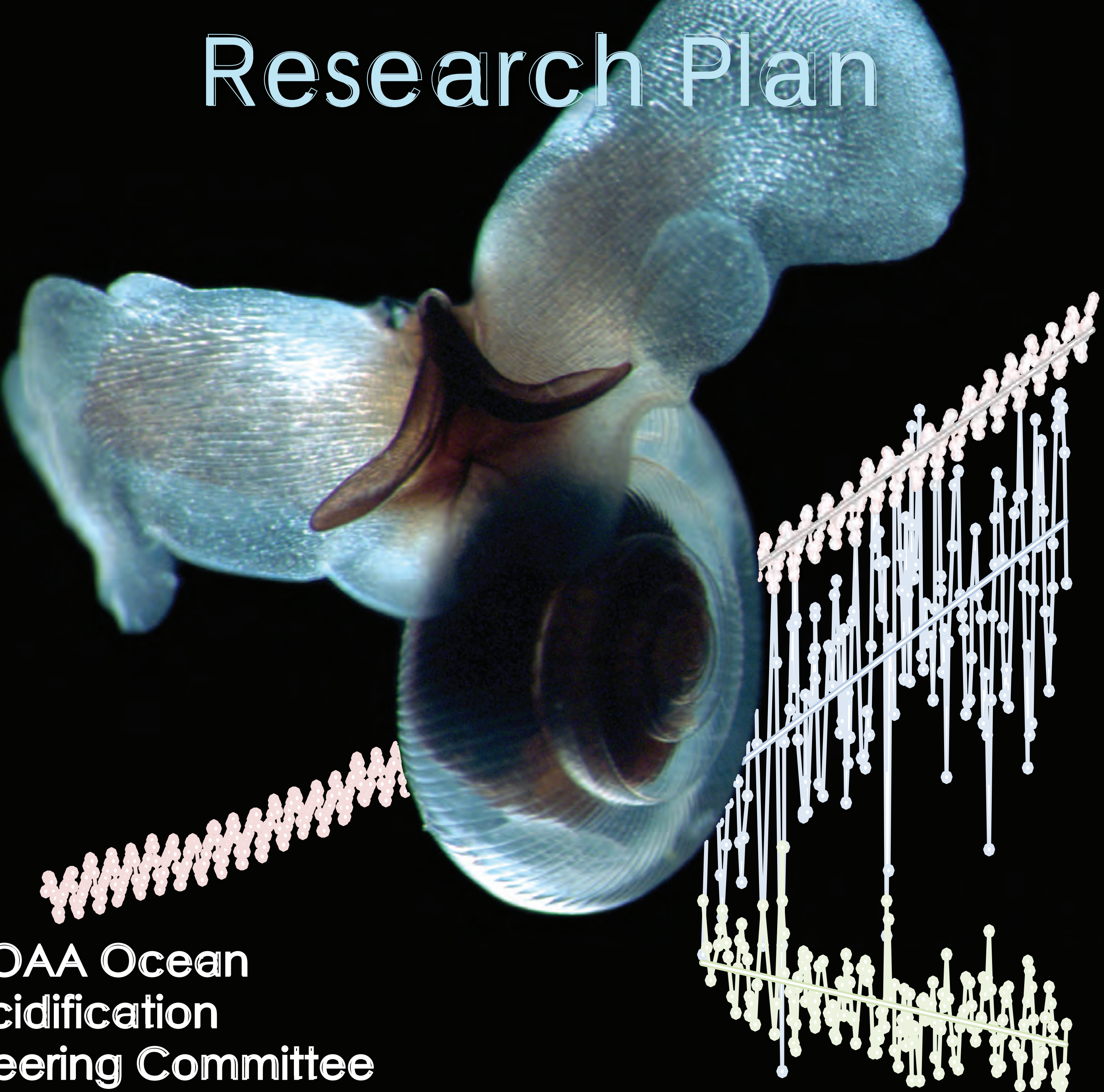
NOAA Ocean and Great Lakes Acidification Research Plan



NOAA Ocean
Acidification
Steering Committee

April 2010

NOAA Ocean and Great Lakes Acidification Research Plan

NOAA Ocean Acidification Steering Committee:

Richard A. Feely (OAR/PMEL)
Rik Wanninkhof (OAR/AOML)
John Stein (NMFS/NWFSC)
Michael F. Sigler (NMFS/AFSC)
Elizabeth Jewett (NOS/CSCOR)
Felipe Arzayus (OAR/OOER)
Dwight K. Gledhill (OAR/AOML)

Editor: Adrienne J. Sutton (OAR/PMEL)

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Credit: Russ Hopcroft (University of Alaska Fairbanks)
Front cover graphic: see Figure 1.1 on page 2

Acknowledgments

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April 2010

UNITED STATES
DEPARTMENT OF COMMERCE

Gary Locke
Secretary

NOTICE from NOAA

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Executive Summary

Ocean acidification has the potential to seriously threaten the future health of the world's oceans and the significant economic benefits they provide to humankind. This rapidly emerging scientific issue has raised serious concerns across the scientific and resource management communities as to possible ecological and economic impacts. As a part of NOAA's mission and *numerous* legislative mandates, we are required to understand and predict changes in Earth's environment as a consequence of continued acidification of the oceans and Great Lakes and conserve and manage marine organisms and ecosystems in response to such changes. The Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009 mandates that NOAA has an active monitoring and research program to determine potential impacts of decreased ocean pH and carbonate saturation states, which are happening in direct response to rising atmospheric CO_2. Other mandates (e.g., Magnuson-Stevens Fishery Conservation and Management Act, Marine Mammal Protection Act, National Marine Sanctuaries Act, Endangered Species Act, Coral Reef Conservation Act, and Clean Water Act) also require that NOAA work to fully understand the consequences of a changing environment to marine and Great Lakes resources. In addition, NOAA must respond to various interagency research planning documents, including *Charting the Course for Ocean Science in the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy*.

Characterizing the extent of acidification in our oceans and Great Lakes and predicting the ramifications for marine and freshwater resources and ecosystem services is critical to national and international climate mitigation discussions and to local communities that rely on these resources to prepare and adapt to ocean acidification. The purpose of NOAA's Ocean and Great Lakes Acidification Research Plan is to present a consensus research strategy for NOAA to advance the understanding of the impacts of ocean acidification and to address related challenges to local and national ecosystems and communities. The organizational construct of the plan allows for the flexible application of ocean acidification research unique to each ocean, coastal, and Great Lakes region. This is a living document that will continue to be revised as NOAA's Ocean Acidification Program develops detailed plans for implementation of monitoring, experimental studies of biological impacts, education and outreach, and data management activities.

The research and monitoring requirements detailed in this plan are designed to achieve tangible progress toward addressing a set of core fundamental hypotheses. These hypotheses are intended to provide strategic science-based guidance to the NOAA research community and to help integrate the broad range of proposed activities toward a common purpose. These hypotheses address the characterization of the biogeochemical changes across a range of environments, evaluating the response of key aquatic organisms and ecosystems, and illuminating the range of vulnerabilities in order to inform adaptive management strategies.

Hypothesis 1. Rates and magnitude of acidification will vary across time, space, and depth as a consequence of local and regional geochemical, hydrological, and biological mechanisms.

Hypothesis 2. Ocean acidification will change ecosystem structure, function, and biodiversity via both direct impacts (e.g., altered growth or survival rates) and indirect effects (e.g., food web and/or habitat changes).

Hypothesis 3. Heterogeneity in species-specific responses, local environmental and regional considerations will confer a broad range of vulnerabilities that differ both locally and regionally.

The overarching goal of the NOAA Ocean and Great Lakes Acidification Research Plan is to predict how ecosystems will respond to acidification and to provide information that resource managers can use to address acidification issues. The research effort will be executed at the regional level with strong national coordination. The monitoring of temporal and spatial trends will be done through ship-based and moored observations of key physical, chemical, and biological parameters. Ecosystem responses will be studied with the same platforms but will also require laboratory experiments to study physiological responses to acidified waters. Modeling studies will delineate large-scale changes in water chemistry and ecosystem response and will be used to develop adaptation strategies in response to ocean and lake acidification.

The primary goals of this research are to: develop the monitoring capacity to quantify and track ocean acidification and its impacts in open-ocean, coastal, and Great Lakes systems (Theme 1); assess the response of organisms to ocean and lake acidification (Theme 2); forecast biogeochemical and ecological responses to acidification (Theme 3); develop management strategies for responding and adapting to the consequences of ocean acidification from a human dimensions perspective (Theme 4); provide a synthesis of ocean and Great Lakes acidification data and information (Theme 5); and provide an engagement strategy for educational and public outreach (Theme 6). These themes will be executed taking full advantage of the observational, experimental, and modeling capacities within NOAA and relying on external research partners to complement and augment NOAA's internal expertise in coastal and ocean sciences. Progress will be gauged from ongoing synthesis and assessment efforts.

The research efforts are partitioned into a global component and a coastal component (including the Great Lakes), both of which are focused on scientific and economic interests of the United States. For the global component, improved coordination of existing field efforts along with modest adjustments and enhancements to on-going and future research plans of the NOAA ocean carbon, biological (fisheries), and modeling communities, will allow us to meet many of the research requirements. For coastal environments, a network of new hydrographic and ecological surveys will be required along with new coastal models to provide an "early warning" system for ocean acidification. Developing an ocean carbon observatory network would provide this capability by ensuring that key parameters (i.e., pH, $p\mathrm{CO}_2$, etc.) for understanding and forecasting the effects of ocean acidification on marine ecosystems are monitored. NOAA is well poised to enhance many capabilities within NOAA that can be utilized to establish an ocean and Great Lakes acidification ecosystem monitoring network that will not only characterize the carbon chemistry of these environments but also will monitor the critical changes in community metabolic processes that are required to determine the ultimate "carbon thresholds" for ecosystem response. Some new technology and enabling activities will need to be developed or adapted for this component, including new biogeochemical sensors for carbon species, gliders, genomic tags, and a center of expertise for carbon measurements. Monitoring carbon and ecosystems is only part of the challenge—another key area of research will be estimating species response and predicting how the effects of acidification on individual species will cause a loss of biodiversity and/or alter entire food webs.

The development of a program to fulfill NOAA Ocean and Great Lakes Acidification Research Plan will benefit from a coordinated national research effort closely linked with other U.S. federal and state government, university, and private efforts. What follows is a detailed plan for NOAA research on ocean acidification. Chapter 1 outlines the overall rationale, common elements and broad goals for the program; Chapters 2 through 7 provide the research plans for the six regions of intensive study; and Chapter 8 provides the program outputs, budgets, and timelines.

1. Rationale and Strategy for a National Ocean Acidification Program

Richard A. Feely, Chris Sabine, Rik Wanninkhof, Simone R. Alin, Elizabeth Jewett, Dwight K. Gledhill, John Dunne, Paul McElhany, Adrienne J. Sutton, D. Shallin Busch, Felipe Arzayus, Bill Sunda, Jessica Geubtner, Jon Hare, Oliver Vetter, and Steve Hankin

1.0 Introduction

SINCE THE BEGINNING of the Industrial Revolution in the mid-18th century, the release of carbon dioxide (CO_2) from our industrial and agricultural activities, commonly referred to as "anthropogenic CO_2" has resulted in an increase in atmospheric CO_2 concentrations from approximately 280 to 390 parts per million (ppm), with 30% of the increase occurring in the last three decades. The atmospheric concentration of CO_2 is now higher than experienced on Earth for more than 800,000 years. These changes in CO_2 are projected to cause significant temperature increases in the atmosphere and the ocean surface in the coming decades. Over the industrial era, the ocean has absorbed about 30% of anthropogenic carbon emissions. This absorption has benefited humankind by significantly curtailing the growth of CO_2 levels in the atmosphere, thereby reducing the global warming realized to date. However, when anthropogenic CO_2 is absorbed by seawater, thereby increasing dissolved CO_2 concentrations, chemical reactions occur that reduce both seawater pH and the concentration of carbonate ions in a process known as "ocean acidification" (OA). The pH of ocean surface waters has already decreased by about 0.1 units since the beginning of the industrial revolution (Caldeira and Wickett, 2003; Feely *et al.*, 2004; Caldeira and Wickett, 2005), with a decrease of ~0.0018 yr^{-1} observed over the last quarter century at several open ocean time-series sites (Bates, 2007; Bates and Peters, 2007; Santana-Casiano *et al.*, 2007; Dore *et al.*, 2009). By the middle of this century atmospheric CO_2 levels could reach more than 500 ppm, and over 800 ppm by the end of the century (Orr *et al.*, 2005). This would result in an additional decrease in surface water pH of approximately 0.3 pH units by 2100. As a result, acidity in the ocean would increase by about 150% relative to the beginning of the industrial era.

Results from global ocean CO_2 surveys over the past two decades have shown that ocean acidification is a predictable consequence of rising atmospheric CO_2 levels. Seawater carbonate chemistry is governed by a series of abiotic chemical reactions (CO_2 dissolution, acid/base chemistry, and calcium carbonate dissolution) and biologically mediated reactions (photosynthesis, respiration, and calcium carbonate precipitation). The first of these reactions is air-sea exchange, which results in CO_2 dissolution in seawater, and its subsequent release back to the atmosphere:

$$\text{Air-sea exchange:} \quad CO_{2(atmos)} \rightleftarrows CO_{2(aq)}. \tag{1.1}$$

Equilibration between the atmosphere and the ocean occurs on timescales of months so that surface waters increase in CO_2 concentration from year to year in proportion to the increased CO_2 concentration in the atmosphere.

Hydration and acid/base reactions:

$$CO_{2(aq)} + H_2O \rightleftarrows H_2CO_3 \rightleftarrows H^+ + HCO_3^- \rightleftarrows 2H^+ + CO_3^{2-}. \tag{1.2}$$

Equilibration of the inorganic carbon species in seawater occurs on timescales of tens of seconds for CO_2 hydration and microseconds for subsequent acid-base reactions. Thus, for most applications, the partitioning of inorganic carbonate species can be assumed to be in equilibrium. For typical surface ocean conditions, about 90% of the total dissolved inorganic carbon (DIC) occurs as bicarbonate ions (HCO_3^-) and ~9% as carbonate ions (CO_3^{2-}), with only ~1% remaining as dissolved $CO_{2(aq)}$ and H_2CO_3. As CO_2 concentrations increase in seawater, CO_2 reacts with water to form carbonic acid (H_2CO_3). Most of the H_2CO_3 dissociates to form a hydrogen ion (H^+) and a bicarbonate ion (HCO_3^-) and most of the resulting H^+ reacts with carbonate ions (CO_3^{2-}) to produce additional HCO_3^- ions. As a result, CO_2 dissolution in the ocean causes increases in H^+ (and thus decreased pH) and decreases in CO_3^{2-} concentration (Figure 1.1). The decrease in CO_3^{2-} reduces the saturation state (Ω) of calcium carbonate ($CaCO_3$), which directly affects the ability of some $CaCO_3$-secreting organisms to produce their shells or skeletons. This is true even though most surface waters in the global ocean are currently supersaturated with respect to calcium carbonate concentrations (e.g., Ω values of 2–4 for aragonite (Ω_{arag}) and 4–6 for calcite (Ω_{cal}), the two most common carbonate biominerals), because non-biological precipitation rates for calcium carbonate minerals are exceedingly slow. Because of the slow chemical kinetics, nearly all calcium carbonate precipitation in the ocean is biologically mediated. Many organisms have optimal carbonate precipitation rates at the existing supersaturation states for these minerals; thus, decreasing CO_3^{2-} concentrations could decrease calcification rates for many species.

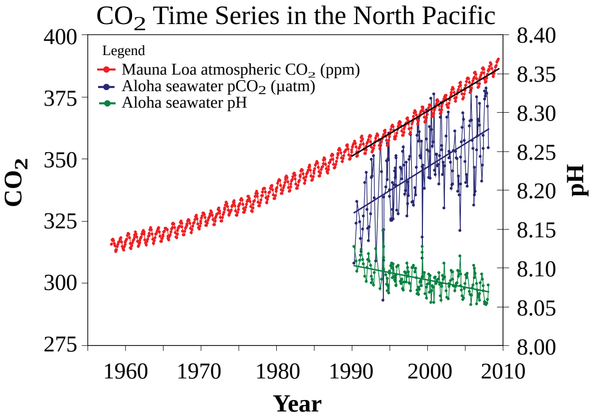


Figure 1.1: Time series of atmospheric CO_2 at Mauna Loa (in ppm) and surface ocean pH and pCO_2 (μatm) at Ocean Station Aloha in the subtropical North Pacific Ocean. Note that the increase in oceanic CO_2 over the last 19 years is consistent with the atmospheric increase within the statistical limits of the measurements. Mauna Loa data: Dr. Pieter Tans, NOAA/ESRL (`http://www.esrl.noaa.gov/gmd/ccgg/trends`); HOT/Aloha data: Dr. David Karl, University of Hawai'i (`http://hahana.soest.hawaii.edu`) (modified after Doney *et al.*, 2009a).

Calcium carbonate precipitation and dissolution:

$$Ca^{2+} + CO_3^{2-} \rightleftarrows CaCO_{3(s)} \tag{1.3}$$

The saturation state of calcium carbonate is defined by $\Omega = [Ca^{2+}][CO_3^{2-}]/K'_{sp}$. The apparent solubility product (K'_{sp}) varies with temperature, salinity, and pressure and differs for different calcium carbonate minerals (e.g., calcite and aragonite) (Mucci, 1983).

1.0.1 Biological consequences of ocean acidification

The gradual process of ocean acidification has long been recognized (Broecker and Takahashi, 1966; Bacastow and Keeling, 1973; Broecker *et al.*, 1971; Feely and Chen, 1982; Feely *et al.*, 1984; 1988; 2002), but the ecological implications of such chemical changes have only recently been examined. Although initial concerns about the effects of acidification focused on the negative effect that decreased $CaCO_3$ saturation state has on the ability of organisms to produce calcium carbonate shells, it is becoming increasingly clear that changes in CO_2 and pH *per se* can affect species growth, survival, and behavior (Pörtner, 2008). Many non-calcareous species are affected by acidification, and the ability of calcareous species to produce shells can be affected by acidification factors other than just saturation state (Pörtner, 2008). In addition to the effects of changes in CO_2, pH, and saturation state, secondary chemical reactions can change other components of seawater, such as the concentration of various forms of trace elements and nutrients, which in turn can affect species growth and survival (Doney *et al.*, 2009a).

The number of studies exploring the biological impact of acidification is increasing rapidly (Figure 1.2). In Table 1.1, we qualitatively estimate the response of species groups to acidification, which can be negative or positive, and describe the species' importance to ecological processes and economic value ("ecosystem services"). Species response to changing ocean conditions will likely depend on both their physiological response once exposed to high-CO_2 environments and the probability of being in a high-CO_2 environment. The response of the majority of species to ocean acidification has not been evaluated in either the laboratory (CO_2 experiments) or field, and estimating the response of untested species is challenging because of the high variability in response, even in closely related species (Miller *et al.*, 2009; Ries *et al.*, 2009). Calcifying organisms (e.g., corals, shellfish, and marine plankton) are generally considered the species most vulnerable to acidification, with mineralogy playing a role in susceptibility. The solubility of calcium carbonate minerals from most to least soluble is: (1) amorphous, (2) high-magnesium calcite, (3) aragonite, (4) low-magnesium calcite, and (5) calcite. The

Potential Direct Effects of Ocean Acidification

- **Reduced calcification rates of shell-forming animals**—The reduced saturation state affects the ability to produce calcium carbonate shell, makes the process more physiologically costly, or leads to dissolution of existing calcium carbonate structures.
- **Altered reproduction and survival from reduced pH**—Organisms generally require energy to maintain appropriate intra-cellular pH balance. Altering the external pH of seawater can overwhelm pH control mechanisms, affecting reproduction or survival.
- **Reduced olfaction in fish**—Increased CO_2 in seawater can affect the ability of fishes to detect critical olfactory cues.
- **Increased photosynthesis**—Because CO_2 is required for photosynthesis, some photosynthetic organisms, especially those without effective carbon concentrating mechanisms, may have increased photosynthetic rates with increased CO_2.
- **Hypercapnia**—Increased CO_2 in internal fluids, especially in highly energetic species like squid, can affect mobility, survival, or reproduction. The ability of organisms to decrease CO_2 concentration in internal fluids by transferring CO_2 across membranes to seawater is reduced when seawater CO_2 concentrations are high.
- **Acoustic disruption from reduced sound absorption**—Changes in ocean pH will alter the acoustic properties of the ocean, increasing transmission of low-frequency sounds, which may affect species relying on acoustic information.
- **Changes in speciation of some metals, nutrients, or toxic compounds**—Acidification will alter speciation (ionic form) of various metals, nutrients, or toxics in a way that may affect species reproduction and survival.

form of calcium carbonate produced by species could be used to rank species in terms of expected vulnerability. However, such rankings are not very reliable because other factors, including the mechanism of biomineralization and differences in basic metabolic processes, affect how calcareous species respond to acidification. For example, two congeneric species of oyster show different responses when exposed to elevated CO_2, perhaps as a result of differing metabolic rates (Miller *et al.*, 2009; Ries *et al.*, 2009). Although no single factor is an absolute predictor of how a species will respond, we relied on extrapolations from existing studies and basic principles (e.g., mineralogy and taxonomy) to develop the expected responses in Table 1.1.

The indirect effects of acidification are likely to impact nearly every species in marine food webs to some extent through food web predator-prey interactions, increased prevalence of invasive species, changes in pathogen distributions, and alterations of physical ecosystem structure (e.g., decline in oyster reefs). Although all ecosystem types are likely to be impacted, some are expected to experience greater effects than others.

Although it is premature to predict how severely each ecosystem type will be affected by acidification, we can anticipate that some ecosystems are particularly vulnerable to change. For example, a decline in coral reef accretion rates due to simultaneous increases in temperature and decreases in carbonate ion concentration (Silverman *et al.*, 2009) would have negative impacts on coral reef ecosystems, with consequent effects on fisheries, tourism, and coastal protection from storms. In addition, many non-reef benthic ecosystems are likely to be highly vulnerable because they are often dominated by calcareous species such as filter-feeding bivalves and predatory echinoderms and gastropods. Moreover, benthic communities are likely to experience more prolonged exposure to acidified water masses sooner than shallower communities. Recent observations indicate that bivalve shellfish hatcheries on both the West and East coasts are experiencing a decline in production, and adverse effects on the West Coast may be linked to upwelling of naturally low pH waters coupled with OA (Feely *et al.*, 2008). The response of pelagic communi-

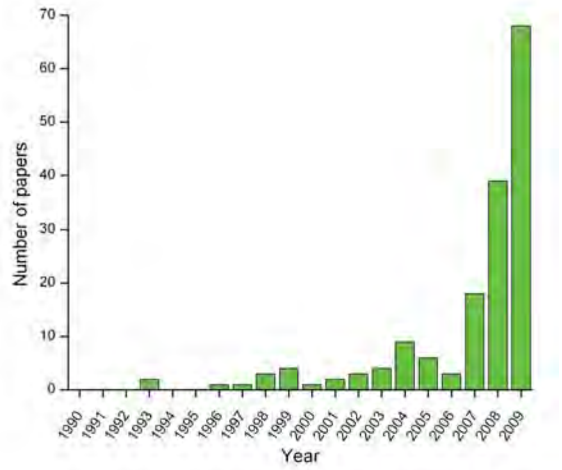


Figure 1.2: Number of papers published on species' response to ocean acidification per year, inclusive of reviews on the subject. Note this figure only partially includes manuscripts on tropical corals, and the publication record for 2009 is incomplete.

Table 1.1: Estimated species vulnerability to direct affects of ocean acidification (Busch *et al.*, in preparation).

Group	Impacts of ocean acidification	Ecosystem services	Selected references
Large animals			
Bivalves	• Negative effects on development (calcification, growth, maturation) • Decreased growth of adults • Decreased calcification • Decreased overall health	• Large industries developed around oyster, clam, and mussel species • Filter marine and estuarine waters • Create habitat for other species	(Beesley *et al.*, 2008; Berge *et al.*, 2006; Gazeau *et al.*, 2007; Kurihara, 2008; Kurihara *et al.*, 2008a; 2007; Michaelidis *et al.*, 2005; Miller *et al.*, 2009; Parker *et al.*, 2009; Sunday *et al.*, 2010; Talmage and Gobler, 2009; Tunnicliffe *et al.*, 2009)
Benthic gastropods—snails, abalone	• Increase in mortality • Decrease in growth • Decrease in metabolism • Less active during development • Some decreased in calcification	• Predators on benthic bivalves	(Bibby *et al.*, 2007; Ellis *et al.*, 2009; Hall-Spencer *et al.*, 2008; Shirayama and Thornton, 2005; Zippay and Hofmann, 2010)
Corals	• Decrease in calcification	• Create habitat for other species • Tourism and recreation • Coastal protection • Source of new medicines	(Jokiel *et al.*, 2008; Maier *et al.*, 2009; Gattuso *et al.*, 1998; Marubini *et al.*, 2001; 2002; Marshall and Clode, 2002; Ohde and Hossain, 2004; Borowitzka, 1981; Gao *et al.*, 1993; Langdon *et al.*, 2000; 2003; Langdon and Atkinson, 2005; Leclercq *et al.*, 2000; 2002; Anthony *et al.*, 2008; Yates and Halley, 2006; Manzello *et al.*, 2008; Kurihara, 2008; Reynaud *et al.*, 2003; Cohen *et al.*, 2009; Holcomb *et al.*, 2009)
Crustacea—Crabs and lobsters	• No change in calcification, mortality, metabolism, or heat tolerance in porcelain and swimming crabs • No change in growth or mortality of lobsters • Nothing known about impacts on cancer crab adults or crab zoea	• Much revenue gained from harvest of crab species (e.g., Dungeness, King) • Important omnivores in food webs	(Calosi *et al.*, 2009; Spicer *et al.*, 2007; Arnold *et al.*, 2009; Pane and Barry, 2007; Walther *et al.*, 2009)
Crustacea—Barnacles	• Negative effects on development • No change in growth • Mixed effects on abundance in field	• Fouls many human structures • Creates habitat for other species	(Dupont and Thorndyke, 2009; McDonald *et al.*, 2009; Hall-Spencer *et al.*, 2008; Wootton *et al.*, 2008)
Cephalopods (squid, cuttlefish, octopus)	• Decrease in metabolic rate and activity bouts	• Revenue gained from commercial fisheries	(Rosa and Seibel, 2008; Lacoue-Labarthe *et al.*, 2009)
Echinoderms—seastars and brittlestars	• Negative effects on development • Increased growth and metabolism as adults • Mixed effects on calcification	• Keystone predators in intertidal systems • Important bioturbators	(Dupont *et al.*, 2008; Dupont and Thorndyke, 2009; Gooding *et al.*, 2009; Wood *et al.*, 2008; 2009)
Echinoderms—urchins	• Negative effects on development • Decreased calcification • Decreased abundance in the field	• Important consumers in benthic food webs • Revenue gained from fisheries	(Byrne, 2009; Clark *et al.*, 2009; Dupont and Thorndyke, 2009; Hall-Spencer *et al.*, 2008; Havenhand *et al.*, 2008; Kurihara, 2008; Kurihara *et al.*, 2004b; Kurihara and Shirayama, 2004a;b; O'Donnell *et al.*, 2010; Shirayama and Thornton, 2005; Siikavuopio *et al.*, 2007; Sunday *et al.*, 2010)
Fish	• Some evidence for negative effects on development • Decrease in olfactory ability • No change in metabolism • Can compensate for acidosis • Some evidence for decrease in growth rate and body condition	• Important food source • Large industries developed around commercial and sport fisheries • Higher tropic level members of food chain • Culturally important as symbols and for sport	(Dixson *et al.*, 2010; Foss *et al.*, 2003; Melzner *et al.*, 2009; Munday *et al.*, 2009; Pörtner, 2008)
Jellies	• Limited to no evidence for a positive relationship with pH • Thrive in eutrophied and warm environments	• Some commercial harvest • Nuisance species for many fisheries • Public health problems related to some species	(Attrill and Edwards, 2008; Attrill *et al.*, 2007; Haddock, 2008; Richardson *et al.*, 2009; Richardson and Gibbons, 2008)

Table 1.1: Continued.

Group	Impacts of ocean acidification	Ecosystem services	Selected references
Large animals (continued)			
Mammals	• Increase in noise pollution	• Top predators in food webs • Tourist industries developed around viewing marine mammals (esp. orcas) • Cultural existence values	(Hester *et al.*, 2008; Ilyina *et al.*, 2010)
Shrimp	• Decreased settling size and adult growth • Increased mortality • Decreased egg production	• Revenue gained from harvest of shrimp species (e.g., spot prawn)	(Kurihara, 2008; Kurihara *et al.*, 2008b)
Tunicates	• Positive effects on development • Increased survival	• Nuisance invasive species	(Dupont and Thorndyke, 2009)
Plankton			
Bacteria—Blue-green algae	• Most species increase growth rate • Longer bloom timing • Increase in nitrogen fixation	• Large biomass pool • Some species can produce toxins • Fix nitrogen in marine food webs	(Barcelos e Ramos *et al.*, 2007; Fu *et al.*, 2007; Levitan *et al.*, 2007)
Foraminifera	• Decreased calcification • Decreased growth	• Important in global carbon cycles	(Bijima *et al.*, 2002; 1999; Guinotte and Fabry, 2008; Doney *et al.*, 2009a; Bernhard *et al.*, 2009; Dissard *et al.*, 2010; Kuroyanagi *et al.*, 2009; Moy *et al.*, 2009)
Phytoplankton (e.g., coccolithophores)	• Mixed effects on growth • Mixed effects on calcification • Some increase photosynthetic efficiency • Most increase C:N and C:P ratios (e.g., they are less nutritious food for consumers)	• Important primary producers • Important in global carbon cycles • Base of food web • Alter local ocean chemistry	(Bellerby *et al.*, 2008; Collins and Bell, 2004; Delille *et al.*, 2005; Doney *et al.*, 2009a; Guinotte and Fabry, 2008; Hare *et al.*, 2007; Iglesias-Rodriguez *et al.*, 2008; Kuffner *et al.*, 2007; Riebesell *et al.*, 1993; 2000; 2007; Rost *et al.*, 2008; Tortell *et al.*, 2008; Hinga, 2002; Iglesias-Rodriguez *et al.*, 2008; Langer *et al.*, 2006)
Zooplankton—crustacean	• Negative effects on development (timing, success, viability) in some copepods, krills, and amphipods • No effect on adult growth and survival in copepods • Limited to no effect on fecundity in copepods and amphipods	• Base of food web for most fish species	(Dupont and Thorndyke, 2009; Egilsdottir *et al.*, 2009; Hauton *et al.*, 2009; Kurihara, 2008; Kurihara and Ishimatsu, 2008; Kurihara *et al.*, 2004a; Mayor *et al.*, 2007)
Zooplankton—pteropods	• Decreased calcification	• Key prey of pink and chum salmon	(Orr *et al.*, 2005)
Plants			
Coralline algae	• Decreased growth • Decreased calcification • Decreased abundance in most studies	• Create habitat for other species	(Anthony *et al.*, 2008; Gao *et al.*, 1993; Hall-Spencer *et al.*, 2008; Jokiel *et al.*, 2008; Kuffner *et al.*, 2007; Martin and Gattuso, 2009; Martin *et al.*, 2008; Wootton *et al.*, 2008)
Kelp	• Differential effects on growth depending on species • Decreases in decomposition rates (e.g., increase in shoreline wrack, decrease nutrients in inter and subtidal food webs)	• Important primary producer • Create habitat for other species, including many economically important fish species	(Klinger and Kershner, 2008; Swanson and Fox, 2007; Thom, 1996)
Seagrasses	• Increase in photosynthesis and growth • Increase in survival and maturation • Increase in flower output • Decrease in calcareous epiphytes	• Important primary producer • Create habitat for other species, especially as nursery grounds • Protects shoreline from erosion and storm surges	(Invers *et al.*, 2010; Palacios and Zimmerman, 2007; Hall-Spencer *et al.*, 2008)

ties to acidification is less obvious because the vulnerability of many key taxonomic groups in the system, such as phytoplankton and zooplankton, is unknown, as is the vulnerability of pelagic fish species; however, many of these species employ some form of calcification during development and are sensitive to ambient pH. How bacteria will respond to acidification is also a key unknown in the potential reshaping of the base of marine food webs (Hutchins *et al.*, 2009).

Another important consideration is that acidification is not the only stressor affecting marine and Great Lake species and ecosystems. Most coastal ecosystems already experience fishing pressures, input of chemical contaminants, and exotic and invasive species and will likely experience changes in dissolved oxygen—not only from altered ocean dynamics but also from anthropogenic nutrient inputs. In addition, the overarching effects of climate change impose challenges to all coastal ecosystems. It is in this context that ocean and lake acidification needs to be evaluated and all ecosystem research should, where possible, integrate information on all possible stressors.

It is also important to note that not all biological impacts from rising atmospheric CO_2 are necessarily deleterious. Nitrogen-fixation by the cyanobacterium, *Trichodesmium*, for example, is enhanced by elevated CO_2 concentrations (Hutchins *et al.*, 2007). Growth and light-saturated photosynthetic rates of seagrasses are also increased under high-CO_2 conditions (Palacios and Zimmerman, 2007; Zimmerman *et al.*, 1997). There will likely be ecological "winners" as well as "losers," resulting in regional changes in ecosystem structure through local competition for resources and possible migration of species populations. The question remains, however, what the ecological and societal consequences will be from the loss of key calcifying and other species, and how the "winners" will alter the ecosystems or the biogeochemical cycles they regulate. Interactions with other climate change effects further complicate our understanding of the ecological consequences of OA.

1.0.2 The ocean's biological pump

Photosynthesis by marine photosynthetic organisms consumes CO_2 and thus reduces the acidity of surface waters and increases the concentration of carbonate ions. It also produces a large fraction of the annual global supply of oxygen and consumes other nutrients such as nitrate, phosphate, and iron, all of which can be limiting in different parts of the ocean. As this plant matter sinks into the subsurface layers of the ocean it is re-oxidized back to CO_2 by microbial respiration. Thus, the coupled biological reactions of photosynthetic fixation of CO_2 in surface ocean waters and microbial remineralization of organic matter to CO_2 in deeper unlit ocean waters represents a biological carbon pump that transports surface CO_2 to the deep ocean. This biological CO_2 pump removes CO_2 from the atmosphere and it increases CO_2 concentrations in the deep ocean waters. And by increasing CO_2 concentration in the deep ocean, it also decreases deepwater pH by up to 0.6 units and substantially decreases carbonate ion concentrations. Thus the biological pump impacts the natural cycles of carbon in the ocean and produces large gradients in CO_2, pH, and carbonate ion concentrations with depth.

$$\begin{gathered}\text{Photosynthesis} \leftrightarrows \text{Respiration:}\\ CO_2 + H_2O \leftrightarrows CH_2O + O_2. \qquad (1.4)\end{gathered}$$

The effect of the coupled biological processes of photosynthesis and respiration may be highly important in coastal, estuarine, and Great Lakes systems that receive high anthropogenic inputs of nutrients (mostly fertilizer) and organic matter derived from sewage and agricultural runoff. High anthropogenic inputs of nutrients can promote algal blooms and drive an enhanced biological CO_2 pump in estuaries (e.g., Chesapeake Bay) and coastal waters (e.g., the Mississippi River plume), similar to that naturally occurring in upwelled ocean waters of the Pacific. When the increased algal biomass is respired at depth by bacteria, it causes a drop in oxygen (hypoxia) and an increase in CO_2, further decreasing pH and the carbonate ion. This phenomenon is particularly acute in systems at the mouths of rivers or in estuaries where water is stratified by salinity, thus preventing aeration of bottom waters (Feely *et al.*, 2010). These indirect anthropogenic effects have the potential to adversely impact ecologically and economically important calcifying organisms (e.g., clams and oysters), especially when combined with increasing atmospheric inputs of CO_2 from the burning of fossil fuels and deforestation.

1.0.3 Evidence of ocean acidification from data and models

The abiotic and biological processes described above are well verified from models, open-ocean hydrographic surveys, and time-series data (Bates, 2007; Bates and Peters, 2007; Caldeira and Wickett, 2003; 2005; Chung *et al.*, 2003; Feely *et al.*, 2002; 2004; 2008; 2009; Orr *et al.*, 2005; Sabine and Feely, 2007; Dore *et al.*, 2009). At the Hawai'i Ocean Time-Series (HOT) station, ALOHA, the increases of surface water $p\mathrm{CO_2}$ and atmospheric CO_2 agree well (Figure 1.1), indicating uptake of anthropogenic CO_2 as the major cause for long-term increases in dissolved inorganic carbon (DIC) and decreases in $CaCO_3$ saturation state (Doney *et al.*, 2009b). While ocean acidification is a global-scale phenomenon, there are near-surface ocean regions that already naturally experience low pH conditions linked to the upwelling or mixing of low pH deep ocean waters to the surface. Additional anthropogenic inputs of CO_2 in these regions may be particularly deleterious. Modeling studies have suggested that the high-latitude surface waters in the Arctic and Southern Oceans, where deep mixing occurs during winter, will experience aragonite undersaturation by the middle of the century (Cao and Caldeira, 2008; Gehlen *et al.*, 2007; Orr *et al.*, 2005); whereas other studies (Steinacher *et al.*, 2008; Feely *et al.*, 2009) indicate that surface waters in the Arctic will start experiencing localized aragonite undersaturation within the next decade (Figure 1.3).

Feely *et al.* (2008) presented data that demonstrated organisms growing in coastal upwelling areas along the continental shelf of the west coast of North America may already be experiencing significant biological impacts resulting from the combined impacts of coastal upwelling and ocean acidification. Here the seasonal upwelling of subsurface waters along the coast brings CO_2-enriched waters onto the shelf and, in some instances, into the surface ocean. It appears that this water, in addition to its original high level of CO_2 resulting from natural respiration processes in the subsurface layers, is also significantly enriched with anthropogenic CO_2. An immediate consequence of this additional CO_2 is that the pH and carbonate saturation state of these upwelled waters is significantly lower than what it would have been in preindustrial times. Since these "acidified" upwelled waters are undersaturated with respect to aragonite, they are already a potential threat to many of the calcifying aragonitic species that live in these coastal regions. Because seasonal upwelling is a common phenomenon in many coastal regions, this process may be affecting coastal ecosystems in other locations as well. Shoaling of undersaturated waters has been observed in the North Pacific (Feely *et al.*, 1988; 2002), and the Chukchi Sea of the Arctic (Bates *et al.*, 2009), where the biological CO_2 pump enhances the seasonal undersaturation of carbonate minerals in subsurface waters.

1.0.4 Goals and scientific rationale

The principal goals for the NOAA Ocean and Great Lakes Acidification Research Plan are to: develop the monitoring capacity to quantify and track ocean acidification in open-ocean, coastal, and Great Lake systems (Theme 1); assess the response of marine and freshwater organisms to ocean and lake acidification (Theme 2); forecast biogeochemical and ecological responses to acidification (Theme 3); provide a synthesis of ocean and Great Lake acidification data and information (Theme 4) that aids in development of tools for managing coastal, open ocean, and Great Lakes ecosystems and preparing human communities for potential OA-related changes (Theme 5); and provide information about ocean acidification to educators and develop materials for public outreach (Theme 6). The NOAA Ocean and Great Lakes Acidification Research Plan will be designed to integrate new methodologies and approaches as they become available. A coordinated multidisciplinary program of field observations, laboratory studies, and modeling is critical to achieving a successful research strategy for ocean acidification. It will facilitate the development of our capability to predict present and future responses of marine and Great Lakes biota, ecosystem processes, and biogeochemistry to acidification (Fabry *et al.*, 2008).

Critical new research elements should include regional and global networks of observations and process studies; manipulative experiments involving a suite of organisms in laboratory experiments and mesocosm and field studies; technological advances; and new modeling approaches. Indices for ocean acidification beyond basic water-column physics and chemistry have yet to be adequately developed. Parameters that can be measured routinely onboard ships include temperature, salinity, oxygen, nutrients, CO_2 partial pressure ($p\mathrm{CO_2}$), pH, total alkalinity (TA), dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), and particulate organic and inorganic carbon (POC, PIC). While some of these chemical parameters now can be measured on moorings, it is not yet possible to collect needed data on a global scale. To expand capabilities of non-ship-based platforms, we need to develop new platform-appropriate methodologies for measuring fundamental chemical parameters (e.g., DIC and TA) and proxies of stress in biological organisms. Two key questions regarding responses to ocean acidification are (1) whether or not there are geochemical thresholds for ocean acidification (e.g., $CaCO_3$ mineral saturation state levels) that will lead to irreversible effects on species populations and ecosystems over the next few decades and (2)

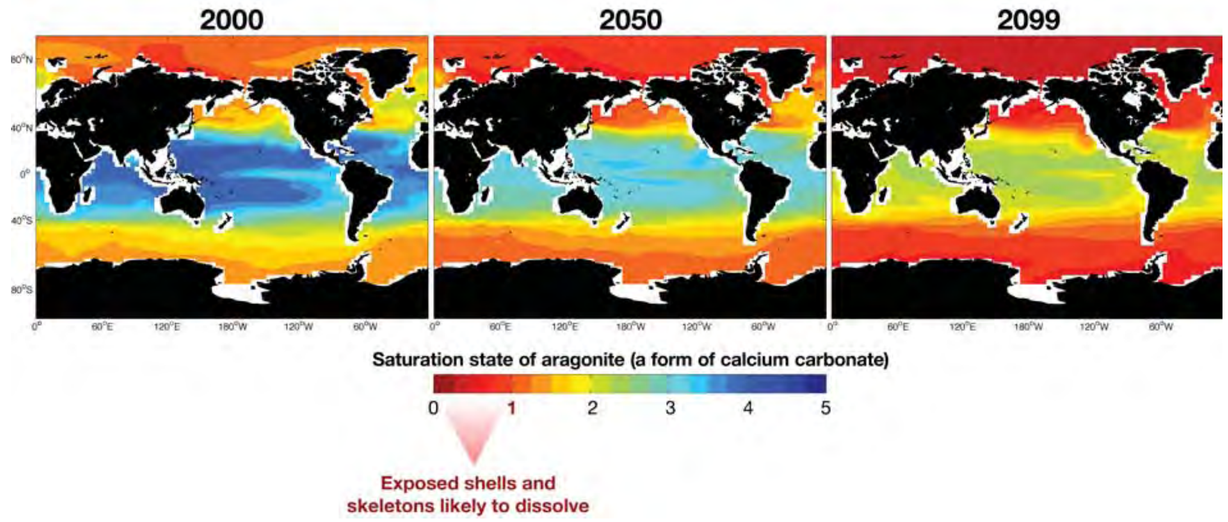


Figure 1.3: Model-calculated aragonite saturation states (Ω_{arag}) throughout the surface ocean in 2000, 2050, and 2099 (from Feely *et al*., 2009 and readapted for *Oceanus*). $\Omega_{arag} < 1$ indicates undersaturation; $\Omega_{arag} > 1$ indicates supersaturation.

whether we can develop new biological methodologies to determine whether organisms and ecosystems can adapt sufficiently to changing seawater chemistry in ways that will reduce potential negative impacts of ocean acidification. In addition, there are four priority research areas that will directly affect management actions: (1) help define atmospheric and ocean limits for anthropogenic CO_2; (2) forecast biodiversity and ecosystem changes at a regional scale to help prepare coastal communities; (3) guide management actions, such as coastal and marine spatial planning and fishery management, by altering where and when activities (like shellfish production) take place; and (4) direct local mitigation of acidification (e.g., buffering of local estuarine conditions).

Finally, as a part of NOAA's mission and numerous legislative mandates, we are required to understand and predict changes in the Earth's environment as a consequence of continued acidification of the oceans and Great Lakes and conserve and manage marine organisms and ecosystems in response to such changes. The Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009 mandates that NOAA has an active monitoring and research program to determine potential impacts of decreased ocean pH and carbonate saturation states. Other mandates (e.g., Magnuson-Stevens Fishery Conservation and Management Act, Marine Mammal Protection Act, National Marine Sanctuaries Act, Endangered Species Act, Coral Reef Conservation Act, and Clean Water Act) also require that NOAA work to fully understand the consequence of a changing environment to marine and Great Lakes resources. U.S. fisheries are extensive, and NOAA is responsible for maintaining sustainable fisheries under the Magnuson-Stevens Act and for protecting ESA-listed species. Both the commercially important fisheries and the ecosystems that support them will be affected by ocean acidification. In addition, NOAA has management responsibilities for National Marine Sanctuaries (NMS), which protect some of the unique habitats and organisms vulnerable to acidification, such as the deep water corals at the Olympic NMS off of the Washington Coast. Recently, another regulatory issue arose regarding the federal government's regulation of ocean acidification impacts on waters and ecosystems under the Clean Water Act (i.e., Center for Biological Diversity vs. the Environmental Protection Agency). The research described in this plan is intended to inform NOAA's management decisions, NOAA's interagency partners, and decision makers at the local and national levels.

This document provides a NOAA plan for an ocean and Great Lakes acidification observing system, species-specific and ecosystem response studies to the high CO_2 levels, modeling studies of large-scale physical and biogeochemical changes in carbonate chemistry and pH, and modeling studies of ecosystem responses to predicted changes in the major ocean basins, the Great Lakes, marginal seas, and coasts surrounding the United States and its territories. These goals will be achieved with both in-house expertise and NOAA's funding of extramural researchers through competitively awarded grants. While much of the following description of a national ocean acidification program applies to the Great Lakes directly, the specifics of the Great Lakes acidification research strategy will be described in detail in Chapter 7.

1.1 Developing an Ocean Acidification Monitoring Network (Theme 1)

The existing global oceanic carbon observatory network of repeat hydrographic surveys, time-series stations (ship-based and moored) and ship-based underway surface observations in the Atlantic, Pacific, and Indian Oceans provide a strong foundation of carbonate chemistry observations to begin addressing the problem of ocean acidification. Indeed, much of our present understanding of the long-term changes in the carbonate system is derived from the repeat ocean sections and time-series measurements (Bates, 2007; Feely *et al.*, 2008; 2004; 2002). Enhancing these activities and expanding the global moored time-series network with new carbon and pH sensors will provide important information on the changing conditions in the open ocean. U.S. coastal and estuarine environments do not currently have coordinated carbon observing networks and are presently grossly under-sampled. Building on existing infrastructure, however, coastal and estuarine networks of shipboard and remote autonomous measurements similar to the open ocean network can be established.

At this point, most of the current, moored carbon observatories only contain instrumentation to measure $p\mathrm{CO_2}$ (i.e., partial pressure of CO_2), which is insufficient to fully constrain the carbon system. An effective monitoring and forecasting system for ocean acidification needs to include measurements of a second carbon parameter. Sensors or automated, in situ analytical systems for measuring total dissolved inorganic carbon (DIC) and total alkalinity (TA) would be beneficial for detecting changes in the marine inorganic carbon system caused by changes in CO_2 concentrations or the introduction of other non-CO_2 sources of acidification, particularly in coastal regions (Doney *et al.*, 2007; Ilyina *et al.*, 2010). Ideally, this network would also have the capability to measure $CaCO_3$ saturation states and $CaCO_3$ production/dissolution rates. Measurements of net primary production, either directly or from nutrient or oxygen inventories along with hydrodynamic considerations in estuarine and coastal waters, are also important to allow physical and biological effects on ocean DIC chemistry to be identified. These additional measurements are needed to predict ecosystem 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 should be conducted at the existing time-series stations to place these studies in a proper context relative to the local temporal variability. An ocean acidification observational network can be constructed by enhancing the capabilities of existing autonomous analytical systems, by increasing the number and distribution of time-series stations, and by repeat surveys and underway measurements in open-ocean and coastal regions. This network will provide a better understanding of the temporal and spatial scales of variability in ocean carbon chemistry and biology and the observational basis for developing predictive models for future changes in ocean acidification and its consequences for marine ecosystems. NOAA has several long-term monitoring programs, some associated with protected resources, such as the National Estuarine Research Reserves and the National Marine Sanctuaries. Using these existing resources will take advantage of long-term baseline data characterizing coastal conditions for these place-based protected sites.

Task 1.1: Develop and implement program for monitoring carbon-cycle-related oceanographic parameters in U.S. coastal, Great Lakes, and open-ocean waters.

1.1.1 Measurement requirements

1.1.1.1 General requirements

On **ship-based, oceanographic cruises**, such as the CLIVAR/CO_2 Repeat Hydrography Program or the ocean time-series programs, DIC, $p\mathrm{CO_2}$, TA, and pH can be measured with very high accuracy and precision. The methods are well established and described in great detail in the "Guide to Best Practices for Ocean CO_2 Measurements" (Dickson *et al.*, 2007). In addition, appropriate standards are available for DIC, TA, and $p\mathrm{CO_2}$. For ocean acidification research at least two, and preferably three, of the four carbon parameters should be measured at each of the sampling depths to allow determination of all DIC species and parameters and to ensure internal consistency of the data sets. International data synthesis efforts, such as that being carried out as part of the CLIVAR/CO_2 Repeat Hydrography Program, must be continued to ensure the precision and accuracy re-

Common Analysis Protocols for Ocean Acidification Monitoring

A key to the ocean acidification research plan is to develop a set of common parameters and analysis protocols for monitoring sites (e.g., moorings and sentinel sites) such that accurate long-term and consistent measurements are obtained for all locations. The measurements listed in **Table Box 1** will provide the core data required to document the evolution of ocean acidification. In addition to these measurements, each site will likely have unique measurements and process studies tailored to evaluate the local or regional OA ecological responses. Physical and biological processes affect seawater chemistry in different ways such that several inorganic carbon species and related parameters must be determined to obtain an accurate temporal record of changes.

The product delivery is challenging because not all instrumentation is at a stage of development to deliver accurate data over the envisioned endurance periods of autonomous instruments ranging from 6 months to a year. The most robust measurement of inorganic carbon system parameters on buoys is surface water CO_2 (i.e., from a MAP-CO_2 system). Instruments are also commercially available for surface and subsurface pH and pCO_2. However, the pCO_2-pH pairing is not ideal for constraining the ocean carbon system. Subsurface sensors will be particularly important in areas where benthic organisms are likely to be impacted (e.g., coral reefs).

For calcifying organisms the following carbon parameters and measurements are needed roughly in order of priority: saturation states[a], carbonate ion (CO_3^{2-}), pH[b], pCO_2[c]. The saturation state and carbonate ion concentration are calculated parameters from inorganic carbon system measurements while the pH and pCO_2 are two measured parameters with the most mature autonomous in situ analytical systems. The saturation states and CO_3^{2-} can be calculated with two measured parameters, knowledge of the carbonate dissociation constants, temperature, and salinity. The sensitivity with which the saturation states and CO_3^{2-} can be calculated is dependent on the parameter measured; pH and pCO_2 yield the greatest uncertainty, followed by the TA, DIC pair. pH or pCO_2 with DIC yields the greatest precision, closely followed by pH or pCO_2 and TA. The uncertainty in the pH or pCO_2 and TA combination is impacted by incomplete knowledge of the minor acids and bases in seawater, especially in estuarine systems, that contribute to TA. An ambitious instrument development and testing effort is called out, focused on improving current pH and pCO_2 sensors and developing robust DIC and TA sensors for autonomous operation.

In addition to the carbon system parameters all sites should measure temperature and salinity at the specified frequency and precision. Some key biological indicators are required as well to estimate the ecological response of OA. Oxygen, chlorophyll, and turbidity are recommended as indicators of photosynthesis/respiration and planktonic biomass because the autonomous sensors are reasonably mature. Additional sensors should be evaluated to determine if they provide additional constraints on the system.

The discrete measurements in **Table Box 1** are critical for validation and assessment of accuracies. All measurements should follow procedures and protocols outlined in the Best Practices guides (Dickson *et al.*, 2007; Riebesell *et al.*, 2010). The discrete and autonomous samples will be used to create algorithms with salinity, oxygen, and temperature to estimate saturation states and other pertinent parameters in areas that do not have the full suite of measurements (e.g., Gledhill *et al.*, 2009; Juranek *et al.*, 2009).

Table Box 1: Minimum core measurements at OA monitoring sites

Parameter	Frequency	Precision	Comment
pCO_2	8 × day	3 μatm	autonomous/surface & subsurface
pH	8 × day	0.004	autonomous/surface & subsurface
O_2	8 × day	2 μmol kg^{-1}	autonomous/surface & subsurface
Chlorophyll	8 × day	0.1 μg kg^{-1}	autonomous/surface & subsurface
Turbidity	8 × day	0.1 NTU	autonomous/surface & subsurface
T	8 × day	0.02°C	autonomous/surface & subsurface
S	8 × day	0.02	autonomous/surface & subsurface
DIC	4 × year	3 μmol kg^{-1}	discrete/water column/characterization
TA	4 × year	3 μmol kg^{-1}	discrete/water column/characterization
pH	4 × year	0.004	discrete/water column/validation
O_2	4 × year	2 μmol kg^{-1}	discrete/water column/validation
Chlorophyll	4 × year	0.1 μg kg^{-1}	discrete/water column/validation
pCO_2	4 × year	3 μatm	underway/surface/val. & char.

[a] Saturation states is the degree to which seawater is saturated with respect to a particular carbonate mineral. A value less then 1 means the mineral will, from a thermodynamic perspective, dissolve in seawater. It is defined as the product of calcium and carbonate ion concentration divided by the solubility product of the mineral phase.

[b] The pH has to be referenced to a certain scale at a certain temperature. The recommended expression, $pH_F(T)$ refers to pH on the free hydrogen ion scale at in situ temperature.

[c] The pCO_2 must be referenced to a certain temperature. $pCO_2(T)$ is the partial pressure of CO_2 at in situ temperature.

quired to determine the anthropogenic CO_2 contributions to ocean acidification.

