A Strategic Planning Session for Ocean Acidification Research

Proceedings of Think Tank #5
Little Cayman Research Centre
Little Cayman, Cayman Islands
December 3-7, 2007

Dr. James C. Hendee, Editor

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Attendees (alphabetically):

Rebecca Albright, Dr. Ken Anthony, Felipe Arzayus, Dr. Mark Eakin, Dr. Richard Feely, Dr. Dwight Gledhill, Lew Gramer, Abbie Rae Harris, Dr. James Hendee, Dr. Joanie Kleypas, Dr. Chris Langdon, Dr. Carrie Manfrino, Dr. Derek Manzello, Dr. Christopher Moses, Dr. Chris Sabine, Dr. Lisa Robbins, John Tomczuk, and Dr. Kim Yates

National Oceanic and Atmospheric Administration

March 2010

NOAA Technical Memorandum CRCP X

United States Department of Commerce

Gary Locke
Secretary

National Oceanic and Atmospheric Administration

Dr. Jane Lubchenco
Administrator

National Ocean Service

David Kennedy
Assistant Administrator (Acting)

Forward

This report has been finalized a little over two years after the meeting held on Little Cayman Island in December, 2007. During the ensuing time, the manuscript languished as an "unpublished manuscript," yet the recommendations that came out of this meeting were felt to be so sound and the agreement so strong, they were instituted on several fronts following the meeting. The reasoning and visions for action still hold relevance today. (For instance, a MAP-CO2 buoy was installed at La Parguera, Puerto Rico in January, 2009, and a CREWS station was installed at Little Cayman in July, 2009.) It was thus decided to publish the document from that meeting so that others can read what the collective vision and recommendations for action were and still are.

JCH

March, 2010

Introduction

The decrease in pH of the world's oceans has now been documented in all three major oceans, and laboratory studies worldwide are providing mounting evidence of the possible consequences of this decrease on marine biota. How this "ocean acidification" (OA) can and will affect humans and the fisheries and resources they depend upon is now an urgent, front-and-center issue before all major U.S. federal agencies, but a well coordinated plan of how to both further study the process and deal with the consequences is not yet in place.

The primary purpose of the meeting described herein was to bring together some of the world's experts on this subject, those from the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the National Center for Atmospheric Research (NCAR), the University of Miami's Rosenstiel School for Marine and Atmospheric Sciences (RSMAS), the University of South Florida, the University of Queesland, and others. We assembled to discuss our various research results and to build a consensus for recommending to federal agencies, the U.S. Congress, and others how best to proceed in an efficient and effective manner to both understand and to ameliorate the OA process.

The secondary purpose of this meeting was to provide an understanding and appreciation of the complexities and cost in deployment of a robust instrumental array for providing continuous sensing of the environment near a coral reef. The Integrated Coral Observing Network's (ICON) Coral Reef Early Warning System (CREWS) growing network of stations at coral reef areas in the Caribbean provides an infrastructure for adding instruments, as well as for information in the way of not only near real-time reporting of hourly data, but also in the integration of satellite and other data sources in the region for providing models and other data products for further research. Another reliable and robust instrumental and information architecture is that developed at NOAA's Pacific Marine Environmental Laboratory, the Coastal CO_2 Program. Both the ICON/CREWS and PMEL architectures are described herein.

To gain an overview of the various ongoing aspects of research, each invitee was asked to present his or her work as a PowerPoint presentation. To facilitate the context under which such work (and future work) might proceed within NOAA, an overview of the NOAA budget process was also presented so that the confusing and sometimes difficult budget approach could be considered. Each presenter was asked to provide their PowerPoint presentation (links provided herein), as well as relevant documents and/or links via the Web that would allow the reader to become more enlightened.

The meeting was held at the Little Cayman Research Center (LCRC), which is the next site for an installation of an ICON/CREWS station, and it is at this facility that plans are building to serve as an OA center of research. The researchers thus had the first hand opportunity to witness the value (aesthetic, cultural, ecological and economic) of the reef system and to understand the local complexities of establishing LCRC as an OA research center.

Figure 1. Participants at Think Tank #5. Left to right: Jon Clamp, Richard Feely (blue), Felipe Arzayus, Chris Langdon (white), Jim Hendee (front row), Derek Manzello, Ken Anthony, Joanie Kleypas, Lew Gramer, Chris Moses, [who in back in blue with white hat?!!], John Tomczuk, Mark Eakin, Abbie Rae Harris, Carrie Manfrino, Dwight Gledhill, Lisa Robbins, Rebecca Albright, Chris Sabine, Kim Yates.

Climate Change Research at the Little Cayman Research Centre

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Summary
Think Tank #5 was hosted by the Central Caribbean Marine Institute (CCMI) to highlight the reef system surrounding Little Cayman which is the fifth site where a NOAA ICON station is currently being installed. The partnership between CCMI and NOAA was established because of the need for a reference site for research where reefs are under low local human pressure. The partnership is intended to build a research profile for the Little Cayman Research Centre as a centre of excellence to better understand the direct relationships between climate change and coral reef stress as well as adaptations to climate change. In summary, because the reefs are still highly productive and not confounded by human activities such as overfishing, coastal development, run-off and pollution, understanding the community changes in response to climatic variations by establishing in-situ experiments is highly feasible.

In 2006, CCMI built the Little Cayman Research Centre (LCRC) with the intent of becoming a premier marine institute providing research and education facilities and programs based in the Caribbean. The organization has identified the need to fully establish distinctive research programs that will benefit from the assets of the local oceanographic, geographic, and biological setting and that will fully fund the research mission.

The Carbonate System Around Little Cayman

<u>Previous Work</u>

Since 1999, CCMI has directed research to establish long term trends on the reef communities around the Cayman Islands. The organization has an umbrella program called the Long Term Assessment and Monitoring Program (LAMP) that provides information on threatened species and critical habitats in the Cayman Islands. Ecological information is collected using AGRRA, CARICOMP, and standard photo-transect methods. Overall, a major decrease in coral cover occurred between 1999 and 2004 but the reef has stabilized since 2004. Fish populations are healthy and have not changed since 1999 (except parrotfish which are measurably larger now), and fleshy algae is unchanged since 1999.

<u>Research Results 1999 - 2007</u>

- Coral Cover, Fish Biomass and density remains above average.
- Algae competition was insignificant and continues to not be an issue.
- Recruitment was above average and we see little change over the years.
- White Plague (syndromes) were taking a toll especially on the large massive colonies, cover has been reduced from 26 – 17% on average.
- No clear trend in disease and mortality in relation to human activities

The organization oversees a Reef Resiliency which focused on the early history of juvenile corals addressing the concern of better understanding how reefs are being regenerated after stress primarily from bleaching, storms, and diseases. Data collected since 1999 indicate that recruitment has not declined over all the years. A study of tagged juveniles that began in 2005 provides information on juvenile growth rates per species and juvenile survival over time. This work is illustrating that juvenile coral growth and that the community structure is similar to the overall adult population. We infer that the history of low fishing pressure and low growth of fleshy algae results in resiliency despite mortality.

