xFOCE: An Open Source, Multi-disciplinary Resource for in-Situ Ocean Acidification Research

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Abstract - The open source Free Ocean CO_2 Enrichment (xFOCE) technology is a resource to enable the oceanographic community to study the long-term impacts of rising levels of CO_2 *in the world's ocean environment.*

The issue of worldwide ocean acidification (OA) is a well-established fact. The impact of this change on the organisms and ecosystem of the ocean is not well understood, and has become a focal point for scientific inquiry. Meanwhile OA research is transitioning from laboratory experiments to in situ experiments. The Monterey Bay Aquarium Research Institute (MBARI) has been at the forefront of in-situ OA research through the use of the Free Ocean CO_2 Enrichment (FOCE) concept.

FOCE uses fundamental concepts in OA research to conduct in-situ research in a stabilized, long term, user-defined pH environment. Stemming from its experience, MBARI has taken the initiative to develop xFOCE. The "x" in xFOCE denotes the multi-disciplinary nature of OA research, and refers to the many and varied environments for experimentation.

xFOCE is intended to provide the OA community with resources to help address their specific needs. Economic realities have resulted in stiff competition for funding to conduct ocean acidification research and xFOCE helps by providing a free reference design, community advice and cost saving information. The expectation is that xFOCE will be a long-term repository of FOCE information for OA research.

The xFOCE website is a community-driven repository for information such as suitable materials, experiment chamber fabrication techniques, chamber stabilization, sensor recommendations, software and applications, and numerous other tools to assist researchers with their OA work. Although MBARI is providing the initial framework for xFOCE, the intention is that the OA community will use the open source concept and contribute resources to enrich the OA community.
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Keywords—ocean acidification; FOCE; xFOCE; cpFOCE; dpFOCE; eFOCE; swFOCE; Free Ocean CO_2 Enrichment

I. INTRODUCTION

An increasing awareness of Ocean Acidification (OA) has resulted in a broad international effort to study the biological and ecological impacts of this process. It is a well-observed fact that increasing CO_2 in the atmosphere is reacting with the world's oceans and is reducing the oceanic pH. However, the cumulative long and short-term effects on marine plants and animals are not entirely understood. Since 1999, the Monterey Bay Aquarium Research Institute (MBARI) has conducted a variety of in-situ chemistry experiments related to the projected effects of OA [1]. From this research a new series of experiments was started in 2003 that is identified by the acronym FOCE: "Free Ocean CO_2 Enrichment". The FOCE experiments are conducted in-situ with the intent of achieving a long-term stabilized user defined CO_2 enriched environment with minimal impact on other environmental parameters.

FOCE is modeled after a terrestrial research program that used an extensive number of large-scale multi-disciplinary CO_2 experiments. These Free Air CO_2 Enrichment (FACE) [2] experiments were carried out routinely over the last two decades. Since CO_2 has no chemical reaction in air, only mixing it into the air was required to perform these experiments. The rates of CO_2 release were controlled depending solely on wind speed and turbulent mixing. The FOCE system concept is in part based upon the success of the FACE systems. The notable difference between FACE and FOCE is that the oceanic FOCE concept must address the slow kinetic rates of pH change in seawater (rates dependent upon temperature and pressure) as well as the closed loop control variables of current velocities, mixing dynamics and pH.

MBARI engineers built a prototype FOCE device early in this research to attain important information regarding in-situ control in as short a time frame as possible. The team quickly discovered that there was a need to have accurate measurements of temperature, pressure, and the other issues relating to carbonate chemistry if proper control of CO_2 enrichment was to be accomplished.

II. xFOCE CHEMISTRY BASICS

CO_2 chemistry in seawater is complex with reaction kinetics significantly slowed by cold temperatures. It is also highly dependent on the original fluid pH values. The net result of adding a small quantity of CO_2 to seawater is to reduce the concentration of dissolved carbonate ion, and an increase in bicarbonate ion through the following reaction:

$$CO_2 + H_2O + CO_3^{2-} \rightarrow 2HCO_3- \qquad (1)$$

In practice the reaction between CO_2 and H_2O is a complex function of temperature, pH, and TCO_2, with the reaction proceeding more rapidly at lower pH and higher temperatures. The early experiments at MBARI confirmed that the Zeebe and Wolf-Gladrow [3] model of carbonate chemistry should be followed for accurate function and a thorough understanding of this chemistry is essential to any FOCE system design [4].