For **unmanned platforms**, including moorings, gliders, autonomous vehicles and floats, additional technology development is needed to properly assess the full carbon system. Commercial systems are available for moored measurements of pCO$_2$ and pH (see `http://www.ioccp.org/` for a list of available sensors). However, the combination of pCO$_2$ and pH sensors does not allow for the most accurate and precise calculation of $CaCO_3$ saturation state, and some of these systems are not ideal for sustained deployments, especially in coastal and estuarine environments. Consequently, there is an immediate need to develop autonomous, commercial analytical systems for continuous measurements of DIC and TA on a variety of unmanned platforms. Robust, low-power sensors also need to be developed for the variety of other autonomous platforms that are becoming available to the community. Although currently there are no carbon sensors ready for profiling floats, the addition of commercially available oxygen sensors to the Argo array would help constrain carbon distributions through empirical relationships as well as directly evaluating biogeochemical changes in the ocean. There is a critical need for intensive time-series measurements from sensors and other analytical devices on moored buoys in at least some high productivity coastal and estuarine systems as CO_2 and carbonate ion concentrations in these waters can vary substantially on timescales from hours to decades due to tides, photosynthesis (which occurs only during daytime), and river or ground water inputs. Variations in calcium concentrations in these systems also affect the solubility of calcium carbonate minerals produced by molluscs (e.g., clams and oysters) and other ecologically or commercially important marine organisms. A full evaluation of the response of marine ecosystems to ocean acidification will require a wide range of measurements of existing and evolving community compositions, interactions, and distributions, as well as experimental studies of the responses of organisms and communities to elevated CO_2 and concomitant changes in carbonate ion concentrations.

1.1.1.2 Ecosystem-specific requirements

In the case of **coral reefs**, baseline studies that encompass the natural temporal (diurnal- to inter-annual) and spatial (latitudinal) changes in near-reef carbonate chemistry are still not available. Such baselines are being ascertained through the use of in-situ, high-frequency water samplers and water sampling at selected reefs across large latitudinal gradients. In addition, methods have been established for measuring calcification and extension rates from cores of massive reef-building scleractinian corals. These methods need to be applied systematically to both older massive corals and younger branching and encrusting corals broadly distributed across gradients of aragonite saturation state. In addition, a global array of simple calcification plates (or similar devices) should be deployed to monitor the calcification rates of sessile calcareous organisms, such as crustose coralline algae, a major reef builder that often acts as the cement holding reefs together. As an example of tools to assess spatial patterns and monitor temporal shifts in biodiversity, the coral reef projects of the Census of Marine Life have developed Autonomous Reef Monitoring Structures (ARMS) as systematic collecting devices, and they are currently developing mass parallel molecular sequencing capabilities to allow comparative and time-series analyses of indices of invertebrate biodiversity of hard-bottom habitats around the globe (Brainard *et al.*, 2009). Similar systematic collecting devices should be employed to assess biodiversity changes in soft-bottom and planktonic communities. Other cost-effective tools for monitoring biological shifts in community structure include passive Ecological Acoustic Recorders (EARs) (Lammers *et al.*, 2008; Sueur *et al.*, 2008).

It has already been well established that calcification rates of whole coral reef communities are sensitive to changes in ambient aragonite saturation state and temperature and that rates of $CaCO_3$ dissolution significantly affect the $CaCO_3$ budgets of these communities (Ohde and van Woesik, 1999; Silverman *et al.*, 2009; 2007). Thus, in concert with assessing the community structure of both shallow and deep-sea corals, it is equally important to make measurements of community calcification and dissolution rates. These measurements will establish a baseline for important environmental processes and will be able to demonstrate the effect of acidification in situ and in real time using relatively simple, non-destructive methods. Additionally, if the community metabolism method adds measurements of carbonate chemistry in situ within coral reefs and becomes a viable part of the monitoring system, community metabolism measurements will provide data on ocean acidification and its immediate effects within the water of coral reefs. Changes in the trophic balance of coral reef ecosystems can also be easily discerned by variation in the photosynthesis to respiration ratio, which can be observed using continuous dissolved oxygen measurements (Silverman *et al.*, 2007). For critical regions, such as high latitudes and coastal areas, abundances and distributions of key taxa should be tracked with sufficient precision and resolution to detect possible shifts in relation to the changes in the geochemical parameters. There is an immediate need for such baseline data on calcifying organisms in regions that are projected to become undersaturated with respect to aragonite in the coming decades. Rapid, cost-effective technologies for quantifying abundances of targeted organisms should be a central component of an integrated ocean acidification observation network.

Opportunities to examine the carbonate chemistry and ecological impacts of severe ocean acidification in the natural environment are sparse. Certain **hydrothermal venting systems**, such as the Maug Caldera in the Northern Mariana Islands, provide a unique opportunity to study the effects of a low pH, high temperature environment. Water near the vent site has a temperature of 60°C, a pH of 6.07, a total alkalinity of 3.56 and aragonite saturation state of 0.25. Investigations of the ecological response of such extreme, but naturally occurring, non-anthropogenically forced environments can yield valuable information about the future impacts of ocean acidification.

There is a strong need to assess the impact of anthropogenic increases in CO_2 and associated acidification on key benthic and pelagic organisms in coastal and estuarine systems, such as phytoplankton, sea grasses, calcareous crustose and macro algae (e.g., kelp), molluscs (e.g., clams, oysters, scallops), crustaceans (e.g., krill, crabs, lobsters), and other invertebrates. Many of these organisms constitute or support commercially important fisheries and play central roles in the local ecology of these systems. Long-term, regional baseline surveys, such as those conducted by NMFS (e.g., CalCOFI along West Coast, Seamap in the Gulf of Mexico), that monitor changes in distribution and abundance of organisms will provide key information about potential impacts of ocean acidification, especially if done in concert with close monitoring of the geochemical properties of ocean waters. Additionally, in **open-ocean, coastal, and estuarine environments**, emerging molecular tools can be used to better understand the genetic diversity of various populations and how they are changing with time. These new approaches together with traditional techniques for assessing the composition of biological communities (e.g., bio-optical sensors and optical plankton imaging systems) can be used to evaluate the response of organisms and ecosystems to changing ocean chemistry.

1.1.2 Strategy for an observational network for ocean acidification

1.1.2.1 Repeat surveys of chemical and biological properties

Most of the sampling principles and strategies that are being developed for open-ocean and coastal carbon surveys apply to the development of an observational network for ocean acidification. For example, decadal surveys are extremely useful for determining basin-scale changes in the aragonite and calcite saturation states over timescales of 10–15 years (Feely *et al.*, 2008). The sampling plans for the next phase of the CLIVAR/CO_2 Repeat Hydrography Program could effectively provide the required long timescale information for the open ocean. Spatial sampling should continue to repeat the transect lines carried out in the Atlantic, Pacific, and Indian oceans, with the Southern Ocean integrated as part of the other basins. The Arctic is of increasing importance and should be emphasized, adding new transects where appropriate. We recommend adding additional chemical and biological measurements to the repeat surveys to address ocean acidification issues, such as highly resolved depth distributions and abundances of calcifying plankton, estimates of $CaCO_3$ calcification and dissolution rates, and other CO_2-sensitive processes as appropriate. For coastal and estuarine environments, a similar sampling strategy as outlined for the open-ocean carbon measurements is recommended. These activities will be integrated with ongoing NOAA ship-based surveys. Underway sampling on research vessels and Voluntary Observing Ships (VOS) could include the additional pH and carbon parameters necessary to address ocean acidification and acidification impacts. These data would help establish large-scale trends in acidification in much the same way as established basin-scale trends in $p\mathrm{CO}_2$ (Checkley, Jr. *et al.*, 2009).

1.1.2.2 Time-series measurements at fixed stations and on floats and gliders

Carbon and pH sensors on Argo-type systems could resolve shorter space-time scale variability of the upper ocean more readily than repeat sections, but the sensor technology must be developed and tested in the field before it can be implemented on a large scale. In the mean time, the addition of oxygen sensors would enhance the biogeochemical relevance of the Argo program. Time-series measurements on fixed moorings appear to be a reasonable alterna-

The Role of the National Estuarine Research Reserve System in Ocean Acidification Research

Determining the impact of rising atmospheric CO_2 on near-shore coastal and estuarine systems and the economically important shellfish industries in these regions is an important focus of NOAA's OA research. Estuarine systems can experience a broad range of mineral saturation states as a consequence of drainage basin characteristics, local anthropogenic activities, and biological activity. It is particularly challenging to attribute ecosystem response to OA in these systems because of large natural variations in mineral saturation states, $p\mathrm{CO}_2$, and pH levels, and the interaction with a multitude of other stressors. In estuaries, in situ respiration contributes most of the CO_2 due to the high level of biological activity which varies spatially and temporally. How rising atmospheric CO_2 will affect this natural variability in estuaries is unknown.

In addition, estuaries represent the complex interface between freshwater rivers and saline, ocean waters. Freshwater has naturally low alkalinity making it more vulnerable to reduced pH. Some systems can periodically discharge corrosive freshwater plumes into coastal margins due in part to the mineralogy of the drainage basin (Salisbury *et al.*, 2008). Other systems can exhibit elevated mineral saturation states due to high-levels of riverine carbonate alkalinity and biological drawdown of CO_2 (Keul *et al.*, 2010). These regions also often experience low oxygen levels (hypoxia) (CENR, 2010) and the combined stress of low O_2 and low pH on organisms could be appreciable.

NOAA has a unique resource which can be leveraged to conduct OA estuarine studies, the National Estuarine Research Reserve System (`http://nerrs.noaa.gov/`. As detailed "[It] uses its network of living laboratories to help understand and find solutions to crucial issues facing America's coastal communities. [It is] perfectly positioned to study and predict the effects of climate change on the coasts so that managers can rely on good science as they make decisions about the use and protection of coastal resources. The Reserve System has developed a plan to engage all of its sectors—research, education, stewardship and training—in this effort." All the Reserves currently measure pH as part of the core System-wide Monitoring Program (SWMP). In some Reserves, deployment capacity needs to be upgraded to include the capacity for ongoing, in situ deployment. A next step after upgrading will be to build the capacity to incorporate additional carbonate chemistry parameters (e.g., total dissolved inorganic carbon and total alkalinity) into SWMP.

The NOAA OA research effort will initially augment ongoing measurements at two locations within the NERRS network to establish them as Sentinel Estuary OA sites. As part of the augmentation, protocols and analyses techniques currently applied at the sites will be upgraded to meet accuracy, precision and reporting standards needed to monitor OA trends. Selection of sites will be based on susceptibility to impacts of OA; current measurement suite; infrastructure; and magnitude of possible economic and social impacts of OA on the local communities. Based on size and importance, the reserves in Chesapeake Bay and Puget Sound are likely initial candidates. A full listing of NERRS sites and current measurements can be found at (`http://cdmo.baruch.sc.edu/`).

tive for more limited time-space variability studies. These studies could be conducted at the Ocean Sustained Interdisciplinary Timeseries Environment observation System (SITES) time-series stations and the Long-Term Ecological Research (LTER) sites. Time-series stations are also urgently needed in other open-ocean and coastal regions. Consequently, new moored buoys equipped with carbon system sensors for ocean acidification should be added to the present carbon network. Bio-optical sensors and optical plankton imaging systems should be deployed to track possible shifts in abundances of key biological functional groups. Seasonal measurements of calcification rates and other CO_2-sensitive processes not currently measured at time-series sites should be conducted in order to assess the long-term response of ecosystems to ocean acidification. Figure 1.4 and Tables 1.2–1.4 provide our recommended distribution of time-series sites based on the global plans for ocean acidification research and discussions of what is needed by the Ocean Acidification Interagency Working Group. The coral reef monitoring sites have a unique label in Figure 1.4 to help distinguish them from the open-ocean and coastal time-series sites. As soon as carbon and pH sensors on floats and gliders are fully tested and deemed ready for large-scale deployment, we recommend their implementation into the next phase of the Argo Program.

The Integrated Ocean Observing System (IOOS) is a federal, regional, and private-sector partnership working to enhance our ability to collect, deliver, and use ocean information. IOOS moorings deliver data and information needed to increase understanding of our oceans and coasts, so decision-makers can take action to improve safety, enhance the economy, and protect the environment. The NOAA Ocean Acidification Program will work directly with IOOS to incorpo-

Table 1.2: Planned open-ocean ocean acidification monitoring sites. Minus signs indicate S latitudes and W longitudes.

Latitude	Longitude	Site name	Basin	Climate or Ecosystems	Year of Deployment	Rationale	Partner Entities
50.10	−144.80	Papa	North Pacific	C	2010	fisheries and food webs impacts, sentinel site	Univ. Washington
33.00	−122.00	CCE1	North Pacific	C	2011	Long-Term Ecological Research site, CalCOFI time-series back to 1950s	Scripps Inst. Oceanogr., NSF-funded LTER program
22.70	−158.00	WHOTS	North Pacific	C	2011	long-term, important time-series at Hawai'ian Ocean Time-Series station	Woods Hole Oceanogr. Inst.
32.30	144.50	KEO	North Pacific	C	2011	key heat transport pathway from W. Equatorial Pacific to N. Pacific via the Kuroshio Current	PMEL-Ocean Climate Stations
−20.00	−85.00	Stratus	South Pacific	C	2011	long time series site in eastern South Pacific	WHOI
−8.00	165.00	Warm water pool	South Pacific	C	2011	warm water pool of western equatorial Pacific, northern end member of western South Pacific	CSIRO (Australia)
−45.00	140.00	SOFS	South Indian	C	2011	Southern Ocean Site	CSIRO/WHOI
−64.20	31.70	BTM	North Atlantic	C	2012	long-term time series site with better than monthly shipboard sampling of many parameters	BIOS
38.50	−65.00	Gulf Stream	North Atlantic	C	2012	key heat transport pathway from W. Equatorial Atlantic to N. Atlantic	WHOI
0.00	−125.00	TAO	Equatorial Pacific	C	2012	monitor changes in equatorial Pacific upwelling zone, long time-series of underway data	NDBC-TAO
0.00	90.00	RAMA—Equator	Equatorial Indian	C	2012	Indian Ocean dipole study site	PMEL-RAMA, India?
−10.00	0.00	PIRATA 5	South Atlantic	C	2012	constrain equatorial Atlantic	PMEL-PIRATA
29.18	−15.50	ESTOC	North Atlantic	C	2012	long time series site in eastern Atlantic with regular shipboard measurements	Spain/Germany
12.00	70.00	RAMA—Arabian	North Indian	C	2013	unique Arabian sea geochemistry	PMEL-RAMA, India?
12.00	90.00	RAMA—Bengal	North Indian	C	2013	unique Bay of Bengal geochemistry	PMEL-RAMA, India?
−42.00	55.00	ARC	South Indian	C	2013	western boundary current region with large heat flux	PMEL—Ocean Climate stations?
−50.00	−37.00	Falklands	South Atlantic	C	2013	western boundary current region with large heat flux	PMEL—Ocean Climate stations?
49.00	−16.50	Porcupine	North Atlantic	C	2013	long time biogeochemical study site including sediment trap work	UK
55.00	−177.00	Bering open basin	Arctic	C	2014	fisheries and food webs impacts, sentinel site	PMEL-FOCI
47.27	−57.35	St. Lawrence	North Atlantic	C	2014	important freshwater influence in N. Atlantic, vicinity of Labrador Sea	Environment Canada, Dept. Fisheries & Oceans (Canada)

Table 1.3: Planned coastal early warning ocean acidification monitoring sites. Minus signs indicate S latitudes and W longitudes.

Latitude	Longitude	Site name	Basin	Climate or Ecosystems	Year of Deployment	Rationale	Partner Entities
43.08	−70.75	Gulf of Maine	Atlantic	C	2010	shellfish, river inputs	Univ. New Hampshire, NERACOOS
47.95	−124.83	LaPush, Washington	Pacific	C	2010	upwelling, hypoxic shelf conditions, Columbia River influence	NANOOS, Univ. Washington
30.09	−88.77	Northern Gulf of Mexico (Biloxi, MS)	Gulf of Mexico	C	2010	Mississippi River plume influence	Univ. Southern Mississippi, NDBC, GCOOS
31.40	−80.87	Gray's Reef	Atlantic	C	2010	distinct chemistry of river inputs in South Atlantic Bight, marine sanctuary	Univ. Georgia Athens, NDBC, NMS
34.40	−120.70	CCE2, Point Conception, California	Pacific	E	2010	important feature in California Current large marine ecosystem, causes upwelling that influences circulation/chemistry in S. Cal. Bight, location of repeat glider and CalCOFI sampling	Scripps Inst. Oceanogr.
44.62	−124.53	NH10, Stonewall Banks (Newport, OR)	Pacific	C	2010	upwelling, hypoxic shelf conditions, historical observations of oxygen, nutrients, plankton composition, OOI cabled observatory to be located here	NANOOS, Oregon State Univ., NSF OOI program
41.96	−124.48	Trinidad Head	Pacific	C	2011	core of California Current upwelling system	California State Univ.–San Marcos
52.43	−171.45	Amukta Pass 1 (Aleutians, AK)	Gulf of Alaska	E	2011	key location reflecting chemistry of North Pacific water entering the Bering and Arctic basins	PMEL-FOCI
25.25	−82.22	Everglades National Park, Florida (USF-C17)	Gulf of Mexico	E	2011	acidic terrestrial inputs associated with groundwater or rivers	Univ. South Florida, SECOORA, GCOOS
48.06	−87.78	Lake Superior	Great Lakes	E	2011	most susceptible of Great Lakes to acidification due to low alkalinity, lowest zebra mussel density	GLERL, NDBC, Univ. Wisconsin, GLOS
45.34	−86.41	Lake Michigan	Great Lakes	E	2011	highest alkalinity so susceptibility should be lowest, highest zebra mussel density	GLERL, NDBC, Univ. Wisconsin, GLOS
39.47	−74.25	LEO-15	Atlantic	E	2012	long time-series of observations, multi-platform observational focus area (gliders, etc.)	Rutgers Univ., NJ Shelf Observing System
27.50	−83.72	Tampa-St. Petersburg, Florida (USF-C10)	Gulf of Mexico	E	2012	acidic terrestrial inputs associated with groundwater or rivers	Univ. South Florida, SECOORA, GCOOS
26.97	−96.70	Corpus Christi/Port Aransas, Texas	Gulf of Mexico	E	2012	key location in W. Gulf of Mexico where terrestrial signatures associated with episodic events can be monitored, Mission-Aransas NERR	Univ. Texas, NDBC, NERR
58.28	−147.67	FATE-1/GAK-14 (near Kodiak Island, AK)	Gulf of Alaska	E	2012	interest in fisheries, food web impacts in N. Pacific region, other regular sampling in area	PMEL-FOCI, Univ. Alaska Fairbanks
45.35	−82.84	Lake Huron	Great Lakes	E	2012	high susceptibility to acidification, low zebra mussel density	GLERL, NDBC, Univ. Wisconsin, GLOS
43.62	−77.41	Lake Ontario	Great Lakes	E	2012	lower susceptibility to acidification, higher zebra mussel density	GLERL, NDBC, Univ. Wisconsin, GLOS
56.88	−164.06	M2	Bering Sea	E	2012	long time-series of biophysical observations, southernmost mooring in series, ice cover averages 10% each winter/spring	PMEL-FOCI
62.19	−174.67	M8	Bering Sea	E	2012	long time-series of biophysical observations, northernmost mooring in series, ice cover averages 60% each winter/spring	PMEL-FOCI
36.61	−74.84	Chesapeake Bay	Atlantic	E	2013	key area for terrestrial inputs and hypoxia studies on East Coast, several agencies have monitoring programs	NDBC?, NERRS, Maryland DNR, Chesapeake Bay Program
35.01	−75.40	Cape Hatteras	Atlantic	E	2013	key location for characterizing Gulf Stream before it separates from the continental shelf	NDBC
29.23	−94.41	Galveston, Texas	Gulf of Mexico	E	2013	fisheries, shellfish, terrestrial inputs	NDBC
37.76	−122.83	off San Francisco Bay	Pacific	E	2013	enriched nitrogen inputs from SF Bay shown to affect offshore biogeochemistry	San Francisco State Univ.
42.02	−81.65	Lake Erie	Great Lakes	E	2013	lower susceptibility to acidification, higher zebra mussel density	GLERL, NDBC, Univ. Wisconsin, GLOS
71.50	−156.00	Barrow Canyon, Chukchi Sea	Arctic	E	2013	Arctic area with some background work on carbon cycling	PMEL-FOCI
35.08	−76.28	Pamlico/Albemarle Sound & Neuse River estuary	Atlantic	E	2015	largest estuary in SE, important shellfisheries and finfish nursery, very productive lagoonal estuary, Rachel Carson Estuarine Reserve, hypoxic/anoxic conditions and fish kills in Neuse R.	NERR, Univ. North Carolina?

Table 1.4: Planned coral reef ocean acidification monitoring sites. Minus signs indicate S latitudes and W longitudes.

Latitude	Longitude	Site name	Basin	Climate or Ecosystems	Year of Deployment	Proposed NOAA Sponsoring Program/Lab	Rationale	Partner Entities
21.40	−157.80	CRIMP #2	USA—Pacific	E	2010	CRCP/PMEL/PIFSC	important ancillary oceanographic and meteorological data, potential for strong metabolic signal, current Pacific OA test-bed	Univ. Hawai'i
17.94	−67.05	Cayo Enrique	USA/Puerto Rico—Caribbean	E	2010	CRCP/AOML/PMEL	important ancillary oceanographic and meteorological data, potential for moderate metabolic signal, reasonably well-defined hydrodynamics, current CRCP Atlantic OA test-bed, represents a Greater Caribbean System	UPRM, USGS, UM, CarICOOS
32.46	−64.82	Hog Reef	Bermuda	E	2010	PMEL	high-latitude Atlantic coral reef ecosystem, may experience net-negative calification within a decade, hard coral cover ~30–70%, compliment to Bermuda Atlantic Time-series Study (BATS), potential "early warning" site for Greater Caribbean reefs	Bermuda Inst. Ocean Sciences
25.00	−80.37	Florida Keys National Marine Sanctuary	USA, FL	E	2011	CRCP/AOML/PMEL	most extensive living coral reef system in N. America and third largest in the world, easily accessible technology test-bed, nearby moored ADCP station, no-take protected zone within FKNMS but high exposure to local land-based and recreational stressors, existing CMAN/ICON station, ongoing monitoring of coral communities and *A. palmata* demographics	IOOS, UM, ICON, FKNMS
7.42	151.82	Chuuk Islands	Micronesia	E	2011	PMEL	important coverage of Micronesian community diversity	KORDI (Korean Ocean Res. & Develop. Inst.)
−17.00	−149.50	Moorea	Moorea—Pacific	E	2012	CRCP/PMEL/PIFSC	LTER site, southernmost node of a Pacific latitudinal "transect" network, single site that offers all major coral reef types, reefs in excellent condition, active process-oriented studies/modeling/synthesis efforts	NSF LTER, Richard B. Gump South Pacific Research Station (UCLA, UC Berkeley)
5.00	−161.00	Palmyra Atoll	USA—Pacific	E	2012	CRCP/PMEL/PIFSC	remote Pacific system, considerable coral cover, few convoluting factors, potential for very strong metabolic signal, Pacific Remote Islands Marine National Monument	The Nature Conservancy
23.74	−166.26	French Frigate Shoals	USA—PMNM	E	2012		remote Pacific system, few convoluting factors, Papahanaumokuakea Marine National Monument (PMNM)	CRCP, PMEL, PIFSC
28.22	−177.37	Midway Atoll	USA—PMNM	E	2012		less scientifically interesting than many sites in PMNM but far more accessible, OA monitoring station should be located at here until a regional vessel is available	
−0.69	−90.66	Galapagos	Eastern Tropical Pacific, Panama	E	2012		lowest saturation states and highest $p\mathrm{CO}_2$ in reef system globally documented here, strong upwelling system, affected by ENSO, key site for studying thermal impacts of ENSO on reefs, well studied reef fauna since 1970s	Smithsonian Tropical Research Institute, Charles Darwin Research Institute
−23.44	151.916	Heron Island	Great Barrier Reef	E	2013	PMEL	recently initiated ARC project to conduct multi-scale analysis of the vulnerability of the GBR to ocean acidification; site of manipulative flume and mesocosm experiments as well as regular field surveys of carbonate chemistry	CSIRO, UQ, Stanford University, GBRMPA
19.699	−80.06	Bloody Bay Marine Park	Little Cayman	E	2013	CRCP/AOML/PMEL	isolated from continental and anthropogenic influences, some of the most biologically diverse reef systems in the Caribbean, excellent water quality, 37 coral species, shallow lagoon sites with potential for strong metabolic signal, existing ICON station	Central Caribbean Marine Institute, Little Cayman Research Centre, NOAA ICON
19.29	166.66	Wake Atoll	USA—PRINMN	E	2013		represents new geographic area with important connectivity between Micronesia and Polynesia	CRCP, PMEL, PIFSC
−5.14	150.48	Kimbe Bay	Coral Triangle, New Guinea	E	2013		very accessible, TNC flagship MPA, strong community/industry partnership (dive resort)	The Nature Conservancy, CRCP, PMEL, PIFSC
24.62	−81.10	Dry Tortugas	USA—Gulf of Mexico	E	2014	CRCP/AOML/PMEL	USGS sentinel site for climate change, some of highest seasonal variability in carbonate chemistry—important contrast to the lower latitude Caribbean systems, Research Natural Area (RNA) reserve, annual coral monitoring and assessment	USGS, Dry Tortugas Research Natural Area RNA, FKNMS, Interagency S. Florida coral reef evaluation and monitoring project

Table 1.4: Continued.

Latitude	Longitude	Site name	Basin	Climate or Ecosystems	Year of Deployment	Proposed NOAA Sponsoring Program/Lab	Rationale	Partner Entities
18.35	−64.98	Tektite, Great Lameshur Bay	St. Thomas, USVI	E	2014	CRCP/AOML/PMEL	coral cover high, opportunity to investigate synergistic effects including coastal runoff, proposed ICON station	ICON, Univ. Virgin Islands, Ctr. for Marine and Environmental Studies
−0.61	130.9	Raja Ampat	Coral Triangle, Indonesia	E	2014		joint conservation area by TNC/CI/WWF, significant pearl oyster industry there	The Nature Conservancy, Conservation International, World Wildlife Fund
8.62	−79.07	Saboga Reef	ETP, Panama	E	2015	CRCP/PMEL/AOML	lowest aragonite saturation and highest $p\mathrm{CO}_2$ of any coral reef area documented to date, regular warming disturbances with ENSO, long-term ecological monitoring site, MPA	Smithsonian Tropical Research Institute
20.03	145.23	Maug Caldera Monument	USA—CNMI	E	2015	CRCP/PMEL/PIFSC	hot vent site—a natural laboratory for extreme acidification chemistry, baseline work already started	
−0.37	−160.00	Jarvis Island	USA—Pacific	E	2015	CRCP/PMEL/PIFSC	remote Pacific system with considerable upwelling and associated fauna, little to zero anthropogenic pressure, potential for very strong metabolic signal, Pacific Remote Islands Marine National Monument	Coral Reef Ecosystem Division and Pacific Remote Islands Marine National Monument, CRCP, PMEL, PIFSC
7.48	134.38	Palau	Palau, West Pacific	E	2015		high diversity, strong political support, strong conservation ethic, research station there associated with PICRC	Palau International Coral Reef Center (PICRC)
52.13	−172.42	Seguam Pass (deep-sea coral)	USA—Pacific/Bering Sea	E	2015	EOP/PMEL/AFSC	most diverse deep-sea corals in the world, northward flow through these passes brings N. Pacific water into Bering, carbonate saturation horizons are shoaling, fisheries research can provide ecosystem baseline	
28.23	−94.2	Stetson Bank	Flower Garden Banks National Marine Sanctuary	E	2016	CRCP/AOML/PMEL	healthiest reefs in the Gulf of Mexico, recently completed NOAA biogeographic survey characterizing the benthic and fish resources, National Marine Sanctuary	National Marine Sanctuary
52.00	−178.00	Western Aleutians (deep-sea coral)	USA—Pacific/Bering Sea	E	2016	EOP/PMEL/AFSC	most diverse deep-sea corals in the world, northward flow through these passes brings N. Pacific water into Bering, carbonate saturation horizons are shoaling, fisheries research can provide ecosystem baseline	
28.00	−176.00	Pearl & Hermes Atoll	USA—PMNM	E	2017*	CRCP/PMEL/PIFSC	high-latitude coral atoll in the PMNM, part of Pacific latitudinal 'transect', well-defined lagoon with good potential for strong metabolic signal, baseline work started at Pearl and Hermes	Papahanaumokuakea Marine National Monument
25.00	−169.00	Maro Reef	USA—NWHI	E	2017*	CRCP/PMEL/PIFSC	submerged high-latitude coral atoll, largest coral reef in the PMNM, greater abundance and diversity of coral than most reefs in the NWHI chain (37 stony coral species), baseline carbonate chemistry work already begun	
−14.55	−168.15	Rose Atoll Monument	USA—American Samoa	E	2017*	CRCP/PMEL/PIFSC	remote, unimpacted coral reef, reachable by partners in American Samoa—part of the American Samoa Monument, node for a Pacific latitudinal "transect," baseline work started	
28.41	−178.33	Kure Atoll Monument	USA—PMNM	E	2017*	CRCP/PMEL/PIFSC	highest latitude coral atoll in PMNM, essential for constraining the latitudinal gradients of carbonate chemistry near reefs, northernmost node of a Pacific latitudinal "transect," well-defined lagoon with good potential for strong metabolic signal	

* A provisional target deployment year has been given because of logistical or technological uncertainty. Should additional funding or logistical/technological capacity become available sooner, the date may be moved up.

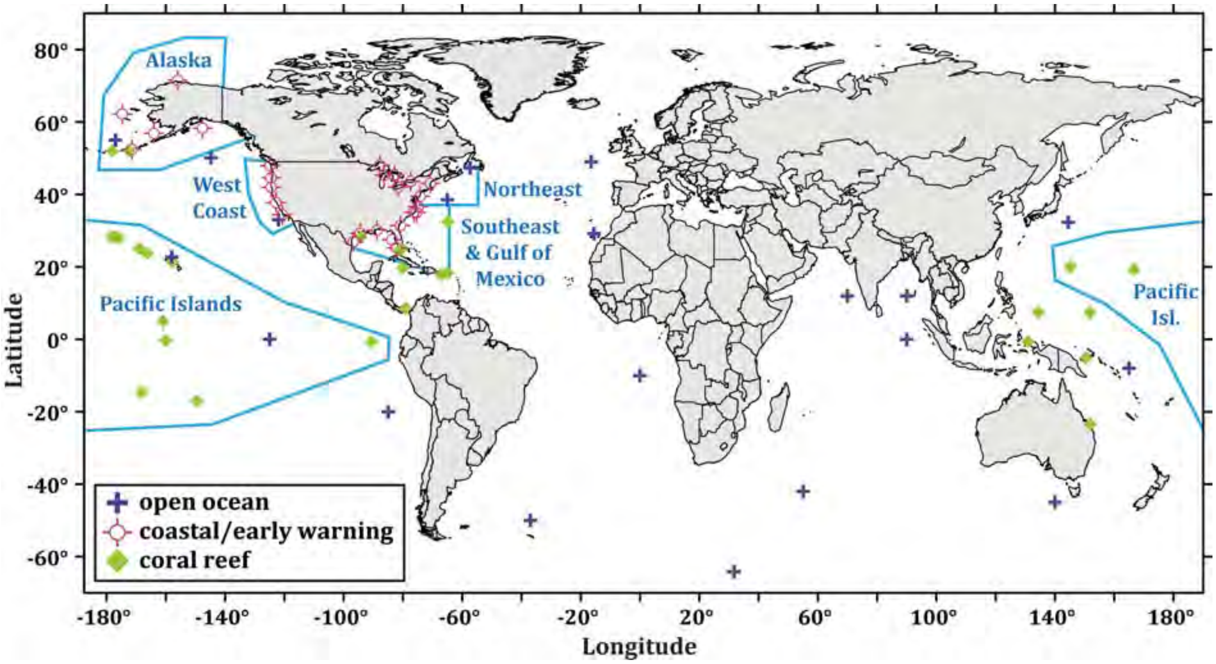


Figure 1.4: Planned ocean acidification monitoring sites in open-ocean, coastal ocean, and coral reef regions for time-series measurements and process studies. The station locations are given in Tables 1.2–1.4.

rate the required carbon and pH sensors at selected mooring stations to determine the timing and extent of acidification in coastal waters.

National Estuarine Research Reserves System (NERRS) is a network of protected areas established for long-term research, education and stewardship. This partnership program between NOAA and the coastal states protects more than one million acres of estuarine land and water, which provides essential habitat for wildlife; offers educational opportunities for students, teachers and the public; and serves as living laboratories for scientists. NERRS has engaged in sustained monitoring of water quality and weather since 1995, and a subset of the Reserves systemically monitor biological parameters, such as plankton and submerged and emergent vegetation. The NERRS System-wide Monitoring Program can incorporate new parameters important for tracking OA in estuaries. The NERRS System-Wide Monitoring Program (`http://www.nerrs.noaa.gov/RCDefault.aspx?ID=18`) measures certain variables systematically across all NERRS sites, including: pH, conductivity, salinity, temperature, dissolved oxygen, turbidity, nitrate, ammonia, ortho-phosphate and chlorophyll a. Very little research has been done on how the impacts of ocean acidification might manifest in estuaries and nearshore coastal areas such as Puget Sound, San Francisco Bay, and Chesapeake Bay. Partnerships, such as the NERRS network, are essential to building a comprehensive observational network for ocean acidification in coastal estuaries. Additional capabilities within the National Weather Service, such as the River Forecast Centers, may also contribute to understanding the effect of freshwater inputs on ocean acidification in estuaries and nearshore coastal areas.

1.1.2.3 Satellite-based observations

Direct, in situ measurements of ocean chemistry provide the most accurate means of tracking ocean acidification for the foreseeable future. However, these in situ measurements are inherently limited in space and/or time in ways that satellite observations are not. While satellites do not directly measure ocean carbonate chemistry, they can provide synoptic observations of a range of physical and optical parameters that allow us to model changes in the distribution of carbonate chemistry within the surface ocean where no in situ observations are available. Through the application of a variety of techniques, satellite observations are being applied to upscale and extend in situ carbonate chemistry measurements, permitting examination on spatial and temporal scales not practical through in situ observation alone. For example, the carbonate chemistry of predominantly oligotrophic oceanic waters of the Greater Caribbean Region has been modeled using empirical relationships between surface ocean carbonate chemistry, satellite sea surface temperature, and model derived sea surface salinities (Gledhill *et al*., 2008). More complex systems such as those affected by upwelling and significant biological modifications will demand increasingly sophisticated algorithms that combine multiple satellite data streams to infer processes beyond the simple thermodynamic forcing that dominates the variability in the Caribbean. Furthermore, the basin-scale effects of OA on certain planktonic calcifiers (e.g., coccolithophores) can be monitored through the measurement of their apparent optical properties using satellite remote sensing techniques (e.g., Balch and Utgoff, 2009).

1.2 Organism response to ocean acidification (Theme 2)

It is important to determine the potential impacts of reduced pH and carbonate ion availability on the living marine resources under NOAA's purview. Living marine resources encompass not only commercially important species but the organisms and ecosystems on which commercially important species rely through trophic or other ecological interactions. NOAA has ample expertise in studying and managing fisheries throughout its territorial waters; however, NOAA will also collaborate with academic researchers to address knowledge gaps on species response to ocean acidification and to complement internal efforts. The species to be studied under NOAA's Ocean and Great Lakes Acidification Research Plan vary by region, but the general functional groups are the same across regions.

Existing studies on organism response to ocean acidification are listed in Table 1.1. The number of studies addressing species response is increasing greatly (Figure 1.2), but basic information is lacking for many important taxa. Additionally, the effects of multi-stressor interactions (e.g., temperature, dissolved oxygen, toxics, pathogens) are only in the very early stages of evaluation. An understanding of potential evolutionary responses by organisms to OA is also lacking. The incorporation of new genomics technologies into studies of organismal response to OA may provide predictive insight into this subject. The research projects presented in this theme will address these many gaps.

Task 1.2: Conduct ocean acidification experiments on individual species and species assemblages. Create state-of-the-art NOAA facilities for these experiments which will also be available for non-NOAA researchers.

1.2.1 Marine phototrophs

Anthropogenic increases in ocean CO_2 and concomitant decreases in pH and carbonate ion concentrations will likely impact the growth, survival, and species abundance of many marine phototrophs, including phytoplankton, sea grasses, and calcareous algae. Most marine phototrophs utilize energy-dependent carbon-concentrating mechanisms to support their photosynthetic fixation of carbon (Kaplan and Reinhold, 1999), and increasing oceanic CO_2 levels will decrease the energy needed to drive this process and increase the supply of CO_2 for photosynthesis. Thus, increasing oceanic CO_2 levels are likely to stimulate the growth rates of at least some marine phototrophs. Furthermore, rates of nitrogen fixation by cyanobacteria, which regulate the ocean's inventory of biologically available fixed nitrogen, are stimulated by elevated CO_2 (Fu *et al*., 2008; Hutchins *et al*., 2007). By benefiting some species but not others, some species will essentially become winners and others will become losers, and consequently increased CO_2 is likely to shift the species composition of marine communities. The stimulation of nitrogen and carbon fixation rates by higher oceanic CO_2 will have the beneficial effect of increased CO_2 consumption, which will tend to increase the ocean's biological CO_2 pump. However, changes in species composition of marine phototrophs may have unforeseen deleterious effects on the overall structure and function of marine food webs.

Elevated CO_2 and associated ocean acidification is likely to have a large impact on calcifying marine algae such as calcareous benthic macroalgae, which are important in tropical coastal and lagoonal systems, and calcifying marine phytoplankton (e.g., coccolithophores). The effects of ocean acidification on the latter group may be most important globally, as coccolithophores are responsible for most of the biogenic formation of calcium carbonate in the world ocean. Therefore, they play an import role in regulating the alkalinity of ocean waters, and the ability of these waters to absorb CO_2 (Dymond and Lyle, 1985). Coccolithophores deposit calcium carbonate plates called coccoliths on their surfaces, which have an unknown biological function. It has been proposed that they help provide a defense against bacterial and viral infection and grazing by zooplankton, and therefore may serve to decrease mortality rates (Hamm and Smetacek, 2007). Coccolithophores are also major producers of the gas dimethyl sulphide, which influences climate through its critical role in cloud formation (Charlson *et al.*, 1987). Because of their abundance and important influences on climate (Charlson *et al.*, 1987; Dymond and Lyle, 1985), effects of ocean acidification on coccolithophore populations may have profound effects on the future rate of climate change.

Ocean acidification may have unexpected effects on growth and species composition of marine phytoplankton communities by influencing the biological availability of the trace metal iron, which limits algal growth in roughly 30% of the world ocean (Coale *et al.*, 1996). Iron limitation is particularly prevalent in the Southern Ocean, which plays a critical role in regulating this ocean's biological carbon pump. The biological uptake of iron is dependent on its chemical speciation, which is highly sensitive to seawater pH (Sunda and Huntsman, 2003; Sunda, 2001). Consequently, decreasing seawater pH from acidification may have significant effects on iron uptake by phytoplankton, with potential impacts on ocean productivity and the pace of climate change. These effects must be quantified if we are to construct robust predictive models of oceanic carbon cycling and climate feedbacks.

Experiments are planned to determine the effect of elevated CO_2 concentrations and associated changes in pH and carbonate ion levels on the rates of growth and calcification of key species of calcifying coccolithophores, such as *Emiliania huxleyi*. Comparative experiments will be run to measure the effect of elevated CO_2 on non-calcifying plankton, including diatoms and dinoflagellates. In addition to open-ocean species, it will be important to determine the impact of ocean acidification on harmful algal species, which are a growing concern along all U.S. continental and island coasts. Data from these experiments will be incorporated into planktonic ecosystem models to predict the impact of future increases in CO_2 on phytoplankton productivity, calcification rates, and biogeochemical cycling of carbon. These models will also allow for prediction of CO_2 impacts on phytoplankton species composition and overall food web dynamics. Additionally, system-level primary productivity forms the basis for fisheries productivity (Chassot *et al.*, 2007; Ware and Thomson, 2005). Quantifying the effect of ocean acidification on primary producers is critical to maintaining the long-term sustainability of exploited resources.

1.2.2 Coral reef ecosystems

A primary concern with respect to coral reef ecosystems is coral health and their ability to precipitate calcium carbonate. Any decline in rates of calcification or increase in net dissolution rates is a concern for the persistence of reef systems. Within U.S. coral reef ecosystems, rates of accretion on healthy, undisturbed reefs are known to only slightly outpace rates of reef loss (Glynn and Morales, 1997). Coral reefs in the past have been able to grow to keep up with sea level rise. Ocean acidification, by reducing both calcification and net carbonate balance, is likely to reduce the ability of corals to keep up with sea level rise. Experimental observations beginning in the 1990s reveal a functional relationship between Ω_{arag} (saturation state) and coral calcification rate, e.g., (Anthony *et al.*, 2008; Borowitzka and Vesk, 1979; Gao *et al.*, 1993; Gattuso *et al.*, 1998; Kleypas *et al.*, 2006; Marshall and Clode, 2002; Marubini *et al.*, 2001; 2002; Ohde and Hossain, 2004; Reynaud *et al.*, 2003), suggesting declining levels of calcification will occur with increasing ocean acidification.

Increasing net dissolution is also a concern. While the oceanic subtropical surface waters will remain supersaturated with respect to aragonite for several centuries, most reefs are not solely composed of aragonite. Instead much of the reef is comprised of more soluble high-Mg calcites (Morse *et al.*, 2006). Furthermore, the diurnal amplitude in $p\mathrm{CO_2(aq)}$ levels within the reef zone can be 10 times that of the oceanic waters and often exhibit a decrease in overall saturation state due to calcification and respiration processes. As a result, there may be periods at night when many reefs currently exhibit net dissolution rates: for example, Yates and Halley (2006) found that net dissolution across a range of reef substrates on the Molokai reef flat, Hawai'i, occurred 13% of the time under present-day conditions. Yates and Halley (2006) also found that when atmospheric $\mathrm{pCO_{2(air)}}$ exceeds about 580 μatm, rates of dissolution of reef sediments are likely to exceed net rates of calcification. So, while coral skeletons will likely not dissolve within this century, the sediments are already dissolving in some reef systems and net dissolution at the reef-scale could occur within this century. Furthermore, recent findings suggest that the calcium carbonate cementation that serves to bind reef framework together may be eroded if Ω_{arag} values fall much below 3.0 (Manzello *et al.*, 2008). Such effects could compromise reef resiliency in the face of other acute threats, such as thermal stress, diseases, increasing storm intensity, and rising sea level, (e.g., Silverman *et al.*, 2009). Indeed, in CO_2-enriched waters of the Galapagos Islands, reef structures were completely eroded to rubble and sand in <10 years following one acute warming disturbance (i.e., 1982–83 El Niño event: Manzello *et al.*, 2008). Here, the upwelling of CO_2-rich deep waters caused ambient Ω_{arag} values to be similar to those expected with a tripling of atmospheric CO_2. Beyond the direct calcification/dissolution concerns there are other effects that need to be considered as well. For example, recent findings suggest that high CO_2 may act synergistically to lower thermal thresholds for coral bleaching (Anthony *et al.*, 2008). In addition, there is evidence that OA inhibits the rate of recruitment and growth of crustose coralline algae, which could cause significant changes in benthic community structure in coral reef habitats (e.g., Kuffner *et al.*, 2007).

Research has shown that the aragonite saturation horizons are shoaling; therefore it has been projected that the first reefs to be affected by ocean acidification are likely to be deep-sea coral ecosystems (Cairns, 2007; Guinotte *et al.*, 2006) and possibly intermediate-depth mesophotic coral ecosystems (characterized by the presence of light-dependent corals and associated communities typically found at depths ranging from 30 m to over 150 m in tropical and subtropical regions). Among shallow water coral reef ecosystems in U.S. jurisdictions, those in the Northwestern Hawai'ian Islands are likely to be the first to pass below levels where net calcium carbonate balance can be maintained. It has been hypothesized that mesophotic coral ecosystems, such as those located in the Au'au channel in Hawai'i, may serve as a potential refuge for shallow-water coral populations predicted to be impacted by ocean warming (Puglise *et al.*, 2009). While this may be true, concerns are now being raised that the deeper range of these ecosystems may be among the first to be impacted by ocean acidification (Sabine *et al.*, 2004).

Continuation and augmentation of a Coral Reef Ocean Acidification Monitoring Network is a high-priority of the NOAA Coral Reef Conservation Program. Each observatory within the network involves the autonomous measurements of a suite of chemical, physical, and meteorological parameters. These measurements will allow the determination of community-scale metabolic processes (net calcification, photosynthesis, and respiration) through the application of a Eulerian flow respirometry method as adopted for coral reefs (Barnes *et al.*, 2001; Gattuso *et al.*, 1999; 1996; 1993; Griffith *et al.*, 1987; Marsh and S. V. Smith (editors), 1978). The basic approach would require the deployment of dual autonomous carbonate chemistry moorings (e.g., enhanced $MAPCO_2$) upstream and downstream of selected forereefs that exhibit unidirectional flow and near-reef studies across a broad latitudinal scale. By combining these measurements with current flow measurements of water mass transit times, one is able to compute a sustained time-series of aragonite saturation state, track reef metabolic performance, and derive robust estimates of annual net rates of reef accretion. The Coral Reef Ocean Acidification Monitoring Network will provide the enhanced characterization of the short-term temporal and spatial variability in carbonate chemistry within coral reef environments that is necessary to assign critical thresholds for adverse effects of ocean acidification.

1.2.3 Shellfish and deep-sea corals

Experiments will be conducted, on a regional basis, to determine the physiological responses of economically and ecologically important species of calcifying organisms to elevated CO_2 levels and associated decreases in pH and carbonate ion concentrations. The organisms to be examined include lobsters, crabs, oysters, clams, mussels, scallops, shrimp, and deep-sea corals. Experiments will focus on larval and juvenile stages as these are likely to be the most sensitive to adverse OA effects. Parameters measured in these experiments should include survival and rates of growth rates, larval metamorphosis, and calcification. The data from these studies will be incorporated into ecosystem and bioeconomic models to forecast impacts of ocean acidification on ecosystems and resource-dependent communities.

1.2.4 Fish

The direct and indirect responses of fish species to ocean acidification will be studied, and the results of this work incorporated into ecosystem models to forecast ecosystem impacts. Ocean acidification could impact the recruitment dynamics of fishes through either direct physiological effects or indirect food web effects. Experiments will be conducted to examine both the direct physiological and indirect food web effects of ocean acidification on the early life stages of a commercially important fish species (e.g., walleye pollock) and other important forage species (e.g., herring).

1.2.5 Other species

The group categorized here as "other species" is very large and likely includes species that are both vulnerable to OA and of significant ecological and economic importance. These include echinoderms (e.g., sea urchins and sea stars) and crustaceans (e.g., crabs, krill, etc.), as well as more cryptic but locally important groups such as bryozoans. The regional sections of this plan (Chapters 2–7) provide a discussion of species of research focus in the different geographic areas.

1.2.6 Protected species

In addition to the direct impacts of ocean acidification on corals, shellfish, and finfish, many protected vertebrates may also be directly affected by ocean acidification. For example, Hawai'ian monk seals are the most critically endangered marine mammal living entirely within U.S. waters. Among many important stressors, monk seals, as well as green sea turtles, are threatened by significant habitat loss as sea level rise erodes away many of the small sandy nesting and breeding beaches in the Northwest Hawai'ian Islands. As the beaches are composed entirely of coral fragments and calcareous algae, ocean acidification impacts on sand production and transport dynamics could have significant impacts on the survival of these threatened species. Reduction of seawater alkalinity could eventually result in net dissolution of these beaches, potentially devastating the land habitats essential for supporting these already threatened species. Both monk seals and green sea turtles already face significant habitat limitations. Similarly, at least 46 species of cetaceans are known in the Pacific Islands region, though population assessments are severely limited. One of the key threats facing cetaceans, which actively and extensively use sonar for feeding and communicating, is acute or chronic increases in ocean noise. Recent studies have demonstrated that sound propagation in the ocean increases with decreasing pH (Hester *et al.*, 2008; Ilyina *et al.*, 2010), which suggests a noisier ocean and potential impacts, such as increased strandings, to cetacean populations in the Pacific Islands region. Similar impacts might be expected for marine mammals and birds in the other five regions.

A large number of tropical corals in the Pacific and Caribbean are currently under consideration by NOAA for listing as threatened or endangered under the Endangered Species Act, largely because of threats from climate change and acidification. This is the first listing consideration where ocean acidification is thought to be among the primary threats. Other species that are already listed under the ESA for which OA is a factor include white and black abalone (*Haliotis sorenseni* and *H. cracherodii*) and the previously listed elkhorn and staghorn coral species (*Acropora palmata* and *A. cervicornis*).

1.3 Biogeochemical and Ecosystem Models (Theme 3)

Ocean general circulation models (OGCMs) that utilize biogeochemical parameterizations have been used to assess the past, present, and future states of ocean acidification (Caldeira and Wickett, 2003; 2005; Orr *et al.*, 2005; Cao and Caldeira, 2008; Gehlen *et al.*, 2007). Because OCGMs were established as coarse-resolution models, processes in coastal and estuarine systems are not properly represented in most of the current model versions. Nevertheless, the models have been useful for identifying regions of high vulnerability to ocean acidification, such as the Southern Ocean and the subarctic Pacific (Orr *et al.*, 2005). The data from repeat hydrographic surveys and time-series measurements provide an excellent means of testing and evaluating model outputs. For coastal and estuarine environments, higher-resolution biogeochemical models will need to be developed and tested. Furthermore, in order to address ocean acidification impacts on organisms, ecosystem models will need to be improved to include responses and feedbacks between lower and higher trophic levels of the marine food web, which have implications for ecosystem structure and function. An integrated approach employing both a detailed observational network and high-resolution physical-biogeochemical-ecosystem models are required for coastal regions and estuaries.

Task 1.3.1: Develop regional biogeochemical models coupled to global carbon cycle models to predict local changes in carbon chemistry at multiple temporal scales.

Future atmospheric CO_2 levels, which influence ocean pH, will depend on many factors, but anthropogenic emissions from the burning of fossil fuels are chief among these. A global energy-economic growth model (Dalton *et al.*, 2008) will be used to project CO_2 emissions from fossil fuels. An earth system model of intermediate complexity (Cao *et al.*, 2007) will take fossil fuel emissions from the economic model as input, track baseline greenhouse gas emissions from other sources, and project atmospheric CO_2 levels and changes in ocean pH. Assumptions in the scenarios about future technological and demographic change will be based on updates of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions.

Task 1.3.2: Develop regional ecological and bio-economic models coupled to regional biogeochemical models to predict local changes in ecosystem, food web, and economic interactions.

A diverse array of species and a variety of trophic levels are expected to experience direct effects of OA (see section 1.2). Ecosystem modeling will be required to estimate how these individual species effects will impact all of the species interacting in complex ecological food webs. The ecosystem models used to explore the effects of OA will largely be developed from models capable of examining multiple ecosystem stressors, such as fishing, thermal stress, and nutrient additions.

1.4 Human Dimensions (Theme 4)

Human dimensions activities include the development of a process for deciding what to do about ocean acidification. As described in the introduction, based on current understanding, management options for dealing with acidification may be somewhat limited. However, there will be choices about whether to reduce CO_2 emissions, how to confront other stressors to the marine system, how to prepare communities for ecosystem changes, whether to implement spatial or temporal fisheries changes, etc. Making these decisions will require consideration of ecological predictions, the value of ecosystem services, and the economic and social costs of proposed actions.

1.4.1 Bio-economic models

Task 1.4.1: Estimate anticipated changes to ecosystem services as a consequence of ocean acidification and evaluate alternative management options.

The economic consequences of OA will depend on the combined adaptation of marine ecosystems and human resource management efforts. For example, in 2006, shellfish and crustaceans provided 50% of the U.S. $4 billion domestic commercial harvest value in the U.S. Processing, wholesale, and retail activities led to sales of U.S. $69.5 billion, contributing U.S. $35 billion in value added to the U.S. gross national product, and providing an estimated 70,000 jobs (Fabry *et al.*, 2008). Ocean acidification-driven declines in commercial shellfish and crustacean harvests from the present day to 2060 could decrease U.S. primary commercial revenues by U.S. $860 million–$14 billion, depending on CO_2 emissions, discount rates, biological responses, and fishery structure. This estimate excludes (1) losses from coral reef damage and possible fishery collapses if OA pushes ecosystems past ecological tipping points (Cooley and Doney, 2009) and (2) the benefits of marine resources that extend to ecosystem services not directly monetized, including beaches, coastal protection, and cultural considerations (e.g., traditional harvest activities, Moberg and Folke, 1999).

Bio-economic models will be developed for and applied in each of the regions to address how changes in ecosystem services will impact communities and economies. The structure of the proposed models will vary by region and application. Many will incorporate results from the experiments on species response to ocean acidification (Theme 2). In addition, results from ecosystem models that consider ocean acidification will be used to test the impacts of different decision rules for fishing effort.

1.4.2 Mitigation and adaptation strategies

Task 1.4.2: Test mitigation approaches under laboratory and field conditions. Develop adaptation strategies.

At least two possible local mitigation methods have been proposed to counter the effects of ocean acidification: (1) sediment buffering, and (2) electrochemical deposition. With the sediment buffering approach, calcium carbonate from ground bivalve shells or limestone would spread over the existing sediments to alter the saturation state of the local benthic environment (Green *et al.*, 2009). Electrochemical deposition is a method developed to create artificial reefs by running an electric current though metal structures placed in the ocean (Goreau *et al.*, 2004; Hilbertz, 1979). The electric current alters local saturation state and could potentially provide a local means to mitigate ocean acidification. Neither method is likely to be practical for mitigation at large geographic scales.

