Results from OA/feeding experiment: carbonate chemistry and coral skeletal weight, symbiont density, and total tissue lipid content of samples collected from northwestern Bermuda patch reefs; 2010

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Project

» An Investigation of the Role of Nutrition in the Coral Calcification Response to Ocean Acidification (OA Nutrition and Coral Calcification)

Programs

» Science, Engineering and Education for Sustainability NSF-Wide Investment (SEES): Ocean Acidification (formerly CRI-OA) (SEES-OA)
» Ocean Carbon and Biogeochemistry (OCB)

Contributors	Affiliation	Role
Cohen, Anne L	Woods Hole Oceanographic Institution (WHOI BCO-DMO)	Lead Principal Investigator
de Putron, Samantha J.	Bermuda Institute of Ocean Sciences (BIOS)	Co-Principal Investigator
McCorkle, Daniel C	Woods Hole Oceanographic Institution (WHOI)	Co-Principal Investigator
Tarrant, Ann M.	Woods Hole Oceanographic Institution (WHOI)	Co-Principal Investigator
Drenkard, Elizabeth	Woods Hole Oceanographic Institution (WHOI)	Contact
Rauch, Shannon	Woods Hole Oceanographic Institution (WHOI BCO-DMO)	BCO-DMO Data Manager

Abstract

Results from OA/feeding experiment: carbonate chemistry and coral skeletal weight, symbiont density, and total tissue lipid content of samples collected from northwestern Bermuda patch

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Dataset Description

Data from an experiment conducted at the Bermuda Institute of Ocean Sciences (BIOS) in St. George, Bermuda. Pregnant adult corals were collected from the northwestern Bermuda patch reefs in the area of Bailey's Bay; adult corals were returned to their resident reefs following larval collection. Results of this experiment were analyzed at the Woods Hole Oceanographic Institution in Woods Hole, MA.

Related Publications:
Drenkard E. J., Cohen A. L., McCorkle D. C., de Putron S. J., Starczak V. R. & Zicht A. E., 2013. Calcification by juvenile corals under heterotrophy and elevated CO2. *Coral Reefs*, 32, 727-735. doi: 10.1007/s00338-013-1021-5

Acquisition Description

Experimental setup and conditions
This experiment was conducted at the Bermuda Institute of Ocean Sciences (BIOS) in St. George's, Bermuda. The experimental treatments were two CO2 levels (high and ambient) and two feeding conditions (fed and unfed). The two pCO2 levels were established in static 5.5 gallon aquaria filled with serially filtered (50, 5 um) seawater prior to the addition of metamorphosed larvae. These conditions were achieved and maintained by directly bubbling air (in the ambient condition) or CO2 -enriched air (high CO2 treatment) through micropore bubble "wands" fixed horizontally approximately 5 cm from the base of each aquarium. A pair of Aalborg mass flow controllers maintained the CO2 concentration of the enriched treatment. The resultant average calculated pCO2 for ambient and high CO2 conditions were 421 ± 35

and 1,311 ± 76 uatm (mean ± SD), respectively, with corresponding average Ωar of 3.66 ± 0.15 and 1.63 ± 0.08 (mean ± SD), respectively. Ωar of the high CO2 treatments is within range of average global surface ocean Ωar predicted by global climate models for the end of this century under the IPCC SRES A2 (Steinacher et al. 2009). Corals in fed treatments were isolated (every night for 2 weeks, every other night for the third week) for 3 h in 12.5 cm x 12.5 cm x 3 cm plastic containers filled with seawater from their respective treatment tanks and provided with 24-h-old *Artemia nauplii* (brine shrimp). Feeding took place at night, shortly after lights were switched off to mimic crepuscular feeding and temporal zooplankton abundance observed in local coral reef environments (Lewis and Price 1975). Unfed corals were not provided nauplii during the 3-week experiment and were not isolated in empty feeding containers. Each CO2 -feeding treatment was conducted in triplicate for a total of twelve aquaria, and all treatments were kept on a 12/12 h light–dark cycle. Fluorescent aquarium lamps maintained maximum light levels of 62 ± 8 umol quanta m-2 s-1 (mean ± SD), which were monitored using a LI-COR probe/meter assemblage. The compensation range for *F. fragum* spat on Bermuda is not yet known. The investigators used the low end of known compensation ranges for corals (e.g. 3–233 umol quanta m-2 s-1 as reported by Mass et al. 2007) for two reasons. The first was to ensure that corals under elevated CO2 did not bleach (as experienced by Anthony et al. 2009), and the second was to minimize the potential for enhanced photosynthesis to overwhelm or inhibit the feeding-modulated calcification response to elevated CO2. Aquarium temperatures were maintained by in-line chiller/heater systems and monitored every 15 min (Hobo temperature loggers, Onset Corp.). Average temperature for all treatments over the course of the experiment was 27.6 ± 0.1 degrees C (± SD).