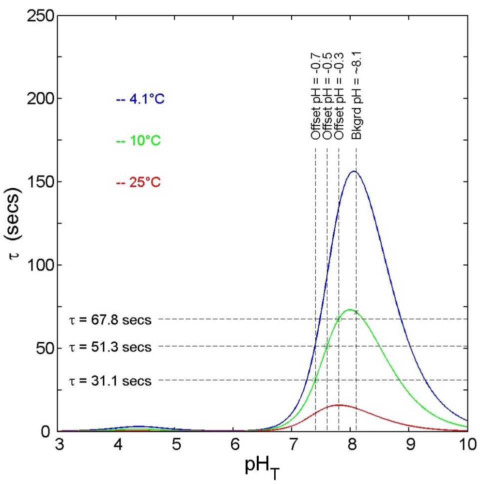

Figure 1: The calculated relaxation time versus pH for three different temperatures.

The Zeebe and Wolf-Gladrow model yields the resulting curves that give us the e-folding time tau (τ) for carbonate chemistry is shown in figure 1. One tau (τ) represents a 63% complete reaction, two tau (2τ) gives us an 86% complete reaction and three tau (3τ) is considered a complete reaction at 95%. Working in very cold waters with a background pH close to 8.0, as is the case with many places around the world's oceans, means a very long time for the carbonate chemistry to come to equilibrium and resulting pH change. Alternatively the graph shows us that in warmer waters, common around coral reefs, the timing can be very short. When working with CO_2 and implementing OA experiments it is important to keep in mind that the kinetics are site specific variables that must be addressed to properly implement an xFOCE type system.

III. xFOCE Implementations

MBARI's FOCE platform experience began with the prototype we refer to as protoFOCE (Fig.2). This experiment used hydrochloric acid to create the CO_2 kinetics (instead of liquid CO_2) as a quick way to get into the water and determine what parameters would be needed for a closed loop controlled pH system. The experiment used a 2-meter circular frame for injection and the delay of 0.5 meters for a control volume of 1 meter across in the center. The information gained through this first iteration has proven extremely useful in building the subsequent FOCE units. Foremost among the issues was the need to provide an additional time delay for chemical stability of the enriched seawater to occur prior to entering the controlled experiment.

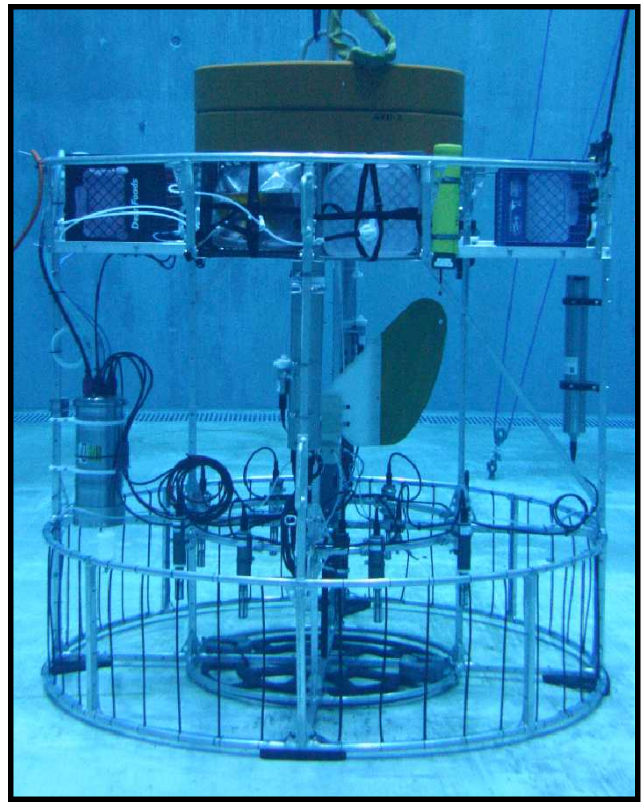

Figure 2: Proto FOCE in the test tank at MBARI
Image courtesy of Todd Walsh © MBARI 2005