Social scientists will conduct socioeconomic vulnerability assessments at regional-to-local scales to evaluate of the degree of societal dependence on ecosystem services affected by OA. Such information will be used to inform adaptive management strategies that promote social resiliency and may require adapting local/regional policies. Adaptation strategies might include (1) educating communities about how ocean acidification may impact the marine and Great Lake resources on which they rely, and (2) helping communities utilize alternative, less vulnerable resources. For instance, certain indigenous communities may rely on vulnerable species for subsistence or cultural traditions. Preparing these communities for changing population stocks will be critical. Development and application of decision-support frameworks are also needed to improve proactive management actions and transparently incorporate the considerable uncertainty that exists in all of the input parameters, including those on how ecosystem services will be impacted by ocean acidification. Management decisions related to ocean and lake acidification should also be incorporated into new coastal and marine spatial planning efforts for two reasons: acidification may (1) require alterations in how and where humans obtain benefits from the sea and Great Lakes and (2) drive demand for new ocean and lake uses, such as renewable energy projects.

1.5 Synthesis of Data and Information Products (Theme 5)

Task 1.5.1: Develop data and information tools for evaluating the consequences of ocean acidification to create more effective management strategies.

The data management strategy that will support data synthesis for ocean acidification studies must address a number of heterogeneous elements. It must bring together the outputs of global networks, such as CLIVAR/CO_2, Argo, and OceanSITES with new coastal platforms and surveys. It must bring together physical, chemical, and biological observations that differ widely in character, and datasets both recent and historical. It must ensure that detailed metadata are captured along with the observations. Constraining the uncertainties in observations will be essential for successful synthesis, so the data management procedures must ensure that uniform quality control procedures are applied. It must distinguish versions of data at several stages of calibration and quality control. The timely release of synthesis products will depend upon timely access to many independently managed sources of data.

No single data management system can address this diversity of requirements; the data management strategy must necessarily involve coordination among a significant number of distinct systems. Where the dynamics of the ocean play a strong role, as is the case for physical and chemical properties of sea water, the data management strategy will be patterned after the concepts that have proven successful in Global Ocean Observing System (GOOS)—data assembly centers (DACS) feeding into one or more Global Data Assembly Center (GDAC). DACs provide the level of regional or institutional independence that is needed to address the deployment and management of platforms. A national DAC (analogous to GDAC) can provide the higher level of integration necessary for synthesis. Where the dynamics of the ocean do not so dominate the data synthesis, as in regional benthic biology and ecosystem studies, greater independence of DACs will be sufficient.

Several data centers currently provide data management services for particular types of hydrography data and biogeochemical data. We recommend establishing these and other centers as ocean acidification DACs with agreed sets of policies and data standards to govern their operations. We also propose to develop a single national ocean acidification information center (NDAC) that will serve as a central repository, the locus for secondary data QC and synthesis and the communication and coordination hub for the DACs. This NDAC will also develop new strategies for archiving and serving ecological response data to facilitate the synthesis of information across a range of species and ecosystems.

The NOAA Ocean and Great Lakes Acidification Research Plan will need to continually provide data products, indices, publications, and data synthesis activities and products. Data synthesis activities should include standardizing and merging of basin- and global-scale data sets, synthesis with data from other platforms and model outputs, and integrated synthesis reports. The synthesis process should include: science and technical workshops; product development workshops; and international synthesis meetings. An international program on ocean acidification would provide the necessary framework for producing coordinated global basin-wide and regional-scale data products and synthesis reports on a regular basis, and provide the right forum to provide integrated synthesis products to resource managers and policymakers.

1.6 Engagement Strategy (Theme 6)

Task 1.6: Implement an education and outreach program to communicate the science and ecosystem consequences of ocean acidification to the public and stakeholder communities.

The NOAA Ocean and Great Lakes Acidification Research Plan is designed to engage researchers, policymakers, teachers, and the public, and thus will require skilled and dedicated effort operating alongside the research program. Emphasis should be placed on engaging stakeholder support for and participation in marine ecosystem conservation. Examples of education and outreach activities include: workshops and training programs with constituents to provide internet access and orientation to current research findings and data; planned development and distribution of educational materials and displays; fostering local community involvement in conservation and restoration projects; and hosting two-way discussions with stakeholders to improve mutual understanding of resource needs and management goals.

In order to foster collaborative planning across the range of ocean acidification engagement activities and programs, the ocean acidification engagement strategy has the following objectives:

- Continue to develop and improve NOAA's Ocean and Great Lakes Acidification Research Plan to ensure integration across NOAA's line offices;
- Be responsive to national ocean acidification issues raised by NOAA leadership, stakeholders and general public that require integrated education and outreach activities across the agency;
- Serve as a mechanism for coordination of education and outreach activities and information exchange from the laboratories to NOAA leadership and outside communities; and
- Ensure the development and incorporation of ocean acidification assessment and adaptation policies within NOAA line offices and with NOAA partners.

1.6.1 Education and outreach

This plan for ocean acidification research and monitoring includes education and outreach activities to improve the public's understanding of the issue. A well-informed public will support government research and management plans and energize communities to take the necessary actions to mitigate ocean acidification's causes. The FOARAM Act of 2009 calls for educational and public outreach opportunities to improve the understanding of current scientific knowledge of ocean acidification and its impacts on marine resources. The NOAA Office of Education, the National Sea Grant Program, the Climate Program Office, the Coral Reef Conservation Program, and the National Marine Sanctuaries Program can play integral roles in meeting FOARAM mandates by developing an increased awareness of the causes and potential effects of ocean acidification on our coast and ocean ecosystems.

For example, NOAA's Competitive Education Grants Program provides funding to an array of educational organizations and institutions that use innovative technologies, such as Science on the Sphere, to reach out to millions of people across the country on NOAA-related issues, including ocean acidification. The NOAA Coral Reef Conservation Program, along with Estuarine Reserves Division, is leading the development of an ocean acidification educational module, consisting of five scalable lesson plans and a dedicated web interface for both teachers and students, using field data and near-real-time data on several parameters relating to the study and monitoring of ocean acidification. Educators nationwide will be trained in the use of this module through our partnership with the National Science Teachers Association and other partners. Collaboration with the Climate Program Office and the NOAA Climate Services Portal will also be instrumental in meeting the FOARAM mandates and increasing public education and outreach on ocean acidification. The National Marine Sanctuaries and National Estuarine Research Reserves can also serve as sentinel sites, not only for research and monitoring, but also as places communities go to learn. Robust primary, secondary, and adult education programs exist at most sanctuaries and NERRS sites, reaching thousands of students and members of the public each year. Through at-school, in the field, and visitor center programs, as well as community lecture series and teacher workshops, sanctuary and NERRS staff and volunteers reach a large and diverse audience. In addition to school programs and curricula, a variety of other outreach and education activities exist at sanctuary sites.

Outreach goals would include developing an information delivery system where ocean acidification data and current research activities within each region would be made available to scientists, managers, educators, stakeholders, and interested citizens through a web portal and various internet resources. The first steps to producing an ocean acidification education and outreach plan will be:

- Identifying target audiences;
- Determining appropriate programs and products for each audience;
- Developing a comprehensive needs assessment to education and outreach programming;
- Matching ocean acidification needs with existing education and outreach activities; and
- Developing innovative approaches for community involvement.

1.6.2 Communications

A major component of NOAA's Ocean and Great Lakes Acidification Research Plan will be the communication of research results, mitigation and adaptation strategies, and other ocean acidification products and services to the news media, government officials, stakeholders, and the public. This will be accomplished by the Ocean Acidification Program Office working in collaboration with the regional Sea Grant Offices, the National Marine Sanctuaries and NERRS Programs, other federal and state agencies, and the private sector. A web site will be established as a resource for information exchange and data delivery.

1.7 Enabling Activities

Key components of any scientific program are the enabling activities that facilitate its execution. This is particularly true for ocean acidification research, which is rapidly developing into a cross-matrix, multi-line office program with many facets. The following enabling activities are required to efficiently reach the stated goals and address the hypotheses that are in this research plan.

1.7.1 Program office

The structure and function of the NOAA Ocean Acidification Program Office are given in Table 1.5. The Program Director will provide overall direction for the program and will initially be supported by a staff of 2–3 persons. The Program Director will be responsible for coordinating all of NOAA's ocean acidification activities, and development of an implementation plan for NOAA's Ocean Acidification Program will be one of the Director's first priorities. He/she will be guided by the objectives outlined in this research plan and the National Academy of Sciences report, "Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment." He/she will be advised by an Executive Committee consisting of scientific experts and program managers from each of the line offices, the Program Director, and the NOAA member of the Interagency Working Group on ocean acidification.

Aside from the core activities of the office, it will also actively strive to maintain the preeminence of NOAA in ocean acidification research through sponsorship of workshops ranging from small technical workshops to wider-ranging synthesis and forward-looking meetings. The program office will serve as the nucleus to guide and document the need for future observations and research by keeping track of developments in the ocean acidification research and the results of the sponsored activities to date. This will be accomplished by facilitating synthesis activities, publishing reports from meetings and workshops, and maintaining an active web presence.

1.7.2 Technology development

A deficiency in ocean acidification research is specific instrumentation for continuous autonomous monitoring in the field. This holds true specifically for the measurement of inorganic carbon species impacting the ocean biota, but also for the bulk and specific indicators of ecological response. In particular, while autonomous surface measurement capabilities for pH and $p\mathrm{CO}_2$ on buoys and other platform are commercially available, promising methods for subsurface measurements, including in the benthos across a range of depths and habitats, are still under development. To constrain the inorganic carbon parameters to the precision and accuracy necessary to assess spatial and temporal variability of ocean acidification and its impacts, total alkalinity and/or dissolved inorganic carbon measurement capabilities are also required. Several promising developmental efforts are underway but require continued resources and field-testing. Field deployments are often lacking in funded development efforts. In addition to new instrumentation, adaptation of established instruments for ocean acidification research is necessary. This includes increased precision, accuracy, and sample throughput

Table 1.5: Structure and functions of the NOAA Ocean Acidification Program Office.

Duties and Responsibilities

- Execute the NOAA Ocean Acidification Program in accordance with the NRC Panel Report and the FOARAM Act of 2009
- Serve as the focal point of all NOAA Ocean Acidification activities including:

A. Program Development

- Work with Legislative Affairs to brief Congress
- Work through the budget process to build the program for the future, writing alternatives, working across line offices and programs
- Coordinate ocean acidification activities with other federal agencies via the Joint Subcommittee on Science and Technology (JSOST) Ocean Acidification Interagency Working Group
- Coordination of ocean acidification cruise and experimental activities within NOAA

B. Record Keeping on Program Progress

- Write and track budget narratives, working with line office (LO) budget staff
- Write and track the program, quad charts and quarterly reporting
- Write and track performance measures

C. Communications

- Communicate with implementation committee to set priorities and direction for program
- Management of personnel in the program office
- Point of contact for line office planning, communications, prepare materials for Congress, budget preparation, and reporting
- Point of contact for NOAA on ocean acidification issues and serve as interagency representative

for discrete samples in laboratory and research ship settings. Adaptation of novel platforms such as gliders, AUVs, drifters, and autonomous surface vehicles to accommodate sensors for ocean acidification research is also desired.

1.7.3 Best practices methods

Proper protocol in executing ocean acidification studies is essential. The European Project on OCean Acidification (EPOCA) has established a best practices guide for ocean acidification research that will be adopted for the NOAA work (`http://www.epoca-project.eu/index.php/Best-Practices-Guide/`). However, as outlined in several chapters of this report, best practices are an evolving activity such that support for guide updates and working groups are essential. As stated in the best practices guide's chapter on the carbon dioxide system in seawater:

"Additional efforts are required to document procedures effectively and to establish a community-wide quality assurance scheme for each technique. Such a scheme will involve:

- Writing appropriate Standard Operating Procedures for the techniques in use,
- Inter-laboratory comparison exercises to assess the various figures of merit for each method (trueness and precision),
- Regular use of certified reference materials to assist in the quality control,
- Regular laboratory performance testing using blind samples,"
- Working collaboratively with other federal agencies to ensure that high-quality standards and reference materials are made available to the scientific community.

The NOAA Ocean Acidification Program must take the U.S. lead in such efforts and assure each of the regional NOAA labs engaged in ocean acidification activities are trained in the best practices.

1.7.4 Centers of expertise for data quality assurance

The current analytical capacities and expertise in carbon system dynamics, as it pertains to ocean acidification, are not sufficient in most NOAA and academic labs. Fortunately, several NOAA research labs have acquired personnel with appropriate expertise and instrumentation to perform key measurements for ocean acidification as part of their decades' long involvement in the global ocean CO_2 survey. These laboratories will provide analytical services, lead efforts to continue best practices, and train personnel in the field in proper protocols and analysis. They will also serve as a nexus for design of perturbation studies to predict response of organisms to future anticipated CO_2 levels. They will serve mainly as quality control and training centers.

1.7.5 Data management

A lesson learned from previous carbon programs is that data management must be an integral part of the program from the onset. The NOAA Ocean Acidification Program will advocate an open and rapid dissemination of all data to the community at large. The broad scope of the efforts ranging from global monitoring of ocean acidification trends to bench-top incubation studies makes data management challenging. Also, to take full benefit from the multi-agency collaborations in ocean acidification, the data management activities should cover all interagency ocean acidification activities. The NOAA Ocean Acidification Program will coordinate and advocate QC procedures as well as standards and policies for data interchange. A National DAC for physical, and biogeochemical measurements will need to be established. At the distributed DACs some center functions will need to be augmented particularly for coordinated management and dissemination of the data and meta-data from perturbation studies. Well-defined service interfaces and a user-friendly web portal will disseminate data and generate visualization products in a uniform manner.

1.7.6 Stakeholder interactions

Changes in ocean chemistry in response to ocean acidification are anticipated to impart a suite of primary and secondary effects from species to ecosystem-levels that will affect a broad range of human communities dependent upon the ecosystem services they provide. Locally, communities that directly depend on affected ecosystems for sustenance, livelihood, and coastal protection will need to be proactive in preparing for or mitigating, where possible, the effects of ocean acidification. Policy makers and managers responsible for marine natural resource management, environmental regulation, coastal and marine spatial planning, and energy policy will need to incorporate ocean acidification as a consideration to long-term planning and legislation. The private sector dependent upon impacted living marine resources that could include finfish, shellfish, and aquaculture need to be apprised of the potential effects of ocean acidification to their industries. Conservation groups, NGOs, and the public have a need to be informed by the best science with regard to the potential consequences of ocean acidification. To meet these needs, a robust two-way interaction between stakeholders and experts in ocean acidification is essential for a well-directed program. NOAA is fortunate to have established links with the public through the outreach efforts of the National Marine Sanctuaries, ICCS Regional Associations, and Sea Grant Programs. Resources are required to produce materials and outreach activities pertaining to ocean acidification. A dedicated effort must be established with guidance of the program office to quantify the socio-economic impacts of ocean acidification, particularly as it pertains to fisheries and coral reefs. Accurate assessment of the impacts will be the cornerstone for justification of allotting resources for continued monitoring and research, as well as assessing the economic feasibility of mitigation approaches.

1.8 Interagency and International Cooperation

1.8.1 Interagency cooperation

The United States Joint Subcommittee on Ocean Science and Technology (JSOST) provides for the coordination of science and technology across multiple federal agencies. As part of the Federal Ocean Acidification Research and Monitoring Act of 2009, JSOST is designated as the subcommittee that will coordinate federal activities on ocean acidification. Under this plan, JSOST has established the Interagency Working Group on Ocean Acidification (IWGOA) to develop the strategic research and monitoring plan to guide federal research on ocean acidification. This plan would include: (1) assessing of the potential impacts of ocean acidification on marine organisms and marine ecosystems; (2) developing adaptation and mitigation strategies to conserve marine organisms and ecosystems exposed to ocean acidification; (3) facilitating communication and outreach opportunities with nongovernmental organizations and members of the stakeholder community with interests in marine resources; (4) coordinating the United States federal research and monitoring program with research and monitoring programs and scientists from other nations; and (5) establishing an ocean acidification information exchange to make information on ocean acidification developed through or utilized by the interagency ocean acidification program accessible through electronic means, including information which would be useful to policymakers, researchers, and other stakeholders in mitigating or adapting to the impacts of ocean acidification. Interagency partners include: the National Science Foundation, the National Aeronautics and Space Administration, the Environmental Protection Agency, the U.S. Fish and Wildlife Service, the U.S. Geological Survey, the Minerals Management Service, the Department of the Navy, and the Department of State.

1.8.2 International cooperation

International cooperation will be coordinated through the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and Surface Ocean–Lower Atmosphere Study (SOLAS) Working Group on Ocean Acidification. This international group has two main goals: (1) coordinate international research efforts in ocean acidification; and (2) undertake synthesis activities in ocean acidification at the international level. Two members of the U.S. Interagency Working Group on Ocean Acidification are also members of the IMBER/SOLAS Working Group on Ocean Acidification and will carry out the coordination activities between the two groups.

1.9 Expected Outcomes

The NOAA Ocean and Great Lakes Acidification Research Plan is designed to identify and monitor global and local-scale ecosystem changes resulting from ocean acidification. The expected outcomes of this research include: (1) a comprehensive evaluation and characterization of the threat ocean acidification poses to NOAA-managed ecosystems and the dependent living marine resources; (2) the monitoring capacity to quantify and track ocean acidification and resolve its direct and indirect ecological impacts within oceanic, coastal, and estuarine ecosystems and their NOAA-managed living marine resources; (3) a mechanistic understanding of direct and indirect (e.g., via food webs) impacts of ocean acidification on regional species and ecosystems that will enable the development of accurate ecological and socioeconomic forecasting; and (4) identification of useable adaptation strategies for severely impacted marine ecosystems. Specifically, these outcomes will include:

- A chemical/biological monitoring protocol designed to identify and track critical levels of ocean acidification within selected habitats (e.g., carbonate mineral saturation state within coral reef ecosystems);
- An improved ocean acidification forecasting capability that accounts for local-scale ancillary effects on carbonate chemistry (e.g., geology, hydrography, terrestrial/ground water inputs, and biota) and provides stakeholders with the capacity to proactively and appropriately respond to ocean acidification at the regional-scale;
- A regional contribution to a national database of ocean acidification monitoring data and scientific results;
- Adaptive management tools and requisite scientific knowledge for understanding and responding to ocean acidification in support of ecosystem-based management;
- National web-accessed resource for data and information on ocean acidification.

2. NOAA Alaska Region Ocean Acidification Research Plan

Michael F. Sigler, Robert J. Foy, Mark Carls, Michael Dalton, Lisa B. Eisner, Kris Holderied, Thomas P. Hurst, Joseph F. Morado, Phyllis Stabeno, and Robert P. Stone

2.0 Ocean Acidification in the Alaska Region

The North Pacific Ocean is a sentinel region for signs of ocean acidification. Corrosive waters reach shallower depths more so there than in any other ocean basin, especially in Alaska, and so impacts of ocean acidification on marine calcifiers will likely occur earlier there than in many other places. Waters below the $CaCO_3$ saturation horizon are corrosive to calcifying organisms. The $CaCO_3$ saturation horizon is relatively shallow in the North Pacific Ocean and is projected to reach the surface of the North Pacific Ocean during this century (Orr *et al.*, 2005). At that point, a wide range of North Pacific species will be exposed to corrosive waters.

Alaska's marine ecosystems are highly responsive to shifts in climate (e.g., Hare and Mantua, 2000; Hollowed *et al.*, 2001; Connors *et al.*, 2002; Hunt, Jr. *et al.*, 2002; Moore *et al.*, 2003). At high-latitude cold oceans, two other climate-related effects may act synergistically with ocean acidification effects: loss of sea ice and ocean warming. Two of the four Large Marine Ecosystems (LMEs) within the Alaskan complex (Bering Sea/Aleutian Islands and Gulf of Alaska) have experienced documented regime or phase shifts in community organization and productivity related to changing climate (Anderson and Piatt, 1999; Ciannelli *et al.*, 2005; Grebmeier *et al.*, 2006; Litzow *et al.*, 2006; Litzow and Ciannelli, 2007; Mueter and Litzow, 2008). Three of the four LMEs are extremely susceptible to loss of sea ice and all four of the LMEs are susceptible to the impacts of ocean acidification. General circulation models predict that the largest changes in global temperatures will occur at high latitudes, and such change has already begun on both land and in the oceans surrounding Alaska (ACIA, 2004; Stabeno and Overland, 2001). At risk are Alaska's seafood production, the recovery of endangered and threatened marine species, the living marine resources that nourish and provide continuity of Alaska's native cultures, and natural resources that support Alaska's large tourism industry. Possible consequences of predicted ocean pH changes may be particularly acute in the North Pacific Ocean and especially Alaskan waters.

2.1 Developing an Ocean Acidification Monitoring Network (Theme 1)

Task 2.1: Develop and implement program for monitoring carbon-cycle-related oceanographic parameters off Alaska.

Ocean pH measurements of Alaska's seas are sparse. Few measurements have been collected in the Bering Sea, which is the source of about 40% of U.S. fisheries catch. A few studies in this region have documented waters impacted by ocean acidification in the Gulf of Alaska. University of Alaska scientists measured calcium carbonate concentrations at a cross-shelf transect (GAK line, approximately 147°W) in 2008. Continental slope water was undersaturated for aragonite below 250 m in May 2008 and 200 m in September 2008 (Figure 2.1). We propose spatially and temporally comprehensive coastal and oceanic monitoring of ocean carbon chemistry (saturation state, dissolved inorganic carbon, alkalinity), including continuous monitoring of seawater intakes at coastal laboratories and oceanographic moorings as well as periodic monitoring during dedicated oceanographic surveys.

Alaska Region Description

The Alaska region covers 842,000 square nautical miles and produces about half the fish caught in U.S. waters. The Alaskan ecosystem complex is comprised of four large marine ecosystems (LMEs): Gulf of Alaska, East Bering Sea/Aleutian Islands, Chukchi Sea, and Beaufort Sea. Large-scale atmospheric and oceanographic conditions affect the productivity of the LMEs. The region's cold, nutrient-rich waters support a biologically diverse ecosystem, including a number of commercially important fisheries for crab, shrimp, scallops, walleye Pollock, Pacific cod, rockfishes, halibut, and salmon (pink, sockeye, chum, Coho, and Chinook). Marine fisheries of Alaska provide almost 50% of the nation's seafood harvest, and this harvest is important to our balance of trade with other countries. The Bering Sea is directly or indirectly the source of over 25 million pounds of subsistence food for Alaska residents, primarily Alaska Natives in small coastal communities (Bering Ecosystem Study, 2004). Alaska's nearly 44,000 miles of coastline constitute about two-thirds of the total U.S. coastline and support a wide variety of habitats and user communities. The region's natural beauty and resident and migratory species are the basis of a billion dollar tourist industry.

2.1.1 Coastal laboratories and oceanographic moorings

Coastal laboratories are located across the Gulf of Alaska and normally house seawater tanks supplied by fresh seawater. The laboratories provide both the capacity to conduct cost-effective sampling from small boats and a convenient supply of seawater for monitoring temporal variation of shallow coastal water. This variability is driven by inputs of fresh water, high biological productivity, and coastal upwelling. We propose coordinated estuarine and coastal monitoring in Kachemak Bay, near Kodiak, and near Juneau, based from the NOS Kasitsna Bay and NMFS Kodiak and Auke Bay Laboratories. Kachemak Bay is also part of the NOAA Kachemak Bay NERR. This effort will also be coordinated with near-shore monitoring system deployments in other regions (see section 5.1.7) and with oceanographic mooring and ship survey measurements.

Oceanographic moorings exist in the Bering Sea and Gulf of Alaska. We propose deploying instruments to measure carbon parameters, most on standard oceanographic moorings. The locations of coastal laboratories and oceanographic moorings are shown in Figure 2.2. See Tables 1.2 and 1.3 for more detailed information about each mooring.

2.1.2 CO_2 cruises: Bering Sea, Gulf of Alaska, Arctic Ocean, southeast Alaska

The purpose of these cruises is to establish baseline CO_2 measurements for coastal seas which have not been measured previously. Sampling is planned for the Bering Sea in FY2011, the Gulf of Alaska in

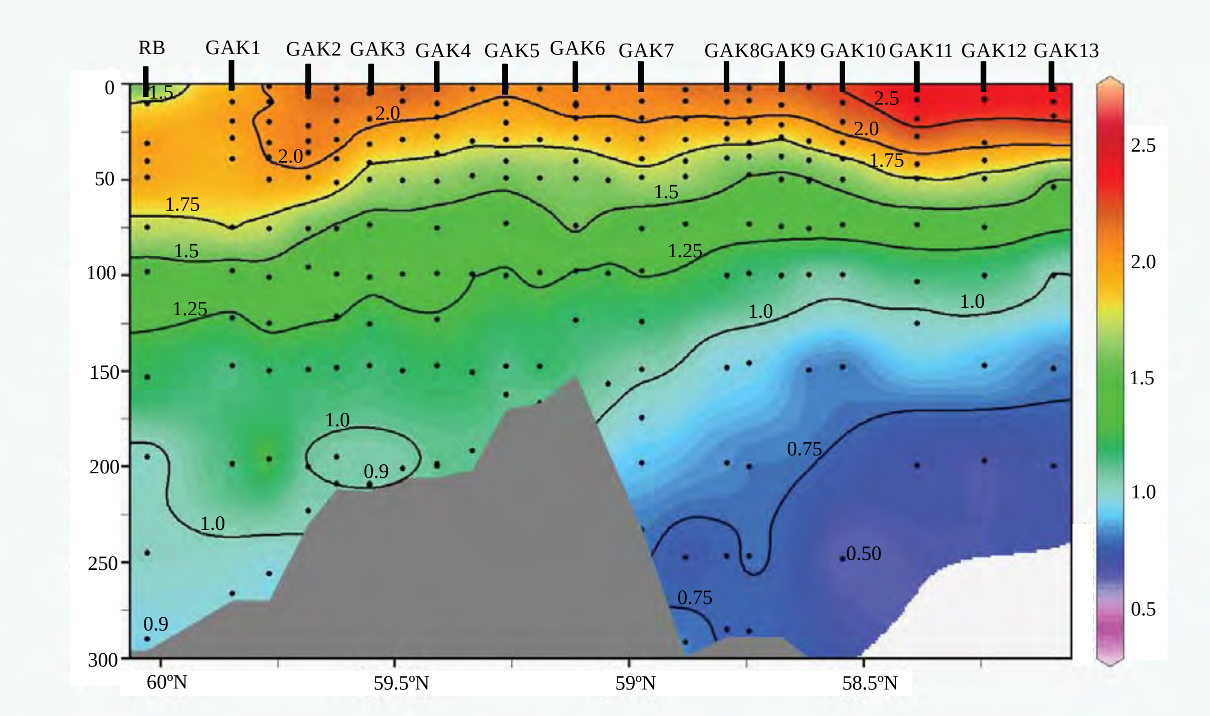


Figure 2.1: Aragonite saturation state (Ω_{arag}) in the Gulf of Alaska in September 2008 (Jeremy Mathis, University of Alaska). $\Omega_{\text{arag}} < 1$ indicates undersaturation; $\Omega_{\text{arag}} > 1$ indicates supersaturation.

FY2012, the Arctic Ocean in FY2013, and inside waters of southeast Alaska in FY2014. Depending on results of those cruises, repeat sampling will continue in FY2015 and FY2016 in the coastal seas where observations reveal the most impact from ocean acidification. Equipment purchases are planned for FY2010. Operations on these cruises will consist of point-specific sampling of dissolved CO_2 profiles and ocean acidity along track lines, with station sampling nominally every 30 nautical miles. Biological samples will be collected near observing sites using standard net tows. A typical field operations day consists of CO_2, oxygen, and nutrient sampling, Conductivity, Temperature, and Depth (CTD) profiler casts, mooring recoveries and deployments, California Cooperative Oceanic Fisheries Investigation (CalCOFI) Vertical Egg Tow (CalVET) and Marine Assessment Monitoring and Prediction (MARMAP) Bongo net tows, various bio-optical instrument deployments, and Towed Undulating Vehicle (TUV) operations. This acidification cruise is best executed during summer, when biota are at peak production, to enable comparison of ocean pH with abundance and condition of organisms.

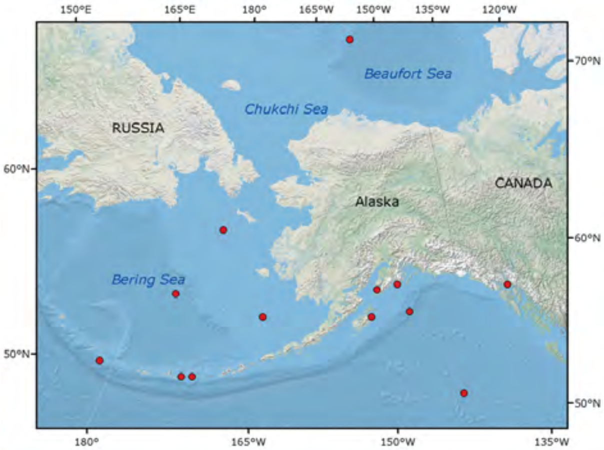


Figure 2.2: Locations of coastal laboratories and oceanographic moorings in the Alaska Region with proposed ocean acidification monitoring capabilities.

2.2 Organism Response to Ocean Acidification (Theme 2)

The species-specific physiological response to ocean acidification is unknown for most marine species. Lacking basic knowledge, we recommend a broad research effort directed toward several taxa, including

Organisms of Near-Term Focus

King crab (above)
Euphausiids
Deep-sea corals
Pollock

shellfish, calcareous plankton, deep-sea corals and fish. We also recommend prioritization within this research effort, with earlier and/or larger investments directed toward taxa more likely to be affected by ocean acidification and commercially and ecologically important species, especially the larval and juvenile stages. Commercially important calcareous species (e.g., king crab) are first priority because of their economic value and because these species are likely to suffer direct effects of reduced $CaCO_3$ availability. Second priority is calcareous prey (e.g., euphausiids) of commercially important species (e.g., walleye pollock) and marine mammals, because the most likely effects on fish and marine mammals are indirect effects through predator-prey relationships. Direct effects on fish and marine mammals are less likely because their calcareous tissues are internal. Third priority is deep-sea corals whose ecological importance includes sheltering marine organisms (e.g., rockfish). Fourth priority is commercially important fish species; some research will screen for early life history effects. We will add a focus on marine mammals if we find effects on prey of planktivorous (baleen whales) or piscivorous (pinnipeds, toothed whales, porpoise, and dolphin) species.

Task 2.2.1 Create state-of-the-art facilities for conducting ocean acidification experiments on individual species and species assemblages.

To evaluate how species in Alaska ecosystems will respond to acidification, we will build state of the art facilities for conducting species response experiments. These facilities will be set up as shared-use centers, where scientists from NOAA and academic institutions can perform experiments. The advantages of such share-use facilities are many-fold and include economic efficiency and promotion of collaboration among researchers. The Alaska Fisheries Science Center (AFSC) ocean acidification facilities will be located in Kodiak and Juneau, Alaska, and Newport, Oregon, and are scheduled to be completed in 2010 as part of the NMFS FY2010 Ocean Acidification Plan. The AFSC has already developed pilot ocean acidification treatment systems at each site, which have been used for preliminary experiments on king crab, herring, pollock, and cod. Scientists at each site have many years of experience conducting experiments with their focal species (e.g., king crab at the Kodiak Lab). Knowledge gained in the development of the pilot systems will be applied to the creation of the larger facilities. During the development pilot system, AFSC researchers have established collaborations with scientists from the University of Alaska and the Northwest and Northeast Fisheries Science Center, where there is strong support for shared-use facilities.

Task 2.2.2: Conduct acidification response experiments on species and species assemblages of interest in Alaska ecosystems.

AFSC scientists have been conducting preliminary ocean acidification research on Alaska king crab species since 2006 (R. Foy, S. Persselin). Their approach has included identification of shellfish species that may be affected; development of laboratory studies to test hypotheses related to the direct effects of decreased pH and undersaturation of $CaCO_3$ in seawater; identification of response variables that would be appropriate to assess ocean acidification impacts; and development of in situ process studies to address the magnitude of importance that ocean acidification may have on coastally important shellfish species. AFSC scientists have also begun conducting ocean acidification research on walleye pollock (T. Hurst with J. Mathis, UA) and Pacific herring (F. Sewall, M. Carls) in 2009. A pilot ocean acidification treatment system to assess larval crab response to acidification will be set up in 2010 at the Kasitsna Bay Laboratory, through partnerships with the University of Alaska Fairbanks and Kachemak Bay NERR and in coordination with AFSC scientists.

The shellfish, calcareous plankton, coral, and fish studies proposed below were developed to form a coherent ocean acidification research plan. These studies are described in more detail in the AFSC Ocean Acidification Research Plan (Sigler *et al.*, 2008).

Species-specific effects identified by these studies are apt to have ecosystem-level consequences; these study results will be used to inform models and forecast population, ecosystem, and economic impacts.

2.2.1 Shellfish

The species-specific physiological responses of king crab to ocean acidification will be measured and then these results will be incorporated into a bioeconomic model to forecast population and economic impacts. In addition, a survey of North Pacific shellfish will be conducted to assess species vulnerabilities to ocean acidification. The survey will measure $CaCO_3$ concentration and form (e.g., aragonite). The species-specific physiological response (growth, survival, reproduction) of larval, juvenile, and reproductive female king crab species to mixtures of pCO_2 levels of 280, 400, 500, 750, and 1,000 ppmv (ppmv = parts per million by volume) will be tested. The mixtures were chosen to reflect past, current, and predicted future levels of CO_2 concentrations in seawater. The performance of the CO_2 delivery system will be monitored because the chemical changes induced in the affected seawater will depend on the salinity, dissolved inorganic carbon, and initial pH. The $CaCO_3$ content of the shells of the experimental animals in the different treatments will be measured. Genomic microarrays will be used to indicate sublethal effects. These study results will be incorporated into a two-area bioeconomic model of Alaska's king crab fishery (see the "Human Dimensions" section).

2.2.2 Calcareous plankton

The species-specific physiological responses of calcareous plankton to ocean acidification will be measured experimentally in the laboratory and distribution of the natural population will be monitored in the Bering Sea and Gulf of Alaska. These results will be incorporated into an ecosystem model to forecast ecosystem impacts. In addition, a survey of North Pacific calcareous plankton will be conducted to assess species vulnerabilities to ocean acidification. Monitoring of calcareous plankton distributions will continue in the Bering Sea and Gulf of Alaska from satellite observations and shipboard sampling by research vessels and ships of opportunity. These distributions may be compared to water mass properties (e.g., temperature, salinity, nutrients, and pH) and distribution of zooplankton and fish to understand factors promoting blooms and potential food web implications. In addition, we plan to conduct at-sea experiments to test for effects of ocean acidification on calcareous plankton (e.g., pteropods) through collaboration between external and in-house experts.

2.2.3 Deep-sea corals

A survey of North Pacific corals will be conducted to assess species vulnerabilities to ocean acidification and these results will be evaluated in a risk assessment. The species-specific physiological responses of representative coral species to ocean acidification will be measured in the laboratory. The degree to which North Pacific Ocean corals will be affected by ocean acidification will depend on the $CaCO_3$ saturation state and type and their depth distribution. Fairly good information on coral depth distribution exists, but information on $CaCO_3$ composition of the skeletons is limited. A survey will be conducted then to construct a risk assessment for North Pacific Ocean corals. Measurements on the aragonite and calcite saturation horizons will be critical to this assessment. Species-specific physiological responses will be measured for representative coral species in the field and laboratory. The species will be chosen based on the risk assessment.

2.2.4 Fish

The direct and indirect responses of walleye pollock, Pacific cod, and Pacific herring will be measured and these results will be incorporated into an ecosystem model to forecast ecosystem impacts. Ocean acidification could impact the recruitment dynamics of fishes through two distinct pathways, reduced growth and survival through direct physiological effects and, alternatively, by altering the production of lower trophic levels and thus the foraging environment of the early life stages. Experiments will be conducted to examine both the direct physiological and indirect food web effects of ocean acidification on the early life stages of commercially valuable fish species (e.g., pollock) and important forage species (e.g., herring). The walleye pollock experiment will extend previous research on prey quality effects on larval walleye pollock.

2.3 Biogeochemical and Ecosystem Models (Theme 3)

The population and ecosystem models described in this Plan will incorporate the results of the species-specific physiological studies to forecast population, ecosystem, and economic impacts of ocean acidification. These models are described in this section and in Section 2.4. The planned studies build upon a substantial number of existing population, ecosystem, and economic models. In general, the planned studies add an ocean acidification component to an existing model and leverage substantial existing capability.

2.3.1 Ecosystem sensitivity to ocean acidification and valuation of indirect effects

Task 2.3.1: Develop models to predict how Alaska ecosystems will change in response to ocean acidification and alternative ocean management actions.

Future ocean pH levels, climate, and the combined direct and indirect ecological effects of ocean acidification and climate change, are uncertain. The AFSC has developed trophic (i.e., food-web) models of the Bering Sea and Gulf of Alaska ecosystems (e.g., Aydin *et al.*, 2007) that have been used with climate change scenarios to forecast how reduced calcareous prey (pteropods) abundance could affect the abundance of commercially important species (pink salmon) in the Gulf of Alaska. Pteropods can be important prey for pink salmon (Aydin *et al.*, 2005). These models predict substantial impacts of reduced production of pteropods on growth of pink salmon (Aydin *et al.*, 2005). An exploratory analysis using these models with climate change/ocean acidification scenarios can be conducted at relatively low cost and could yield important insights regarding model sensitivity and the range of ecosystem effects. In particular, this component of the project will examine how direct effects of changes in ocean pH and temperatures can be transmitted across trophic levels to create indirect effects in the ecosystem models. In addition, an economic model will be developed to evaluate impacts of these indirect effects.

2.3.2 Climate change/ocean acidification scenario development

Task 2.3.2: Develop regional biogeochemical models coupled to global carbon cycle models to predict local changes in carbon chemistry at multiple temporal scales.

A current study on climate scenario development for projections of atmospheric CO_2 levels and changes in ocean pH will be developed by NOAA scientists and collaborators. Future atmospheric CO_2 levels, which influence ocean pH and $CaCO_3$ saturation state, will depend on many factors, but anthropogenic emissions from the burning of fossil fuels are chief among these. A global energy-economic growth model (Dalton *et al.*, 2008) is being used to project CO_2 emissions from fossil fuels. An earth system model of intermediate complexity (Cao *et al.*, 2007; Feely *et al.*, 2009) will take fossil fuel emissions from the economic model as input, track baseline greenhouse gas emissions from other sources, and project atmospheric CO_2 levels and changes in ocean pH. Assumptions in the scenarios about future technological and demographic change will be based on updates of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions.

2.4 Human Dimensions (Theme 4)

Task 2.4: Estimate economic consequences for Alaska king crab fisheries due to ocean acidification.

A two-area bioeconomic model of Alaska's king crab fishery will be used to evaluate fishery performance in each of the climate change/ocean acidification scenarios. The structure of the proposed model will be based on previous work (Dalton, 2001; Dalton and Ralston, 2004). In addition, the proposed model will incorporate an explicit population growth function that will be calibrated to experimental results on king crab growth and survival with varying pH and water temperatures. A first version of the population model will quantify growth and survival information from early life history stages. As results from additional experiments become available, the population model will be extended to quantify effects of acidification on later stages of a crab's life. Decision rules for fishing effort which depend on expected abundance, climate, and prices will be estimated (and tested) using time series data from Alaska's fish tickets, observers, and information on vessel costs from the Bering Sea and Aleutian Islands Crab Economic Data Collection Program and the Alaska Department of Fish and Game. Simulations will test effects of ocean acidification and warming both singly and combined.

2.5 Synthesis of Data and Information Products (Theme 5)

Task 2.5: Synthesize, archive, and report results of ocean acidification research in products usable for fisheries management.

Information from ocean acidification research will be synthesized into products usable for fishery management, archived in standard formats for scientific exchange, and reported in the scientific literature. The population, ecosystem, and economic models will be used to forecast the abundance of species impacted by ocean acidification. These forecasts will synthesize results of the species-specific physiological studies, state-of-the-art models, and climate scenarios and will be reported to the North Pacific Fishery Management Council. Marine resource managers will be able to use these forecasts to develop mitigation strategies for the effects of ocean acidification on regulated and protected species.

Data from ocean monitoring will be archived in standard hydrography databases at PMEL and will be sent to national and international ocean acidification databases, including the Alaska Ocean Observing System. Results of the ocean monitoring, species-specific physiological studies, and forecasting will be reported in the scientific literature.

2.6 Engagement Strategy (Theme 6)

Task 2.6: Implement an education and outreach program to communicate the science, economic, and ecosystem consequences of ocean acidification to the public and stakeholder communities.

NOAA will coordinate with existing resources already present in the region, such as Alaska Sea Grant, NMFS Alaska Regional Office, and the Alaska SeaLife Center, to communicate the causes and potential effects of ocean acidification on the Alaska coast and ecosystems to fishermen, boat operators, tour guides, the seafood industry, the general public, and K–16 educators. This effort will include producing and distributing a variety of education and outreach tools, including summary literature, news releases, and interactive displays at aquaria. Through these partnerships, NOAA can play an integral role in developing an increased awareness of the causes and potential effects of ocean acidification in Alaska marine ecosystems.

Public workshops held to communicate the status of ocean acidification knowledge, to provide information on the effects of ocean acidification on Alaska marine resources, and to create a dialogue between NOAA scientists and the public will be required as a part of this effort. This is especially true for those that may be impacted by a changing ocean, i.e., the fishing industry, coastal resource managers, and Alaska residents that depend on subsistence fishing.

2.7 Collaborators

Alaska Region Collaborators

Pacific Marine Environmental Laboratory
Alaska Fisheries Science Center
Kasitsna Bay Laboratory
Kachemak Bay NERR
Arctic Research Program
University of Alaska
Alaska Sea Grant
Alaska Department of Fish and Game
Alaska Ocean Observing System
Alaska SeaLife Center

3. West Coast Region Ocean Acidification Research Plan

Paul McElhany, Simone R. Alin, D. Shallin Busch, Robert Pavia, Kelley Higgason, Steve Katz, Jonathan Phinney, Adrienne J. Sutton, Richard A. Feely, John Stein, Mary Sue Brancato, Ed Bowlby, Jan Roletto, and Lisa Etherington

3.0 Ocean Acidification in the West Coast Region

3.0.1 Carbon Chemistry Patterns

The deep waters of the Northeast Pacific Ocean are considered the "oldest" water in the ocean conveyor belt and carry the cumulative signature of respiration processes that have taken place about 1,000 years ago when the water mass was last exposed to the atmosphere. The upwelled waters along the coast are thus naturally rich in carbon dioxide (CO_2) and nutrients, lower in oxygen (O_2) and lower in pH than the waters they replace. This natural high-CO_2 condition is exacerbated by the uptake of anthropogenic CO_2 at the surface. Upwelled waters also characteristically have lower saturation states for the major carbonate minerals, aragonite (Ω_{arag}) and calcite (Ω_{cal}), than surface waters. Species with calcareous shells, tests, or skeletons may have more difficulty biomineralizing or maintaining their shells in the low pH surface water anticipated for the West Coast under changing climate conditions, even if Ω remains above one (Guinotte and Fabry, 2008; Fabry *et al.*, 2008).

Because of the aged composition of upwelled waters, ecosystems in the northeastern Pacific Ocean are particularly vulnerable to ocean acidification impacts. The aragonite saturation horizon in the northeastern Pacific is within a few hundred meters of the ocean surface and naturally shallower than in most other parts of the global ocean (Feely *et al.*, 2004). Mixing of anthropogenic CO_2 absorbed from the atmosphere into the upper ocean of the northeastern Pacific over the last few hundred years has shoaled the depth of aragonite and calcite saturation horizons by 30–100 m since the preindustrial era and saturation horizons are continuing to shoal at a rate of 1–2 m yr^{-1} (Feely *et al.*, 2004). Thus, less anthropogenic CO_2 is required to reduce aragonite and calcite saturation to levels that may be stressful or lethal for marine organisms in the Northeast Pacific than elsewhere in the world ocean.

Extrapolations from open ocean conditions in marine carbon cycle models suggest that undersaturated waters will shoal to depths that affect the West Coast ecosystems that are home to rich fisheries, deep-sea corals, and diverse communities over the next several decades to a century (e.g., Feely *et al.*, 2004; Orr *et al.*, 2005; Feely *et al.*, 2009). However, recent observations during a late spring–early summer cruise demonstrated that the upwelling waters already had pH values less than 7.70 and aragonite saturation index values less than 1, presumably as a result of the combined effects of respiration and the added contribution of anthropogenic CO_2 (Figure 3.1).

Within the California Current System (CCS), there is strong regional variability in the intensity and duration of upwelling, as well as in the dominance of upwelling in controlling biogeochemical cycling, ecosystem susceptibility to ocean acidification, and the related problem of hypoxia in the coastal ocean. Of critical importance to ecosystems is the spatial and temporal scales of upwelling. The strong gradients in water conditions that are observed across the shelf or along the CCS are punctuated by intense localized upwelling that may be as focused as a hundred meters or as diffuse as hundreds of kilometers, and are ephemeral with time occurring over days to months (Graham, 1994; Marchesiello and Estrade, 2009). The granular scales, in both space and time, of the hydraulic events that bring corrosive water to

West Coast Region Description

Image: Summer climatology of chlorophyll from SeaWiFs (NASA)

The West Coast Region covers the marine waters off of the coasts of California, Oregon and Washington and, to a lesser extent, adjacent areas of Baja and British Columbia. Our focus is primarily on the continental shelf and inland seas and encompasses the California Current System (CCS). Ecological dynamics and biogeochemistry in CCS are strongly influenced by natural climactic cycles, such as the El Niño-Southern Oscillation and Pacific Decadal Oscillation, and the seasonal development of upwelling conditions during spring and summer months. As North Pacific atmospheric highs and lows shift at the end of the winter storm season, equatorward winds develop along the coast and push surface waters away from the coastline through Ekman transport (e.g., Hickey and Banas, 2003; Hill *et al.*, 1998; Pennington and Chavez, 2000). Deeper water masses replace these displaced surface waters in the process of upwelling. Upwelling brings cold, nutrient rich water to the surface, supporting high primary productivity and the diverse marine life dependent on that food source. The CCS supports important commercial and recreational fisheries, including salmon, pelagic fish, groundfish, and invertebrates including shellfish.

shallow depths are the scales at which their impacts on ecosystems will be observed first. This granularity also sets important demands on the monitoring system necessary to assess both the progress of ocean acidification and the consequences of acidification to ecosystems and commerce. In addition, there are strong gradients in rainfall, continental shelf width, and riverine inputs of nutrients and freshwater from north to south along the CCS coastline, each of which also plays a role in determining the effects of ocean acidification and hypoxia. For instance, the influx of freshwater, nutrients, and excess carbon dioxide from river inputs can have profound effects on circulation (Hickey, 1998), primary production (Lohrenz *et al.*, 1990), and aragonite saturation state (Salisbury *et al.*, 2008) in coastal waters.

The Northeast Pacific along the West Coast shows strong spatial and temporal variability in primary production, CO_2 and O_2 concentrations, and, we expect, also in aragonite saturation. However, historical carbon measurements along the West Coast have been infrequent and localized, with the exception of the 2007 North American Carbon Program West Coast Cruise (Feely *et al.*, 2008). In order to improve our ability to forecast and monitor the development of corrosive conditions and to predict their biological impacts, it is necessary to improve our observations and to conduct studies and develop models aimed at understanding the impact of ocean acidification and its relationship with hypoxia on ecosystems along the West Coast. Improved understanding of these processes through research will help the public and natural resource managers adapt and, in very localized instances, possibly mitigate impacts.

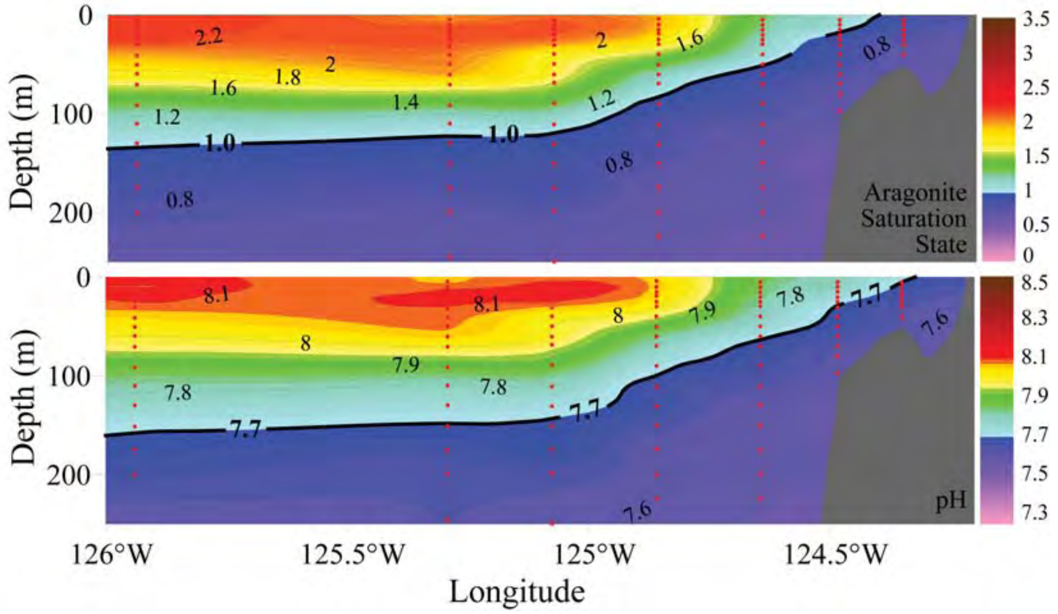


Figure 3.1: Cross-sections of aragonite saturation state (Ω_{arag}) and pH from the West Coast Cruise transect off of northern California measured in May–June 2007. These cross-sections clearly show the upwelling of water masses undersaturated with respect to aragonite ($\Omega_{arag} < 1.0$) and with low pH values (Feely *et al.*, 2008).

3.0.2 Vulnerable species and ecosystems

The coastal marine ecosystem on the West Coast experiences some of the oldest and most corrosive upwelled water in the world. While this may suggest that these species and ecosystem are already adapted to periodic low pH environments, the magnitude of pH change expected from the addition of anthropogenic CO_2 will create corrosive environmental conditions at spatial and temporal extents that have not been observed for millions of years. The number of studies exploring the biological impact of acidification is increasing rapidly (Figure 1.2). The growing literature on OA is greatly expanding our appreciation of how acidification could alter West Coast marine ecosystems. We have already conducted a comprehensive literature review to explore which West Coast species are most vulnerable to the impacts of ocean acidification (Table 1.1). Many economically and ecologically important West Coast species are expected to show direct response to ocean acidification. These species include bivalves (e.g., oysters, mussels, geoduck), which are both economically valuable and serve an ecological role in altering substrate conditions for other species. Many crustaceans are also directly vulnerable and include species directly harvested (e.g., crab, shrimp) and crucial components of the marine food web (e.g., krill, copepods). Echninoderms (e.g., sea stars and urchins) are top predators or grazers in some benthic systems and are expected to be negatively impacted by OA because they are composed of a more soluble form of calcium carbonate (high-magnesium [Mg] calcite). Some echinoderms (e.g., urchins and sea cucumbers) are also directly harvested. Crustose algae are also composed of high-Mg calcite and are an important component of rock substrates ecosystems. Phototrophic organisms (e.g., phytoplankton, eelgrass, kelp) with obvious importance to West Coast ecosystems have shown mixed response in lab experiments to changes in CO_2 (Table 1.1). Introduced species (e.g., green crab) have already altered West Coast ecosystems and may respond differently to OA from native species which have evolved with West Coast upwelling patterns. This is not an exhaustive description of the direct and indirect effects of OA expected on West Coast ecosystems. We anticipate refining our vulnerability predictions as we implement the species response experiments in this plan (Theme 2) and develop a large enough sample of tested species to identify patterns of attributes correlating with acidification response, and as we develop predictive ecosystem models (Theme 3).

3.0.3 Immediate risk in shellfish

For four of the last five years, there has been a near-total failure of developing oysters in both aquaculture facilities and natural ecosystems on the West Coast. The developing oyster failure appears correlated with naturally occurring upwelling events that bring low pH waters undersaturated in aragonite as well as other water quality changes to nearshore environments. Lower pH values occur naturally on the West Coast during upwelling events, but a recent study indicates that anthropogenic CO_2 is contributing to seasonal undersaturation (Feely *et al.*, 2008). Low pH may be a factor in the current oyster reproductive failure; however, more research is needed to disentangle potential acidification effects from other risk factors, such as episodic freshwater inflow, pathogen increases (Elston *et al.*, 2008) or low dissolved oxygen (Brewer and Peltzer, 2009). It is premature to conclude that acidification is responsible for the recent oyster failures, but acidification is a potential factor in the current crisis to this $100 million a year industry, prompting accelerated research on ocean acidification and potential biological impacts.

3.1 Monitoring Ocean Acidification (Theme 1)

To document the development of ocean acidification along the West Coast, it is critical to implement a comprehensive program to monitor changes in ocean carbon chemistry, vulnerable species distribution and abundance, and ecosystem status. This section describes current and proposed monitoring for ocean acidification. There is no historical monitoring older than a few years dedicated explicitly to the issue of ocean acidification (though monitoring for carbon parameters has taken place in a limited area of the Southern California Bight since the 1980s). The monitoring program described in this plan is intended both to serve as a means to observe long-term patterns and to act as an ocean acidification "early warning system" that will provide near real-time, local information about imminent threats, especially to the oyster aquaculture facilities, from low pH conditions.

3.1.1 Oceanographic monitoring

Task 3.1.1: Develop and implement a program for monitoring carbon-cycle-related oceanographic parameters on the West Coast.

