NOAA Pacific Islands Fisheries Science Center (PIFSC)
Ocean Acidification Research Implementation Plan for FY10

1. Introduction

1.1. Geographic Domain and Ecosystems

The Pacific Islands Region (PIR) encompasses 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. Exclusive Economic Zones (EEZ) waters combined. These areas; which span from Hawaii 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.

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 deepwater coral systems. Coral 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* 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). As well as the immediate affect 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.

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* 2007). Reefs of the Main Hawaiian Islands (MHI) have an estimated net value of nearly $10 billion with an average annual benefit of $385 million, with the largest contribution from recreation and tourism (*Cesar* 2000, 2008). According to even the most optimistic climate models, a critical atmospheric CO_2 threshold of 480 - 500ppm 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 (*Hoegh-Guldberg* 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.

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 Hawaiian 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 pristine nature and lack of any 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). 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.

1.2. Urgent Management Issues

On October 20, 2009, the Center for Biological Diversity (CBD) filed a formal petition seeking to protect 83 coral species under the Endangered Species Act, 75 of which are believed to occur in the Pacific Islands Region (compared with only 8 for the Western Atlantic/Caribbean). The premise for the CBD petition is that these 83 coral species face a growing threat of extinction due to rising ocean temperatures caused by global warming and ocean acidification. The petition argues that "coral reefs are the world's most endangered ecosystems… 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." The NMFS provided a 90-day finding that the petition is warrants further review for 82 of the petitioned coral species. The PIFSC will be leading the Biological Review Team in producing a biological status review, which will use the best available science 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, PIFSC requires a much more thorough understanding of the potential impacts of ocean acidification to these specific coral species.

2. Recent PIFSC Ocean Acidification Research

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. While there have been many important mesocosm experiments in recent years examining responses of a few specific organisms to changes in carbonate chemistry (*Doney et al.*, 2009), and there is an exponential increase in the number of such experiments being undertaken, there has been very little effort to systematically assess the ecological

impacts of ocean acidification in nature. For biologically diverse and complex coral reef ecosystems, PIFSC has initiated an ecosystem approach to assessing and predicting the ecological impacts of ocean acidification.

As part of NOAA's interdisciplinary Pacific Reef Assessment and Monitoring Program (Pacific RAMP), led by the PIFSC Coral Reef Ecosystem Division (CRED), efforts to establish baselines and monitor changes in both carbonate chemistry and the associated ecological impacts of ocean acidification were initiated in 2005 and have been slowly evolving ever since.

2.1. Carbonate Chemistry

The carbonate chemistry monitoring led by CRED, in collaboration with NOAA's Pacific Marine Environmental Laboratory (PMEL), Coral Reef Watch, and Atlantic Oceanographic and Meteorological Laboratory (AOML) has 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 (Fig. 1). Though initial surveys (2005-2006) were conducted around populated high islands in American Samoa, results were confounded by other issues, such as freshwater runoff and land-based sources of pollution. Since 2008, monitoring of carbonate chemistry has focused on simpler unpopulated low islands and atolls, mostly within PMNM, the Pacific Remote Islands Marine National Monument (MNM), the Mariana Trench MNM, and Rose Atoll MNM, which do not have these confounding issues. Water samples were 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 in nearshore coral reef habitats compared with the surrounding open ocean environment. 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.).

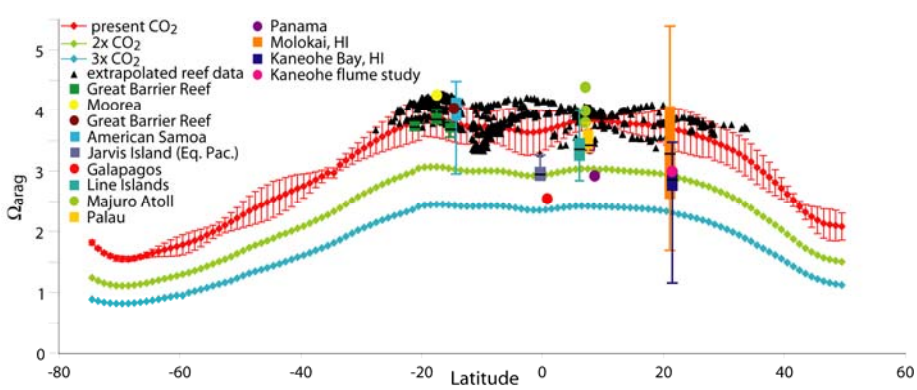

Figure 1. Studies of aragonite and carbonate ions around the Pacific and other coral reef regions, dependent on latitude (courtesy *Shamberger et al.* 2010).

2.2. Biological Monitoring

In the PIR, PIFSC-CRED has initiated efforts to assess and monitor the broad-scale, long-term ecological impacts of ocean acidification on coral reef ecosystems, which include the nesting and breeding habitats for endangered monk seals and threatened sea turtles, as part of the existing Pacific RAMP, which since 2000 has conducted 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 (Fig. 2). 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.