Visiting Research
Visiting scientists have conducted research at the Little Cayman Research Centre since inception on a variety of topics from measuring and identifying herbivores (including David Bellwood), to examining fish evolution (Elizabeth Whiteman and Isobel Cote,) and exploring the deep reef communities (Marc Slattery, Michael Lesser).

Assets of Little Cayman's Carbonate System
Marine protected areas surround the island with more that 50% of the area having some form of protection. Low human population and development, a variety of reef setting, the availability of a long-term database, low fishing pressure, and easy access to deep open ocean water are among the assets of working in Little Cayman.

Setting
The Cayman Islands lie in the middle of the Caribbean Sea, about 240 km south of Cuba. They are comprised of three small (12–18 km long) low-lying, limestone islands with Little Cayman (LC) 125 km northeast of Grand Cayman (GC) and just 7.5 km to the southwest of Cayman Brac (CB). Little Cayman has a permanent resident population of about 150, and remains relatively undeveloped with four small dive lodges and one 40-room resort (and the Little Cayman Research Centre). There are 2,200 residents and two dive resorts on CB. Grand Cayman has a resident population of 42,000. Dive tourism is the only economy on Little Cayman. Grand Cayman and Cayman Brac are also important Caribbean dive destinations. Banking, legal services, and real estate development are leading employment services in Grand Cayman. No commercial fishing occurs in the Cayman Islands. A small fishing operation supplies local fish in the center of Georgetown Harbour. Fishing pressure is low on Little Cayman where the only remaining grouper spawning site in the Cayman Islands is located off the west side of the island. Fishing is an important cultural tradition in Cayman Brac where many of the residents are ancestors of the original settlers in the Cayman Islands.

Reefs of the Cayman Islands
Two shallow-sloping submarine terraces occur around the islands with a few exceptions (e.g. Bloody Bay on LC is missing the lower terrace) (Rigby and Roberts, 1976; Blanchon et al., 1997). The upper terrace extends from the shoreline to a mid-shelf scarp at depths of 8–15 m and a lower terrace from the base of this scarp to the edge of the shelf at 15–20 m. Spectacular shelf-edge "walls" occur around all three islands. Fringing reefs and boulder ramparts are nearly continuous around LC and GC (except off the western side of GC) and occur along the south side (western third) of CB. In many locations, the boulder rampart (in 0.5–5 m water depth) was formerly a reef crest dominated by *Acropora palmata* on the upper terrace along the windward coasts (east, south, north of GC and LC, south of CB). High-relief (to 12 m) spur-and groove or buttress reefs have developed at several sites at the edge of the upper terrace in the more exposed (eastern, northeastern, southeastern) sides of the islands (Manfrino et al. 2003). At "more protected" windward locations on the northern and southern coasts, low- to medium relief (1–3 m) spurs and grooves are found at the edge of the upper terrace. In leeward locations (western side of GC; Bloody Bay on LC), where a reef crest is lacking, there are narrow, low-to-medium relief spurs and grooves or shelf-edge reefs with poorly developed spurs and grooves, although a few high-relief, elongated spurs occur along the upper terrace in Bloody Bay (Manfrino et al. 2003).

Episodes of coral bleaching were reported in the Cayman Islands in the late 1980's, 1995, 1998, 2003, and 2005. Major storms to impact the Caymans were Hurricanes Allen in 1980, Gilbert in 1988, and Mitch in 1998, Ivan in 2004, and Dennis in 2005. Hurricane 'Ivan' passed south of Little Cayman and Cayman Brac but made direct landfall on Grand Cayman on 12 September, 2004. Large masses of sand piled up on back-reef corals and in lagoons on the south side of Little Cayman and Grand Cayman. Corals above 15 m were broken or totally displaced along both sides of the islands, but damage was patchy and recovery is being recorded. Boulder ramparts on many of the beaches of all three islands and reef-crest zones that are largely biodetrital provide historic evidence of the continuous impact by major storms.

Threats and Protection
A Marine Conservation Law was passed in the Cayman Islands in 1979. Marine park areas (15 km^2), replenishment zone areas (15 km^2), an environmental zone (17 km^2) in the North Sound of GC, and animal sanctuaries/RAMSAR sites were designated in 1986. Conservation regulations have continued to change to increase protection of conch, lobster, and to protect grouper spawning grounds. Little Cayman has a productive spawning aggregation site on the western side of the island.

Think Tank Outcomes

- The group identified a need for an open ocean low impact site for ocean acidification research. Little Cayman is a good site to meet this research objective.
- A pilot project to take water samples to measure carbonate chemistry was planned.
- The group outlined a suite of experiments and permanent instruments that could be installed on or nearby the Little Cayman ICON stick.

References

Coelho V. and Manfrino C., 2007, Coral Community Decline at Remote Caribbean Islands: Marine No-Take Reserves Are Not Enough, Aquatic Conserv: Mar. Freshw. Ecosyst. 16:1-20.

Manfrino, C., B. Riegl, J.L. Hall, R. Graifman, 2003, Status of Coral Reefs of Little Cayman,

Grand Cayman & Cayman Brac, British West Indies in 1999 & 2000 (Part 1: Stony Corals & Algae), J.C. Lang (ed.), Status of coral reefs in the western Atlantic: Results of initial Surveys, Atlantic & Gulf Rapid Reef Assessment (AGRRA) Program, Atoll Res. Bull. 496, p. 204-225.

Blanchon, P., Jones, B., and Kalbfleisch, w., 1997, Anatomy of a fringing reef around Grand Cayman: Storm rubble, not coral framework. Journal of Sedimentary Research, 67, pgs. 1-16.

Rigby, J.K., and Roberts, R.H., 1976m Geology, reefs and amrine communities of Grand Cayman Islands, BWI. In: Geology Studies Special Publ. No.4: Grand Cayman Island- Geology, Sediments, and Marine Communities, (ed by J.K. Rigby and E. Shaw) pp 1-95, Department of Geology, BYU, Provo, UT USA, 122pp.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Carrie_Manfrino_Think_Tank-5.ppt

Think Tank #5 Goals, LCRC ICON Station Overview, and Introductions of Participants

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The goal of installing an ICON/CREWS station near the Little Cayman Research Center is to provide, a) long-term data sets of the basic meteorological and oceanographic parameters near a coral reef with minimal anthropogenic impacts, b) provide a structure for the attachment of ocean acidification measuring instruments, and, c) to provide data and information products from the installed instrumentation, as well as from satellite data and from other future data sources. The integration of such data will provide for more robust models, and the direct observation by field technicians at the Center will validate those in a very timely manner. The following presentation shows all aspects involved in the installation of an ICON/CREWS station, and which may be subdivided into these main steps:

1) Site survey.
2) Agreement among all parties for cost and labor effort through an approved Memorandum of Understanding.
3) Bottom plate installation.
4) Pylon construction.
5) Instrument purchase and testing.
6) Shipment of all station equipment to site of installation.
7) Installation of the pylon.
8) Installation of the instruments.
9) Maintenance and upkeep, including yearly calibration and timely repair of the instruments.

