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Is there a CO_2 tipping point for coral reefs?

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Only one coral reef in the entire Galápagos Archipelago has recovered and persisted after El Niño Southern Oscillation (ENSO) warming caused large-scale coral bleaching and mortality in 1982-1983 (*1*). This reef occurs where pH > 8.0 and aragonite saturation state (Ω_{arag}) > 3. Coral reefs that were located where pH < 8.0 and Ω_{arag} < 3 were completely lost within approximately 10 years of this warming event and have not exhibited any recovery (Figs. 1a and 1b). These results suggest that *Porites* reefs can rebound from significant warming (+3-4°C for > 2 months), but only at acidification levels of pH > 8.0. On the other side of the Pacific, in Palau, high coral cover (Fig. 2) and *Porites* calcification rates are maintained under chronically high temperatures (~30°C), across a natural gradient in pH (average pH = 7.8-8.1) and Ω_{arag} (average Ω_{arag} = 2.3-3.7) (*2*).

The CO_2 tipping point in Galápagos, where reefs are lost, generally agrees with initial observations that present-day reefs rarely occur in regions where open ocean surface water Ω_{arag} < 3. However, field evidence from other naturally high CO_2 sites have shown reef persistence at higher levels of acidification. At the volcanic CO_2 seeps in Papua New Guinea (PNG), Fabricius et al. (*3*) reported the loss of reef framework structures at a pH of ~7.7. In Palau, reefs with high coral cover and diversity exist at Ω_{arag} < 2.7 (*2*). Among the naturally high-CO_2 reef sites currently identified, Palau is unique in supporting high coral cover, diversity, and *Porites* calcification rates at Ω_{arag} < 2.7.

What is causing these differences between naturally high CO_2 coral reef sites? Is the threshold concept not applicable to ocean acidification? Manzello et al. (*1*)

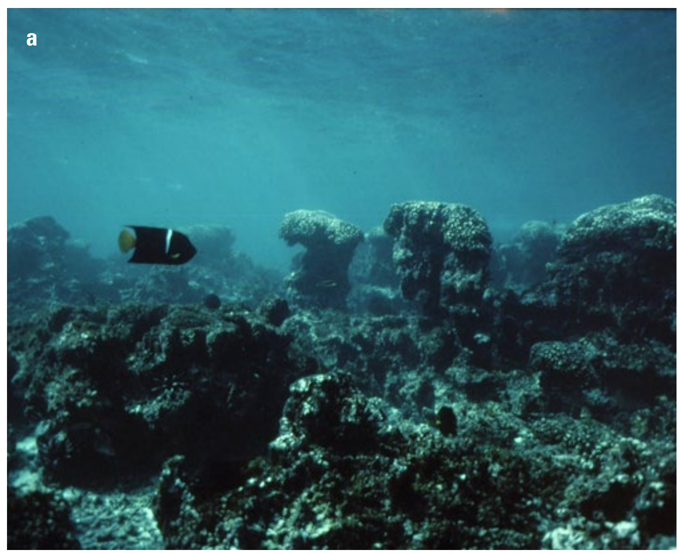

Figure 1. Devil's Crown coral reef in the Galapagos in **a.**1976 (photo credit: Peter Glynn) and **b.** 2012 (photo credit: Derek Manzello)

proposed the following hypotheses to explain why the acidification threshold in Galápagos is higher than these other sites:

1. Coral communities in PNG and Palau have not experienced the extent of thermal stress and coral mortality that Galápagos has: 95-97% mortality due to +3-4°C of warming for > 2 months during the 1982-83 and 1997-98 ENSO events. Warm-water thermal stress and bleaching mortality have been considerably less in both PNG and Palau (< +2°C thermal anomaly). Coral bleaching and mortality directly reduce $CaCO_3$ production, affecting framework production and persistence
2. Bioerosion rates are stimulated by high nutrients and high CO_2 in the Galápagos and other Pacific reefs (*4*), with the Galápagos having the highest rates ever documented
3. Warmer temperatures in PNG and Palau allow more rapid calcification, even with low pH
4. Corals recruit to the low-pH areas in PNG at higher rates than Galápagos because they come from nearby, non-acidified areas. However, Palau's low pH reefs occur within bays and inlets that are somewhat isolated from nearby high pH reefs and most coral recruitment to low pH sites probably occurs from within low pH waters. In addition, unlike the other naturally high CO_2 sites that experience large fluctuations in pH levels seasonally or on shorter time scales, Palau's reefs experience relatively stable low pH conditions over short (tidal, diel) and long (seasonal, annual) time scales. These factors may contribute to Palau's reefs maintaining high coral cover, diversity, and calcification rates under low pH conditions.

These results collectively suggest that if a CO_2 tipping point for coral reefs does exist, it may not be absolute and can be modified significantly by other factors. Heat stress and coral bleaching mortality, in particular, seem to be a vital determinant. Bleaching has increased significantly across the globe over the past several decades due to warming and is only expected to get worse over this century. One thing is clear, the recent Galápagos study provides a clear recipe for the complete elimination of coral reefs: 1) +3-4°C warming, 2) acidification levels expected for the rest of the tropical surface ocean with a doubling of atmospheric CO_2, and 3) elevated nutrients. In the absence of CO_2 emission reductions or unforeseen rapid coral adaptation/acclimatization, the warming and acidification that eliminated coral reefs from the Galápagos Islands will occur for nearly all reefs by midcentury. Palau's high-CO_2 reefs developed over thousands of years and coral reefs globally will experience similar levels of acidification by the end of the century. Even if coral adaptation or acclimatization to acidification is possible, it is likely that there is insufficient time for this to occur for many reefs. In addition, the recent history of Galápagos coral reefs provides field evidence that reefs exposed to elevated nutrients may be the most affected and least resilient to changes in climate and ocean chemistry. Comparing the responses of a range of coral reefs exposed to naturally high-CO_2 conditions provides important insights into the factors that determine the sensitivity of individual reefs to climate change.

