AN INTEGRATED COASTAL OCEAN ACIDIFICATION OBSERVING SYSTEM (ICOAOS)

D. K. Gledhill[1], E. B. Jewett[1], K. Arzayus[2], J. Bennet[1], J. Newton[3], J. Salisbury[4], A.J. Sutton[5]
[1]*NOAA Ocean Acidification Program, Silver Spring, USA, email:dwight.gledhill@noaa.gov, libby.jewett@noaa.gov*
[2]*NOAA NODC, Silver Spring, USA, email: krisa.arzayus @noaa.gov*
[3]*University of Washington NANOOS, Seattle, USA, email: newton@apl.washington.edu*
[4]*University of New Hampshire NERACOOS, Durham, USA, email: joe.salisbury@unh.edu*
[5]*NOAA PMEL, Seattle, USA, email:* Adrienne.Sutton@noaa.gov *@noaa.gov*

Abstract

Atmospheric carbon dioxide (CO_2) concentrations have now reached levels greater than and increasing a rates not experienced for 300 million years [Honisch et al., 2012] with oceans absorbing about a quarter of the excess carbon each year [Sabine et al., 2004; Le Quéré et al., 2009]. As CO_2 reacts with seawater it fundamentally changes its chemistry through a process termed *ocean acidification*. Changes not only include declining pH, but also changes in the availability of a range of carbon compounds tightly linked with biological processes (i.e., productivity, respiration, and calcification) having significant ecological consequences for the marine environment. How these changes are expressed within coastal ecosystems represents a key area of uncertainty. Resolving this uncertainty is a core requirement of NOAA's Ocean Acidification Program (OAP) and demands the implementation of an integrated coastal ocean acidification observing system (ICOAOS) that tracks both changing physio-chemical conditions and the ecological responses to those changes. We propose a close partnership between the NOAA OAP, IOOS Regional Associations, state and local agencies, tribal nations, and academic researchers to ensure we meet this formidable challenge.

Key words: observing, operational oceanography, ocean acidification, data stewardship, partnership

1. INTRODUCTION, BACKGROUND, HISTORY, OR ACCOMPLISHMENTS

NOAA's Ocean Acidification Program (OAP) was established under SEC. 12406. of the Federal Ocean Acidification and Monitoring Act (FOARAM) to oversee and coordinate research, monitoring, and other activities consistent with the Strategic Plan for Federal Research and Monitoring of Ocean Acidification developed by the National Science and Technology Council's Subcommittee on Ocean Science and Technology interagency working group on ocean acidification currently under public review (https://www.federalregister.gov/articles/2012/07/11/2012-16919/strategic-plan-for-federal-research-and-monitoring-of-ocean-acidification). This plan closely aligns with NOAA's Ocean and Great Lakes Acidification Research Plan (2010) and with international research and monitoring priorities.

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 (Theme 1); assess (Theme 2) and forecast (Theme 3) biogeochemical and ecological responses; provide for data synthesis and management tools (Theme 4), better prepare human communities (Theme 5); and provide for ocean acidification education and outreach (Theme 6).

The research efforts of this national strategy are partitioned into a global and coastal component. For coastal environments, a network of new hydrographic and ecological surveys is required along with new coastal models to provide an "early warning" system for ocean acidification particularly in regions where episodic low pH events can occur. Augmentation and expansion of the existing ocean carbon observatory network in partnership with other federal, state, academic and regional IOOS partners provides the most cost-effective means of achieving ICOAOS requirements by ensuring key parameters for understanding and forecasting the effects of ocean acidification on marine ecosystems are monitored.

2. TECHNICAL REQUIREMENTS

A core part of the NOAA Ocean Acidification Program (OAP) mission is to foster and direct the establishment of a long-term monitoring program for ocean acidification (OA) utilizing existing global and national ocean observing assets and adding instrumentation and sampling stations as appropriate to the aims of the research program. These aims include quantifying OA and the ecological ramifications within the dynamic coastal environments.

How the long-term secular changes in surface ocean chemistry driven by rising atmospheric CO_2 manifest within the coastal environments can be complex. Local processes including dynamic changes in temperature and salinity [Gledhill et al., 2008], upwelling [e.g.