A. dpFOCE

The information gained with the protoFOCE was incorporated into a 900-meter depth project designated dpFOCE (Deep FOCE). The dpFOCE project (Fig. 3) uses a flue concept for maintaining greater control over the experiment volume while still permitting the introduction of natural seafloor sediments, organic material, and nutrients. The incorporation of two time delay wings accommodates

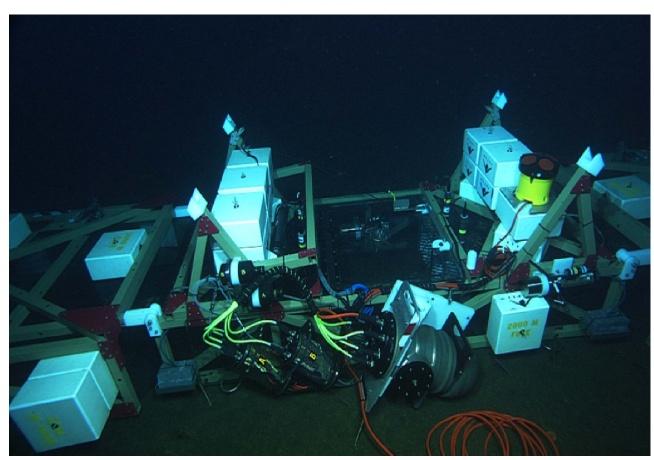

Figure 3: dpFOCE deployed at the Monterey Accelerated Research Site (MARS) in the Monterey Bay

tidal changes and allows for nearly complete chemical reaction of the CO_2 enriched seawater to take place before entering into the experiment chamber. Fans are integrated into the design to control and simulate regional and tidal conditions and their impact [5]. Multiple sensors (pH, CTD, ADV, and ADCP) used in conjunction with the fans and the metered addition of enriched seawater allow the control loop software to achieve the desired pH setpoint. The dpFOCE system operated over 17 months and verified the effectiveness of the design hardware and software.

B. cpFOCE

International interest in the FOCE concept started with researchers from the University of Queensland in Australia looking to perform OA respiration experiments on coral at their Heron Island facility on the Great Barrier Reef. The Coral Prototype FOCE (cpFOCE), Fig. 4, was comprised of four plastic flumes, each about one meter long. Three of the flumes had the internal pH modified to specific levels and the third was used as a regional environmental control operating in parallel. The Australian researchers worked closely with MBARI engineers to develop the cpFOCE system for use on coral reefs. The chamber also incorporated features to permit short periods of closure in order to evaluate the carbonate chemistry of the reef and to measure oxygen levels. These data are crucial for determining rate of calcium growth or dissolution occurring on the reef [6,7].