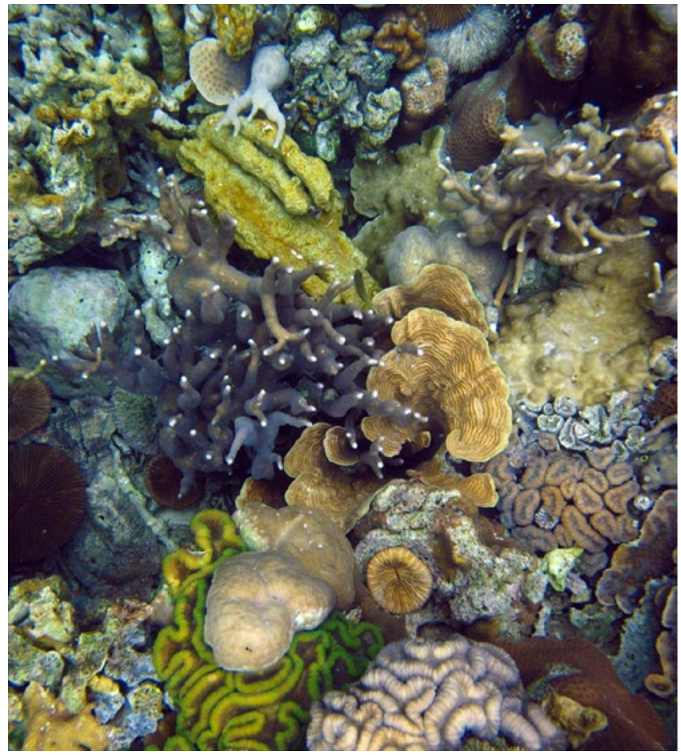

Figure 2. Picture of a Palau reef (Nikko Bay in the Rock Islands) at lowest pH site (photo credit: Kathryn Shamberger).

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Carbonate chemistry co-variation with temperature and oxygen in coastal environments and the design of ecologically relevant ocean acidification experiments

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Introduction

Ocean acidification (OA) is expected to have major impacts on marine ecosystems by directly influencing organismal performance (e.g., growth, development, survival) and indirectly through shifts in food web structure or competitive interactions. Our ability to predict the effects of OA on most species is currently limited but growing, and CO_2 exposure experiments are central to efforts to increase understanding.

Typically, experiments include control conditions that attempt to simulate contemporary or preindustrial seawater CO_2 concentrations and acidified treatments that correspond to potential future CO_2 uptake by the oceans. For studies focused on organisms from low productivity, open-ocean surface waters, researchers can rely on IPCC simulations of future atmospheric CO_2 partial pressure (pCO_2) to identify potential carbonate chemistry treatments because assumptions of air-sea pCO_2 equilibrium are often nearly met (*1*). In contrast, pCO_2 can be far from air-sea equilibrium in many coastal systems, and considerable spatial and temporal variation can exist due to multiple processes, including high rates of primary production and respiration, freshwater inputs, and upwelling (*2, 3*). To estimate the potential impact of OA on organisms from these regions, control pCO_2 levels that reflect contemporary ambient conditions are needed. Recognition of this issue has led researchers to use data from coastal seawater chemistry monitoring programs to inform treatment levels in several recent OA experiments.

Less appreciated from an experimental perspective, however, is the possibility that carbonate chemistry conditions may also naturally co-vary with other biologically relevant variables, including temperature and O_2 (*4*). This may have important implications for the design of appropriate controls and treatments. Organismal physiology and interspecific interactions are strongly influenced by temperature and O_2 and may have non-additive interactions with carbonate chemistry (*5*). Consequently, the

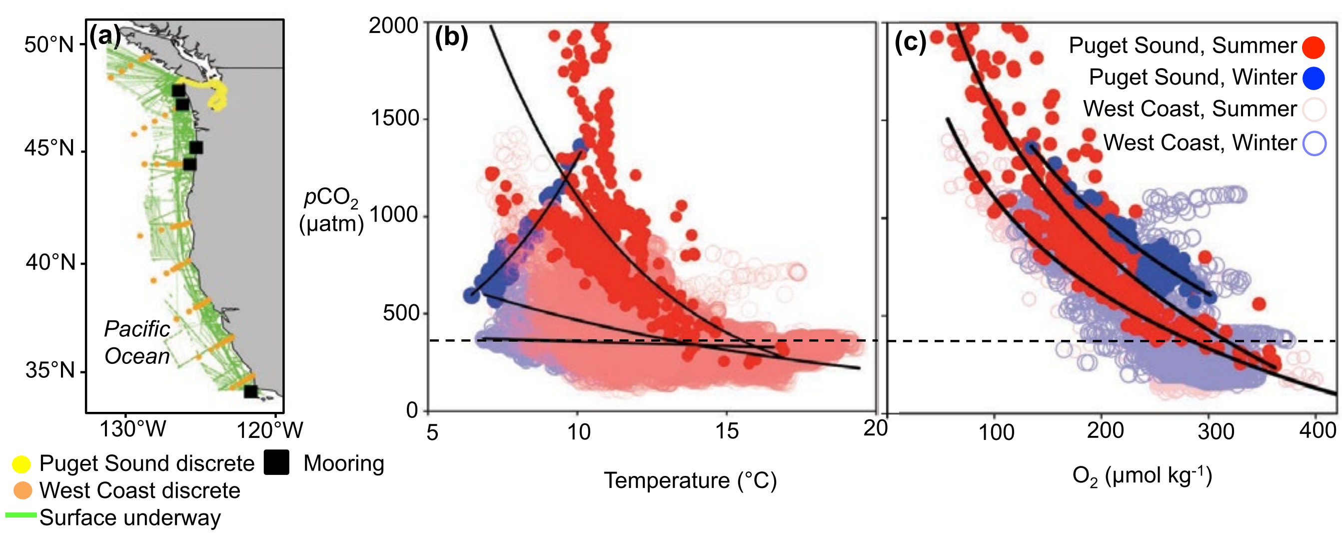

Figure 1. (**a**) Map of coordinates from which environmental carbonate chemistry data were obtained from moorings and ship-based underway and discrete water samples. Relationship between (**b**) pCO_2 and temperature and (**c**) pCO_2 and oxygen (O2) in the CCE during upwelling (summer) and downwelling (winter) oceanographic seasons, respectively. Regression lines are overlaid to aid evaluation of patterns. For reference, approximate present-day pCO_2 levels (~390 µatm) are indicated by the dashed horizontal line. In (a), samples coded as Puget Sound also include measurements from the adjoining Strait of Juan de Fuca. Figures modified from 4.

temperature and O_2 level of seawater used in experiments may influence the estimated effect of OA. A danger is that temperature and O_2 levels that do not normally co-occur might be selected for the control pCO_2 treatment. If the desire is to use experimental results to help draw inferences on the likely future impacts of OA, such controls might provide inaccurate baselines, reducing the relevance of the experiment (*4*). The need for identifying appropriate control conditions also extends to multi-stressor climate change experiments in which temperature, O_2 or other variables might be crossed.

