Present and Future Impacts of Ocean Acidification on Marine Ecosystems and Biogeochemical Cycles

Report of the
Ocean Carbon and Biogeochemistry Scoping Workshop
on Ocean Acidification Research

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This report should be cited as:

Fabry, V.J., C. Langdon, W.M. Balch, A.G. Dickson, R.A. Feely, B. Hales, D.A. Hutchins, J.A. Kleypas, and C.L. Sabine (2008) Present and Future Impacts of Ocean Acidification on Marine Ecosystems and Biogeochemical Cycles, report of the Ocean Carbon and Biogeochemistry Scoping Workshop on Ocean Acidification Research held 9-11 October 2007, La Jolla, CA, XX pp.

Acknowledgements

This workshop was jointly sponsored by the U.S. Ocean Carbon and Biogeochemistry Program with support from the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautical and Space Administration (NASA). We specifically acknowledge the program managers Phil Taylor, Don Rice and Roberta Marinelli of the NSF Chemical and Biological Oceanography Programs, and the Antarctic Organisms and Ecosystems Program (OEP), respectively; Boris Uz of the NOAA Global Carbon Cycle Program; and Paula Bontempi of the NASA Ocean Biology and Biogeochemistry Program for their support. Special thanks goes to Mary Zawoysky of WHOI and the Scripps Institution of Oceanography for providing excellent meeting logistics, and Ryan Layne Whitney of NOAA/PMEL for his excellent editing and formatting skills. We also want to thank all of the workshop participants and speakers for their extensive contributions to the workshop and for providing input to the content of this report.

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[include appendix 1 – workshop agenda; appendix 2 – List of participants]

Summary

Oceanic uptake of anthropogenic CO_2 is altering the seawater chemistry of the world's oceans with consequences for marine biota, ecosystems, and biogeochemistry. Understanding these impacts requires integrative approaches to understand the linkages among ecosystem components and feedbacks to climate. The Ocean Carbon and Biogeochemistry (OCB) program, a scientific community-driven coordinating body that promotes U.S. research and international cooperation to investigate the ocean's role in the global Earth system, sponsored a Scoping Workshop on Ocean Acidification Research. With support from the National Science Foundation, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and U.S. Geological Survey, a multidisciplinary assemblage of 93 scientists participated in the 3-day workshop, held at the UCSD Scripps Institution of Oceanography on 9–11 October 2007.

The goals of this Scoping Workshop on Ocean Acidification Research were to:

1. Develop coordinated research implementation strategies to address present and future ocean acidification impacts; and
2. Identify specific activities and timelines needed to advance research priorities.

Previous meetings and reports on the impacts of ocean acidification emphasized substantial knowledge gaps at the ecosystem level. Therefore, this workshop focused on developing comprehensive research strategies for four critical ecosystems:

- Warm-water coral reefs;
- Coastal margins;
- Subtropical/tropical pelagic regions; and
- High latitude regions.

Four individual focus groups (one for each of these ecosystems) were asked to address each of the two goals noted above.

Plenary discussions identified common approaches as well as ecosystem-specific differences. These discussions highlighted the need to integrate modeling into the design, execution, and interpretation of manipulative experiments, as well as recognizing the possibility for interactions between the effects of increasing $p(CO_2)$ and effects due to climate-induced changes in variables such as temperature and nutrients.

Participants strongly endorsed the establishment of an interdisciplinary U.S. national program on ocean acidification that would coordinate research activities among different U.S. Federal agencies. They also stressed the need for continuing international cooperation to develop a coordinated, global network of ocean observations and process studies that could leverage existing infrastructure and programs as far as possible, while noting the need for additional sites for monitoring and process studies aimed explicitly at ocean acidification.

Key recommendations include:

- Establish a national program on ocean acidification research;
- Develop new instrumentation for the autonomous measurement of CO_2 system parameters, particulate inorganic carbon (PIC), particulate organic carbon (POC), and physiological stress markers;
- Standardize protocols for manipulation and measurement of seawater chemistry in experiments and for calcification and other rate measurements;
- Establish new monitoring sites/surveys in open-ocean and coastal regions, including sites of particular interest such as the Bering Sea;
- Build shared facilities to conduct well-controlled CO_2-manipulation experiments;
- Progressively build capacity and initiate planning for mesocosm and CO_2-perturbation experiments in the field;

- Develop regional biogeochemical and ecological models that explicitly incorporate biological responses to carbonate system changes and conduct model/data intercomparison exercises;
- Establish international collaborations to create a global network of ocean acidity observations and process studies relevant to ocean acidification; and
- Initiate specific activities for education, training, and outreach.

The 2006 reauthorization of the Magnuson-Stevens Act called for NOAA to enter into an agreement with the National Academy of Sciences (NAS) to initiate a study on acidification and its impacts (see Public Law 110-161). This review: *Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment*, will be conducted by the Ocean Studies Board through the year 2009. Building on the recommendations of this workshop report (*i.e.*, the creation of a U.S. National Research Program on ocean acidification), the NAS report will "recommend priorities for a national multi-agency research, monitoring, and assessment plan to advance understanding of the biogeochemistry of carbon dioxide uptake in the ocean and the relationship to atmospheric levels of carbon dioxide, and to reduce uncertainties in projections of increasing ocean acidification and the potential effects on living marine resources and ocean ecosystems." The Ocean Carbon and Biogeochemistry Program strongly supports this activity, and will cooperate fully with the NAS to provide any necessary scientific information and guidance.

1. Introduction

Rising atmospheric carbon dioxide (CO_2) is tempered by oceanic uptake, which accounts for nearly a third of the anthropogenic carbon added to the atmosphere (Sabine & Feely 2007; Sabine *et al*., 2004), and without which atmospheric CO_2 would be about 450 ppmv today with consequences for climate change. Ocean CO_2 uptake, however, is not benign. It leads to pH reductions and changes in seawater chemistry that together are commonly referred to as "ocean acidification" (Figure 1). The addition of anthropogenic CO_2 to seawater results in an increase in total dissolved inorganic carbon (DIC) and a decrease in seawater pH, carbonate ion concentration and calcium carbonate ($CaCO_3$) saturation state. Evidence is now accumulating that these direct effects of anthropogenic CO_2 on ocean chemistry have profound consequences for marine organisms, potentially altering ecosystem structure, food webs, and biogeochemical processes.

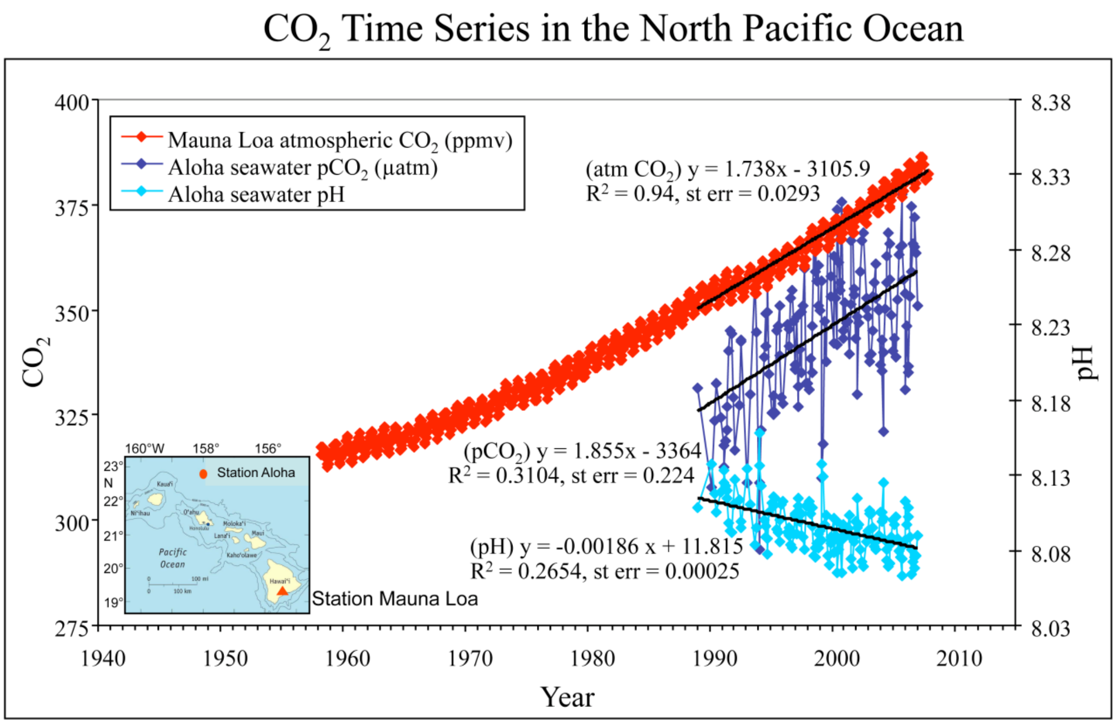

Figure 1. Time series of atmospheric CO_2 at Mauna Loa (ppmv) and surface ocean pH and pCO_2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean. Note that the increase in oceanic CO_2 over the last 17 years is consistent with the atmospheric increase within the statistical limits of the measurements. Mauna Loa data: Dr. Pieter Tans, NOAA/ESRL (http://www.esrl.noaa.gov/gmd/ccgg/trends); HOTS/Aloha data: Dr. David Karl, University of Hawaii (http://hahana.soest.hawaii.edu) (after Feely, 2008).

A multidisciplinary assemblage of 93 scientists participated in a 3-day workshop to develop coordinated research implementation strategies that address present and future ocean acidification impacts. The Ocean Carbon and Biogeochemistry program (http://www.us-ocb.org) sponsored this workshop, together with support from the National Science Foundation, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, U.S. Geological Survey, and UCSD Scripps Institution of Oceanography.

The goals of the workshop were to:

1. Develop coordinated research implementation strategies to address present and future ocean acidification impacts; and
2. Identify specific activities and timelines needed to advance research priorities.

Earlier reports on the impacts of ocean acidification emphasized substantial knowledge gaps at the ecosystem level (Royal Society, 2005; Kleypas *et al.*, 2006). Thus, this workshop focused on developing 10-year research strategies for four critical ecosystems:

- Warm-water coral reefs;
- Coastal margins,
- Subtropical/tropical pelagic regions; and
- High latitude regions.

Each of these research strategies involves a mix of field observations and perturbation experiments to investigate the impacts of ocean acidification on key ecosystem processes and organisms. Discussion went beyond calcification and calcium carbonate dissolution to include the effects of ocean acidification on many other important issues such as nitrogen fixation, review community structure, and fisheries. Special attention was paid to potential applications of new innovative approaches involving functional genomics, remote sensing, mesocosms, and models to improve or accelerate the research strategies. The focus of this report is on research recommendations, rather than providing a synthesis of current knowledge; however, we note that several recent publications provide such overviews of the impacts of ocean acidification (*e.g.*, Kleypas and Langdon, 2006; Fabry *et al.*, 2008; Guinotte and Fabry, 2008; Doney *et al*., 2009). In this report, some research elements are ecosystem-specific, while others are common across all four ecosystems chosen. Section 2 of this report discusses activities that are needed to advance ocean acidification research in the U.S., typically without reference to specific ecosystems. Ecosystem-specific research strategies, activities and timelines are discussed in Section 3. Throughout, an effort has been made to prioritize the various proposed activities into three categories:

1. Urgent and Important: Research activities that need to begin immediately and are essential to a successful program.
2. Important: Research activities essential to a successful program.
3. Desired: Research activities that are highly desirable, but which are not essential.

2. Overarching Workshop Recommendations (not specific to a particular ecosystem)

Ocean acidification has implications for many aspects of the Earth system (*i.e.*, chemical, physical, biological, ecological, geological), and any successful research strategy that aims to develop the ability to predict present and future responses of marine biota, ecosystem processes, and biogeochemistry requires a coordinated multidisciplinary approach. Critical research elements will require technical advances, regional and global networks of observations and process studies, manipulative experiments involving a suite of organisms in laboratory studies, mesocosm and field experiments, and new modeling approaches.

One of the key questions regarding responses to ocean acidification is resolving the distinction between “tipping points” and adaptation. Are there geochemical thresholds or tipping points for ocean acidification (*e.g.,* $CaCO_3$ mineral saturation state levels) that, if crossed, will lead to irreversible effects on species and ecosystems over human timescales? How can we determine whether organisms and ecosystems can adapt sufficiently to changing seawater chemistry in ways that will reduce potential negative impacts of ocean acidification? Ocean acidification-relevant indicators beyond basic water-column carbonate chemistry have yet to be adequately developed. Parameters that can be measured routinely and that detect biotic effects of ocean acidification reliably, such as indicator-species abundance, biochemical signatures of physiological stress, or ecosystem species composition, do not yet exist.

Ocean acidification (OA) research must produce an accessible parameterization of the effects and risks of acidification. Towards that end, we first identified the recommended research needs that were common to all four ecosystems chosen. These are described below in terms of immediate (0–2 years), intermediate (2–5 years), and long-term (5–10 years) priorities. Also common to all four ecosystems were the needs for a national ocean acidification program, data management, and programs to ensure education of the public and training of graduate students in ocean acidification research. Table 1 summarizes the research activities needed to advance ocean acidification research across the four critical ecosystems of warm water coral reefs, ocean margins, tropical/subtropical pelagic regions, and high latitude regions.

Table 1. Activities needed to advance ocean acidification research across all four critical ecosystems. Activities are prioritized as follows: (1) Urgent and Important; (2) Important; (3) Desirable. The recommended time window within the 0-10 year timeframe for each activity is denoted with "X."

Activity	Priority	0–2 years	2–5 years	5–10 years	Rationale
Technical needs					
Standardize protocols for rate measurements of calcification, carbonate dissolution, and respiration; manipulation and measurement of CO_2 chemistry in experiments	1	X	X	X	Needed to compare results across space, time, and laboratories; intercomparison studies of methods also necessary
Develop autonomous measurements of additional parameters of CO_2 system in seawater	1	X	X		Surface and subsurface total dissolved inorganic carbon, total alkalinity, and pH measurements needed for OA monitoring network
Develop physiological stress markers, including genomic tools, for key functional groups and economically important species	2		X	X	Assess OA impacts on wide range of physiological processes in organisms
Baseline monitoring, surveys & process studies					
Expand existing time series sites/surveys and long term ecological studies and establish new sites where necessary in coastal regions, high latitudes, coral reefs and tropical pelagic regions	1	X	X	X	Urgently need baseline information on changes in carbonate chemistry, abundances and distributions of CO_2-sensitive organisms, and other ecological monitoring
Establish network of moored buoys, gliders, floats, and survey lines for CO_2/carbonate chemistry observations in open-ocean and coastal waters	1	X	X	X	Provide input to design of manipulative experiments and to verify ecosystem models
Manipulative experiments					
Build infrastructure and capacity for controlled lab CO_2-	1	X	X		Need facilities to perform variety of lab experiments in

perturbation experiments					which the seawater CO_2 chemistry is well-controlled and defined
Build coastal/near-shore mesocosms	2		X	X	Plan and build shared, multi-purpose mesocosm facilities
Build open-ocean mesocosms	3		X	X	Plan and build shared multi-purpose open-ocean mesocosm facilities
Modeling					
Incorporate OA into coastal and regional biological-chemical-physical models; conduct simulations for historical, present-day and projected future conditions	1	X	X		Assist in design of experiments; urgently needed in coastal regions; provide information for resource managers and for assessing socio-economic impacts
Enhance large scale global models	3		X	X	Needed to scale up regional models
Conduct model/data intercomparison exercises	1	X	X	X	Needed to validate model output

Table 1. *Continued*

Activity	Priority*	0–2 years	2–5 years	5–10 years	Rationale
National & International Coordination					
Establish a national program on ocean acidification	1	X	X	X	Coordinate U.S. interagency activities
Initiate international coordination to develop an international program on ocean acidification	1	X	X	X	Create global network of observations and process studies; take advantage of existing facilities and expertise where available
Education & outreach					
Train graduate students, post-docs, PIs in OA research methods	1	X	X		Develop a cadre of scientists to undertake OA research at all levels
Establish OA website and public outreach programs	1	X	X		Educate stakeholders, public

2.1 Immediate Priorities (0–2 years)

Technical Needs

Workshop participants agreed that it was essential to develop standardized measurement protocols and data reporting guidelines for ocean acidification research as soon as possible. An internationally agreed upon guide to best practices for OA research is critical for the comparison of results across space, time, and laboratories. Participants agreed that the inorganic carbon system should be monitored throughout CO_2-perturbation experiments and that certified reference materials should be used to estimate accuracy and precision of CO_2 system measurements. Because certified reference materials currently exist for total dissolved inorganic carbon and total alkalinity (http://andrew.ucsd.edu/co2qc/), and standards for $p(CO_2)$ measurements are also available, these parameters of the inorganic carbon system in seawater are recommended for measurement during CO_2-manipulation studies. Standardized protocols with well-defined accuracy and precision are urgently needed for the following:

- Calcification rate measurements of planktonic and benthic calcifiers, including comparison of different methods;
- Manipulation of seawater CO_2 chemistry for perturbation experiments, including comparison of CO_2 bubbling and acid/base manipulation experiments;
- Measurements of seawater CO_2 system parameters and pH for laboratory and field studies;
- Respiration rate measurements; and
- Calcium carbonate ($CaCO_3$) dissolution rate measurements of diverse biogenic carbonates.