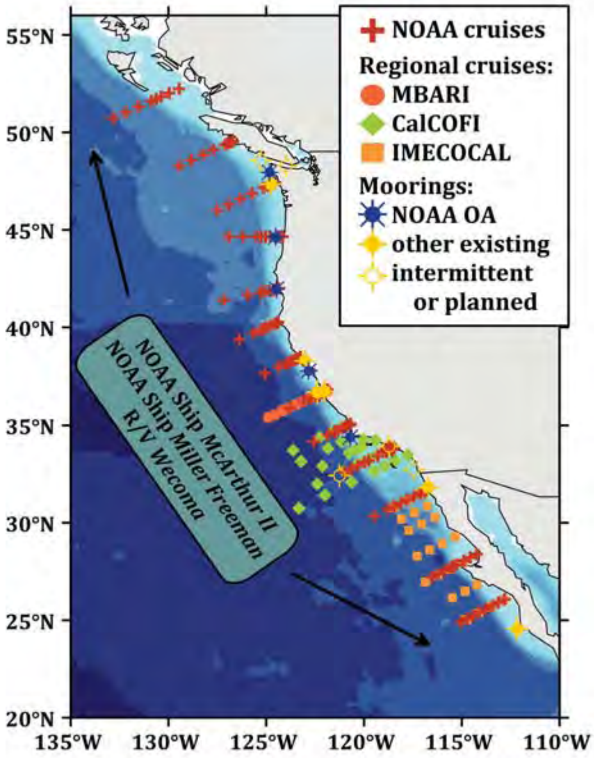


Figure 3.2: Planned West Coast regional OA observational network.

In order to meaningfully monitor ocean acidification and its ecosystem impacts in the CCS, it will be necessary to deploy and maintain an observational network that can accurately convey data in near real time on oceanographic conditions from sub-regions along the West Coast with differing biogeochemical and ecological processes. To meet this challenge, NOAA scientists and other regional researchers working on coastal carbon and ocean acidification have designed an observational network for the West Coast (Figure 3.2, Tables 1.2 and 1.3). The network will consist of a combination of pre-existing and new moored and underway sensor platforms, strategically placed for maximum integration, as well as regional and larger-scale hydrographic and carbon chemistry cruises to place the automated platform observations into a broader regional and process-based context.

3.1.1.1 Open ocean and coastal observatory

Moored observational systems with sensor packages at discrete depths and deployed in key locations will provide higher temporal resolution observations and will serve as the core platform of an early warning ocean acidification system. The Northeast Pacific open ocean OA network includes moorings near the northern and southern ends of the CCS at 50°N, 145°E and 33°N, 122°E, respectively (Figure 3.2, Table 1.2). The coastal OA observatory in the CCS will consist of a network of five moorings deployed near La Push, Washington; Newport, Oregon; Trinidad Head, California; the mouth of San Francisco Bay, California; and Pt. Conception, California (Figure 3.2, see Table 1.3 in Chapter 1). These coastal moorings should capture the major modes of variability in biogeochemical controls among the sub-regions within the CCS that are most susceptible to OA impacts in the near-term as a result of upwelling and river inputs. Two of the new moorings will be placed in the context of finer-scaled moored sensor arrays for oxygen and temperature within the National Marine Sanctuaries.

Ship-based observations can provide good spatial coverage along the full West Coast, as well as larger-scale oceanographic context, and will include both dedicated research cruises, during which a full suite of hydrographic and chemical parameters will be measured on depth profiles, and surface observations off of research and volunteer observing ships (e.g., ferries or other commercial vessels) using underway sensor packages. The CLIVAR/CO_2 Repeat Hydrography open-ocean cruises provide contextual information on Pacific basin-scale changes in circulation and biogeochemical processes relevant to coastal acidification. PMEL also has underway systems equipped to measure $p\mathrm{CO}_2$, salinity, and temperature on the NOAA ship *Ka'imimoana* and a commercial vessel (M/V *Albert Rickmers*) that routinely collect CO_2 data in the equatorial Pacific, as well as a commercial vessel (M/V *OOCL Tianjin*) that traverses the North Pacific twice each month, as part of the "Surface water $p\mathrm{CO}_2$ measurements from ships" program funded by the NOAA Climate Observation Division. These trans-Pacific ships all spend time in West Coast waters each year, and those that do not already measure two carbon parameters can be upgraded with new pH sensor technology at minimal additional expense to the OA program to allow the most accurate and precise assessment of OA conditions available for underway systems at this time. PMEL also has two dedicated coastal underway CO_2 systems on NOAA ships with excellent West Coast coverage, the *McArthur II* and the *Miller Freeman*, and will develop plans for the *Bell M. Shimada*, which will be operational in FY2010. These underway systems will be augmented with new pH and O_2 sensors to monitor the outcropping of corrosive and hypoxic water masses in upwelling regions along the West Coast. The *McArthur II* and the *Miller Freeman* support a wide variety of NOAA Fisheries research cruises along the West Coast, and collaborations are being forged to pair chemical measurements with the fisheries and ecosystem-based assessments typically conducted on these cruises. PMEL investigators are developing collaborations with NMFS, NMS, and academic partners to integrate carbon chemistry measurements into regular observation programs that monitor oxygen, as well as biological and physical conditions reflecting the health of fisheries and sanctuaries resources.

The map in Figure 3.2 shows the full West Coast network that is envisioned by the NOAA community and partners at academic institutions and other state and federal agencies. Moored observational systems with sensor packages at discrete depths and deployed in key locations will provide higher temporal resolution observations and will serve as the core platform of an early warning ocean acidification network. Both moored and underway platforms can support existing sensors for measuring $p\mathrm{CO}_2$, pH, salinity, temperature, and O_2, as well as a host of ancillary sensors that can be valuable for resolving the biological and physical processes contributing to the development of corrosive or hypoxic conditions. In addition to the biogeochemical monitoring, it is critical to include measurements to understand ocean circulation patterns (e.g., currents to understand advection, winds to understand upwelling and mixing). Inadequacy in capturing circulation patterns is a primary source of error in ocean carbon models, and monitoring the dynamics of ocean currents is critical for understanding the controls on the biogeochemistry. Observations from moored and underway systems can be telemetered back to NOAA laboratories in near real time, so they can undergo preliminary analysis and be distributed to stakeholders in a timely fashion. Finally, gliders could be utilized to provide depth-resolved transects of parameters related to the development of corrosive conditions in coastal ecosystems. High-frequency, cross-shelf glider transects can provide insight into key physical and biogeochemical processes influencing the development of corrosive conditions with greater spatial resolution than stationary moorings. NOAA scientists are currently working together across divisions and line offices and with our academic collaborators to design and implement coupled carbon chemistry and biological monitoring strategies for floats and gliders.

3.1.1.2 OA observatory for inland marine waters and bays

Although the West Coast does not have as many large rivers draining it as the East and Gulf coasts, a few large river-estuary systems on the West Coast may be particularly important in terms of their potential role in the development of corrosive conditions in coastal environments (cf. Emmett *et al.*, 2000; Dame *et al.*, 2000). Efforts to implement OA-capable moorings, underway systems, and sampling surveys in these water bodies are at various stages of development. A number of CO_2 moorings are either planned or deployed that can be upgraded to be OA-capable by adding a second carbon parameter (Figure 3.2). Puget Sound, the Columbia River estuary and plume (the largest river system emptying into the Pacific from the Americas), and San Francisco Bay are the most likely river-estuary systems along the U.S. West to experience enhanced ocean acidification as a result of anthropogenic inputs to the coastal ocean. All three already have significant anthropogenic impacts within their watersheds, including issues associated with invasive species, pollutants, and significantly altered freshwater, acid deposition, nutrient run-off, and sediment budgets because of the 4–8 million people living in each system. In 2008, PMEL collaborated with scientists from the University of Washington and the Washington Department of Ecology to conduct the first extensive high-quality carbon surveys in Puget Sound and found evidence suggesting that OA and other anthropogenic stressors are having synergistic negative impacts on this rich ecosystem.

In California, San Francisco (SF) Bay is a productive estuary that provides nursery habitat for economically important Dungeness crab, Pacific halibut, and Pacific salmon populations. The United States Geological Survey (USGS) has been monitoring water quality along a 145-mile transect in San Francisco Bay for the past four decades (Table 3.1). Measurements of inorganic carbon parameters to assess OA impacts on the SF Bay estuary should be added to the USGS surveys.

To the south of SF Bay, Monterey Bay is perhaps the only place on the West Coast where two carbon parameters have been sampled regularly since 1993, and this time series supports the hypothesis that acidification is occurring along the West Coast. This ongoing time series shows an increase in $p\mathrm{CO}_2$ and decrease in pH that are both greater than the changes seen at open ocean time-series sites and clearly discernible over the signature of interannual variability (Chavez *et al.*, 2002; 2007; Borges *et al.*, 2010) (Figure 3.2, Table 3.1). Investigations throughout central and southern California since the 1940s (CalCOFI) have collected physical, chemical, and biological oceanographic data at roughly seasonal resolution (Table 3.1), and carbon sampling on CalCOFI cruises will be expanded to include OA measurements through a collaboration between Scripps Institute of Oceanography and PMEL.

3.1.1.3 International coordination and collaboration

In addition to working with domestic partners, especially NOAA, state agencies, and academic institutions, NOAA scientists are coordinating international efforts with Canadian and Mexican scientists along the entire western continental shelf of North America. For instance, scientists from all three countries will be participating in ocean acidification cruises led by Canadian and U.S. PIs in FY2010 and 2011, respectively. Both neighboring countries have long-term hydrography and chemical oceanography observation programs that sample at least in part in coastal CCS waters such as IMECOCAL (Investigaciones Mexicanas de la Corriente de California) in Mexico and the Line-P Time-Series Program in Canada (Table 3.1). Carbon chemistry measurements of the highest quality have already been integrated into both sampling programs, which will facilitate the robust comparison of conditions, processes, and ecological impacts throughout the CCS without regard to international borders.

3.1.1.4 Center for ocean carbon chemistry

Task 3.1.2: Establish a Pacific Center of Expertise for ocean carbon chemistry at PMEL.

The oceanic inorganic carbon system has four measurable parameters: pH, dissolved inorganic carbon (DIC), total alkalinity (TA), and the partial pressure of CO_2 ($p\mathrm{CO}_2$). Because the rate of pH change related to ocean acidification is so slow (~0.002 y^{-1}), it is not possible to measure pH with sufficient accuracy and precision using widely available potentiometric pH sensors (generally ±0.01 accuracy and precision), which are also notoriously drift-prone. Rather, it is preferable to measure DIC and TA, for which the most robust methods are currently available. Both the DIC and TA methods used in PMEL's marine carbon laboratories are among the community standard analyt-

Table 3.1: Sampling programs within the California Current System that have historically collected physical, chemical, and biological oceanography data of relevance for hindcasting the development of ocean acidification along the West Coast. Abbreviations: T = temperature, S = salinity, O = oxygen, P = pressure, chl = chlorophyll, pheo = pheophytin.

Program	Location	Years of sampling	Parameters measured
Fisheries and Oceans Canada Line-P Time-Series	From Vancouver Island to Station Papa	1956–present	T, S, P, O (later years), nutrients
Race Rocks Lighthouse	Strait of Juan de Fuca, Vancouver Island	1921–present	T, S
Washington Department of Ecology Marine Water Column Ambient Monitoring Program	Washington coast, Puget Sound	1967–present	T, S, O, nutrients, chl, pheo, bacteria, Secchi
Puget Sound Regional Synthesis Model (PRISM)	Puget Sound, Strait of Juan de Fuca (WA)	1998–present	T, S, O
Newport Hydrographic Line (NH1)	Newport, Oregon, cross-shelf transect	1950–present	T, S, O, plankton tows, chl, nutrients
United States Geological Survey Water Quality Program	San Francisco Bay (CA)	1969–present	T, S, O, chl, nutrients, light, suspended solids
Monterey Bay Aquarium Research Institute (MBARI)	Monterey Bay (CA), cross-shelf transect	1993–present	T, S, O, $p\mathrm{CO}_2$, pH
California Cooperative Oceanic Fisheries Investigation (CalCOFI)	Central to southern California coastline	1949–present	T, S, P, O, chl, pheo, nutrients
Investigaciones Mexicanas de la Corriente de California (IMECOCAL)	Baja California coastline	1997–present	T, S, O, chl, primary production (^{14}C), zooplankton, DIC and TA (starting in 2006)
Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO)	Washington, Oregon, and California nearshore coasts	1999–present	T, S, O, ecological parameters (including recruitment and biodiversity)

ical methods for ocean carbon measurements (Dickson *et al.*, 2007).

The PMEL Carbon Program will develop a facility to serve as a NOAA Pacific “Center of Expertise” (CoE) for analyzing ocean carbon chemistry samples. This facility will serve mainly as a quality control and training center but will also be used to analyze samples collected by PMEL and other regional laboratories in support of the national OA program. West Coast regional labs (e.g., NMFS Science Centers) that require high-volume carbon chemistry analysis for experiments or field monitoring will develop in-house or partnership capabilities using the CoE carbon lab as a technical and quality control resource. Such a CoE is necessary because of the significant technical challenges in adequately measuring ocean carbon chemistry.

3.1.2 Biological monitoring

Task 3.1.3: Develop and implement a program for biological monitoring to detect ecosystem changes caused by acidification and changes in biology that affect the carbon cycle on the West Coast.

The purpose of an ocean acidification biological monitoring program is to detect changes in ecosystem processes from acidification at an early stage. To some extent, existing monitoring programs, such as the hydrographic, plankton, and krill surveys off Newport, Oregon (Hooff and Peterson, 2006), Trinidad Head, Bodega Bay, Monterey Bay, and the Southern CA Bight, provide information on general patterns in ecological communities that will help detect responses to acidification. However, these surveys were designed for other reasons and we have to improve our abilities to detect ecosystem response by targeting the monitoring on species most likely to be affected by acidification. Species likely to respond include both those vulnerable to direct effects (Table 1.1) and those vulnerable via indirect effects (e.g., trophic cascades).

Biological monitoring will be used to address two distinct questions: (1) Is acidification affecting species of commercial, social, and ecological importance? (2) Are there biological changes that affect marine carbon cycling and hence the rate of acidification? The first question involves detecting response to acidification. The second question involves changes to the "biological pump" driving marine carbon cycling. Prioritizing species and ecosystems to monitor for biological impacts of acidification will be based on species vulnerability and ecosystem services value (Table 1.1). Initial acidification monitoring projects will likely include a focus on benthic community structure and on zooplankton dynamics. Sedentary calcareous organisms in the benthos are expected to be one of the first to respond to acidification because calcareous organisms are a significant part of the benthic community and deeper benthic environments generally experience higher levels of CO_2. Autonomous Reef Monitoring Structures (ARMS) can be used to systematically monitor changes in benthic communities and can be coupled with broader survey methods to provide a comprehensive view of how benthic communities respond to acidification. Zooplankton are also a high priority for initial acidification monitoring because many zooplankton species appear vulnerable to acidification, and zooplankton are an important component of the marine food web for commercially important and endangered species.

Changes in species composition and activity, brought on by ocean acidification or other factors (e.g., climate change) can alter the cycling of carbon in the ocean, which can in turn affect the rate and location of acidification (Feely *et al.*, 2009). Previous studies have suggested that carbon cycling depends primarily on the activity of phytoplankton, protists, zooplankton, microbes, and other small invertebrates, especially calcareous species like coccolithophores, foraminfera, and pteropods (Fabry *et al.*, 2008). However, a recent study suggests that fish may play an important role in carbon cycling as well (Wilson *et al.*, 2009), such that an activity like fishing has the potential for direct impacts on ocean chemistry. A comprehensive biological monitoring system for ocean acidification will require the ability to detect significant changes in major biological components of the ocean carbon cycle. Information on changes to the biological pump will be used to recalibrate biogeochemical models that forecast acidification. Monitoring the functioning of the biological pump will require careful coordination between biological and oceanographic monitoring to track processes, such as the sinking of organic particles, that are affected by both biological and non-biological processes. Because of the challenges in monitoring microbial communities and plankton, a metagenomic approach will likely need to be developed (Woyke *et al.*, 2009).

Over the next year (FY2010), the NW and SW Fisheries Science Centers will develop a comprehensive ocean acidification biological monitoring plan for the West Coast. Plan development will involve a review of existing monitoring programs, such as the monthly (Newport, OR, Trinidad Head, CA, Bodega Bay, CA) as well as the quarterly ship survey lines (Monterey Bay and CalCOFI), to explore whether modifications will allow for better tracking of both acidification impacts and biological pump processes. It is also likely that new monitoring approaches, such as for benthic community changes, deep-sea coral AUV surveys, and microbial metagenomics will be proposed. Another consideration in developing this monitoring plan will be coordinating biological and carbon chemistry sampling for more robust correlations between acidification and biological change. During development of the monitoring plan, we will address the management of data and coordination with regional implementations of the Integrated Ocean Observing System Regional Associations (NanOOS, CenCOOS, SCCOOS) and NOAA's ecological observing program PaCOOS (see section 3.5 for more details).

Task 3.1.4: Establish an immediate monitoring program focused on bivalve recruitment patterns.

Because of the recent failures in oyster recruitment on the West Coast, we propose rapid implementation of a program to monitor bivalve recruitment patterns. The current recruitment failure, primarily observed in aquaculture, may be an early indicator of the effects of acidification. A comprehensive monitoring program for wild bivalve populations of multiple species will allow tracking of potential trends and spatial patterns. Monitoring will be coordinated with projects at the Oregon State University, University of Washington (Newton *et al.*, 2009), and with the shellfish industry. Details on oyster and other commercially targeted shellfish monitoring will be included in the NMFS West Coast OA monitoring plan.

3.1.3 Intensively studied marine areas

3.1.3.1 NOAA's National Marine Sanctuaries (NMS) program

The mission of NOAA's National Marine Sanctuaries (NMS) program is to serve as the trustee for the nation's system of marine protected areas, to conserve, protect, and enhance their biodiversity, ecological integrity and cultural legacy. Consequently, The NMSP has a mandate and responsibility to protect and conserve the extraordinary marine resources in the marine protected areas that are harbored within the Sanctuaries. While global CO_2 emissions reduction is one of the most pressing needs with respect to protecting the ocean, addressing and preparing for ocean acidification will require an array of additional efforts, including research, monitoring, public education, and development of resource management strategies in the context of a rapidly changing physical oceanographic context.

Task 3.1.5: Establish Intensively Studied Marine Areas for monitoring ocean acidification.

Marine protected areas in the California Current, including five National Marine Sanctuaries, are key sites for establishing Intensively Studied Marine Areas for monitoring to detect and track the impacts of climate change and ocean acidification on marine ecosystems. The Intensively Studied Marine Area (ISMA) approach is based on the need to understand complex oceanographic processes that are likely to deliver acidic, corrosive water to coastal communities; broad-scale monitoring is insufficiently detailed to illuminate complex local process, and detailed process monitoring is too expensive to deploy everywhere. Thus, ISMAs capture the need for an ocean research field study where the local and regional dynamics of the ocean system can be examined in greater detail than is possible with generic monitoring. The ISMA aims to (1) determine the local impacts of processes such as acidification and (2) generate the understanding needed to extrapolate results from large-scale or regional monitoring to forecasts for local areas not within a IMSA-site monitoring program.

ISMAs are key components of any system aimed at monitoring temporal change in environmental conditions and of any large-scale monitoring plan, and may serve as test beds for an ocean acidification early warning system. If possible, the footprint of an ISMA should match scales of the process of concern—acidified waters shoaling and impacting coastal communities. National Marine Sanctuaries encompass representative ecosystems at appropriate spatial scales and have the required administrative stability in the Office of National Marine Sanctuaries (ONMS) to make effective ISMAs for both oceanographic and biological monitoring. Channel Islands, Monterey Bay, Gulf of the Farallones, Cordell Bank, and Olympic Coast National Sanctuaries encompass over 31,000 km^2 of ocean habitat extending from intertidal habitats to deep canyons (Figure 3.3, Table 3.2). Each of the sanctuaries provides conditions suitable for examining ecosystem effects of ocean acidification. Table 3.2 highlights important species, habitats, or ecological settings that are already the focus of research efforts within NOAA's sanctuaries.

The West Coast National Marine Sanctuaries have an ocean observing backbone that can support additional ocean acidification measurements. Some of these measurements, such as those for Harmful Algal Blooms (HABs) in the Olympic Coast and Gulf of the Farallones sanctuaries, have a direct bearing on understanding ocean acidification's biological impacts. Others, such as long-term temperature measurements, provide background for understanding ecological trends. Establishing or augmenting the ocean acidification observation and monitoring capacity in sanctuaries will gain added benefit from a wide range of ecosystem research already being conducted by partner institutions. NMFS Fisheries Science Centers will collaborate with West Coast NMS in FY2010 on development of the West Coast ocean acidification biological monitoring plan.

Organisms of Near-Term Focus

Zooplankton (krill, copepods, pteropod)
Bivalves (geoduck, oysters)
Deep-sea Coral
Dungeness Crab
Echinoderms (sea stars, urchins)
Fish (Pacific sardine, rockfish)

Table 3.2: Features of marine sanctuaries on the West Coast.

Name	Area (km^2)	Key Species	Key habitats
Olympic Coast	8,573	Salmon, Orca Whales, murres, tufted puffins	Kelp forest, deep water coral, rocky intertidal
Cordell Bank	1,370	Rockfish, krill, Dungeness crabs, hydrocorals, blue and humpback whales, auklets, albatross	Offshore rocky bank, continental shelf and slope, upwelling plume
Gulf of the Farallones	3,250	Blue Whale, Cassin's Auklets, Common Murres, Brandt's Cormorants	Estuaries, rocky intertidal, neritic zone and shelf break
Monterey Bay and Davidson Seamount	15,791	Sea otters, orca whales	Sea mount, kelp forest, rocky intertidal, Monterey canyon, estuary
Channel Islands	4,294	Blue, Humpback whales, seals, sea lions, storm petrels, Xantus' Murrelets, Cassin's Auklets, brown pelicans, urchins, lobster, abalone (red, white, black), and other calcifying invertebrates	Kelp forest, rocky reefs, deep canyons and basins, rocky islands

3.1.3.2 National Estuarine Research Reserve System (NERRS)

Through agreements between NOAA and coastal states, NERRS sites protect select estuary areas for long-term research, water-quality monitoring, education, and coastal stewardship. This research focus makes the five West Coast NERRS sites (Tijuana, San Francisco Bay, Elkhorn, South Slough, and Padilla) appropriate candidates for ISMAs targeting OA in estuarine habitats. These habitats are greatly influenced by terrestrial activities and interactions between OA and terrestrial inputs, and biological processes are likely to be complex in these environments that are often presumed to naturally experience great variability in carbon chemistry. The NERRS sites are positioned to provide unique insights into these environments. They have a history of long-term monitoring and have substantial infrastructure in the form of platforms, sampling capabilities, and IOOS connections. With improved carbon monitoring capabilities and other directed research, NERRS sites, which are protected areas, can enhance our understanding of how OA might impact these dynamic ecosystems.

3.2 Organism Response to Ocean Acidification (Theme 2)

3.2.1 *Exposure experiments*

To predict how ecosystems will respond to ocean acidification, there is a critical need to know how individual species and species assemblages will respond under controlled conditions. Results from controlled experiments provide three basic types of information: (1) direct predictions about species of interest (e.g., oysters, Miller *et al.*, 2009), (2) data to refine models of the ocean carbon cycle (e.g., microbial respiration rates in high CO_2 environment, Doney *et al.*, 2009a), and (3) key growth and survival parameters for food-web/ecosystem models that predict indirect effects of acidification.

Task 3.2.1: Create a state-of-the-art NOAA facility on the West Coast for conducting ocean acidification experiments on individual species and species assemblages.

To evaluate how species in West Coast ecosystems will respond to acidification, the NWFSC will build a state-of-the-art facility for conducting species response experiments. This facility will be set up as a shared-use center, where scientists from across NOAA

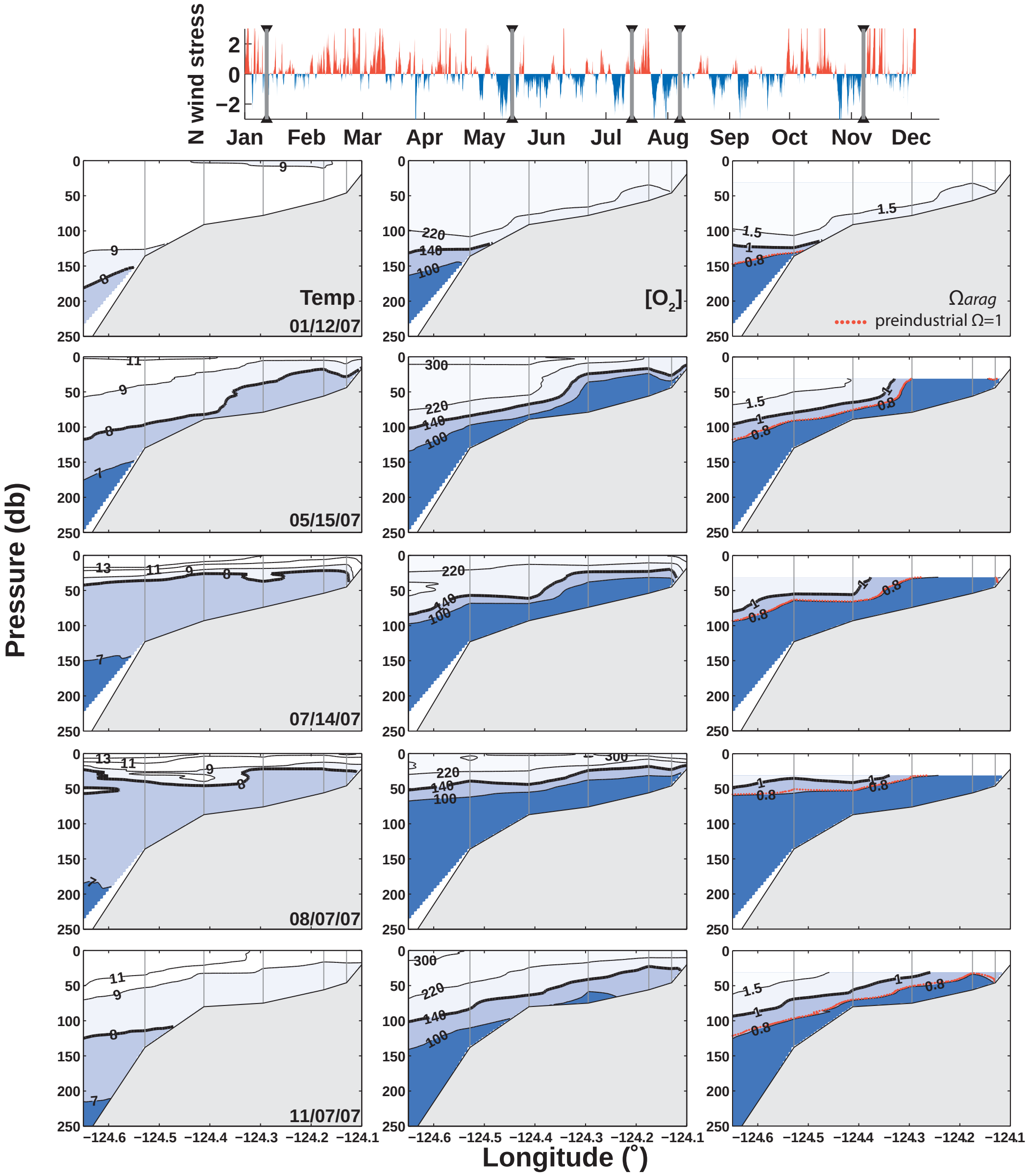


Figure 3.3: Upwelling indicated by wind stress (top), compared with ocean variables (bottom). (Bottom) Seasonal changes in the temperature, oxygen concentration, and corrosiveness ($\Omega_{arag} < 1.0$; dark blue colors) of "ocean acidified" coastal waters off Newport, Oregon, in 2007 (Juranek *et al.*, 2009). Pressure (in decibars, db) is roughly equivalent to depth in meters. (Top) Northward wind stress (dynes cm^{-2}) from NDBC buoy 46050 (with upwelling-favorable winds denoted in blue and downwelling-favorable winds denoted in red).

can perform experiments. The NWFSC facility will be located in the Seattle area, and the first stage is scheduled to be completed in 2010 as part of the NMFS FY2010 OA Plan. The NWFSC has already developed a pilot ocean acidification treatment system, which was used for preliminary experiments on geoducks and krill. Knowledge gained in the development of the pilot system is being applied to the creation of the larger facility. During development of the pilot system, NOAA researchers established collaborations with scientists from the University of Washington, where there is strong support for the shared-use facility.

To simulate more realistic conditions than is possible with many acidification treatment systems, the NWFSC-based facility will allow researchers to mimic natural patterns of variation, such as rapidly changing tidal patterns, and vary a number of environmental parameters, including CO_2, pH, O_2, and temperature. Much of the biological action on the West Coast takes place in coastal and nearshore environments where fluctuations in key environmental parameters, such as pH, are large, so that simply exploring species' behavioral or physiological response to changes in average CO_2 may miss how the species will actually respond to future conditions. The NWFSC system will also be capable of conducting large-scale multi-factorial experiments on multiple species simultaneously with statistically defensible replication. As noted in the introduction, options for mitigating acidification in the field are extremely limited, so management response will to a great extent rely on reducing other, potentially more controllable stressors, such as low oxygen levels from nutrient loading. Multi-factorial experiments that include these other stressors are required, which necessitates a facility capable of simultaneously maintaining a large number of different environmental conditions. Analytical chemistry needs for the NWFSC facility will be met by a combination of on-site capabilities and collaboration with the PMEL Carbon group.

Task 3.2.2: Support development of collaborative facilities for acidification response experiments.

A number of research institutions on the West Coast have developed or are developing facilities for conducting experiments on species response to acidification. For example, a consortium of researchers from academic institutions has developed plans for a research facility at Scripps Institution of Oceanography (SIO). Other facilities include a shared-use center being developed by the University of Washington at Friday Harbor Labs, a facility at the Monterey Bay Aquarium Research Institute (MBARI), and the facility being constructed by the Alaska Fisheries Science Center in Newport, Oregon. In addition, there are several smaller systems at individual labs, such as in UC Santa Barbara, UCD Bodega Marine Lab, Moss Landing Marine Laboratory, San Francisco State University Romberg Tiburon Center for Environmental Studies, and Western Washington University's Shannon Point Marine Center. Each of these facilities have different capabilities and the number of key species that need to be evaluated is vast. So the multiple facilities will meet the scientific and management needs on OA effects on the West Coast. Where NOAA scientists are collaborating with external labs on species response experiments, NOAA should assist in the development, construction, and maintenance of the experimental facilities.

Task 3.2.3: Conduct acidification response experiments on species and species assemblages of interest in West Coast ecosystems.

Research at the NWFSC will initially focus on exploring the response of bivalves and zooplankton. This work will build on preliminary acidification experiments we have already conducted at the NWFSC on geoducks (*Panopea abrupta*) and krill (*Euphausia pacifica*). Bivalves are ecologically and economically important and, as previously described, West Coast shellfish aquaculture is experiencing a recruitment failure suspected to be at least partially attributable to acidification. Zooplankton play a critical role in the food web and serve as the primary food source for economically important fisheries. Future plans include experiments on fish (especially olfaction effects), deep-sea corals, Dungeness crab, and echinoderms and expand to mechanism of physiological responses using latest molecular biological and genetic tools.

In addition to single species experiments, the NWFSC will focus on evaluating the response of wild-collected, multi-species assemblages. The approach of this research is to take a sample of, for example, zooplankton or species collected on a settlement plate, from the local environment, then compare in the laboratory how species composition changes over time when exposed to different simulated future ocean conditions. This approach will evaluate the response of multiple species simultaneously and show how interactions among species may play out under future conditions. As with any laboratory experiment, there are limits to how the results could be extrapolated to natural conditions, but the experiments are likely to reveal new avenues of research that would not be apparent from single species analyses.

Initial species response experiments at the SWFSC will complement the activities at the NWFSC and will take place at the facility planned for SIO. The initial studies will be on commercially and ecologically important forage fish such as sardines and squid, for which the SWFSC has 30 years of experience spawning. In addition, the SWFSC will work on endangered abalone that are of great commercial and cultural importance in California.

The response variables for species exposure experiments include basic metrics such as growth and survival but also more sophisticated metrics such as molecular genetics, biochemical and physiological measures of stress (enzyme activity, respirometry), energy reserves (lipids), crystallography, fish otolith trace metal chemistry, response to disease challenge, and calcium content.

3.2.2 Experiments on biological pump parameters

Some of the species exposure experiments will focus on species and processes important to marine carbon cycling. For example, if acidification affects the abundance of foraminifera or other highly abundant pelagic calcareous species, there will likely be feedbacks on carbon cycling that would alter the future progression of acidification processes. These potential effects will be considered in prioritizing species for evaluations in laboratory experiments.

3.2.3 Calcium carbonate mineralogy

Task 3.2.4: Assess the calcium carbonate mineralogy of species important to West Coast ecosystems.

One potential approach to predict species response for calcifying organisms is based on analysis of calcium carbonate mineralogy. In general, calcium carbonate solubility is, from most soluble to least: amorphous calcium carbonate, high-magnesium calcite (>7 mole percent), aragonite, low magnesium calcite, dolomite (Morse and Mackenzie, 1990). Theoretically, species vulnerability could be ranked based on the type of calcium carbonate used in their structures. However, the pattern of vulnerability observed in study species is not this simple: species response also depends on developmental stage, methods of calcification, and other factors such as rate of mineralization, temperature, or overall physiological stress. It is important to know the mineralogy of ecologically and economically important species. However, the mineralogy of many calcifying species (e.g., most crustacean and gastropods) on the West Coast is unknown.

The Alaska Fisheries Science Center has proposed to assess the mineralogy of many species found in Alaska. We will work with the AFSC to evaluate additional species found off California, Oregon, and Washington to create a comprehensive inventory of important species in the Northeast Pacific. Given that we will never be able to do controlled experiments on all species, extrapolating species response based on factors like mineralogy will be necessary to model ecosystem response.

3.2.4 Detecting historical species response

Task 3.2.5: Correlate hindcasts of West Coast saturation states with historical biological time-series of species abundance to estimate how species and communities responded to past changes in saturation state.

Based on the methods described in Section 3.3.2 on hindcasting biogeochemical conditions (Task 3.3.2), it is possible to estimate the historical saturation states and other carbon system parameters using data commonly collected on oceanographic cruises and moorings. By correlating historical time-series of pH and saturation states with historical biological time series, we may be able to detect historical changes in species abundance, distribution, or morphology caused by acidification. This information will help us project what may happen in the future. The historical time series of pH can tell us something about how species and communities responded to lowered pH conditions in the past.

The biological time-series collected on the Newport Hydro Line is one of several valuable data sets available for these analyses. In addition to oceanographic data, time series on zooplankton and other species have been collected there since 1966. Given their vulnerability to acidification (Fabry *et al.*, 2008), pteropods (*Limacina*) will be a focus of initial study. Researchers will look at patterns of abundance and analyze the morphology and shell thickness of archived samples to see how changes in saturation state may be reflected in historical shell formation and condition.

In California, the CalCOFI data set contains an extensive time series of oceanographic and biological data for reconstructing saturation states and biological communities. Again, pteropods are a potential initial focus of study, and archived samples for morphological analysis go back to 1949. Since 1997, the samples have been stored in ethanol, which reduces the chance of potential shell degradation as often occurs when samples are traditionally stored in formaldehyde.

Otoliths of Pacific sardine (*Sardinops sagax*) appear to record OA and temperature conditions in their shape, making the otoliths potential archived environmental indicators. Sardine otoliths are also used in fisheries research to age fish. The SWFSC has retained samples of ichthyoplankton, which includes sardine otoliths, since 1949. Since 1996, part of each ichthyoplankton sample has been stored in ethanol to preserve calcified tissues, such as otoliths. Sardine otolith samples are also potentially available from sediment cores off Southern California and British Columbia, which contain records over multiple centuries.

3.2.5 Testing ecosystem models with in situ experiments

Task 3.2.6: Explore technologies for in situ open-ocean and semi-permeable mesocosm experiments to test predictions from ecosystem models and species not amenable to laboratory culture.

As described in Theme 3, it is difficult to completely validate an ecosystem model. However, it may be possible in an in situ mesocosm setting or using in situ CO_2 exposure systems to test specific model predictions. Mesocosm and in situ experiments on entire ecological communities provide some information of how interactions among species may play out in a high CO_2 world. However, those very interactions can be difficult to interpret (Bellerby *et al.*, 2008). Investment in systems for conducting these in situ or mescosm experiments can be very high at this time, and we are not convinced that they provide the best use of funds. However, the methods have potential for testing specific predictions of ecosystem models and for evaluating the response of species that cannot readily be cultured in the lab. We therefore propose establishing an active research program to explore and develop these technologies so that they may potentially be deployed effectively in the future.

3.2.6 Evaluating potential mitigation methods

Task 3.2.7: Conduct laboratory and field experiments on potential local mitigation methods.

At least two possible local mitigation methods have been proposed to counter the effects of ocean acidification: (1) sediment buffering and (2) electro-deposition. Neither method is likely to be practical for mitigation at large geographic scales. With the sediment buffering approach, calcium carbonate from ground bivalve shells or limestone would be spread over the existing sediments to alter the saturation state of the local benthic environment (Green *et al.*, 2009). Electro-deposition is a method developed to create artificial reefs by running an electric current though metal structures placed in the ocean (Hilbertz, 1979; Goreau and Sammons, 2003). The electric current alters local saturation state and could potentially provide a local substrate to mitigate ocean acidification.

We propose conducting laboratory and field experiments to evaluate whether either of these methods could be use for local mitigation to protect high-value resources like commercial shellfish beds, rare or endangered species, or to promote biostabilization of sediments to prevent beach erosion. Laboratory experiments will be conducted in species exposure systems on target species (e.g., oysters) where the mitigation techniques are one of the experimental treatments. We will conduct small-scale field trials of the potential mitigation methods.

3.3 Biogeochemical and Ecological Models (Theme 3)

3.3.1 Biogeochemical models—forecasting future conditions

Task 3.3.1: Develop regional biogeochemical models coupled to global carbon cycle models to predict local changes in carbon chemistry at multiple temporal scales.

Over the last decade, coarse-scale, coupled climate/carbon-cycle models have been developed to determine future changes of ocean carbon chemistry and ocean acidification for the next two centuries (Kleypas *et al.*, 1999; Caldeira and Wickett, 2003; Orr *et al.*, 2005; Caldeira and Wickett, 2005; McNeil and Matear, 2008; Cao and Caldeira, 2008; Feely *et al.*, 2009). These models have provided information on the geographical distributions of open-ocean carbon chemistry under different atmospheric CO_2 stabilization scenarios. They have been validated with the WOCE and CLIVAR/CO_2 Repeat Hydrography data sets. However, these models are not sufficiently resolved to address ocean acidification issues on a smaller scale such as coastal upwelling regions or adjacent to large estuaries where corrosive, "acidified" water may already be having significant negative impacts on biological systems (Feely *et al.*, 2008; Salisbury *et al.*, 2008). A better approach would be to nest a high-resolution coupled climate/carbon model within a global model (e.g., the GFDL MOM4 model or the NCAR CCSM3).

We propose to develop a West Coast regional model (or suite of models) that will be part of a nested set of models of ocean acidification in U.S. coastal waters. Model output will be verified with observational data collected from shipboard surveys, moorings, and gliders. A coordinated set of nested models will both provide information for local planning and improve the performance of global carbon models, which do not yet match acidification conditions in coastal regions well (Hauri *et al.*, 2009). Modelers working on this project would be based at PMEL and work in collaboration with GFDL and AOML. PMEL also has collaborative relationships with research groups at other academic and government institutions domestically and internationally that do carbon cycle modeling at appropriate space-time scales for the open coastline within the CCS. At even finer spatial scales, local circulation models such as those developed for Puget Sound can be modified to predict carbon cycle dynamics.

Task 3.3.2: Design and implement experiments and observation projects to estimate critical parameters for regional carbon models

Accurate predictions of future carbon dynamics require accurate physical circulation models and accurate estimates of key biogeochemical process rates. In global models, the accuracy of the physical circulation models appears to be a key factor in the consistency of model predictions (Doney *et al.*, 2004). Additional experiments or observations may be needed to ensure that adequate modeling of regional carbon dynamics is possible. Additional experimental work will also be needed to constrain key biogeochemical process rates in the models. Many of the parameters needed for ocean carbon cycle modeling are not available for nearshore, coastal, or embayment environments. Important parameters to be constrained within the models (and parties engaged in quantifying them) include the input rates of freshwater (USGS), nutrients (SFSU), and carbon (PMEL, OSU, UCB); dissolution rates of abundant marine calcifiers (NMFS, CSUSM, UW), export rates of carbon to sediments and open ocean (MBARI); and air-sea gas exchange (PMEL, OSU, SIO, UW).

3.3.2 Biogeochemical models—hindcasting historical conditions

Task 3.3.3: Develop and apply algorithms to reconstruct historical carbon chemistry conditions over local to regional scales.

In addition to forecasting the future trajectory of ocean acidification conditions along the West Coast, it will be valuable to mine historical data archives (e.g., World Ocean Database at NODC) of biological, chemical, and physical oceanographic measurements to understand the historical development of OA conditions along our coastline. A number of long-term sampling programs for hydrographic data have operated in various parts of the CCS over the past several decades (Table 3.1). The PMEL Carbon Program team has developed new robust regional algorithms for estimating the seasonal extent of corrosive waters along the West Coast of North America using archived biogeochemical and hydrographic data sets that lack carbon measurements (Figure 3.3) (Juranek *et al.*, 2009).

The approach utilizes regression techniques to model aragonite saturation values as a function of more commonly collected hydrographic and chemical data (e.g., temperature, salinity, oxygen) so that a broader range of cruise data sets can be used to evaluate spatial and temporal variability in aragonite saturation state, which is an indicator of where the corrosive, acidified water exists along the coast. The calculated saturation states agree well with the measured values. The method is reasonably straightforward and has good resolving power for aragonite saturation. This approach, when combined with shipboard observations, mooring, and glider data could be utilized to verify the nested coupled climate models of ocean acidification and help to delineate acidification hotspots and thereby identify potentially vulnerable marine ecosystems in U.S. coastal waters. As part of the PMEL collaboration with NMS and NMFS scientists, seasonal or more frequent carbon chemistry samples would be collected within sanctuaries or other regular sampling stations to validate the performance of these algorithms. The seasonal sampling would yield valuable information on the influence of seasonal and interannual variability on the algorithms, and in particular whether the stoichiometric relationship between CO_2 and O_2 in coastal water masses changes with seasonal or annual variability in the ecological balance of production and respiration processes.

3.3.3 Ecosystem models

Task 3.3.4: Develop models to predict how West Coast ecosystems will change in response to ocean acidification and alternative ocean management actions.

Ultimately, we need to predict how ecosystems will respond to changes brought about by ocean acidification and other stressors and how alternative management actions can affect that response. Of particular interest is the response of higher trophic species, like harvested fish, that may be indirectly affected as acidification leads to declines in their prey species. One goal of ecosystem modeling is to translate the chemical and ecological implications of acidification into ecosystem services such as commercial harvest, recreational opportunities (i.e., clam digging or whale watching), that matter to stakeholders and NOAA policy makers.

In general and with reasonable justification, ecosystem models that look at food web and higher trophic effects do not explicitly model the carbon system, and likewise, carbon system models do not explicitly consider what happens at higher trophic levels. Therefore, we have partitioned this plan into separate tasks dealing with biogeochemical forecasting of carbon system changes (Task 3.3.1) and models forecasting ecosystem response (Task 3.3.4). However, there is potential for more complex models that combine both types of models, and we do not intend to preclude such efforts. Recent analysis indicates that high trophic levels can, in fact, directly affect the carbon cycle, so coupled models may be necessary to address some questions.

Puget Sound has been a focus for ecosystem models and can be used as an example of what can happen in nearshore, inland marine waters under ocean acidification. Existing NOAA modeling efforts that are currently being modified to address ocean acidification issues include an Ecopath model with Ecosim applications (Busch *et al.*, in prep.) and a SLAM modeling application focusing on a geoduck-centric food web (Busch and McElhany, in prep.).

In the California Current System (CCS), the Atlantis model has already been used by NWFSC researchers to explore how acidification may affect the food web (Kaplan and Levin, in prep.). Results suggest that harvested species such as English sole (*Pleuronectes vetulus*) that feed heavily on benthic bivalves and echinoderms are likely to see large declines in abundance (Figure 3.4). Key fishery management reference points, such as maximum sustainable yield (MSY) and unfished biomass (B_0) are predicted to fall by a factor of 10. Cumulative impacts of acidification and fishing must be considered in concert: catches of English sole that are sustainable without acidification lead to drastic overfishing under regimes with strong acidification effects on bivalves and echinoderms. NWFSC researchers are currently exploring the food web response to a number of predicted climate change impacts (ocean acidification, hypoxia, temperature increase) with a suite of Ecopath with Ecosim models along the West Coast from California to Alaska (Ainsworth *et al.*, in prep.), including a model of the entire CCS system (Field *et al.*, 2006).

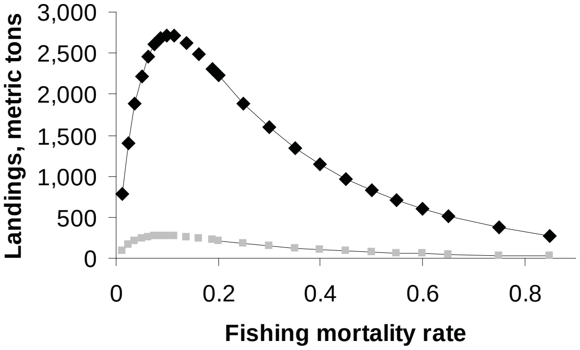


Figure 3.4: Yield (metric tons landed) of English sole (*Pleuronectes vetulus*) under various fishing mortality rates (x-axis) with current ecological processes (top curve) vs. strong ocean acidification impacts on benthos (bottom curve). Yield is based on catches in year 50 of a 50-year 964 simulation; this is an approximation of an equilibrium sustainable yield (Kaplan *et al.*, 2010).

Ecosystem models are a valuable tool for "stress testing" management options. With ecosystem models that can incorporate impacts of acidification, we can simulate alternate management policies (i.e., different harvest quotas, shellfish aquaculture locations, or daily loads of pollutants), and identify which policies are most robust to reasonable scenarios for acidification. Similarly, we can identify what type of monitoring, on what frequency or spatial scale, is needed to detect food web effects of acidification and to inform adaptive policies. This strategic approach of testing management and monitoring schemes against realistic ecosystem "operating models" has been called Management Strategy Evaluation (MSE, Sainsbury *et al.*, 2000). Overall, the approach can inform our efforts to both monitor acidification and its food web effects (Theme 1), and to develop policies that can adapt to it (Theme 4).

3.4 Human Dimensions (Theme 4)

Human dimensions research on ocean acidification will consist of two major (and interrelated) components. The first is estimating how acidification is likely to affect human communities though impacts on "ecosystem services." The second is the development and application of decision-support frameworks to improve the selection of appropriate management actions to deal with acidification and its effects.

3.4.1 *Impact of acidification on ecosystem services*

Task 3.4.1: Estimate anticipated changes to West Coast ecosystem services as a consequence of ocean acidification.

As ocean acidification may severely alter marine ecological processes, it has the potential to have a big impact on ecosystem services. The term *ecosystem services* refers to the value of benefits to human communities as a result of functioning ecosystem processes, including both obvious economic benefits (e.g., value of a fishery) as well as less obvious values such as clean beaches, protection from coastal erosion, and cultural "existence value" of species (e.g., orca, salmon). Anticipating changes to ecosystem services can provide an incentive for mitigating the effects of acidification by reducing CO_2 emissions, reducing other ecosystem stressors, or preparing communities for economic and cultural disruption if the ecological impacts cannot be prevented. The development of ecosystem services models will be linked to the ecosystem prediction models described above in Theme 3.

3.4.2 *Management decision framework*

Task 3.4.2: Develop technical tools for evaluating the consequences of potential management actions related to ocean acidification on the West Coast to create more effective management strategies.

Of critical import is development of a process for deciding what to do about ocean acidification. As described in the introduction, management options for dealing with acidification may be somewhat limited. However, there will be choices about whether to reduce CO_2 emissions, how to confront other stressors to the marine system, how to prepare communities for ecosystem changes, whether to implement spatial or temporal fisheries changes, etc. Making these decisions will require consideration of ecological predictions, the value of ecosystem services, and the economic and social costs of proposed actions. The decision process will need to transparently incorporate the considerable uncertainty that exists in all of the input parameters. A number of decision support tools have been applied to these sorts of problems in a variety of fields, including management of ESA-listed Pacific salmonids. While the ultimate decision about what action to take in any given situation is clearly a policy determination, there is substantial technical work needed to develop the tools to analyze the consequences of any particular policy choice.

3.5 Synthesis of Data and Information Products (Theme 5)

Task 3.5.1: Develop and participate in effective management and dissemination of regionally produced data and data products related to ocean acidification.

Management of biological data will, at least initially, occur at the scale of the West Coast region or local labs. Biological data will generally take the form of time-series data from ongoing monitoring efforts, results from experimental studies, and databases of species vulnerability to OA. Results from experimental studies and information about species vulnerability to OA will be published in the research literature or in agency reports, with data distribution managed by individual research teams. Biological time-series data would benefit from other data management frameworks such as NOAA IOOS Program. However, we expect the data relevant to this plan to be generated by a host of different entities, with studies of ocean acidification being only one of the reasons for collecting biological time-series data. Because of the diffuse nature of data collection and management and the number of species involved, it will be challenging to access and evaluate these disparate data sources. Although the diffuse and nested nature of the data is the reasons a central system for managing biological data is difficult to create, they are precisely the reasons why a central system is needed.

Methods for carbon chemistry measurements and quality control have been established for suite of observations that will make up the core of oceanographic OA monitoring efforts (Dickson *et al.*, 2007). Thus, oceanographic data from the West Coast region should be entirely consistent in format, content, and quality control with data from all other regions. Chemical and physical measurements of oceanographic conditions are thus more amenable to archival in a centrally managed center for OA data, such as the Global Data Assembly Center model described in Chapter 1.

3.6 Engagement Strategy (Theme 6)

Task 3.6.1: Implement an education and outreach program to communicate the science and ecosystem consequences of ocean acidification to the West Coast public and stakeholder communities.

In order to improve the public's understanding of OA, a comprehensive plan for ocean acidification research and monitoring must include education and outreach activities. A well-informed public will support government research and management plans and energize communities to take the necessary actions to mitigate the root causes of ocean acidification. The five NOAA National Marine Sanctuaries along the West Coast can play an integral role in meeting FOARAM Act mandates by developing an increased awareness of the causes and potential effects of ocean acidification on our coast and ocean ecosystems. Sanctuaries can serve as sentinel sites, but also as places communities go to learn.

Robust primary, secondary, and adult education programs exist at all five West Coast sanctuaries, reaching thousands of students and members of the public each year. Through at-school, in the field, and visitor center programs, as well as community lecture series and teacher workshops, sanctuary staff and volunteers reach a large and diverse audience. Ocean acidification education and outreach can be incorporated into existing programs and curricula that West Coast sanctuary sites lead or participate in, including: Multicultural Education for Resource Issues Threatening Oceans (MERITO) Academy, providing bilingual ocean conservation-related products and services to students, teachers, adults, and families; Long-term Monitoring Program and Experiential Training for Students (LiMPETS), providing sandy beach and rocky intertidal monitoring experiences to middle and high school students, as well as teacher workshops and online teaching resources; Ocean Science Professional Development Workshops, preparing teachers to facilitate inquiry-based, marine science-rich experiences for students; and Animals in Curriculum-Based Ecosystem Studies (ACES), providing teachers with curriculum-based activities with NOAA remote sensing data to improve environmental and ocean literacy.

In addition to school programs and curricula, a variety of other outreach and education activities exist at West Coast sanctuary sites. Reaching local, national, and international audiences, West Coast sanctuaries have current or planned exhibits in many aquariums and museums, including Seattle Aquarium, Monterey Bay Aquarium, Aquarium of the Bay, Oakland Museum of California, and California Academy of Sciences. Olympic Coast, Gulf of the Farallones, and soon, Monterey Bay National Marine Sanctuaries have visitor centers where thousands of students and members of the public come to learn about ocean resources. Adult field seminars and naturalist-led cruises are organized throughout the region each year. All West Coast sanctuaries offer community lecture series, and some, such as that organized by Channel Islands Sanctuary, have over 1000 participants each year from three different counties. Interpretive signage is prevalent along coastal areas of West Coast national marine sanctuaries, and radio is also used as an outreach tool with Cordell Bank National Marine Sanctuary hosting the monthly radio program, "Ocean Currents."

Sanctuaries are also places where scientists can reach into communities to help develop local plans and actions addressing ocean acidification. Each sanctuary has an Advisory Council comprised of representatives from public interest groups, local industry, commercial and recreational user groups, academia, conservation groups, government agencies, and the general public who provide advice to sanctuary managers. Sanctuary Advisory Council members at all five sites, totaling almost 170 representatives, have identified ocean acidification as a regional priority.

Each West Coast sanctuary has a network of volunteers that support public education programs and conduct citizen science. At three sites, volunteers collect data on beach-cast birds and mammals that provide early warning signals of changes in ocean productivity. This network of volunteers can be a valuable pool of support for ocean acidification research and mitigation efforts.

For estuary habitats, the five West Coast NERRS sites (Tijuana, San Francisco Bay, Elkhorn, South Slough, and Padilla) will take a lead role in education about OA. In addition to protection and research, these NERRS sites have an education and outreach focus, particularly with managers and local communities. Their experience in communicating with these audiences will be a valuable asset to engage the public in understanding and responding to OA.

Outreach goals for the West Coast would include developing an information delivery system where ocean acidification data and information on current research activities within the region would be made available to scientists, managers, educators, stakeholders, and interested citizens through a web portal and various internet resources. The first steps to producing an ocean acidification education and outreach plan for the West Coast region will be:

- Identifying target audiences;
- Determining appropriate programs and products for each audience;
- Developing a comprehensive needs assessment for education and outreach programming;
- Matching ocean acidification needs with existing education and outreach activities;
- Developing innovative approaches for community involvement.