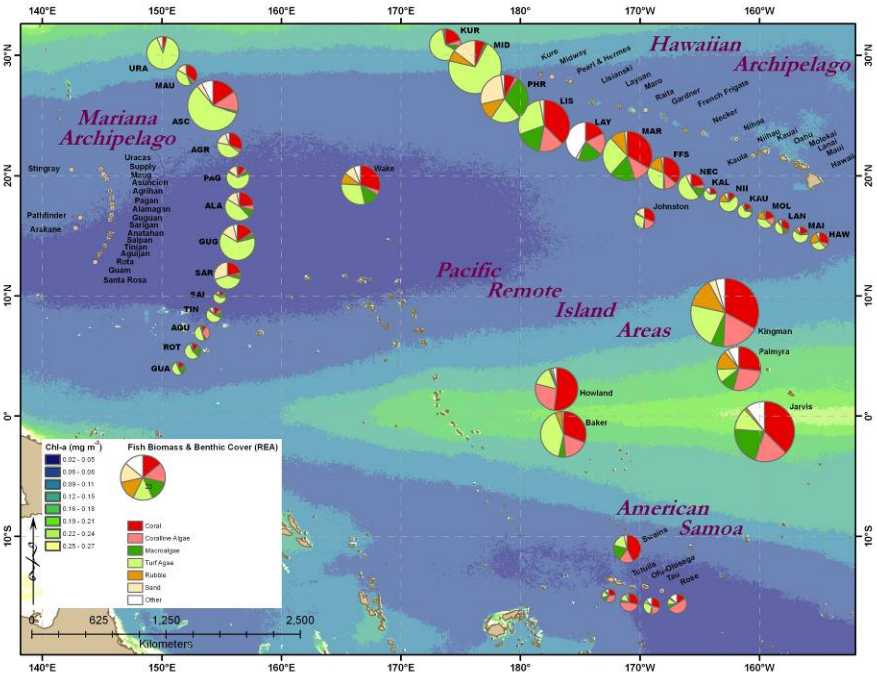

Figure 2. Breadth and scope of Pacific RAMP across the Pacific Islands region. Size of pie charts represent total reef fish biomass for 40 islands and atolls from rapid ecological assessment (REA) surveys. Composition of pie charts represents benthic composition from towed-diver benthic surveys. Pie charts are plotted over mean chlorophyll a concentrations from SeaWiFS ocean color. (*Brainard et al.*, 2010).

In 2008 and 2009, as part of both Pacific RAMP and the Census of Marine Life's Census of Coral Reef Ecosystems (CReefs) project, PIFSC-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 ocean acidification. To date, CRED has deployed an array of over 400 standardized Autonomous Reef Monitoring Structures (ARMS) at select islands/atolls across the PIR, Coral Triangle, Indian Ocean, and Caribbean Sea (Fig 3, *Brainard et al., 2009, Brainard et al., 2010*). These efforts will also be used to examine the role of biodiversity in sustaining ecosystem goods and services and enhancing ecosystem resilience.

Figure 3. Map showing the current and nearterm deployment locations of Autonomous Reef Monitoring Structures (ARMS) for establishing global baselines of cryptic coral reef biodiversity (*Brainard et al*., 2010).

Research has shown that the aragonite saturation horizons are shoaling (*Feely et al*., 2004), therefore it has been projected that the first reefs to be affected by ocean acidification may be deepwater non-hermatypic corals and recently discovered mesophotic coral ecosystems (low-light hermatypic reefs in the depth range 30 – 150 m) (*Rooney et al*., in press). Mesophotic reefs, like the ones found within the Au'au channel in Hawai'i, were originally thought to provide a potential refuge for coral organisms, since they will less likely be impacted by ocean warming induced coral bleaching. However, with the advancement of carbonate chemistry research, it is apparent that these deeper reef systems will likely be among the first to be impacted by decreasing aragonite saturation states (*Sabine et al.*, 2004).

3. Proposed PIFSC Ocean Acidification Research

While PIFSC has initiated and slowly evolved the above ocean acidification research since 2005, these efforts have remained primarily exploratory due to severe funding limitations. Over the past year, PIFSC has led the development of the Pacific Islands Regional Implementation Plan as a chapter of the NOAA Ocean Acidification Research Implementation Plan. That long-term comprehensive plan includes three primary related components that are currently be implemented: 1) assessing and monitoring the ecological impacts of ocean acidification; 2) characterizing and monitoring carbonate chemistry; and eventually 3) modeling and predicting biogeochemical and ecosystem responses to climate change. While the numerous elements of these primary components are included in the NOAA OA Research Implementation Plan, the portions of this plan that PIFSC will implement in FY10 with approved NMFS Ocean Acidification funding are outlined below.