Currently, $p(CO_2)$ and pH sensors are available for stationary platforms and underway shipboard measurements. However, as $p(CO_2)$ and pH co-vary strongly, they are not the ideal parameters to measure if other components of the carbonate system are to be determined from them. Consequently, workshop participants emphasized the vital importance of developing autonomous systems for measurement of additional parameters of the seawater CO_2 system, particularly total dissolved inorganic carbon (DIC) or total alkalinity (TA). Prototype systems for these parameters exist, which can be deployed *in situ*. However, they require additional engineering before they are robust enough to be distributed widely throughout the community and used in routine operations on mid-ocean platforms that are only infrequently accessible. The engineering skills needed to transition prototype instruments from academic labs to commercial products are not widely available in oceanographic institutions. Further, commercial entities cannot transfer the expense of this engineering to users because the costs spread over a relatively modest number of units makes purchase prices too high. One option to solve this problem is establishment of a national center for instrument development. Additionally, experimentalists voiced a strong need to develop new methods for high quality measurements of at least two parameters of the marine CO_2 system suitable for small volume samples ($\leq$5 ml).

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Field Observations

The existing oceanic carbon observatory network provides insufficient *in situ* observations of sea surface carbonate chemistry and pH to adequately address the problem of ocean acidification. Expanding this network with new carbon and pH sensors will provide new information on the changing conditions in the Atlantic, Pacific and Indian basins, which are currently grossly under sampled. In addition, the current carbon observatories only accommodate measurement of the partial pressure of CO_2 (pCO_2), which is insufficient to fully constrain the carbonate system necessary for effective monitoring and forecasting biological effects. Ideally, this network would also have the capability to measure calcification and $CaCO_3$ dissolution rates, and such measurements are needed to improve models in order to predict responses to ocean acidification. Leveraging existing infrastructure and monitoring programs will enable research to be conducted efficiently and quickly. For example, additional inorganic carbon system measurements and process studies could be conducted at Long-Term Ecological Research sites such as those in the California Current, Moorea, and near Palmer Station, Antarctica. However, new monitoring sites, time series stations and surveys are urgently needed in open-ocean and coastal regions. To create a global network of observations, for example, new moored buoys equipped with carbon system sensors should be added each year starting immediately (Figure 2).

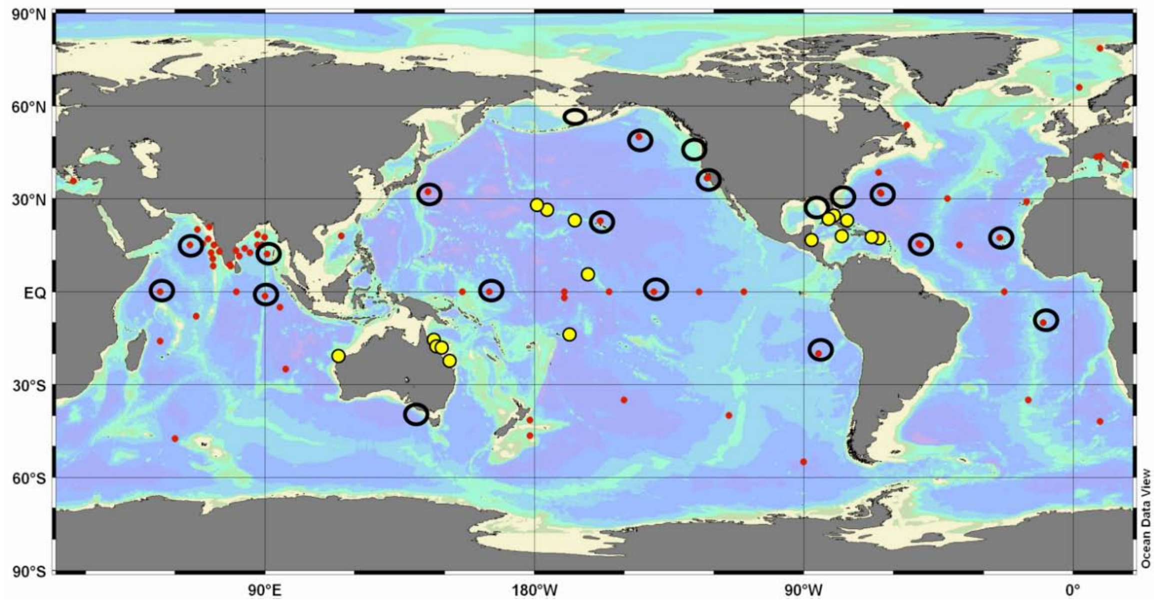

Figure 2. Potential ocean acidification monitoring sites in coral reefs and open ocean regions. ● OceanSITES moorings; O Ocean acidification monitoring sites; ◯ Coral reef monitoring sites.

Manipulative Experiments

Workshop participants agreed that controlled laboratory experiments are essential to investigating potential OA impacts. Experimental approaches must consider the possibility for interactions between the effects of increasing $p(CO_2)$ and other variables such as temperature, nutrients, light, and trace metals. Additional experimental data are urgently needed on the impacts of reduced carbonate saturation states on all life stages of a variety of calcareous organisms, particularly those species that are ecologically or economically important. However, responses to OA are not limited to calcification (or even dissolution). Fecundity, metabolism, and other physiological processes of both calcifying and non-calcifying organisms may also have sensitivities to changing ocean CO_2 chemistry. Research is urgently needed to identify which physiological and biogeochemical processes are sensitive to increased CO_2. Facilities to perform well-controlled CO_2 perturbation experiments are vital.

Processes currently known to be affected by ocean acidification (*e.g.*, calcification, dissolution, nitrogen fixation) are "ripe" for investigation at the ecosystem level – either in mesocosms or in small-scale field experiments, and planning for such investigations should start in the near-term. Potential effects of ocean acidification on other processes should be investigated further (*e.g.*, laboratory experiments) prior to undertaking large-scale investment of field campaigns.

Modeling

Participants highlighted the need to integrate modeling into the design, execution, and interpretation of field observation studies and manipulative experiments. Opportunities for interaction and communication between modelers and experimentalists are essential. There is an urgent need to develop coastal and regional models of OA changes in seawater chemistry coupled with ecosystem processes including trophic dynamics and biogeochemical cycles in the water column. Models are critically needed to assist in the design of field programs and to synthesize research results. Model benchmarks/intercomparison studies are needed and should be planned in the near-term.

2.2 Intermediate-Term Priorities (2–5 years)

Technical Needs

During the next 2–5 years, it is anticipated that additional autonomous measurements of parameters of the inorganic carbon system (DIC, TA, pH) and physiological stress markers (including genomic tools) will become available. These new sensors will serve an increasingly important role in detecting OA-related changes in multiple ecosystems and over large spatial scales.

Field Observations

Regional networks of ocean acidity observations and process studies should be developed. As new autonomous sensors become available, they should be added to existing moored platforms, floats and gliders. High precision pH sensors and PIC sensors are currently in development for deployment on profiling floats and moorings. We can anticipate that they will also become available for autonomous measurements within this timeframe. This would allow the initiation of specific experiments designed to establish the feasibility of operating a global ocean acidification observing system in all ocean regions. Ecological monitoring studies in key habitats should be continued.

Manipulative Experiments

Planning for shared-use, mesocosm facilities should begin. Mesocosm experiments may be necessary to address questions and test hypotheses regarding possible OA-mediated effects on marine communities such as those involving changes in species interactions, shifts in community structure, and biogeochemical impacts. Because of the expected costs of such facilities, mesocosm facilities must emphasize flexibility. Planning should consider the feasibility and desirability of designing such facilities so that they can relocate to other regions/study sites.

Modeling

Regional ecosystem/biogeochemical models should be parameterized with new experimental and observational results and used to identify "tipping points" beyond which irreversible ecological changes occur. Regional models of OA-impacts should be scaled up to global models. Another potentially useful product would be the development of a regional OA index that would succinctly incorporate the frequency, duration, intensity and extent of acidification into a single parameter, following other indices that represent complex processes such as ENSO, PDO, NAO, or upwelling intensity. Marine ecosystem-biogeochemical models with OA should be used to develop projections of future OA impacts following a suite of CO_2 emission scenarios. A hierarchy of biological models is required, spanning from physiological simulations for targeted organisms to more integrated ecological simulations. Physiological models will need to consider organism life histories including both juvenile and adult stages and need to be closely coupled with laboratory and mesocosm studies. Preliminary efforts should be initiated to integrate natural science models with economic and resource models to estimate potential future socioeconomic impacts of ocean acidification as well as impacts on human health and nutrition.

2.3 Long-term Priorities (5–10 years)

Technical Needs

Within the next 5-10 years, diverse genomic and molecular tools should become readily availability for the *in situ* assessment of CO_2-sensitive physiological processes in different ecologically and economically important organisms.

Field Observations

An international, global network of ocean acidity observations and process studies should be established. Autonomous sensors on moored buoys, floats and gliders should be used extensively. Chemical (dissolved oxygen and nitrate) and bio-optical (chlorophyll fluorescence and light scattering) sensors are now routinely deployed on platforms such as profiling floats and they have demonstrated long-term stability for multi-year periods. If pH and PIC sensors now in development are demonstrated to also have multi-year stability, a globally distributed, ocean acidification observing system could be established. This system could link direct observations of ocean acidification with changing biogeochemical cycles, such as $CaCO_3$ production and dissolution, and it would provide the framework for a global assessment of the impacts of increasing carbon dioxide levels. Ecological monitoring using satellite data and other technologies (*e.g.*, LIDAR to discern structural changes in coral reefs and rapid methods to quantify abundances and distributions of key planktonic taxa) will enable detection of some potential OA-related changes over regional and basin-wide spatial scales.

Manipulative Experiments

Mesocosm experiments and small-scale field experiments should be conducted in diverse coastal habitats. Free Ocean CO_2 Experiments (FOCE) should be planned and pilot tested in coral reefs. If logistical challenges can be successfully resolved, such FOCE experiments should be conducted in other regions as well.

Modeling

With additional data from manipulative lab, mesocosm, and field experiments, regional and global models can be improved. Regional and global risks associated with OA and climate change should be projected. Maximum atmospheric CO_2 levels that can sustain ecological functions of diverse marine ecosystems should be estimated. More mature models should be developed that integrate specific organisms with food web and ecological models. There also is a need to couple models of natural science with both socioeconomic and human health impacts of OA. Work should begin on decision-support tools for marine resource and conservation managers.

2.4 Data Management

Data management and dissemination must be an integral part of OA research with data management planning incorporated into both the design and implementation of field, laboratory, manipulative, modeling and remote sensing studies. Data must be reported and archived such that it is readily accessible now and in future decades. Participants suggested that data management for OA research be charged to the BECO–DMO Data Management Office. Additional existing data centers (*e.g.,* CDIAC) also manage OA-relevant data.

2.5 National Program and International Collaboration

Participants strongly endorsed establishment of an interdisciplinary U.S. national program on ocean acidification that would coordinate research activities among several U.S. federal agencies. There is a need to clearly define how the various agencies will work together in implementing an ocean acidification research program. Oversight by the Joint Subcommittee on Science and Technology could achieve this while recognizing the importance of ocean acidification as a separate research program that is independent from climate change research. Formation of an ocean acidification subcommittee that reports to the OCB Steering Committee and federal agencies is one mechanism that could facilitate this. Workshop participants also stressed the need for early international cooperation to develop a coordinated, global network of ocean observations and process studies that could leverage existing infrastructure and programs as far as possible, while noting the need for additional sites for monitoring and process studies aimed explicitly at ocean acidification. As previously noted, international coordination will also be necessary to agree upon standardized protocols for various OA research methods.

2.6 Education and Outreach

Workshop participants recognized the necessity for interdisciplinary training of graduate students, post-doctoral investigators, and PIs. Participants suggested holding multidisciplinary summer "boot camps" for experimentalists and modelers which would include national and international scientists. Initiatives for public outreach and education were also recommended. Meetings with coral reef managers, fisheries managers and other stakeholders should be held to engage specific communities to develop ideas for adaptation and mitigation strategies. Participants recommended tapping into existing programs to advance public education, such as the teacher-at-sea program. Readily accessible presentations and fact sheets on ocean acidification and its effects on marine life should be created for the public (including schools). Additional information should be made available via website (*e.g.*, OCB website, ocean acidification network website).

3. Research Implementation Strategies for Four Key Ecosystems: Warm Water Coral Reefs, Ocean Margins, Tropical/Subtropic Pelagic Regions, and High Latitude Regions

Meeting participants divided into four groups which met three times during the workshop. Recommendations and research priorities were developed for each of the key ecosystems. Instances of overlap across the individual reports are indicative of strong consensus among workshop participants. Specific research activities are organized by the following themes: technical needs, baseline monitoring, surveys, manipulative experiments, and modeling.

3.1 Group A: Warm Water Coral Reefs

Discussion leader: Joan Kleypas

Rapporteur: Marlin Atkinson

3.1.1 Introduction

The response of coral reef ecosystems to ocean acidification includes many issues common to all ocean ecosystems, but there are some important and unique problems. Coral reefs are shallow benthic ecosystems whose climax state includes the net accumulation of calcium carbonate to form geologic structures resistant to strong hydrodynamic conditions (Figure 3). Skeletal

Figure 3. Coral colony on the Panama reef where bioerosion has outstripped calcification (*photo by Dr. Tyler Smith, USVI*).

formation by coral reef organisms, particularly corals and calcareous algae, produce the great bulk of calcium carbonate that makes up the coral reef structure. Calcium carbonate production is thus central to this ecosystem in several ways. The organisms themselves depend on their calcium carbonate shells, but the ecosystem as a whole depends on reef formation, because the reef structure provides the spatial complexity necessary to support biodiversity, sedimentary stability, nitrogen fixation, and in times past, the ability to build the ecosystem upward with sea level rise, and maintain its position within the photic zone. Coral reef environments are shaped not only by the production of calcium carbonate rock and sediment, but also by the breakdown, transport and dissolution of that rock and sediment. The interactions between the reef structure, the reef community structure, and the hydrodynamic regime give coral reefs their high spatial heterogeneity. The typical reef zones change over 10–100 meter scales. Indeed, a coral reef system includes the typical fore-reef and reef crest zones dominated by corals and calcareous algae, and also the back reef lagoons and sediment aprons that support other ecosystems such as sea-grass beds and mangroves. This complexity contributes to the overall ecological, biogeochemical, and economic value of coral reef ecosystems, but it also results in a much more complex set of responses to ocean acidification than those currently expected in open ocean ecosystems.

Shifts in the balance between biogeochemical processes on the reef can either reinforce the decline in saturation state or counterbalance it. A decrease in the photosynthesis/calcification ratio, such as might follow a bleaching event, would reinforce the decline in saturation state. An increase in the photosynthesis/calcification ratio, such as might result from eutrophication would cause the saturation state to increase counterbalancing the change due to ocean acidification.

Studies on the response of coral reefs to ocean acidification have thus far concentrated primarily on the photosynthesis, respiration, calcification, and dissolution response of single coral species in small tanks under a limited range of conditions and a few larger scale mesocosm experiments on simple systems consisting of sediment, corals and coralline algae. The opinion of the coral reef working group is that these are but the first steps toward understanding the overall response of the coral reef system to ocean acidification. Most of our recommendations thus promote a research strategy that works toward understanding the response of the entire reef system. This strategy includes research priorities that fall within: (1) technical needs; (2) monitoring and observational needs; and (3) experimental needs. Table 2 lists the research priorities recommended by working group participants.

3.1.2 Technical Research Needs

Several important and urgent technical needs were highlighted. A most urgent need is to increase the quality of carbonate chemistry observations in reef systems, as well as the spatial and temporal resolution of those observations. This need can be met either by increased discrete sampling or improvements in autonomous instrumentation. Neither of these is readily available to the broader coral reef research community, which is delaying the acquisition of important baseline information regarding the spatial and temporal variability of the carbonate system on reefs. The main advantage of technical development of autonomous carbon system monitoring is the ability to obtain high temporal resolution measurements. The disadvantage is the likelihood of the high cost of implementing such instrumentation to cover the spatial heterogeneity of a reef system. Another option is to establish a centralized laboratory for processing water samples. This would facilitate water sampling by a broader array of researchers, and would increase comparability between the carbon system measurements. Such a lab might also establish the protocols and training for proper collection and preservations of samples, as well as training for individuals who wish to establish their own carbonate system laboratories.