Lachkar and Gruber, 2012; Manzello et al., 2008; Feely et al., 2008], eutrophication [Cai, 2011], physiological processes (e.g., photosynthesis, respiration, calcification) [e.g., Barton et al., 2012, Salisbury et al., 2009, Suzuki and Kawahata, 2004], atmospheric deposition [Doney et al., 2007], land fluxes [e.g. Cai, 2011 ; Salisbury et al., 2008] and carbonate production [Balch et al., 2005], play important roles in regulating local carbonate chemistry within coastal environments (Figure 1). These biogeochemical drivers may prove more significant than the atmospheric driving effects to OA in the near-term within coastal environments. This complexity is likely to yield a range of susceptibilities to OA.

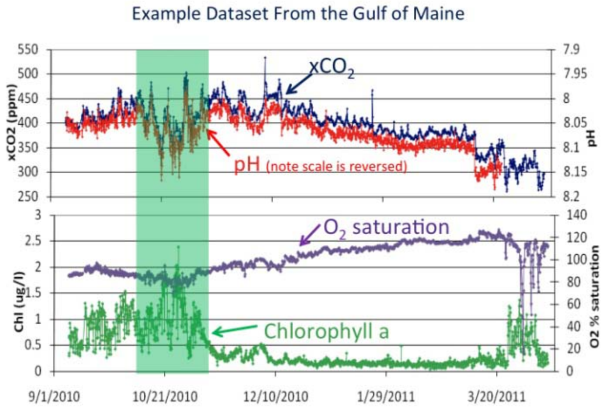

Figure 1: Time series showing pCO_2, pH, oxygen saturation and chlorophyll fluorescence. Biological processes impart important effects to carbonate chemisty within coastal waters..

A fully realized coastal monitoring network would not only characterize the carbon chemistry of these environments, but also monitor the changes in ecosystem response and community feedback to local chemistry (Figure 1). New technologies will need to be developed for this component, including new biogeochemical sensors for carbon species (particularly dissolved inorganic carbon (DIC) and total alkalinity (TA), gliders, genomic tags, as well as targeted process observations (e.g. measures of net community metabolism).

Currently, the NOAA OAP and associated academic partners are working towards achieving this requirement in concert with several IOOS Regional Associations (RAs) through which the OAP provides for the deployment and maintenance of a number of fixed OA observing assets in coastal and coral reef waters. The vision for this integration is evolving as the community identifies a consistent suite of core measurements with common protocols and QA/QC requirements.

3. STATE OF THE OBSERVING SYSTEM

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 OA. However, historically much of the focus has been on assessing open ocean carbon inventories and coastal waters remain under-sampled considering their variability. Currently, NOAA, in close coordination with regional associations of IOOS and academic partners, maintains 19 moored autonomous pCO_2 (MAPCO2) systems on buoys in coastal systems, 7 of which are within coral reef environments (Figure 2).

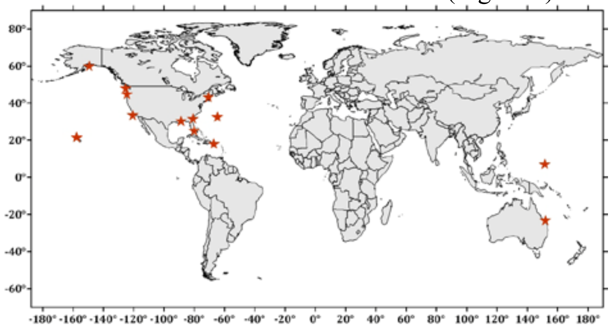

Figure 2: Existing coastal and coral reef monitoring sites. Real-time data is available from NOAA PMEL at www.pmel.noaa.gov/co2/map.