3.1. Ecosystem Impacts of Ocean Acidification

As requested, all NMFS ocean acidification funding for FY10 will be directed toward research under the theme Ecosystem Impacts of Ocean Acidification. These efforts will expand upon on-going exploratory efforts to assess and monitor the impacts of ocean acidification on coral reef ecosystems. With these funds, PIFSC will conduct five key projects (Table 1) to assess and/or initiate monitoring of the ecological impacts of ocean acidification on coral reef ecosystems across the PIR, with initial efforts focusing on

examine reef-building calcifying organisms and broad biodiversity indicators. Of the reef-building calcifiers, particular emphasis in FY10 will be directed toward efforts to improve our understanding of the likely impacts of ocean acidification on the 75 coral species from the PIR Petitioned for listing under the Endangered Species Act. These efforts will be directly applied as part of the biological status review that PIFSC will be leading. Specifically, the NMFS funding will support the first three listed projects to assess the distribution, status, recruitment, calcification rates, and potential risk of extinction due to ocean acidification of the 75 Pacific coral species. The 2nd of these projects will be used to initiate collaborative controlled laboratory experiments with colleagues at the Univ. of Hawaii's Hawaii Institute of Marine Biology (HIMB – P. Jokiel, *Jokiel et al.* 2008). These preliminary efforts will expand on-going HIMB controlled experimental mesososm studies of the organismal responses to ocean acidification to include some of the key Pacific coral species in the Petition to list 82 corals under ESA.

The 3rd of these projects will be used to initiate collaborative efforts with A. Cohen at Woods Hole Oceanographic Institute (WHOI) to collect coral cores and sample collections to determine historical coral growth and accretion rates across key oceanographic (nutrient) gradients from American Samoa to the Line Islands. Samples will be sent to WHOI for CAT scan analyses of the three-dimensional growth structure of the corals (Fig. 4; *Cohen et al.* 2009). Paleoceanographic studies of calcification and growth rates will advance understanding of how accretion rates have changed since the industrial revolution and improve our ability to predict future changes in a high CO_2 world. These funds will be granted to the UH Joint Institute for Marine and Atmospheric Research (JIMAR) to support scientific staff for data collection, laboratory experiments, data processing and analyses, and shipping of samples to WHOI.

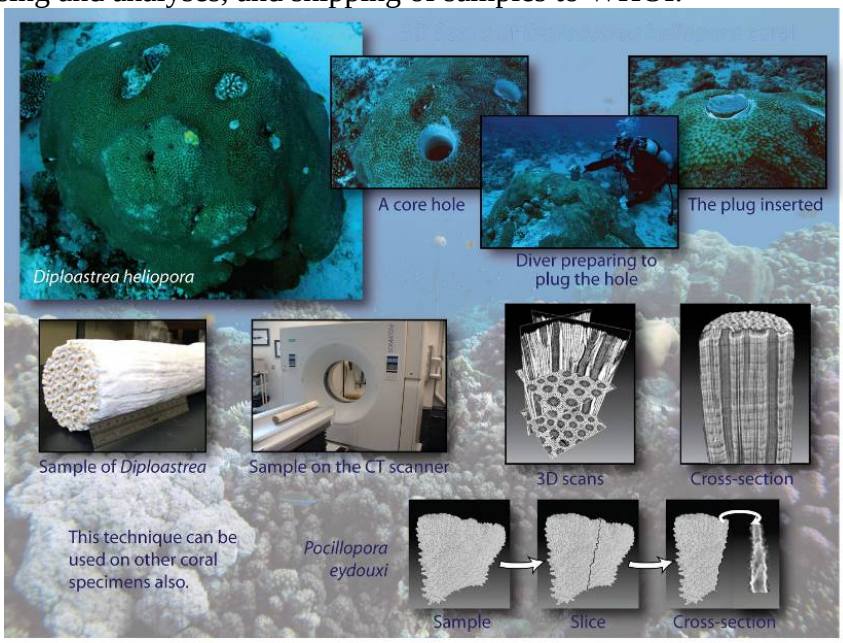

Figure. 4. Diagram showing coring of *Diploastrea heliopora*, sample on the CT scanner, and 3D images. Bottom figures show same for *Pocillopora eydouxi*. Courtesy Anne Cohen, WHOI.