A closely related priority is the establishment of calcification measurement protocols. There have been few intercomparison studies between the various techniques used to measure calcification and calcification rates. Many of the techniques, even when working with single organisms, are not directly comparable because they measure either gross or net calcification, or because the rate is normalized to different parameters, i.e. protein, mass, surface area. Field techniques vary widely with regard to the temporal and spatial scale the measurement represents, accounting for water residence time, *etc*. The working group thus recommends an intercomparison workshop that specifically addresses protocols for calcification measurements at organism, mesocosm and field scales.

A final priority is to reduce the large uncertainty in solubility parameterizations of biogenic carbonates. Estimates of the solubilities of biogenic high-magnesium calcites vary more than 5-fold and need to be better established with respect to kinetic effects related to skeletal characteristics specific to taxa and the environments in which they grow.

3.1.3 Baseline monitoring

There is an urgent need to put in place baseline monitoring of carbonate chemistry and biological responses at select sites in coral reefs to complement the time series stations already in place for the tropical/subtropical pelagic habitats at HOTS and BATS. This could include multiple platforms (ships, moorings). This is the only way to document how the chemistry in reef environments is changing as well as the rate of change. Monitoring over a minimum of 10 years may be necessary to detect the anthropogenic signal against the background of high natural variability in the CO_2 system on reefs. This effort should include measurements of fundamental community processes of organic and inorganic carbon production and destruction, as well as characterization of community structure.

Within this priority are strong recommendations to establish the spatiotemporal variability of carbonate chemistry and calcification/dissolution measurements across the various reef system environments, as a function of both physical-chemical and community-ecosystem variables. Retrospective analyses, such as those that can be obtained through skeletal banding and stratigraphic analyses are also recommended. These baseline studies should include the natural range of carbonate saturation states, from high latitude reefs and those in upwelling regions to equatorial reefs, as well as reefs from both terrigenous-dominated and carbonate-dominated settings. Finally, baseline conditions of reef systems should be augmented with high-resolution studies that will enable scaling up of habitat-related carbonate system measurements to the reef scale.

3.1.4 Manipulative Experiments

Meeting participants agreed that there is a priority need for manipulative experiments. These are experiments performed in the lab, in micro- or mesocosms, or in the field where the carbonate chemistry is intentionally manipulated and the organism or community responses are observed. Manipulative experiments are needed to expand our knowledge of the range of responses we can expect in the ocean in the coming 50-100 years and beyond. This needs to include a broad spectrum of calcifying organisms, but also should include non-calcifying taxa that may compete with corals for space, or are otherwise ecologically important in reef function (*e.g.*, picoplankton that may be an important source of primary production and nitrogen fixation). There is increasing agreement that these experiments should include multiple life stages. Related to this are two additional priorities: studies that establish the mechanisms of calcification across taxa and life stages, and cross-factorial studies that examine the interactive effects between saturation state and temperature, nutrients, and light on calcification/dissolution rates. It was widely agreed that the timeline for increasing our understanding of organism-level responses to ocean acidification, and the ability of organisms to adapt to these changes, could be enhanced through genomic studies.

As stated earlier, a consensus among working group members was the need for an integrated system approach to understanding ocean acidification effects on coral reef systems. The ultimate goal is an experimental design similar to that of the terrestrial Free-Air Carbon dioxide Experiments (FACE), whereby the seawater CO_2 chemistry of a coral reef system is elevated in the field for an extended period of time, allowing the response of the entire system to be measured at the organism, community, ecological, sedimentary, and biogeochemical perspectives. Full implementation of such *in situ* experiments still requires significant technical development and funding. However, working group members agreed there was a need for a research strategy that will inform and improve the design of Free-*Ocean* Carbon dioxide Experiments (FOCE). This research strategy includes three phases: planning, pilot study, and implementation. Planning for such experiments should begin now, to highlight the most important research needs and ensure the most efficient path toward understanding the full ecological and biogeochemical response of coral reef systems to ocean acidification.

Below is a list of specific recommendations for conducting various types of manipulative experiments.

a. Lab

Laboratory and microcosm experiments are needed to investigate the sensitivity of single and multiple species of key groups to elevated $p(CO_2)$ and temperature conditions. Several talks at the meeting demonstrated the importance of multi-factorial experiments to rooting out the response of organisms to future climate scenarios, i.e. sometimes there was only a response when both temperature and $p(CO_2)$ were increased. These studies should not be limited only to calcifying organisms. Effort should be made to identify molecular markers of ocean acidification stress response in different organisms. Can the metabolic cost of dealing with reduced pH and carbonate ion concentration of different organisms be measured?

b. Mesocosm

Participants considered the role of mesocosm-based research as a step toward developing techniques for field research and to test specific questions that can be transferred to field experiments for verification in a real reef environment. Pilot studies should include both mesocosm experiments and small-scale CO_2 fertilization experiments within natural environments. Some existing field/lab facilities are already well suited for these types of experiments (Figure 4). Some concern was raised over public opinion and regulations related to artificial acidification of natural reef environments, and conducting reverse experiments (*e.g.*, CO_2-removal) was mentioned as a possibility; however, these experiments would realistically test a narrow range (*e.g.*, restoring to preindustrial conditions is a 100 ppmv change in atmospheric CO_2 forcing), and the technical challenges of removing CO_2 are greater than for adding CO_2.

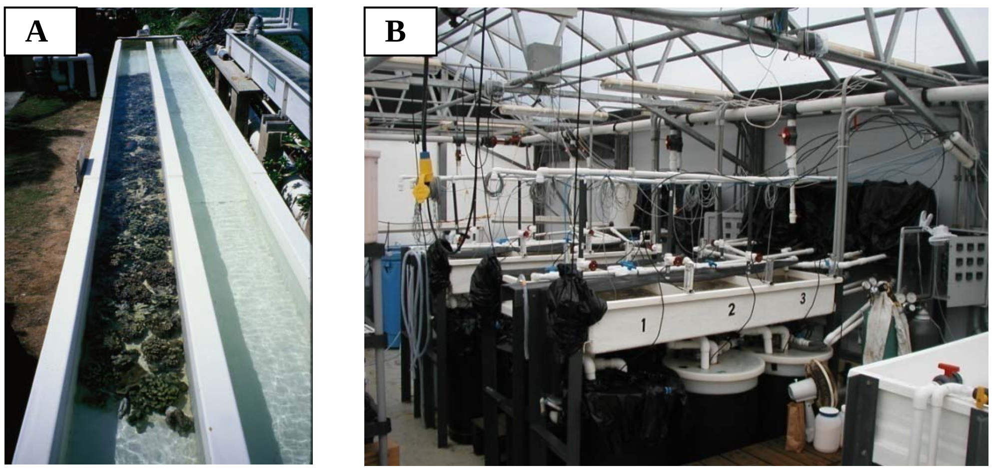

Figure 4. A. Flume mesocosm at the Hawaiian Institute of Marine Biology. B. South Florida Corals and Climate Change Laboratory at the University of Miami in which corals and other organisms grow under controlled temperature and CO_2 conditions in natural light. (*Photo courtesy C. Langdon).*

c. FOCE

Similar to the FACE program, a successful FOCE program would include a network of reef sites. Like terrestrial systems, coral reefs include a broad array of reef types (fringing, atoll, barrier), community composition (*e.g.*, high versus low species diversity), and environmental settings (*e.g.*, high versus low latitude; terrigenous versus carbonate; turbid versus clear waters). These types of experiments will by far provide the best measures of reef response to ocean acidification and will allow accurate predictions of reef response into the future, as well as provide insights into management strategies that minimize impacts. Given our current gaps in technology, modeling, mechanistic understanding of reef systems, and funding, such experiments may not be feasible now, but participants set a goal of five years to work toward successful implementation of the first FOCE-like experiment.

An alternative to meeting the engineering challenges that would be required by FOCE experiments would be to look for natural CO_2 seeps in the vicinity of reefs. An example of such a site is a shallow water benthic carbonate ecosystem (non-coral reef) in the Mediterranean (Hall-Spencer *et al.*, 2008). The abundance of carbonate secreting organisms decreased with proximity to this seep, while that of the non-calcareous algae and sea-grass communities increased, providing insights into community structure changes across a strong gradient in the seawater inorganic carbon system. Field experiments could thus be designed to take advantage of natural CO_2 sources driving local ocean acidification, although no similar vents have yet been identified in coral reef regions. Also, the spatial scale of the gradient is important; if one wishes to observe the potential for adaptation of organisms to the local acidified conditions, the seep must affect an area greater than the region occupied during the life history of those organisms.

3.1.5 Field Experiments

Participants at the meeting were in agreement that the ultimate proof that ocean acidification is adversely impacting the health of a coral reef is to observe the evidence in the field. This work needs to go forward in parallel with the lab, micro- and mesocosm studies. We envision that new methods will first be tested under controlled conditions in the lab and outdoor mesocosm facilities but they should be brought into the field as early as possible. Lab and mesocosm studies have demonstrated a causal link between the saturation state of the ambient seawater and the calcification rate of a wide range of coral and algal species. Therefore, it is reasonable to hypothesize that the carbonate saturation state of seawater may impose a fundamental biogeochemical limit on the development of coral reefs, just as temperature and light do, and that a significant reduction in seawater saturation state may cause fundamental changes in ecosystem function, community structure and biodiversity. Much like how an excess of nutrients can give rise to anoxia (scarcity of O_2) and in turn to drastically reduced productivity and biodiversity of aerobic organisms, an excess of CO_2 may give rise to a scarcity of carbonate ions that in turn will result in reduced activity of calcifying organisms and ultimately to a decrease in the abundance of carbonate secreting organisms (*i.e.*, a loss of biodiversity and a fundamental shift in community structure and ecosystem function).

Field experiments need to include careful, high precision measurements of seawater chemistry and, where applicable, calcification rates. These measurements need to be made in many different types of environments on the reefs, in recognition that the reef comprises several different zones, each containing biota evolved to adapt to that zone's particular set of environmental conditions. Therefore, organisms in different reef zones may exhibit variable sensitivity to changes in seawater carbonate chemistry depending on the range they normally experience in their specific zone. Work should not be limited to the study of calcification. The soft tissues of the corals are responsible for carrying out the process of biomineralization. Factors that impact the condition of this tissue, such as changes in the supply of dissolved or particulate nutrients, photosynthetic output of the zooxanthellae, disease, or the amount of energy devoted to reproductive activity, may have an indirect impact on calcification rates. With time, changes in organism physiology will be reflected in changes in the abundance of these organisms and ultimately in a shift in the structure and function of the ecosystem. Therefore, field studies should also include efforts to observe potential shifts in community structure that may reflect an underlying shift in carbonate saturation state of seawater.

A recent paper by Cooper *et al.* (2008) reported that the calcification rate of massive *Porites* corals on two widely separated reefs on the Great Barrier Reef declined by 21% between 1988 and 2003. Given the remoteness of these reefs and their protected status, this decline may reflect the influences of warming and acidification. These data, therefore, provide an estimate of the magnitude of the climate change signal, *i.e.*, approximately 1.3% y^{-1}.

To determine whether human activities are adversely affecting the health of coral ecosystems, a global network of coral reef observations is necessary. To achieve this goal, it will be necessary to monitor critical coral reef characteristics (calcification rate and community structure at a minimum) in addition to temperature and carbonate chemistry at a representative sampling of coral reefs around the globe. The magnitude of the observed changes in the field can be compared with results from lab and mesocosm sensitivity studies to assess cause and effect responses. Detecting climate change effects on coral reef calcification will require significant improvement of current measurement techniques to broaden the spatial scale of measurements so that whole reef systems are represented, not only lagoons or reef flats. Such new measurements must yield average rates over weeks to months rather than the currently reported hourly rates and must be able to be applied widely and over long time periods to provide an integrated view of how the complete reef ecosystem is responding. The classic Eulerian and Lagrangian methods need to be automated using autonomous sensors or automated water samplers. New methods of determining water residence time using geochemical tracers and numerical modeling should be investigated in order to improve the accuracy and temporal and spatial resolution of the alkalinity depletion method. The potential to adapt methods from air-sea CO_2 flux work should also be investigated.

To ensure a representative look at how reef systems will respond to ocean acidification, monitoring sites should be established across a spectrum of coral reefs in the Pacific, Indian and Atlantic Oceans. These sites should be located far from the influence of humans so that the observed changes can reasonably be attributed to climate change alone. These sites should also fully exploit the natural range in seawater carbonate saturation state. Low latitude reefs in the Atlantic, Pacific and Indian (but not near equatorial upwelling) could provide a high saturation state end member to the study. These could be contrasted with reefs located in the eastern tropical Pacific that are naturally bathed in low saturation state water during the upwelling season. Lagoonal reefs with long residence times may also provide opportunities to study the impacts of naturally low carbonate saturation state conditions.

Test bed reefs

Before the field monitoring efforts begins it will be advisable to conduct trials at a few test bed sites to check out new methods, make sure they agree with the tried and true methods and find out which are most promising. These test bed sites would have the following attributes:

- Convenient accessibility to investigators;
- Existing infrastructure for supporting research;
- Simple hydrodynamics;
- Existing environmental and ecosystem information; and
- Reasonably high coral cover so calcification signal is strong.

Examples of locations meeting these criteria include Kaneohe Bay, Hawaii; Moorea, Tahiti; Bermuda; La Parguera, Puerto Rico; and Heron Island, Australia.

3.1.6 Modeling

The planning stage should include a strong modeling component to guide the design and inform the selection of potential reef test sites. Several existing models such as the Shallow-water Ocean Carbonate Model (SOCM) which is a process-driven biogeochemical box-model, are well suited for this work, and should be developed side-by-side with ecological models, and pilot and field studies described above.

Models are needed to constrain the temporal and spatial variability of carbonate chemistry of the scale of coral reefs and biological/biogeochemical responses, as well as to explore the mechanisms controlling this variability. To accomplish this, a wide range of modeling efforts at different scales are required, including physiological/biomineralization models of individual coral polyps and reef organisms, spatial high resolution population and community models, full ecological/food web models, and basin to global scale models integrating coral reefs into large-scale ocean biogeochemistry. Models investigating carbonate dissolution processes including the effect of seawater carbon chemistry in conjunction with microbial remineralization of organic matter and bioeroders are also needed as integrated components of ecosystem scale models. It is also important to establish model benchmarks for regional nested biogeochemical models, as well as global models, in order to ascertain the accuracy of future predictions of ocean acidification. A useful modeling product will be high-resolution maps that assess the risks of reefs around the world to decline once established thresholds are exceeded.