References

Hendee, JC, Gramer, L, Kleypas, J, Manzello, D., Jankulak, J, Langdon, C. 2007. The Integrated Coral Observing Network: Sensor Solutions for Sensitive Sites. ISSNIP IEEE 2007: Proceedings of the Third International Conference on Intelligent Sensors, Sensor Networks and Information Processing December 3-7, 2007, Melbourne, Australia, pp. 669-673.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Jim_Hendee_Think-Tank-5-crews-install.ppt

Coral Reefs, the Carbon Cycle, and Ocean Carbonate Chemistry

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Coral reefs play a major role in the global carbon cycle, mostly through their high rates of calcium carbonate ($CaCO_3$) production. The "coral reef hypothesis" embodies this role. This hypothesis refers to the fact that the waxing and waning of $CaCO_3$ on continental shelves, in concert with the glacial-interglacial fluctuations in sea level, has contributed to the glacial-interglacial fluctuations in atmospheric CO_2 concentration. Although $CaCO_3$ production by coral reefs and associated shallow-water carbonate environments occurs over a much smaller area than $CaCO_3$ production in the open oceans, the estimated high rates of production and the preservation of $CaCO_3$ on shallow shelves (compared to lower production rates and higher dissolution rates at depth) result in a net shelf production about equal to that of the open ocean. This presentation reviews these estimates and their uncertainty, and highlights several intriguing and recent discoveries (e.g., the wide distribution of both coralline algae and deep coral bioherms) that could affect the global $CaCO_3$ production estimates.

A second motivation of this talk is to discuss the various controls (including mineral saturation state) on reef carbonate production, particularly in light of several recent geological approaches. One modeling study (Demicco and Hardie 2002) illustrates the strong effect of residence time on reef growth on the Bahamas Bank; demonstrating the self-limiting role of $CaCO_3$ production and potentially explaining why $CaCO_3$ production is highest along shelf edges. While this study illustrates the relationship between $CaCO_3$ production and saturation state on the spatial scale, another study illustrates the larger scale, temporal effects of shelf carbonate production over time. Ryan et al. (2001) applied geological techniques to quantify reef $CaCO_3$ production over time on Wistari Reef, Australia, and showed that production peaked shortly after the last sea level transgression (about 8,000 years before present) and has since declined. They suggest that this decline reflects the progressive drawdown of alkalinity and increase in atmospheric CO_2 (mechanisms of the "coral reef hypothesis"). Temperature and light are also known to be strong factors in reef $CaCO_3$production. Preliminary results from a reef $CaCO_3$ production model were presented that demonstrate how seasonal changes in light production can limit $CaCO_3$ production, and therefore reef development, at higher latitude.

In summary, the controls on reef $CaCO_3$ production (both biological and inorganic processes) can significantly alter the significance of coral reefs in the global carbon cycle. One major factor, seawater carbonate chemistry, has gained increased recognition over the last decade. The geological sciences have long addressed factors that control $CaCO_3$ production, particularly with respect to the implications for oil exploration. Ocean acidification offers a promising new hypothesis that may help us understand the variations in reef $CaCO_3$ production over time, and as such, variations in the global carbon cycle.

References

Demicco RV, Hardie LA (2002) The "carbonate factory" revisited: A reexamination of sediment production functions used to model deposition on carbonate platforms. J Sed Res 72:849–857

Ryan DA, Opdyke BN, Jell JS (2001) Holocene sediments of Wistari Reef: Towards a global quantification of coral reef related neritic sedimentation in the Holocene. Paleogeogr Palaeoclim Palaeoecol 175:173–184

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Joanie_Kleypas_thinktank5_reefs.ppt

Variability In The Surface Water Inorganic Carbon Parameters Of A Hawaiian Coral Reef System And Implications For Calcification Rates

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High frequency and long term variability of inorganic carbon parameters is of particular interest in coral reef ecosystems because changes in these parameters have implications for calcification and dissolution, especially as concerns over ocean acidification grow. A Coral Reef Instrumented Monitoring and CO_2 Platform (CRIMP-CO_2) mooring has collected surface water temperature, salinity, pCO_2, pO_2 and air pCO_2 and pO_2 data every 3 hours almost continuously since December 2005 in Kaneohe Bay, Hawaii. All measured values showed significant variability over a range of time scales. Surface water pCO_2 ranged from 230 to 590 μatm but was generally higher than atmospheric due to net calcification. A linear TA/salinity relationship was derived from discrete surface water samples collected near the mooring. Using this relationship and the mooring data, we evaluate the full carbon system with particular attention to factors influencing calcification rates. Surface water saturation state with respect to aragonite, for example, varied from 1.2 to 3.5 with low values occurring during storm fresh water input.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Richard_Feely_ThinkTank5.ppt

Hot Sour Soup: Good for Colds, Bad for Corals

C. Mark Eakin, Dwight K. Gledhill, Scott F. Heron, William Skirving, Tyler Christensen, Jessica Morgan, Gang Liu, Alan E. Strong
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Coral reefs live within a fairly narrow envelope of environmental conditions constrained by water temperatures, light, salinity, nutrients, bathymetry and the aragonite saturation state of seawater. As documented in numerous studies, the world's coral reefs are "in crisis" as a result of human impacts on their environment. While local stresses currently dominate, coral reefs are increasingly confronted with global-scale changes due to rising greenhouse gas concentrations. These changes are rapidly modifying the environmental envelope of coral reefs through both increased thermal stress and ocean acidification. In the former case, there is a well-documented relationship between thermal stress and the response of corals that include coral bleaching, disease, and mortality. Clear tolerance thresholds exist beyond which high temperature and accumulated thermal stress have deleterious effects. However, the synergistic effects of increasing temperature and ocean acidification are not yet fully understood. Dropping ocean pH may also be causing an increase in boring sponges and other forms of reef bioerosion, increasing reefal destruction as accretion by corals drops. At this time, there is mounting concern that decreasing pH and aragonite saturation state will cause net reef accretion to cease or become negative. The threshold at which this could occur is likely to be reached much sooner than the pH drop necessary to induce carbonate dissolution. Both the thermal and chemical limits that control coral survival and reef growth will likely be passed before 2100 assuming even conservative projections reported in the 4th Assessment Report of the Intergovernmental Panel on Climate Change.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Mark_Eakin_hot-sour-soup_lcrc-short.ppt

Wrap Up Of the OCB Ocean Acidification Scoping Workshop And New Results From La Parguera, Puerto Rico

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The Ocean Carbon Board Scoping Workshop for Ocean Acidification was held at Scripps Oceanographic Institution Oct. 9-11, 2007. The purpose of this meeting was to set out recommendations on how the US science funding agencies should address the questions posed by ocean acidification. The goals of the workshop were to develop coordinated research implementation strategies to address present and future ocean acidification impacts and identify specific activities and timelines needed to advance research priorities. The workshop focused on developing comprehensive research strategies for four critical ecosystems: warm-water coral reefs, estuarine and coastal regions, subtropical/tropical pelagic regions and high latitude regions. The preliminary recommendations were that the following general activities needed to begin immediately: data mining to synthesize existing knowledge on the state of carbonate chemistry in each of the focus environments; baseline monitoring is urgently needed for both the chemistry and for those processes known to be sensitive to ocean pH; laboratory and microcosm single and multiple species experiments to determine the sensitivity of key species to elevated pCO_2 and temperature conditions; planning for a free ocean carbon experiment (FOCE); development of an automated submersible total alkalinity sensor.