Aquarium water was replaced with filtered seawater every week to prevent the build-up of dissolved inorganic nitrogen and other wastes. Prior to removing water from the aquaria, discrete water samples were collected for salinity, alkalinity (Alk), and dissolved inorganic carbon (DIC) from every aquarium. Salinity was measured at BIOS with an Autosal salinometer. The Alk/DIC samples were poisoned with mercuric chloride immediately after collection and analyzed using a Marianda VINDTA-3C analysis system at WHOI. Alkalinity was determined by nonlinear curve fitting of data obtained by open-cell titrations, and DIC concentrations were determined by coulometric analysis. Both measurements were standardized using certified reference materials obtained from Dr. A. Dickson (Scripps IO). The pH (NBS) of each tank was measured every 3–4 d (Orion pH meter and temperature-compensated electrode) to provide a real-time assessment of tank chemistry. Short-term variations in NBS pH were also assessed on a higher-resolution time scale: for one, 24-h period, by measuring pH in each aquarium at 3-h time intervals. The pH within each tank was maintained within ± a few hundredths of a pH unit on both sub-weekly and sub-daily time scales. The carbonate system parameters used to compare treatments (pCO2, [HCO3-], [CO32-], and Ωar) were calculated from the average temperature and discretely sampled salinity, Alk, and DIC data using the CO2SYS program (Lewis and Wallace 1998; Pelletier et al. 2007) with the constants of Mehrbach et al. (1973) as refit by Dickson and Millero (1987).

Coral collection, spawning, and larval settlement

In July 2010, approximately 1 week prior to anticipated peak larval release date (Goodbody-Gringley and de Putron 2009), the investigators collected 30 mature colonies of the brooding coral, *F. fragum*, from the Bailey's Bay patch reefs off the northwest Bermudan coast at approximately three to seven meters water depth. Adult colonies were maintained in outdoor flow-through seawater aquaria at BIOS under ambient light and temperature conditions. Parent colonies were kept isolated in glass jars during planula release, which occurred over the course of 6 nights. The live zooxanthellate planulae were collected from all parents and pooled together. Ceramic tiles, approximately 9 square cm, were left out on the reef for 2 months prior to the start of the experiment and further conditioned for larval settlement by scattering bits of freshly collected crustose coralline algae on the tiles. Immediately after collection, actively swimming larvae were transferred to small plastic tubs each containing ceramic tiles and filled with seawater preset to targeted CO2 levels. The tubs had mesh lids, allowing for water exchange, while they are submerged in the treatment aquaria. After 48 h, larvae had settled and metamorphosed into primary polyps (at this stage, larvae are "spat"). Spat on tiles were quickly counted, and tiles were pseudo-randomly distributed among the experimental aquaria so that each aquarium had approximately the same number of juvenile corals. Calcification was visible approximately 3 d after settlement. At the end of 3 weeks (± 1 d), 20–50 primary polyps (including their primary corallite) per treatment were removed from the tiles and frozen at- 80 degrees C for analysis of total lipid. Tiles were then removed from treatments and submerged in a 10% bleach solution for 1 h, which removed the polyp tissue from all of the remaining juvenile corals and exposed the calcified skeleton or primary corallite.

Quantification of baby coral skeletal development, size, and weight

Each bleached skeleton was digitally photographed, removed from the tile, and weighed using a Metro-Toledo micro-balance. Images of the baby corals (i.e. spat) were examined for skeletal development and size using Spot Imaging software. Length of the primary septa (present in all samples) was used to estimate corallite diameter (i.e., size). The septa are lateral CaCO3 plates that corals accrete in cycles. In our experiment, most spat accreted both primary and secondary septa; the tertiary septa were the last septal cycle accreted by any of the juvenile corals. Rate of skeletal development was defined as percent spat exhibiting tertiary septa, and a two-way ANOVA was used to test for differences in the mean proportion of spat with tertiary septa between the treatments. Feeding treatment and CO2 level were fixed effects. Data were arc sin square root transformed to homogenize variances prior to analyses. To test for differences in mean spat weight and diameter among treatments, a two-way, nested multivariate analysis of variance (MANOVA) was performed on natural log transformed weight data and square root transformed diameter data. Feeding treatment and CO2 levels were fixed main effects, while tank effect was the random factor nested within feeding and CO2 levels. Eight univariate F tests were conducted to test each of the dependent variables. A Bonferonni corrected alpha value of 0.0062 was used to declare significance of F statistics. It should be noted that the MANOVA only considers corals that have data for both diameter and weight. If

part of a corallite is lost during weighing or was attached to coralline algae, both coral size and weight were excluded from the MANOVA analyses. Likewise, if the skeleton was irregularly shaped (i.e., primary septa did not lie in a straight line), the data for those corals were not included. In order to account for any bias that may have resulted from corallite exclusion in the MANOVA, ANOVAs for the dependent variables, weight, and diameter were conducted. These tests considered all data for a given dependent variable to compare with the MANOVA's univariate results.