Table 2. Research priorities for warm water coral reefs. Activities are prioritized as follows: (1) **Urgent and Important; (2) Important; (3) Desirable. The recommended time window within the 0-10 year timeframe for each activity is denoted with "X"**

Activity	Priority	0–2 years	2–5 years	5–10 years	Rationale
Technical needs					
Develop protocols for lab and field calcification measurements	1	X			Lab and field calcification measurements need to be expressed in similar units so that are intercomparable
Develop remote sensing methods for classifying benthic habitats	2		X	X	Needed for scaling up small-scale studies to whole reef scale
Develop genomic techniques for corals	2			X	Need to find genes that are expressed when a coral is under low saturation state stress
Refine solubilities and kinetics of biogenic carbonates, particularly high Mg-calcites	2		X	X	Labile biogenic carbonates will be first "responders" to ocean acidification; needed to develop reef $CaCO_3$ budgets
Baseline monitoring					
Conduct paleostudies of coral growth and skeletal chemistry	1	X	X	X	Provide valuable information on historical coral responses to changes in temperature and possibly pH using ^{11}B
Establish a network of water sample collection and CO_2 chemistry moorings	1	X	X	X	Need to establish spatio-temporal variability of carbonate chemistry in reef waters. May need to start with a program of collection of bottle samples but should move to mooring as soon as a reliable sensor of second carbonate parameter becomes available
Surveys					
Conduct high precision, high-resolution measurements of species abundance, coral reef calcification and photosynthesis at a subset of carefully selected coral reefs	1	X	X	X	Need to establish a baseline in these measures of coral reef metabolism so that change can be detected. Sites should be widely distributed and chosen to include a wide range of natural carbonate saturation states
Conduct repeat field surveys	2		X	X	Species abundance, calcification and seawater chemistry need to repeated over a minimum of 10 years in order to ensure a sufficient time period for

					detecting a climate change signal
Conduct repeat LIDAR surveys	3			X	Carefully benchmarked, such surveys provide the opportunity for detecting structural loss or changes on coral reefs

Table 2. *Continued*

Activity	Priority	0–2 years	2–5 years	5–10 years	Rationale
Manipulative experiments					
Conduct lab experiments with representative number of coral species and other reef species at all life stages	1	X	X	X	Test interactive effects of CO_2 with temperature, nutrients, light, etc. to understand the underlying processes essential for developing predictive models.
Conduct mesocosm experiments to investigate species interactions under elevated CO_2	1	X	X	X	Examine whether low saturation state influences interactions between corals and bioeroders, between coral larvae and crustose coralline algae, and between corals and macroalgae
Investigate importance of $CaCO_3$ saturation state buffering through dissolution in mesocosms or natural environments	2		X	X	Determine whether dissolution proceeds rapidly enough in some environments to buffer the drop in saturation state
Build and share infrastructure	1	X	X	X	Build common facilities that can be shared by investigators for culturing organisms under controlled CO_2 and temperature
Modeling					
Develop organismal physiological and biomineralization models; and ecological population and community models	1	X	X	X	Required to understand consequences of OA at cellular, organismal, community and ecosystem levels.
Construct dissolution models of carbonate sediments, substrates and structures	1	X	X	X	Determine how carbonate dissolution is affected by surface water OA, microbial mineralization of organic matter and bioerosion
Develop biogeochemical reef and regional models	1	x	x	x	Needed to assist in design of field experiments, synthesize what has been learned and to make future predictions under different CO_2 emission scenarios
Integrate coral reefs into large-scale ocean biogeochemistry models	2		x	x	A significant fraction of global PIC accumulates in coral reef regions

3.3 Group B: Coastal Margins — Coastal and Estuarine Regions

Dicussion leader: Burke Hales

Rapporteur: Richard Jahnke

3.3.1 Introduction

Ocean margins play a potentially dominant role in setting the net carbon balance—and hence the acid-base balance—of the open ocean. Approximately 1 Pg C y^{-1} is delivered globally to estuaries by rivers and approximately half of global ocean export productivity occurs in ocean margins; yet essentially none of this material can be accounted for in long-term preservation reservoirs such as marine sediments; similar arguments can be made for alkalinity. This argues for a state of net heterotrophy in coastal settings. However, the preponderance of evidence suggests that coastal oceans are *net sinks* for atmospheric CO_2, which argues against this. The form and magnitude of carbon and alkalinity exchange between the coastal and open oceans are poorly constrained, but may be large.

Variability in carbonate system parameters is extreme over a wide range of space and time scales (Chavez *et al*., 2007; Feely *et al*., 2008). Regularly-experienced conditions currently exceed Y2100 'worst-case' IPCC projections for atmospheric-equilibrium $p(CO_2)$, and are currently corrosive to aragonitic and high-magnesium calcite mineral phases (Feely *et al*., 2008). The variability is such that, while we probably do know the dynamic range in acidic conditions, we do not yet have a sense of other statistical parameterizations such as frequency distributions.

Recently it has been suggested that organisms growing in waters along the west coast of the United States may already be experiencing large impacts as a result of the synergistic effects of coastal upwelling and ocean acidification (Feely *et al.*, 2008). During upwelling along this coast, water with increased CO_2 levels, resulting from organic mineralization through respiration at depth, is brought onto the shelf and into the surface ocean (Figure 5). It appears that this water, in addition to its original high levels of CO_2 by virtue of its subsurface source, is also significantly contaminated with anthropogenic CO_2 as it was last in contact with the atmosphere only 50 years ago and thus has taken up additional CO_2 from the atmosphere. An immediate consequence of this is that the CO_2 concentration in upwelled water at any particular site will be greater than it would have been in preindustrial times. Similarly, the areal extent of the coastal ocean that exceeds a particular threshold CO_2 value (or that is below a particular carbonate saturation state) will be greater than in prior decades. Furthermore, each year will draw on water that has been exposed to the atmosphere still more recently, resulting in yet higher CO_2 levels, lower pH and lower saturation states.

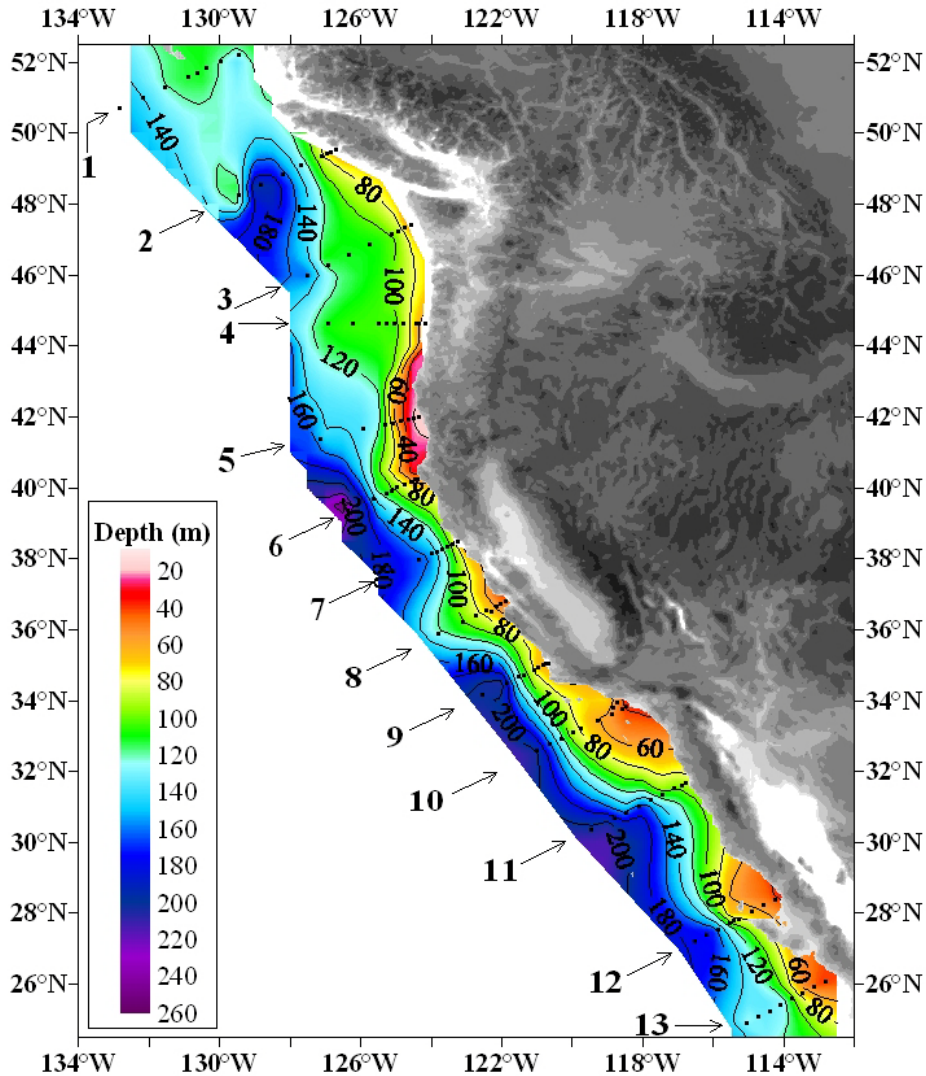

Figure 5. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada to San Gregorio Baja California Sur, Mexico. On transect line 5 the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations. (From Feely *et al.*, 2008)

As a result, there is a potential for this enhanced level of acidification, especially when combined with the observed low O_2 levels found in the upwelled waters (Bograd *et al.*, 2008), to exert significant impacts on organisms and their associated ecosystems both in the natural environment and in coastal mariculture facilities.

Coastal and estuarine ecosystems are subject to several anthropogenic acidity inputs. These include hydrologic changes to freshwater input, watershed land-use changes, acid deposition, and eutrophication-respiration. Owing to acidification, as well as other processes associated with carbon degradation, a quantitatively significant proportion of biogenic $CaCO_3$ produced shoreward of the shelf-break can dissolve in both terrigenous and carbonate sediments underlying waters saturated with respect to carbonate minerals. Several studies have explored the effect of exposure to carbonate undersaturation at the water-sediment interface on calcifying fauna in such coastal regions. For example, Green *et al*. (2004, 2008) showed that death by dissolution is an important size-dependent mortality factor for aragonitic juvenile bivalves (the clam *Mercenaria mercenaria*) when these larvae are exposed to sediments undersaturated with respect to aragonite (Figure 6). Commercially important mussels and oysters have reduced calcification rates in response to elevated CO_2 and decreased saturation state of seawater with respect to aragonite (*e.g.*, Gazeau *et al*. 2007; Kurihari *et al.,* 2008). Sea urchin larvae, which secrete high magnesium calcite, are also adversely impacted by high CO_2/low pH water (Kurihari and Shirayama, 2004). These studies suggest that continued acidification of coastal waters could have catastrophic effects on shellfish populations. Currently, the annual U.S. landing of three bivalve species alone — the clam *Mercenaria mercenaria,* the scallop *Argopectin irradians*, and the oyster *Crassostrea virginica* — exceeds 200 million dollars (Voorhees, 2007); the ecosystem services these species provide may far exceed that amount.

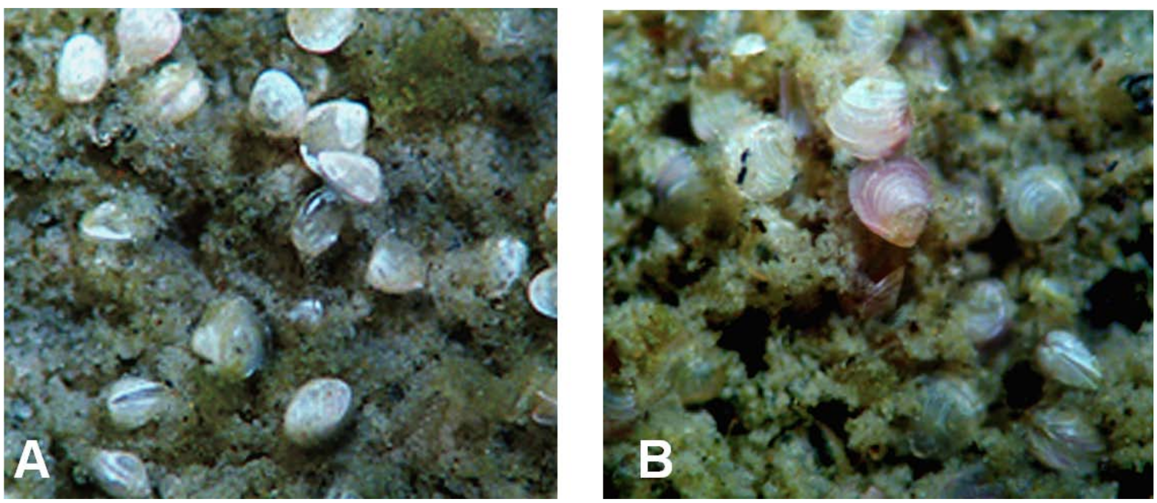

Figure 6. Photographs of juveniles of the hard shell clam *Mercenaria mercenaria* after ~ 24 hour exposure to (A) experimental sediments in which the sediment pore waters were undersaturated with respect to aragonite and (B) control sediments in which sediment pore waters were supersaturated with respect to aragonite. Bivalves in undersaturated sediments show evidence of massive shell dissolution compared to controls (after Green *et al*., 2004).

The exposure of viable ecosystems to extreme conditions presents unique natural-experiment opportunities that strike to the heart of OA research questions: Are ecosystems that regularly experience low pH conditions in today's environment more likely to be pushed past 'tipping points' by continued anthropogenic acidification? Alternatively, do these systems possess elasticity that makes them more likely to adapt to changing conditions? In either case, such systems that experience wide variability in seawater pH/CO_2 chemistry may be useful models of how ecosystems in less variable settings might respond to OA.

In coastal margin systems, close juxtaposition of dominant process-regimes (benthic/water-column; terrestrial/ocean; pelagic/coastal) forces holistic research approaches to carbon cycle (and hence OA) research. Over-specialization carries huge risk in these settings, more so than in less variable environments. This multiplicity of processes complicates the isolation of OA impacts on coastal systems more so than in other systems. Many other potential perturbations (beyond CO_2 increase and warming), from fishing activities to urbanization to shoreline modification to watershed usage changes, may co-vary with OA forcing. Interpretation of natural experiments will face significant challenges as a result of this lack of a true 'control' case.

Nevertheless, the substantial importance of coastal margins to regional and national economies and human health warrant scientific investment aimed at forecasting the impacts of OA on coastal ecosystems and resources.

Human impacts are felt in the marginal setting in ways that are more immediate than in pelagic settings. Over half of the population of the USA now lives within a half-hour drive of our major coastlines, and direct anthropogenic impacts such as pollutant discharge, coastline modification, river-discharge modulation, watershed land-use changes fishing activities, etc. affect margin carbon cycling in more direct ways than in more remote pelagic settings (see Hales *et al.,* 2008). Such effects may be additive with those from OA and need to be considered in designing observational and experimental studies.

Human influences in coastal settings may strongly facilitate OA research. Long histories of observations, both as a result of scientific research programs (*e.g*., CUEA, CalCOFI, COOP, OMP, GLOBEC) and monitoring efforts from federal to local levels, provide abundant historical data that have not yet been synthesized from the perspective of OA study. The proximity to infrastructure, ranging from dedicated research vessels and marine science labs to coastal fisheries and tourism vessels to aquaculture facilities to infrastructure that could serve as observational platforms (weather and navigational buoys, piers, jetties, bridges, *etc*.) greatly increases the feasibility of many potential observational or experimental studies over other more remote environments.

The high variability experienced by the ocean margins, and the abundance of potential observation platforms, calls out for development of more accessible technology for measurement of relevant parameters. While state-of-the-art accuracy is still essential for assessing long-term responses of any ecosystem to rising atmospheric CO_2, it may be worthwhile to consider new systems that offer increased ease-of-use and speed of analysis, even if those come at the expense of somewhat reduced precision.

3.3.2 Technical Needs for Measurements and Monitoring

The core measurements constraining the physical, chemical, and biological environment in coastal margins include winds, currents, temperature, salinity, nutrients, O_2, carbonate system parameters ($p\mathrm{CO}_2$, DIC and TA) and pH. Biomass standing stock measurements (*e.g.*, particulate inorganic carbon, particulate organic carbon, chlorophyll) typically made in open ocean projects, should be included in ocean margin monitoring, survey, and process studies. These studies should additionally include, as appropriate, information about tides and river discharges, sediment transport, measurements of potential tracers of hydrological or aeolian inputs from the adjacent terrestrial environment, pollutant species, etc. The list could rapidly grow out of all proportion or feasibility; however, this should not be interpreted to mean that no study should proceed without exhaustive coverage of the above list. Ultimately, OA is related to carbon cycling, and a host of measurements have relevance as a result. The most immediate need for observation with existing technology is to incorporate high quality measurements of the inorganic carbon system into coastal observations, including routine water quality monitoring programs.

There are significant shortcomings in existing measurement technologies that should be addressed immediately as well. There are no reliable, specific indicators of OA-induced stress at the population or community levels. Efforts should be undertaken at the earliest opportunity to develop such indicators. Additionally, the nature of the coastal ecosystems calls out for abundant monitoring sites, however, high quality carbonate measurement techniques are currently beyond the budgets and/or expertise of all but a few groups. Participants suggested that (1) development of lower-cost, user-friendly dual-parameter analytical systems; (2) creation of centralized facilities where samples can be analyzed at low-cost; and (3) offering training services where novice users can learn to make quality measurements would all lead toward improved data quality and expanded spatial and temporal coverage of monitoring.

Preferably, measurements should cover the shortest spatial (1–10 km) and temporal (tidal) scales of variability. There are, however, longer time (up to interannual) and space (up to regional) scales that would be valuable for study. A potential model for designing long-term studies would be to identify a few ocean margin 'regimes' (*e.g.*, ice-impacted high-latitude; temperate upwelling; river-dominated; and tropical) that could each be the subject of repeated, detailed, seasonal monitoring efforts. Again, these large-scale long-term goals should not be interpreted as exclusive of smaller efforts. The immediate implementation of existing observational technologies on existing platforms, even if at sub-optimal resolution and coverage, should be encouraged even in the absence of more comprehensive efforts.