Preliminary results from work at La Parguera, Puerto Rico were presented. Two pairs of SAMI – pCO_2 and SAMI – spectrophotometric pH have been deployed on a fringing reef. One pair is mounted to the NOAA ICON LPPR1 mooring and the second pair is located 1.5 km away at an upstream location on the same reef. The sensors are sampling every 30 min. The data are being used to study the temporal variability in carbonate parameters and to attempt to obtain automated measurements of calcification. The data reveal that in June 2007 aragonite saturation state varied from a minimum at night of 3.4 to a maximum in the day of 4.1 and that the average over a one week period was 3.7. It was also observed that a difference in total alkalinity based on discrete measurements could be observed between the upstream and downstream locations and that this difference was 2 μEquiv kg^{-1} at 0800 and grew to 15 μEquiv kg^{-1} by 1130. Based on surface drifter estimates of the current this translates to a calcification rate of 1-8 mmol $CaCO_3$ m^{-2} h^{-1}.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Chris_Langdon_Think_Tank_5.ppt

The Effect of Depressed Aragonite Saturation State on Larval Settlement, Post-Settlement Survivorship, and Growth of the Brooding Coral *Porites astreoides* and the Broadcast-Spawning Coral *Montastraea faveolata*

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In conjunction with the projected increases in pCO_2 of the coming century, adult coral growth and calcification are expected to decrease significantly. However, no published studies have investigated the effect of elevated pCO_2 on earlier life history stages of corals. As coral recruitment, post-settlement survivorship, and growth are critical to reef persistence and resilience, it is of timely importance to better understand the repercussions on such factors. Larvae and gametes of *Porites astreoides* and *Montastraea faveolata* (respectively) were collected from reefs in Key Largo, Florida, fertilized (*M. faveolata*) and settled and reared in controlled saturation state seawater. The effect of treatment water on settlement and post-settlement growth was examined. Three treatment levels were targeted based on present (380 ppm) and projected pCO_2 scenarios for the years 2065 (560 ppm) and 2100 (720 ppm). Corresponding saturation states of treatment water were obtained using 1M HCl additions: $\Omega = 3.19 \pm 0.13$ (control), 2.59 ± 0.08 (mid), and 2.16 ± 0.12 (low). Larvae were introduced to their respective treatments and allowed one week to settle onto pre-conditioned limestone tiles. Percent settlement was determined by examination under a dissecting microscope. Settled larvae were placed in flow-through treatment aquaria (25°C) and growth rates were analyzed over the course of twenty-one days, using high magnification photographs and SPOT© Software to monitor changes in total surface area (mm^2). Results indicate that saturation state had no significant effect on percent settlement of *P. astreoides* or *M. faveolata* larvae. Skeletal extension rates of *P. astreoides* spat exhibited a positive correlation with saturation state, while tissue growth rates of *M. faveolata* spat were not significantly affected.

Reference (added post-workshop)

Albright, R., Mason, B., and Langdon, C. (2008). Effect of aragonite saturation state on settlement and post-settlement growth of *Porites astreoides* larvae. Coral Reefs, 27: 485-490.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Rebecca_Albright_TT5_Albright.ppt

Fragile Reefs of the Eastern Pacific: a Model for Reefs in a High-CO_2 World

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Ocean acidification describes the progressive, global reduction in seawater pH that is currently underway due to the oceanic uptake of increasing atmospheric CO_2. Acidification is expected to reduce coral reef calcification and increase reef dissolution, and the relative rates of change will likely be a function of pCO_2 (the partial pressure of CO_2) in seawater, which is directly proportional to pCO_2 in the atmosphere. Little is known about the effects of acidification on processes that affect the persistence and preservation of coral reef framework structures (i.e., early marine diagenesis). Newly analyzed samples agree with previous studies showing that only trace amounts of inorganic cements occur in modern day coral reefs that exist naturally under low ambient pH in the eastern Tropical Pacific (ETP). The variation in cement abundance and rates of bioerosion between sites in Panamá and Galápagos appears to be related to differences in the saturation state of $CaCO_3$ (Ω); suggesting a link between Ω , inorganic cementation and coral reef development in the ETP. ETP reefs provide a real-world model of coral reef growth and structure in low-Ω waters and may thus provide insights into the role of decreasing Ω on reefs beyond the prediction of reduced calcification by corals and other primary reef builders.

Reference (added post-workshop)

Manzello, D. P., Kleypas, J. A., Budd, D. A., Eakin, C. M., Glynn, P. W., and Langdon, C. (2008). Poorly cemented coral reefs of the eastern tropical Pacific: Possible insights into reef development in a high-CO_2 world: Proc. Nat. Acad. Sci., USA, 105: 10450-10455.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Derek_Manzello-TT5_12_2007.ppt

Integrating Near Real-Time Data for Ecological Forecasting on Coral Reefs

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NOAA/AOML's Integrated Coral Observing Network (ICON) Project integrates in situ, satellite, radar, and other data sources from over 120 sites around the world in all three oceans (http://ecoforecast.coral.noaa.gov). We define "integrating" data as merging data for a purpose. The many data sources we integrate may include in situ monitoring stations, satellites, radar, tide stations, biota assessments, archived data, etc. Near real-time data integration is useful or critical for Marine Protected Area (MPA) managers and others when they need to make timely decisions. NOAA's Coral Reef Conservation Program seeks to facilitate those decisions, and is a key member of NOAA's new Integrated Ocean Observing System Program, which also strives to support management. The monitored sites include those in the ICON network in the Caribbean, the NOAA/NMFS Coral Reef Ecosystem Division network in the Pacific, NESDIS HotSpot satellite monitoring sites, Australian Institute of Marine Science Network, SEAKEYS Network in the Florida Keys National Marine Sanctuary, and many other significant coral reef areas. As part of ICON's information architecture, the project utilizes artificial intelligence technology to screen integrated data for outliers, as well as for conditions conducive to many biological and physical events (ecological forecasting). Ecological forecasts ("ecoforecasts") predict the impacts of physical, chemical, biological, and human-induced change on ecosystems and their components. Integrated project data are used as input for ecoforecasting coral bleaching (sea temperature, light, winds, tide), coral spawning (sea temperature, moon phase, hours of daylight), larval drift (sea temperature, winds, currents), onshore flux studies (sea temperature, salinity, winds, currents), and other events. A critical part of each ecoforecasting model is the feedback from the field; this is met by in situ station maintainers, research laboratories, divers, and others via conservation networks. Feedback improves models through a continuous iterative process. Many partners (e.g., in NOAA, NASA, USGS, F&WS, universities, etc.) collaborate with the ICON Program in this process, as well as through research partnerships through funding.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Jim_Hendee_Think-Tank5-ecoforecasting.ppt