The remainder of this article aims to explore some of the challenges researchers face in designing OA experiments when study organisms come from waters in which carbonate chemistry covaries with other biologically important variables. To illustrate the issues, environmental data were assembled from a variety of habitats in the California Current Ecosystem (CCE), a major eastern boundary upwelling system that supports highly productive food webs. First, seasonal and regional covariation patterns between pCO_2 and temperature and O_2 were identified. Next, experimental conditions from published OA studies from the CCE were placed into an environmental context by comparing them to *in situ* pCO_2 and temperature measurements. Last, the implications of covariation between pCO_2 and temperature for OA experimental design were examined for a specific location on the Oregon coast.

Covariation between pCO_2 and temperature and O_2

Covariation patterns between carbonate chemistry and temperature and O_2 were examined for the region extending from northern Vancouver Island, British Columbia (50°N) to Point Conception, California (34°N; Fig. 1a). The data set included measurements from estuary and open coastal water habitats that extended up to 200 km from the coast and down to 50 m depth. Covariation patterns were examined during the upwelling (May – October) and downwelling (November-April) oceanographic seasons. To assess overall patterns of covariation, data were pooled across habitats, except for data from Puget Sound, which were examined separately. Puget Sound is a large, complex fjord that exhibits slow exchange with open coastal waters, high rates of primary productivity and respiration, and therefore pCO_2-temperature relationships that likely differ substantially from elsewhere in the CCE (6). Full details of the data set are available in 4.

Overall, temperature and pCO_2 values spanned 6 to 19°C and 100 to 1500 µatm, respectively, and covariation patterns between pCO_2 and temperature varied depending in part on season and region (Fig. 1b). In general, pCO_2 values tended to increase with decreasing water temperature during summer upwelling months (Fig. 1b). For Puget Sound, a similar but steeper relationship was apparent relative to the open coastal waters, reflecting CO_2-enriched waters (Fig. 1b). Along the open coast, the range of pCO_2 values was also wider at cool relative to warm temperatures. For instance, pCO_2 values at 9°C ranged from 320 to 1400 µatm, while at 16°C, the range extended from 130 to 420 µatm. In Puget Sound, the pCO_2 range was also wider at cooler temperatures (Figure 1b).

In contrast, during the winter, co-variation between pCO_2 and temperature was weaker in open coastal waters, and the range in pCO_2 values and temperatures narrowed relative to summer (Fig. 1b). This was due to the relative absence of cold, high-pCO_2 upwelled waters. In Puget Sound, winter pCO_2 positively co-varied with temperature, and the range of pCO_2 values and temperatures also narrowed relative to summer (Fig. 1b).

Last, covariation patterns between pCO_2 and O_2 were far more consistent between regions and seasons relative to pCO_2 and temperature (Fig. 1c). Overall, summer O_2 measurements from all locations ranged from 40 to 400 µmol kg^{-1}, where concentrations below ~60 µmol kg^{-1} reflect hypoxic conditions (Fig. 1c). The negative relationship between pCO_2 and O_2 corresponds to the well-understood effects of aerobic respiration and photosynthesis in marine ecosystems. When aerobic respiration dominates, CO_2 is remineralized and O_2 levels are drawn down, while the reverse occurs when photosynthesis dominates.

Environmental pCO_2-temperature vs. experimental conditions

Given covariation patterns in the CCE, how well have experimental conditions from published OA studies matched environmental measurements? To answer this, the literature was reviewed for experiments that included organisms (or broodstock) obtained from habitats within CCE. In total, 26 OA experiments (22 published studies) were found (Fig. 2a; see *4* for details). For nearly all studies, experimental O_2 concentrations were not reported nor could saturation conditions be safely assumed. Comparisons of environmental and experimental conditions therefore focused exclusively on pCO_2 and temperature.

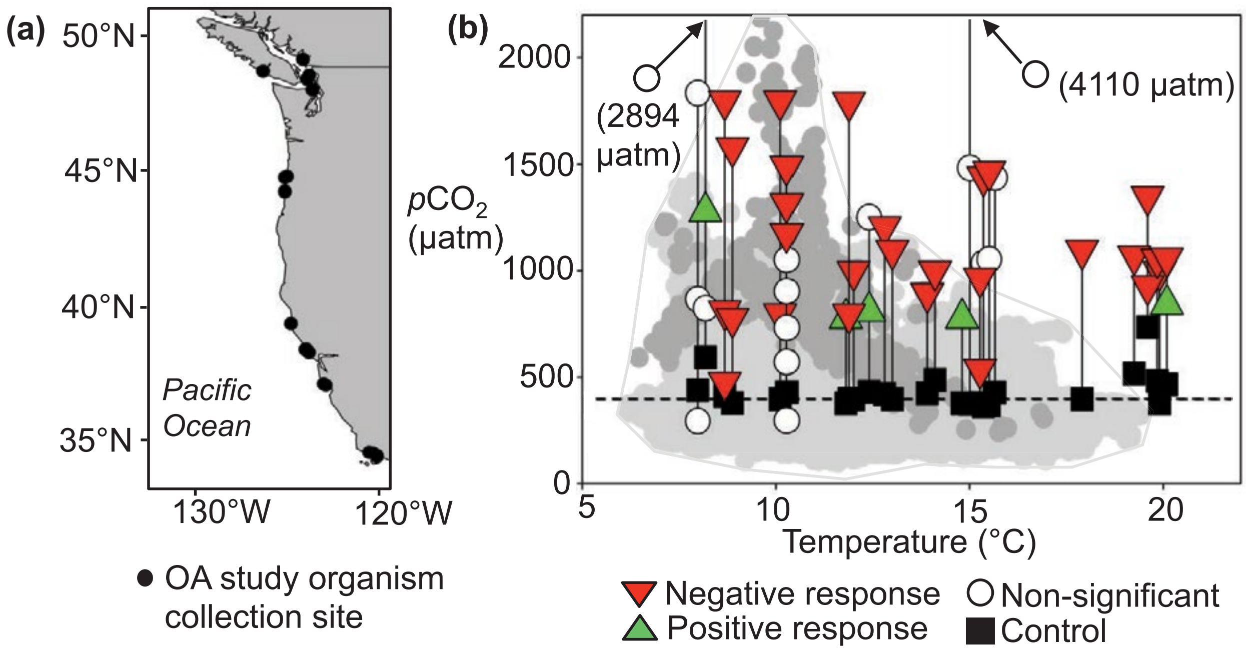

Figure 2. (**a**) Map of locations where organisms (or their broodstock) included in published OA experiments were collected. (**b**) Environmental pCO_2 and temperature measurements for the CCE and conditions maintained in OA experiments performed on organisms from the same region. Dark grey circles correspond to environmental measurements from Puget Sound; light grey circles correspond measurements from all other regions. pCO_2 treatment levels included in in an individual experiment are connected by solid black vertical lines. A convex hull (solid grey line) demarcating the extent of all environmental pCO_2 and temperature measurements is depicted to aid visual comparisons. For reference, approximate present-day atmospheric pCO_2 levels (~390 µatm) are indicated by the dashed horizontal line. Figures modified from 4.