These include international sites in Bermuda, the Chuuk Islands of Micronesia, and at Heron Island along the Great Barrier Reef. At a minimum, these fixed autonomous platforms provide for measures of air and sea CO_2 along with temperature and salinity every three hours for up to a year before servicing. Recently, a subset of these stations (approximately 10; Figure 2) have been equipped with pH, dissolved oxygen, fluorescence, and turbidty sensors thus providing for full constraint of the carbonic acid system in addition to information about what might be driving carbon dynamics. These stations are referred to as the “OA moored array”. At most stations, discrete water samples are collected at least seasonally and analyzed for at least TA and spectrophotometric pH for sensor validation. The fixed mooring stations at the Atlantic Ocean Acidification Test-bed at Cayo Enrique Reef, La Parguera, PR and at Cheeca Rocks in the Florida Keys National Marine Sanctuary have been tied to repeated targeted process studies to quantify coral reef community metabolism (net calcification, productivity, respiration), coral growth, bioerosion, and dissolution rates. In addition, NOAA conducts research cruises to determine distributions of pH, DIC, TA, oxygen, nutrients, and biological and hydrographical parameters in U.S. coastal waters. These observations validate sensors and provide for algorithm development for obtaining high-resolution spatial-temporal information on pH and $CaCO_3$ saturation from hydrographic data collected on gliders and moorings. NOAA is also monitoring surface ocean pCO_2 utilizing ships of opportunity in coastal environments and upgrading those underway systems with a second carbon parameter to measure OA along those tracks. NOAA also uses new platforms, such as wave and subsurface gliders, to make carbon measurements in coastal waters.

4. DATA INTEGRATION

The OA science community is purposefully diverse, and the data being collected is equally heterogeneous, spanning experiments, sustained ocean monitoring, satellites, and models. The challenge of integrating these data sources for broad application requires a cooperative approach between scientists and data managers. The OA data integration framework needs to both develop new and build on existing relationships between scientists and data managers. Associated roles and responsibilities of these partners are distinct as well as complimentary. Given limited financial resources, it is critical that these relationships be enhanced. To that end, each distinct community (observing, experimental, modeling, and satellites) must self-identify and ensure a coordinated approach for development of content and formats of data and metadata and defined quality control procedures that are both human and machine-readable, with standardized units and variable names, and metrics to indicate completeness of metadata. Data management staff must work to bridge the communities, to agree on data access services and a strategy for data citations, translate scientific metadata content into industry standards for optimal discovery, and make the data available, with clearly designated levels of quality control, using agreed upon web services. As IOOS data collection efforts become more sophisticated, it will be integral to build all aspects of OA data management on agreed upon standards and data access services, to facilitate the full range of data access and integration. Initial steps have been taken toward these goals through the first OA program data management workshop, held in March 2012. This workshop convened attendees from several agencies and academia, laying the groundwork for establishing agreed components of an OA data set, as well as an initial draft of an OA data management plan.

5. THE WAY FORWARD

It remains important from a global perspective to quantify long-term (decadal) changes in surface ocean chemistry as driven by secular increases in atmospheric CO_2 to best inform national policy on carbon regulation. However, an important consideration is that physiological responses to carbonate chemistry have been observed to occur at short-time scales and the response is independent of the driving agent perturbing the carbonate chemistry. Therefore, marine resource management may benefit from coastal OA monitoring efforts where the identification of event driven processes can be used to alert stakeholder and user groups to emergent risk. An observing system capable of informing user groups in real-time of changing carbonate conditions can be applied in some resource management strategies.

There is a requirement to synthesize the observing datasets (both physiochemical and ecological) into products and management tools that are tailored to meet regional stakeholder and user group needs. IOOS RAs are well suited to work with the OAP in this effort as they have strong ties to local stakeholders who inform their observing data efforts. Through this ICOAS network, the NOAA OAP will coordinate closely with IOOS RAs to identify regional user requirements and then develop together appropriate products and observing tools to better meet management needs.

An example of this is illustrated by the NANOOS OA monitoring efforts happening along the U.S. Pacific Northwest which alert shellfish farmers to periods of undersaturated conditions. These events are driven primarily by summer coastal upwelling whereby deep water enriched by CO_2 by the buildup of respiratory CO_2 at depth is brought up to the near-shore by physical processes and can impact carbonate mineral saturation states experienced at oyster hatcheries along the Washington and Oregon coasts [Barton et al 2012]. Larval production and mid-stage growth of the oyster, *Crassostrea gigas,* have been found to negatively correlate with the carbonate saturation state the larvae are exposed to in early life [Barton et al., 2012] (Figure 3).