These first steps would be completed in year one. The second year will focus on developing and integrating K–12 educational curriculum. It will also be critical to link ocean acidification research and management with undergraduate and graduate students during this time. The third year will focus on exhibit design and development for science centers, aquariums, and sanctuary visitor centers to provide the public a rich user experience. Years four and five will focus on continuing to implement programs and produce products established within the first three years.

3.7 Collaborators

West Coast Region Collaborators

Northwest Fishery Science Center (FSC)
Southwest FSC
Alaska FSC
Pacific Marine Environmental Laboratory
Olympic Coast National Marine Sanctuary (NMS)
Channel Islands NMS
Cordell Bank NMS
Gulf of the Farallones NMS
Monterey Bay NMS
National Centers for Coastal Ocean Science
Geophysical Fluid Dynamics Laboratory
Regional OOS (NANOOS, CeNCOOS, SCCOOS, PaCOOS)
National Estuarine Research Reserve System
University of Washington
Oregon State University
University of California, Santa Barbara
University of California, Davis
Scripps Institution of Oceanography
Monterey Bay Aquarium Research Institute
California State University—San Marcos
Pacific Northwest National Laboratory
Washington Department of Ecology
Oregon Department of Fish and Wildlife
California Department of Fish and Game

4. Pacific Islands Region Ocean Acidification Research Plan

Russell E. Brainard, David Butterfield, Mark Eakin, Richard A. Feely, Dwight K. Gledhill, Elizabeth Kehn, Kathyrn Shamberger, Adrienne J. Sutton, Oliver Vetter, and Charles Young

4.0 Ocean Acidification in the Pacific Islands Region

THIS CHAPTER PRESENTS NOAA's research strategy toward understanding the ecological impacts of ocean acidification (OA) within the U.S. Pacific Islands region (PIR). As the precise effects of OA on the marine ecosystems of the PIR remain largely unknown, our initial efforts will focus primarily on establishing baseline conditions, initiating robust long-term monitoring programs, and addressing fundamental research needs. These research and monitoring efforts are intended to establish the requisite scientific understandings necessary to forecast the ecological and socioeconomic consequences of OA. This chapter addresses the priorities and unique challenges facing the PIR in regards to the impacts of OA on marine ecosystems and associated ecosystem and economic services (e.g., fisheries and ecotourism). These include evaluating the regional consequences from direct and indirect impacts on coral reef and pelagic ecosystems, protected species, and fishing and tourism industries.

4.0.1 Risks from ocean acidification in the Pacific Islands

Coral reef ecosystems provide substantial ecological goods and services, and economic and cultural vitality to island communities across the PIR through fisheries, tourism, building materials, coastal protection, and biogeochemical research for pharmaceuticals (Hoegh-Guldberg *et al.*, 2007). As an example of their economic value, the coral reefs of the Main Hawai'ian Islands have an estimated net value of nearly \$10 billion (in 2002 dollars) with an average annual benefit of \$385 million, with the largest contribution from recreation and tourism (Cesar (ed.), 2000; Cesar *et al.*, 2003). According to even the most optimistic climate models, a critical atmospheric CO_2 threshold of 480–500 ppm will be surpassed within the next 80 years, at which point coral reef communities will likely undergo significant ecological phase shifts with calcification of reef-building corals and crustose coralline algae unable to keep pace with bioerosion processes (Langdon and Atkinson, 2005; Hoegh-Guldberg *et al.*, 2007). As this occurs, many of the ecological, economic, and cultural values provided by coral reefs to the local communities of the Pacific Islands could be devastatingly impacted. Coral reefs and the resources they provide are central to the cultural practices of the indigenous peoples who have evolved around them for millennia (Bunce *et al.*, 2000).

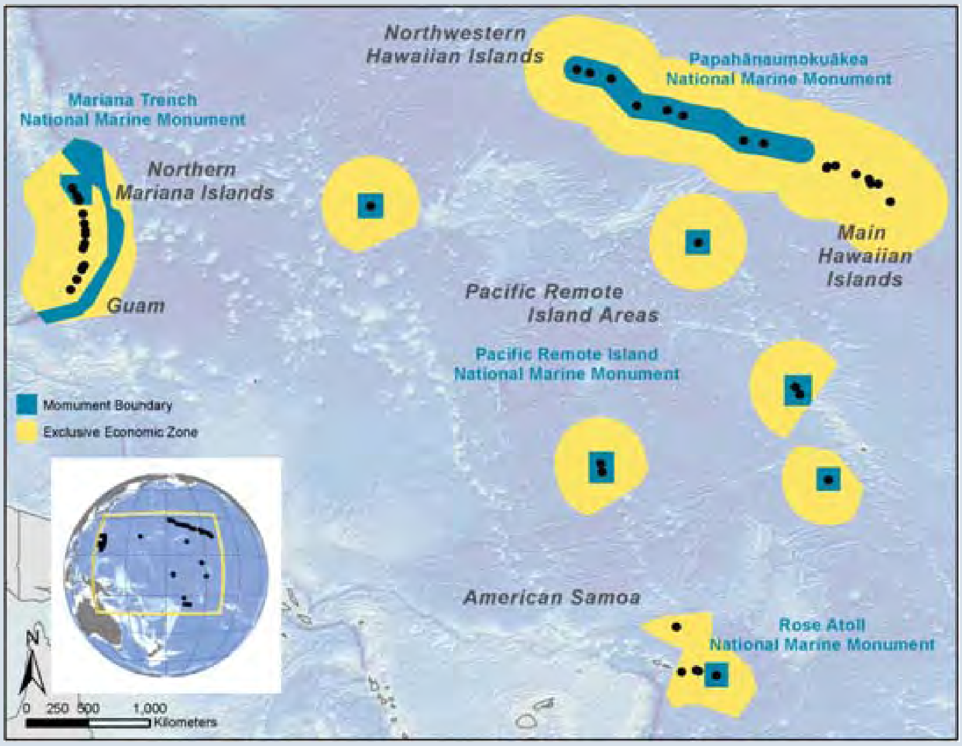
Reduction of the hard substrate provided by coral reefs has immediate impacts on both the nearshore and pelagic fish communities. Coral reefs provide the spawning grounds for many of the world's key commercial fish species, as well as the reef fish caught for recreation and sustenance. The deterioration of spawning grounds affects future communities by forcing a weaker recruitment and reduced fish stocks. More urgently, critically endangered Hawai'ian monk seal and threatened green sea turtles are being impacted by loss of essential breeding and nesting habitat.

4.0.1.1 Coral reef ecosystems

Coral reef ecosystem management and monitoring are spread over a broad suite of habitats, from shallow, nearshore reefs, to protected lagoons and atolls, to the wave- and weather-exposed reef slopes, to mesophotic and deep-sea coral ecosystems. Coral

Pacific Islands Region Description

The U.S. Exclusive Economic Zone (EEZ) of the Pacific Islands Region (PIR) represents the largest geographical management area within NOAA with a total area of responsibility of more than 1.5 million square nautical miles. This is roughly equal to the size of all of the remaining U.S. EEZ waters combined. These areas, which span from Hawai'i in the east, to Guam and the Northern Mariana Islands (NMI) in the west, to American Samoa in the south, are separated by many 1000s of kilometers of vast international waters. This region encompasses a large percentage of the nation's most biologically diverse coral reef ecosystems; is home to endangered and threatened species of sea turtles, monk seals, and cetaceans; and supports abundant and economically important highly migratory species of fish, such as tunas and swordfish. The vastness and remoteness of the region present unique operational, scientific, and management challenges for NOAA to cost-effectively assess spatial patterns, monitor temporal trends, and effectively manage coral reef ecosystem health and biodiversity, the abundance and behavior of cetaceans and other species of concern, and large-scale commercial and subsistence fishing in the PIR. In 2006, the Papahānaumokuākea Marine National Monument (P-MNM) was established in the remote Northwestern Hawai'ian Islands as the single largest conservation area under the U.S. flag, and one of the largest marine conservation areas in the world. It encompasses 139,797 square miles of the Pacific Ocean—an area larger than all the country's national parks combined. In 2009, the Pacific Remote Islands Marine National Monument (PRI-MNM), Rose Atoll Marine National Monument (RA-MNM), and the Marianas Trench Marine National Monument (MT-MNM) were established to conserve and protect an additional 195,274 square miles of marine habitat. For each of these large marine conservation areas, NOAA has significant management responsibilities.



reef ecosystems are the most biologically diverse of all marine systems and one of the most economically, biologically, and culturally important ecosystems on the planet (Hoegh-Guldberg *et al.*, 2007). It has been estimated that there are 1–9 million species on coral reefs around the globe, representing roughly 25% of all marine biodiversity (Reaka-Kudla, 1997). Coral reefs also provide substantial ecological goods and services, and economic and cultural vitality to island communities across the PIR through fisheries, tourism, building materials, coastal protection, and biogeochemical research for pharmaceuticals (Hoegh-Guldberg *et al.*, 2007). As well as the immediate effect of reefs on their surroundings, coral reefs and estuaries often serve as nursery grounds for many pelagic species. As such, degradation of coral reefs will have cascading effects across trophic levels throughout the marine food web, including ecosystem goods and services provided to mankind.

Research has shown that the aragonite saturation horizons are shoaling; therefore it has been projected that the first reefs to be affected by ocean acidification are likely to be deep-sea coral ecosystems (Cairns, 2007; Guinotte *et al.*, 2006) and possibly intermediate-depth mesophotic coral ecosystems (characterized by the presence of light-dependent corals and associated communities typically found at depths ranging from 30 m to over 150 m in tropical and subtropical regions). Among shallow water coral reef ecosystems in U.S. jurisdictions, those in the Northwestern Hawai'ian Islands are likely to be the first to pass below levels where net calcium carbonate balance can be maintained. It has been hypothesized that mesophotic coral ecosystems, such as those located in the Au'au channel in Hawai'i, may serve as a potential refuge for shallow-water coral populations predicted to be impacted by ocean warming (Puglise *et al.*, 2009). While this may be true, concerns are now being raised that the deeper range of these ecosystems may be among the first to be impacted by ocean acidification (Sabine *et al.*, 2004).

4.0.1.2 Anthropogenic stressors

Many of the coral reefs of the Pacific islands and atolls represent the most geographically and oceanographically isolated marine ecosystems on Earth, e.g., the Hawai'ian Archipelago has the highest rates of endemism in the world (Randall, 1995; 1998). Due to their remoteness and federal protections as National Marine Monuments, Sanctuaries, and Wildlife Refuges, many of these coral reefs are among the most pristine or least impacted by humans anywhere in the world. Their near pristine nature and low level of direct anthropogenic stressors provides a unique and unprecedented opportunity to examine the ecological impacts of ocean acidification without the confounding influences of local stressors, such as land-based sources of pollution (sedimentation, nutrient eutrophication, freshwater run-off, etc.), fishing, tourism, recreational overuse, and coastal development). Among shallow water coral reef ecosystems in U.S. jurisdictions, those in the Northwestern Hawai'ian Islands are likely to be the first to pass below levels where net calcium carbonate balance can be maintained. While the ecological impacts of ocean acidification on human-degraded reefs should also be monitored and studied to support local management actions, the understanding acquired by studying the simpler remote ecosystems will support improved implementation of ecosystem approaches to management of the more stressed and degraded reef ecosystems globally.

On higher elevation and well-populated islands, such as the Main Hawai'ian Islands, anthropogenic stressors, such as coastal development, land-based sources of pollution (nutrient eutrophication, sedimentation, etc.), fishing, and invasive species, coupled with natural influxes of fresh water runoff and nutrients, are likely to increase stress to nearshore coral reefs, and confound the effects of ocean acidification by compromising coral immunity and ecosystem resilience.

4.0.1.3 Vulnerable species

All reef-building scleractinian corals (at least 400–450 species, Richmond *et al.*, 2008; Riegl *et al.*, 2008; Friedlander *et al.*, 2008) and crustose coralline algae across the PIR are considered vulnerable to direct impacts of ocean acidification due to reduced ability to calcify their carbonate skeletons. As the structural foundation for most insular ecosystems in the region, these impacts would indirectly impact thousands, or perhaps millions, or reef-associated species. Seventy-five of these Pacific coral species have recently been petitioned for listing under the Endangered Species Act (Center for Biological Diversity, 2009). In addition, numerous species of calcareous macroalgae (e.g., Halimeda sp.), which provide abundant nursery habitat for many reef-associated species and produce significant volumes of calcareous sand, are likewise vulnerable to ocean acidification.

The critically endangered Hawai'ian Monk Seal (*Monachus schauinslandi*), endangered hawksbill sea turtle (*Eretmochelys imbricate*), and threatened green sea turtle (*Chelonia mydas*) are vulnerable to indirect impacts of OA as decreasing calcification rates of sand-producing calcareous algae and corals threaten to impact essential nesting beach habitats and poorly understood trophic interactions potentially threaten their prey species.

While the impacts of ocean acidification to the 46 known cetacean species in the PIR are not understood, it is likely that their forage will also be significantly modified through poorly known food web dynamics. It is known that ocean acidification will increase low-frequency sound propagation in the ocean and that the resulting ocean will be significantly noisier (Hester *et al.*, 2008; Ilyina *et al.*, 2010). As cetaceans use sound extensively for communicating, navigating, foraging, and reproducing, many of these species could be significantly impacted by these changes in ocean sound characteristics.

Numerous benthic and pelagic invertebrates, including crustaceans (crabs, lobsters, copepods, shrimps, etc.), molluscs (shellfish, squid, octopus, etc.), echinoderms, and tunicates, are vulnerable to direct and indirect impacts of OA as their calcification processes, life histories, and habitats respond to changing carbonate chemistry. Exploration of the deep ocean in the Marianas Trench Marine National Monument, for example, has shown impacts of high CO_2 on bathymodiolus mussel species living at 1600 m depth on a submarine volcano (Tunnicliffe *et al.*, 2009). Even the phytoplankton, other zooplankton, and protozoans at the base of the food web for the vast Pacific pelagic ecosystems are likely vulnerable to direct and indirect impacts of ocean acidification, though the biogeochemical processes of these planktonic species are only poorly known at best. As these primary producers are impacted, so too will be the larger predatory animals, including fish, marine mammals, turtles, and seabirds.

4.0.1.4 Species and ecosystems at immediate risk

Many calcareous organisms and protected species are at immediate risk from the effects of ocean acidification across the PIR. These at-risk organisms and ecosystems include: all reef-building corals and crustose coralline algae which form the structural base of insular ecosystems of the PIR; sand-producing calcareous benthic macroalgae which provide essential nursery habitat for many fish species and produce much of the sand for beaches that are essential nesting habitat for many endangered species and economically important areas for recreation and tourism; and many ecologically or economically important invertebrates (giant clams, lobsters, urchins, etc.). As well as the calcifying organisms the secondary effect of habitat loss from coral reef decline has an immediate effect on spawning grounds, reef fish, and beach production. More generally, the biological diversity, resilience, and long-term viability of the coral reef ecosystems of the PIR are at immediate risk.

The potential immediacy of the risk to coral reef ecosystems was highlighted on 20 October 2009 when the Center for Biological Diversity (CBD) filed a formal petition to list 83 coral species under the Endangered Species Act. Seventy-five of the petitioned corals are believed to occur in the PIR. The premise for the CBD petition is that these 83 coral species face a growing threat of extinction due primarily to ocean warming and ocean acidification. Using paleoclimate observations showing past mass extinctions of coral genera, the petition argues that "coral reefs are the world's most endangered ecosystem and within a few decades, global warming and ocean acidification threaten to completely unravel magnificent coral reefs that took millions of years to build." The petition states that "greenhouse gas pollution makes it difficult for corals to grow and rebuild their colonies." More recently, the NMFS responded that the petition warrants a one-year status review to assess the existence of and extinction risk to the 75 coral species petitioned for the PIR. To effectively and responsibly respond to this petition, NOAA requires a much more thorough understanding of the potential impacts of ocean acidification to these specific coral species.

Hawai'ian monk seals (*Monachus schauinslandi*), with a declining population of less than 1100 animals, are the most critically endangered marine mammal living entirely within U.S. waters (Antonelis *et al.*, 2006). Among many important stressors, monk seals, as well as threatened green (*Chelonia mydas*) and endangered hawksbill (*Eretmochelys imbricate*) sea turtles, are threatened by significant habitat loss as sea level rise erodes away many of the small sandy nesting and breeding beaches in the NWHI (Baker *et al.*, 2006). As the beaches are composed primarily of coral fragments and calcareous algae (*Halimeda spp.*), the impacts of ocean acidification on sand production and transport dynamics could have significant impacts on the survival of these endangered and threatened species. Both monk seals and sea turtles already face significant habitat limitations. Reduction of the sea water alkalinity will likely result in decreased carbonate production and, though less likely, increased dissolution of these essential nursery habitats required for their long-term viability. Moreover, monk seals are known to forage on fish associated with deep and mesophotic coral habitats (Parrish *et al.*, 2002), which, as discussed previously, will also likely be impacted by ocean acidification.

At least 46 species of cetaceans are known in the PIR, though population assessments are severely limited. Though not well understood in the region, one of the key threats facing cetaceans, which actively and extensively use sonar for feeding, navigating, and communicating, is acute or chronic increases in ocean noise, as demonstrated by repeated NMFS litigation over alleged violations of the Marine Mammal Protection Act. Recent studies (Hester *et al.*, 2008; Ilyina *et al.*, 2010) have demonstrated that sound propagation in the ocean increases with decreasing pH. That work suggests that the ocean will get noisier and that acute sounds will propagate further as ocean acidification increases. This could result in increased impacts to cetacean populations, such as increased strandings.

4.1 Developing an Ocean Acidification Monitoring Network (Theme 1)

Until recently, most of our knowledge and understanding of ocean acidification was based in pioneering open ocean carbonate chemistry surveys around the globe (Feely *et al.*, 2004; Sabine *et al.*, 2004). Though the "halo effect" (increased carbonate ion concentration from dissolution of carbonate reefs) of coral reefs has been known for over a decade (Sabine and Mackenzie, 1995), little is known about the spatial patterns or temporal variability of the biogeochemical processes in nearshore ecosystems generally and coral reef ecosystems in particular. It is known that constantly dissolving and accreting coral reefs and coral atolls provide various sources and sinks for carbonate and calcium ions (Andersson *et al.*, 2009; Bates *et al.*, 2009).

Establishing a Coral Reef OA Monitoring Network is currently a high-level priority of the NOAA Coral Reef Conservation Program. Each station within the network will constitute a suite of near-continuous autonomous (where feasible) measurements of key chemical, physical, and biological parameters at regular intervals (See Table 1.4 for station locations).

4.1.1 Oceanographic monitoring

4.1.1.1 Existing carbon chemistry monitoring

As part of NOAA's Pacific Reef Assessment and Monitoring Program (Pacific RAMP), led by the Coral Reef Ecosystem Division (CRED) at the Pacific Islands Fisheries Science Center (PIFSC), exploratory surveys of nearshore carbonate chemistry were initiated in collaboration with NOAA's Pacific Marine Environmental Laboratory (PMEL), Coral Reef Watch (CRW), and Atlantic Oceanographic and Meteorological Laboratory (AOML) in 2005. Carbonate chemistry surveys have focused on determining spatial patterns and temporal variability across gradients of biogeography, oceanographic/environmental conditions, and habitat types (pelagic, forereef, backreef, lagoon, etc.) throughout the PIR. Since 2008, monitoring of carbonate chemistry has focused primarily on relatively pristine unpopulated low islands and atolls, mostly within four remote Pacific Marine National Monuments (P-MNM [in collaboration with Hawai'i Pacific University (HPU)], PRI-MNM, RA-MNM, and MT-MNM), which are not confounded by high island watershed discharge issues or direct human-induced stressors, such as coastal development and overfishing. Water samples collected at the surface and below the mixed layer in offshore-onshore transects upstream and downstream (out to ~100 km) of several island ecosystems confirmed significant biogeochemical influences (e.g., "halo" effect) in nearshore coral reef habitats compared with the surrounding open ocean environments. In 2008, HPU specifically examined this "halo" effect in P-MNM. Surface and near-bottom (<0.5 m) water samples collected in differing habitat types (forereef, lagoon, high coral cover, sand, etc.) and hydrodynamic exposures (long versus short residence times) have revealed significant biogeochemical differences across nearshore habitat and exposure gradients (Gledhill, pers. comm., Winn, pers. comm.).

In 2007, CRED and PMEL also initiated studies to examine the carbonate chemistry and ecological impacts to coral reefs at shallow water (10 m) hydrothermal venting systems at Maug Caldera in the MT-MNM. Direct measurement of shallow water vents found streams of gas bubbles, temperatures of 60°C, pH of 6.07, total alkalinity of 3.56 meq/L, and aragonite saturation state (Ω) of 0.25. The shallow vents are fed from magmatic heat and acidic gases (dominated by CO_2) from deeper within the volcano. The gases dissolve into seawater within the porous rock and as the heated fluids rise through and react with volcanic rock, they pick up iron, manganese, and alkali trace metals. The hydrolysis reactions that dissolve metal oxides from the rock partially consume the magmatic acids and convert some of the excess $CO_{2(aq)}$ to bicarbonate, raising the alkalinity and potentially mitigating the effects of ocean acidification (Butterfield, pers. comm.). The process of magma releasing acidic gases is common on submarine volcanoes of the western Pacific (Lupton *et al.*, 2006; 2008; Resing *et al.*, 2007; Embley *et al.*, 2006; 2007), and this process provides natural sites where the long-term impact of increased acidification on ecosystems and biogeochemical processes can be studied. Many sites of what may be called "volcanic ocean acidification" are below the photic zone and provide opportunities to study the impact on deep benthic communities (Tunnicliffe *et al.*, 2009). The shoreline zone of Maug Island is a prime example of the interaction of volcanic ocean acidification with a coral reef in a remote, pristine tropical environment. Initial sampling efforts at Maug indicate that the effects were localized to the active vent sites, with normal carbonate chemistry parameters observed only meters away. Ecologically, there appeared to be a localized dead zone surrounding the immediate area of the venting site, with high live coral cover found relatively nearby. As one of only a few known shallow water venting sites in coral reef habitats, Maug provides a unique opportunity to potentially assess the future impacts of ocean acidification in a natural environment.

The NOAA Coral Reef Conservation Program has also begun advancing the development of a Pacific Ocean Acidification test-bed in Kaneohe Bay, Hawai'i (Shamberger *et al.*, 2010). The project is a joint effort between NOAA AOML and PMEL, and the Universities of Hawai'i (UH) and Miami. The test-bed serves as a nexus of federal agency and academic monitoring and research activities related to OA. Since 2007, sustained monitoring of near-reef $p\mathrm{CO}_{2(\mathrm{aq})}$ has been conducted using a Moored Autonomous $p\mathrm{CO}_{2(\mathrm{aq})}$ (MAPCO_2) measuring system developed by NOAA PMEL. In 2008, PMEL and UH established two additional MAPCO_2 systems along the south shore of Oahu.

4.1.1.2 Enhanced carbon chemistry monitoring

Task 4.1.1: Implement a comprehensive program for monitoring carbon-cycle-related oceanographic parameters in the Pacific Islands.

As part of this OA research plan for the PIR, NOAA plans to implement a comprehensive program for monitoring and understanding the carbon cycle and biogeochemistry across this vast region, including both nearshore waters of coral reefs and offshore waters of pelagic ecosystems. This multifaceted plan includes: expanded spatial surveys of carbonate chemistry across oceanographic gradients (T, S, nutrients, etc.) and nearshore benthic habitat types, course resolution time series observations of carbonate chemistry from repeat spatial surveys, and high-resolution time series observations from moored instrument arrays and satellite remote sensing.

NOAA will significantly expand the breadth and scope of in situ surveys to map spatial patterns of carbonate ion concentrations and improve understanding of the biogeochemical and hydrodynamic processes driving calcification of coral reef associated species. These spatial surveys will be conducted over scales ranging from basin/regional scales (100–1000s km) to examine changes across oceanographic gradients to island/atoll scales (1–25 km) to examine changes across fine-scale habitat and exposure gradients. The basin/regional scale surveys will be accomplished by installing shipboard flow-through surface $p\mathrm{CO}_2$ and pH systems aboard the NOAA ships *Hi'ialakai*, *Oscar Sette*, *Ka'imimoana*, and *Okeanos Explorer* to broadly map surface aragonite and carbonate ion concentrations across the PIR during ongoing Pacific RAMP, fisheries and protected species assessment, TAO buoy array maintenance, and ocean exploration cruises across the region. The vertical structure will be examined by conducting deepwater CTD profiles and water sampling for carbonate chemistry parameters, nutrients, oxygen, and chlorophyll.

On island/atoll scales, NOAA will conduct shallow-water CTDs and water sampling across different biological habitats and wave/current exposures. In 2010, NOAA will be transitioning from simply conducting exploratory surveys to long-term monitoring of carbonate chemistry at established biological monitoring sites, where calcification rates and biodiversity will concurrently be monitored (see below). At a small subset of these sites, NOAA will begin examining the magnitude and timing of the diurnal cycle of biogeochemical processes in nearshore systems associated with natural photosynthesis and respiration of reef-associated biota using a McLane Remote Access Sampler (RAS) to collect nearshore water samples every 1–2 hours for the 2–5 day visits during biennial Pacific RAMP surveys. These diurnal observations of carbon cycling will provide an estimate of community calcification and dissolution rates.

In addition to the repeat spatial surveys conducted across the PIR using shipboard $p\mathrm{CO}_2$ systems and offshore and nearshore water sampling, NOAA will significantly augment ocean acidification monitoring efforts by establishing moored autonomous OA Observatories to provide near continuous monitoring of a suite of chemical, physical, hydrodynamic, and meteorological measurements of community-scale metabolic performance (net calcification, photosynthesis, respiration). The approach envisioned is based upon a Eulerian flow respirometry method as adopted for coral reefs (Gattuso *et al.*, 1993; 1996; 1999). It requires autonomous monitoring of carbonate chemistry parameters (e.g., enhanced MAPCO_2) along with oxygen, nutrients, and other ancillary data both upstream and downstream of selected reef environments exhibiting unidirectional flow. Together with information on water mass residence time, it's possible to track reef metabolic performance and derive robust estimates of reef growth contemporaneously with offshore estimates of changing ocean chemistry. The moorings provide for an enhanced characterization of the short-term variability in carbonate chemistry within coral reef environments. This information, in conjunction with data from the physiological research efforts, is needed to assign critical geochemical thresholds for OA impacts on reef ecosystems. These OA Observatories, which will be enhanced versions of the existing Pacific OA test bed mooring in Kaneohe Bay, will be deployed at select coral reef sites across key oceanographic gradients across the region using information derived from the spatial surveys to guide mooring placements. Planned coral reef monitoring sites in the PIR include: Oahu, Palmyra Atoll, Midway Atoll, French Frigate Shoals, Wake Atoll, Maug Caldera, Pearl and Hermes Atoll, Maro Reef, Jarvis Island, Rose Atoll, Kure Atoll. Additionally, international Pacific Islands sites include: Chuuk (Micronesia), Moorea (French Polynesia), Galapagos (Ecuador), Heron Island (Australia), Kimbe Bay (Papua New Guinea), Raja Ampat, (Indonesia), Palau (Table 1.4).

NOAA will also collaborate with colleagues at Scripps Institution of Oceanography (SIO) to test and deploy next-generation Honeywell Durafet® pH sensors at a subset of the sites where calcification rate studies will be conducted (see below). The Durafet® provides a valuable tool for studying CO_2 dynamics in coral reef ecosystems and will likely play a role in many studies related to ocean acidification. An Ion Sensitive Field Effect Transistor (ISFET) pH sensor has been modified to operate at low power in an unattended setting. Though still developmental, the sensors have exhibited greatly improved stability, relative to glass pH electrodes, in excess of two months in the surface ocean of a high-productivity environment. The glass electrode is a problematic device when operated in the ocean because it exhibits extremely high electrical impedance which commonly drives stray currents through the conductive seawater media creating ground loop problems. ISFETs, however, are very low impedance devices. Reference electrodes are another factor that may cause unpredictable behavior in the pH sensor response. Although the Durafet appears to remain stable using its conventional internal reference electrode, the Martz lab commonly deploys a secondary reference electrode that appears to exhibit even better stability in seawater (Martz *et al.*, 2010).

The many submarine volcanoes in the PIR provide natural laboratories for the study of ocean acidification and other processes with global importance. Although the flux of carbon dioxide out of submarine volcanoes is less than 2% of the anthropogenic source (Holmen, 1992; Resing *et al.*, 2004), the likelihood that high fluxes of CO_2 into the oceans at a range of depths have been maintained for tens to thousands of years at particular submarine volcanic sites means that conditions of "volcanic ocean acidification" have prevailed in some localities long enough to select for organisms that can tolerate high CO_2/low pH environments (Tunnicliffe *et al.*, 2009; Hall-Spencer *et al.*, 2008). Scientists from PMEL, PIFSC, and other collaborators plan to expand systematic studies of such ecosystems through a combination of monitoring (Pacific RAMP and OA-specific), targeted ecological studies, and exploration. A major component of the research will be enhanced sampling and analysis for carbonate chemistry, nutrients, and trace metals around shallow vents in coral reef environments and around other important benthic habitats.

Collectively, these research and monitoring observations will document spatial patterns and temporal changes in aragonite and carbonate saturation states across the nearshore and offshore waters of the PIR. In addition to the above mentioned efforts focusing specifically on carbonate chemistry, since 2001 CRED has established a suite of long-term oceanographic moorings to measure temperature, salinity, currents, and wave energy at coral reefs across the Pacific Islands region. As a subset of this array, CRED has 23 Sea Surface Temperature (SST) buoys which telemeter SST in near real time. The carbonate chemistry of the Greater Caribbean Region has been modeled using empirical relationships between surface ocean carbonate chemistry, satellite sea surface temperature, and model-derived sea surface salinities (Lee *et al.*, 2006; Gledhill *et al.*, 2008; 2009). Such a system would be especially valuable in the PIR, where vast distances make frequent cruises or tightly spaced moorings unfeasible. As the waters of the PIR include oceanographic conditions that violate assumptions used in the Caribbean model, application of these techniques across the Pacific will require further work to refine the algorithms used. This suite of instruments will be used to help develop and validate these algorithms to calculate and subsequently map aragonite saturation state in the Pacific Islands region.

4.1.2 Biological monitoring

4.1.2.1 Existing biological monitoring—coral reef ecosystems

In the Pacific Islands region, PIFSC-CRED has initiated the early stages of a planned comprehensive effort to monitor the long-term ecological impacts of ocean acidification in conjunction with the above efforts to establish baseline levels and monitor carbonate chemistry. For both of these components, most of the ongoing efforts to date have focused on coral reef ecosystems, which encompass the nesting and breeding habitats for endangered and threatened monk seals and sea turtles. Operationally, both of these monitoring components are being operationalized primarily within the logistical infrastructure of Pacific RAMP, which conducts biennial interdisciplinary integrated coral reef ecosystem assessments and long-term monitoring of fish, corals, other invertebrates, algae, and microbial communities in the context of their benthic habitats and oceanographic environments across the entire PIR. Pacific RAMP surveys include quantitative spatial and temporal monitoring of composition, abundance, distribution, size, and condition of non-cryptic biota, and key oceanographic parameters influencing ecosystem health, such as temperature, salinity, wave energy, nutrients, chlorophyll *a*, and turbidity (Figure 4.1).

In partnership with federal, state, and territorial resource managers and academic partners, Pacific RAMP cruises have been conducted in the NWHI (2000, 2001, 2002, 2003, 2004, 2005, 2006, 2008, and 2009), in the MHI (2005, 2006 and 2008), in American Samoa (2002, 2004, 2006, 2008), in Guam and CNMI (2003, 2005, 2007, and 2009), and in the PRI-MNM (2000, 2001, 2002, 2004, 2006, and 2008).

In addition, the Protected Species Division (PSD) of the PIFSC has been conducting annual population assessments of Hawai'ian monk seals in the NWHI since the early 1980s and intermittent aerial assessments in the MHI in recent years. The PSD, in collaboration with the U.S. Fish and Wildlife Service, has also been monitoring nesting beaches for green sea turtles at French Frigate Shoals in the NWHI since the mid-1980s. The Fish Biology and Stock Assessment Division of PIFSC has been conducting annual or biennial stock assessment surveys of spiny and slipper lobsters at Necker Island and Maro Reef in the NWHI since the mid-1980s.

4.1.2.2 Enhanced monitoring of the ecological impacts of ocean acidification

In addition to maintaining on-going Pacific RAMP and protected species monitoring in the PIR, which are both essential components of this Research Plan, NOAA plans to enhance monitoring efforts to understand the ecological impacts of OA by monitoring a taxonomically and ecologically diverse suite of key management-relevant organisms and ecosystems. The proposed monitoring efforts will provide important and timely information about changes in distributional patterns, community structure, growth rates, and trophic interactions of benthic and pelagic community structures and protected species of the PIR in response to OA and related synergistic threats.

Task 4.1.2: Implement a comprehensive program for monitoring coral reef systems likely to be impacted by ocean acidification in the Pacific Islands.

As a vital component to understanding and addressing the direct ecological impacts of ocean acidification on natural reefs, it is necessary to assess and monitor calcification and accretion rates of key reef-building organisms, particularly scleractinian corals and crustose coralline algae. While several important laboratory experiments have been conducted (Kuffner *et al.*, 2007; Jokiel *et al.*, 2008; Doney *et al.*, 2009a), surprisingly few studies have thus far focused on monitoring the direct impacts of lowering pH on the calcification/accretion of corals and crustose coralline algae in natural reef environments. Recent laboratory experiments have revealed that some zooxanthellate corals are capable of accreting calcium carbonate even in highly corrosive (strongly undersaturated) seawater, provided the corals had access to a steady supply of nutrients or food (Cohen *et al.*, 2009).

Predictions of coral reef community responses to OA are complicated by the fact that reef organisms secrete species-specific types of calcium carbonate (i.e., aragonite, calcite, and high-Mg calcite); each of these forms of $CaCO_3$ have different dissolution thresholds. Thus, in order to understand the direct ecological impacts of OA on natural coral reef communities, it is necessary to have time series observations of both carbonate chemistry/saturation states (outlined above) and the resulting calcification and accretion rates. In collaboration with SIO, PIFSC-CRED will initiate the deployment of an extensive array of jointly-developed Calcification Acidification Units (CAUs) at existing long-term CRED benthic rapid ecological assessment sites in forereef habitats across the ~50 islands/atolls surveyed during Pacific RAMP in 2010 and 2011 (Figure 4.2a). CAUs are simple 10 cm × 10 cm sandwiched PVC plates bolted together and staked into the benthic substrate. They will be deployed at existing long-term CRED benthic rapid ecological assessment sites, in conjunction with water sampling and OA coral reef monitoring instruments for carbonate chemistry (Table 1.4). Upon recovery after 2-year deployments, comparative calcification rates will be directly determined and monitored in their natural reef environments across diverse oceanographic and habitat gradients in the PIR.

In addition to calcification rates, the continued monitoring of the entire ecosystem reveals the true

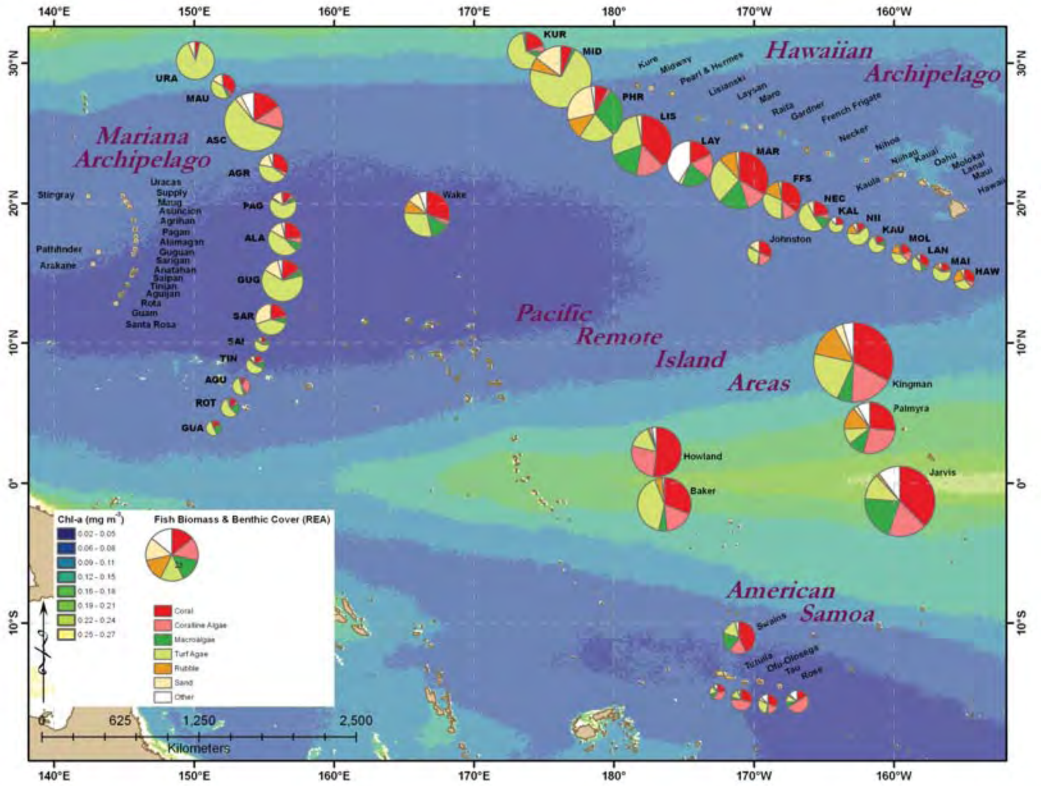


Figure 4.1: Pacific RAMP integrated map of visual observations of fish biomass and benthic composition at coral reefs in the Pacific Islands overlaid on remotely sensed chl *a* concentration from SeaWiFS ocean color. (Sizes of pie charts indicate island-wide mean total reef fish biomass from NOAA Pacific RAMP rapid ecological assessment surveys over the period 2000–2008). Composition of pie charts indicates mean island-wide benthic composition from Pacific RAMP benthic towed-diver surveys over the period 2000–2008 (NOAA PIFSC CRED).

extent and breadth of not just the effects of a lower ocean pH, but the changes in climate that may compound the issues—such as increased storm intensity and damage. Therefore comprehensive monitoring includes the continued study of benthic and fish communities, and oceanographic properties such as waves, currents, temperature, salinity, nutrients, chlorophyll *a*, DIC, total alkalinity, and acoustics). Use of satellite and in situ wave and current moorings are being used to develop wave metrics around islands, to try and couple ecosystem and taxonomic distributions, based on wave and current forcing—shown to be the single most significant factor affecting distributions of reefs (Dollar, 1982; Grigg, 1998; Storlazzi *et al.*, 2005). Climate change has been attributed to the increase in the intensity and frequency of storms around the world. Increasing the rate and impact of episodic storms could impact growth rates of corals even further, potentially working in concert with ocean acidification to slow growth rates of corals.

4.1.2.3 Existing monitoring of cryptic species and biodiversity effects of ocean acidification

Ecological theory suggests that conservation of biological diversity enhances ecosystem resilience and sustainability of ecosystem goods and services. As part of both Pacific RAMP and the Census of Marine Life's Census of Coral Reef Ecosystems (CReefs) project, CRED and multi-institutional partners have initiated a global assessment of cryptic biodiversity associated with coral reefs, often calcifying invertebrates and algae, to serve as an essential baseline by which to measure changes in benthic community structure in response to climate change, generally, and ocean acidification, in particular. To date, CRED and partners have deployed an array of over 400 standardized Autonomous Reef Monitoring Structures (ARMS, Fig. 4.2b) at select islands/atolls across the PIR, Coral Triangle, Indian Ocean, and Caribbean Sea (Fig. 4.3, Brainard *et al.*, 2009). These efforts will also be used to examine the role of biodiversity in sus-

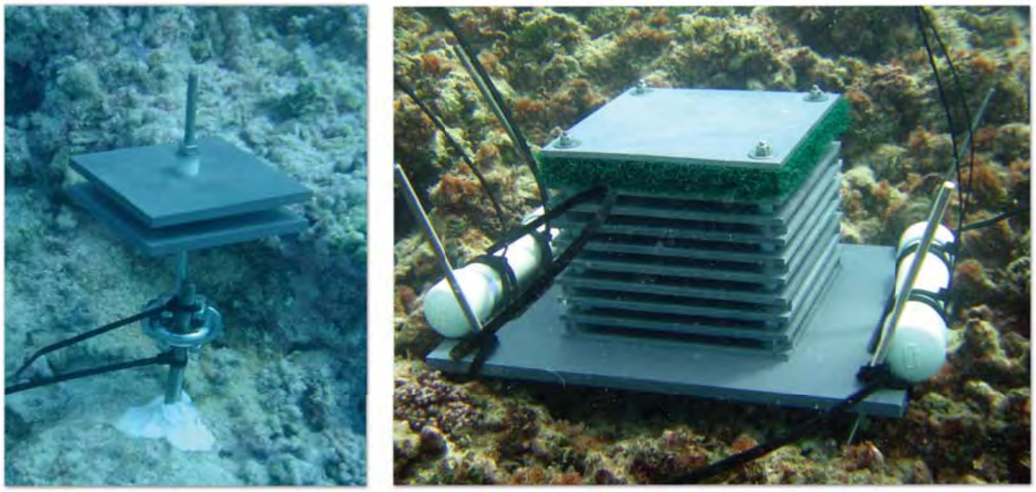


Figure 4.2: (a) Photos of Calcification Acidification Unit (CAU) deployed in reef substrate to monitor calcification rates and (b) Autonomous Reef Monitoring Structure (ARMS) deployed in reef substrate to assess and monitor cryptic biodiversity. Photos credit NOAA PIFSC CRED, D. Merritt.

Figure 4.3: Map showing the current and nearterm deployment locations of Autonomous Reef Monitoring Structures (ARMS) for establishing global baselines of cryptic coral reef biodiversity. Courtesy NOAA-PIFSC-CRED.

taining ecosystem goods and services and enhancing ecosystem resilience.

4.1.2.4 Expanded monitoring of cryptic species and biodiversity effects of ocean acidification

Task 4.1.3: Monitor cryptic species and biodiversity for the effects of ocean acidification in the Pacific Islands.

As part of the OA strategy in the PIR, NOAA will initiate analyses of ARMS to establish baseline assessments of the cryptic and poorly known biodiversity of coral reefs. In FY2010 and FY2011, CRED will for the first time, recover and initiate biodiversity analyses from the ~300 ARMS currently deployed in coral reef habitats in American Samoa (including RA-MNM), PRI-MNM, P-MNM, main Hawai'ian Islands, Guam, and CNMI. Organisms will be photographed and preserved in alcohol for barcoding and mass parallel molecular sequencing by collaborators at Smithsonian Institution, University of Florida, San Diego State University, and Moss Landing Marine Laboratory. As the ARMS are recovered for the baseline assessments, they will be replaced to initiate long-term monitoring of biodiversity impacts of ocean acidification. Water samples will be collected at all ARMS deployment locations to concurrently monitor changes in carbonate chemistry and community composition over time.

As part of NOAA's OA research strategy internationally, NOAA will be collaborating with international partners in employing ARMS to assess to assess baseline spatial patterns of cryptic biodiversity and monitor temporal changes in diversity in response to ocean acidification.

In addition to monitoring the biodiversity impacts of OA to nearshore coral reef ecosystems, NOAA will initiate baseline assessments and long-term monitoring of the composition, abundance, and distribution of plankton in the pelagic waters of the PIR using Continuous Plankton Recorders (CPR, Warner and Hays, 1994) or equivalent standardized methods that allow comparative spatial and temporal analyses across oceanographic gradients. Through collaborations between PIFSC and the Sir Alister Hardy Foundation for Ocean Sciences (SAHFOS), NOAA plans to establish repeat CPR transects during routine research and monitoring cruises aboard the NOAA ships *Oscar Elton Sette*, *Hi'ialakai*, and *Ka'imimoana*, in conjunction with Pacific RAMP, fisheries and cetacean surveys, and maintenance of the TAO Array. Each of these ships will also be outfitted with shipboard $p\text{CO}_2$ systems to allow concurrent observations of surface carbonate chemistry. The first phase of this effort, which will span the period 2011—2016, will establish a baseline assessment of planktonic diversity during repeat transects along the Hawai'ian Archipelago, between Hawai'i and the Marianas, and between Hawai'i and American Samoa.

Biodiversity and cetacean responses to ocean acidification will also be monitored acoustically using Ecological Acoustic Recorders (EARs), developed jointly by University of Hawai'i's Hawai'i Institute of Marine Biology (HIMB) and CRED (Lammers *et al.*, 2008) and High-Frequency Acoustic Recording Packages (HARP), developed at SIO (Wiggins and Hildebrand, 2007). EARs will be used to continuously record and monitor time series observations of biological activity on coral reefs acoustically. Following the methods of biodiversity appraisal by Sueur *et al.* (2008) for forest ecosystems, CRED and HIMB will acoustically monitor proxies for coral reef health and biodiversity, as well as nearshore cetacean activity, using changes in the intensity, spectral composition, acoustic signatures, and timing of biological sounds. Temperature and other oceanographic sensors deployed with these instruments allows coupling between the physical and biological changes on the reef.

In addition to the biodiversity impacts of ocean acidification, long-term monitoring of ocean sound levels using EARs and HARPs (in deeper water habitats) will provide essential time series observations of ambient sound levels across the PIR to assess whether predicted increases in sound propagation characteristics in the ocean due to decreasing pH actually occur. These observations will be an essential component to understanding the impacts of cetacean populations across the PIR.

Task 4.1.4: Monitor microbial communities for effects of ocean acidification in the Pacific Islands.

As the foundation for most of the biogeochemical cycling of energy through marine ecosystems, it is necessary to establish a robust program to assess and monitor microbial community composition, abundance, and distribution patterns to determine and better predict the broader ecosystem implications of ocean acidification. Though it is not known whether or not dominant microbes can or will adapt or evolve over the likely timescale of ocean pH change, time series observations of dominant microrganisms in relation to other ecologically important and management-relevant species, such as corals, macroinvertebrates, fish, and marine mammals, should be initiated immediately. In the PIR, NOAA will significantly expand upon limited ongoing collaborative exploratory surveys of marine microbes with San Diego State University (SDSU) to include more comprehensive monitoring at all Pacific RAMP rapid ecological assessment sites where carbonate chemistry, ARMS, and CAUs are currently conducted. To assess the immense diversity of the microbial community, microbial sampling will utilize existing molecular sequencing facilities and capabilities at SDSU and HIMB.

4.1.3 Integrating oceanographic and biological monitoring

As described above, the physical, biogeochemical, and biological monitoring outlined in this PIR OA Research Plan are tightly integrated operationally to allow concurrent and complementary observations and seamless integration during analyses. Each of these datasets will encompass the respective subregions (Hawai'ian, Mariana, American Samoa Archipelagos and the PRI-MNM), habitats, and depths, in order to effectively map and monitor the natural fluctuations of biogeochemical and ecological parameters. Using pelagic and nearshore CTD and water sampling data from spatial surveys and moored instruments at OA coral reef monitoring stations will provide essential information about the calcite and aragonite saturation states and the “halo” buffering effect of calcium carbonate covered islands and submerged banks. Nearshore work will require small boat deployments and SCUBA diving capacity to continue the benthic monitoring program already in place (Pacific RAMP), and will be used to deploy nearshore sampling instruments, ARMS, CAUs, EARs, and the collection of coral cores and samples for CAT scan analyses. These moored biological monitoring instruments will be co-located with the moored physical and biogeochemical instruments to allow interdisciplinary integration and improved understanding. Research cruises aboard the NOAA ships *Oscar Elton Sette*, *Hi’ialakai*, and *Ka’imimoana* will be required to conduct the pelagic and nearshore CTD and water sampling transects, as well as continuous flow-through $p\mathrm{CO}_2$ observations around the Pacific Islands.

4.2 Organism Response to Ocean Acidification (Theme 2)

4.2.1 Species response laboratory experiments

Task 4.2.1: Conduct laboratory experiment to estimate the effect of ocean acidification on important species in the Pacific Islands.

There is an urgent need to continue and expand upon on-going controlled exposure experiments in laboratories and mesocosms to quantify and understand the adverse impacts of OA on individual species or groups of species. In the PIR, these controlled experiments will initially focus on key reef-building species, such as the 75 corals currently being petitioned for listing under the Endangered Species Act, and the primary sand-producing calcareous algae needed to maintain critical nesting habitat for endangered monk seals and sea turtles in the region. The proposed mesocosm experiments will primarily be conducted as a collaborative effort between PIFSC and HIMB using excellent existing facilities that HIMB has developed over the past decade (Kuffner *et al.*, 2007; Jokiel *et al.*, 2008). These experiments will examine responses of these priority taxa to the individual and synergistic effects of changes in carbonate chemistry (including

Organisms of Near-Term Focus

Reef-building corals and crustose coralline algae

Coral reef biodiversity

Critically endangered Hawai’ian monk seals, critical habitat

Threatened hawksbill and green sea turtles, critical habitat

Protected cetacean species

pH), temperature, salinity, nutrients, light, flow conditions, and other key environmental parameters.

In order to understand the broadscale ecosystem impacts of OA, fundamental research is needed to examine the role microbes play in global biogeochemical cycles. In the PIR, NOAA will initiate collaborative laboratory experiments to examine the microbial responses to changing carbonate chemistry and environmental parameters in coral reef ecosystems. These efforts will focus on the understanding and improving our ability to predict how marine microbes will be affected by increased CO_2 and associated decreases in pH. Elevated CO_2 levels increase photosynthesis rates in some but not all microbial species, and laboratory studies suggest that marine nitrogen fixation may also be enhanced. These laboratory experiments are needed to begin understanding the broader ecosystem impacts of OA on coral reef systems, including sand-production dynamics.

4.2.2 Reef response in situ experiments

Task 4.2.2: Conduct in situ experiments manipulating CO_2 to estimate the effect of ocean acidification in the natural environment.

Though the controlled laboratory experiments described above are immensely important for understanding organism responses to ocean acidification, they necessarily cannot fully simulate the ecological responses that will occur in nature due to their inherent simplification of the complexities and synergistic interactions in nature. Rather than risking unintended ecological consequences of direct manipulation of nature, CRED and PMEL plan to conduct intensive ecological and biogeochemical studies at shallow hydrothermal venting sites, such as Maug caldera, in the geologically active Northern Mariana Islands. These focused efforts would closely examine short-term and historic (see below) ecological responses to fine-scale gradients in pH, carbonate chemistry, as well as nutrients and metals, around the vent sites. This research will examine the role microbes play in biogeochemical cycling, energy transduction, and related ecosystem processes under varying carbonate chemistry conditions. This has been one of the main themes of chemical/microbiological research on deeper hydrothermal vent systems, including those elsewhere within the MT-MNM. Microbial oceanographers will make field observations of the distributions, abundances, diversity and metabolic activities of microorganisms at the selected sites. As understanding of the existing conditions increases, these studies will then examine responses of organisms distant from the vent sites to locations adjacent to the vent sites. Complementing the laboratory experiments, these natural experiments will provide unique insights into the potential future of coral reef ecosystems under increasingly acidic ocean conditions predicted over the next century.

4.2.3 Estimate historical response to variation in saturation state

Task 4.2.3: Estimate historical changes to corals as a response to fluctuating CO_2.

Coral sclerochronology of both branching and massive reef-building scleractinian corals will be used to retrospectively assess historical growth and accretion rates. The presence of annual density bands in coral skeletons provide historical records of linear extension rates, skeletal density, and calcification rates over the often long lifespan of many reef-building corals. Historical records of calcification and growth rates will advance our understanding of how calcification rates have changed since the industrial revolution. Similar to counting the rings of a tree, historical annual accretion rates can be determined from coral cores. In collaboration with Woods Hole Oceanographic Institution (WHOI), CRED will initiate a pilot coring project in 2010 and 2011 to collect short (~10 cm) cores at a few select locations across nutrient (upwelling) and latitudinal gradients in the PRI-MNM. The cores will be analyzed using non-destructive CAT scan image analysis techniques that allow an examination of the 3-dimensional internal structure of the coral core and its associated growth rates (Cohen *et al.*, 2009; Saenger *et al.*, 2009). After these initial pilot efforts, this project will be expanded spatially across important oceanographic gradients across the entire PIR and to include coring a small number of ancient massive corals to allow examination of calcification rates since before CO_2 emissions dramatically increased during the industrial revolution.

In addition to examining calcification rates of massive corals using cores, the CAT scan technique will be employed to examine calcification and accretion rates of relatively short-lived branching corals across multiple taxa. This is important since there is no a priori reason to believe that short-lived (years to decades) coral species will respond similarly to corals that have survived for centuries. From an immediate conservation management perspective, efforts will focus initially on examining recent accretion rates of select coral taxa currently being petitioned for listing under the Endangered Species Act.

4.2.4 Experiments on beach forming processes

Task 4.2.4: Conduct experiments on how beach forming processes will be affected by ocean acidification.

Due to the urgency to better understand and predict the fate of critical nesting beach habitats for critically endangered Hawai'ian monk seals and multiple species of threatened sea turtles, it is important to initiate focused laboratory experiments to examine the direct impacts of increasing CO_2 (decreasing pH) on many of the dominant sand-producing calcareous algae, as well as the biogeochemical processes of existing sand deposits.

4.2.5 Response experiments for cetaceans

Task 4.2.5: Behavior response experiments of cetaceans to increased ocean sound propagation with ocean acidification

NOAA will initiate literature reviews of known acoustic behavioral patterns of Pacific Islands cetacean species to improve our understanding of auditory ranges, behavioral uses (navigation, foraging, reproduction, defense, etc.), and potential acoustic vulnerabilities. In the longer term, and based on the gap analyses provided by these reviews, additional research and testing may be proposed.