Research is urgently needed to addresses questions on the affects of OA on the many biological resources of coastal and estuarine regions that contribute to local and regional economies. One immediate area to explore are calcifying groups that are field-harvested commercially or grown in mariculture. Future investigations should focus on the interactions of OA effects on different life stages and development rates of these and other calcareous organisms. Could thinner, weaker shells impact predation rates? How will planktonic larval survivorship, settlement and post-settlement success be impacted? If populations of these calcifying organisms fail, how will this affect predators that depend on them as food? If populations of filter-feeding bivalves are reduced, would this lead to increased frequency of algal blooms and decreased water quality as, for example, observed in the Chesapeake Bay?

Investigation of potential biological impacts should not be limited to calcareous organisms, however. An emerging paradigm in marine science is the elastic ability of jellyfish to dominate in stressed marine environments, and many studies have raised the possibility that gelatinous zooplankton populations are increasing worldwide (reviewed by Purcell *et al.*, 2007). Possible explanations for this phenomenon include increased ecological space due to overfishing, introductions of exotic species, and climatic changes. Medusae are known to be present in waters with very low oxygen concentrations and in some cases anoxic waters, and the physiological mechanisms that allow jellyfish to thrive in low oxygen environments have recently been described (*e.g.*, Rutherford and Thuesen, 2005; Thuesen *et al.*, 2005). Typically, hypoxic waters are also high in CO_2 with a corresponding decrease in pH, yet no information exists on the effects of hypercapnia and lowered pH on the physiology of gelatinous zooplankton. In a recent analysis of 43 y of Continuous Plankton Recorder (CPR) data from the North Atlantic Ocean, Attrill *et al.* (2007) reported that the increase in the frequency of nematocysts in CPR samples was correlated with the decrease in pH of seawater. Because jellyfish compete with fish larvae as well as prey on them, changes in jellyfish populations could affect coastal food webs, with possible impacts on commercial fin fisheries.

The ocean margins are uniquely suited for exploitation of existing infrastructure and study sites. The sites of previous studies have the advantage of possessing a body of knowledge regarding the ecosystems' functioning that would facilitate devising and executing OA-focused studies. The existence of marine institutions' coastal field labs and ship operations facilities provides significant logistical, technical and human resources that could be applied to OA research. The future development of cabled observatories through the Ocean Observatories Initiative (http://www.orionprogram.org/OOI) will only increase these resources. The only drawback to use of these facilities is that they were not originally designed with OA-specific research in mind, and will require some adaptation by OA researchers to take full advantage. OA research themes should be taken into consideration as OOI implementation moves forward.

Recommendations:

1. Develop robust ocean acidification monitoring network for coastal waters including repeat hydrographic surveys, moorings, gliders and drifters**.**
2. Develop affordable, robust technology that can be deployed abundantly in coastal settings, capturing the many scales of variability affecting carbon cycling and the acid-

base balance in the ocean margins. Specifically, development of small, inexpensive, multi-parameter measurement systems that could take advantages of existing infrastructure unique to the ocean margins—such as bridge supports, jetties, piers, navigation buoys, and small commercial and research vessels – is a high priority.

3. Develop physiological or ecological indicators of OA-induced stress that could be applied to readily-accessible organisms (e.g., clams, mussels, oysters, barnacles, sea urchins, fish larvae) either in native or aquacultured conditions.
4. Create "OA Research Centers' based on existing marine research facilities, where the infrastructure to perform state-of-the-art OA research exists or can be developed. Specific examples of such infrastructure would be the maintenance of standard gases, instrumentation and supplies for high quality measurements of total alkalinity, total dissolved inorganic carbon, and pH in seawater; standard cultures of OA target species; aquaria laboratories; and small mesocosm apparatus.

3.3.3 Baseline Monitoring, Survey and Process Studies

Because of the high variability in ocean margins, and the close proximities of different ecosystems, ocean margin survey and process studies must be carefully planned to assure that key features of ecosystems are appropriately identified and incorporated into experimental designs. Benthic environments, estuaries, river plumes, intertidal regions, pelagic/coastal interfaces all play key roles in defining ocean margin ecosystems and carbon cycling. This complexity increases the difficulty of isolating OA effects on coastal ecosystems. This aspect of ocean margins provides unique opportunities to carry out comparison studies of analog environments. Possible examples would be cross-shelf surveys that allowed comparison of the coastal and adjacent open oceans; comparison of adjacent benthic and water-column communities; or surveys from an estuary through the nearshore plume to the coastal ocean.

A number of process studies are urgently needed as well. Small-scale laboratory studies of individual species' responses to realistic OA scenarios, with state-of-the-art control and analyses of the experimental seawater carbonate chemistry, are lacking in coastal settings and/or with coastal biota, as elsewhere. Laboratory studies that target specific trophic level interactions would be valuable, such as, for example, examination of the impact of the loss of a potentially OA-sensitive prey species on an economically important upper trophic level consumer. Small-scale field experiments could take advantage of existing coastal infrastructure to examine the dissolution/precipitation rate of reagent-grade carbonate minerals, following the classic experiments of Peterson (1966), in a wide range of saturation conditions in natural waters. Others might take advantage of existing fisheries and aquaculture facilities, such as oyster farms or fish hatcheries, to examine the effects of OA stress in semi-controlled field settings. Manipulative experiments could also utilize direct injection of CO_2-containing flue gas from coastal power plants, similar to the novel, year-long experiment on eelgrass conducted by Palacios and Zimmerman (2007; Figure 7). The presence of quasi-stationary ecosystems (*e.g.*, benthic or rocky intertidal communities) gives opportunities for deliberate experimentation. At the larger scale, mesocosm experiments in the coastal ocean could benefit from direct coupling to the benthos, with anchored enclosed volumes encompassing the sediment water interface. Recent developments to enable *in situ* CO_2-perturbation experiments include open or semi-enclosed systems (Watz *et al*., 2008). Currently, only prototypes of such Free Ocean CO_2 Enrichment (FOCE) systems are available (*e.g.*, Figure 8), however, continued advances in development will lead to their feasibility in multiple coastal settings.

Large-scale field programs are also needed to tackle some of the uncertainties regarding the carbon cycle in coastal margins, such as those regarding net elemental fluxes across key boundaries. These would likely be forced to target a few representative regions, as the complexity and variability of coastal ecosystems would require large multidisciplinary efforts that spanned a

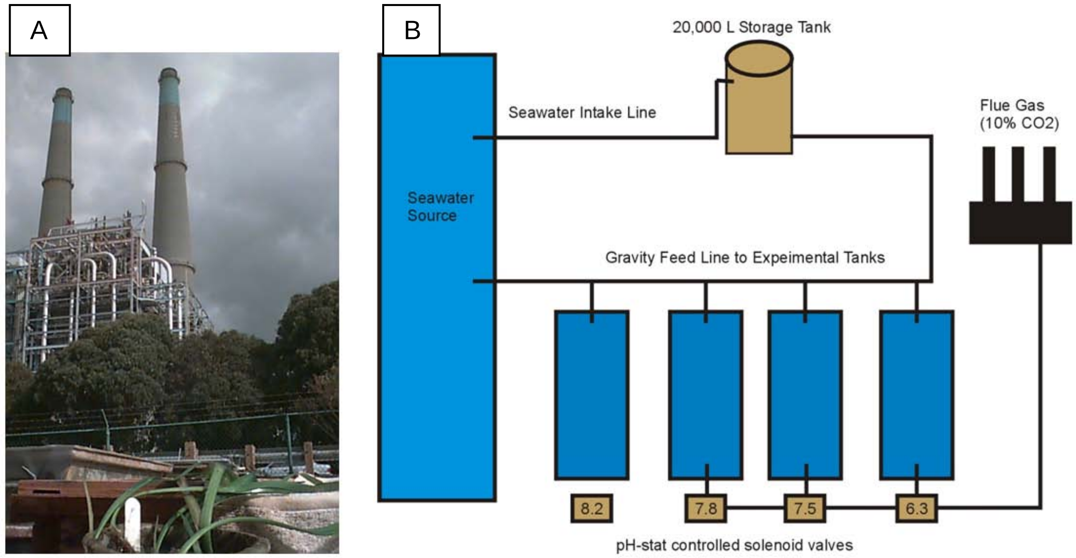

Figure 7. (A) Outdoor, flow-through seawater aquaria and a CO_2 delivery system were constructed at the Duke Energy-North America Power Plant at Moss Landing, CA. (B) Eelgrass was grown in seawater aquaria which were bubbled with industrial flue gas containing approximately 10% CO_2. (after Palacios and Zimmerman, 2007).

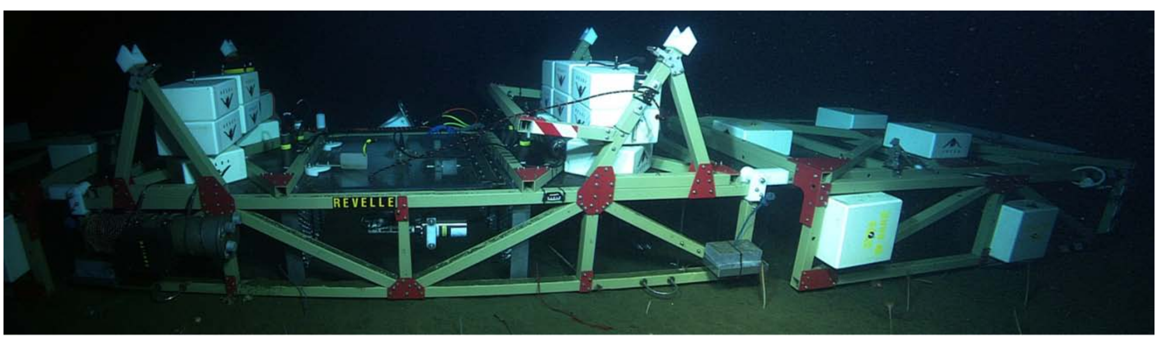

Figure 8. This prototype system for Free Ocean CO_2 Enrichment (FOCE) studies was deployed by ROV at 900 m and connected to the MARS cabled observatory infrastructure in Monterey Bay. This flume design allows for ambient flow in or out of either end, into which CO_2-saturated seawater is injected to maintain a prescribed pH perturbation within the central 1 x 1 x 0.75 m central section (behind the REVELLE label). Control electronics are housed in pressure canisters. White blocks are syntactic foam to allow ROV deployment and recovery. pH sensors and a current meter housed in the central section and along the flume are used for feedback to determine the amount and position of CO_2 injection for pH control. Future FOCE systems will have larger 'working' volumes and will likely be deployed in nearshore habitats. Photo credit: J. Barry, MBARI.

variety of space and time scales. Specific areas to study might include those that are already experiencing corrosive conditions, such as the upwelling coastline of the North Pacific. An analog to this location, with somewhat similar thermal and productivity conditions might be the productive mid-high latitude coastlines of the Atlantic from the Gulf of Maine to the Scotian Shelf. These areas would be distinct in their ocean acidification forcing as a result of their connections with the North Atlantic and North Pacific oceans, which have markedly different carbonate chemistry. Another analog pair might be the East Mexican and West Florida shelves in the Gulf of Mexico. These waters would also experience somewhat similar thermal and productivity conditions, but would be distinguished by the presence of carbonate-rich ground-waters that inundate the West Florida shelf and support significant carbonate bank formations.

Recommendations:

1. Carry out OA research in understudied regions. Few coastal settings have been the subject of OA or carbon cycle research in the past, and large knowledge gaps exist as a result. The Gulf of Alaska, western North American continental shelf, Bering Sea, Chukchi Sea, Arctic Shelf, the Scotian Shelf, Pacific coast of Central America, and the Gulf of Mexico are all regions with a shortage of carbon-cycle and OA observations.
2. Emphasize early-impact regions. Certain areas, such as the upwelling coastlines of the eastern North Pacific and Oxygen Minimum Zones such as the Northern Gulf of Mexico and the western coasts of South America are already naturally poised to experience corrosive conditions. These areas may hold information about the future conditions in other areas, or may hold clues as the adaptive strategies organisms may adopt in the face of continued OA-forcing.
3. Do ‘analog pair’ studies. Because of the high variability of coastal settings, isolating OA effects can be difficult. Field campaigns that paired study regions with differing OA-conditions, but with all other forcings as similar as possible, could be one approach to resolve this. Some specific examples are given above.

3.3.4 Synthesis and Modeling

While the coastal oceans are understudied from the perspective of carbon cycling and OA, there have been many large North American coastal research programs dating back to the 1960s, some of which are still ongoing (*e.g.*, CalCOFI). Other observational efforts, including water-quality measurements made by a variety of government agencies, have also been long in effect in estuarine and coastal waters. While none of these were motivated by or focused on OA, and few had quality carbonate chemistry analyses included in their measurement programs, there is nonetheless relevant information included in observations of biological standing stocks (including potentially OA-sensitive species such as foraminifera) and carbon-cycle-relevant chemical parameters such as nutrient or oxygen measurements. There is thus fertile ground to be plowed immediately in examining historic data through the prism of OA.

Like other research endeavors in the ocean margins, modeling is faced with many difficulties. Models must work at a variety of physical scales, from watersheds to oceanographic regions, which may require nested models with variable grid resolution and distinct prevalence of processes. Similarly, these models must work on different latitudinal scales ranging from the topics to high latitudes. Terrestrial forcing cannot be ignored, nor can interactions with the seafloor, as they can in pelagic models. Unfortunately, there are very few working circulation and biogeochemical models in coastal settings, with notable exceptions of the work being done by the UCLA, Rutgers and Gulf of Maine (GoMOOS) groups. Nonetheless, modeling must be integrated in coastal OA studies at the earliest stages. Even if early models do not perfectly simulate natural conditions, they would still be useful for scenario testing and would help guide hypothesis development and experimental (both lab and field) planning. Model development and testing in application to ocean margin settings, specifically with alkalinity and DIC transport and reaction modules, therefore, needs to be a high immediate priority for OA research. Ultimately, these models will develop in concert with measurement and experimental efforts to include true data-assimilative and predictive capabilities. Similarly, models of a variety of biological scales must be developed for planktonic and benthic communities in coastal environments including organisms, their physiology, populations, communities, food webs and other ecosystem interactions. In particular, models need to be developed and evaluated for key coastal species that are either the focus of human fisheries (*e.g*., scallops) or are ecosystem engineers — those organisms such as seagrasses, cold-water corals, and mussels which provide physical habitat for diverse species. In the long term, these models are needed to evaluate the socioeconomic consequences of OA including effects on human health.

Recommendations:

1. Synthesize historic scientific and monitoring and agency data to determine the availability of OA-relevant information. This could be particularly useful in regard to development of OA-stress indicators as defined above.
2. Build OA modules into biogeochemical models such that mineral saturation state and pH are normal outputs from coastal models.
3. Develop better coastal coverage with biogeochemical circulation models. Currently there is a scarcity of coastal regions described by working models.
4. Begin scenario-testing studies to help guide field campaigns. Biogeochemical models could be used to simulate responses to OA forcing to develop testable hypotheses for ecosystem responses.

3.3.5 Prioritization of Research Needs

The ocean margins discussion group felt that prioritization of research needs was a multidimensional process, with the criteria of Importance, Urgency, and Feasibility all playing significant roles, and each with feedbacks on each other. Importance might be rated on the basis of the magnitude of a potential response to OA, or even the magnitude of our knowledge deficit. This could be assessed from a regional perspective, based, for example, on the magnitude of OA effects that a certain region might experience. Alternatively, importance could be assessed from a process perspective, based, for example, on a food-web's potential response to loss of an OA-sensitive species. Urgency would be distinct from importance in terms of the immediacy of the research need, and this could likewise be based on regional or process terms. Of course, these two criteria are related: an important problem that will never happen (low urgency) is of little concern; likewise for an urgent problem of little importance. Feasibility, defined as the ease with which a problem can be addressed, also feeds back on the other criteria. An important problem that cannot be tackled with any existing technology will by default have lower urgency, while one that can be addressed with current technology will have increased immediacy.

These criteria strongly shaped the Ocean Margins group's recommendations for the research priorities and timelines presented in Table 3.