Following the authors' interpretation, any significant biological response to the treatment was noted along with the direction of response (Fig. 2b). If authors did not explicitly designate a control pCO_2 level in their study, treatments levels with pCO_2 levels closest to present-day air pCO_2 levels (~400 µatm) were considered as the control to facilitate comparisons across studies. When more than one response variable was tested in an experiment, the net outcome of the experiment was coded at a given treatment level based on the result of the variable most sensitive to pCO_2.

Compared with the pCO_2-temperature space defined by the complete set of environmental measurements in our dataset, five experiments were performed at temperatures that matched or exceeded the warmest observed values (~19°C; Fig. 2b). These included three experiments on the early life history stages of the native Olympia oyster, an experiment on sand dollar larvae, and an experiment on the non-native Pacific oyster (which is routinely reared at ~20°C to optimize survival under commercial hatchery conditions). One experiment included a 2.1°C treatment; though this temperature was meant to simulate cool conditions in Alaskan waters, the source stock was collected near Puget Sound. Interestingly, several studies observed negative and positive responses in organisms at pCO_2 and temperature values that occur today in the CCE (Fig. 2b).

How did researchers select pCO_2 levels and temperatures for their experiments? In terms of pCO_2 levels, IPCC estimates of future global surface ocean average pCO_2 levels were cited as justification in 45% of studies, while 31% cited a combination of regional modeling studies, local field measurements, and IPCC estimates to support their choice of experimental pCO_2 treatment levels. Of the remaining studies, 13% provided no rationale for their choice of pCO_2 treatment levels, one based the high pCO_2 treatment level on observations of contemporary upwelling conditions, and one noted naturally high carbonate chemistry variability in coastal upwelling systems that necessitated testing of biological responses to a wide range of pCO_2. For temperature, 80% of studies did not provide a rationale at all. The remaining studies cited similarity to local field conditions. Only two studies performed multistressor experiments, both crossing temperature and pCO_2, and no experiments considered temporal variation in carbonate chemistry conditions.

OA experimental designs

To help illustrate the effect covariation has on experimental design, an example multistressor experimental scheme is presented in Fig. 3a that is typical of published OA studies. Three temperature treatments are included (8, 12, and 16°C) and crossed with two pCO_2 levels that correspond to approximate global surface ocean present-day (400 µatm) and future (800 µatm) conditions (Fig. 3a). All treatments are fully orthogonal, which permits estimation of the effect sizes of the individual predictor variables and of their interaction on the response variable. The method holds merit as a tool for comparing the relative influence that each predictor has on the response variable. However, if a goal of a study is to evaluate the potential sensitivity of organisms to future OA, the design may be inadequate, given natural pCO_2-temperature co-variation.

For example, if the study organism occurs in shelf waters off Oregon during summer upwelling months (e.g., a pelagic larval invertebrate), the assumption that 800 µatm corresponds to a future OA prediction across all temperatures is not accurate. At the Newport, Oregon mooring, pCO_2 levels of 800 µatm already occur at 8°C under present-day conditions and control 400 µatm waters do not (Fig. 3a). At temperatures above 13°C, the mean pCO_2 values approach air-sea equilibrium conditions. The experimental design will certainly provide information on the interactive effects of pCO_2 and temperature, but the utility of the design for drawing inferences on the potential response of wild populations to OA in the region is questionable.

Given potential co-variation between carbonate chemistry and other important environmental variables, how might researchers select pCO_2 treatments that better correspond to OA hypotheses? First, researchers should consider inclusion of multiple controls that reflect the span of pCO_2 levels and temperatures likely to be experienced by the organism under study (Fig. 3b). To design pCO_2 treatments that represent future OA scenarios in highly productive regions, researchers might focus on estimating likely changes in the anthropogenic contribution to *in situ* dissolved inorganic carbon (DIC) (*4*). At the Newport, Oregon mooring, newly upwelled waters