Ecological Forecasting on Coral Reefs

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The National Oceanic and Atmospheric Administration's (NOAA) Integrated Coral Observing Network (ICON), has been operational since 2000 and works closely with many US Governmental and international environmental partners involved in coral reef research. The ICON program has pioneered the use of artificial intelligence techniques to evaluate environmental conditions based on near real-time data streams from networks of monitoring stations such as NOAA's C-MAN SEAKEYS (Florida Keys), the Australia Institute of Marine Science Weather Station network, NOAA's Coral Reef Ecosystem Division buoy network in the Pacific, as well as the ICON stations in the Caribbean. The ICON program together with academic partners, more recently developed techniques for the near real-time integration of satellite and radar data and numerical model outputs, with data from these in situ networks, for the purpose of ecological forecasting of such events as coral bleaching, coral spawning, upwelling or biological productivity changes, and other biological, chemical and physical oceanographic phenomena. The ICON program has also led the field in utilizing innovative in situ instrumentation to monitor coral health in near real-time, including Pulse-Amplitude-Modulating fluorometers to directly measure the photosynthetic performance of endosymbiotic algae within coral tissues, and autonomous sensors to measure dissolved CO_2 and pH in the water column.

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http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Lew_Gramer-TT5.ppt

Existing Technology and Challenges for Monitoring the CO2 System in Seawater

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Understanding the seawater carbon system is difficult because CO_2 reacts with the water molecules to form a variety of dissolved species. However, with knowledge of the carbon dissociation constants the seawater carbon system can be constrained by measuring any two of the four measurable carbon parameters: dissolved inorganic carbon (DIC), total alkalinity (ALK), partial pressure of CO_2 gas (pCO_2), or pH. Methods have been developed to make high quality measurements of all four of these parameters from bottled water samples. A revised guide to best practices for ocean CO_2 measurements has recently been published: http://cdiac.esd.ornl.gov/oceans/Handbook_2007.html. However, not all parameters have the same level of difficulty for making the measurements or the cost of the equipment or how long they can be stored (Table 1). The recommended pair for ocean acidification work is DIC and ALK because these samples can be stored and returned to the lab for careful analysis and because this pair also provides a strong constraint on the full carbon system. If measurements can be made quickly, spectrophotometric pH is also a useful measurement if paired with DIC or ALK.

Table 1. Summary of 4 measurable parameters and relevant issues with their measurement

Parameter	Measurement Difficulty	Instrumentation Cost	maximum storage
DIC	High	High	<3 months
ALK	Medium	Low	<6 months
pH	Low	Medium	<2 hours
pCO_2	Very high	Moderate to very high	<24 hours

There are also a variety of autonomous sensors that are available for ocean acidification studies. The most common high quality carbon parameter measured autonomously is pCO_2. There are at least 4 systems regularly used for ocean CO_2 measurements: $MAPCO_2$ (Sabine), Sami-CO_2 (DeGrandpre), CARIOCA (Merlivat) and Pro-oceanus (McNeil). All of the sensors have their good and bad points and the user needs to be very familiar with how the systems work to ensure that high quality measurements are collected. There are autonomous pH sensors available (e.g. sami-pH), but this is not the ideal parameter to match up with the pCO_2 because pCO_2 and pH co-vary so strongly that they do not provide a strong constraint on the carbon system. Ideally autonomous DIC and/or ALK systems would be useful but there are no commercially available systems at the moment for these parameters. As we look to the future of ocean acidification research, we need to think about our needs for high quality carbon measurements and start investing in technology development now to make sure the systems that we need are available when we need them.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Chris_Sabine-carbonate.ppt

Extending Underway and Geochemical Survey Data Using Satellite Remote Sensing

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The global oceans serve as a prominent natural sink for increasing atmospheric carbon dioxide (CO_2) concentrations. As CO_2 is absorbed by seawater, it reacts to form bicarbonate and hydrogen ions reducing seawater pH (or acidification). This decreases the degree to which seawater is supersaturated with carbonate ions (i.e. saturation state, Ω). Additional controls on Ω include temperature and salinity that collectively impart a dynamic and complex variability to Ω both spatially and temporally at finer scales then are typically appreciated. This is an important consideration when evaluating the potential consequences of ocean acidification which has been demonstrated to negatively impact calcification for a number of marine organisms. Here we upscale observations obtained in situ from Volunteer Observing Ships and multiple geochemical surveys using satellite remote sensing and modeled environmental parameters to derive synoptic estimates of sea surface alkalinity (AT) and surface carbon dioxide partial pressure (pCO_2). Pairing estimates of AT and pCO_2 together with temperature and salinity permits characterization of the variability in Ω throughout the Greater Caribbean Region. The results reveal considerable variability both spatially and seasonally throughout the region. As a consequence of ocean acidification, the aragonite saturation state (Ω_{arag}) has declined at a rate of ~ $-0.12 \pm 0.01\ \Omega_{arag}$ decade^{-1} ($r^2 = 0.97$, $P < 0.0001$).

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Dwight_Gledhill_ThinkTank5_Gledhill.ppt

Regional estimates of carbonate production using Landsat 7 ETM+ and potential impacts from ocean acidification

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Using Landsat 7 ETM+ imagery at 30 m spatial resolution, we scale-up reef metabolic productivity and calcification from local habitat-scale (0.1-1 km^2) measurements to regional scales (1000-10000 km^2). Distribution and spatial extent of the North Florida Reef Tract (NFRT) habitats come from supervised classification of the Landsat imagery within independent Landsat derived Millennium Coral Reef Map geomorphologic classes. This system minimizes the depth range and variability of benthic habitat characteristics found in the area of supervised classification and limits misclassification. Classification of Landsat imagery into 5 biotopes (sand, dense live cover, sparse live cover, seagrass, and sparse seagrass) by geomorphologic class is >73% accurate at regional scales. Based on recently published habitat-scale in situ production measurements, calcification (G = -1.68 x 106 kg $CaCO_3$ yr^{-1}) is estimated over 2,711 km^2 of the NFRT. Similar approaches could be applied over large areas with poorly constrained bathymetry or water column properties and representative in situ sampling. This tool has potential applications for monitoring large scale environmental impacts on reef production, such as the influence of ocean acidification on coral reef environments.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Chris_Moses_tt5_carb_production_200712.ppt

Reef responses to ocean acidification: can we integrate processes at the scales of organism, reef zone, reef system and region?