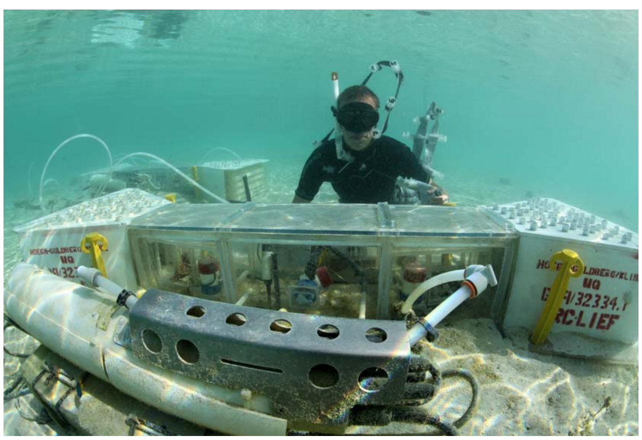

Figure 4: The cpFOCE as deployed at Heron Island

C. eFOCE

The European FOCE (eFOCE) is a project developed to investigate the in situ long-term effects of acidification on benthic marine communities. eFOCE is being constructed to specifically study the effects of OA on a sea grass called Posidonia in the Mediterranean. The installation is located off the shore of Villefranche su Mer in the southern part of France and is being led by the Université Pierre et Marie Curie - Observatoire Océanologique de Villefranche-sur-Mer. The aim of the project is to develop long (> 6 month) experiments in the sea grass beds. The experiment chamber (Shown prior to installation in Fig. 5) receives power from wind and solar sources that are placed on a moored surface expression.

Figure 5: eFOCE engineering test at Villefranche su Mer

IV. xFOCE System Design

Although the current number of FOCE units is still small we are seeing two concurrent trends. First, the interest in FOCE systems is increasing and the percentage of proposals being funded is high. Secondly, the locations are highly varied and each site selection brings with it new challenges. The eFOCE is situated in an area with heavy recreational and commercial. The cpFOCE had extreme current regimes and intense bio-fouling issues. A forthcoming Antarctic FOCE (antFOCE) has recently been funded and will demonstrate that it is possible to place an OA experimental system under the ice. In order to assist the OA community of researchers, MBARI is coalescing their experiences and design information into an on-line resource called xFOCE [8].

One of the greatest challenges that researchers face in conducting in situ OA experiments is to understand a broad set of technical tradeoffs. These are required to adapt experiments for a particular environment. Making these decisions requires expertise and experience spanning several technical and scientific domains. The core objective of xFOCE is to encapsulate the necessary expertise and provide a set of fundamental building blocks for the science user. A number of key factors determine the xFOCE building blocks that comprise a specific OA experimental configuration.

A. Cost of Replicates

Researchers require cost-effective methods to conduct experiments that provide answers to their questions. These methods must be executed in a manner suitable for multi-disciplinary peer-reviewed publication. For example, different scientific disciplines require different numbers of replicates to generate statistically acceptable experimental outcomes. An ocean chemist may need only one or two chambers, a biologist may need six or eight. Therefore, xFOCE aims to provide a cost effective means of conducting in-situ OA research.

B. Diversity of Experiment Sites and Designs

The environmental and logistical features of potential experiment sites introduce challenges to configuring a FOCE experiment. The availability of energy, sources of CO_2, experiment chamber size, and regional seafloor topography are the primary factors that determine the final implementation. Furthermore, the duration of an experiment also has a significant impact on logistics and the associated costs. Taken together, these factors impact maintenance, experimental robustness, and tolerance to potential problems.

C. Technical / Engineering

It is not typically feasible for an OA researcher to hire a team of engineers. It is often the case that a researcher's core team will consist of post-doctorate and graduate students, and perhaps a person with a broad technical background.

The skills needed to successfully execute an xFOCE experiment depend upon its specific configuration and complexity. The researcher would likely need additional expertise from several technical disciplines, such as electro-mechanical design and software engineering.

One of the objectives of the xFOCE concept is to emulate what the community of open source software programmers have recently demonstrated. Enabling users to connect with each other is an effective and economical model for extending users' network of technical support.

D. Reference Designs

Developing new systems for in-situ experiments can be expensive, and requires time and expertise to develop. xFOCE provides reference designs at no cost to enable users to develop a simple application fairly quickly, and to refine them as research questions evolve.

Typical basic concepts of operation include stand-alone moored systems for remote sites (which may or may not have a surface expression), cabled configurations, and hybrids (Fig. 6). Within these basic topologies, there are many potential variants, differing primarily in the capacity and degree of connectivity to shore.