Table 3. Research priorities for ocean margins. Activities are prioritized as follows: (1) **Urgent and Important; (2) Important; (3) Desirable. The recommended time window within the 0-10 year timeframe for each activity is denoted with "X."**

Activity	Priority	0–2 years	2–5 years	5–10 years	Rationale
Technical needs					
Development of OA-stress indicators for various key	1	X	X	X	Commercially and/or ecologically important species/functional

species/functional groups					groups (e.g., calcifiers, fish larvae)
Development of 'accessible' OA monitoring technology	1	X	X	X	Critical for being able to discern OA effects, deduce trends over space and time
Application of OA-stress indicators to monitoring sites	2			X	Goal is to have autonomous measurements of OA-stress on key species
Monitoring & Surveys					
Early impact regions - Deployment of existing technology on new and existing platforms (e.g., pCO_2 sensors on moored buoys)	1	X	X		Coastal upwelling regions of eastern North Pacific; oxygen minimum zones such as northern Gulf of Mexico, western coasts of Southern America
Understudied regions - Deployment of existing technology on new and existing platforms (e.g., pCO_2 sensors on moored buoys)	2		X	X	Gulf of Alaska, Bering Sea; Arctic Ocean, Chukchi Sea, Scotian Shelf, west coast of North America and Central America, Gulf of Mexico
Deployment of new measurement technology in expanded monitoring sites	2		X	X	
Manipulative Experiments/Process Studies					
Lab experiments	1	X	X	X	Experiments on different life stages of variety of species including calcifying organisms, jellyfish, fish larvae; investigate impacts of loss of OA-sensitive prey on commercially important predators; examine possible affects of OA on harmful algal blooms and pathogens
Small scale experiments to examine dissolution - precipitation rates of carbonate minerals	1	X	X		Expand on classic experiments of Peterson over a wide range of saturation conditions in natural waters
Mid-size experiments- using aquaculture facilities or with benthic communities in field	2		X	X	Examine effects of OA stress in semi-controlled, aquaculture settings or manipulative experiments with nearshore/intertidal benthic systems
Mesocosms	2		X	X	Include sediment-water interface and benthos

Table 3. *Continued*

Activity	Priority	0–2 years	2–5 years	5–10 years	Rationale
Data Synthesis					
From historic scientific research programs	1	X			CalCOFI and other programs measure biological standing stocks and carbon-cycle relevant parameters
From government monitoring	2		X		Variety of local, state and federal

'gray literature'					agencies monitor water quality in coastal and estuarine areas
From new OA-specific studies	3			X	
Modeling					
Incorporation of carbonate chemistry into existing models	1	X	X		Build OA modules into biogeochemical models such that mineral saturation state and pH are coastal model outputs
Greater regional application of existing models	1		X	X	Need additional regions included in coastal biochemical circulation models; scenario testing could be used to develop testable hypotheses
Improvement of ocean margin-focused models	2			X	Include sediments, estuaries, watersheds and other appropriate ecosystems

3.4 Group C: Subtropical/Tropical Pelagic Regions

Discussion leader: David Hutchins

Rapporteur: Peter Sedwick

3.4.1 Introduction

The tropical and subtropical ocean regimes encompass most of the ocean on an areal basis, and indeed the oligotrophic central gyres together are considered to be the largest biome on the planet. The low latitude ocean includes both the largest natural oceanic source of CO_2 to the atmosphere (the equatorial Pacific), and some of the biggest CO_2 sinks (the gyre ecosystems). The responses of these regimes to anthropogenic pCO_2 increases and attendant acidification have obvious consequences for not only the biology and biogeochemistry of the ocean, but also for climate/ocean interactions on a global basis.

Particular processes that are dominant features of the tropical and subtropical pelagic realm are likely to be especially sensitive to changing ocean carbonate chemistry. Among the most important of these are key aspects of ocean nutrient cycles, given the importance of N, P and Fe limitation in this region. The oligotrophic subtropical gyres support nearly all of the biological nitrogen fixation in the ocean, a critical source of new nitrogen to the biota and one that has recently been shown to have a strong dependence on CO_2 changes (Hutchins *et al.*, 2007; Levitan *et al.*, 2007). In addition to dominating this input term to the marine fixed nitrogen inventory, the subtropical/tropical oceans likewise have a large role in other key nitrogen cycle processes such as nitrification and denitrification. Phosphorus limitation and transformation are also especially important in the warm water oceans, especially in the Atlantic basin. Similarly, micronutrient biogeochemistry in the low latitude oceans needs to be carefully considered under any future global change scenario. Most of the world's total flux of aeolian iron deposition to the ocean happens in the subtropical/tropical regimes. Biological production in the equatorial Pacific High Nutrient Low Chlorophyll (HNCL) area is strongly limited by iron, and some functional groups such as diazotrophs are likely iron-limited in the central gyres as well. A substantial fraction of global water column calcification and carbonate dissolution and organic carbon export also occurs in these regimes.

Thus, even when considered solely from a biogeochemical perspective, understanding the ways in which the world's subtropical and tropical oceans will react to ocean acidification needs to be a priority. Obviously, though, accompanying changes in marine biological communities and productivity throughout these large regimes are equally important to consider. The discussion group suggests that 'ocean carbonation' (rather than 'ocean acidification') might be a better term to describe the changes in the carbonate buffer system of seawater resulting from human activities, because some of the significant impacts on the biota may primarily reflect changes in the pCO_2 of seawater rather than pH decreases. Regardless of the terminology chosen, though, the group agrees on a number of research approaches needed to address acidification and carbonation impacts in the low latitude oceans.

3.4.2 Technical Research Needs

The discussion group feels that the most important task is to identify critical processes and questions associated with the subtropical/tropical oceans – particularly processes related to the consequences of ocean acidification/carbonation that are likely to defy biological adaptation. Some of the key processes in these regimes include include nitrogen fixation, nutrition and speciation, nitrification/denitrification, iron deposition and limitation, calcification and carbonate dissolution, and phosphorous limitation and transformation. Other research needs include an examination of ocean acidification effects on decomposition and dissolution of organic matter, including enzyme activities, sorption and coagulation processes, and impacts on kinetics and thermodynamics. There is also currently a lack of information on how physical processes are likely to exert feedbacks on ocean acidification and rates of environmental change, on acidification impacts on carbon export in general (organic and inorganic), on metabolism of organisms at higher trophic levels, and on spatial and temporal shifts in species distributions and biogeochemical regimes.

There are many other processes that have not been fully considered in the context of ocean acidification, but that could potentially have major impacts on the low latitude oceans. These may include the growth and physiology of phytoplankton in general and associated impacts on biogeochemical cycling, changes in nitrogen cycling (*e.g.*, nitrification, efflux of ammonia) due to increases in ammonium relative to ammonia, shifts in the speciation of iron and other bioactive trace elements, pH-mediated changes in particle aggregation, particulate carbon export and remineralization, and particle surface charge (hence scavenging and adsorption). Equally uncertain are effects on heterotrophic bacterial production and community structure and decomposition processes, and activity of ecto-enzymes and subsequently nutrient cycling. Other unknowns include potential acidification interactions with changes in oxygen distribution, with non-oxygenic photosynthesis (which may be pH sensitive), and with production of other biogenic climate-active gases such as dimethylsulfide, nitrous oxide and methyl halides.

3.4.3 Baseline Monitoring

There is general agreement for the need to continue and expand observations made at the existing time-series stations in the subtropics/tropics (BATS, HOT, ESTOC, TENATSO, *etc*.) in order to provide baseline observations against which ocean acidification may be assessed. It is suggested that additional time-series stations might be added, particularly in the tropical ocean and in regions of large seasonal or spatial gradients in properties and processes relevant to ocean acidification. Moorings that will accommodate autonomous measurement of two or more carbon system parameters are required to fully constrain the carbonate system necessary for effective monitoring and forecasting biological effects (Figure 9). Ideally, this network would also have the capability to measure calcification and $CaCO_3$ dissolution rates, and such measurements are needed to improve models in order to predict responses to ocean acidification. Autonomous sensors should also be developed for deployment on gliders and floats to obtain large-scale regional coverage. Also desirable would be additions to measurements/monitoring at existing ocean time-series stations, including information on rates of critical processes such as nitrogen fixation, distribution and abundance of zooplankton that may be sensitive to acidification,

Figure 9. An example of a mooring with an autonomous pCO_2 sensor being deployed in the tropical Pacific.

complete measurements of inorganic carbon-system parameters where lacking, information on flux and composition of particulates, and information on physical context to constrain process attribution.

3.4.4 Surveys

It is recommended that survey observations should include as much as possible of the critical measurements and observations mentioned under monitoring (above), including the core hydrographic and biogeochemical measurements of the time-series programs. Exceptions to this would be measurements that are not readily compatible with survey-type cruises, such as flux and composition of sinking particles. The study of ocean acidification calls for an integration of survey observations made at a number of different levels; for instance, biogeochemical measurements and observations of organisms in the upper trophic levels, such as fisheries surveys. Another general recommendation is to expand observations that make use of ships of opportunity, perhaps by providing incentives (*e.g.*, carbon credits) to commercial ships or using underway observations as an outreach opportunity on cruise ships (as has been done on Explorer of the Seas).

3.4.5 Manipulative Experiments / Process Studies

The group discussion first addressed perturbation experiments in general as a research strategy, ranging from laboratory-scale studies to mesocosm and *in situ* experiments. It is acknowledged that there are inherent problems with the timescales of these approaches, which are necessarily much shorter than those involved in acidification of the natural system. This has implications for predicting the ability of organisms to acclimate and adapt to ocean acidification. However, it is generally agreed that such experiments will be useful and indeed essential to test hypotheses associated with ocean acidification, to ascertain which of today's organisms are "pre-adapted" to benefit from high CO_2 ocean conditions, and to identify possible ecological winners and losers that may result from future ocean acidification.

For perturbation experiments, recommended 'standard perturbation conditions' (*e.g*., pre-industrial, present-day, and projected year-2100 pCO_2 levels) may be desirable, in order to facilitate comparisons between different studies. Such experiments are most useful if realistic conditions are used with reference to past, present and likely future atmospheric pCO_2 levels or seawater pH, but some published work has employed extreme/unrealistic perturbations. It is also recommended that, in such perturbation experiments, the inorganic carbon system should be fully determined at the beginning of the experiment, monitored regularly throughout the experiment. Certified reference materials should be used to estimate accuracy and precision of CO_2 system measurements.

A. Laboratory

Laboratory studies using isolated cultures of organisms from key tropical and subtropical functional groups such as N_2 fixers, calcifiers, and picophytoplankton have some obvious advantages over experiments using natural communities in the field. Some types of basic chemistry investigations into impacts on nutrient and micronutrient speciation and cycling may also be most easily accomplished in the lab. Lab experiments are generally better controlled and much more economical than field studies, and are amenable to investigations into multivariate interactions between $p(CO_2)$ and other global change variables, as well as long term studies of processes like biological adaptation and evolution. For these reasons, the group generally agreed that laboratory studies of processes such as physiological responses to acidification should be a high priority and should be among the first research directions to be taken. However, culture studies also present inherent limitations such as questionable representation of natural biological variability ("lab weeds"), and unculturability of some organisms. Lab work also cannot fully simulate important environmental physical forcing mechanisms or complex natural biological community interactions such as predation, succession and competition.

B. Mesocosms

The discussion group feels that the mesocosm approach that has been applied by European researchers to manipulations of coastal and benthic communities may be more difficult to accomplish in the pelagic ocean. However, the group recommends considering the possibility of using floating mesocosms (which, however, need to be robust enough to withstand rough seas), or even a barge-based portable tank system to carry out large volume manipulative experiments in the open ocean. Such large mesocosms are, however, difficult to adequately replicate, and realistic simulation of acidification interactions with other global change variables such as rising temperature or changing mixed layer depth may be difficult or impossible. These types of multivariate experiments are probably best carried out using smaller volume, shipboard-based manipulative experiments. For example, a continuous culture system onboard ship has been used in multivariate experiments with natural phytoplankton communities grown under different conditions of pCO_2, temperature, light, and nutrients (Hare *et al*., 2007; Figure 10). In general, enclosed manipulative experiments of any size need to be limited in duration, as enclosure artifacts increase significantly in long incubations, so extrapolation of their results to long term decadal trends needs to be done in a careful and considered manner. Despite this caveat, enclosed manipulative experiments are a promising and versatile research tool that yield unique insights not readily available from other research methods. Accordingly, enclosed manipulation experimental techniques should be further developed for studying acidification impacts on the pelagic ocean ecosystem.

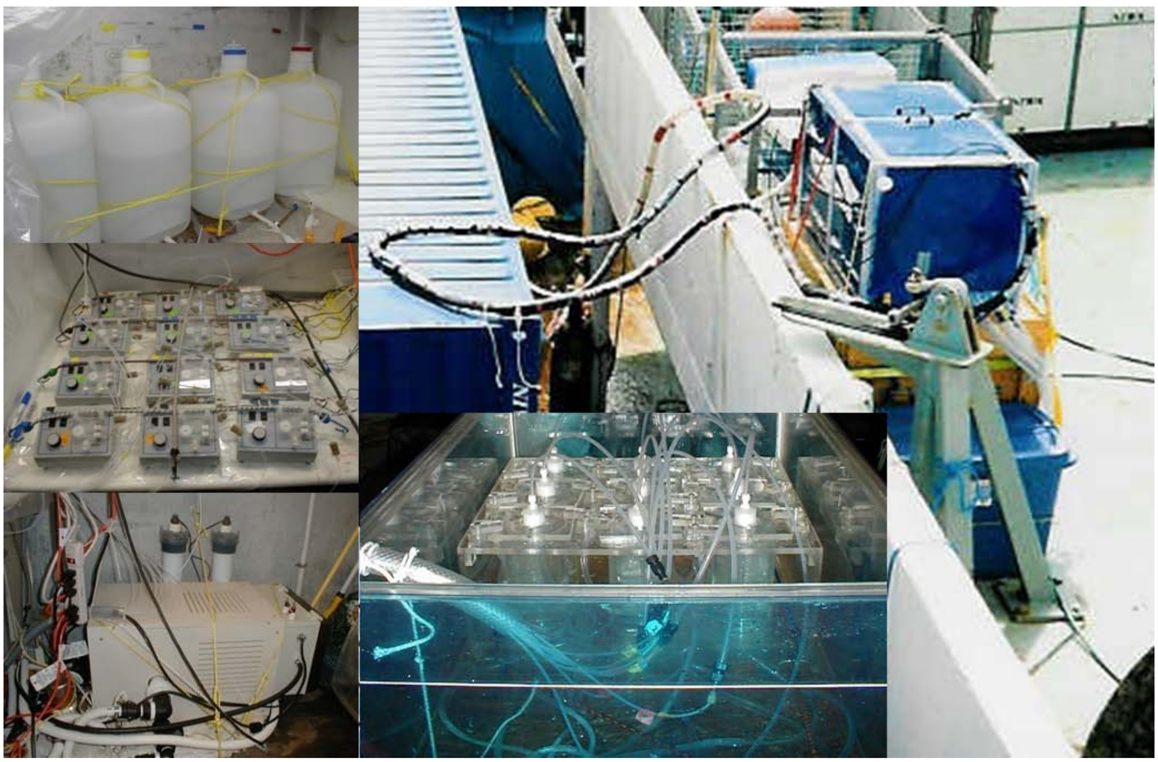

Figure 10. Methods such as this shipboard continuous culture system can be used in extended experiments to acclimate present day natural plankton communities to simulated future conditions of pCO_2 and acidity, either alone or in combination with other global change variables such as altered temperature, light and nutrient availability (Hare *et al*., 2007). Along with other methods such as laboratory culture experiments, computer models, and long term observations, these types of natural community manipulative experiments offer a potentially valuable tool to formulate hypotheses about how pelagic communities could respond to increasing ocean acidification.

C. Field

Another research strategy is the use of mesoscale, *in situ* perturbation experiments, similar to the ocean iron fertilization experiments. It is generally agreed that such unenclosed experiments would be extremely useful and informative, although again the timescale of the experimental perturbation is unrealistically short. There are also other caveats to consider, some of which also apply to the iron experiments (*e.g.*, edge, mixing, dilution and strain effects, etc.). In addition, there would be significant logistical difficulties in conducting such experiments, such as the large volumes of acid or CO_2 required. Back-of-the-envelope calculations by the discussion group members suggest that an *in situ* acidification experiment would require adding at least 100,000 liters of concentrated HCl.

Natural and anthropogenic $p(CO_2)$/pH gradients also have potential utility for such larger experiments. Upwelling regions, shallow, CO_2-rich hydrothermal vents and power-plant outfalls are all possible sites for such studies. Sites where alkaline/CO_2-poor fluids are added to seawater, such as cold seeps – the opposite situation of ocean acidification – are also potentially useful study areas with regard to process and mechanism. It is acknowledged that simultaneous gradients in other variables (*e.g.*, temperature, dissolved oxygen) might complicate interpretation, although such experiments and observations in judiciously chosen locations might provide useful analogs for future ocean acidification.

3.4.6 Modeling

There is a general group consensus for the need to better integrate modeling activities with experimental, survey and monitoring work, in order to better predict the impacts of ocean acidification and to guide empirical studies. To ensure that predictive modeling is effectively incorporated into ocean acidification research, it is suggested that modeling efforts should be integrated with experimental/observational studies from the start, as essential components of research projects. This should be followed by continued dialog between modelers and experimentalists/observationalists at the level of data generation and interpretation. Experimental studies should be specifically designed to provide the mechanistic information that is required by the modelers. Observational studies should also aim to provide modelers with basic information on biological community structure and the distribution of key organisms. Thus, needed model inputs should influence both experimental designs and field observations.