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Predictions of ocean-acidification threats to coral reefs have been based mainly on models of changes in ocean chemistry, and have given limited consideration to how reef systems influence the chemistry of the reef water. Here, I present a model that integrates benthic processes (productivity, calcification and metabolism) with water-column processes to achieve an improved understanding of how vulnerable different coral-reef habitats and communities are to ocean acidification in a spatial context. Specifically, model simulations suggest that high reef productivity may potentially counter-balance ocean acidification on some reefs, whereas factors such as mass bleaching make coral reefs more susceptible to ocean acidification. Two large acidification projects are being initiated on the Great Barrier Reef (GBR, Australia) to integrate ocean influences with reef-system processes at multiple scales ranging from reef habitat to the entire GBR lagoon system. It is proposed that the southern GBR, for which extensive oceanographic, hydrological, ecological and physiological information is available, can provide an excellent test bed for how ocean acidification affect complex reef systems, and how reef processes in turn can affect their vulnerability to ocean acidification at scales ranging from habitat to region.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Ken_Anthony-Cayman_Island_Think-Tank-5.ppt

Integrated geologic studies of coral reefs: impacts of ocean acidification

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One of the primary consequences of increased atmospheric pCO_2 is acidification of the ocean that results when carbon dioxide combines with seawater to produce a naturally occurring acid called carbonic acid. In coral reef ecosystems, the three dimensional structure of the reef is developed as corals and other reef organisms produce calcium carbonate skeletons via calcification. A number of experimental and modeling studies indicate that ocean acidification will result in a decrease in rates of calcification of reef organisms, and an increase in dissolution of reef sediments that form the foundation of reef structure. The ocean acidification process and resulting impacts will affect coastal and marine ecosystems globally and indiscriminately. The severity of the impact to coral reef systems depends in part upon the balance between calcification (production of reef structure) and dissolution of sediments.

For the past 6 years, USGS Coastal and Marine Geology Program studies in St. Petersburg, FL have focused on development of technology and methodologies for quantifying reef health in terms of fundamental metabolic processes (calcification, dissolution, photosynthesis, and respiration), and on development of modeling capabilities that allow extrapolation of reef processes over larger (local to regional scale) geographic areas and prediction of the impact of water quality change on reef function. This type of predictive capability can assist resource managers in assessing the impacts of climate change, hurricanes, coastal development, terrigenous sediment run-off, coastal eutrophication, etc. on water clarity and reef function. Additionally, rates of calcification and carbonate sediment dissolution in response to change in atmospheric pCO_2 have been measured providing in situ measurements of thresholds for the response of reef calcification and dissolution to elevated atmospheric pCO_2 in coral reef ecosystems. These studies have laid the foundation for developing predictive capabilities for assessing the impact of ocean acidification on reef calcification and dissolution.

USGS has developed a five-year research project focused on ocean acidification impacts to coral reefs. The project is based on partnerships with NOAA, NCAR, University of Miami-RSMAS, University of South Florida, University of the West Indies, Buccoo Reef Trust, and University of Puerto Rico. The general project approach will focus on combining process rate measurements of pCO_2 effects on reef metabolism with spatial distribution models at the reef scale, and hydrodynamic and water chemistry models to predict future impacts of elevated atmospheric pCO_2. The primary question and focus of the activities in this project is whether or not reefs will be able to continue to calcify enough to keep up with sea level rise and out-compete other opportunistic species such as algae, sponges, etc., or if they will begin to erode away or become dominated by non-calcifying reef species in the face of rising atmospheric pCO_2.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Kim_Yates-OA-think-tank-5.ppt

Response of Florida Shelf Ecosystems to Climate Change

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The processes and effects caused by climate change and chronic anthropogenic forcing of increased pCO_2 on Florida shelf organisms and sediment production are not known, yet, the information from which managers and the public will benefit is critical. Baseline information is needed that will feed into models for which observational databases are extremely limited.

Declining oceanic pH and carbonate-ion concentrations are well-known consequences of increased atmospheric and surface-ocean pCO_2. The possible impact of shifts in seawater carbonate chemistry on biocalcification and survival rates of marine organisms are pressing questions that are amenable to both experimental and field study. If reduced calcification decreases a calcifying organism's fitness or survivorship, then such calcareous species may undergo shifts in their latitudinal distributions and vertical depth ranges as the CO_2/carbonate chemistry of seawater changes.

To date, very limited quantitative data exist with which to test this hypothesis, particularly in shelf environments. The continental shelves of Florida provide an ideal natural laboratory in which to test latitudinal (and depth) shifts in habitat ranges of calcifying organisms. Both the east and west Florida shelves extend from warm temperate to subtropical latitudes. Along this gradient, carbonate sedimentation changes from predominantly animal-produced shell hashes known as "heterozoan" carbonates that accumulate at rates of centimeters per 1000 years, to subtropical reef environments in which "photozoan" carbonate sediments are produced in association with photosynthesis, at rates that can exceed a meter per 1000 years (i.e., hypercalcification). Changes in either latitudinal or depth distributions of benthic assemblages on the Florida shelves would provide convincing evidence of ecosystem-level effects of ocean acidification on calcifying organisms.

A research cruise in April 2008 will focus on retrieving sediments and mapping variations in ocean chemistry, including carbonate-saturation states. Sediment composition will be analyzed and will allow us to map the transition from heterozoan sediments (dominated by mollusks and bryozoans) to photozoan sediments (dominated by remains of Halimeda and foraminifera that host algal symbionts). We will utilize continuous flow-through SEAS-II and MICA (Multiparameter Inorganic Carbon Analyzer) instrumentation developed by Dr. Robert Byrne, University of South Florida (USF), and engineers from SRI St. Petersburg and USF College of Marine Science for Ocean Technology.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Lisa_Robbins-Ocean-Acidification-USGS.ppt

A NOAA-Wide Ocean Acidification Effort

Dwight Gledhill, John Tomczuk, Felipe Arzayus

A strategy for proposal writing and the NOAA PPBES (Planning, Programming, Budgeting and Execution System) was described and presented in the context of gaining research and funding to deploy a network of instrumentation and provide for research in the years ahead.

PowerPoint Presentation
http://www.coral.noaa.gov/noaa/icon/powerpoints/tt5/Dwight_Gledhill-Think5_Planning.ppt

Appendix 1

Reef Site Selection Criteria
For Early Success

1. Existing infrastructure for supporting research
2. Potential for strong calcification signal (e.g. high coral cover, long residence time)
3. Simple hydrography or where hydrographic models already exist
4. Existing long-term environmental information (existing time-series stations, CREWS, LTER sites, ecology)
5. Carbonate-simple (minimal complicating factors)
6. Potential for funding
7. Measurable seasonal amplitude in oceanic saturation state

Additional Considerations

1. Ecology is particularly sensitive to carbonate chemistry changes (lots of high-Mg calcite?)
2. Has naturally high pCO_2, or has strong natural gradients in carbonate chemistry
3. Ecologically or economically important systems (e.g., high biodiversity, fisheries-related, tourism-related)
4. Already near thresholds (high-latitude reefs; ETP)

Appendix 2

Essential Needs

- Basic implementation plan: two test-beds (Caribbean & Pacific) using a "package" of instrumentation and other techniques, performed at existing CREWS site, that can be proof of concept for deployment in more remote areas
- What about sensor development? Development of say, TAlk automated sensing, is a top priority
- Subsurface packages better than buoys because of permitting limits, vandalism, etc.
- Even without autonomous systems, we still need to go ahead with interim steps to characterize the carbonate chemistry of the system (perhaps through automated water samplers)
- Carbon cycle questions – source or sink of CO_2?