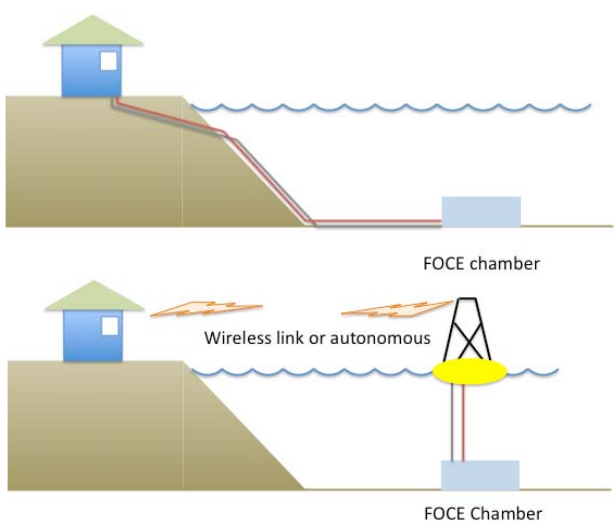

Figure 6: Cabled (top) and moored FOCE configurations

The central concepts of xFOCE reference designs include modularity, robustness, ease of use, and adaptability. While it isn't possible to build a single solution suited to every possible FOCE experiment, our goal has been to provide some fundamental building blocks (Fig. 7) that are easily used and modified to suit many configurations.

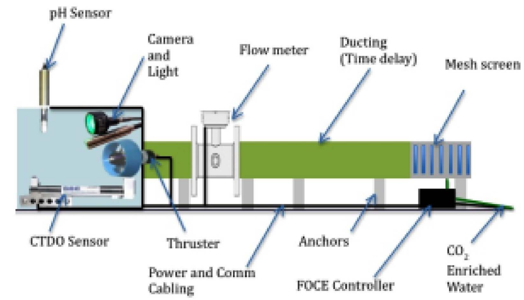

Figure 7: An xFOCE conceptual drawing

We are initiating a repository of reference designs, based on the shallow water FOCE (swFOCE), designed specifically as an implementation of xFOCE. Designs will include a system for delivering CO_2 enriched seawater (ESW), a modular experimental chamber and anchoring system, a power distribution system for a cabled observatory, and electronics and software for collecting data and controlling a FOCE experiment.

V. swFOCE as an Application of xFOCE

Working with Stanford's Hopkins Marine Station (HMS) and the Center for Ocean Solutions (COS), MBARI is designing a new FOCE experiment designated swFOCE (Shallow Water FOCE). swFOCE will be a multi-year, multi-institution operation, having a sophisticated infrastructure for data telemetry, power distribution, and future expansion. This system will be the first implementation of the xFOCE concept. Designs will include a system for delivering CO_2 enriched seawater (ESW), a modular experimental chamber and anchoring system, a power distribution system for a cabled observatory, and electronics and software for collecting data and controlling a FOCE experiment.

A. swFOCE System Overview

The swFOCE system will look at the effects of OA on a number of regional flora and fauna. The system will use a shore side station for control and creating the enriched seawater and will use the existing HMS cabled Kelp Forest Array (KFA) to connect the swFOCE main node in a depth of 15 m of water about 300 m offshore. The node will provide real-time monitoring capabilities for currents, temperature, pH, and O_2, as a cabled observatory platform for scientific research.

The shore-side building will house the operational control hardware for the observatory. The building is also used by HMS as a pump house, and offers a suitable seawater source preparing and supplying enriched seawater for ongoing experiments. A 1500 liters enriched seawater (ESW) mixing tank will be used to mix the CO_2 and seawater in the pumphouse. The tank volume is large enough to permit mixing plus have a supply surplus for delivery to the experiment site. The water will be delivered to the offshore experiments through a buried hose.

Although the primary purpose of the proposed system is to investigate the effects of OA, it should be noted that OA is not occurring in isolation, but changes in climate and hypoxia (reduction in dissolved oxygen levels) are occurring simultaneously. The swFOCE system will be capable of simple modification for experimental studies of hypoxia by lowering levels of oxygen in the working fluid.

B. swFOCE Science Experiments

swFOCE will be installed in late summer or early fall of 2013, and will support a variety of science experiments involving collaborators from the sponsoring institutions. Initial studies will focus on the effects of ocean acidification on larval settlement and recruitment of barnacles, as well as the role of OA in mediating interactions between newly settled barnacle juveniles and their potential predators and competitors.