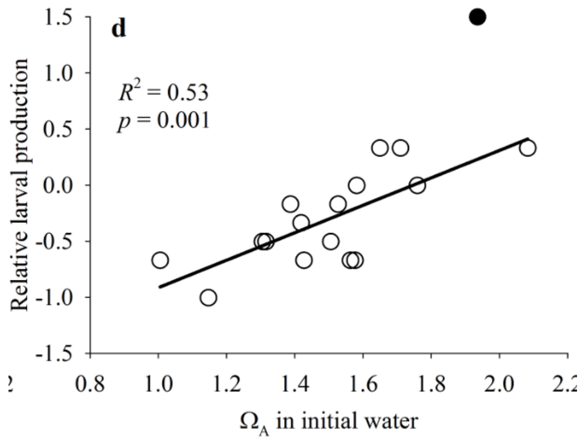

Figure 3. Relationship between saturation state of aragonite and overall relative production of Crassostrea gigas oyster cohorts (from figure 5d of Barton et al., 2012).

Some of these oyster hatcheries monitor real-time carbonate chemistry of their intake waters and use this information to adapt their operations to enhance oyster larval success rates. Real-time seawater pCO_2 at moored locations on the Pacific Northwest coast and

Puget Sound is also gathered by the NANOOS Visualization System for additional information on surface ocean conditions (see www.nanoos.org/nvs). Furthermore, short-term carbonate dynamics overlying coral reef environments may inform local resource managers of acute environmental stresses in real-time. For example, Kayanne et al. (2005) demonstrated enhanced seawater pCO_2 overlying a coral reef community in Ishigaki Island, Japan in response to bleaching induced shifts in community metabolism. A coral reef OA network could provide near-real-time alerts of coral community acute stress in addition to tracking long-term changes related to OA and climate.

To better meet local stakeholder and user group needs, an ICOAOS should encompass a diverse range of spatial (coastal watersheds to coral reefs) and temporal (seconds to decades) regimes, and provide data and products as needed (at real-time and delayed mode) to monitor OA, the ecological impacts, and biogeochemical feedbacks. The technical requirements have been detailed several times previously in community white papers produced as part of Ocean Obs '09 [Iglesias-Rodriguez et al., 2009; Gruber et al., 2009; Feely et al., 2010]. Briefly, a fully realized ICOAOS would be comprised of physio-chemical 'core' variables designed to track dynamics in carbonate and related water column chemistry parameters. These measures must minimally include at least 2 of the carbonate parameters to constrain the carbonic acid system), dissolved oxygen, temperature, and salinity across diel and seasonal cycles, if possible.

Additionally, there is a further need to compliment the physio-chemical monitoring with measures that can better constrain the primary forcing of short-term carbonate dynamics and provide specific insight into ecological response to OA. In the future, we envision that more specific biological response indicators will be added to the monitoring protocol although these will likely be variable with latitude and ecosystem. For example, community-scale measures of rates of calcification and other physiological processes known to be strongly impacted by high CO_2 should be measured in repeated and consistent fashion overtime for coral reef ecosystems.

5.1. Identify Key Stakeholders Requirements.

There is a need to foster connections to stakeholder and user groups of coastal OA monitoring data. A number of shellfish industry groups already serve as supportive stakeholders with a demonstrated use for coastal OA monitoring and information products which provide advanced warning of episodic OA events. The West coast shellfish industry has already put together a west coast OA stakeholder network, called the California Current Acidification Network (CCAN). CCAN's efforts could be applied as a model in other regions. Shellfish industry scientists, managers and harvesters could benefit from coastal OA information products derived from the ICOAOS data.

Regional and state agencies which have responsibility for state water quality have a need to: 1) better understand the ramifications of OA for water quality and ecosystems within their purview, and 2) better understand how they might monitor changing conditions in those waters (contribute to an established ICOAOS) in order to consider any remedial actions to be taken, such as reducing nutrient inputs which can impart significant effects on local carbon dynamics. The Washington State Blue Ribbon Panel on OA is in the midst of developing recommendations related to Puget Sound which might be more broadly applicable to other coastal systems. The ICOAOS' technical experts need to consider the best approach for providing this guidance in an understandable but scientifically robust manner.