Appendix 3

Essential Elements of Testbeds (and Integration)

1. CREWS station
2. MapCO2 buoy X 2
3. Automated multi-samplers (RAS or AquaMonitor)
4. Current meters
5. Community system calcification/dissolution/production/respiration
6. SHARQ
7. Discrete sampling? (for calibration and to cover spatial heterogeneity) Autonomous vehicle? Including offshore waters
8. Ecosystem monitoring (regional benthic surveys incl. biodiversity; recruitment; spawning; rugosity)?
9. Remote sensing (regional and/or benthic classification; LIDAR bathymetry?)
10. Hydrodynamic modeling? Community response modeling and scaling-up models for eco-forecasting
11. Laboratory studies on key species or functional groups at site (including physiological responses?)
12. Data management, data synthesis and delivery (including information infrastructure) and stakeholder engagement, outreach
13. Validation against other sites

Appendix 4

Tier-2 Desired Elements

1. Paleo studies (isotopes, community structure… coring… etc.); proxy development and calibration
2. Cementation
3. Skeletal composition (organics) and integrity (density, banding, extension, strength)
4. Manipulation experiments (in-situ?)
5. Carbonate budget analysis? Sediment export?
6. Water column/resuspension effects on seawater chemistry
7. Sedimentological/Mineralogical analyses
8. Explicit address of dissolution/buffering
9. Pore-water chemistry and flux

Appendix 5

What are the main questions that need to be answered in the near future?

- Develop an idea of identifying thresholds or producing risk maps that will inform management, etc.
    - Can we determine thresholds, or alternatively, identify the types of changes we can expect at 2X and 3X pre-industrial (e.g., biodiversity)?
    - "threat characterization"
- Should we consider rate of change versus absolute values?
- How do we consider other environmental changes (e.g. T) at each site?
- What kinds of output are valuable to reef managers?

Appendix 6

"The Package"

- Our job here is not to do all of NOAA's work – e.g., we may or may not want to take on the species-by-species response.
- Our package is community/ecosystem response, and can we identify the processes behind that response.
- Do we want to consider organism response, or stick with the community? Combined lab-field work is probable.
- Should we follow Kim Yates' (USGS) list of elements? Or what should we add to that?
    - Mapping and monitoring (habitat, bathy, hydrodynamics)
    - Carbonate system variations temporally and spatially
    - Community level response to elevated CO_2 with experiments
    - Modeling
    - Remote sensing
- Research that informs stakeholders and management (resilience, adaptive cap., etc)

Appendix 7

Prioritized Station List

Pacific, U.S. CRTF (Coral Reef Task Force purview)

1. Hawaiian Islands
2. American Samoa
3. CNMI (Guam, Saipan)
4. Johnston Atoll (extremely remote)
5. Howland/Baker Atolls (extremely remote)
6. Palmyra/Kingman Atolls (extremely remote)

Here are Rusty Brainard's NMFS/CRED sites:

- *Enhanced Buoys*
  - French Frigate Shoals, NWHI (FFSH1)
  - Kure Reef, NWHI (KURE1)
  - Maro Reef, NWHI (MARO1)
  - Pearl and Hermes, NWHI (PEHE1)
  - Palmyra, Central Pacific (PACP1)
  - Saipan, Guam/CNMI (SAIP1)
  - Rose I., American Samoa (SAMO1)

- *SST-only Buoys*
  - NWHI: Kure | Laysan | Lisianksi | Midway
  - CNMI: Guam | Maug | Pagan | Rota
  - Samoa: Amanave | Aunuu | Tau | Fagasa | Fagatele
  - Central Pacific: Palmyra | Wake | Jarvis | Kingman

Pacific U.S. and Non-U.S.

Here are the NESDIS Coral Reef Watch sites:

- American Samoa - Ofu (OFAS1)
- Davies Reef (DROZ1) *
- Enewetok (ENEW1)
- Fiji - Beqa (BEFJ1)
- Galapagos (GALP1)
- Guam (GUST1)*
- Heron Island (QUOZ1)
- Midway Atoll (HMST1) *

- Oahu - Maui (MAUI1)
- Palau (PLAU1)
- Palmyra Atoll (PACP1) *
- Tahiti - Moorea (MOTA1)
- (more)

And here are some ICON "virtual station" sites:

- Uva Island, Pacific Panama (PANA1)
- Kenting Park, South China Sea (KENC1)
- Penghu Island, South China Sea (PENC1)
- 'Green' Island, South China Sea (GREC1)
- Pratas Island, South China Sea (PRAC1)

Atlantic/Caribbean, U.S.

- La Parguera, Puerto Rico
- Salt River, St. Croix, USVI
- Brewer's Bay, St. Thomas, USVI
- Buck Island, St. Croix, USVI
- Two Brothers Cay, St. John, USVI
- Culebra, Puerto Rico
- Navassa Island

Here are the Coral Reef Watch sites:

- Bahamas (CMRC3) *
- Bermuda (BERM1)
- Glover's Reef, Belize (G1BZ1)
- Puerto Rico (LPPR1) *
- Sombrero Reef (SMKF1) *
- Virgin Islands (SRVI2) *
- (more…)

Atlantic/Caribbean, Non-U.S.

Table 2 (following page) comes from an earlier proposed project, "Pan-Caribbean Climate Change Program," convened by Peter Ortner, University of Miami, Rosenstiel School of Marine and Atmospheric Science. A lot of thought and discussion went into this list.

Table 2. Proposed list of locations for a comprehensive Ocean Acidification project in the Caribbean Sea. (Compiled during a "Pan-Caribbean Climate Change Program" consortium; Peter Ortner, UM/RSMAS.)

Station Location	Collaborating Institution	Principal Contact(s)	Real/Provisional Lat/Long	Comments
Lee Stocking Island, Bahamas	Perry Institute for Marine Science	John Marr	23.7907, -76.1393	Instruments removed in October, 2007
Salt River Canyon (NPS), St. Croix	UVI	Rick Nemeth	17.7840, -64.7615	INSTALLED. National Park Service MPA
La Paguera, Puerto Rico	UPR	Richard Appeldoorn	17.9386, -67.0520	INSTALLED. Good marine lab facilities
Discovery Bay , Jamaica	Discovery Bay Marine Lab, UWI	Peter Gayle	18.4727, -77.4158	INSTALLED. CCCCC station
Bloody Bay Marine Park, Little Cayman	Little Cayman Research Center	Carrie Manfrino, Marilyn Brandt	19.6990, -80.0604	High biodiversity, station to be installed in 2008
North Sound, Antigua	UM/TAMU	Us	17.1571, -61.7382	Best Google guess
Glovers Reef, Belize	Wildlife Conservation Society	Cheri Recchia, Janet Gibson	16.8292, -87.7832	MPA, best western site, on the barrier reef
Archipelago Los Roques, Venezuela	Fundation Los Roques	Juan Posada	11.8628, -66.7826	MPA, good southern site
Seaflower Biosphere Reserve; San Andreas, Columbia	Coralina (NGO)	Marion Howard, Elizabeth Taylor	13.3677, -81.3434	Best Google guess, good oceanic southwestern site
Isle of Pines, Cuba	Inst. Invest.Ocean.	Pedro Alcolado	21.4990, -82.6518	Best Google guess
San Bernado, Columbia	Invesmart	Diaz Pulido	09.7883, -75.8656	Best Google guess
Folkstone Marine Reserve, Barbados	UWI	Robin Mahon	13.1890, -59.6480	MPA, eastern-most site
South Island area, Martinique	IFREMER/IRD	Lionel Reynal	14.4171, -60.8338	Best Google guess, badly threatened
Bocos del Toro, Panama	Smithsonian	Rachel Collin, Juan Mate	09.3314, -82.1024	Isla Bastimentos National Marine Park?
Three Mary Cays, Turks and Caicos	Turks and Caicos School for Field Studies	Paul Houlihan	21.9615, -72.0214	MPA
	~~ "Backups" ~~			
Arrecife Alacranes; Sisal, Mexico	UNAM	Xaviar Chiappa	21.1653, -90.0319	Willing Partner
Del Este; Punta Cana, Santo Domingo	NCORE	John McManus	18.1720, -68.6267	Closest MPA for this area
Bonaire NMP, Bonaire	Bonaire National Marine Park	Ramon De Leon	12.1623, -68.2863	Best Google guess
Buccoo Marine Park,Tobago	USGS	Owen Day	11.1760, -60.8338	MPA
Mochima, Venezuela	Univ. Oriente	Freddy Arocha	10.3065, -64.4794	MPA
Akumal, Mexico	Centro Ecological Akumal	Paul Sanchez	20.4102, -87.3013	Best Google guess

