the organisms are actually experiencing. Further research must also be conducted looking at local adaptations to seasonally high $p\text{CO}_2$ conditions to understand what genotypes are more resilient and what mechanisms they employ to deal with stressful conditions.

Ocean Acidification and Ocean Biology

Jim Barry

Monterey Bay Aquarium Research Institute

Ocean acidification can result in a variety of physiological stresses on organisms including: reduced calcification, increased respiratory stress, disruption of acid/base balance, and metabolic depression. Ocean acidification will affect calcification in many taxa because with increasing CO₂ and decreasing saturation of aragonite, it will become increasingly more energetically expensive to calcify. Additionally, enzymes and proteins are optimized for pH, therefore, as the pH of the oceans is gradually reduced, organisms may undergo acidosis which will result in disruption of enzyme function, protein synthesis, and other cellular functions. Furthermore, CO₂ is a sedative, and in increased CO₂ environments can depress metabolic function and place organisms in a state of torpor. Consequently, organisms may experience respiratory stress and decreased performance, growth, and reproduction. Organisms faced with environmental stresses like ocean acidification have few options: migrate, acclimate, adapt, or die. The current understanding of ocean acidification limits our ability to predict what route specific species may take. Whether or not a specific organism can acclimate or adapt to the environmental change has consequences for the entire population, as well as the whole ecosystem.

We know that ocean acidification is ongoing, massive, and increasing. That it causes physiological stress for many species, and can only be mitigated by reduced CO₂ emissions. We expect that food webs will be affected and that ecosystem services (e.g., fisheries) will change. But we do not know the capacity for acclimation and adaptation of individual populations, what the effects will be on marine communities and ecosystems, whether there are any tipping points, what the difference will be between coastal and the open ocean systems (i.e., environments with high versus low natural pH variation respectively), and the effects on productivity and stability of fisheries. Furthermore, we do not understand the synergistic effects of warming, acidification, and reduced oxygen levels and how the interaction of these stressors may further impact ocean ecosystems. To this end, a number of field and laboratory experiments are underway. Including liquid CO₂ release experiments in the deep sea (3600 m) to study the effects of CO₂-rich seawater on animals *in situ* and laboratory studies varying pH, O₂, and CO₂ to look at the interaction of these three stressors in controlled environments.

Placing West Coast Efforts into a National Context

Phil Taylor

National Science Foundation

Fundamental research is required to answer the question of what is in store for our ocean and coasts as well as the species, ecosystems and human systems build upon these resources. The Federal Ocean Acidification Research and Monitoring Act (FOARAM) authorizes appropriations for NOAA and NSF for ocean acidification and establishes an interagency committee to develop an ocean acidification research and monitoring plan, as well as an ocean acidification program within the National Oceanic and Atmospheric Administration. The first act of the Interagency Working Group on Ocean Acidification (IWG-OA) was to provide an initial Report on federally funded ocean acidification research and monitoring activities. The second action, due in spring 2011, is to develop a strategic research plan for ocean acidification. This plan will include:

- 1) Monitoring of chemistry and biological impacts in coastal and open-ocean regions to characterize marine ecosystems, changes in marine productivity, and changes in ocean chemistry. This may integrate current efforts in global surveys, ocean time-series (HOT, BATS, LTERs), and OOI, Argo, and glider surveys;
- 2) Research to understand the species-specific physiological responses of marine organisms, and to develop environmental and ecological indices that track ecosystem responses;
- 3) Modeling to predict changes in the ocean carbon cycle as a function of CO₂ and changes in temperature, ocean circulation, biogeochemistry, and terrestrial inputs, as well as impacts on marine ecosystems and individual marine organisms;
- 4) Technology development and standardization of carbonate chemistry measurements on moorings and autonomous floats;
- 5) Assessment of socio-economic impacts and development of adaptation and mitigation strategies to conserve marine organisms and marine ecosystems;
- 6) Education and outreach; and
- 7) Synthesis of data and information products.

There are presently many available resources and reports to provide input to the strategic plan and individual agency discussions and research planning are ongoing. The group is also soliciting recommendations from the external Task Force on Ocean Acidification of the Ocean Research and Resources Advisory Panel (ORRAP) as well as scientists, NGO's, and foundations, managers, and stakeholders in industry sectors. The group is presently working towards setting priorities of actions and articulating the budget needs to accomplish the program. Currently each federal agency has a number of ongoing research programs related to ocean acidification and efforts. What follows is a summary of the activities of each of those activities by agency.

The National Oceanic and Atmospheric Agency (NOAA) has several programs related to ocean acidification including: 1) Caribbean ocean carbon chemistry monitoring through assimilation of satellite and in situ data established in FY 2009, 2) ocean acidification observing network established in FY 2010, 3) Coral reef test beds established in FY 2010, 4) development of technology for carbon measurements on moorings, and 5) organism response studies. Some ocean acidification-related data are made accessible and preserved by NOAA and they are working on developing future access to other ocean acidification data and information both within NOAA and in collaboration with existing partnerships, such as the Department of Energy (Carbon Dioxide

Information Analysis Center). Furthermore, NOAA is developing the Ocean Acidification Program Office and is preparing the Implementation Plan for Ocean Acidification Research is in preparation.