4.3 Biogeochemical and Ecosystem Models (Theme 3)

Task 4.3.1: Develop finescale, wave-driven hydrodynamic circulation models for coral reef habitats throughout the Pacific Islands region.

Biogeochemical processes in coral reef habitats are dynamic interactions involving coupled physical, chemical, and biological processes each working on different space and time scales. In order to develop effective predictive models of the biogeochemistry (for calcification rates), sand transport dynamics (for nesting beaches for monk seals and turtles), and numerous other ecosystem processes (larvae transport and recruitment, coral bleaching, coastal sedimentation, etc.) it is essential to have well-developed hydrodynamic models that can predict wave and tidally driven circulation patterns at fine spatial scales (~10 m). Therefore, NOAA's PIFSC will significantly expand preliminary hydrodynamic modeling efforts (Hoeke *et al.*, 2010) by establishing internal scientific capacity to sustain an on-going hydrodynamic model development effort for the PIR. This effort will require a full-time hydrodynamic modeler, computing infrastructure, and an inventory of acoustic Doppler current profilers, wave and tide recorders, and other oceanographic instrumentation to conduct intensive hydrodynamic surveys at select reef sites that will be used to develop and validate the models. Due to the complex flow-topography interactions in reef habitats, it is also important to acquire high-resolution bathymetry for each of the areas to be modeled. The in situ instrumentation will be rotated to different prioritized coral reef sites around the PIR to repeatedly develop and validate models for the different reef areas. These modeling efforts will provide lagoon and reef residence times for developing biogeochemical models, sand transport models, and ecosystem interaction models for reefs across the PIR.

Task 4.3.2: Develop biogeochemical models to predict Pacific Islands ecosystem responses to ocean acidification.

Biogeochemical processes of coral reefs involve complex physical, chemical, and biological interactions that are dependent upon boundary layer dynamics, benthic composition, water flow characteristics, and seawater chemistry. In order to assess, predict, and develop effective mitigation strategies to minimize the ecosystem impacts of OA, it is necessary to understand and develop biogeochemical models at a range of spatial and temporal scales. In the PIR, NOAA plans to initiate the long-term development of a biogeochemical modeling program that will be closely integrated with the hydrodynamic (Task 4.3.1) and ecosystem modeling efforts (Task 4.3.3), as well as the OA (carbonate chemistry) and biological monitoring efforts. As this effort will necessarily require internal capacity building, it is essential to have full-time biogeochemist positions established at PIFSC to coordinate this interdisciplinary OA effort in the PIR, and in collaboration with other regional OA teams across the country. At large spatial scales (basin and regional), this effort will utilize ocean circulation models, satellite imagery of surface conditions, and shipboard spatial carbonate chemistry surveys across the Pacific to develop improved hindcast and prediction models of saturation state, following methods developed by Gledhill *et al.* (2008) and Gledhill *et al.* (2009).

Task 4.3.3: Refine existing trophic interaction ecosystem model (Ecopath with Ecosim) to predict ecosystem impacts of ocean acidification in the Pacific Islands.

In 1984, J. Polovina and his colleagues at PIFSC developed EcoPath, an innovative marine ecosystem model of the coral reef ecosystem at French Frigate Shoals (Polovina, 1984). It was the first model to apply a type of statistics called "path analysis" to the field of marine ecology. EcoPath estimates a biomass budget for the marine ecosystem, in a static situation under the assumption that the ecosystem is at equilibrium conditions. The model accurately identifies ecological relationships, and helps untangle complex marine ecosystems. The model can be used to estimate the direction and strength of all factors that influence the way ecosystems function, and can be adapted to help locate marine protected areas, and model the effects of changing climate on a coral reef ecosystem.

Much of the modeling work on ecosystems has been through the use of the output of global climate models as drivers for multispecies or trophic models. While these studies have produced insights into potential effects of climate change, feedback mechanisms have typically been inadequate. Ecosystems involve complex direct and indirect pathways between their many ecological, physical, biogeochemical, and human components. To adequately model and predict ecosystem impacts of OA, the non-stationary nature of the ecosystems and their dynamics needs to be addressed explicitly. In the PIR, NOAA will establish a long-term ecosystem modeling team at PIFSC, along with NOAA and academic partners, to examine and predict the ecosystem impacts of OA in both coral reef and pelagic ecosystems across the Pacific using the Ecopath with Ecosim (EwE) ecosystem modeling suite. We plan to couple EwE with biogeochemical models, and through them global climate models (GCMs), to begin to build models that have dynamic feedback connections. Though there are significant scientific challenges involved in successfully and seamlessly coupling models with different temporal, spatial, ecological, anthropogenic, and process resolutions, this long-term effort must be an essential component to our OA implementation plan.

Task 4.3.4: Develop coupled sand transport and biogeochemistry models to predict the impacts of ocean acidification on critical nesting beach habitats.

Critically endangered Hawai'ian monk seals and threatened sea turtles require sandy beaches for pupping and nesting, respectively. In the remote P-MNM, sea level rise and other processes are threatened to eliminate many, and possibly all of these critical nesting beaches over the next century (Baker *et al.*, 2006). In addition to sea level rise, these beaches are potentially threatened by decreased sand production, as OA is predicted to decrease calcification rates of sand-producing calcareous algae and corals that comprise the large majority of these nesting beaches. As conservation of these endangered species is among NOAA's highest management priorities, NOAA plans to initiate the development of coupled hydrodynamic, biogeochemical, and climate models to predict the future status of these nesting beach habitats in the NWHI. This work will involve collaborative work among PIFSC, UH, and the U.S. Geological Survey (Storlazzi *et al.*, 2005). The necessary hydrodynamic field work for this effort was described in task 4.3.1. In addition, aerial LiDAR and repeat satellite imagery will be acquired to provide the finescale bathymetry needed the model development and validation.

Task 4.3.5: Develop sound propagation models to predict the impacts of ocean acidification on protected cetacean species across the Pacific Islands region.

Recent research has demonstrated that low-frequency sound propagation in the ocean will increase significantly with decreasing pH as ocean acidification unfolds over the next century (Hester *et al.*, 2008; Ilyina *et al.*, 2010). These increases in sound propagation will mean that sound travels further and that the ocean will become noisier. The impacts of these changes in ocean sound propagation on the 46 known species of cetaceans in the PIR are not currently known. To address these unknowns, NOAA will complement the acoustic monitoring outlined in Task 4.1.3 and the behavioral characterizations outlined in Task 4.2.5 by developing regional sound propagation models under a range of climate and OA model scenarios.

4.4 Human Dimensions (Theme 4)

Task 4.4: Estimate the impact of ocean acidification on socioeconomic activities.

Ecosystem services in the Pacific Islands are economically dominated by tourism and commercial fisheries; however the natural shoreline defense and deep cultural roots embedded in reef systems as a subsistence resource, although more difficult to evaluate, are also vital to island communities across the region. The economic value of Main Hawai'ian Island reefs alone are estimated at nearly $10 billion, with an average annual benefit of $385 million (Cesar *et al.*, 2003). The socioeconomic impacts of projected changes to nearshore coral reef ecosystems, commercial, recreational, and subsistence fishery resources, protected species, beaches, and cultural identity in the Pacific Islands will be examined through retrospective analyses of past changes across the region and through initiation of regional surveys of key demographics of communities user groups in the main Hawai'ian Islands, Guam, CNMI, and American Samoa. This work will be conducted by sociologists and economists at PIFSC, in collaboration with NOAA and academic partners across the PIR. The surveys in the respective subregions (Hawai'i, Guam, CNMI, and American Samoa) will require either extensive contracting or travel.

4.5 Synthesis of Data and Information Products (Theme 5)

Task 4.5: Develop data and information tools for evaluating the consequences of ocean acidification in the PIR to create more effective management strategies.

Database infrastructure and agreement on standardization of data format, metadata, and storage, is vital for the smooth running of this project. Since NOAA PIFSC CRED has extensive experience and capability developed for managing the complex interdisciplinary mapping, monitoring, oceanographic, and biodiversity data of Pacific RAMP and CReefs using a fully relational Oracle database, that is proposed as the baseline by which to expand and build upon. This effort will identify at least one full-time data manager for the organization and upkeep of the expanding database and one full-time applications programmer to ensure appropriate tools are continually developed and refined to ensure that all data are disseminated broadly to stakeholders and the public in user-friendly graphical formats in a timely manner. These positions should be implemented as the early states of this effort.

All of the data gathered as part of this Ocean Acidification Research Plan for the Pacific Islands will be promptly disseminated to the national ocean acidification information center, as well as the NOAA NESDIS National Oceanographic Data Center, the Pacific Integrated Ocean Observing System (PacIOOS), the Surface Ocean $p\mathrm{CO}_2$ Atlas (SOCAT) coastal effort overseen by the International Ocean Carbon Coordination Project of the Intergovernmental Oceanographic Commission (IOC) (`http://ioc3.unesco.org/ioccp/UW.html`). Biodiversity data will be submitted to the Ocean Biogeographic Information System (OBIS).

4.6 Engagement Strategy (Theme 6)

Task 4.6: Implement an education and outreach program in the PIR to increase public understanding of ocean acidification.

A key goal of the PIR OA Research Plan is to effectively engage policy makers, resource managers, key stakeholders, and the general public, both in island communities and on the mainland U.S. This engagement will focus primarily on identifying and developing audience-specific information products through a diverse range of multi-media communication tools, including social networking tools, public meetings, workshops, and local and national news outlets. These efforts will be led by NOAA public affairs professionals at the Office of National Marine Sanctuaries, particularly the Papahānaumokuākea Marine National Monument, NOAA Fisheries, NOAA Coral Reef Conservation Program, the NOAA Climate Service, NOAA IDEA Center, NOAA Pacific Services Center, Hawai'i Sea Grant, and the many federal, state and territorial agencies (see collaborators). In local jurisdictions, field staff and existing scientific and management liaisons in the local jurisdictions will be asked to communicate findings and solicit suggestions for effective public engagement at local levels. Timely dissemination of data and data information products will be made available online shortly after collection, and telemetered data are available near real time on the internet.

Stakeholders, as well as the public at large, will be kept informed about recent discoveries about ocean acidification from on-going work and other findings internationally on the topic. Efforts must be made to engage local communities and schools to actively participate in the process of addressing the problem of ocean acidification through “think globally act locally” activities. NOAA must actively strive to provide unbiased scientifically credible information that stakeholders can rely upon to make challenging policy decisions effecting local, regional, and national issues. It is important that managers and stakeholders understand that they must be part of the solution locally if society is to address the issue of ocean acidification nationally and internationally.

4.7 Collaborators

Pacific Islands Region Collaborators
Pacific Islands Fisheries Science Center
Pacific Marine Environmental Laboratory
Atlantic Oceanographic and Meteorological Laboratory
Coral Reef Conservation Program
Coral Reef Watch
Pacific Services Center
Papahānaumokuākea Marine National Monument
Pacific Remote Islands Marine National Monument
Fagatele Bay National Marine Sanctuary
Hawai'ian Islands Humpback Whale National Marine Sanctuary
Western Pacific Regional Fishery Management Council
University of Hawai'i (UH) School of Ocean and Earth Science and Technology
UH Hawai'i Institute of Marine Biology
Hawai'i Sea Grant
University of California, San Diego—Scripps Institute of Oceanography
Woods Hole Oceanographic Institution
Smithsonian Institution—National Museum of Natural History
University of Guam—Marine Lab
University of Florida—Florida Museum of Natural History
University of Miami—Rosenstiel School of Marine and Atmospheric Sciences
Hawai'i Pacific University
Hawai'i Department of Land and Natural Resources
Waikiki Aquarium
American Samoa Department of Marine and Wildlife Resources
American Samoa Department of Commerce
National Park of American Samoa
Guam Division of Aquatic Resources
CNMI Division of Fish and Wildlife
CNMI Division of Environmental Quality
CNMI Coastal Resource Management Office
The Nature Conservancy
Marine Conservation Biology Institute
Australian Institute of Marine Sciences
Sir Alister Hardy Foundation for Ocean Science

5. Southeast Atlantic and Gulf of Mexico Region Ocean Acidification Research Plan

Dwight K. Gledhill, Theresa Goedeke, Kevin Helmle, James Hendee, Anna Hilting, Elizabeth Jewett, Brian Keller, Derek Manzello, Margaret Miller, Erica Rule, Bill Sunda, Fran Van Dolah, and Rik Wanninkhof

5.0 Ocean Acidification in the Southeast Atlantic and Gulf of Mexico Region

THIS CHAPTER PRESENTS NOAA's research strategy toward addressing ocean acidification (OA) within the U.S. Southeast Atlantic Coastal Region, Greater Caribbean, and Gulf of Mexico (henceforth denoted as SER/GOM). As the precise effects of OA on the SER/GOM remains largely unknown, our initial efforts must be heavily geared toward addressing fundamental research and monitoring needs. However, these research and monitoring efforts are intended to establish the requisite scientific understandings necessary to forecast socioeconomic consequences. This chapter offers a strategy directed toward the unique challenges and priorities of the SER/GOM in regards to the impacts of OA on marine ecosystems and associated eco-services (e.g., fisheries and eco-tourism). These include evaluating the regional consequences from direct and indirect impacts on shellfish, fishing, and tourism industries.

5.0.1 Regional planning drivers

The Gulf of Mexico Alliance (`http://gulfofmexicoalliance.org/`) has recently enacted an Action Plan II (`http://gulfofmexicoalliance.org/pdfs/ap2_final2.pdf`) to address the most serious ecosystem threats to the Gulf. The plan calls for providing better information to coastal residents about the potential impacts of climate change. The Governors' South Atlantic Alliance: A Call To Action Framework (North and South Carolina, Georgia, Florida) emphasizes a significant need in the region for standardized, integrated, and accessible spatial and temporal data for the management of coastal marine resources in this region. The alliances will enhance collaborations necessary to address region-wide ecosystem issues. In addition, protected resource management plans developed by the South Atlantic and Gulf of Mexico Fishery management councils should include OA-relevant impacts where appropriate. This also applies to the management plans of the three National Marine Sanctuaries in the region (Flower Garden Banks, Florida Keys, and Gray's Reef).

5.0.2 Regional changes in carbonate chemistry

The warm tropical oceanic waters of the South Atlantic and Caribbean exhibit some of the highest carbonate mineral saturation states of global oceans and are expected to remain supersaturated with respect to most carbonate mineral phases for the foreseeable future. However, due to the projected decline in carbonate mineral saturation states and experimentally demonstrated positive relationship between the degree of supersaturation and calcification rates (e.g., Langdon and Atkinson, 2005), OA will likely impact NOAA living marine resources within the region. Carbonate ion concentrations have already declined in tropical oceanic waters by more than 20% over the industrial period (Orr *et al.*, 2005) with corresponding changes in carbonate mineral saturation. This degree of saturation is currently decreasing across the SER/GOM at a rate of about 3% per decade and exhibits considerable spatial and seasonal variability (Gledhill *et al.*, 2008, Figure 2).

While "ocean acidification" typically refers to the global-scale changes occurring in surface ocean

Southeast Atlantic and Gulf of Mexico Region Description

The **NOAA Southeast and Caribbean (SER)** component of this regional plan covers the U.S. coast from North Carolina through Texas, including the U.S. Caribbean and Puerto Rico. This region is composed of the oceanic and coastal zones of North Carolina, South Carolina, Georgia, Florida, Puerto Rico, and the U.S. Virgin Islands and associated marine environments. The region contains over 18,000 miles of coastline, with extensive riverine, estuarine, marsh, barrier island, mangrove, shallow coral reefs, and mesophotic and extensive deep-sea coral ecosystems. They support a diverse assemblage of marine life, with 18 protected marine species, over 600 marine managed areas, including unique mid-depth (80–100 m) reefs of the Oculina Banks and the western hemisphere's second largest barrier reef system. The only two ESA-listed coral species (Elkhorn [*Acropora palmata*] and Staghorn [*A. cervicornis*]) and the only ESA-listed marine plant species (Johnsons' seagrass [*Halophila johnsonii*]) occur exclusively in the SER/GOM. Important oceanic circulation systems, including the Loop Current, Florida Current, and Gulf Stream, have an important influence on the biological, chemical, and physical characteristics of many of the region's ecosystems. Climate is warm-temperate to tropical.

The **NOAA Gulf of Mexico (GOM)** region includes the oceanic and coastal zones of Florida, Alabama, Mississippi, Louisiana, and Texas. The Gulf of Mexico is a 218,000 square mile semi-closed, oceanic basin that is connected to the Atlantic Ocean by the Straits of Florida and to the Caribbean Sea by the Yucatan Channel. The Gulf of Mexico is the ninth largest water body in the world and teems with sea life that includes unexplored deep-sea corals, unique deep sea brine seep communities, and one of the most pristine and healthy coral reef ecosystems of the Caribbean at the Flower Garden Banks. Watersheds from a total of 33 of the 48 contiguous states drain into the Gulf of Mexico through the Mississippi River watershed. The Gulf's coastal region contains half the coastal wetlands in the U.S. (17.2 million acres of marsh and nearly 30,000 miles of tidal shoreline) and is home to abundant wildlife resources, including colonial waterfowl rookeries, sea turtles, oysters, and fisheries. In addition, two species of sturgeon, the Gulf and the Short nose sturgeon, and the Small-tooth Sawfish, all of which are native to this region and could be affected by OA due to the vulnerability of their prey, are listed as either endangered or threatened. These resources are supported by rich natural habitats, including bays, estuaries, tidal flats, barrier islands, hard and soft wood forests, and mangrove swamps. The Gulf region's ecological communities are essential to sustaining nationally vital economic and recreational industries.

chemistry in direct response to changing atmospheric chemistry, there are many natural processes that can influence seawater carbonate chemistry on local and regional scales that need to be considered when evaluating the potential long-term consequences of OA. These can include changes in seawater carbonate chemistry attributed to biological processes (e.g., respiratory production or photosynthetic removal of CO_2), advection or mixing (both lateral and vertical) of waters with different chemical compositions, fresh water inputs, gas exchange processes, and other anthropogenically influenced processes unrelated to changes in atmospheric CO_2. Eutrophication, algal blooms, and hypoxia are common features of estuaries and coastal waters of the SER/GOM and can exacerbate acidification in surface sediments and bottom waters. In addition, changes in alkalinity and calcium ion concentrations due to river or ground water inputs can affect carbonate mineral saturation states. Such processes contribute to considerable variability within the coastal, coral reef, and estuarine systems throughout the SER/GOM.

5.0.3 Eutrophication and hypoxia

Eutrophication and associated oxygen depletion and acidification of bottom waters are widespread in the SER/GOM. A large area near the mouth of the Mississippi River in the Gulf of Mexico develops hypoxia (dissolved oxygen below 2 mg/l) in the bottom waters every summer due to large inputs of nutrient-rich river water from the Mississippi and Atchafalaya Rivers. The areal extent of the hypoxic zone has increased 3-fold since systematic monitoring began in 1985 (Rabalais *et al.*, 2007; 1999). Similar but smaller regions of hypoxia also develop in (or are a potential concern for) many euthrophic SER/GOM estuaries (an estimated total of 151 systems along the U.S. Gulf coast and another 109 along the Southeast Atlantic coast; (Committee on Environmental and Natural Resources (CENR), 2010). Eutrophic estuaries are prone to hypoxia as a result of the input of nutrient-rich river water that fuels algal blooms. In estuaries, the inflowing river water flows out over the denser saline water, causing a pycnocline which prevents oxygenated surface waters from mixing with bottom waters. The particulate organic matter from the algal blooms settles to the bottom and is respired by bacteria, which simultaneously remove oxygen and produce CO_2. Although hypoxia has been well studied and linked to nutrient enrichment in many eutrophic estuaries and coastal systems, the combined effects of hypoxia and ocean acidification has been little studied. Hypoxia and acidification are known separately to adversely impact economically important shellfish and finfish (Lewitus *et al.*, 2009; Green *et al.*, 2004; Kurihara, 2008), and the combined effect of the two stressors may be particularly deleterious.

5.0.4 Vulnerable species and ecosystems in the SER/GOM

In this section we review potential impacts of OA on some of the SER/GOM's ecologically sensitive and/or economically important marine species, including molluscs (oysters and clams), crustaceans (shrimp and blue crabs), reef-building corals, and calcifying macro- and microalgae.

5.0.4.1 Coral reefs

A key concern with regard to OA and coral reef ecosystems is the maintenance of net positive rates of annual accretion (reef growth). Any decline in calcification or increase in net erosion or dissolution could compromise the persistence of reef systems within the SER/GOM because rates of accretion on healthy, undisturbed reefs are known to only slightly outpace rates of reef loss due to physical and biological erosion (see Glynn, 1997 for review). Significant historical declines in growth rates of Caribbean corals have been documented (Edmunds, 2007; Bak *et al.*, 2009), and likely result from a combination of local and global changes, with the specific effects of OA being difficult to discern. While oceanic surface waters in the SER/GOM will remain supersaturated with respect to aragonite for several centuries (e.g., $\Omega > 1$), net dissolution of coral reefs could be reached much sooner (around $\Omega > 3$ [Manzello *et al.*, 2008; Hoegh-Guldberg *et al.*, 2007]). Dissolution of reef structures and sediments could be a concern well above saturation as well because most reefs contain appreciable amounts of more soluble high-Mg calcite (Morse *et al.*, 2006). Furthermore, diurnal variations in CO_2 concentrations within the reef zone can be 10 times that of oceanic waters due to high rates of photosynthesis, calcification, and respiration. High net rates of respiration at night can lead to critically high CO_2 concentrations and low pH that may result in periods when many reefs exhibit net dissolution.

Beyond the direct calcification/dissolution concerns to coral reefs, there are several other effects that need to be considered. Several incidences of mass coral bleaching due primarily to thermal stress have occurred in recent decades in the SER/GOM (McWilliams *et al.*, 2005). Recent findings suggest that OA may act to lower thermal thresholds for bleaching (Anthony *et al.*, 2008) and thereby contribute to coral bleaching events. It is possible that decreased Ω_{arag} values could contribute to population declines in coral species. Caribbean reef-building corals have very low rates of recruitment and OA might further inhibit recruitment rates owing to the increased costs of calcification in energy-limited and temperature-stressed larval and adult corals in low Ω_{arag} waters. Recruitment could be adversely affected by declines in gamete production (Cohen and Holcomb, 2009), fertilization success, and larval development and survival rates.

The SER/GOM is also home to extensive deep-sea coral ecosystems (Lumsden *et al.*, 2007), which may exceed shallow coral reefs in spatial extent. They support extensive fisheries production and are thus targeted in greatly expanded spatial management areas (Habitat Areas of Particular Concern) by the South Atlantic Fishery Management Council. Due to their position nearer the aragonite saturation horizon (ASH), they may experience greater threat and more rapid impacts from OA than their shallower counterparts (Guinotte *et al.*, 2006). Depth and inaccessibility means that the biology and ecology of these ecosystems is relatively little known, but the lesser diversity of deep-sea scleractina and their greater exposure to reduced saturation state threats make them an important model system to address in OA research.

5.0.4.2 Shellfish

Shrimp, crabs, and mollusc fisheries represent important economic resources in the SER/GOM. Cooley and Doney (2009) estimate the entire $600 million commercial fishery in the Gulf and the entire $550 million commercial fishery along the Atlantic coast may be affected by OA. In addition to their commercial importance, many shellfish such as oysters and shrimp are of central ecological significance in their respective coastal and estuarine habitats. Oysters are a historically important commercial and recreational fishery in the Carolinas and Gulf region, and state and federal agencies have allocated significant resources toward oyster restoration. Oyster reefs provide habitat for a range of marine species and help stabilize shorelines. Their viability depends on their ability to vertically accrete at a rate sufficient to maintain the reefs above the sediments. Oysters are significant consumers of marine microalgae in southeast estuaries and play an important role in their removal, helping to maintain water clarity and prevent algal blooms.

5.0.4.3 Marine plants

Seagrass meadows are often found in close proximity to corals and their ecosystem functions are interdependent. By increasing seawater pH, seagrass photosynthesis can significantly increase the calcification rate of calcareous reef algae (Semesi *et al.*, 2009). This has led some researchers to speculate that dense, shallow, highly productive seagrass meadows can mitigate potential effects of OA on seagrass-associated organisms, including corals (Semesi *et al.*, 2009). Extensive seagrass beds are found in SER/GOM estuaries and coastal shelves and may perform a similar mitigating effect on OA in these environments. Seagrass meadows provide critical habitats for scallops and other molluscs and may help protect these calcifying organisms from the adverse impacts of OA via photosynthetic removal of CO_2. Such potential protective effects of photosynthesizing plants need to be directly examined by field observations and experimentation.

5.0.4.4 Calcifying and competing non-calcifying marine phytoplankton

Increasing CO_2 concentrations may stimulate the growth rates of at least some marine phytoplankton. Furthermore, rates of nitrogen fixation by cyanobacteria, which regulate inputs of available fixed nitrogen in coastal and offshore waters throughout the SER/GOM, has been shown to be stimulated by elevated CO_2 (Hutchins *et al.*, 2007; Fu *et al.*, 2008). By benefiting some species but not others, increased CO_2 is also likely to shift the species composition of marine phytoplankton communities. Changes in species composition of marine phototrophs may have unforeseen effects on the overall structure and function of marine food webs. Studies have already shown that the growth of the N_2-fixing cyanobacterial species, *Trichodesmium*, is stimulated by higher CO_2 levels (Levitan *et al.*, 2007; Hutchins *et al.*, 2007). *Trichodesmium* is found in close association with *Karenia brevis*, and may facilitate blooms of this species in the Gulf of Mexico. *Karenia* is a toxic alga that causes red tides along the west Florida shelf and the coast of Texas (Lenes *et al.*, 2008).

5.0.4.5 Coastal and oceanic finfish

Many species of ecologically and commercially important fish spawn in offshore waters of the outer continental shelf and coastal ocean with larvae dispersed through ocean currents. The pH and $p\mathrm{CO_2}$ regiment of this environment is relatively stable in comparison to coastal estuaries. This lack of wide variations in pH and $p\mathrm{CO_2}$ may confer that early life stages of these species could lack an innate ability to cope with OA. The fossil record shows that modern bony fish, Osteichthyes, diversified in the late Cretaceous and early Cenozoic at atmospheric CO_2 levels below 1000 ppm and some Families (sea basses, croakers, and drums), as late as the Miocene/Pliocene, transition at CO_2 levels of 300–400 ppm. NOAA ship surveys (SEAMAP) using plankton nets continue to collect, study, and archive larval fish and eggs from the GOM at the Southeast Fisheries Science Center. These early life stages are those first expected to indicate reproductive impairment from

OA. In addition, additional laboratory studies of egg fertilization and larval survival at reduced pH will be a crucial part of determining the level of susceptibility of coastal and oceanic fin-fish resources and an assessment of when changes to fisheries and ecosystems might occur.

5.1 Developing an Ocean Acidification Monitoring Network (Theme 1)

Atlantic Oceanographic and Meteorological Laboratory (AOML) has been conducting measurements of sea surface CO_2 throughout the SER/GOM for more than a decade to evaluate oceanic uptake and storage of CO_2. The measurements of surface CO_2 are routinely conducted using both NOAA research vessels and volunteer observing ships (VOS) and have provided the basis for developing satellite-based algorithms now being regularly applied to map the distribution and variability of aragonite saturation states across much of the SER/GOM region. Synoptic estimates of sea surface carbonate chemistry are distributed monthly through NOAA's Coral Reef Watch (CRW) and efforts have begun to extend this throughout the full SER/GOM region and to better constrain the model in more dynamic regions such as in the northern Gulf of Mexico.

The NOAA Coral Reef Conservation Program has also begun advancing the development of an Atlantic Ocean Acidification test-bed in La Parguera, PR. The project is a joint effort between NOAA AOML and PMEL, the University of Miami/RSMAS (Rosenstiel School of Marine and Atmospheric Science) and the University of Puerto Rico Mayagüez. The test-bed serves as a nexus of federal agency and academic monitoring and research activities related to OA. Since January 2009, sustained monitoring of near-reef $pCO_{2(aq)}$ has been conducted using a Moored Autonomous $pCO_{2(aq)}$ ($MAPCO_2$) measuring system developed by NOAA PMEL. The mooring observations are supplemented by weekly carbonate chemistry surveys across the Cayo Enrique forereef and rely on the nearby ICON/CREWS station to provide meteorological and oceanographic observations. PMEL currently has two other $MAPCO_2$ buoys deployed in the SER/GOM, including one in the northern Gulf of Mexico off the coast near Biloxi, Mississippi (30.0°N, 88.6°W) and one at Gray's Reef National Marine Sanctuary off Savannah, Georgia, in the South Atlantic Bight on NDBC buoy 41008 (31°N, 081°W).

5.1.1 Oceanographic monitoring

Task 5.1.1: Establish requisite analytical capability for conducting high-quality carbonate chemistry measurements and training at AOML.

A critical need to achieving the research requirements detailed below is to assure quality standardized measurements of the seawater CO_2-system and associated chemistry. To achieve such measurements, it will be necessary to establish a centralized shared facility within the SER/GOM that will serve as a companion facility to NOAA PMEL and that is equipped and staffed to provide quality assured measurements of total alkalinity (TA), coulometric total dissolved inorganic carbon (DIC), and spectrophotometric pH according to the Guide to Best Practices for Ocean CO_2 Measurements (Dickson *et al.*, 2007). The facility would also provide for regular SER/GOM regional training on best sampling and storage practices for carbonate chemistry and would coordinate closely with NOAA PMEL as described in the enabling activities in Chapter 1.

Task 5.1.2: Establish SER/GOM ocean acidification coastal/oceanic mooring network.

Moorings along the continental shelf and within the open-ocean will be refurbished and augmented with additional sensors to provide comprehensive biogeochemical data with high temporal resolution necessary for evaluating changes in ocean chemistry related to OA (Figure 5.2). This effort will leverage existing CO_2 sensors and infrastructure designed to measure air-sea CO_2 fluxes, which are at or past their project completion dates. The OA program, along with extramural partners, will utilize existing moorings and provide for annual refurbishments, sensor augmentation, telemetry, data quality assurance, and data product delivery. Seasonal discrete samples will be taken at the sites to provide for validation and supplemental measurements (e.g., total alkalinity [TA], total dissolved inorganic carbon [DIC], nutrients, and calcium). The moorings are to be strategically located to provide optimal scientific value toward advancing NOAA's understanding of OA as it relates to resource management and will leverage other federal and academic research activities substantially (see Tables 1.2 and 1.3, and Figure 1.4 of the National Chapter). In FY2010, this refurbishment will happen for

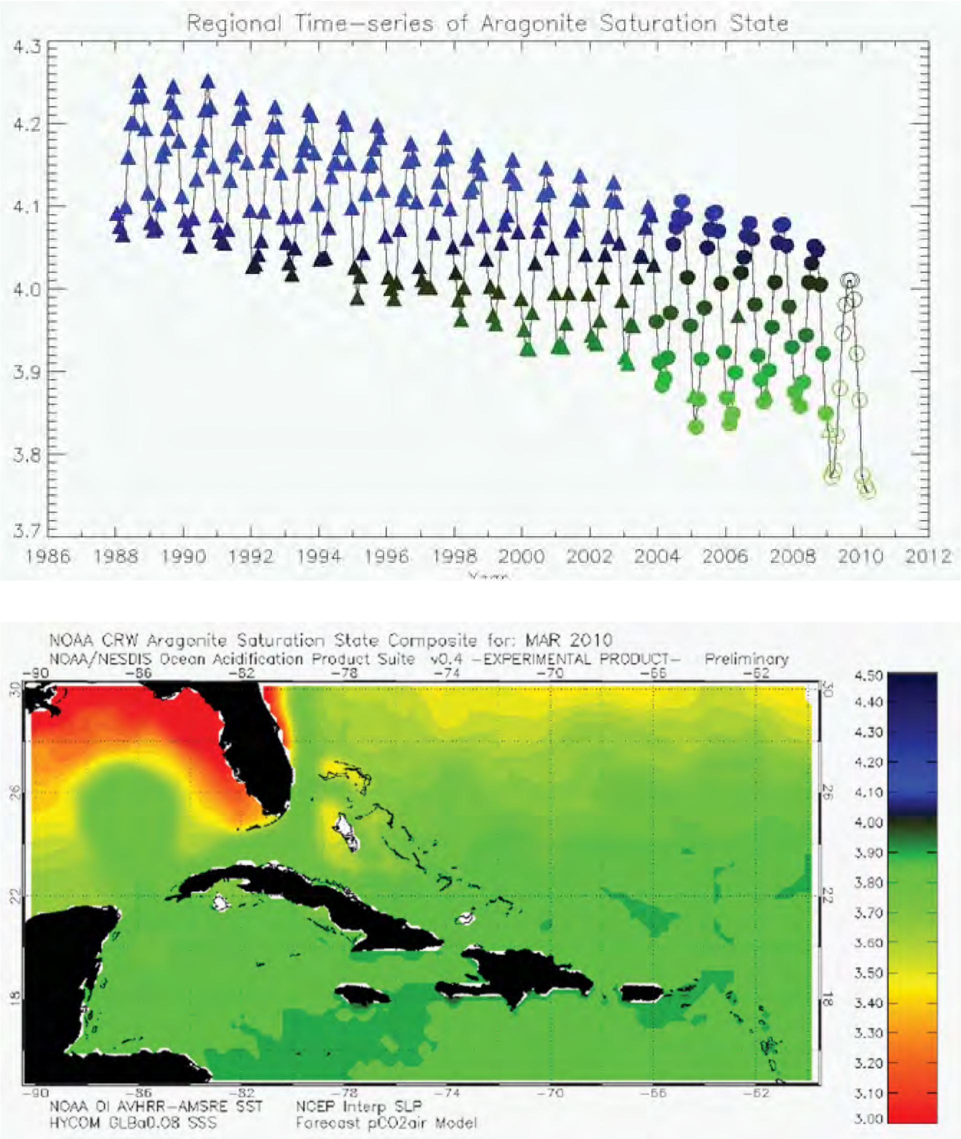


Figure 5.1: Aragonite saturation state within oceanic surface waters of the Greater Caribbean Region (top) and regional distribution for March 2010 (bottom) based on Gledhill *et al.* (2008) and available from NOAA Coral Reef Watch.

both the Gray's Reef and Mississippi Bight fixed mooring buoys.

Priority moorings within the SER/GOM that are targeted for upgrade and incorporation into the OA network include those in the Northern Gulf of Mexico off the coast near Biloxi, Mississippi (30°N, 89°W) and in the South Atlantic Bight off of Georgia (31°N, 81°W). The northern Gulf of Mexico mooring will provide information on the interactions between hypoxia and OA near the Mississippi River Plume in an ecosystem containing diverse marine resources. The mooring in the South Atlantic Bight will reveal the interaction between open-ocean, shelf waters, and river waters with low alkalinity from the southeastern U.S. The OA buoy-based monitoring system will be expanded as outlined in Chapter 1.

Task 5.1.3: Conduct SER/GOM ocean acidification hydrographic/geochemical ship surveys.

To assess spatial dynamics in OA and evaluate potential interactive effects with coastal processes, we will leverage our Ship of Opportunity Program (SOOP) infrastructure (Figure 5.2). Underway observatories will be enhanced by the collection and analysis of discrete DIC and TA samples. Oxygen sensors will also be deployed and are necessary for improved under-

Figure 5.2: A broad range of experiments, process studies, and monitoring activities are required to assess the impact of ocean acidification on marine resources of the southeast, Caribbean, and Gulf of Mexico ocean and coastal waters. Some of the Theme 1 (Section 5.1) activities detailed in the research plan are depicted here: coral reef OA monitoring sites (yellow), coastal/oceanic OA moorings (red), hydrographic/geochemical ship surveys (black lines).

standing of biological response to the interaction of OA and low oxygen conditions and for development of proxy algorithms for inorganic carbon parameters. To adequately sample the variability along the Gulf and East coasts, AOML will install automated systems on the NOAA fisheries ships *Gordon Gunter* and *Bigelow*, and NOAA research ship *Nancy Foster*. AOML will also augment the SOOP $p\mathrm{CO}_2$ surface water measurements sponsored by the NOAA Climate Observation Division on open-ocean vessels with oxygen sensors. Outfitting these NOAA vessels with underway $p\mathrm{CO}_2$ systems will enhance their on-going ecosystem and fisheries research and assessments activities. The ships also provide a convenient means to obtain validation samples. As part of the advanced technology requirements, discrete manual sampling will be augmented by ship-based auto-samplers to automatically obtain sample sets.

Evaluating the susceptibility of deep sea coral communities (e.g., mapping of the aragonite saturation horizon) and tracking the seasonal shoaling of low pH waters will demand full 3D mapping of carbonate chemistry. While the SOOP effort will provide a comprehensive surface mapping, dedicated NOAA shiptime will be required to obtain the requisite 3D subsurface measurements. Such cruises will require 30 days at sea every two years on a class I or II vessel with a full complement of biological and chemical measurements. In addition, two annual cruises of 10–14 days duration (e.g., NOAA ship *Nancy Foster* or equivalent charter) are required for specific process studies, such as estimations of riverine influences on OA, validation cruises of saturation state algorithms, reef system-wide calcification rates, and assessing the bio-optical signature of key processes affected by OA.

Task 5.1.4: Regional carbonate chemistry synoptic mapping.

NOAA AOML is advancing the development of regionally synoptic maps of surface carbonate chemistry in near real time. A quasi-operational product is currently distributed by NOAA CRW. The current product delivers a monthly × 0.25 degree synthesis of satellite and modeled environmental datasets to provide a synoptic estimate of the distribution of sea surface carbonate chemistry throughout the Greater Caribbean Region (GCR) (Gledhill *et al.*, 2008). The satellite-based algorithms that drive this experimental model are regionally specific to the GCR and efforts are needed to synthesize existing and proposed geochemical survey data to extend the algorithm throughout the full SER/GOM.

5.1.2 Ecosystem coastal monitoring

Task 5.1.5: Establish the SER/GOM portion of a coral reef ocean acidification monitoring program.

The NOAA Coral Reef Conservation Program (CRCP) has made preliminary investment toward establishing a Coral Reef OA Monitoring Network. The Atlantic elements of this network would be distributed at selected reef systems throughout the SER/GOM (Figure 5.2). Each node within the network will constitute a suite of near continuous autonomous (where feasible) measurements of key chemical, physical, and biological parameters at regular intervals. The current Atlantic OA Test-bed in La Parguera, PR and the observatories at Kilo Nalu, Hawaii (see Chapter 4), serve as important precursors. While similar technologies will be adopted for observing systems in both the Atlantic and the Pacific, the greater access of many of the reef systems within the Atlantic will allow for a more comprehensive suite of observations in most cases. For example, observations of near-reef seawater $p\mathrm{CO}_2$ have been sustained for more than 1 year at the Atlantic OA Test-bed in Puerto Rico. While similar achievements have been made at Kilo Nalu, Hawaii, many of the remote systems within the Pacific are precluded from similar sustained observations given the logistical requirements of servicing such systems at sufficient frequency given the existing technologies.

5.1.2.1 Autonomous measurements

The primary objective of the moored autonomous OA observatories is to provide near continuous monitoring of a suite of chemical, physical, hydrodynamic, and meteorological measurements that allow monitoring of community scale metabolic performance (net calcification, photosynthesis, respiration). The approach envisioned is based upon a Eulerian flow respirometry method as adopted for coral reefs (Gattuso *et al.*, 1993; 1995; 1999). It requires autonomous monitoring of carbonate chemistry parameters (e.g., enhanced $MAPCO_2$) along with oxygen, nutrients, and other ancillary data both upstream and downstream of selected reef environments exhibiting unidirectional flow. Together with information on water mass transit time, it is possible to track reef metabolic performance and derive robust estimates of reef growth contemporaneously with offshore estimates of changing ocean chemistry. The moorings provide for an enhanced characterization of the short-term variability in carbonate chemistry within coral reef environments. This information, in conjunction with data from the physiological research efforts, is needed to assign critical geochemical thresholds for OA impacts on reef ecosystems.

5.1.2.2 Biological and biophysical indicators

A suite of biological and biophysical indicators monitored at regular intervals could provide important information with regard to changing coral communities in response to multiple and synergistic threats acting on coral reefs. This could include:

- Evaluation of benthic/cryptic biodiversity;
- Remote sensing images (satellite, aerial) that indicate the extent of live versus dead cover, structural features, coral reef zonation;
- Process studies of community metabolic performance;
- Species-specific calcification and/or metabolism monitoring and experimental field studies examining key organisms such as corals and macroalgae; and
- Ecological monitoring to include benthic community assessment, demographic processes (e.g., recruitment, growth, mortality) for key species, and rugosity.

5.1.2.3 Site selection

Preliminary year efforts beginning in FY2011 will work to evaluate selected candidate sites across the SER/GOM as potential nodes in the Coral Reef Ocean Acidification Monitoring Network prior to committing long-term infrastructure (Table 5.1). Selection of candidate sites will be specifically informed by the CRCP National Goals and Objectives and the CRCP State and Jurisdictional Priorities Documents. Sites identified as a high monitoring priority to the CRCP will then be further evaluated based on the criteria listed in unranked order in Table 5.2.

Several of these candidate sites (e.g., Gray's Reef, Florida Keys, and the Flower Garden Banks) could include marine protected areas within the National Marine Sanctuary System (`http://sanctuaries.noaa.gov/`) and could serve as climate change sentinel sites. As protected areas, National Marine Sanctuaries (NMS) staff are interested in developing OA monitoring protocols to implement across these sanctuaries.

North America's only living coral barrier reef lies about six miles seaward of the Florida Keys (a 220-mile long string of islands extending south and west of the Florida mainland). The Keys are located on the southern tip of the Florida peninsula, beginning just south of Key Biscayne and ending 70 miles west of Key West. The Florida Keys NMS consists of 900 square nautical miles of coastal and offshore waters surrounding the Florida Keys, and extending westward to encompass the Dry Tortugas islands, which are managed by the Dry Tortugas National Park. They are part of a fragile interdependent ecosystem that includes mangroves, hard-bottom communities, and seagrasses that grow both on the ocean and bay side of the Florida Keys. Six C-MAN stations (SEAKEYS) are located within the Sanctuary, and there are long-term, comprehensive monitoring projects for water quality, seagrasses, coral reefs, and fishery resources that can serve as baselines (`http://sanctuaries.noaa.gov/science/conservation/fk_report.html`).

Flower Garden Banks NMS is located 70 to 115 miles off the coasts of Texas and Louisiana. These underwater communities rise from the depths of the Gulf of Mexico atop underwater mountains called salt domes. NOAA recently completed a biogeographic survey of this sanctuary characterizing the benthic and fish resources (Caldow *et al.*, 2009) (`http://ccma.nos.noaa.gov/`

Table 5.1: Candidate reef sites to serve as nodes within a Coral Reef Ocean Acidification Network within the SER/GOM (unranked).

Lat.	Lon.	Site Name	Reef Type	Reef Location	Proposed Observations
17	–67	Cayo Enrique Forereef	Mid-shelf reef	USA/Puerto Rico—Caribbean	Autonomous measurements; Biophysical indicators
32	–80	Molasses Reef	Bank/shelf reef	Florida Keys National Marine Sanctuary	Autonomous measurements; Biophysical indicators
25	–81	Dry Tortugas	Back and patch reef	Dry Tortugas National Park	Autonomous measurements
25	65	Buck Island National Monument	Bank and patch reef	St. Croix, USVI	Autonomous chemical/hydrologic; Regular biophysical surveys
18	–94	Stetson Bank	Bank reef	Flower Garden Banks National Marine Sanctuary	Biophysical indicators
31	–81	Gray's Reef	Hard-bottom community	Grey's Reef National Marine Sanctuary	Autonomous chemical/hydrologic; Regular biophysical surveys

Table 5.2: Criteria for coral reef OA monitoring site evaluations.

1. Leveraging infrastructure (e.g., ICON/CREWS, Sea Keys) that provides important ancillary oceanographic and meteorological data
2. Potential for strong metabolic signal (e.g., moderate to high coral cover)
3. Well-defined hydrodynamics (e.g., unidirectional flow, existing hydrodynamic models)
4. Historical data (carbonate chemistry time series, previous calcification studies, prior biological community surveys)
5. Reef-dominated carbonate chemistry (minimal convoluting factors)
6. Other federal, international, and academic partners
7. Robust estimates of offshore carbonate chemistry (endmember)
8. Local logistical support (nearby labs, sanctuaries, etc.)
9. Perceived vulnerability to OA
10. Economic and cultural significance

`products/biogeography/fgb/report.html`). This survey will provide a good baseline for monitoring potential OA impacts

Gray's Reef NMS is one of the largest nearshore live-bottom reefs in the southeastern United States. The sanctuary is located 17.5 nautical miles off Sapelo Island, GA. Gray's Reef is not a coral reef such as those found in the tropics. Instead it is a consolidation of marine and terrestrial sediments (sand, shell, and mud) which was laid down as loose aggregate between two and six million years ago. Gray's Reef is a submerged hard bottom (limestone) area that, as compared to surrounding areas, contains extensive but discontinuous rock outcropping of moderate (6 to 10 feet) height with sandy, flat-bottomed troughs between. A MAPCO$_2$ surface water monitoring buoy is currently located in the Gray's Reef.

Task 5.1.6: Establish a seagrass OA monitoring program.

A network of seagrass monitoring sites would serve as an important extension to the Coral Reef OA Monitoring Network. Such a network would provide for a more comprehensive characterization of OA impacts within tropical benthic systems. Specific observations would include species-specific distributions of seagrasses and associated epiphytic and benthic algae in seagrass meadows along with rates of photosynthesis and calcification in epiphytic and benthic algae. The monitoring network would document changes in the distribution, density, and productivity of seagrass meadows to determine the role of seagrasses in mitigating OA effects on biogenic reef structures. The information would provide for the development of forecast scenarios designed to inform regional management response.

Task 5.1.7: Establish an estuarine OA monitoring program.

Estuaries are regions of high biological productivity. They also experience variable inputs of river water and ground water owing to variations in rainfall and often exhibit high rates of exchange between bottom sediments and biota, and overlying water. Hence, they experience much variability in carbonate chemistry and carbonate mineral solubility on a number of spatial and temporal scales. There is a great need to document this variability if we are to develop capabilities to forecast impacts of OA on estuarine ecosystems and living marine resources in the SER/GOM.

A research estuarine monitoring program for OA in selected SER/GOM estuaries will address the issue of temporal variability in CO_2, pH, and carbonate mineral solubility on timescales of hours, days, seasons, and years. We plan to continuously measure pH, pCO_2, temperature, and salinity, which will allow us to evaluate the entire CO_2 acid-base system and the solubility of carbonate minerals from equilibrium calculations. These measurements will use similar instrumentation and methodology as used to monitor the CO_2 system and carbonate mineral solubility in the coral reef monitoring network outlined above. DIC or TA will also be monitored when in situ automated methods become available for these parameters (see Chapter 1). In addition, several additional chemical and biological parameters will be measured that can be used to evaluate the impact of biota on CO_2 concentrations and related carbonate ion levels. These parameters include concentrations of nutrients (ammonium and nitrate+nitrite), chlorophyll fluorescence, light attenuation, and water depth. The necessary sensors and in situ measuring devices (e.g., nutrients) are all currently commercially available, with the exception of those for alkalinity and total CO_2, which are currently under development. In situ chlorophyll fluorescence will be calibrated by fluorescence measurements on discrete samples collected at different times of day and in different seasons.

The monitoring system will be initially deployed in the Newport River Estuary adjacent to NOAA's Center for Coastal Fisheries and Habitat Research (CCFHR) in Beaufort, NC. This site is also adjacent to the Rachel Carson Estuarine Reserve, which is part of NOAA's NERRS and will serve as a sentinel site for climate change monitoring. Once the initial monitoring site is operational, one or two additional moored monitoring systems will be deployed in Pamlico Sound roughly an hour's drive from the CCFHR facility. The Pamlico/Albemarle Sound system is the largest estuarine system in the SER/GOM and is the largest lagoonal estuarine system in the U.S. It is one of the most productive lagoonal estuaries in the world and supports important shrimp, crab, scallops, oysters, and flounder fisheries (Boynton *et al.*, 1982). It also provides an important nursery for numerous species of commercial and recreational finfish. Subsequent comparative monitoring sites in tropical and subtropical estuaries (e.g., Biscayne Bay or Florida Bay FL, GOM, Jobos Bay, PR NERR) would follow. Existing ecosystem monitoring activities in these areas would be leveraged.

Organisms of Near-Term Priority

Calcifying phytoplankton
Seagrass
Reef building Corals
Eastern oyster
Brown, White and Pink shrimp

5.2 Organism Response to Ocean Acidification (Theme 2)

The intended outcome of experiments on single species in the SER/GOM described below is to understand the impact of OA on the broader ecosystem. These necessary species-specific exposure experiments will allow the analysis of SER/GOM ecosystem vulnerability.

Task 5.2.1: Conduct species-specific OA exposure experiments.

There is a need to undertake controlled exposure experiments in the laboratory and, when possible, in the field to quantify adverse OA impacts on individual species or biological communities. Combined impacts of elevated CO_2/low pH and other associated factors such as elevated temperature (O'Donnell *et al.*, 2009; Pörtner, 2008), changing salinity, or hypoxia also need to be quantified for relevant species as warming and rainfall changes are likely to co-occur with OA. The manipulative experiments to be conducted as part of the SER/GOM implementation strategy will adopt the key recommendations and standard/guidelines outlined above.

Organism response parameters will include survival, growth, reproduction, development, and calcification rates where appropriate. Genomics approaches should also be considered in order to gain insight into the mechanisms that confer resilience as organisms adapt to OA, and to predict the presence or absence of that capacity in critical species. Global gene expression profiling using microarrays has been successfully used to explore the effects of OA on the physiology and distribution of calcifying marine organisms (e.g., Hoffman *et al.*, 2008; Place *et al.*, 2008) and is rapidly becoming an established tool in marine ecology (Dupont *et al.*, 2007). NOAA is also well positioned to apply genomics approaches to addressing the effect of OA on organisms critical to the SER/GOM. The NOAA genomics facility at Center for Human Health Risk (CHHR) has developed microarrays to a number of species including shrimp, oyster, fishes in the genus *Fundulus*, bottlenose dolphin, and the dinoflagellate *Karenia brevis* and maintains the molecular and bioinformatic expertise to support exposure studies and develop additional species-specific tools needed to address OA.

5.2.1 Marine phytoplankton

Experiments will be performed for a number of potentially sensitive calcifying species and competing non-calcifying phytoplankton species found in coastal and offshore regions of the SER/GOM. Controlled laboratory experiments will be conducted to investigate the effects of OA on the rates of photosynthesis, growth, and biogenic calcium carbonate precipitation in representative species of marine coccolithophores, which are responsible for most biological precipitation of calcium carbonate in the ocean and are important biological regulators of climate (Dymond and Lyle, 1985; Charlson *et al.*, 1987). The effects on coccolithophores will be compared with effects of varying pH/CO_2 on rates of photosynthesis and growth of diatoms and other non-calcifying marine phytoplankton. The combined effect of increasing temperature will also be examined because OA is expected to be accompanied by global warming. The culture experiments will be run at CCFHR, which has decades of knowledge and experience in controlled laboratory experiments with marine phytoplankton, including experiments examining effects of pH/CO_2 variations (Sunda and Huntsman, 2003). The experiments should help us to determine the relative impact of OA on different phytoplankton species, which should provide information on the future composition of marine phytoplankton communities, and associated changes in marine food webs.

Toxic algal species present in the SER/GOM region are high-priority species for investigating responses to OA. Experiments are currently underway at the Center for Coastal Environmental Health and Biomolecular Research (CCEHBR) and Texas A&M to investigate the effects of increased temperature and CO_2 on the Florida red tide dinoflagellate, *Karenia brevis*. Key physiological parameters monitored include growth, photosynthesis, and toxicity. In addition, the genomic responses of the dinoflagellate to these changes are assessed using a *K. brevis* specific DNA microarray. The molecular mechanisms by which phytoplankton accommodate these changes may provide some insight into how and why certain phytoplankton will be winners and others losers in the predicted OA scenario. Genomic approaches have successfully been used in *K. brevis* to characterize diurnal responses, stress responses, and responses to nutrients (Van Dolah *et al.*, 2007; Lidie, 2007; Van Dolah *et al.*, 2010). Genomic tools are currently being generated at CCEHBR to conduct similar studies in the coral reef associated dinoflagellate, *Gambierdicus toxicus*, responsible for ciguatera, the most prevalent form of seafood poisoning worldwide. Toxic diatoms in the genus *Pseudo-nitzschia* are also present in the SER/GOM and have been associated with certain marine mammal mortalities. Research is currently underway at CCEHBR/CHHR to identify the distribution and toxicity of the multiple *Pseudo-nitzschia* species present in the region. Examination of the differential responses of these species to OA may provide insight into the future prevalence of domoic acid poisoning in the SER/GOM region.

5.2.2 Bivalves

Laboratory experiments will also be conducted at CCFHR to determine the response and sensitivity of larval and juvenile stages of key molluscan species to OA. Organism response parameters will include survival rates, rates of growth and calcification, and duration of metamorphic stages. Such studies are needed to forecast the impacts of OA on estuarine bivalve populations and fisheries. Species to be examined will include the eastern oyster (*Crassostrea virginica*) and the common quahog (*Mercenaria mercenaria*), both commercially and ecologically important species in the SER/GOM. This research will support (1) efforts to restore bivalve populations in the SER/GOM, (2) the marine aquaculture industry, and (3) coastal habitat restoration. CCFHR offers a unique combination of staff expertise and laboratory facilities in shellfish cultivation and estuarine ecology, proximity to estuarine shellfish resources, an ongoing collaboration with aquaculture facilities, and strong interactions with state and federal habitat restoration efforts.