Quantification of baby coral total lipid and symbiont density
Ten individual spat from each aquarium were pooled per tissue lipid sample for quantification of total lipid by gravimetric analysis. Pooling was necessary due to the small size of the spat at 3 weeks. Extraction methods follow that of Folch et al. (1957) and Cantin et al. (2007). Five individual spat from each aquarium were pooled per sample for quantification of symbiont density. Spat were homogenized, centrifuged and the resultant pellet was re-suspended in 250 l L filtered seawater. Symbionts from multiple (6–9) aliquot sub-samples of the slurry were counted on a known volume hemocytometer grid. Both total tissue lipid and symbiont counts were normalized to the circular area described by the average primary septa length (diameter) for a respective tank and then divided by the number of corals pooled in the sample (i.e., 10 or 5). Both area-normalized lipid content and symbiont density were compared among levels of CO2 and feeding conditions using two-way ANOVAs with tank as a random factor nested within the CO2 and feeding combinations. Total lipid concentration was transformed to - 1/x in order to homogenize the variances. All statistical analyses were conducted on SYSTAT.

Processing Description

BCO-DMO Processing Notes:
- Combined "Water Chemistry" and "Coral Data (by treatment)" tables in original Excel file into one dataset.
- Separated the standard deviation values into separate columns from the data values.
- Modified parameter names to conform with BCO-DMO naming conventions.

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Parameters

Parameter	Description	Units
treatment	Experimental treatment/condition.	text

sal	Salinity; average of all replicate tanks for the given experimental treatment.	psu
sal_sd	Standard deviation of 'sal'.	psu
alk	Alkalinity; average of all replicate tanks for the given experimental treatment.	microequivalent per kilogram (ueq/kg)
alk_sd	Standard deviation of 'alk'.	microequivalent per kilogram (ueq/kg)
DIC	Concentration of dissolved inorganic carbon; average of all replicate tanks for the given experimental treatment.	micromoles per kilogram (umol/kg)
DIC_sd	Standard deviation of 'DIC'.	micromoles per kilogram (umol/kg)
pH	pH; average of all replicate tanks for the given experimental treatment.	NBS
pH_sd	Standard deviation of 'pH'.	NBS
HCO3	Concentration of bicarbonate ions; average of all replicate tanks for the given experimental treatment.	micromoles per kilogram (umol/kg)
HCO3_sd	Standard deviation of 'HCO3'.	micromoles per kilogram (umol/kg)
CO3	Concentration of carbonate ions; average of all replicate tanks for the given experimental treatment.	micromoles per kilogram (umol/kg)
CO3_sd	Standard deviation of 'CO3'.	micromoles per kilogram (umol/kg)

AragSat	Aragonite saturation state; average of all replicate tanks for the given experimental treatment. (The saturation state of seawater with respect to aragonite is a measure of the thermodynamic potential for aragonite to form or to dissolve, and is defined as the product of the concentrations of dissolved calcium and carbonate ions in seawater, divided by their product at equilibrium.)	dimensionless
AragSat_sd	Standard deviation of 'AragSat'.	dimensionless
PcntSpat3oSepta	Percent of spat with tertiary septat; average of all replicate tanks for the given experimental treatment.	%
PcntSpat3oSepta_se	Standard error of 'PcntSpat3oSepta'.	%
SeptaDiam	Septa diameter; average of all replicate tanks for the given experimental treatment.	micrometers (um)
SeptaDiam_se	Standard error of 'SeptaDiam'.	micrometers (um)
CoralliteWt	Total corallite weight; average of all replicate tanks for the given experimental treatment.	micrograms (ug)
CoralliteWt_se	Standard error of 'CoralliteWt'.	micrograms (ug)
TotLipid_per_area	Area-normalized total tissue lipid weight; average of all replicate tanks for the given experimental treatment.	micrograms per square millimeter (ug/mm^2)
TotLipid_per_area_se	Standard error of 'TotLipid_per_area'.	micrograms per square millimeter (ug/mm^2)
SymbiontDensity	Symbionts per area; average of all replicate tanks for the given experimental treatment.	x1000 cells per square millimeter (x10^3 cells/mm^2)