Coral reef managers and scientists need to better understand the threat posed to coral reef ecosystems by OA. The coastal OA monitoring network can directly inform risk assessment mapping and guide development of marine protected areas in support of coral reef conservation efforts. Finfish scientists and harvesters are an important user group as some studies have demonstrated sublethal effects on finfish sensory responses and behavior [Nilsson et al., 2012]. Finally, OA represents a rapidly emerging topic of interest to a cross-disciplinary community of researchers, modelers and forecasters that can make specific use of the coastal OA monitoring data as it helps constrain the rates and dynamics of chemical change and ecosystem response. The ICOAS data will be valuable in assigning boundary conditions and testing model outputs.

5.2. Advanced Technology Development.

At this point, most of the current, moored carbon observatories only contain instrumentation to measure pCO_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. While some moorings have been configured with pH sensors, the pairing of pH and pCO_2 to solve the carbonic acid system is not preferred as they co-vary and yield considerable uncertainty. Sensors or automated, in situ analytical systems for measuring DIC and total alkalinity would constrain the inorganic carbon parameters to the precision and accuracy necessary to assess spatial and temporal variability of OA and its impacts. Triple constraint of the system (e.g. measure of three carbonate parameters) 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]. Several promising developmental efforts are underway but require continued resources and field testing. In addition to new instrumentation, adaptation of established instruments for ocean acidification research is necessary, including methods for subsurface measurements. 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 carbon chemistry to be identified.

5.3 Maintain and Enhance Existing Autonomous Capacity

In terms of the achieving the physiochemical monitoring requirements, there is a need to conduct any expansion to the existing network strategically to best resolve coastal uncertainty and leverage ecological monitoring. Observing System Simulation Experiments (OSSEs) represent an objective method that can be used to evaluate improvements to observing skill due to additional or altered observing system configurations. Where feasible, OSSEs should be devised for coastal waters to guide OA observing asset deployment. Ideally, achieving the physiochemical requirements should be done in partnership with IOOS RA's through enhancing the capabilities of existing autonomous analytical systems, by promoting an increase in the number and distribution of time-series stations as dictated by OSSEs findings where appropriate, and be coordinated with repeat surveys and underway measurements in coastal regions. Unfortunately, the biogeochemical coastal models which could provide underlying structure for an OSSE have not been resolved to the scale that would be helpful for coastal deployments yet.

5.4 Coordinate Physiochemical and Ecological Monitoring

The physiochemical observing assets should be aligned to leverage existing ecological monitoring efforts (Figure 3). NOAA has several long-term ecological monitoring programs, some associated with protected resources, such as the National Estuarine Research Reserves and the National Marine Sanctuaries. The NOAA Marine Fisheries Service has several long term biological monitoring transects (SEAMAP, CALCOFI) which could serve as good locations for in situ OA observing. In fact, the California Current Ecosystem 1 and 2 moorings are located on the CalCofi line 80 for this reason.

Many IOOS and academic partners working to maintain the NOAA coastal OA observing array frequently monitor a number of key ecological measures (e.g chl, species abundance, larval status). In addition, bio-optical instrumentation can be better used to assay ecological conditions on cruises and autonomously (e.g. spectral absorption contains info on species composition).

The NOAA Coral Reef Conservation Program (CRCP) is establishing ecological monitoring across U.S. jurisdictions to measure key biological coral which can be aligned with physiochemical OA monitoring at selected stations.

Figure 4: A fully realized integrated coastal ocean *acidification observing system (ICOAOS) should be comprised of e a suite of physiochemical and ecological measures. Shown are examples including a MAPCO$_2$ buoy (upper left), discrete carbonate chemistry sampling (upper right), a Coral Reef Oxygen Sensor System designed to measure benthic boundary layer net community productivity (lower left), CCA calcification and accretion plate (lower right).*

6. CONCLUSIONS

Although this vision for ICOAOS is primarily focused on a partnership between the NOAA Ocean Acidification Program (and its relevant components including academic partners) and the regional associations of IOOS, it is important to note that the partnerships will extend well beyond these two. Given the relatively recent onset of concern about OA, organizing efforts for coastal management are just beginning. This framework for an integrated OA observing system must remain flexible and highly leveraged (due to limited funding) to achieve its overarching mission.

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