Thus, FOCE technology will help identify the role of ocean acidification in shaping not only the performance of individual species (e.g. growth, behavior, survival, reproduction), but also the strength of biological interactions among species.

C. xFOCE Designs for swFOCE

The swFOCE design aims to be highly extensible by using designs that are modular, simple, and freely available. swFOCE is also addressing the demanding issue of working in an area which experiences near continuous wave action and strong winter storms. This near shore, highly energetic environment requires not only anchoring, but also employs techniques to prevent the undercutting of the platform due to sand scouring. Other challenges include bio-fouling remediation both on the chamber and the sensors, materials compatibility for PAR, and diver serviceability.

The technology being used for swFOCE has been developed by MBARI specifically as a reference implementation to prove the xFOCE concept. The designs will form the basis of the xFOCE community technical repository. Some of the key components are described in table 1.

FOCE chambers	• Modular, scalable design • Diver serviceable • Deploy, replace, recover with small boat
ESW management system	• Uses bottled CO_2 supply • Inexpensive COTS components
Power distribution system	• 2 kW @ 300V input, 48V output • Gigabit Ethernet • Custom electronics and housings
Gateway node hardware	• Beaglebone processor • Open source custom carrier card may be distributed by low volume open hardware house (e.g. Sparkfun)
Gateway software	• Data collection and management, process control • Written in C • Open source code and development tools
Sensor node hardware	• Serial IO expansion for gateway node • Open source C firmware • Open source custom hardware may be distributed by low volume open hardware house (e.g. Sparkfun)

Table 1: xFOCE key components

D. xFOCE Website

In addition to technology reference designs, xFOCE aims to enable OA research with a library of FOCE-related technical publications, links, tools, and for a community of experienced users to form a network of technical support.

Through its website, xFOCE plans to host a series of publications (and links to publications) covering a range of topics to guide users through the process of designing FOCE experiments. These resources will be valuable to scientists and technical staff who plan to conduct a FOCE experiment: where to begin, what resources may be required and strategies for implementation [9].

Whitepapers, articles, engineering application notes and other content contributed by the xFOCE community can cover relevant topics with the depth and specificity needed to develop new OA experiments and properly estimate new proposal funding. Topics ranging from materials, chemistry, fabrication techniques, and sensor selection to budgeting, logistics, permitting strategies and experiment design will be of interest to anyone considering conducting in situ OA experiments. Scientific data resulting from the experiments will be published elsewhere.

VI. Conclusions

In order to design their own in-situ OA experiments and implement them efficiently, researchers need to understand how different implementation strategies will impact their experiment, and how to minimize technology development effort. Fundamental technical building blocks are needed, designed and packaged in a way that makes them easy to use, and easy to adapt to build new applications.

MBARI is working with our collaborators to advance OA research by building a user community around xFOCE. We have implemented a community web site and are working with the Center for Ocean Solutions to host the web site. We expect that thiss will be a useful tool for OA researchers interested in doing field studies and are trying to quickly advance their work (http://www.xfoce.org).

Once completed, the full set of swFOCE technology reference designs will be made available to the xFOCE community. The designs include the source code, detailed mechanical and electrical designs, vendor lists, and all the analyses we used to make our selections. We are including the software tools used for estimating a CO_2 budget as well as the expected enriched seawater pH level that can be achieved in a given atmospheric condition.

The FOCE concept has already been broadly adopted. There are a number of FOCE experiments currently on-going or in development that establish the technology as an accepted method to perform in situ OA research.

The xFOCE community is a place for information, technology, and news that OA researchers can use for successful in-situ OA experiments. It was built for OA researchers around the globe. The next phase is to let the global OA researchers form a base of contributing members who will constitute the core community that carries in-situ OA science forward. We hope and expect that properly conducted OA experiments, using FOCE methods and technology, will be a useful resource for local policy makers, international governments, and citizens who are concerned about our changing planet.

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