Specific modeling requirements for the tropics/subtropics include treatment of OA responses to ecological and biogeochemical processes that are dominant in these regions. This would include emphasis on CO_2 and OA responses of nitrogen fixation by diazotrophs in oligotrophic stratified regions, nitrification and denitrification in the water column, planktonic calcification by coccolithophores, foraminifers, and thecosomatous pteropods, water column dissolution above the lysocline, and pH driven changes in the bioavailability of organic nutrients and trace metals, in particular iron. Modeling efforts along with field studies in the subtropics and tropics should take advantage of existing and on-going long-term time-series and associated modeling efforts.

3.4.7 Prioritization of Research Needs

The discussion group identifies the following as criteria for prioritizing ocean acidification research in the subtropical/tropical pelagic ocean:

1. Research related to the ocean’s capacity to take up anthropogenic CO_2.
2. Research related to the impact of ocean acidification on ‘ecosystem services’. This term is used in its broadest sense to include important functions from both human and Earth system perspectives.
3. Research related to the impact of ocean acidification on climate feedback processes.
4. Research that provides the greatest potential for interaction between empirical work and predictive models.

A set of experiments and observations are recommended as immediate priorities (0–2 year timeframe) for ocean acidification research related to the subtropical/tropical pelagic oceans over the next few years. These are described here in approximate order of priority, as well as in Table 4. First among these are basic laboratory experimental studies focusing on key functional groups and poorly-understood organisms and processes in the low latitude oceans. Laboratory work is also badly needed to examine the timescales of change and adaptation of organisms and the biogeochemical processes that they mediate in the context of ocean acidification impacts.

The other immediate priority is enhancement of existing monitoring and survey activities to establish baseline conditions and detect changes in response to ocean acidification. These activities would focus on ocean acidification effects on critical biogeochemical pathways, on the distribution and abundance of key organisms, and on capturing seasonal changes to allow discrimination of longer-term trends. Such projects would make use of ships of opportunity, autonomous platforms and drifters, time-series programs, and existing or new survey programs (*e.g*., CLIVAR, GEOTRACES, LTER cruises), where possible. Other activities that should be undertaken in the short term are mining the significant body of historical data related to ocean acidification research, and commissioning review papers or reports on key topics related to ocean acidification, perhaps with incentives (*e.g*., small grants) for such work. Finally, urgent efforts are needed towards developing and using chemical and biological standards relevant to ocean acidification research (*e.g*., standard mineral phases for dissolution studies).

The second priority over a 2–5 year timeframe is support of mesocosm studies and other small-scale enclosed field perturbation experiments, in order to establish a set of informed hypotheses about possible future acidification-driven changes in natural subtropical and tropical biological communities and biogeochemical regimes. At the same time, field studies utilizing natural gradients/processes (*e.g.,* upwelling regions) as analogs of ocean acidification should be undertaken.

Following these near-term priorities, the group recommends a set of long-term (5–10 years) priorities for experimental and observational research related to ocean acidification. These may include the development of *in situ*, mescoscale field perturbation experiments. Although the results of these types of open ocean experiments are expected to be of primary theoretical importance, the apparent logistical obstacles mean that their actual priority needs to be guided by feasibility. Other priorities in this category would include survey work that is not possible in the short term (*e.g*., dedicated ocean sections), addition of new time-series stations and observations in critical areas dictated by the results of empirical and modeling work, and addition of new sensors and other observational tools to moorings, drifters, autonomous vehicles, and ships of opportunity.

As noted above, the discussion group recommends that modeling efforts be integrated throughout the 1–10 year timeframe of the projects outlined here. The pelagic ocean group also identified a set of important ‘core’ and ‘ancillary’ measurements for the all of the research approaches listed above. The designation as core or ancillary will vary according to the research needs of individual projects. These include measurements of key biogeochemical rates such as N_2 fixation, CO_2 fixation, and export fluxes of carbon-bearing particles; precipitation and dissolution of carbonate phases; evaluation of the mineralogy, associated organic species, and surface properties of particles; examination of the role of different organisms in the precipitation/dissolution of particles; detailed assessments of biological community composition; and measurements of the distribution and speciation of bioactive elements, including macronutrients (at low levels in subtropical surface waters) and trace metals (Fe and others). Also critical is the development and use of new molecular approaches to characterize community structure and change (species composition, acclimation, adaptation). It is noted that metagenomics and other molecular methods are emerging tools that hold great potential for these studies. In this vein, it is suggested that researchers should consider archiving biological material from ongoing monitoring, surveys and perturbation experiments for possible future application of these tools.

Finally, the group recommends addressing data management needs for ocean acidification research early in the research process by having data (at least those from field studies) and metadata from NSF-funded ocean acidification research archived by the OCB Data Management Office. Other recommendations include working toward formats that would allow management and archiving of the diverse types of data generated by experimental studies (an issue not unique to ocean acidification research), linking various existing/new repositories for data relevant to ocean acidification research (*e.g.*, OCB Data Management Office, CDIAC, OBIS, international data management offices), recommending the use of electronic data supplements to accompany published research, as increasingly used by journals.

Table 4. Research priorities for subtropical and tropical pelagic regions. Activities are prioritized as follows: (1) Urgent and Important; (2) Important; (3) Desirable. The recommended time window within the 0-10 year timeframe for each activity is denoted with "X."

Activity	Priority	0–2 years	2–5 years	5–10 years	Rationale
Technical needs					
Provide 'climate quality' satellite data for key parameters related to OA	2			X	Improve remote sensing measurements of parameters relevant to OA research (e.g., ocean color, SST, wind speed)
Develop and implement standardized materials and protocols	1	X			Assure the usefulness of measurements at different time and space scales
Baseline monitoring					
Add OA-related measurements at existing time series stations: deep export, phytoplankton and zooplankton abundance and dynamics, nitrogen dynamics	1	X	X	X	Essential for detecting OA-related changes. Take advantage of present investments and establish baselines for variables, processes and organisms likely to be impacted by OA
Add new time series stations in tropics and other areas of strong variability of relevance to OA research	3		X	X	Tropical pelagic region not well-represented in survey and time series observations, relative to subtropical pelagic oceans
Surveys					
Augment existing autonomous platforms (e.g., OOI), floats and ships of opportunity with sensors and other tools	2			X	Expand and extend autonomous observations of parameters relevant to OA
Undertake survey observations in areas previously studied in carbon-focused programs such as NABE, EqPac	3		X	X	Take advantage of legacy of JGOFS research in these areas
Manipulative experiments					
Conduct individual laboratory scale experiments investigating processes such as primary productivity, N_2 fixation, nitrification, denitrification, decomposition, particle aggregation	1	X	X	X	Determine the processes and parameters (including those that area currently unknown) impacted by OA and to investigate mechanisms of impacts
Conduct small-scale field perturbation experiments: floating, barge or ship-based mesocosms	2		X	X	Investigate effects of OA and interactive effects with other variables (e.g., temperature) on natural mixed communities
Conduct field process studies in	2		X		Leverage natural gradients to look

natural analogs of OA (e.g., upwelling areas)					at competing effects of OA and interactive effects of with variables (e.g., temperature)
Conduct open ocean in-situ experiments (mesoscale)	3			X	Investigate impacts and processes of OA using natural system with minimal containment artifacts

Table 4. *Continued*

Activity	Priority	0–2 years	2–5 years	5–10 years	Rationale
Data management					
Set up data management process	1	X	X	X	Ensure data are collected, archived and disseminated in a consistent and useful manner
Data synthesis					
Data mining	2	X			Take advantage of previous work; digitize old data; develop common datasets for modeling
Written review activities	2	X			Take better advantage of previously published research relevant to ocean acidification
Modeling					
Develop robust mechanistic biogeochemical model representations	1	X	X	X	Produce mechanistically accurate models that consider interactions among changing environmental variables
Establish common datasets for use in modeling activities	2		X		Enable consistent and robust testing and development of numerical models
Achieve true collaboration between modelers and observationalists	1	X	X	X	Improve research design and synthesis and modeling activities

3.5 Group D: High Latitude Regions

Discussion leader: W. M. Balch

Rapporteur: John Guinotte

3.5.1 Introduction

The high latitude group discussed ocean acidification impacts over the entire water column (including pelagic, mesopelagic and benthic environments) and covering boreal, subpolar and polar latitudes. Calcifying organisms throughout the marine food web are particularly susceptible to ocean acidification. These organisms range from unicellular algae (coccolithophores) and protists (foraminifers) to cold water corals and a host of planktonic and benthic metazoan species (*e.g.*, thecosomatous pteropods). Owing to a combination of factors including carbon chemistry, temperature and ocean circulation, the high latitude, near-surface environments are unique in that they will be the first surface waters of the world ocean to continuously experience carbonate saturation states <1.0. For this reason, it is *imperative* that baseline observations of chemical and biological variables in high latitude environments be initiated quickly. The group discussed how changes were already taking place rapidly in high latitude environments and noted the extreme urgency of obtaining high resolution baseline data from these regions.

The working group addressed several issues relevant to all the focus groups. For example, in terms of the processes affected by ocean acidification (other than calcification), participants discussed three fundamental process categories. The first category was “System processes” including: (1) biogeochemical processes such as $CaCO_3$ dissolution, export, ballasting, decomposition, remineralization, and metal complexation; and (2) physiological processes such as respiration, photosynthesis, nutrient uptake/transport, chemical signaling, *etc*. While it would be ideal to have a physiological threshold for OA that would also be useful for policy decision making, it was recognized that such a physiological threshold is difficult to define without further research and may be species-specific. Indeed, the physiological pathways that may be affected by OA, the energetics of calcification, and mechanisms of calcification are not well understood for calcifying autotrophs and heterotrophs. Metagenomic information could be used with indices of physiological processes to explore whether gene expression is affected by changing seawater CO_2 chemistry. A second major area of study discussed by the group concerns feedbacks and interactions with other environmental variables such as feedbacks from UV interactions and potential interactions with changes in temperature, stratification and albedo. The third fundamental process category that the group agreed should be given high priority concerns ecosystem shifts, including changes in biodiversity, population genetics, food web structure/trophic dynamics, genetic selection, range shifts, and impacts on functional groups.

3.5.2 Technical Research Needs

The high-latitude group agreed that a major component of needed advances in technolgy involves faster, better and cheaper ways to accurately measure two of the four variables of the inorganic carbon system in seawater, including pCO$_2$, DIC, alkalinity and pH. In order to accurately track and assess impacts of ocean acidification, technical advances in measuring the ocean carbon system are critical. Less expensive means to sample the ocean are needed. For example, creative use of gliders to operate between moored buoys with autonomous sensors would improve efforts to resolve OA effects in space and time. Moreover, instruments will have to be designed that are smaller and draw less power in order to be operable from buoys and autonomous vehicles for long durations. Technologies for the rapid identification and quantification of calcareous holoplankton and meroplankton would enable high quality measurements of the abundances and vertical distributions of target calcifying organisms. These biological distributions could then be tracked and correlated with changes in seawater carbonate chemistry. Ideally, autonomous measurement of the seawater CO_2 system will be accompanied by the capability to measure calcification and $CaCO_3$ dissolution rates. Seasonal data of ocean carbonate chemistry and distributions of calcifying organisms are urgently needed, including the critical, difficult-to-sample winter months. Such measurements are needed to improve models in order to predict responses to ocean acidification. Future research advances in understanding mechanisms of calcification will benefit from access to genomic sequences of key organisms such as coccolithophores, planktonic foraminifers and thecosomatous pteropods.

3.5.3 Baseline Monitoring

Group participants strongly agreed that baseline monitoring is a critical, high-priority focus for the high latitude environments, owing to the rapidity with which OA will impact high latitude marine organisms. High quality data on the distributions of calcareous planktonic and benthic organisms coupled with seawater CO_2 chemistry must be obtained as soon as possible. These critically vulnerable, high latitude regions include the Southern Ocean (Ross Sea, West Antarctic Peninsula), North Pacific (Bering Sea) and the Arctic Ocean, which is particularly data-poor.

Seasonal monitoring must be a central priority for chemical and biological monitoring, as OA effects are particularly pronounced in winter. In addition, high latitude coastal regions associated with upwelling of high CO_2/low carbonate seawater may be affected by OA in the near future. Influx of CO_2 from the atmosphere is presumably slowed by the presence of ice, but this will change dramatically as the polar ice melts.

3.5.4 Surveys

High-latitude surveys to track present and future changes are vital since, as outlined above, such polar and subpolar regions will be the first to experience surface waters that are undersaturated with respect to aragonite, then calcite, on a continuous basis. The same vulnerable areas outlined for baseline studies are considered critical areas for surveys. In addition, the Bering Sea was recognized as a key survey area due to its strategic importance to fisheries. Dedicated OA surveys should be started immediately for data poor areas within high-latitude environments of both hemispheres.

There are a number of important scientific questions that could be directly addressed by surveys. These include: (1) Where is acidification happening and at what rates? (2) What are the seasonal cycles in the abundances and vertical distributions of coccolithophores, pteropods, foraminifera and how are they changing with OA? (3) What are the key indicator species of high latitude ecosystems and how are they changing with OA? Organisms that secrete aragonite and high-magnesium calcites include pteropods, benthic bivalves, sea urchins, cold water corals (Figure 11), and coralline algae; many of these organisms are important in polar and subpolar marine food webs. Yet, such aragonite and high magnesium-calcite producers are especially at risk, owing to the high solubility of these carbonate phases. Biological surveys with sufficient temporal and spatial resolution to detect potential impacts of OA are a top priority. Surveys of calcareous holoplankton and meroplankton as well as surveys of benthic calcareous fauna, many of which are major food resources for whales, birds and other indigenous species, will be important in developing ecological forecasts of OA impacts. (4) What are the climate feedbacks, and will oceanic CO_2 uptake continue at present rates? Regional surveys will central for input to global models. (5) How will fisheries be affected by OA impact on their prey species? (6) Will OA cause regime shifts within ecosystems?

Figure 11. Photograph of the cold water coral, *Lophelia pertusa,* a bioherm-forming coral which secretes a calcium carbonate skeleton of aragonite. Such cold water coral reef systems have high biodiversity and provide habitat for commercially important fish. (Photo credit: Martin Hovland, Statoil).

Surveys should be designed to measure a number of key variables. Primary production, rain rates of POC and PIC, sediment trap studies, and the standing stocks and production rates of biogenic $CaCO_3$ producers would be highly relevant elements of successful survey programs. Remote sensing will play an essential role since it can provide basin scale observations, and techniques now exist for deriving the concentration of PIC based on spectral measurements of water-leaving radiance (although the different mineral phases of PIC cannot be ascertained remotely) – see Figure 12. At least two of the four carbon variables (pH, $p\mathrm{CO}_2$, DIC and alkalinity) will be essential in all surveys.

The high latitude group promoted long-term monitoring at specific sites, using moorings equipped to estimate carbon system parameters ($p\mathrm{CO}_2$, alkalinity, pH, DIC, hydrographic and bio-optical variables. Other variables of interest at specific monitoring sites would be calcification and dissolution rates of biogenic carbonates, including all of its mineral forms. The research community should take advantage of ship transits to monitoring sites to service moorings as a means to provide more survey observations such as described above. Temporal sampling scales should be as frequent as one sample every three hours. Other more time-consuming, expensive sampling obviously would have to be performed less frequent.

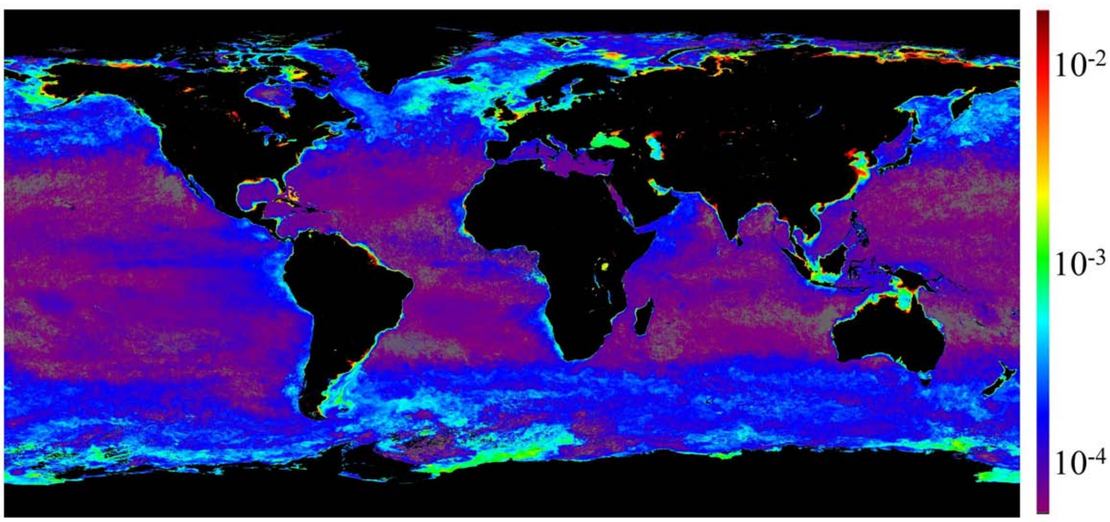

Figure 12. Annual 2006 binned average PIC concentration (mol m^{-3}) estimated using MODIS Aqua data and the merged two-band (Balch *et al.*, 2005) and three-band (Gordon *et al.*, 2001) PIC algorithm. Color scale is shown to right of panel.