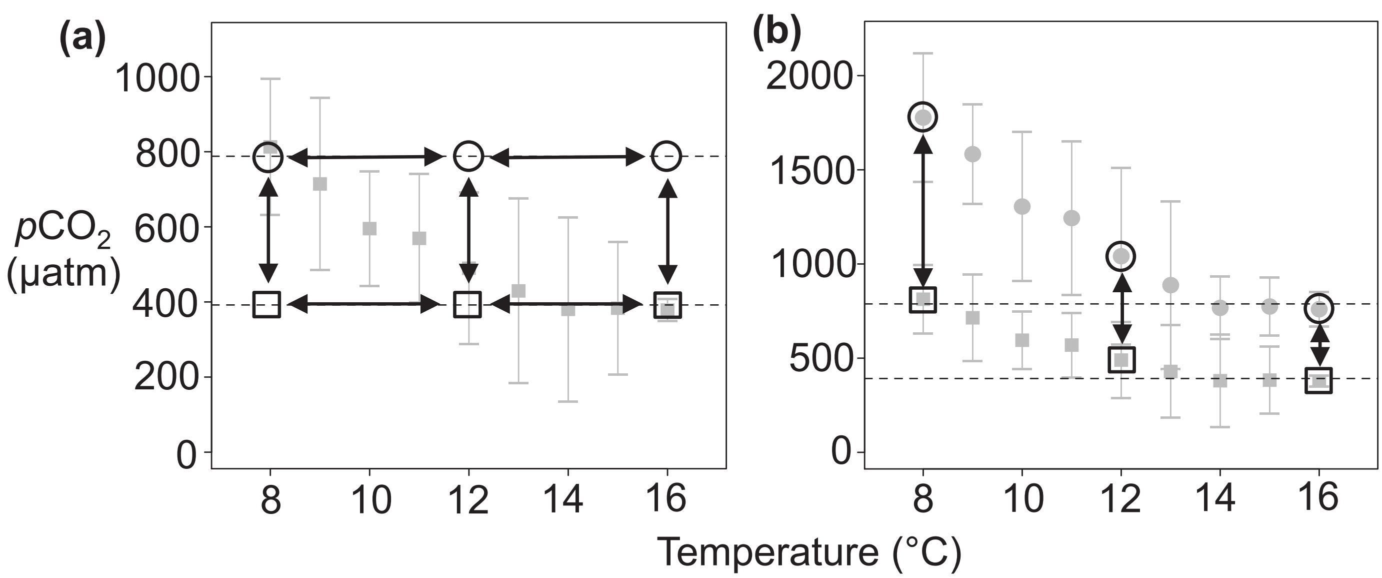

Figure 3. Schematic of potential experimental approaches to evaluate OA effects, given co-variation between pCO_2 and temperature. To illustrate the benefits and drawback of each approach, in situ pCO_2 and temperature measurements from the NH10 mooring near Newport, Oregon during summer upwelling season (2008) are depicted (grey, filled squares; bars indicate standard deviation). (**a**) A conventional temperature (three levels: 8, 12, and 16°C) by pCO_2 experimental design, in which control pCO_2 values are based on approximate present-day global average surface ocean pCO_2 levels and the acidified treatments correspond to IPCC emissions scenario IS92a projections for the year 2100 (390 and 788 µatm; open square and circle symbols, respectively). Arrows indicate statistical comparisons permitted by the design. (**b**) Experimental design informed by in situ pCO_2 and temperature measurements. Under this design, three controls are included to account for natural co-variation in temperature and pCO_2. Treatment levels that more closely correspond to an OA hypothesis were obtained by specifying an increase in DIC attributed to anthropogenic CO_2 emissions (see text and 4 for additional details). The future DIC estimate and estimates of alkalinity were used to recalculate the carbonate system to obtain target pCO_2 treatment levels. Figures modified from 4.

exhibit pCO_2 values that are elevated relative to air-sea equilibrium conditions due to the remineralization of organic material before surfacing (*7*). However, after surfacing, CO_2 concentrations can be drawn down rapidly by photosynthesis (*2, 7*), often at rates that far exceed CO_2 equilibration times across the air-sea interface (e.g., *8, 9*). Consequently, the anthropogenic CO_2 burden of upwelled waters is primarily acquired when they were last in contact with the atmosphere and before DIC changes due to biological processes post-surfacing. In our example, pCO_2 treatments reflecting future OA hypotheses could be obtained by increasing *in situ* DIC concentrations by an increment (ΔDIC) expected under a given CO_2 emissions scenario. The future DIC estimate (ΔDIC + *in situ* DIC), along with a second parameter from the carbonate system, could then be used to recalculate the carbonate system to estimate treatment pCO_2 levels.

Under this approach, and assuming the same number of treatments is used as depicted in Fig. 3a, the effects of temperature and pCO_2 can no longer be separated because orthogonality in the design is lost (Fig. 3b). However, a more realistic set of control treatments are included that offer a firmer basis for drawing inferences about future OA impacts at a given temperature. The experimental design could be improved further by using O_2 concentrations that currently occur at the three different pCO_2-temperature controls.

Summary

The need for OA researchers to use pCO_2 levels that correspond to ambient conditions a study species or life history stage is likely to experience is now widely recognized in the literature, but patterns of co-variation with temperature and O_2 have yet to be incorporated into OA experimental designs. This issue should be of concern to researchers in coastal systems where water conditions are highly dynamic over a range of spatial and temporal scales and where co-variation between pCO_2, temperature, and O_2 are generally expected. Because inferences on the potential response of organisms to future conditions are premised on the notion that experimental controls reflect present-day conditions, we strongly recommend that researchers consider how pCO_2 naturally varies with other biologically important variables in their experimental designs.

Although we focused on pCO_2, the challenges associated with covariation in water conditions also extend to experimental efforts to understand the main and interactive effects of other climate change phenomena, including global warming and ocean deoxygenation. We caution that while simple crossed multistressor experiments can provide information on the interactive effects of variables on organisms in a statistical sense, treatments should be considered and interpreted in light of covariation patterns experienced by organisms over their distribution.

With the continued collection of high-quality carbonate chemistry measurements and their archival on freely accessible databases, analyses like the one we present here for the CCE may yield further insight into the relevance of carbonate chemistry variability to contemporary ecological processes, as well as guide climate change experimental designs in other marine systems.

Acknowledgments. The authors thank all co-authors from the more extended version of this published work. This is PMEL contribution number 4300.

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Important Dates

June 9-11, 2015: 3rd US Ocean Acidification PI Meeting (Woods Hole, MA, NSF-supported OA PIs)

June 12, 2015: NOAA Ocean Acidification PI Meeting (Woods Hole, MA, NOAA-supported OA PIs)

June 22-July 1, 2015: Instrumenting our oceans for better observation: A training course on autonomous biogeochemical sensors (Sven Lovén Center for Marine Sciences, Kristineberg, Sweden)

July 20-23, 2015: OCB Summer Workshop (Woods Hole, MA) - website and registration to open in April

October 5-8, 2015: OCB Scoping Workshop Trait-based Approaches to Ocean Life (Waterville Valley, NH)

Mid-2016: Joint GEOTRACES-OCB Workshop on Micronutrients and Tracers of Carbon Flux (details TBA)

OCB Leadership Changes

OCB is pleased to welcome five new Scientific Steering Committee (SSC) members: Debbie Steinberg (Virginia Institute of Marine Science), Angel White (Oregon State Univ.), Mike Lomas (Bigelow Laboratory), Ben Van Mooy (Woods Hole Oceanographic Institution), Nicole Lovenduski (Univ. Colorado, Boulder).

Many thanks to outgoing SSC members Simone Alin (NOAA/PMEL), Jorge Sarmiento (Princeton Univ.), Barney Balch (Bigelow Laboratory), Sonya Dyhrman (Lamont-Doherty Earth Observatory), and Ricardo Letelier (Oregon State Univ.) for their service and contributions to OCB over the past three years.

Recent Meetings and Activities

Ocean's Carbon and Heat Uptake: Uncertainties and Metrics

A joint US CLIVAR/OCB workshop

December 12-14, 2014 (San Francisco, CA)
By Heather Benway, Mike Patterson, and Kristan Uhlenbrock

For the past two years, OCB and US CLIVAR have been jointly funding two working groups:

> Ocean carbon uptake in the CMIP5 models, the goal of which is to identify common metrics of physical ocean/climate forcing (primarily wind strength, mixed-layer stratification, and ocean mixing), compare metrics in the various models and in the observations for the North Atlantic and the tropical Pacific, and coordinate model evaluation of the climatic influence on CO2 uptake at different time scales.
>
> Southern Ocean carbon and heat uptake, the goal of which is to identify observational targets and develop data/model metrics to improve understanding of the role of winds and ocean physics (mesoscale eddies, stratification, etc.) in the heat and carbon uptake by the Southern Ocean.