Though not directly related to the Corals Petition, the 4th project will initiate deployment of an extensive array of approximately 700 Calcification Acidification Units (CAUs, Fig. 5.a) across the Pacific Remote Islands, American Samoa, and the Northwestern Hawaiian Islands in FY10 to establish a baseline and begin monitoring calcification rates of calcareous algae, predominantly crustose coralline algae, and sessile invertebrates. This project, done in collaboration with J. Smith and N. Price at Scripps Institute of Oceanography (SIO), will utilize funding for supplies, materials, and shipping for the 700 CAUs and for JIMAR staff scientists to build and deploy the CAUs.

a) b)

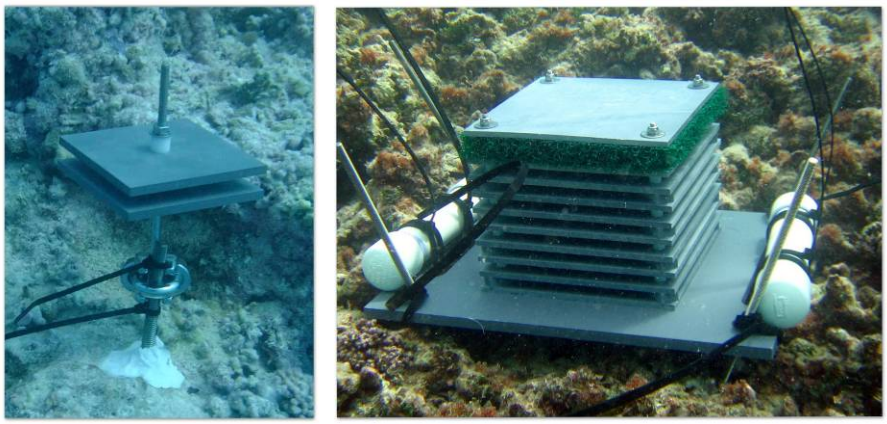

Figure. 5..a). Calcification Acidification Unit (CAU) deployed in reef substrate to monitor calcification rates. b). Autonomous Reef Monitoring Structure (ARMS) deployed in reef substrate to assess and monitor cryptic biodiversity. Photos credit NOAA PIFSC CRED, D. Merritt.

The final NMFS-funded OA project is designed to augment and leverage efforts to establish baselines for assessing and monitoring shifts in biodiversity caused by ocean acidification using ARMS (Fig. 5b.). Understanding the biodiversity impacts of ocean acidification is critical due to the role of biodiversity in providing ecosystem services and maintaining ecosystem resilience. This project leverages significantly on related projects that provide most of the funding for field survey and important ancillary data collection efforts (Pacific RAMP, CoML-CReefs, and Physical and Biological Monitoring Stations projects) led by PIFSC-CRED. The NMFS funding will be used to contract for ARMS materials and supplies and for JIMAR scientific staff support to build and deploy replacement ARMS, recover ~150 ARMS, and initiate taxonomic, photographic, and molecular analyses of ARMS samples. Organisms will be photographed and preserved in alcohol for mass parallel molecular sequencing by collaborators at Smithsonian Instit. (Drs. N. Knowlton, C. Meyer, L. Plaisance), Univ of Florida (Dr. G. Paulay), San Diego State University (SDSU, Dr. F. Rohwer), and Moss Landing Marine Laboratory (Dr. J. Geller).

Significant amounts of funding for each of these NMFS-funded Ocean Acidification research projects will be leveraged by existing related projects funded primarily by NOAA's Coral Reef Conservation Program (CRCP) and sea days provided aboard the NOAA ships *Hi'ialakai* and *Oscar Elton Sette* for Pacific RAMP. Specifically, the

CRCP will be funding efforts to initiate monitoring of the key carbonate chemistry parameters at all of the sites where CAUs and ARMS deployments and coral cores will be taken. Colleagues at WHOI and SIO have submitted companion proposals to NSF to cover their analysis costs.

Theme	**Deliverable Product**	**Description**
2. Ecosystem impacts of ocean acidification	Improved status review of petitioned coral species due to estimated impacts of OA	Expand Pacific RAMP efforts to determine status of Petitioned coral species and assess OA risk of extinction.
	Continue HIMB controlled mesocosm experiments	Conduct experiments on the effect of CO_2 and temperature on corals and crustose coralline algae, increased focus of Petitioned species.
	Initiate study of calification rates of key Petitioned coral taxa	Collect specimens of key Petitioned coral taxa to assess calcification/accretion rates. CAT-Scan image analysis at WHOI.
	Initiate monitoring of calcification rates of crustose coraline algae	Deploy Calcification Acidification Units (CAUs) across Am Samoa, PRI-MNM, PMNM to assess calcification rates of sessile invertebrates, particularly reef-building crustose coraline algae.
	Initiate monitoring of biodiversity and ecosystem function shifts caused by OA	Recover and initiate photographic, morphological, & molecular analyses of 150 ARMS from Am Samoa, PRI-MNM, and PMNM. Collaboration w/ Smithsonian (Knowlton, Meyer), U.Florida (Paulay), AIMS (Caley), SDSU (Rohwer), and MLML (Geller). Examine recruitment of Petitioned coral species.

Table 1. PIFSC NMFS-funded ocean acidification research projects for FY10.

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