Potential monitoring sites could be at ongoing LTER or OOI sites since there is much to be gained by pre-existing time series. However, emphasis must be on those regions which are projected to undergo high rates of change, particularly with regard to the carbonate saturation state of seawater. Repeated Longhurst-Hardy plankton surveys span decades and may provide valuable information on occurrence of foraminifera and pteropods in the surface ocean dating back to the 1940's. Group participants recommended that these surveys be maintained.

3.5.5 Manipulative Experiments / Process Studies

Standardization of protocols is considered a key component to controlled experimentation with calcifying organisms, whether in laboratory, mesocosm or field manipulation experiments. Improved techniques for separating PIC from POC are also necessary. There are critical information gaps concerning the natural history and physiology of foraminifera, made especially acute given that foraminifera may contribute 50% of the deep PIC fluxes to the sea floor. Such information is important if we are to examine the effects of OA on this protozoan group. There are major gaps in our knowledge of low metabolic rate, benthic calcifiers, including major uncertainties about their early life stages and larval development. Cold-water corals are also poorly understood, yet their three-dimensional structures provide essential fish habitat in many high-latitude regions.

A large range of hypothesis-driven laboratory experiments is needed which would test the response of organisms to OA across a host of phyla. Specifically, experiments are crucially needed to elucidate the impact of OA on fecundity, mortality, and growth rate of the target organisms. Moreover, physiological experiments that examine the genetic response to OA will be useful as we search for environmental indicators of OA effects. Reliable genetic indicators could also be a critical technology, since remote, autonomous genetic analyses are now becoming possible.

Mesocosms will be needed for addressing questions beyond basic lab-bench experiments, in which the complexity of the natural system is a key component of the question. "Portable" mesocosms, run by a mesocosm facility, were viewed as the most cost effective means for investigators to run such experiments in a wide variety of environments. Particularly appealing in coastal environments are mesocosm bag experiments that include the entire water column as well as the sediments.

Field observations will likely utilize the results from laboratory and mesocosm experiments to examine the space-time extent of biological response to OA. Long time-series will remain a critical component in understanding the impacts of OA. Large-scale manipulative CO_2-perturbation experiments might provide a way to integrate the short-term ecosystem response over a broader range of eddy scales (analogous to previous Iron-Ex experiments), at a scale not achievable with standard mesocosm experiments. Such experiments should make use of remote sensing to elucidate the large-scale impacts. Natural perturbation experiments (resulting from intrusions of corrosive waters into a region) could provide a more holistic view of the community response to OA.

3.5.6 Modeling and Data Management

The High Latitude group felt that quick advances could be made by adapting existing models (e.g. ECOSIM) for understanding OA rather than generating new models *de novo*. The focus of these models should be present and future changes in ocean chemistry. Shallow ocean $CaCO_3$ dissolution is currently not well accounted for in most existing models and there are few models that addressing the carbonate saturation state in the coastal ocean. Both researchers and policy makers would benefit from models that address ecosystem response. Models would be useful to incorporate range of responses over a range of pH as well as to define the feasibility of defining OA thresholds and risks.

The other major utility of models is to aid in experimental design. To this end, modelers should be involved in OA research from the outset. Small-scale cellular models will also be important for OA questions, since they address mechanistic processes at the most fundamental level of physiological reactions. Larger-scale ecosystem models provide the ideal vehicle to couple lower trophic models with fisheries models.

Data management was discussed within the context of modeling since the success of models relies on the availability of input data. Data management needs to be transparent, available to the community, all inclusive, and developed well in advance of taking measurements, in order to derive the most robust model conclusions. International data sharing agreements should be forged, with communities working together to ensure that data are freely available.

3.5.7 Prioritization of Research Needs

There are several factors that should be considered in prioritizing research needs. High priority should be given to: (1) irreversible chemical and biological changes; (2) well-standardized observations; (3) observations and modeling that significantly improve prediction (*e.g.* observations that describe complex nonlinear processes, fill in data gaps or models that easily allow for scale-up of temporal and spatial scales); (4) feedbacks and synergistic effects; (5) ecosystem and economic impacts, such as observations that provide early detection, and/or directly relate to human health, welfare, or ecosystem health; and (6) research that dovetails with international programs (e.g., European Union, Canada).

Table 5. Research priorities for high latitude regions. **Activities are prioritized as follows: (1) Urgent and Important; (2) Important; (3) Desirable. The recommended time window within the 0-10 year timeframe for each activity is denoted with "X."**

Activity	Priority	0–2 Years	2–5 Years	5–10 Years	Rationale
Technical needs					
Develop genomic resources of key high latitude species; request sequencing by Joint Genome Institute	1	X	X	X	Pteropods, foraminifers, cold water coral (*Lophelia pertusa*), crustose coralline algae
Standardize protocols for manipulation of seawater chemistry and rate measurements (*e.g.*, calcification rates)	1	X			Critical for being able to discern OA effects, deduce trends over space & time
Develop new instrumentation for autonomous measurements	2		X	X	Alkalinity, pH, DIC, carbonate ion, POC, PIC, physiological markers such as genes that are activated under OA
Baseline monitoring					
Establish new time series/ adding new measurements to existing monitoring programs	2	X	X	X	Augment existing programs: Marathon line (152° W), AMT line, McMurdo to Christchurch (170° W), Ocean Station Papa; Longhurst-Hardy Plankton Recorder surveys; Coastal time series in North Pacific; New time series in the Bering Sea due to its large economic impact to US fisheries.
Deploy moorings equipped with carbon sensors	2	X	X	X	Add new moorings each year for CO_2 system parameters

Develop network of moorings, monitoring and process studies off the US west coast	1	X	X	X	Document movement of seawater undersaturated with respect to aragonite/ impacts on coastal ecosystems

Table 5. *Continued.*

Surveys					
Conduct high resolution baseline surveys of calcareous planktonic and benthic organisms and calcification rates	1	X		X	Track changes in abundances, distributions, and calcification rates of benthic and planktonic target organisms; include high resolution measurement of CO2 chemistry; Bering Sea process study; high latitude regions in which surface waters are projected to become undersaturated with respect to aragonite within decades
Augment existing survey programs to track CO_2 chemistry and abundances and distributions of key species	2	X	X	X	Palmer LTER, Repeat Hydro, Geotraces, pCO_2, time series
Conduct repeat surveys	2	X	X	X	Species abundances, calcification rates, oceanographic trends, Spatial/depth variability, continue observations/process species
Satellite algorithm development	1	X	X	X	Coccolithophore PIC, DIC, $p(CO_2)$, chlorophyll, alkalinity, climate quality data

Table 5. *Continued.*

Activity	Priority	0–2 Years	2–5 Years	5–10 Years	Rationale
Manipulative Experiments/Process Studies					
Conduct lab experiments	1	X	X	X	Wide range of experiments on different taxa, examining response of growth, mortality, fecundity to OA
Build laboratories	2		X	X	Central facilities for OA research
Conduct mesocosm experiments	3			X	Plan and build mesocosm facility
Integrate US activities with international partners	2	X	X	X	Establish coordinated US-EU program, PICES/ ICES
Conduct manipulative process studies	2		X	X	e.g., Manipulative studies on Cold water corals
Develop network of process studies in the open ocean with drifters and floats added	2		X	X	Plan coordinated mooring turnaround process studies
Investigate possible impacts of OA on pathogens, harmful algal blooms, and invasive species	2		X	X	Determine whether pathogens and invasive species proliferate during OA and assess possible impacts to communities
Modeling					
Develop organismal physiological and biomineralization models; and ecological population and	1	X	X	X	Required to understand consequences of OA at cellular, organismal, community and ecosystem levels

community models					Predictions
Develop fisheries models coupled with OA projections	1	X	X	X	Required to assess OA ecological, and socioeconomic impacts under different CO_2 emissions scenarios
Develop nested biogeochemical regional models, essential to include the coastal zone	1	X	X	X	Needed to assist in design of lab and field experiments, synthesize what has been learned, and make projections for different CO_2 scenarios
Enhance large scale global models	2	X	X	X	Changes in saturation state (calcite, aragonite), pH, ecosystems
Develop methods for data / metadata management	3		X	X	Centralize; archive in manner that will be accessible in future decades

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Appendix 1

Ocean Carbon and Biogeochemistry Scoping Workshop on
Ocean Acidification Research
Scripps Institution of Oceanography
La Jolla, CA
Sumner Auditorium
October 9-11, 2007

(Shuttles will leave La Jolla Shores Hotel starting at 7:45 a.m. It will take 3 trips to get everyone to Scripps.)

Tuesday, October 9, 2007

800 Continental Breakfast — Outside the Sumner Auditorium

(Posters can be put up immediately on the wall outside Sumner Auditorium. It is a concrete wall so we will provide tape to use.)

830 Logistics by **Vicki Fabry**, *California State University, San Marcos*

840 Welcome by **Tony Haymet**, *Scripps Institution of Oceanography*

850 NSF, NOAA, NASA

920 What we hope to accomplish **Chris Langdon**, *University of Miami*, and **Vicki Fabry**

930 Session A, Moderator: **Cynthia Pilskaln**, *University of Massachusetts*

Hugh Ducklow, *Marine Biological Laboratory*: How will polar plankton ecosystems respond to ocean acidification?

1010 Coffee break (30 min) — Outside the Sumner Auditorium

1040 **Mark Green**, *St. Joseph's College*: Death by Dissolution: The fate of carbonate-bearing organisms in nearshore marine environments in a high CO_2 world

1120 Session B, Moderator: Richard Feely, NOAA/PMEL

Ulf Riebesell, *IFM-GEOMAR,* Kiel: Pelagic mesocosms for future ocean simulations

1200 Lunch and posters: 1 hour — Outside Sumner Auditorium: Seating will be anywhere you can perch on the wall or at the nearby Pawka Green

1300 **Kerim Aydin**, *NOAA Alaska Fisheries Science Center*: Impacts on fisheries

1340 Breakout 1 (Participants will be given instructions and questions to be answered)

Breakouts rooms are:
- Sumner Auditorium
- Hubbs 4500
- SIO Library Conference room (Helen Raitt Room): 20 people
- IGPP 12B: ~24 people
- Room 10: 20 people

1500 Coffee break — There will be two set ups. One outside Sumner Auditorium and one outside Hubbs 4500.

1530 Breakout 1 continued

1640 Report back to from Breakout 1 to plenary — Sumner Auditorium

17:00 Posters — Outside Sumner Auditorium

Shuttle will leave Sumner to the Birch Aquarium at 1800.

1800-2000 **Scoping Workshop for Ocean Acidification Reception, hosted by Scripps Institution of Oceanography** — Birch Aquarium

Shuttles will leave from outside of Birch Aquarium starting at 1945 to get everyone back to the hotel. It will take 3 trips to get everyone back to the hotel.

Wednesday, October 10, 2007

800 Continental Breakfast — Outside the Sumner Auditorium
830 Update: **Chris & Vicki** — Sumner Auditorium
845 Session C, Moderator: ***Peter Edmunds****, California* State University, Northridge
Anne Cohen, *Woods Hole Oceanographic Institution*: Biocalcification Responses to Ocean Acidification: the Interplay of Physicochemical and Physiological Factors
925 **Brad Seibel**, *University of Rhode Island*: Physiological response to ocean acidification: squids as extreme animal models
1005 Coffee break — Outside the Sumner Auditorium
1035 Session D, Moderator: **Chris Sabine**, *NOAA/PMEL* — Sumner Auditorium
Gretchen Hofmann, *University of California, Santa Barbara*: Using Functional Genomics to Explore the Impacts of Ocean Acidification on Calcifying Marine Organisms
1115 **Fred Mackenzie**, *University of Hawaii*: Carbonate Dissolution Under Rising Atmospheric CO2 and Ocean Acidification
1200 Lunch and posters: 1 hour — Outside the Sumner Auditorium
1300 **Scott Doney**, *Woods Hole Oceanographic Institution*: Modeling Challenges for Ocean Acidification — Sumner Auditorium
1340 Breakout 2 (Participants will be given instructions and questions to be answered)
Breakouts rooms are: Sumner Auditorium
Hubbs 4500
SIO Library Conference room (Helen Raitt Room): 20 people
IGPP 12B: ~24 people
Room 10: 20 people
1500 Coffee break There will be two set ups. One outside Sumner Auditorium and one outside Hubbs 4500.
1530 Breakout 2 continued
1640 Report back from Breakout 2 to plenary — Sumner *Auditorium*
1700 Evening talk over beer: ***Danny Harvey****, University* of Toronto: Ocean Mitigation Strategies — Sumner Auditorium
Shuttles will leave for the hotel starting at 1800.
1800 Dinner on your own

Thursday, October 11, 2007
800 Breakfast — Outside the Sumner Auditorium
830 Update: Chris & Vicki — Sumner Auditorium
845 Session E, Moderator: **Andrew Dickson**, *Scripps Institution of Oceanography*
David Hutchins, *University of Southern California*: Rising pCO2 and Oligotrophic Ocean Biology: Winners and Losers in the Central Gyres
925 **Uta Passow**, *University of California, Santa Barbara*: Respiration, decomposition and export
1005 Coffee break — Outside the Sumner Auditorium
1035 Session F, Moderator: **Dwight Gledhill**, *NOAA Coral Reef Watch* — Sumner Auditorium
Ilsa Kuffner, *U.S. Geological Survey*: Ocean Acidification Impacts on Coral Reefs - Changes in Community Structure
1115 **Barney Balch**, Bigelow Laboratory for Ocean Sciences: Using Remote Sensing to Assess Ocean Acidification Impacts
1200 Lunch and posters: 1 hour — Outside the Sumner Auditorium
1300 Breakout 3 (Participants will be given instructions and questions to be answered)

Breakouts rooms are: Sumner Auditorium
Hubbs 4500

SIO Library Conference room (Helen Raitt Room): 20 people
IGPP 12B: ~24 people
Room 10: 20 people

1500 Coffee Break There will be two set ups. One outside Sumner Auditorium and one outside Hubbs 4500.

1530 Breakout 3 continued
1640 Report back from Breakout 3 to plenary Sumner Auditorium
1700 Workshop Wrap up/recommendations
1730 Dinner on your own
Shuttles will leave for the hotel starting at 1735.

This workshop focuses on four habitats: warm water coral reefs, coastal areas/estuaries, tropical/subtropical pelagic regions and high latitudes. Each afternoon, participants will split up into these four groups and discuss a set of questions that the steering committee has formulated. The questions will change on days 1, 2 and 3. At the end of each afternoon, participants will assemble to report on their discussions and recommendations to the entire group. Each breakout group will have a leader and rapporteur.

Group	Discussion Leader	Rapporteur
1 Coral reefs	Joanie Kleypas	Marlin Atkinson
2 Coastal/estuaries	Burke Hales	Richard Jahnke
3 Tropical/subtropical pelagic	David Hutchins	Peter Sedwick
4 High latitudes	Barney Balch	John Guinotte

Participants will be initially assigned to groups based on the organizers' knowledge of their interests. A number (from 1 to 4) will be printed on each name tag. Participants may switch groups if the organizers were wrong about their interests, but obviously it is desirable to maintain a rough balance in numbers across the four groups.

Overview of Rooms:
Plenary Sessions are in Sumner Auditorium
Breakouts rooms are: Sumner Auditorium
Hubbs 4500
SIO Library Conference room (Helen Raitt Room): 20 people
IGPP 12B: ~24 people
Room 10: 20 people
Breakfasts, morning breaks, lunch, are outside Sumner Auditorium.

Afternoon coffee breaks are in 2 areas: outside Sumner Auditorium and outside Hubbs Hall 4500.

Appendix 2

Ocean Carbon and Biogeochemistry Scoping Workshop on Ocean Acidification Research Scripps Institution of Oceanography La Jolla, California October 9-11, 2007

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