The working groups collaborated in organizing a workshop to catalyse progress toward understanding the ocean's role in carbon and heat uptake. The workshop convened scientists from the physical oceanography, climate dynamics, and biogeochemistry communities to strengthen communication and collaboration across disciplinary boundaries, facilitate the exchange of results from recent studies, and discuss the most promising directions for future research. Key scientific foci for this meeting included:

- Oceanic regions critical for heat and carbon uptake (e.g., Southern Ocean, North Atlantic, tropics)
- Processes governing the heat and carbon uptake in these regions and the main challenges of representing these processes in climate models
- Critical observational targets in these regions
- Development of data/model metrics to improve the models and guide future observational campaigns

The workshop featured four plenary sessions, each with a series of talks followed by an open panel discussion, and a set of talks looking at new initiatives:

- *Model Biases and Uncertainties in CMIP5 Models*
- *Observational Gaps and Uncertainties*
- *Process Studies: Gaps, New Measurements, and Parameterizations*
- *Southern Ocean: Circulation and Carbon Cycle* (co-sponsored by the WCRP Polar Climate Predictability Initiative)

A detailed meeting report by the working group chairs summarizing discussions from the workshop is in preparation. In addition, two upcoming issues of OCB and US CLIVAR newsletters will be published jointly, featuring scientific articles relevant to each working group. For more information and/or to view the agenda and talks from the workshop, please visit the workshop website. Other products and outcomes of these two joint working groups will be publicized and distributed broadly via the US CLIVAR and OCB communication outlets.

Ocean Acidification

Studying ocean acidification's effects on marine ecoystems and biogeochemistry

Ocean Acidification News

- Apply to participate in Graduate Student Course: Research Methods in Ocean Acidification (July 20-August 22, 2015, Friday Harbor, WA, USA)
- Ocean Conservancy Blog - Where are the "Hotspots" For Ocean Acidification?
- New legislation, the Ocean Acidification Research Partnership Act, introduced to support research on ocean acidification through partnerships between the seafood industry and the academic community
- Formation of Southeast Ocean and Coastal Acidification Network (SOCAN) to support and encourage discussions on ocean and coastal acidification in the Southeast region (check out SOCAN state-of-the-science webinar series on ocean acidification)
- Open-access data sets of biological response to ocean acidification available at Pangaea (accepting contributions!)
- Recommended new version (3.0.6) of the R package seacarb for calculating seawater carbonate system parameters. Includes useful functions for ocean acidification research
- WMO Greenhouse Gas Bulletin reports on ocean acidification

Community News and Resources

- National Research Council released pre-publication versions of two reports *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration* and *Climate Intervention: Reflecting Sunlight to Cool Earth* (4-page brief available here)
- New NRC report: Decadal Survey of Ocean Sciences
- New L&O e-lecture on the biological pump: Neuer, Susanne, Morten Iversen, and Gerhard Fischer. 2014. The Ocean's Biological Carbon Pump as Part of the Global Carbon Cycle. Limnol. Oceanogr. e-Lectures, doi:10.4319/lol.2014.sneuer.miversen.gfischer.9
- Apply for Thinkable.org $5000 open innovation grant
- Revised North Atlantic-Arctic science plan available on the International North Atlantic-Arctic research planning website
- IMBER Special issue from IMBIZO lll on Biogeochemistry-ecosystem interaction on changing continental margins in the Anthropocene (2015, Journal of Marine Systems, Volume 141)
- IMBER-ADApT Framework: A decision support tool for response to global change in marine systems
- Paul Shrivastava appointed as Future Earth Executive Director
- New Future Earth website
- Future Earth Strategic Research Agenda (2014)
- Alliance for Coastal Technologies looking to stimulate development of low cost, accurate nutrient sensors - For details, see http://www.act-us.info/nutrients-challenge/

Partner Programs

IMBER IMBIZO IV October 26-30, 2015 (Trieste, Italy)

IMBER seeking nominations for new members to serve on its Scientific Steering Committee

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Register and submit abstracts for SOLAS Open Science Conference (September 7-11, 2015, Kiel, Germany, Abstract submissions due May 27, Registration deadline: July 1

SOLAS Science Plan for 2015-2025

SOLAS/CLIVAR session The Earth's energy imbalance and exchanges at the atmosphere-ocean interface: from fundamental research to societal concern at Our Common Future Under Climate Change conference

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Summer Course on biogeochemical sensors: Instrumenting our oceans for better observation (June 22-July 1, 2015, Sven Lovén Center for Marine Sciences, Kristineberg, Sweden)

Survey on the 2014 GEOTRACES Intermediate Data Product to help improve the data product for the next release (2017)

View Winter issue of US CLIVAR newsletter Variations

What's inspiring our next generation of ocean biogeochemists?

By Elisha M. Wood-Charlson, C-MORE

Ocean and phytoplankton health, and playing with cool science tools! Take a moment to sit back and think about what hooked you as a curious young scientist and you have to admit that it was probably something similar. I caught up with a few of our new recruits exploring microbial oceanography through C-MORE (Center for Microbial Oceanography: Research and Education) at the University of Hawaiʻi, Mānoa. Graduate student Chris Schvarcz has worked diligently to purify and culture phytoplankton, mainly with the intent of killing them. He is a marine virologist after all! Kirena Clah, an undergraduate and C-MORE Scholar, is working with Chris and Grieg Steward (Professor in Oceanography at UH Mānoa and a C-MORE founding investigator) to determine what is causing the death of his algal cultures. Kirena's project has focused on one of Chris's most recent algal fatalities. Beyond identifying the culprit, she has set up an experiment to determine if the pathogen is specific to this culture or a general phytoplankton killer, and how it carries out its lethal mission.

Using Koch's postulates, Kirena discovered that the culprit was a bacterium. "This yellow one," she said as she points to a petri dish spotted with white and yellow bacterial colonies. She took filtered lysate from a dying algal culture, plated it to get single colonies, and re-inoculated fresh algal cultures with various concentrations of the white and yellow colonies. "The white ones didn't do anything, at any dilution we tried, but this yellow one did!"