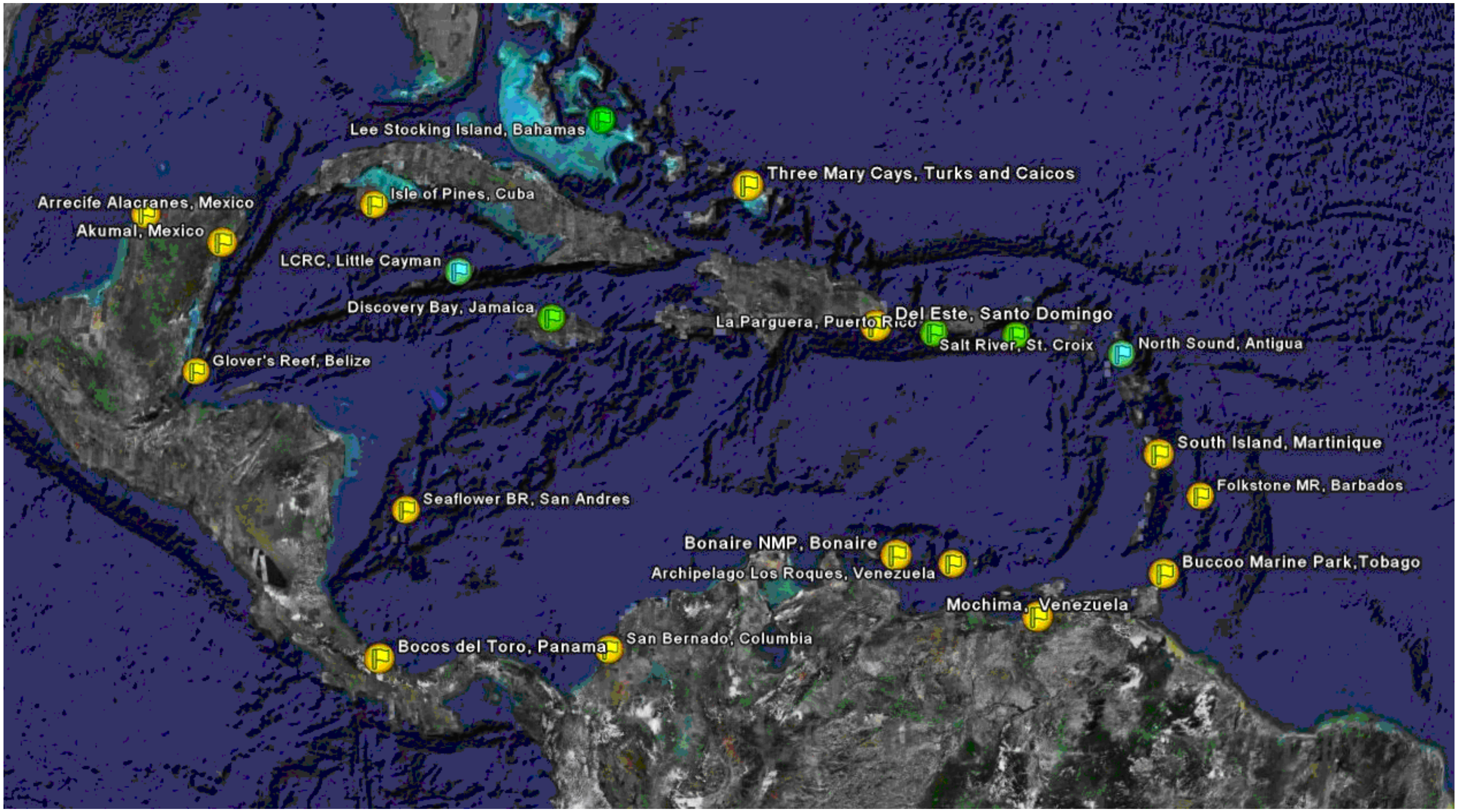

Figure 2. Map of proposed Caribbean stations for an Ocean Acidification program. Green flags indicate ICON/CREWS stations installed, blue flags for stations planned, and yellow flags for stations herewith proposed.

Here are some links for more information about the possible Caribbean sites:

- Navassa Island, Caribbean (NAVA1)
- Glover's Reef, Belize (GRBZ1)
- Archipelago de los Roques, Venezuela (ARVE1)
- Isle of Pines, Cuba (IPCU1)
- San Bernardo, Colombia (SBCO1)
- San Andres, Seaflower, SW Caribbean (SACO1)
- Old Providencia, Seaflower, SW Caribbean (OPCO1)
- Folkstone MR, Barbados (FOBB1)
- South island area, Martinique (SIMA1)
- Bocos del Toro, Panama (BTPA1)
- Three Mary Cays, Turks & Caicos (TMTC1)
- Arrecife Alacranes, Sisal, Mexico (SIMX1)
- Del Este, Punta Cana, Santo Domingo (PCSD1)
- Bonaire NMP, Bonaire (BOBO1)
- Buccoo Marine Park, Tobago (BUTO1)
- Mochima, Venezuela (MOVE1)
- Akumal, Mexico (AKMX1)

Indian Ocean

Here's a tentative beginning list, based on the ICON list of stations/sites monitored, mentioned above:

1. Rowley Shoals, W. Australia (RSOZ1)
2. Addu Atoll, Maldives (MALD1)
3. Ari Atoll, Maldives (ARMD1)
4. Baa Atoll, Maldives (BAMD1)
5. Diego Garcia? [7°20'10.92"S, 72°25'20.96"E]

United States Department of Commerce

Gary Locke
Secretary

National Oceanic and Atmospheric Administration

Dr. Jane Lubchenko
Under Secretary of Commerce for Oceans and Atmospheres

National Ocean Service

David Kennedy
Assistant Administrator (Acting) for National Ocean Service