The National Science Foundation (NSF) is currently seeking research proposals to address the following questions: 1) What are the impacts of changing pH upon marine chemical phenomena? 2) What are the impacts of elevated seawater CO₂ and decreased pH upon marine organisms and their physiological adaptation, on species genetic diversity, on community structure, and ecosystem processes of coastal, open ocean, and deep water systems? 3) In today's oceans, what are the major drivers impacting seawater acidity and alkalinity? 4) What does the geologic record reveal about the relationship between seawater pH and carbonate ion levels, marine species and their evolution? 5) Can changes in the physical chemistry of the ocean affect other parameters in the water column, e.g., particle aggregation? and 6) What are some existing and potential observational, experimental, and theoretical approaches for studying past, present, and future trends in ocean acidification? NSF also is soliciting proposals for the Climate Research Initiative which focus on molecular and cellular biology, physiology, marine chemistry and physics, ecological sciences, paleoecology, and earth system history. Because ocean acidification which involves fundamental geochemical phenomena that are highly interconnected to oceanic biology, physics, and geology, the proposals must incorporate diverse approaches for research (observational systems, experimental studies, theory and modeling). The aim of these projects should be to predict the consequences on ecosystem health and function

The Environmental Protection Agency (EPA) is currently reviewing the pH water quality standard, and is working towards developing a number of biological criteria specifically related to impacts from ocean acidification. They are also developing methods and approaches to support water quality criteria authorized by the Clean Water Act and tools to support broader consideration of socioeconomic benefits of coral reefs in actions taken in coastal zones and watersheds.

The National Aeronautics and Space Agency (NASA) has incorporated ocean acidification research into the umbrella of understanding the ocean carbon cycle and associated biogeochemical processes. Efforts are underway to look at productivity and ecosystem change with species or group-based remote-sensing.

The Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), formerly the Minerals Management Service, has a few programs which include the Biogeochemical Assessment of the North Aleutian Basin Ecosystem and an investigation of deep-sea Corals (*Lophelia*).

The U.S. Geological Service (USGS) has a number of research programs including: 1) monitoring of ocean chemistry and biological impacts such as coral reefs, florida subtropical shelf ecosystems, and Arctic Ocean chemistry, 2) species specific physiological responses, development of environmental indices for Corals, forams, and calcifying algae, and 3) technology development including low-through systems for the rapid measurement of CO₂ levels in water and development of software for PC, MAC, and iphone apps that will provide expanded capability and use of CO₂Sys on various platforms (CO₂Calc).

Appendix C. Proposal for Formation of West Coast Ocean Acidification Coordination/Working Group

Need

- Improved cross-discipline communication and collaboration to develop a biological and oceanographic monitoring system on the US West Coast to expand OA research and outreach.
- The system must be informed by available and future shellfish recruitment assessments, production and research studies that can be standardized and correlated with integrated ocean observing system [IOOS] measurements.

Urgency

- Organisms living along the Pacific Coast of the continental United States may already be experiencing significant biological effects as a consequence of the combined impacts of upwelling and ocean acidification. Shellfish industry representatives are observing recruitment failures of valuable wild shellfish resources, in tandem with severe larval mortalities within some West Coast shellfish hatcheries.
- A 2007 oceanic survey, led by Dr. Richard Feely of the NOAA Pacific Marine Environmental Laboratory, found that the upwelled water along the West Coast was significantly contaminated with anthropogenic carbon, further enhancing the already high level of CO₂ resulting from natural respiration processes. As a result, such waters – even at shallow depths – are undersaturated with respect to aragonite, and may pose a threat to calcifying species.

Goal of Group

To facilitate development of a coordinated research and monitoring system and dissemination of information to academic, local, state, tribal and federal/national agencies, fishery and aquaculture industry members and other stakeholders.

Objectives of Group

Coordinate/facilitate:

- Collaborative efforts to develop a system including standardized research protocol(s) and data management
- Potential funding
- Communication among ocean acidification researchers, industry members and policy makers.
- Information and outreach to agencies and the public

Development / Implementation

- A steering committee identified at the Ocean Acidification – Shellfish Workshop in July 2010 has agreed to interact to develop the framework for a cross-discipline coordination working group
- Steering Committee members: Andrew Dickson, SIO; Chris Langdon, Hatfield MSC, OSU; Gretchen Hofmann, UCSB; Jan Newton, NaNOOS, UW; Teri King, Washington Sea Grant; Debbie Aseltine-Neilson, CDFG; Ian Jefferds, Penn Cove Shellfish; Robin Downey, Pacific Coast Shellfish Growers Association; Bruce Steele, CA sea urchin diver

Appendix D. Workshop Participants and Contact Information

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