She and Chris will use DNA sequencing to determine what kind of bacterium creates the yellow colonies, but in the meantime, they have identified the host. "It is a *Chaetoceros* diatom," she says, "but we aren't sure if this is the only sensitive algal culture." So, in order to find out, she has been in the lab at 0700 every morning for the past 9 mornings, screening 60+ algal cultures Chris has been busy isolating. She puts the inoculated algal cultures into a plate reader and looks for a decrease in chlorophyll autofluorescence, which indicates an unhealthy culture.

Another young and intrepid C-MORE investigator is Kyla Cantillo, a senior at Kailua High School on O'ahu. Her research curiosity developed during her high school coursework, when she began to realize the effect that rising atmospheric CO_2 is having on our environment. Wanting to understand this topic better, she approached Dan Sadler, a family friend and staff member at C-MORE, with ideas on how to explore the effects of this CO_2 overload on marine organisms. After consultation with Chris, they chose one of his most photogenic phytoplankton cultures, a lovely coccolithophore.

Figure 1. Kirena Clah reading chlorophyll autofluorescence on a plate reader as a measure of algal culture health after inoculating the cultures with the purified bacterium.

With guidance from her C-MORE mentors, Dan, Chris, and Matt Church (Associate Professor in Oceanography at UH Mānoa), Kyla designed and set up growth experiments comparing present day levels of CO_2 (400 ppm) to levels predicted into the future (1000 ppm). She recently presented her research at a district science fair, where she was awarded NOAA's 2015 "Taking the Pulse of the Planet" Award, Windward Rotary Award, the Best in Category (microbiology), and 2nd place overall, as well as a spot in the Hawai'i State Science Fair (late March) and the Intel International Science and Engineering Fair 2015 in Pittsburgh, PA. (Phew, a mouthful of awards!)

So, what's next for both of these projects?

Kirena says, "After this, we want to determine how the bacteria kill the algae. Potentially through physical contact or by releasing a chemical product into the water." Finally, when asked if she had a hypothesis for which mode of killing she thought the algae were up against, she responded, "I hope it is through physical contact because that would make for some really cool SEM pictures."

For Kyla, she has started looking at universities on the mainland to pursue environmental studies and public policy. When asked what she would miss about this project, she also agreed that the SEM was an amazing tool for young scientists to experience. And to her credit, she took some amazing pictures!

It was refreshing to hear the voices of our young scientists, and to know that they are just as excited today by the pursuit of knowledge and the importance of playing with cool science tools, as we were (and still are).

Figure 2. Images of Kyla's algal culture, taken by Kyla on a scanning electron microscope (SEM).

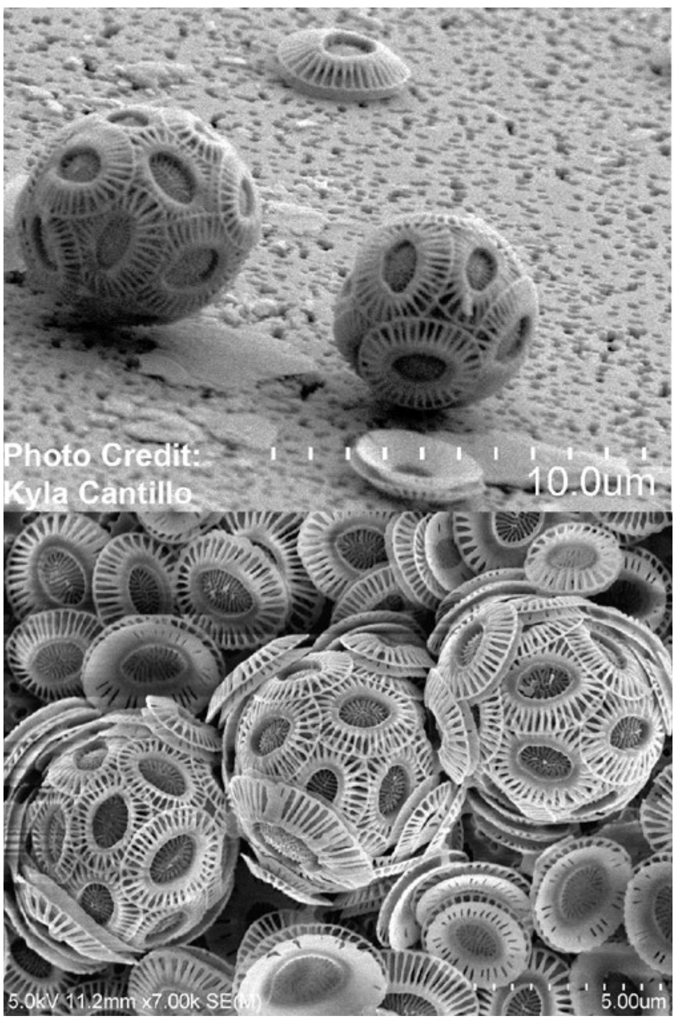
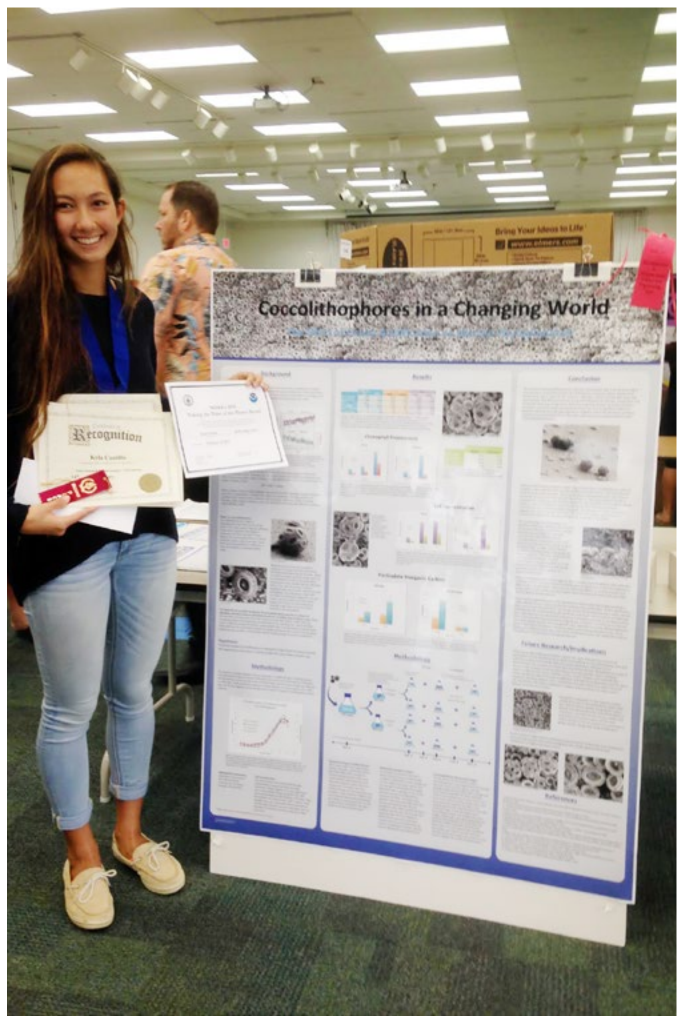


Figure 3. Kyla next to her award winning poster at the district science fair, Windward, O'ahu.