5.2.3 Crustaceans

Similar experiments are also planned in the Southeast Fisheries Science Center to examine effect of OA on economically and ecologically important species of crustaceans in the SER/GOM, particularly shrimp, which represent one of the largest (if not the largest) commercial fishery in the SER/GOM in terms of dollars. Experiments will focus on the three commercially most important species, brown shrimp (*Farfantepenaeus aztecus*), white shrimp (*Penaeus setiferus*), and pink shrimp (*Penaeus duorarum*) which, in addition to commercial importance, are widely utilized as ecosystem indicators in the South Florida Ecosystem Restoration program. As with molluscs, experiments will focus on larval and juvenile life stages and will examine effects on survival, growth, and duration of metamorphic stages. Data from the OA experiments with molluscs and shrimp will be combined with existing data and forecasts of anthropogenic changes in CO_2/pH to help assess the impact of current and future OA on bivalve mollusc and shrimp populations, and associated adverse impacts to shellfish fisheries.

5.2.4 Other organisms

Exposure experiments should be conducted for a host of the region's other key ecological and economically important species. It is suggested that NOAA extramural research funds be directed for research on these species. Early life phases and a range of physiological (e.g., respiration, photosynthesis, growth) and ecological (e.g., reproduction, survivorship) and possibly functional (e.g., gene expression to examine potential mechanisms of resilience within species) responses should be included as appropriate for particular organisms in these experimental assessments of OA risk. Below is a beginning list of other key SER/GOM organism groups that require targeted experimental assessment:

- Reef-building corals (including deep-sea *Oculina varicosa*, *Lophelia pertusa*, as well as species of shallow genera such as *Acropora*, *Montastraea*, and *Diploria*)
- Calcifying reef macroalgae (e.g., *Halimeda* spp. and crustose coralline algae)
- Non-calcifying reef plants (e.g., seagrasses) and macroalgae (e.g., *Dictyota*, *Lobophora*, *Laurencia*)
- Other calcifying reef organisms (e.g., *Diadema*, crustaceans)
- Calcifying targeted fisheries (e.g., conch, blue crab, spiny lobsters)
- Fin fishes (including reproductive functions and otolith development)
- Specific prey organisms important to fishery and protected-resource species
- Heterotrophic organisms
- Suspension feeders
- Boring sponges

Task 5.2.2: Conduct lab and/or field experiments to determine OA impacts on key species interactions (e.g., competition, predation, facilitation).

As species-specific responses to OA are further delineated by activities under Task 5.2.1 above, relevant and specific hypotheses can be formulated relative to how these species' specific responses will propagate through food webs and ecosystems. For example, competition between calcareous reef corals and benthic algae is believed to be an important structuring factor in benthic reef communities and OA could shift the balance between these communities. Also, calcareous prey species may prove more vulnerable to predation if their shells/tests are rendered less robust by OA (McDonald *et al.*, 2009). The use of large mesocosm facilities may be needed to test species interactions similar to those planned for the University of Washington at Friday Harbor for experiments on the west coast (see Chapter 3).

Center for Coastal Environmental Health and Biomolecular Research (CCEHBR) laboratory in Charleston, South Carolina, maintains a modern 1800 ft^2 coral research facility, the Coral Culture and Collaborative Research Facility (CCCRF), to support studies with live coral colonies and to provide laboratory space and equipment for conducting related challenge experiments on the effects of a variety of environmental stressors, including OA. The facility provides a resource for laboratory investigations that can enhance our understanding of the potential effects of natural and human stressors on corals and coral-reef communities. While the initial focus of work within CCCRF has been on shallow-water tropical/sub-tropical species, recent efforts have been devoted to adding a cold-water culture and testing capability. Upcoming plans include conducting experiments to test the response of deep-sea corals (e.g, *Lophelia pertusa* and others) to low (<1) carbonate saturation states and low pH.

In addition, the newly completed Marine Environmental Research Laboratory (MERL) of the University of Southern Mississippi's Gulf Coast Research Laboratory, is strategically situated on the northern shore of Mississippi sound. This 8,000-sq-ft research facility houses two fully equipped laboratories with seawater delivery systems and experimental mesocosms suitable for studies on critical early life stages of shrimp, shellfish, and finfish.

Task 5.2.3: Conduct coral sclerochronology for retrospective OA assessment to detect the coral calcification historical response.

Potential impacts of ocean acidification on coral reef systems include decreases in coral calcification, growth rates, structural integrity of reef-building corals, and thus the constructional mechanism of coral reefs. Coral sclerochronology provides the only mechanism to retrospectively determine coral calcification over the past several hundred years, including pre-industrial conditions. The presence of annual density bands in coral skeletons provide historical records of linear extension rates, skeletal density, and calcification rates over the often long lifespan of many reef-building corals. Several coral genera (*Montastraea*, *Siderastrea*, and *Diploria*, among others) possess annual density band records which will enable identification of the species response to OA. The presence of reef-building corals throughout the tropical and sub-tropical Atlantic allows assessment of the coral calcification response to OA over a wide latitudinal range spanning pre-industrial to present-day conditions. It is necessary to assess coral growth and calcification records across a wide latitudinal range in order to identify specific regions of increased susceptibility to the potentially compounding impact of OA, climate change, and land-based pollution. Coral growth records, in conjunction with the in situ and ship-based measurements of physical and chemical variables, provide a means of teasing apart the relative importance of impacts from OA, thermal stress, and land-based pollution. Understanding the limiting environmental controls on coral calcification is necessary to identify manageable parameters at local and regional scales in order to mitigate the effects of expected increases in OA.

Additionally, the boron isotopic composition of the skeleton presents a paleo-proxy of seawater pH which provides a metric for quantifying past OA. Research is currently underway at the Atlantic Ocean Acidification Test-bed in La Parguera, PR, to measure past coral growth and calcification along with reconstructed paleo-records of pH using the boron isotope proxy prior to and following the industrial revolution. Understanding the historical baseline values and the relationship between coral calcification rates and recent changes in seawater carbonate chemistry is a necessary component for assessing current and future susceptibility to OA.

5.3 Biogeochemical and Ecosystem Models (Theme 3)

The monitoring and manipulative experiments advanced in Themes 1 and 2 are intended to serve as an underlying architecture and validation toward the development of biogeochemical models. These models, if coupled with ecological and economic models, will provide the basis for evaluating the socioeconomic implications of continued OA under a range of scenarios.

The Southeast Coastal Ocean Observing Regional Association (SECOORA) not only facilitates integrating regional monitoring efforts but also has an inventory of oceanographic models under development (`http://seacoos.org/`). Many of the models available by SECOORA are related to physical parameters (sea surface height, salinity, currents, and winds); these models will be evaluated for potential expansion to include OA-relevant parameters. Additional models that could be leveraged include those available from the Gulf of Mexico Coastal Ocean Observing Regional Association.

Task 5.3.1: Develop regional biogeochemical forecast models coupled to global carbon cycle models to predict local changes in carbon chemistry at multiple temporal scales.

Over the last decade, coarse-scale, coupled climate/carbon-cycle models have been modified to determine the present-day and future changes of ocean carbon chemistry and OA for the next two centuries (Kleypas *et al.*, 1999; Caldeira and Wickett, 2003; Orr *et al.*, 2005; Caldeira and Wickett, 2005; Cao and Caldeira, 2008; Feely *et al.*, 2009). These models have provided information on the geographical distributions of open-ocean carbon chemistry under different atmospheric CO_2 stabilization scenarios and validated with the WOCE and CLIVAR/CO_2 Repeat Hydrography data sets. However, these models are poorly constrained for the marginal basins, including the Greater Caribbean and Gulf of Mexico. Furthermore, while the rate of OA for the open ocean may be reasonably well constrained, it is less so for the oceanic margins. Within these systems, global-scale OA is overlaid onto variability in Ω as a result of highly complex biogeochemical dynamics and riverine input (e.g., Salisbury *et al.*, 2008). There is a requirement to nest a high-resolution coupled climate/carbon model within a global model, such as the GFDL MOM4 model. We will develop a SER/GOM model (or collection of models) that will be part of a nested set of models of OA in U.S. coastal waters and to verify the model outputs with observational data collected from shipboard surveys and moorings. These efforts would be advanced as an extension to the modeling efforts being led by PMEL with collaboration with GFDL and AOML as identified within the West Coast Regional Plan.

Task 5.3.2: Develop regional biogeochemical hindcast models to evaluate historical changes in carbonate chemistry within the SER/GOM.

A core requirement toward providing context to the current and projected OA trajectories is evaluating historical changes. It is necessary to mine the wealth of historical data archives (e.g., World Ocean Database at NODC) of biological, chemical, and physical oceanographic measurements to deduce the historical development of OA conditions within the SER/GOM. The PMEL OA team has developed new robust regional algorithms for estimating the seasonal extent of corrosive waters along the West Coast of North America using archived biogeochemical and hydrographic data sets that lack carbon measurements (Juranek *et al.*, 2009). This approach will be extended and applied along the oceanic margins of the SER/GOM, where archival hydrographic and chemical datasets permit the derivation of such algorithms. The details of this approach are outlined within the West Coast regional plan. This approach, when combined with shipboard observations, mooring and glider data could be utilized to verify the nested coupled climate models of OA and help to determine potential hotspots and vulnerability of sensitive marine ecosystems in U.S. coastal waters.

Task 5.3.3: Develop regional ecoforecast models.

Full-scale regional ecosystem models need to be developed for the SER/GOM. Where in-house capabilities do not support the development of such models, it will be necessary to fund extramural modeling efforts. The wide range of ecosystems/habitats (e.g., pelagic Gulf of Mexico, Caribbean coral reef, South Atlantic continental shelf, and diverse lagoonal and estuarine habitats from Florida Bay to Pamlico/Albemarle Sound) makes the task particularly challenging. Constructing and utilizing such models constitutes a long-term goal across many NOAA interests requiring effective coordination between the OA program and other NOAA programs.

In addition to comprehensive ecosystem models, more restricted modeling tools (e.g., Ecopath with Ecosim) should also be implemented on shorter timescales to yield important insights on potential OA impacts to ecosystems and ecosystem services by allowing propagation of single-species responses (determined in experimental work described above) through food webs. Many such models already exist for ecosystems within the SER/GOM (searchable at ecopath.org). Existing Ecopath with Ecosim models should also be consulted to help identify particularly sensitive species that play key roles in regional food webs and ecosystems, and thus high-priority targets for experimental studies. Ongoing recruitment models being developed at NOAA entities at the Stennis Space Center that integrate climate change-associated physical variables, hydrography, and ecological process parameters will also help fulfill this need for comprehensive ecosystem models, as well as help represent the economically important northern GOM region within the scope of the OA plan.

A multimillion dollar, multiyear modeling effort is underway to characterize the northern Gulf of Mexico waters and ecology over the LA/Tex continental shelf. NOAA, MMS, and ONR all have made large investments in this region. The NOAA investment at Texas A&M is focused on a coupled hydrodynamic and ecological model with the potential to forecast hypoxia of the GOM Dead Zone using water discharge, nutrient concentration, and sediment loads to predict algal blooms and algal remineralization. Integrated conceptual ecosystem models are also being developed for South Florida coastal marine ecosystems as part of the MARES (Marine and Estuarine Goal Setting for South Florida) project (`http://www.sofla-mares.org/`). We will seek to augment these models to incorporate an OA module that includes both carbonate chemistry and biological response.

5.4 Human Dimensions (Theme 4)

Limited research has been conducted on the potential consequences of OA on human communities. Core objectives of human dimensions research are to evaluate how changes in ecosystems caused by OA will affect human communities, marine and coastal resource-based industries, and the national economy. These effects could impact both social and economic systems through their influence on consumptive and non-consumptive industries (e.g., recreation, tourism) and the existence value of various biological resources.

Task 5.4.1: Forecast impacts to ecosystem services within the SER/GOM.

We will forecast the impacts of OA on ecosystem services within the SER/GOM by developing a ecosystem services models linked to ecosystem forecasting models (Task 5.5.3). Forecasts of ecosystem services could be designed explicitly to inform national, regional, and local decision makers. For example, such models could explore how ecosystem services change over time with and without actions taken to alter habitat susceptibility to OA (e.g., altering local hydrodynamic regime, changes in coastal runoff, reduce point source stressors).

Task 5.4.2: Conduct necessary social impact and vulnerability assessments to ascertain probable social impacts of OA and identify possible mitigation strategies within the SER/GOM.

OA will not impact all human communities in the same manner or to the same extent. For example, a coastal community relying exclusively on tourism related to a coral reef ecosystem may be more culturally and economically vulnerable than a community having a highly diversified economic base. In addition, impacts to non-commercial species of cultural interest, such as those gathered for subsistence or cultural practices, will need to be considered. For this reason, social scientists will use data gathered from monitoring programs and forecasts of ecosystem and ecosystem services changes under OA to inform social impact and vulnerability assessments for human communities in the SER/GOM. These assessments will identify those communities likely to suffer disproportionate effects of OA on vital ecosystem services.

Task 5.4.3: Develop mitigation and community adaptation strategies.

Choices about adopting various CO_2 emission scenarios need to be informed by the best available science—science that includes the impacts of OA. However, decision-makers will need to consider this science within the broader context of how to confront other stressors to the marine system, how to prepare communities for ecosystem changes, whether to implement spatial or temporal fisheries changes, etc. Such decisions demand consideration of ecological predictions, the value of ecosystem products and services, and the socioeconomic costs versus benefits of proposed actions.

Results from the prior two tasks—development of a model to forecast changes in ecosystem services and the analysis of which communities are most vulnerable to changes in ecosystem services—will be utilized to develop strategies for (1) mitigating the impacts of OA and (2) helping communities adapt to unavoidable change. While management options for dealing with OA may be limited in most cases, there may be instances, particularly within the coastal zones, where local management actions can promote the resiliency of many ecosystems under continued OA. The strategies we identify and develop could help resource managers, policymakers, and other decision-makers make cost-effective, informed decisions. In addition, the tools developed under this task will help resource managers anticipate stakeholder and constituent interests so that human activities might be effectively governed in vulnerable ecosystems.

5.5 Synthesis of Data and Information Products (Theme 5)

The primary strategy for data synthesis and product delivery within the SER/GOM is to adopt those outlined within the National Plan chapter in which existing data assembly and archive centers are engaged, including CLImate VARiability and predictability ($CLIVAR/CO_2$) and Carbon Dioxide Information Analysis Center (CDIAC). When the single national OA information center is established as proposed in Chapter 1, it will serve as a central communication and coordination forum and directory for the data assembly centers. Data synthesis activities will include standardizing and merging of regional datasets to basin and global scale, synthesis of data across multiple platforms and model outputs, and integrated synthesis reports. The synthesis process should include: science and technical workshops, product development workshops; and international synthesis meetings.

5.6 Engagement Strategy (Theme 6)

Communicating the processes governing OA and its impacts is critical to educating and engaging the public on this topic and to the policy debate on regulation of carbon dioxide emissions. As research is completed and new discoveries are made, advances must be clearly communicated to both decision makers and the public at large. This communication should be addressed through both formal and informal education activities as well as making use of multi-media outlets as much as possible.

Task 5.6.1: Create and distribute media that clearly and concisely describe the chemistry of OA as well as the known and hypothesized impacts.

To better inform the public on this critical issue, we need targeted messages in engaging forms of media (e.g., feature documentary, animated film, graphic novel), that accurately describe the earth's and ocean's carbon cycles and the impact of anthropogenic CO_2 emissions on those cycles. Specifically, these media projects need to tell general audiences how increasing atmospheric CO_2 is acidifying the ocean and thereby altering its chemistry and how these chemical changes are impacting the ocean's biology. These media projects should be made via collaboration between NOAA Communications and established media developers. Specific examples that relate to research and impacts in the Southeast Atlantic and Gulf of Mexico should also be highlighted. Any efforts for similar programs underway in other NOAA programs (such as the CRSP) should be joined in this effort or created in such a way that they build upon one another in a related series.

Task 5.6.2: Create an interactive website focused on OA in the SER/GOM.

With the majority of the general population turning to internet search engines for quick research on almost any topic, it is essential that NOAA have a comprehensive web-based presence representing this topic. The website would offer resources for both the general population and the research community. For the research community, information on current research priorities and data access should be available as well as related meetings and publications. Podcasts, short videos, and visualizations explaining OA will allow for quick and easy access to overviews that meet the expectations of today's younger generations. Innovative multimedia tools such as NOAA's Second Life should also include sections about OA and specially designed examples of current research. An explanation of common myths and facts about the history of carbon dioxide levels on Earth and known impacts to ecosystems would facilitate greater understanding of the topic.

Task 5.6.3: Develop regular summary literature that provides a State of the Science of OA and Known Impacts in the SER/GOM.

Create non-technical documents that use plain language, images, and graphics to explain the current understanding, major accomplishments, and new endeavors related to OA in this region. These materials should be widely distributed and available in offices conducting OA research and at professional meetings.

Task 5.6.4: Install interactive displays at aquaria in the southeastern United States.

Following a similar approach to the kiosks employed in the Sant Ocean Hall at the Smithsonian in Washington D.C., a display that allows visitors to listen and view short videos on OA should be developed and installed at major aquaria in the southeast U.S. With a tailored focus on the regional-specific impacts, visitors will be able to explore exactly how various scenarios under OA will impact their communities and local environments.

Task 5.6.5: Create education modules and curricula that can be used by teachers to help describe OA and its impacts to students.

Modules describing new and innovative topics that have been vetted and meet state and national standards for science and math are much more likely to be utilized by teachers. Developing such modules and curricula in concert with leading experts in OA will ensure that students will begin learning about OA much earlier in their educational career. This will also provide opportunities for students to learn about what NOAA and its university partners are doing to research this phenomenon and its impacts.

5.7 Collaborators

Southeast Atlantic and Gulf of Mexico Region Collaborators
Atlantic Oceanographic and Meteorological Laboratory
Pacific Marine Environmental Laboratory
Coral Research Conservation Program
Southeast Fisheries Science Center
Center for Coastal Fisheries and Habitat Research
Center for Coastal Environmental Health and Biomolecular Research
Center for Human Health Risk (Hollings Marine Laboratory)
Regional OOS (SECOORA, GCOOS, CarICOOS)
Florida Sea Grant
Georgia Sea Grant
South Carolina Sea Grant
North Carolina Sea Grant
Mississippi-Alabama Sea Grant Consortium
Louisiana Sea Grant
Puerto Rico Sea Grant
Gray's Reef National Marine Sanctuary
Florida Keys National Marine Sanctuary
Flower Garden Banks National Marine Sanctuary
National Estuarine Research Reserves
Cooperative Institute for Marine and Atmospheric Studies
Cooperative Institute for Ocean Exploration, Research, and Technology
Northern Gulf Institute

6. Northeast Region Ocean Acidification Research Plan

Beth Phelan, Jon Hare, Ellen Mecray, Gary Wikfors, Shannon Meseck, Christopher Chambers, Daniel Wieczorek, Vincent Guida, Ronald Goldberg, Dean Perry, Michael Fogarty, Paul Ticco, and Charles Stock

6.0 Ocean Acidification in the Northeast Region

Decreases in pH and the saturation state (Ω) of the surface oceans and subsurface waters are larger at higher latitudes, due in large part to the strong temperature dependence of the solubility of CO_2 in seawater. It is expected that the saturation state of surface waters off the coast of New England will decline sooner than other areas of the Northeast, especially during the winter months. In addition, hypoxia is a growing threat in all estuaries in the Northeast, particularly Narragansett Bay, Long Island Sound, and Chesapeake Bay. A relationship exists between hypoxia (low oxygen) and ocean acidification because respiration which causes hypoxia is also producing high levels of CO_2, lowering the carbonate ion levels. In all, OA has the potential to significantly affect living marine resources in the Northeast, as well as alter the ecosystem's structure, function, and productivity. Given the social and economic importance of living marine resources on the Northeast U.S. continental shelf, the potential large-scale and long-term impacts of OA must be evaluated.

We describe here a coordinated research plan with the goal of providing the first assessment of the effects of OA on living marine resources in the Northeast U.S. continental shelf ecosystem. During the Marine Resources Monitoring Assessment and Prediction Program (MARMAP, 1977–1987), some pH and alkalinity measurements were made as part of primary productivity studies. Preliminary analyses of those data show seasonal and spatial variability. These observations also demonstrate differences between surface and near-bottom conditions, which are likely related to the strong stratification that occurs seasonally in different parts of the system. We intend to conduct a monitoring program that will define and track the status of OA in the shelf ecosystem. Since the effects of acidification are not well studied, a large part of this plan includes experimental research. These laboratory and field efforts will be directed at collecting specific information for the parameterization of single-species and ecosystem models, which will then be used to assess the effect of acidification on living marine resources and overall ecosystem productivity.

6.1 Developing a Northeast Ocean Acidification Monitoring Network (Theme 1)

Task 6.1: Develop and conduct a monitoring program to assess the current state of ocean acidification and track its development in the northeast U.S. shelf ecosystem.

A baseline for OA on the Northeast U.S. shelf must be determined along with potential changes in the carbonate chemistry as part of the larger ecosystem monitoring programs. A collection of long-term monitoring data can then be coupled with forecast models to provide assessments of the effect of OA on marine resources. The monitoring data will also be used to direct field work resource species. Preliminary analysis of MARMAP data (1977–1987, Figure 6.1) shows spatial variability in pH and total alkalinity, which indicates that measurements are needed over the entire ecosystem to assess the potential effects of OA on resource species. Further, these observations need to be made both at the surface and through the water column, since few marine species inhabit the surface

Northeast Region Description

The Northeast U.S. region (for the purposes of this report) extends from the Virginia/North Carolina border to the western Scotian Shelf (see above) and spans a large latitudinal gradient from south to north. Structurally, this ecosystem is complex, with temperature and climactic changes, winds, river runoff, estuarine exchanges, tides, and multiple circulation regimes. The Northeast ecosystem has been divided into four regions: Mid-Atlantic Bight, Georges Bank, Gulf of Maine, and the Scotian Shelf/Bay of Fundy, each with different properties and dynamics. The circulation of the region is dominated by five large-scale processes: the Labrador Coastal Current inflow, estuarine and riverine input, the Gulf Stream, wind and tidal forcing. This area is characterized by a temperate climate, and local water temperatures have a large seasonal range from approximately 5–10°C in the northern Gulf of Maine to near 20°C along the Mid-Atlantic coast. The range in climatic conditions and the variety in geomorphology among regions contribute to a wide array of pelagic and benthic habitats, which contribute to the large productivity of the ecosystem. Approximately 30 marine mammal, 6 sea turtle, and 1,000 fish species occur in this ecosystem. Many of these fish species support a large fishing industry, which in 2006 produced fish and shellfish landings worth over $1.2 billion. Other Northeast economic activities include agriculture, natural resource extraction, a service industry dependent on large metropolitan areas, recreation and tourism, and manufacturing and transportation of industrial goods.

and there is extensive stratification in different parts of the water column and to provide a framework for the studies of the effects of OA on primary productivity and systems at different times of year.

We propose using the dedicated Ecosystem Monitoring (EcoMon) surveys as the primary basis for water column monitoring of OA. A Seabird Electronics 911+ CTD system with bottle carousel and auxiliary oxygen sensor will be deployed at stations along transect lines extending from the coast to the shelf break (Figure 6.2). Surface, mid-depth, and bottom samples will be collected and prepared at sea for onshore determination of pH, dissolved inorganic carbon (DIC), and total alkalinity (TA). We will also measure a suite of other parameters at these stations to elucidate relationships between OA, nutrient availability, carbonate formation, and dissolved oxygen. Further, we propose to install surface $p\text{CO}_2$ instrumentation on the two NOAA research vessels used by the Northeast Fisheries Science Center (NEFSC) in fishery and ecosystem surveys to acquire year-round measurements. This sampling design will be re-evaluated periodically after three years, based on temporal and spatial variability and through a comparison with the MARMAP era data.

In addition to shipboard sampling, we propose a number of fixed mooring sites that will be outfitted with OA sensors providing high-frequency measurements that will complement the survey-based measurements. Refer to Table 1.2 and 1.3 in Chapter 1

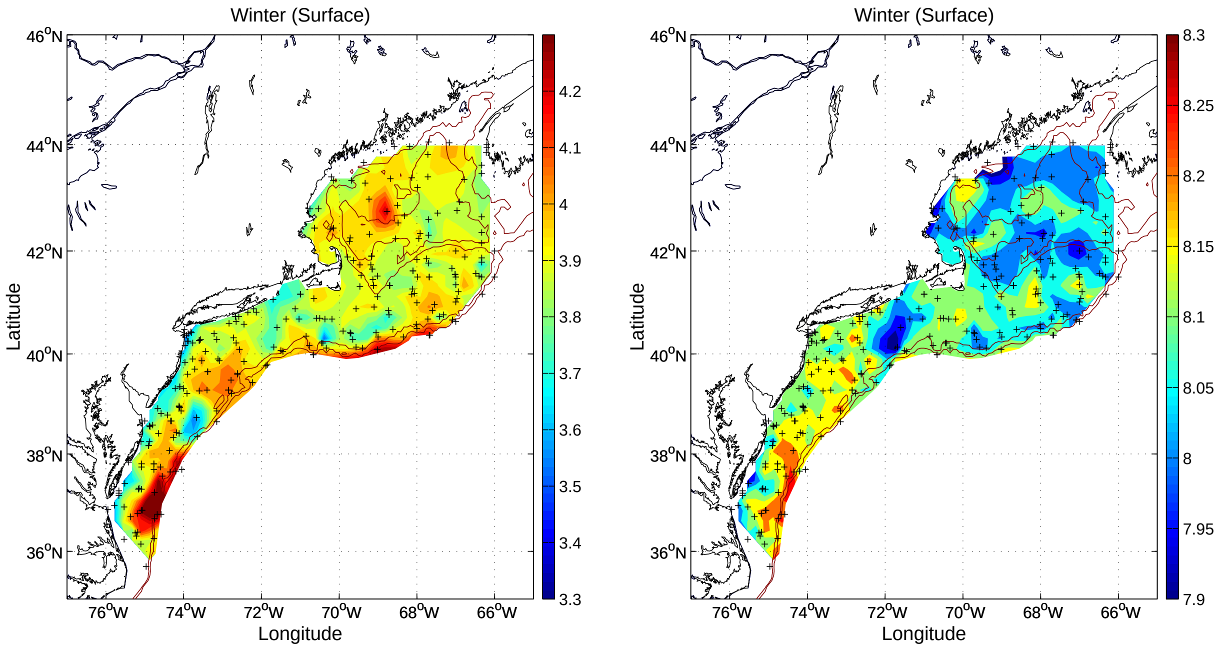


Figure 6.1: Winter climatology of surface layer pH (left) and total alkalinity (right) derived from MARMAP samples (1976–1984).

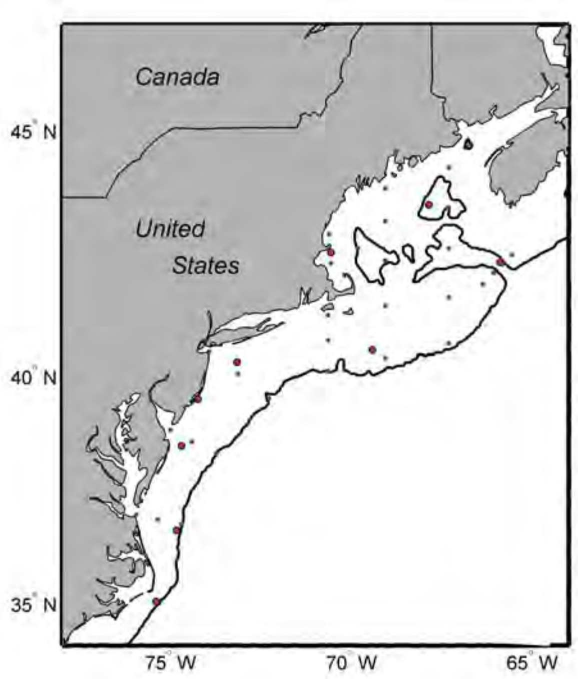


Figure 6.2: Proposed sampling design for an ocean acidification monitoring program. Program includes fixed station sampling during Ecosystem Monitoring cruises (blue) and moorings with OA sensors (red).

for a list of locations. The sensors will be phased in over a period of five years. As sensor technology advances, we would like to take advantage of the numerous moorings in the national Data Buoy Center to expand the spatial coverage of the system. Sensor technology is currently being developed, but will require regional involvement and participation to accelerate sensor development.

Marine protected areas in the northeast region, including nine National Estuarine Research Reserves (NERRs [Wells, Maine; Great Bay, New Hampshire; Waquoit Bay, Massachusetts; Narragansett Bay, Rhode Island; Hudson River, New York; Old Woman Creek, Ohio; Chesapeake Bay, Maryland and Virginia; Delaware Bay, Delaware and New Jersey, and Jacques Cousteau, New Jersey]) and two National Marine Sanctuaries (the Stellwagen Bank NMS in the western Gulf of Maine and the Monitor NMS off Cape Hatteras, North Carolina) are potential sentinel sites for existing and new monitoring programs to detect impacts from ocean acidification. Protected areas are ideal for long-term research, water-quality monitoring, education, and coastal stewardship. Reserves and sanctuaries provide sentinel sites that attract and support research collaborations and seek to understand processes that affect ecosystems. Further, they work with local communities and regional groups to address natural resource issues and improve our ability to intelligently manage, mitigate, and/or adapt to changes in the environment due to OA. Sentinel sites will provide opportunities for researchers to collaborate and will support research devoted to understanding OA patterns and processes that affect the Northeast ecosystem and living marine resources.

The monitoring network will also coordinate with other researchers measuring dissolved CO_2 in the ecosystem. The goal of this coordination is to develop a merged dataset based on the various OA activities in the ecosystem. Current cooperation will continue with AOML researchers who are measuring pCO_2 from vessels in the NEFSC Ship of Opportunity Program. The NEFSC, in collaboration with investigators from the National Aeronautics and Space Administration (NASA) and Old Dominion University (ODU), have started to make preliminary dissolved inorganic carbon and total alkalinity measurements as part of a shelf-wide monitoring effort. There have been several recent efforts to make surface pCO_2 measurements in the Gulf of Maine. The University of New Hampshire (UNH) Coastal Ocean Observing Center's Coastal Carbon Group has been working in the New Hampshire coastal regions since 2004. Two Regional IOOS (Integrated Ocean Observing System) Regional Associations (NERACOOS and MaCOORA) are active in the northeast ecosystem and have a broad range of observing platforms. Activities include satellite observations, buoys, glider transects, HF radar, and modeling. MaCOORA through Rutgers University has been collaborating with the NEFSC within the New York Bight on ECOS (Ecology of Coastal Ocean Seascapes), which has been measuring spatial changes in environmental parameters related to changing distribution patterns of living marine resources. Therefore, the regional associations are complementary to the NEFSC shipbased OA activities.

6.2 Organism Response to Ocean Acidification (Theme 2)

A comprehensive overview of the biological components of the northeast U.S. shelf ecosystem provided by NEFSC Energy Modeling and Analysis eXercise (EMAX) identified functional groups and established trophic relationships between them (Link *et al.*, 2006). The Northeast U.S. shelf ecosystem is highly interconnected through its trophic relationships, raising the expectation that OA effects could be propagated throughout it. To predict how ecosystems will respond to OA, it is important to first determine how individual species will respond under controlled experimental conditions. Results from these experiments will provide information about direct effects and predictions about priority species, data to refine models of the ocean carbon cycle and data for models such as EMAX that could predict indirect effects of OA.

Organisms of Near-Term Focus

Primary producers
Scallops
Lobster (American above)
Atlantic surf clams
Hard and soft shell clams
Mussels
Oysters
Summer and Winter Flounder
Black Sea Bass
Shortnose Sturgeon
Deep-sea Coral
North Atlantic Right Whale

Given the diversity of fish and shellfish species, the numerous protected and endangered taxa (e.g., the North Atlantic Right whale and shortnose sturgeon) and the importance of bottom-up forcing (e.g., lower trophic levels), we will conduct research on a range of taxa utilizing regional expertise and then focus future research based on those results. In addition, NOAA's extramural research funds will be directed to fill the gaps in NOAA expertise and facilitate partnerships with academic institutions.

It will be important for NOAA researchers to work closely with academic partners given the wealth of expertise in the region. A research group at Woods Hole Oceanographic Institution (WHOI) is actively involved in working to understand the effects of OA on marine ecosystems and resources. Doney *et al.* (2008) document the state of knowledge regarding impacts of acidification on marine species, and Cooley and Doney (2009) provide a preliminary economic assessment of the effect of OA on commercial fisheries. A second group at WHOI (Ries *et al.*, 2009) is investigating the effect of acidification on calcification of invertebrates and algae. They have found OA can greatly affect initial shell formation in shellfish such as bay scallops, which has potential major effects on the shellfish industry in the northeast region. Similar research at the State University of New York at Stony Brook (SUNY) confirms these results (Talmage and Gobler, 2009). At the University of Massachusetts at Amherst (UMass Amherst), preliminary research investigations have started to examine the relationship between OA and lobster shell disease.

Current priorities for NOAA research in the Northeast region on organism response to ocean acidification are: primary and secondary productivity, shellfish, finfish, deep-sea corals, and protected species.

6.2.1 Primary producers

Task 6.2.1: Conduct laboratory and targeted field studies to quantify the impact of ocean acidification on primary producers.

A critical concern is the effect of OA on primary and secondary productivity in the ecosystem. The Northeast U.S. shelf is strongly driven by bottom-up processes. Impacts on phytoplankton and zooplankton ecology could have important ramifications for overall system productivity. Understanding the relationship between acidification and nutrient chemistry is also a clear need, as primary productivity is ultimately limited by nutrient supply.

Ocean acidification can affect primary productivity both directly and indirectly. Many marine phytoplankton are sensitive to changes in pH and temperature. A series of experiments will be conducted that quantify the interactive effects of pH and temperature on phytoplankton growth, physiology, and competition. These experiments will be complemented by a retrospective analysis of field-collected data and targeted comparative field sampling, with a specific goal of examining some of the effects and relationships observed in the laboratory.

We will start with 15 individual strains of marine phytoplankton from the Milford Microalgal Culture Collection and add several calcifying strains (*Coccolithus huxleyi*; *Ochrosphaera neopolitana*) that will be acquired from the Provasoli-Guillard Center for the Culture of Marine Phytoplankton. Cells from each strain will be cultured at different pH levels and flowcytometry will be used to quantify phytoplankton abundance and cell-division rate and characterize selected physiological characteristics such as nutrient status and internal pH. The second stage of experiments will examine the competitive interactions between pairs of microalgal species under varying pH levels selected to examine important ecological and physiological contrasts. These experiments will provide broad generalizations about likely shifts in phytoplankton community structure as a consequence of competition modified by OA. The third stage of experiments will be based on phytoplankton communities (multi-species) with several cultured species. These experiments will be hypothesis-driven, in terms of ecological principles, e.g., does the presence of a calcifying species modify the interaction between diatom species and will present a more ecologically relevant simulation of OA effects upon phytoplankton communities.

In the field, we will examine the effect of pH on natural phytoplankton communities in the Northeast U.S. continental shelf ecosystem. Natural communities will be collected and experiments conducted at conveniently located facilities (i.e., Howard Laboratory, Stellwagen Bank National Marine Sanctuary). The laboratory experimental systems will be modified for field studies and will build upon the experience and knowledge gained in previous experiments.

A retrospective analysis of monitoring data will be examined to determine whether changes in phytoplankton species composition have occurred and evaluate the potential link to OA. The Ship of Opportunity Program has been collecting data on phytoplankton species composition since 1961 and there is spatial variability in pH throughout the system. A detailed analysis of the species composition with available dissolved CO_2 measurements will be examined. Based on lab results, predictions will be made as to components of the phytoplankton community that should be observed in areas of differing dissolved CO_2. These natural contrasts will inform both future experiments and help in understanding the laboratory results in the context of the natural system.

An additional approach will be to develop genomic assaying techniques to quantify genetic diversity and to look at variation in phytoplankton community structure over time. This technique can be used at different taxonomic resolutions (i.e., species, genera, families, etc.) and is being developed for several types of marine organisms by researchers working under umbrellas such as the Census of Marine Life and the Marine Barcode of Life. Stellwagen Bank National Marine Sanctuary will serve as the regional test-bed for the development of genetic diversity indices and assaying techniques through collaboration with other research partners. Indices will then be monitored over time to characterize the status of and changes in primary producer diversity in relation to available dissolved CO_2 and other environmental measures collected via EcoMon sampling in sanctuary waters.

6.2.2 Shellfish and finfish

Task 6.2.2: Create a state-of-the-art capability in the Northeast for conducting acidification experiments on individual species and species assemblages of shellfish and finfish and estimate the impact of ocean acidification on Northeast ecosystem resource species.

To evaluate how finfish and shellfish species in the ecosystems associated with the Northeast U.S.A. will respond to acidification, we will design and construct the capability for experimentally evaluating species' responses. The NEFSC facility will be located at the Howard Marine Sciences Laboratory and the first phase is scheduled to be completed in 2010 as part of the NMFS FY2010 OA Plan. The NEFSC has already developed a pilot-scale OA treatment system that is currently being tested. Knowledge gained in the development of the pilot system will be applied to the design of the larger one. The NEFSC system will be capable of conducting large-scale and replicated multi-factorial experiments. Analytical chemistry needs for the NEFSC facility will be met by a combination of on-site capabilities, collaboration with the Milford Laboratory, and quality control analysis with the Pacific Marine Environmental Laboratory (PMEL) carbon group.

We will use several test species of shellfish and finfish in order to draw the broadest levels of inferences about the potential effects of OA. Our selected species will be determined by economic value, habitat usage, season of spawning, and feasibility of captive rearing, among other criteria. We will estimate the effects of OA on shellfish and finfish resource species and measure responses that represent critical organismal functions.

6.2.2.1 Shellfish

Given preliminary results on the effect of OA on shell formation and calcification rates, research on the region's shellfish species is a clear priority. The sea scallop and lobster fisheries are two of the most valuable fisheries in the U.S., with landings exceeding $340 million in 2007. Other important shellfish fisheries in the region are Atlantic surf clams, ocean quahogs (hard clams), bay scallops, softshell clams, mussels, and oysters. Sea urchins and sea cucumbers are also minor fisheries in the Gulf of Maine. Several of these species are being used in aquaculture, raising the concern that OA will have an impact on commercial and stock enhancement culture operations.

Culture techniques for the Atlantic surf clam were developed in the NEFSC Milford Laboratory 20 years ago and this capability remains current at this facility. In the initial experiments, we will rear newly hatched larvae, juveniles, and adults. The formation of the shell will be measured in larvae and the growth of the shell will be measured in all life stages. Due to the variable salinity and pH of the seawater at the Milford Laboratory, we will be partnering with the Martha's Vineyard Shellfish Group (MVSG) to conduct the experiments. We will also evaluate the potential increase in predation risk as a consequence of increased $p\mathrm{CO}_2$ by exposing Atlantic surf clams reared at different pH levels to natural starfish predators in the lab. Changes in shell growth may make Atlantic surf clams more susceptible to size-selective predation and changes in shell rigidity may facilitate predation at all sizes.

After the experiments have been fine tuned for Atlantic surf clams, a focused effort will be directed on the effects of OA on sea scallops. Sea scallop culture is notoriously difficult but its status as the most valuable fishery species in the U.S. warrants attention and effort. MVSG has some experience in culturing sea scallop and will be a valuable partner in these experiments.

6.2.2.2 Finfish

A clear need exists to understand the impacts of OA on finfish species. For fish, the limited number of prior reports has noted effects of OA on a suite of life stage, behavioral, and morphometric features important to the survival of young fish. Some research has shown that OA can affect the olfactory system and otolith growth in larval fish indicating potential ecological consequences environment (Checkley, Jr. *et al.*, 2009). The otolith is an important sensory organ and changes in calcification may affect behavior, including feeding and predator avoidance. In addition to direct metabolic, sensory, and calcification effects, there could be physiological consequences, reducing the energy available for activity, growth, and reproduction. These physiological costs could be magnified when OA conditions are combined with other climate change parameters such as reduced levels of dissolved oxygen, alterations in ocean temperatures, and changes in ocean circulations patterns. Moreover, increased ocean acidity has the potential to elicit substantial sublethal effects on fish by means of affecting their normal developmental and behavioral capabilities during their sensitive early life-stages. For example, Munday *et al.* (2009) reported that settling reef fish reared at high levels of $p\mathrm{CO}_2$ failed to successfully discriminate among reef microhabitat flora that are key to subsequent survival.

We have identified finfish species that would not only provide us with a high likelihood of experimental success but provide the broadest possible basis for inferences about OA effects in the Northeast U.S.A. Atlantic ecosystem. These fish species represent shelf and inshore waters and they differ in their economic and ecosystem values, ecology, habitat, and other key features relevant to projected OA and temperature regimes (Table 6.1).

All of these species have been maintained and reared under controlled laboratory conditions. These experiments will mostly focus on the reproductive and early life history features of the fish life cycle. The use of a diverse set of species allows us to quantify OA effects and address broader questions of interest including: (1) Are species that spawn and have early life-stages offshore more sensitive to changes in pH than species that spawn and have early life-stages inshore? (2) Are species that spawn in winter and whose early life-stages experience low temperatures more sensitive to change in pH than species that spawn and whose early life-stages experience warm summer temperatures? (3) Are populations of species near the extreme of their geographic distributions more likely to be sensitive to the individual and/or combined effects of projected OA and temperature regime shifts associated with climate change? (4) Do the data suggest that responses differ among taxonomic groupings?

In addition to the laboratory work, we also propose targeted field sampling to use the documented spatial variability in pH (Theme 1) to evaluate whether shell and otolith growth in selected shellfish and finfish species can be related to ambient pH and carbonate chemistry. Locations will be chosen based on dissolved CO_2 distribution resulting from the monitoring program. This work will include the collection of species of interest as well as the collection of DIC and TA samples to verify chemical conditions at the time of collection. The purpose of this component is to evaluate whether there are already signals of the effect of pH among species in the ecosystem.

6.2.2.3 Deep-sea coral

Habitats used by marine organisms may be impacted. Deep-sea corals are found along much of the shelf edge, especially near the Hudson canyon and at locations in the Gulf of Maine along with pockets of shallow water corals and areas of calcareous algae. These habitats, which may represent nursery grounds for finfish, may be especially vulnerable to OA.

Relatively little is known about the ecology of the deep-sea corals found in the northeast. Recent efforts have been made to characterize their distribution and abundance. In other oceanic regions, many commercial and non-commercial fish species are associated with deep corals. While most associations are believed to be facultative, fish and crabs use coral habitat as refuge and as focal sites of high prey abundance. During 2010, photo reconnaissance with a camera-equipped AUV will identify coral patches in the area around the Hudson Canyon. Collections of the solitary deep-sea hard coral *Dasmosmilia lymani* will be made to determine coral age and growth rates in collaboration with other collaborative partners (e.g., NOAA Coral Reef Conservation Program) in order to develop a baseline against which to monitor OA effects at the shelf edge.

6.2.2.4 North Atlantic Right Whale

Protected species will also be impacted and initial efforts will focus on forecasting the effect of OA on the North Atlantic right whale, owing to their extremely low population sizes. Endangered right whales feed on copepod zooplankton which are vulnerable to OA and some researchers have hypothesized that OA will affect low-frequency sound propagation with negative consequences for marine animal communication. This work will primarily involve data synthesis and modeling built from existing information with some focus on new data collection.

The North Atlantic right whale has become rare (300–400 individuals) and endangered and even marginal impacts can have grave consequences for the species. We will examine the potential effect of changes in sound propagation on right whale communication in Stellwagen Bank National Marine Sanctuary (SBNMS). Increasing acidification may affect frequency sound propagation conditions, which in turn could have negative consequences for vocalizing marine animal communication ranges. The Stellwagen Bank National Marine Sanctuary, the NEFSC, and Cornell University have established a high-resolution acoustic monitoring program to map

Table 6.1: Proposed finfish species for OA experiments and their economic and ecosystem values, ecology, habitat, and other key features.

Species	Spawning season	Spawning habitat	Egg/larval habitat	Primary value
(1) summer flounder (*Paralichthys dentatus*)	autumn	shelf	water column	economic
(2) winter flounder (*Pseudopleuronectes americanus*)	winter	estuaries	benthic/water column	economic
(3) black sea bass (*Centropristis striata*)	summer	shelf	water column	economic
(4) shortnose sturgeon (*Acipenser brevirostrum*)	spring–summer	estuaries (upper fresh)	benthic	endangered

human-induced noise in greater sanctuary waters in relation to the behavior of vocally active marine species. The sanctuary-based study has included empirically driven propagation modeling for this system, including calculations of communication range for individual calling animals. This model will be used to predict the consequences of OA on communication ranges for different species, and to better understand the influence of spatial and temporal variance in propagation conditions on low-frequency communication.

6.3 Biogeochemical and Ecosystem Models (Theme 3)

Task 6.3: Develop and implement models to assess the effects of ocean acidification on single-species dynamics, multi-species interactions, and overall ecosystem productivity.

The region has a strong modeling community and numerous regional models; however, these have yet to be applied to the OA issue. The NEFSC has vast experience with single-species population models and is continuing to develop environmentally explicit, single-species models as well as multi-species models, habitat suitability models, trophic network models, and aggregate production models. Through the Global Ocean Ecosystem Dynamics (GLOBEC) program, a number of numerical circulation models were developed for the region; some of these have been coupled with regional nutrient-phytoplankton-zooplankton (NPZ) models and some have included early life stages of fishes. NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) and other climate modeling centers have developed Earth System Models capable of hindcasting and forecasting OA globally over multiple decades that can be used to inform regional ecosystem simulations. Finally, there is strong expertise in ocean carbon and biogeochemistry at regional NOAA/academic institutions and this experience could be brought to bear within the region.

Initially, the results of single shellfish and finfish species will be used to parameterize population models relative to different levels of dissolved CO_2 in the system. As results become available for multiple species, models will be parameterized with the effects of acidification on growth, reproductive output, and natural mortality. The experimental results from larvae and juveniles will be included in population models as recruitment effects. The coupled OA-population models will then be used to forecast population productivity under several acidification "scenarios" which will be developed based on IPCC carbon emission scenarios and resulting forecasts of dissolved CO_2 on the northeast U.S. shelf. Comparison of the MARMAP data with present-day data will assist with estimating dissolved CO_2 from atmospheric CO_2. These forecasts will have a range of uncertainties, which we will try to capture, but the goal is to provide an initial assessment of the effect of OA on marine resource species over the coming decades and through the coming century.

The results of the research on phytoplankton will be used to assess the effect of OA on system-wide productivity and phytoplankton community structure. Existing planktonic ecosystem models (i.e., NPZ) will be expanded to include multiple phytoplankton types that encompass the range of important ecological phytoplankton groups studied. The response of each group to acidification will be parameterized based on experimental data generated in Task 6.2.2. The expanded ecosystem models will be embedded in regional hydrodynamic simulations, validated against past observations and those carried out as part of this study, and used to predict the impact of a range of plausible acidification changes. This will be translated to an estimate of total sustainable fisheries extractions through methods established at the Groundfish Assessment Review Meeting (GARM). Additional modeling efforts will be developed as more information is generated during the course of laboratory and targeted field studies.

To address the effects of increasing acidification on the endangered right whale, the Whale Habitat Informatics Project (WHIP, `http://gmri.org/whales/`) is currently developing a right whale likelihood product which merges model forecasts with field observations and merges satellite sea surface temperature (SST) and chlorophyll to model the right whale's main zooplankton prey. A second model developed by collaborators at the Provincetown Center for Coastal Studies predicts individual right whale feeding behavior in relation to spatial distribution and abundance in Cape Cod Bay. The integration of higher-resolution empirical data that reflects a better understanding of OA impacts on the availability and quality of food resources could increase the predictive strength of these models and enhance NOAA's ability to manage right whales within northeast waters.

Ultimately, the expanded NPZ and biogeochemical models will be linked with upper trophic level responses and incorporated into regional ocean model simulations. Multi-decadal hindcast simulations forced by atmospheric reanalysis products will be conducted to refine model dynamics and provide a holistic understanding of past observed variations in primary productivity, phytoplankton community structure, and resource species. Climate change projections will also be conducted through either (a) off-line coupling to hydrodynamic fields from high resolution physical climate model simulations which are under development; or (b) regional hydrodynamic simulations driven by global ESM boundary conditions and atmospheric forcing. The approach taken will be contingent upon progress toward high-resolution global climate model development and progress toward robust nesting approaches for regional models of the eastern United States within coarse global climate simulations. This holistic model will be constructed through collaborations across NOAA line offices and in academia.

6.4 Human Dimensions (Theme 4)

Task 6.4: Estimate anticipated changes to northeast ecosystem services as a consequence of OA and develop a decision framework for adaptation strategies.

The analysis of the human dimensions of OA will consist of two interrelated components. First is estimating how acidification is likely to affect the human community though impacts on "ecosystem services" or the value of benefits to human communities as a result of functioning ecosystem processes. Analysis of the value of the fishery declines anticipated in the Northeast region is needed, although Cooley and Doney (2009) have done an initial analysis of the potential economic cost from a national perspective. The human dimension analysis also includes the development of a framework for deciding what to do about acidification. Choices about adopting various CO_2 emission strategies and the implications of those adopted scenarios will need to be informed by the best available science. In the Northeast, these choices will need to be considered within the broader context of how to confront other stressors to the ecosystem such as eutrophication, how to prepare fishing-based economies for ecosystem changes, whether to implement spatial or temporal fisheries changes, etc. Making these decisions will require consideration of ecological predictions, the value of ecosystem services, and the economic and social costs of proposed actions. The decision process will need to transparently incorporate the considerable uncertainty that exists in all of the input parameters. There is substantial technical work required among NOAA and academic partners in the Northeast to develop socioeconomic models and decision frameworks to address the unique impacts of ocean acidification on Northeast communities and the economy.

6.5 Synthesis of Data and Information Products (Theme 5)

Task 6.5.1: Provide a first integrated assessment of the effects of OA on the northeast U.S. continental shelf ecosystem.

The work described above is directed toward the development of an assessment of the effect of OA on the northeast U.S. continental shelf ecosystem. The audience of the assessment will be scientists and policymakers alike. The form of the assessment will be similar to other Integrated Assessments produced within NOAA. The assessment will draw heavily on work done as part of this project, but will also incorporate the results of all research that is relevant. There are several groups that are working within the northeast

U.S. shelf region (e.g., UNH, AOML, and WHOI) and there will certainly be additional research conducted around the globe that will be relevant. Data management staff and improvements to computer-based infrastructure will be required to ensure an organized and coordinated result. The resulting document will provide the first regionally specific assessment of the effects of OA and serve as a tool for identifying critical gaps in our understanding and providing a basis for future research to fill these knowledge gaps. Importantly, this assessment will provide a quantitative framework describing the effects of OA on resource species in the northeast U.S. continental shelf ecosystem. The assessment will be iterative, similar to that described for the IEA process; the timescale of reassessment will be approximately five years.

6.6 Engagement Strategy (Theme 6)

Task 6.6: Identify target audiences and determine appropriate programs and products utilizing innovative approaches for community involvement.

Using resources already present in the region, NOAA can begin the process of disseminating important information on the causes and potential effects of ocean acidification on our coast and ocean ecosystems to ocean user groups and the general public. The first steps in developing an action plan for education and outreach for the northeast are to:

1. Identify target audiences;
2. Determine appropriate programs and products for each audience;
3. Develop a comprehensive needs assessment to education and outreach programming;
4. Match ocean acidification needs with existing education and outreach activities; and
5. Develop innovative approaches for community involvement.

NOAA regional offices (NMFS, NERRS, NMS, Sea Grant, Office of Ocean and Coastal Resource Management, National Weather Service) and their research partners can provide OA information in general outreach tools and programs. The SBNMS can also include OA stories in publications, such as Stellwagen Banknotes and Stellwagen Soundings, as can other NOAA publications released in the region. Possible products for development include a standard PowerPoint presentation for the general public that illustrates the issues; a general traveling exhibit for use at public venues; press releases and backgrounders for dissemination through the NOAA public affairs network; the use of new media, including podcasts, blogs, YouTube videos, tweets, etc; and distance learning programs that are broadcast over the internet to reach educators and other interested members of the general public, and to serve as educational resources to supplement content in college courses. Education and outreach programs can include science experiments for the classroom, student data collections, workshops and training programs with constituents, and internet access to research findings and data that inform stakeholders and provide mutual understanding of issues related to OA.

Periodic workshops could be held for coastal managers. The purpose would be to communicate the status of OA investigations, provide information as to the current and potential future state of OA in the northeast region, and maintain a dialogue between NOAA OA scientists and the region's management community. Attendance would be open and would include: the regional fishery management councils, NOAA managers (e.g., NERR's and NMS's), state fishery managers, and others who have interest. The state managers would also be included through the involvement of the Northeast Regional Ocean Council, which is composed of state and provincial representatives for the New England region. A similar group is under development in the Mid-Atlantic region and would be included in these workshops.

The NEFSC is involved in numerous joint activities with the Canadians, providing multiple pathways for cooperation. Several fisheries stocks are assessed under a Transboundary Resource Assessment Committee; information on single species effects can be coordinated in this framework. Additionally, joint ecosystem-based management activities are underway in the Gulf of Maine, providing an avenue for communication and cooperation on ecosystem effects. To contribute to these management activities, the NEFSC already shares data with the Canadians and these existing protocols will be used. Canadian scientists also are involved in one of the Regional IOOS Associations and the Northeast Regional Ocean Council includes representatives of provincial governments providing additional venues for cooperation and communication. International cooperation exists with Norway.