OCB hosts four C-MORE Science Kits in Woods Hole

OCB currently hosts four C-MORE Science Kits: Ocean acidification, marine mystery, and ocean conveyor belt. The ocean acidification kit (two lessons, grades 6-12) familiarizes students with the causes and consequences of ocean acidification. The ocean conveyor belt kit (four lessons, grades 8-12) introduces students to some fundamental concepts in oceanography, including ocean circulation, nutrient cycling, and variations in the chemical, biological, and physical properties of seawater through hands-on and computer-based experiments. With the marine mystery kit (grades 3-8) students learn about the causes of coral reef destruction by assuming various character roles in this marine murder-mystery. The marine debris kit focuses primarily on plastic marine debris. Students critically examine data and samples and take part in activities that explore the causes, geographical distribution, and biological impacts of marine debris. Teachers along the eastern seaboard may use these kits for free. To reserve a kit, please submit a request.

Calendar

Please note that we maintain an up-to-date calendar on the OCB website.
**OCB-led activity **OCB co-sponsorship or travel support*

2015	
March 21-22	Workshop on Effects of climate change on the biologically-driven ocean carbon pumps (Santos, Brazil)
March 23-27	Third International Symposium on Effects of climate change on the world's oceans (Santos, Brazil)
April 7-8	Workshop and Symposium: Organic Ligands – A Key Control on Trace Metal Biogeochemistry in the Ocean (Šibenik, Croatia)
April 12-17	EGU General Assembly (Vienna, Austria)
April 20-24	2015 NASA Carbon Cycle and Ecosystems Joint Science Workshop (College Park, MD)
April 23-30	Arctic Summit Science Week (Toyama, Japan)
May 4-8	47th International Liège Colloquium on Ocean Dynamics Marine Environmental Monitoring, Modeling and Prediction (Liège, Belgium)
May 18-21**	7th International Symposium on Gas Transfer at Water Surfaces (Seattle, WA)
May 26-June 26	C-MORE Summer Course (Honolulu, HI)
May 27-29	2nd Blue Planet Symposium (Cairns, Australia)
June 9-11*	3rd US Ocean Acidification PI Meeting (Woods Hole, MA)
June 12	NOAA Ocean Acidification PI Meeting (Woods Hole, MA)
June 15-17	ESSAS Symposium on the Role of Ice in the Sea (Seattle, WA)
June 16-18	International Ocean Color Science Meeting (San Francisco, CA)

June 22-July 1**	Summer Course on best practices for selected biogeochemical sensors Instrumenting our oceans for better observation (Sven Lovén Center for Marine Sciences in Kristineberg, Sweden)
June 23-25	Atlantic Meridional Transect (AMT) Open Science Conference (Plymouth, UK)
July 6-31**	Ocean Optics Summer Course Calibration & Validation for Ocean Color Remote Sensing (Walpole, ME)
July 7-10	Our Common Future Under Climate Change (Paris, France)
July 20-August 22	Graduate Student Course on Research Methods in Ocean Acidification (Friday Harbor, WA)
July 20-23*	2015 OCB Summer Workshop (Woods Hole, MA)
July 21-24	RAPID/US AMOC International Science Meeting: Towards a holistic picture of the Atlantic Meridional Overturning Circulation (Bristol, UK)
July 25-26	Gordon Research Seminar for students and postdocs (Holderness, NH)
July 26-31	Gordon Conference Chemical Oceanography (Holderness, NH)
August 3-6	2015 US CLIVAR Summit (Tucson, AZ)
August 16-21	25th Goldschmidt Conference (Prague, Czech Republic)
August 31-September 4	Hjort Summer School: Fishing and physics as drivers of marine ecosystem dynamics (Bergen, Norway)
September 7-11	SOLAS Open Science Conference 2015 (Kiel, Germany), Note: Joint Surface Ocean CO2 Atlas (SOCAT) & Surface Ocean pCO2 Mapping Intercomparison (SOCOM) event on September 7
September 14-18	"Sustained ocean observing for the next decade" A combined GO-SHIP/Argo/ IOCCP conference on physical and biogeochemical measurements of the water column (Galway, Ireland)
September 14-18	3rd CLIOTOP Symposium - Future of oceanic animals in a changing ocean (San Sebastián, Spain)
September 21-25	2015 ICES Annual Science Conference (Copenhagen, Denmark)
October 4-9	19th International Congress on Nitrogen Fixation (Pacific Grove, CA)
October 5-8*	OCB Scoping Workshop Trait-based Approaches to Ocean Life (Waterville Valley, NH)
October 5-9	9th Symposium of the International Society for Digital Earth (ISDE) "Towards a One-World Vision for the Blue Planet" (Halifax, Canada)
October 26-30	IMBER IMBIZO IV - Marine and human systems Addressing multiple scales and multiple stressors (Trieste, Italy)
November 30-December 4	Indian Ocean Symposium (Goa, India)
December 9-11	Atlantic Summit – Workshop on the Atlantic Ecosystem Model (Honolulu, HI)
August 20-25, 2017	10th International Carbon Dioxide Conference (Interlaken, Switzerland)

Upcoming Funding Opportunities

For more information, please visit OCB's funding opportunities web page. The OCB calendar also lists upcoming deadlines.

Rolling submission: NSF Research Coordination Networks (RCN)

2015	
June 3	NASA ROSES 2015 Advancing Collaborative Connections for Earth System Science proposal deadline (NOIs due April 3)
June 15	SCOR Working Group proposal deadline
August 15	NSF Chemical Oceanography and Biological Oceanography proposal targets
September 8	NASA ROSES 2015 Satellite Calibration Inconsistency Studies proposal deadline (NOIs due July 15)
October 2	NSF Coastal SEES proposal deadline
October 19	NSF Arctic Research Opportunities proposal deadline
November 17	NSF Dynamics of Coupled Natural and Human Systems (CNH) proposal deadline
February 15, 2016	NSF Ocean Technology and Interdisciplinary Coordination, Chemical Oceanography, and Biological Oceanography proposal deadlines

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