6.7 Collaborators

Northeast Region Collaborators
Northeast Fisheries Science Center
Office of National Marine Sanctuaries
Geophysical Fluid Dynamics Laboratory
Atlantic Oceanographic and Meteorological Laboratory
Office of Ocean and Coastal Resource Management
Northeast and Mid-Atlantic Sea Grant Colleges (e.g., RI, MA, NH, DE)
Woods Hole Oceanographic Institution
University of New Hampshire
Old Dominion University
Regional OOS (NERACOOS, MACOORA)
National Estuarine Research Reserve System
Martha's Vineyard Shellfish Group
Stellwagen Bank National Marine Sanctuary
Cornell University
Provincetown Center for Coastal Studies

7. Great Lakes Region Acidification Research Plan

Simone R. Alin, Jennifer Day, Galen McKinley, Craig Stow, Mary Baker, Ellen Brody, Reed Bohne, Thomas Nalepa, Terry Heatlie, Adrienne J. Sutton, and Richard A. Feely

7.0 Lake Acidification in the Great Lakes Region

The Great Lakes provide invaluable ecosystem goods and services to the United States and Canadian economies; they collectively contain 20% of the world's freshwater, yield robust recreational and commercial fish catches, provide critical shipping and transportation routes, and significantly influence regional climate (Bonan, 1995; ILEC, 1999). Despite their enormity, the lakes have been affected by many anthropogenic stressors, including excessive nutrient loading from agriculture and urbanization, toxic pollutants from atmospheric deposition and contaminated sediment (PCBs, pesticides, mercury), invasive species (zebra and quagga mussels, Eurasian ruffe, round gobys, lampreys), and climate change (changes in ice cover, precipitation, water temperature and stratification, lake levels, and terrestrial nutrient and carbon inputs). However, the potential for impacts under increasing atmospheric CO_2 levels and any consequent acidification that may occur in the Great Lakes has not been systematically evaluated. Assessing the susceptibility of the lakes to increasing atmospheric CO_2 is challenging; the acidification actually experienced will be the net result of many simultaneous processes operating at differing spatial and temporal scales, as well as feedbacks that may be difficult to anticipate.

In the open ocean, acidification from anthropogenic CO_2 uptake has been reported to cause a 0.002 yr^{-1} decrease in pH (Bates, 2001; Byrne *et al.*, 2010; Doney *et al.*, 2009a; Santana-Casiano *et al.*, 2007), with higher rates observed in coastal waters (e.g., Borges *et al.*, 2010). However, the Great Lakes may respond differently to acidification than open-ocean systems for several reasons. First, the Great Lakes (GL) have a lower alkalinity than the open oceans and are thus less well buffered against pH changes. The average alkalinity of the GL ranges from 36% (Superior) to 95% (Michigan) of surface ocean alkalinity (Table 7.1). Because these lakes are less buffered than marine environments, they typically experience a greater range of natural variability in pH and related parameters (Table 7.1). If the approximate equilibrium with atmospheric pCO_2 observed in Lake Superior over the last decade (Atilla *et al.*, 2010) continues through the next 80 years, lake pH may decline by on the order of 0.15 pH units by mid-century and 0.30 by 2090 under IPCC emissions scenario A2, which represents a pH decrease of 0.004 yr^{-1}, a rate twice that observed in the ocean (Figure 7.1). This calculation is made for illustrative purposes only, as we expect the future trajectory of lake pH will likely be substantially more complicated.

Although water residence time decreases in the lower Great Lakes (Erie, Ontario), a large portion of the influent waters comes from the upper Great Lakes (Superior, Huron, Michigan), so the lower lakes should inherit the signature of acidification that has accumulated in the upper watershed (Table 7.2) (Quinn, 1980). Also, because the GL are in a continental setting, the deposition of acidic nitrogen (N) and sulfur (S) compounds should be comparable to the coastal oceans, where it has been estimated that N and S deposition can increase acidification by ~10–50% or more over acidification expected from anthropogenic CO_2 uptake alone (Doney *et al.*, 2007). Second, the Great Lakes destratify and mix vertically in spring and fall each year when their water columns are isothermal at 4°C and CO_2 solubility is high, such that, unlike the open oceans, some anthropogenic CO_2 should penetrate the entire water column of the lakes each year. Thus, the rate of acidification at depth may be rapid relative to rates in the ocean (on the order of a few years to decades vs. decades to centuries). Concurrently, the vertical mixing that the GL experience also provides an opportunity for the release of CO_2 that accumulates in the hypolimnion, an

Great Lakes Region Description

Image: Summer climatology of chlorophyll from SeaWiFs (NASA)

The Laurentian Great Lakes—Superior, Michigan, Huron, Erie, and Ontario—contain nearly 20% of the world's freshwater, with a combined lake surface area of 244,000 km^2. Together the five lakes, along with thousands of smaller lakes, lie in the 767,000 km^2 watershed for the St. Lawrence River. The Great Lakes are bordered by the states of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin and the Canadian province of Ontario. The Great Lakes provide the region's ~34 million people with drinking water, transportation corridors, rich fisheries, hydroelectric power, and aesthetic and recreational outlets. The Great Lakes coastline is 17,549 km long, with 35,000 islands among the lakes. Prior to human impact, estimates suggest the Great Lakes had up to 180 indigenous fish species, with varying ecological communities across the five lakes, depending on each lake's prevailing climatic conditions and physical characteristics. Ecologically and economically important native Great Lakes fish species include the Coaster brook trout (*Salvelinus fontinalis*), which resides only in the upper Great Lakes, and the lake trout (*Salvelinus namaykush*), lake sturgeon (*Acipenser fulvescens*), lake herring (*Coregonus artedii*), and lake whitefish (*Coregonus clupeaformis*), which occur in all five lakes. At present, the Great Lakes ecosystems face a number of grave environmental threats, including the ecological impacts of approximately 185 non-native aquatic species, toxic and nutrient pollution, habitat destruction, animal and human disease outbreaks, and climate change.

area of net respiration. In total, either an increase in CO_2 uptake or a decrease in outgassing of CO_2 by the GL resulting from the changed air-lake CO_2 gradient will be manifested as a greater CO_2 inventory in the lakes as a result of increasing atmospheric CO_2. Thus, the processes that influence acidification in the GL differ in many important respects from those in the open oceans. These processes have not been well quantified to date, and their likely net effects are not well understood.

The Great Lakes also differ in many important respects from other freshwater systems in which acidification processes have been studied. Historical studies on poorly buffered, soft-water lakes in landscapes lacking carbonate bedrock in eastern North America and Europe indicated that acidification due to deposition of acidic nitrogen (N) and sulfur (S) compounds could profoundly alter the species composition of freshwater ecosystems (see, for example, special issues on acid deposition and ecosystem impacts in *Water, Air, and Soil Pollution* (1986, vol. 31[3–4] and 1987, vol. 35[1–2]), *Ambio* (1993, vol. 22[5]), and *Journal of Paleolimnology* (1990, vol. 3[3]). All of the Laurentian Great Lakes except Lake Superior have significant proportions of carbonate rocks in their drainage basins. Runoff from landscapes dominated by carbonate rocks, such as limestone and dolomite, has higher alkalinity (or buffering capacity) than runoff from landscapes with granitic, sandstone, and other non-carbonate mineralogies in the Great Lakes basin. Consequently, none of the Great Lakes was observed to undergo acidification related to 20th-century acid deposition. Changes in pH observed in soft-water lakes as a result of anthropogenic acid deposition were frequently on the order of full pH units and over timescales of decades, whereas acidification from uptake of anthropogenic CO_2 is expected to occur at a slower rate over longer timescales, as the problem of

Table 7.1: Temperature and chemical attributes of the five major Great Lake basins. All data are from semi-annual sampling.

Lake	Years sampled by EPA	Temperature (°C)[†]	Alkalinity (μmol kg^{-1})[†]	pH[†]	Ω_{arag}[‡]
Upper Great Lakes					
Huron	1983–2009	6.7 ± 6.7	1561 ± 41	8.21 ± 0.2	0.96 ± 0.62
		(0.2–24.2)	(1263–1854)	(7.23–8.74)	(0.07–4.19)
Michigan	1983–2009	7.1 ± 6.7	2181 ± 39	8.35 ± 0.2	2.32 ± 1.6
		(0.5–27.0)	(1724–2335)	(7.53–9.17)	(0.27–12.99)
Superior	1996–2009	5.4 ± 4.8	834 ± 17	8.00 ± 0.2	0.15 ± 0.08
		(0.3–20.2)	(762–952)	(7.45–8.69)	(0.03–0.78)
Lower Great Lakes					
Erie	1983–2009	11.3 ± 9	1817 ± 97	8.26 ± 0.3	2.37 ± 2.0
		(0.1–27.5)	(1383–2174)	(6.65–9.00)	(0.03–13.78)
Ontario	1985–2009	7.8 ± 7.2	1836 ± 65	8.30 ± 0.2	2.17 ± 1.93
		(1.2–26.4)	(1463–2044)	(7.58–8.98)	(0.33–12.40)
Global Oceans					
Surface[¶]	1990–1998	16.09 ± 10.4	2302.7 ± 48	8.108 ± 0.05	2.98 ± 1.3

[†] Data were downloaded from the Great Lakes Environmental Database (`www.epa.gov/glnpo/monitoring/data_proj/glenda`). Parameters to the right of the sampling years column are average values (±SE) across all years and depths sampled, except as noted. Ranges are reported in parentheses. Number of measurements for each lake for temperature, alkalinity, and pH were as follows: Huron—7396, 6856, and 6438, respectively; Michigan—7641, 7211, and 6701; Superior—5708, 4094, and 4094; Erie—8292, 7920, and 7404; and Ontario—4748, 4476, and 4332.

[‡] Aragonite saturation state (Ω_{arag}) values and carbonate ion concentrations ($[\mathrm{CO}_3^{2-}]$) were calculated from pH and alkalinity data using equations in Dickson *et al.* (2007) in the Excel version of the CO2SYS program (Pierrot *et al.*, 2006). Calcium data were available from all lakes for the period prior to the dreissenid mussel invasion of the lakes from references in Alin and Johnson (2007). Post-dreissenid calcium data for Erie and Ontario were available from Barbiero *et al.* (2006). Saturation states were calculated for the lower Great Lakes for all years and only for the pre-dreissenid years (until 1990) in the upper Great Lakes, as calcium concentrations there may have changed because of dreissenid calcification and there are no data available.

[¶] Global average surface ocean data from the GLODAP project are from Feely *et al.* (2009).

Table 7.2: Physical attributes of the Great Lakes[†].

	Mean depth (m)	Maximum depth (m)	Volume (km^3)	Surface area (km^2)	Land drainage area (km^2)	Water residence time (yr)
Huron	59	229	3,540	59,600	134,100	22
Michigan	85	282	4,920	57,800	118,000	99
Superior	147	406	12,100	82,100	127,700	191
Erie	19	64	484	25,700	78,000	2.6
Ontario	86	244	1,640	18,960	64,030	6

[†] From *The Great Lakes: An Environmental Atlas and Resource Book* (`www.epa.gov/greatlakes/atlas/gl-fact1.html`).

CO_2 emissions will not be reversed as easily as acid deposition has been and the atmospheric lifetime of CO_2 is substantially longer than those of acidic N and S compounds.

It has been argued, on the basis of no observed directional pH trend in the Great Lakes during the 20th-century increase in industrial acid deposition, that the large volume of the lakes and the prevalence of naturally buffering carbonate minerals in GL drainage basins makes them relatively invulnerable to the effects of acid deposition (SOLEC, 2000), and by extension, anthropogenic CO_2 uptake. However, contemporaneous increases in nutrient inputs from atmospheric, agricultural, and urban sources during the 20th century may have countered the acidifying effects of N and S inputs by stimulating the uptake of CO_2 through primary production, resulting in an increase in pH (or decrease in acidity), rather than the

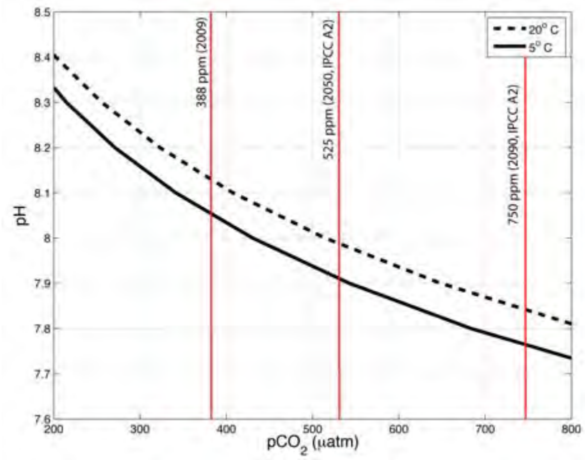
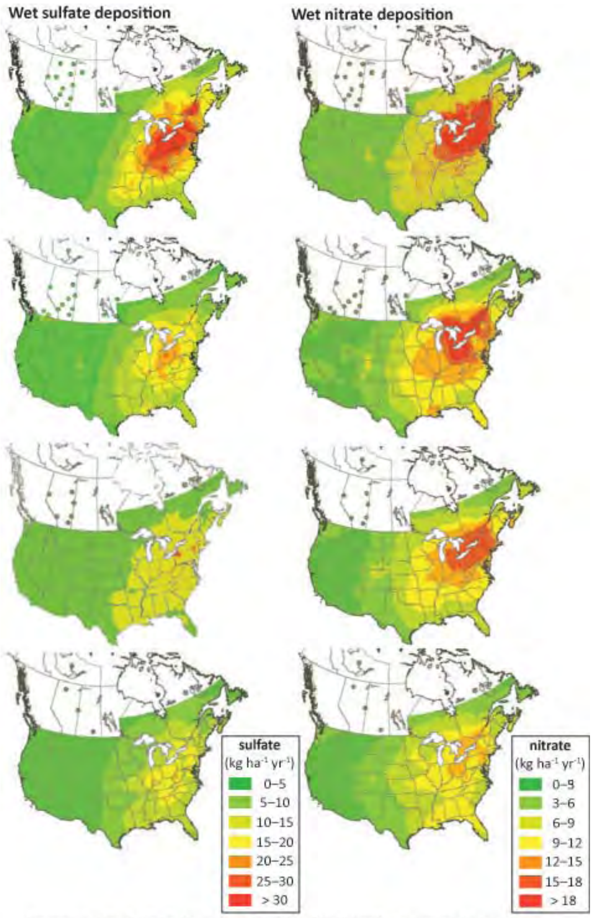


Figure 7.1: Lake Superior's pH can be expected to decrease as a function of $p\mathrm{CO_2}$ over the coming century if the lake $p\mathrm{CO_2}$ continues to keep pace with atmospheric $\mathrm{CO_2}$ increases (alkalinity = 840 μmol kg^{-1}). Red vertical lines indicate atmospheric $p\mathrm{CO_2}$ levels observed in 2009 and expected in 2050 and 2090 under IPCC emissions scenario A2 (moderate). The dashed and solid black lines represent the relationships between $p\mathrm{CO_2}$ and pH at water temperatures of 20°C (dashed line) and 5°C (solid line), respectively.

decrease in pH that would be expected from acidification alone. Enrichment of phosphate and nitrate fluxes to the lakes from agricultural, urban, and atmospheric sources led to basin-wide eutrophication in the lower Great Lakes and localized eutrophication within the upper Great Lakes during the 20th century (Hodell and Schelske, 1998; Hodell *et al.*, 1998; Magnuson *et al.*, 1997; Munawar and Munawar, 2001; Schelske and Hodell, 1991; 1995). Inputs of anthropogenic phosphate to the lakes have been successfully abated during the last 40 years (International Joint Commission, 1980), and acid deposition in the eastern half of North America has also been successfully mitigated during the last 30 years (Figure 7.2) (U.S.–Canada Air Quality Committee, 2008).

Thus, while the GL have some similarities to the open oceans as well as other freshwater systems, there are also important differences that require directed research to more fully understand the likely response of the lakes to atmospheric $\mathrm{CO_2}$ increases. It should be possible to improve our understanding of the relative contributions of acidification, eutrophication, and invasive species to the observed changes in Great Lake biogeochemical cycles, as well as the likely consequence of mitigation efforts, through a combination of high-quality carbon measurements, organismal response experiments, and coupled biogeochemical/ecosystem modeling.



Sources: National Atmospheric Chemistry (NAtChem) Database, National Atmospheric Deposition Program (NADP)

Figure 7.2: Maps of wet sulfate and nitrate deposition in 1990, 1995, 2000, and 2005 (U.S.–Canada Air Quality Committee, 2008).

7.0.1 *Confounding factors*

Since the late 1980s, when invasive zebra mussels were first observed in the Great Lakes, these dreissenid mussels have played an increasingly important role in the energy and nutrient cycles of the Great Lakes. As filter feeders, the mussels are very effective at filtering phytoplankton from the water column of lakes and rivers (Fahnenstiel *et al.*, 1995; Hebert *et al.*, 1991; Holland, 1993; MacIsaac, 1996; Roditi *et al.*, 1996). As an example of the potential ecosystem consequences of this efficient filtration, the hypothesis has been advanced that changes in GL fish populations may reflect the co-optation of the base of the food web by dreissenid mussels from the lakes' native zooplankton and fish species, but this idea is just beginning to be studied.

In addition to their substantial impacts on nutrient and energy flow in GL food webs (Hecky *et al.*, 2004), the overpopulation of GL basins by calcifying organisms like the dreissenid mussels has substantially decreased water column alkalinity and calcium concentrations in the lower Great Lakes (Barbiero *et al.*, 2006). The substantial increase in calcification rates in the Great Lakes (calcification reaction: $2\ HCO_3^- + Ca^{2+} \rightarrow CaCO_3 + CO_2 + H_2O$) would not only reduce alkalinity but would also be expected to cause an increase in CO_2 partial pressure (pCO_2), a decrease in pH, and a decrease in carbonate mineral saturation states (Ω_{arag} for aragonite and Ω_{cal} for calcite) in the absence of other processes (Sarmiento and Gruber, 2006).

Because of the potentially confounding effects of eutrophication, dreissenid mussel metabolism and calcification, and climate change, it is particularly critical in the Great Lakes region that a lake acidification program builds strong partnerships with other agencies and academic institutions to ensure that lake acidification effects can be carefully attributed to distinguish them from the impacts of other environmental stressors in the Great Lakes system.

7.1 Developing a Lake Acidification Monitoring Network (Theme 1)

7.1.1 Water chemistry monitoring

Task 7.1.1: Develop and implement a monitoring network to measure lake carbon chemistry parameters related to acidification, with coverage across all five lakes and all seasons.

A recent compilation of historical water chemistry data from the Great Lakes suggested that the surface waters of the open GL tend to be supersaturated with CO_2 most of the time, which would indicate that the lakes are net sources of CO_2 to the atmosphere (Alin and Johnson, 2007). However, a new analysis suggests that Lake Superior is roughly in equilibrium with the atmosphere (Atilla *et al.*, 2010). Regardless of how saturated the waters are with respect to dissolved CO_2 gas, increasing atmospheric CO_2 can be expected to cause either net invasion of CO_2 into lake waters or a decrease in outgassing of CO_2 to the atmosphere as the air-water concentration gradient changes. Either trend would result in an effective net increase of CO_2 in lake waters, with acidification resulting. With respect to the hypotheses put forth in Chapter 1, we expect that the water columns of the Great Lakes will increase in CO_2 from the atmosphere at a rate that keeps pace with the atmospheric accumulation of anthropogenic CO_2, causing the water columns of the lakes to undergo acidification at a rate equal to or somewhat higher than in the oceans. However, because of the lower buffering capacity of lake water compared to seawater, we expect to see a larger range of natural variation in inorganic carbon chemistry than in the oceans (Table 7.1). We expect that many freshwater organisms have broader tolerances with respect to pH, saturation state, and CO_2 because of their adaptation to the higher natural variability in these parameters expected in freshwater ecosystems. These considerations and the confounding anthropogenic stressors described previously suggest that detecting an acidification trend in the Great Lakes will likely be at least as difficult as in coastal marine ecosystems and will require time-series measurements with high precision and accuracy (cf., Fig. 2 in Borges *et al.*, 2010).

Testing the hypothesis that the Great Lakes will track the atmospheric increase in CO_2 and become acidified will require a combination of observational and modeling approaches. An appropriate observational effort would consist of high-resolution moored and ship-based underway measurements of inorganic carbon (e.g., pCO_2 and a second carbon parameter (cf. Chapter 1) at the lakes' surface, along with high-precision, high-accuracy inorganic carbon analyses of discrete water samples collected throughout the water column of each lake. The semi-annual Great Lakes cruises conducted by the Environmental Protection Agency (EPA) each spring and summer would provide an excellent platform for water column carbon sampling and underway measurements (Table 7.1). The EPA already samples a suite of chemical, biological, and physical parameters in the water, sediments, and air of the Great Lakes. However, the differing conclusions of Great Lakes lake-atmosphere flux studies to date largely hinge on the quality of pH observations used in the calculation of pCO_2 (Alin and Johnson, 2007; Atilla *et al.*, 2010). The potentiometric (i.e., electrode) pH measurements used in the EPA's standard pH protocol have an order of magnitude lower precision and frequently a significant offset from true pH values compared to newer, more accurate methods and are not of sufficiently high quality to track lake acidification (Byrne *et al.*, 2010; Clayton and Byrne, 1993; Dickson *et al.*, 2007; French *et al.*, 2002). The existing semi-annual cruises of the EPA monitoring program would be complemented well by the addition of high-quality carbon measurements through a partnership with NOAA. This potential interagency synergy offers an efficient opportunity to firmly establish the current state of pH and the carbon system in the Great Lakes and to begin developing a robust strategy for long-term monitoring.

To complement water column measurements, underway measurements of $p\mathrm{CO}_2$ and a second carbon parameter at the lake surface could be collected at higher spatial resolution on Great Lakes research and monitoring vessels. It would be beneficial to have underway carbon systems on the NOAA R/V *Laurentian*, which travels throughout the Great Lakes on a regular basis, as well as on the EPA R/V *Lake Guardian*, which is the platform for EPA's semi-annual monitoring cruises. Underway systems can collect surface carbon data anytime the instrumented vessels are on the lakes for research, monitoring, or transit, collecting valuable additional data and improving the understanding of spatial, seasonal, and interannual variability in the lakes' carbon cycle. With the importance of dreissenid calcification in the Great Lakes, ideally the second parameter on both underway and moored (see below) carbon systems would be alkalinity. Surface underway measurements would facilitate improved resolution for generating CO_2 flux maps and estimating net anthropogenic CO_2 accumulation in the lakes.

To provide improved understanding of temporal variability, two approaches would complement semi-annual cruise sampling and opportunistic underway measurements: deploying moored sensors and working with regional partners to establish time-series stations for more frequent water column measurements. Moored deployments should include sensors for $p\mathrm{CO}_2$ or a second carbon parameter (ideally alkilinity), oxygen, and nutrients. Moored sensor packages could be mounted on NOAA National Data Buoy Center (NDBC) weather buoys in the open water domain of the lakes, but would preferably be installed on moorings that would allow for sensor deployment at multiple depths. Moored sensors can yield high-resolution records (~3-hr intervals) of inorganic carbon variability throughout the annual cycle. Ideally at least two moorings (e.g., one open lake, one nearshore) per lake would be deployed across the full range of natural and anthropogenic gradients existing across the Great Lakes system. For instance, primary production varies by a factor of up to ~7 from the upper GL to the lower GL basins (Table 7.3). In addition, human population density, land-use patterns, nutrient loading, and the dominance of invasive species vary strongly across the lakes (Table 7.3, Figure 7.2). Natural factors such as watershed geology, water chemistry, lake size, and water residence time also vary substantially across lakes (Tables 7.1–7.3). Initial mooring efforts are proposed to focus on open-lake environments that would reflect conditions of the majority of the lakes' surface area. However, during the initial year of the GL study, effort will be made to identify representative or critical nearshore locations that will allow more detailed study of the combined impacts of acidification and other stressors, such as dreissenid mussel populations.

Initial acidification surveys should identify potential time-series stations that may be accessible and of scientific interest for more frequent water-column sampling than that conducted by the EPA's semiannual cruises. Ideally, partners at regional institutions would be able to make sensor measurements and collect water samples for inorganic carbon measurements at these time-series stations throughout the water column on a monthly basis throughout the year, with more frequent sampling during the summer growing season. Special emphasis on collecting samples during winter months is also warranted because when carbonate saturation levels would be lowest in winter due to cold water temperatures and historical data for winter are especially lacking. Sampling time-series stations will also provide important verification data for regional biogeochemical models.

Improvements to the long-term monitoring schemes for inorganic carbon chemistry in the Great Lakes will allow us to monitor the pace of lake acidification through the 21st century. The EPA is currently in the process of reevaluating its criteria for monitoring and regulating pH changes in U.S. water bodies. A possible outcome of this review process is that the EPA will adopt the more precise and accurate methods for monitoring pH recommended by the chemical oceanography community in response to an EPA request for information (Environmental Protection Agency, 2009). Collaboration among NOAA, EPA, and academic scientists on the semi-annual Great Lakes cruises would be an opportunity for sharing expertise in an interagency framework.

7.1.2 Biological monitoring

Task 7.1.2: Develop and implement a Great Lakes strategy to monitor biological response to lake acidification.

A broad suite of stressors, including overfishing, nutrient inputs, toxic contaminants, and invasive species, have put Great Lakes ecosystems in a state

Table 7.3: Natural and anthropogenic gradients across the Great Lakes.

Lake	Primary production (g C m^{-2} y^{-1})[†]	Human population in millions[‡§]	Land-use categories[§]			N loading[¶] (t km^{-3} y^{-1})	P loading[¶] (t km^{-3} y^{-1})	Mineralogy in watershed[‖]	Dreissenid density (indivs m^{-2})[£]
			% basin agricultural	% basin residential	% basin forest				
Huron	86	2.7	27	2	68	7.0	1.4	C, Gg, S/Sh	1,255
Michigan	128–144	10.1	44	9	41	n.a.	1.4	C, S, Sh	11,480
Superior	52–66	0.6	3	1	91	7.9	n.a.	Gg, S	n.a.
Erie	104–341	11.9	67	10	21	501	36	C	601–9,480
Ontario	137–242	8.2	39	7	49	107	17	C, S	8,106

[†] From Alin and Johnson (2007).

[‡] From *The Great Lakes: An Environmental Atlas and Resource Book* (`www.epa.gov/greatlakes/atlas/gl-fact2.html`).

[§] Population data are from 1990 (U.S.) and 1991 (Canada)

[¶] Data from the World Lake Database (`wldb.ilec.or.jp`), Bennett (1986), and the Lake Michigan Mass Balance Study (`www.epa.gov/med/grosseile_site/LMMBP/eutrophication.htm`).

[‖] In order of prevalence. Mineralogy abbreviations: Gg, granite and gneiss; C, carbonate (e.g., limestone); S, sandstone; Sh, shale (`water.usgs.gov/ogw/pubs/WRI004008/figure02.htm`).

[£] Densities for 30–90 m water depth. Sources: Huron in 2007 (T. Nalepa, unpub.), Michigan in 2005 (Nalepa *et al.*, 2009), Erie (Patterson *et al.*, 2005), and Ontario in 2003 (Watkins *et al.*, 2007) .

of nearly continuous transition for at least the past 50 years. This constantly changing baseline will make the added impacts of acidification particularly difficult to disentangle. Previous observations from controlled, whole-lake acidification experiments underscore this point. Meticulous monitoring of Little Rock Lake, a 17-hectare lake in northern Wisconsin, revealed numerous surprises as the pH was systematically lowered from approximately 6.1 to 4.7 over six years (1985–1991). *Daphnia* (small planktonic crustaceans) and mayflies exhibited immediate declines, while other biota such as yellow perch responded with initial increases, followed by declines. Extensive filamentous algal growth provided a refuge for some zooplankton species such that these species responded with population increases instead of the decreases that had been predicted from laboratory experiments. In short, even though the Little Rock Lake Project was well planned, carefully manipulated, and intensively monitored, responses were observed that were not anticipated or well understood (Stow *et al.*, 1998). Thus, to document and understand the effects of acidification in the Great Lakes, it will be essential to establish a well-designed observational network that utilizes key chemical and biological indicators, operates at a range of spatial and temporal scales, and is supported by directed studies to reveal the plausible causal links between acidification and any observed changes with time.

To complement water chemistry measurements, concurrent sampling of phytoplankton and zooplankton populations at the semi-annual cruise stations would facilitate the determination of relationships between CO_2 chemistry and key components of the ecosystem that support lake food webs. Biological measurements on the EPA's R/V *Lake Guardian* during the semi-annual monitoring cruises as well as during research and monitoring cruises on NOAA Great Lakes vessels *Laurentian* and *Huron Explorer* should be a priority. Opportunities for leveraged monitoring partnerships with the Thunder Bay National Marine Sanctuary and Old Woman Creek National Estuarine Research Reserve should also be explored. In addition to enhanced phytoplankton and zooplankton monitoring, NOAA's Mussel Watch program, which monitors coastal contamination levels through regular sampling of dreissenid mussel tissue in the Great Lakes, could enhance their ongoing annual collection and analysis of mussel specimens to quantify shell calcification (e.g., shell thickness measurements, hardness, etc.) in invasive mussels. Coordinated collection of water samples from habitats of dense mussel populations sampled by Mussel Watch would also help to develop our understanding of the relationship between water chemistry and mussel tolerances and growth rates. Populations of dreissenid mussels may also be sufficiently high in certain field localities that their in situ calcification rates would be amenable to analysis using remotely collected water samples collected over some interval of time (e.g., diel or seasonal cycle).

7.2 Organism Response to Lake Acidification (Theme 2)

Task 7.2.1: Build NOAA capacity to study organismal response to lake acidification in manipu-

Organisms of Near-Term Focus

Invasive species: Zebra (*Dreissena polymorpha*) and quagga (*D. rostriformis bugensis*) mussels
Native species: Unionid bivalves (42 Great Lakes species)
Native amphipod species: *Diporeia* spp.

> ***lation experiments where effects of environmental factors on species can be studied individually and in combination.***

Prior to European settlement of the St. Lawrence drainage basin, the Great Lakes ecosystem had a rich native fish fauna, with up to 180 indigenous fish species inhabiting the GL basin. Stressors related to human activities in the watershed and on the lakes have significantly and permanently altered the Great Lakes ecosystem, including the introduction of invasive aquatic species, overfishing, nutrient and toxic pollution, and habitat alteration. As a result of these anthropogenic environmental stresses, energy and nutrient flows in Great Lakes food webs have been fundamentally altered, with dreissenid mussels in particular influencing species composition among both primary producers and consumers (e.g., Bykova *et al.*, 2006; Hecky *et al.*, 2004; Nalepa *et al.*, 2009). Phosphorus abatement programs started in the 1970s have generally been successful at reversing the widespread eutrophication in the lower Great Lakes and urbanized embayments of the upper GL, but in localized areas, phosphorus loading is increasing again (SOLEC, 2009), and invasive mussels may play a large role in altering P dynamics in the nearshore zone of lakes with large dreissenid populations (Hecky *et al.*, 2004). Some experimental work has been done to examine the influence of zebra mussels on nutrient ratios (N:P) and in turn on phytoplankton species composition in the lakes (Bykova *et al.*, 2006). However, the impacts of changing carbon chemistry on species physiology and interactions in the Great Lakes have not been considered previously, to our knowledge. Experiments to correctly diagnose and attribute the species-level effects of exposure to acidification alone and in combination with other stressors would be most effectively conducted in a microcosm (i.e., tank) setting.

Any experimental or observational work on lake acidification impacts on organisms will take place in the context of an ecosystem heavily altered by human activities. In turn, anthropogenic climate change and net invasion of the lake ecosystems by anthropogenic CO_2 are processes that are operating in the background of management and restoration efforts to address the impacts of invasive species, eutrophication, and other direct stressors on the lake ecosystems. Thus, effective long-term management and restoration plans should be evaluated in a framework that explicitly considers the potential impacts of acidification and climate change on lake communities and efforts to restore them.

As an example, both dreissenid zebra mussels and native unionid bivalves biosynthesize their shells of aragonite, the more soluble of the two dominant mineral forms of carbonate (Al-Aasm *et al.*, 1998; Checa, 2000). Based on lake average aragonite saturation states (Ω_{arag}), observed dreissenid densities, and known historical distributions of native unionids, both species appear to be capable of biosynthesizing their shells in water with Ω_{arag} values of 2.0–2.5, but substantially lower dreissenid densities occur in the lakes where the lowest aragonite saturations are found (Tables 7.1 and 7.3). Native unionid bivalves have decreased sharply in abundance or been extirpated in many areas of the Great Lakes since dreissenids colonized the Great Lakes, but reproducing populations of burrowing unionids persist in some nearshore environments (Bowers *et al.*, 2005). Subsurface sediment environments typically have high concentrations of porewater CO_2 and correspondingly low carbonate mineral saturation states. Experimental manipulations in microcosm systems could be performed to determine the physiological tolerances of both invasive and native bivalve species to elevated CO_2 and temperature conditions to determine whether conditions exist that may favor the native unionids over invasive dreissenids. If this were found to be the case, efforts could be made to target refuge areas that would allow unionid populations to persist within the Great Lakes while other restoration approaches are researched. Measurements of mussel filtration rates, metabolism, and calcification would also help establish the biological consequences of changes in CO_2 over time. As the previous generation of lake acidification studies taught us, it will be important to conduct these studies of organismal metabolism, calcification, and physiological tolerances both in laboratory experimental manipulations as well as in the field under in situ conditions to be able to carefully attribute causes and consequences (e.g., Stow *et al.*, 1998).

Another suite of critical biological acidification measurements would consist of the quantification of the effects of elevated CO_2 and temperature on phytoplankton species composition and productivity. Previous work on impacts of dreissenids on nitrogen to phosphorus ratios (e.g., Bykova *et al.*, 2006; Hecky *et al.*, 2004), which exert important influence on which phytoplanktonic species dominate primary producer communities, should be linked with this work to yield insights into the interacting effects of acidification and invasive species effects on primary producers. Experiments into physiological effects of acidification on other critical members of the Great Lakes ecosystem, such as native amphipods (*Diporeia* spp.), forage fish species, and ecologically and economically important fish species (see box) should also be developed and executed once experimental capacity is in place (i.e., a tank system in which it is possible to manipulate and maintain CO_2 levels and other parameters).

Ultimately, the insights gained through biological monitoring and experimental manipulations will provide input parameters for regional biogeochemical models and can help validate predictions of models to assess species responses. In turn, outputs and predictions of biogeochemical models will be useful for identifying population and community level effects in forage fish that may be particularly sensitive to changes in zooplankton and phytoplankton populations. Establishing long-term monitoring of indicator species at locations identified to be most at risk from acidification will provide inputs to population models for forage and carnivorous fish. In addition to observations of changes in mussel calcification, filtration, or metabolism, predicted or measured changes in fish populations will inform decisions regarding fisheries management, and other key mitigation and adaptation options.

7.3 Biogeochemical and Ecosystem Models (Theme 3)

Task 7.3.1: Develop and test coupled physical/biogeochemical and food web models and scenarios to address lake acidification effects on each of the Great Lake ecosystems.

Modeling offers synergistic opportunities to complement monitoring and ecosystem response studies. Acidification research in the open ocean has advanced tremendously over recent years because of the strength of the synergy between observations and models (e.g., Feely *et al.*, 2004; Orr *et al.*, 2005). Observations must be limited due to expense, and models offer a physically based platform within which observations can be scaled up to evaluate the bigger picture. Models can also help to determine whether observations of different quantities or taken at different locations or times can be considered consistent with each other given our current process understanding. They allow for hypothesis testing and prediction. Since they integrate knowledge from a range of fields, models can also become invaluable tools with which to integrate the diverse understanding of many scientists.

Initially, relatively simple basin-averaged models with carbon chemistry and highly simplified biological and biogeochemical processes will be developed for each of the Great Lakes so that the first-order effects of acidification due to increasing atmospheric $p\mathrm{CO}_2$ alone can be studied. With such models, historical effects such as the likely masking of acidification due to competing impacts by cultural eutrophication and invasive species can be studied. Future projections under a range of scenarios can also be developed. Such models are computationally efficient and can generate the initial basis for hypothesis testing and scenario development.

Spatially and temporally resolved models that couple physics, ecosystems, and carbon chemistry will also be important. These models, once shown to perform well in comparison with observations (e.g., Stow *et al.*, 2009), will help us to understand the spatial and temporal variability of the environment in which the observations were made. They can also help us to understand what is most likely occurring in the system at times and locations where we are not able to observe. For example, wintertime observations are limited. EPA cruises occur once each during spring and summer on each lake. The lakes are dynamic during these seasons and well-validated models are a rigorous platform that extends our ability to characterize the full system. Furthermore, the lakes are large and can only be sampled at relatively few locations and/or times either by boat or mooring. Models help us to understand variability across both space and time.

McKinley *et al.* (2010) use a coupled physical-ecosystem-carbon model of Lake Superior to study its carbon cycle. They show that high-frequency moored $p\mathrm{CO}_2$ observations, similar to those proposed here, and EPA survey data for $p\mathrm{CO}_2$ (calculated from measured pH and alkalinity) are consistent with the model, and thus with each other. They find strong seasonal variability in the surface $p\mathrm{CO}_2$ of the lake and estimate the trends in surface $p\mathrm{CO}_2$ over the last decade. This is the type of model that can be entrained into this effort to improve our knowledge of acidification and its impacts. Though ecosystem impacts of acidification in the Great Lakes have not yet been studied, as this knowledge grows it can be incorporated into tested models so that larger-scale impacts can be considered.

In addition to coupled physical/biogeochemical models, a variety of approaches has been taken to model Great Lakes food webs and impacts of anthropogenic factors on the lakes' ecological communities (e.g., Kitchell *et al.*, 2000; Krause *et al.*, 2009; Ng *et al.*, 2008; Zhang *et al.*, 2008). Adapting these existing food web/ecological models to evaluate lake acidification scenarios will provide a useful tool for examining the potential for organismal impacts observed through biological monitoring and experimental manipulation efforts to be scaled up to the whole ecosystem level. The results of acidification food web modeling will in turn provide input to bio-economic modeling efforts (Theme 4).

Models are, however, not the real world; they do not always perform well. Fortunately, these failures often reveal critical processes missing from the current model and identify directions for future improvement. Similarly, models can be used to assist in designing and refining observational programs by identifying locations with specific physical, biological or chemical characteristics of interest.

Remote sensing also offers valuable potential for dramatically improving our understanding of temporal and spatial variability in surface lake biogeochemisty that may be modified by acidification. However, reliable chlorophyll algorithms have not previously been available. Mouw and McKinley (2010) show, for the first time, that MERIS data can be used to retrieve surface chlorophyll over Lake Superior within reasonable error bounds. Yet, satellites cannot see below the surface of the lakes. As we have found in global oceanography, synergy between satellite data and numerical models can drive forward understanding of biogeochemistry, ecology, and their changes with time.

Climate change is also affecting the Great Lakes. Warming causes decreased ice cover which leads to a positive feedback that results in faster warming (Austin and Colman, 2007), and these changes have been shown to modify winds over and currents in Lake Superior (Desai *et al.*, 2009). Fully resolved physical-ecosystem-carbon models are needed to understand how the changing physical environment will interact with acidification processes. For example, what are the likely trends in stratification in the Great Lakes? How will this modify the invasion of anthropogenic CO_2? How will this modify primary productivity? What will effects of changes to the environment and species at lower trophic levels be on higher trophic levels? Models are the best way to address these questions.

7.4 Human Dimensions (Theme 4)

7.4.1 Bio-economic models

Task 7.4.1: Estimate anticipated changes to ecosystem services as a consequence of lake acidification and evaluate alternative management options.

The Great Lakes ecosystems support robust recreational and commercial fisheries, as well as a multi-billion dollar tourism and outdoor recreation industry. Bio-economic models will be developed or adapted for and applied to the Great Lakes region to address how lake acidification impacts on ecosystem services may affect regional communities and economies. Significant interaction among biogeochemical, food web, and bio-economic modeling effort is anticipated to facilitate development of ecosystem impact scenarios based on reasonable anthropogenic impact scenarios (i.e., combinations of factors, including acidification, eutrophication, and others). Economic implications of management decisions can be explored by propagating environmental impact scenarios across the suite of modeling efforts.

7.4.2 Mitigation and adaptation strategies

Task 7.4.2: Test mitigation approaches under laboratory and field conditions. Develop adaptation strategies.

Information on the chemical changes in the lakes associated with atmospheric CO_2 accumulation, along with insights into the vulnerability of Great Lakes species to acidification, will provide essential information for resource managers to formulate plans to mitigate ecosystem impacts of acidification in combination with the myriad other environmental stressors confronting the Great Lakes ecosystems. In particular, it will be important to consider lake acidification interactions with the ecosystem effects of eutrophication, invasive species, and other anthropogenic impacts when developing mitigation approaches and adaptation strategies.

Key decisions that will be influenced by the results of research, monitoring, and modeling efforts described in this plan include options to control agricultural runoff, to address invasive species introductions through ballast water, to manage fisheries, and to restore coastal habitats. These mitigation and adaptation measures are already being considered to restore the ecosystem of the Great Lakes. Determining the relationships between ecosystem responses to acidification and reductions in nutrients, control of invasive species, altering fisheries management options, and restoring fish habitat will inform decision-making and allow communities to establish priorities among their adaptation and mitigation options. Models can be tested to some extent through the biogeochemical and food web modeling activities described in Theme 3, but it will be important to test mitigation approaches under laboratory and field conditions as well.

Assessments of socioeconomic vulnerability will be conducted at regional to local scales through a partnership between social scientists, modelers, and other stakeholders. Projected socioeconomic impacts of lost ecosystem services will inform adaptive management strategies, as well as the development of education and outreach programs. Outcomes of acidification impact assessments will be contributed to regional decision-support processes through existing channels to the extent possible (e.g., the biennial State of the Lake Ecosystem Conference [SOLEC] forum described in section 7.7).

7.5 Synthesis of Data and Information Products (Theme 5)

Task 7.5.1: Develop data and information tools for evaluating the consequences of lake acidification and potential management actions to facilitate more effective management.

Data produced through the observational efforts outlined in this plan can likely be accommodated within data management programs either existing at the EPA or proposed in Chapter 1. Data generated from water column carbon analyses during EPA cruises would be complementary to the data already housed in the EPA Great Lakes Environmental Database (`http://www.epa.gov/glnpo/monitoring/data_proj/glenda`). In addition, it would also be useful to mirror the Great Lakes acidification survey data sets in any national ocean acidification data management system that is developed. A partnership between NOAA and EPA to manage GL acidification data would thus likely be the most logical and efficient strategy for managing the carbon data yielded through semi-annual cruises. The moored and underway carbon data resulting from the observational efforts outlined in Theme 1 would probably more easily be accommodated through existing data repositories (e.g., the Carbon Dioxide Information and Analysis Center's Ocean CO_2 repository: `http://cdiac.ornl.gov/oceans/home.html`) and/or any national ocean acidification information center that may be developed under the auspices of NOAA's Ocean Acidification Program (see Chapter 1).

Information products to be derived from water chemistry and biological research and monitoring activities include an improved understanding of the relative contributions of natural and anthropogenic processes to observed trends in Great Lakes biogeochemical cycles and ecosystem health. Information products available as outcomes of acidification observation and modeling efforts will include robust estimates of CO_2 uptake and storage in the lakes, as well as improved ability to quantify contributions of acidification versus eutrophication, invasive species, climate change, and other anthropogenic stressors.

7.6 Engagement Strategy (Theme 6)

Task 7.6.1: Develop and implement coordination, education, and outreach schemes to communicate the science and ecosystem consequences of ocean acidification to the public and stakeholder communities and to facilitate effective communication among regional collaborators.

During the first year of the proposed research effort, we suggest that the principal investigators from NOAA, EPA, and other partner institutions convene a series of workshops, with the help of Great Lakes regional Sea Grant offices. The purpose of these initial meetings would be to gather stakeholders together to refine and develop the lake acidification research, monitoring, and preliminary adaptation plans with input from the broader GL community and to initiate the development of strong collaborative partnerships.

Stakeholders to be invited would include representatives of regional, federal, Canadian, and binational organizations with research and monitoring interests in the Great Lakes, including the International Joint Commission, Environment Canada, NOAA National Estuarine Research Reserve System (NERRS) Thunder Bay National Marine Sanctuary, Great Lakes Observing System (a NOAA Integrated Ocean Observing System Regional Association), and state resource management agencies; academic institutions with GL research programs from bordering states and provinces; and other regional groups to be identified through regional Sea Grant partners. Important outcomes of this kick-off workshop would be the initiation of research partnerships between biological and chemical monitoring teams, as well as between observational and modeling teams to be involved in Great Lakes acidification efforts. In addition, the workshop will provide an opportunity to start developing a network of partners doing research in nearshore GL environments so that open-lake observations and trends can be compared with nearshore patterns. For example, the Old Woman Creek NERR on the Lake Erie shore measures pH and alkalinity, and another NERR will be established at the western end of Lake Superior in 2010. A kick-off workshop would also provide a valuable venue for starting the process of standardizing methodology for making the highest quality carbon chemistry measurements across agency and academic research groups.

After GL acidification research is underway, regular meetings would facilitate dissemination of key results and development of well-coordinated plans for subsequent phases of research and monitoring throughout the Great Lakes community. The U.S. Environmental Protection Agency and Environment Canada convene a biennial State of the Lakes Ecosystem Conference (SOLEC) to assess the current status of the Great Lakes ecosystems using accepted indicators and to facilitate communication, management, and decision-making among local, regional, and international stakeholder groups. Ideally it would be possible to incorporate the lake acidification research and monitoring activities into the SOLEC assessment and reporting framework.

Education and public outreach materials and activities will be developed in subsequent years, depending on initial findings from observational and modeling efforts. These efforts would also be facilitated through participation in the SOLEC framework. The NOAA Office of Education, the National Sea Grant Program, and the Office of National Marine Sanctuaries can play integral roles in meeting these mandates by developing an increased awareness of the causes and potential effects of lake acidification on the Great Lakes ecosystems. The Thunder Bay National Marine Sanctuary can also serve as a sentinel site, not only for research and monitoring, but also as a place where communities can go to learn about the possible effects of acidification on the lakes.

To inform monitoring and adaptation needs, a series of workshops would be initiated with stakeholders focused on water quality management (e.g., those involved in controlling non-point source pollution and invasive species), fisheries managers, commercial and recreational fishing groups, and other interested community stakeholders. The purpose of these workshops would be to ensure that research and monitoring efforts consider the needs of those making decisions about the consequences and options for addressing acidification of the lakes.

7.7 Collaborators

7.7.1 Interagency and international cooperation

The Great Lakes occupy a binational, multistate geopolitical landscape. As such, interagency and intergovernmental cooperation for effective ecosystem and resource management are imperative. The Great Lakes has a tremendous capacity for intergovernmental cooperation and including those from academia

Great Lakes Region Collaborators

Great Lakes Environmental Research Laboratory
EPA Great Lakes National Program Office
Pacific Marine Environmental Laboratory
Thunder Bay National Marine Sanctuary
National Estuarine Research Reserves
Great Lakes Region Sea Grant Offices
NOAA's Mussel Watch
Great Lakes Observing System
University of Wisconsin
University of Minnesota
Michigan Technological University
Regional state natural resource/environmental protection agencies
Environment Canada
International Joint Commission

and civil society. In 1972, the Great Lakes Water Quality Agreement between the United States and Canada established a logistical and advisory board framework under the International Joint Commission (IJC) for binational cooperation "to restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes Basin Ecosystem." In addition, the United States and Canada together have convened a Binational Executive Committee (BEC) to oversee implementation of the Great Lakes Water Quality Agreement (GLWQA). Within this structure, the State of the Lake Ecosystem Conference has been a mechanism for the joint development of scientific indicators and as a venue for reporting on the results of scientific research pertaining to the Great Lakes ecosystem. As outlined in the GLWQA, the Clean Water Act, and Water Resource Development Act, the development and implementation of Lakewide Management Plans for each lake is ongoing under the guidance of BEC. These plans are science-based management documents for the open waters of the Great Lakes, but also include information on nearshore condition. The Great Lakes Regional Collaboration and, most recently, the Great Lakes Restoration Initiative, with the release of its multi-agency Great Lakes Action Plan, are both U.S.-specific initiatives to strategically invest in restoration, science, and monitoring. These existing policy initiatives, legal mechanisms, and organizations focus on emerging issues and provide a context in which lake acidification and climate change effects on the Great Lakes ecosystem can be addressed.

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Contributors

National Environmental Satellite, Data, and Information Service

Center for Satellite Applications and Research

Mark Eakin	Mark.Eakin@noaa.gov

National Marine Fisheries Service

Alaska Fisheries Science Center

Mark Carls	Mark.Carls@noaa.gov
Michael Dalton	Michael.Dalton@noaa.gov
Lisa B. Eisner	Lisa.Eisner@noaa.gov
Robert J. Foy	Robert.Foy@noaa.gov
Thomas P. Hurst	Thomas.Hurst@noaa.gov
Joseph F. Morado	Frank.Morado@noaa.gov
Michael F. Sigler	Mike.Sigler@noaa.gov
Robert P. Stone	Robert.Stone@noaa.gov

Northeast Fisheries Science Center

Christopher Chambers	Chris.Chambers@noaa.gov
Michael Fogarty	Michael.Fogarty@noaa.gov
Ronald Goldberg	Ronald.Goldberg@noaa.gov
Vincent Guida	Vincent.Guida@noaa.gov
Jon Hare	Jon.Hare@noaa.gov
Beth Phelan	Beth.Phelan@noaa.gov
Shannon Meseck	Shannon.Meseck@noaa.gov
Dean Perry	Dean.Perry@noaa.gov
Daniel Wieczorek	Daniel.Wieczorek@noaa.gov
Gary Wikfors	Gary.Wikfors@noaa.gov

Northwest Fisheries Science Center

D. Shallin Busch	Shallin.Busch@noaa.gov
Paul McElhany	Paul.McElhany@noaa.gov
John Stein	John.E.Stein@noaa.gov

Pacific Islands Fisheries Science Center

Russell E. Brainard	Rusty.Brainard@noaa.gov
Oliver Vetter	Oliver.Vetter@noaa.gov
Charles Young	Charles.Young@noaa.gov

Office of Habitat Conservation

Terry Heatlie	Terry.Heatlie@noaa.gov

Southeast Fisheries Science Center

Margaret Miller	Margaret.W.Miller@noaa.gov

Southwest Fisheries Science Center

Jonathan Phinney	Jonathan.Phinney@noaa.gov

National Ocean Service

National Centers for Coastal Ocean Science

Theresa Goedeke	Theresa.Goedeke@noaa.gov
Elizabeth Jewett	Libby.Jewett@noaa.gov
Anna Hilting	Anna.Hilting@noaa.gov
Kris Holderied	Kris.Holderied@noaa.gov
Bill Sunda	Bill.Sunda@noaa.gov
Fran Van Dolah	Fran.Vandolah@noaa.gov

Integrated Ocean Observing System Program

Jessica Geubtner	Jessica.Geubtner@noaa.gov

Office of the National Marine Sanctuaries

Reed Bohne	Reed.Bohne@noaa.gov
Ed Bowlby	Ed.Bowlby@noaa.gov
Mary Sue Brancato	Mary.Sue.Brancato@noaa.gov
Ellen Brody	Ellen.Brody@noaa.gov
Lisa Etherington	Lisa.Etherington@noaa.gov
Kelley Higgason	Kelley.Higgason@noaa.gov
Steve Katz	Steve.Katz@noaa.gov
Brian Keller	Brian.Keller@noaa.gov
Elizabeth Kehn	Elizabeth.Kehn@noaa.gov
Robert Pavia	(retired)
Jan Roletto	Jan.Roletto@noaa.gov
Paul Ticco	Paul.Ticco@noaa.gov

Office of Response and Restoration

Mary Baker	Mary.Baker@noaa.gov

Office of Oceanic and Atmospheric Research

Atlantic Oceanographic and Meteorological Laboratory

Dwight K. Gledhill	Dwight.Gledhill@noaa.gov
Kevin Helmle	Kevin.Helmle@noaa.gov
James Hendee	Jim.Hendee@noaa.gov
Derek Manzello	Derek.Manzello@noaa.gov
Erica Rule	Erica.Rule@noaa.gov
Rik Wanninkhof	Rik.Wanninkhof@noaa.gov

Geophysical Fluid Dynamics Laboratory

John Dunne	John.Dunne@noaa.gov
Charles Stock	Charles.Stock@noaa.gov

Great Lakes Environmental Research Laboratory

Jennifer Day	Jennifer.Day@noaa.gov
Thomas Nalepa	Thomas.Nalepa@noaa.gov
Craig Stow	Craig.Stow@noaa.gov

Office of Ocean Exploration and Research

Felipe Arzayus	Felipe.Arzayus@noaa.gov

Office of Policy, Planning and Evaluation

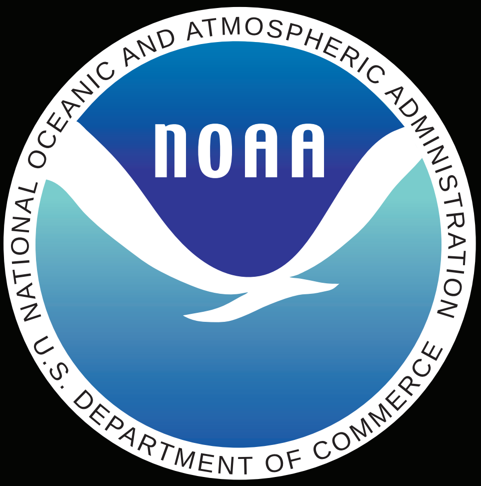
Ellen Mecray	Ellen.L.Mecray@noaa.gov

Pacific Marine Environmental Laboratory

Simone R. Alin	Simone.R.Alin@noaa.gov
David Butterfield	David.A.Butterfield@noaa.gov
Richard A. Feely	Richard.A.Feely@noaa.gov
Steve Hankin	Steven.C.Hankin@noaa.gov
Chris Sabine	Chris.Sabine@noaa.gov
Kathyrn Shamberger	Katie.Fagan@noaa.gov
Phyllis Stabeno	Phyllis.Stabeno@noaa.gov
Adrienne J. Sutton	Adrienne.Sutton@noaa.gov

Non-NOAA Contributor—Cooperative Institute for Meteorological Satellite Studies

Galen McKinley	gamckinley@wisc.edu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