SymbiontDensity_se	Standard error of 'SymbiontDensity'.	x1000 cells per square millimeter (x10^3 cells/mm^2)
tank	Identification number of the experimental tank.	integer
TankAragSat	Aragonite saturation state in the specified tank.	dimensionless
TankAragSat_se	Standard error of 'TankAragSat'.	dimensionless
TankCoralliteWt	Total corallite weight in the specified tank.	micrograms (ug)
TankCoralliteWt_se	Standard error of 'TankCoralliteWt'.	micrograms (ug)

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Instruments

Dataset-specific Instrument Name	Autosal salinometer
Generic Instrument Name	Autosal salinometer
Dataset-specific Description	Salinity was measured at BIOS with an Autosal salinometer.
Generic Instrument Description	The salinometer is an instrument for measuring the salinity of a water sample.

Dataset-specific Instrument Name	Water Temperature Sensor
Generic Instrument Name	Water Temperature Sensor
Dataset-specific Description	Aquarium temperatures were maintained by in-line chiller/heater systems and monitored every 15 min using Hobo temperature loggers (Onset Corp.).
Generic Instrument Description	General term for an instrument that measures the temperature of the water with which it is in contact (thermometer).

Dataset-specific Instrument Name	pH Sensor
Generic Instrument Name	pH Sensor
Dataset-specific Description	The pH (NBS) of each tank was measured using an Orion pH meter and temperature-compensated electrode.
Generic Instrument Description	General term for an instrument that measures the pH or how acidic or basic a solution is.

Dataset-specific Instrument Name	MARIANDA VINDTA 3C total inorganic carbon and titration alkalinity analyser
Generic Instrument Name	MARIANDA VINDTA 3C total inorganic carbon and titration alkalinity analyser
Dataset-specific Description	The Alk/DIC samples were poisoned with mercuric chloride immediately after collection and analyzed using a Marianda VINDTA-3C analysis system at WHOI.
Generic Instrument Description	The Versatile INstrument for the Determination of Total inorganic carbon and titration Alkalinity (VINDTA) 3C is a laboratory alkalinity titration system combined with an extraction unit for coulometric titration, which simultaneously determines the alkalinity and dissolved inorganic carbon content of a sample. The sample transport is performed with peristaltic pumps and acid is added to the sample using a membrane pump. No pressurizing system is required and only one gas supply (nitrogen or dry and CO2-free air) is necessary. The system uses a Metrohm Titrino 719S, an ORION-Ross pH electrode and a Metrohm reference electrode. The burette, the pipette and the analysis cell have a water jacket around them. Precision is typically +/- 1 umol/kg for TA and/or DIC in open ocean water.

Dataset-specific Instrument Name	Aquarium
Generic Instrument Name	Aquarium
Generic Instrument Description	Aquarium - a vivarium consisting of at least one transparent side in which water-dwelling plants or animals are kept

Dataset-specific Instrument Name	Mass Flow Controller
Generic Instrument Name	Mass Flow Controller
Dataset-specific Description	A pair of Aalborg mass flow controllers maintained the CO2 concentration of the enriched treatment.
Generic Instrument Description	Mass Flow Controller (MFC) - A device used to measure and control the flow of fluids and gases

Dataset-specific Instrument Name	Scale
Generic Instrument Name	Scale
Dataset-specific Description	Bleached skeletons were weighed using a Metro-Toledo micro-balance.
Generic Instrument Description	An instrument used to measure weight or mass.

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Deployments

lab_dePutron_BIOS

Website	https://www.bco-dmo.org/deployment/59090
Platform	BIOS
Start Date	2010-07-01
Description	Experiments for the project "An Investigation of the Role of Nutrition in the Coral Calcification Response to Ocean Acidification" were carried out at the Bermuda Institute of Ocean Sciences (BIOS) in St. George, Bermuda. Pregnant adult corals were collected from the northwestern Bermuda patch reefs in the area of Bailey's Bay; adult corals were returned to their resident reefs following larval collection.

lab_Cohen_WHOI

Website	https://www.bco-dmo.org/deployment/59089
Platform	WHOI
Description	Experiments and analyses carried out in Anne Cohen's lab at Woods Hole Oceanographic Institution (WHOI) as part of the project "An Investigation of the Role of Nutrition in the Coral Calcification Response to Ocean Acidification". See: Project description from Cohen Lab

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Project Information

An Investigation of the Role of Nutrition in the Coral Calcification Response to Ocean Acidification (OA Nutrition and Coral Calcification)

Coverage: global; experimental

The project description is a modification of the original NSF award abstract. This research project is part of the larger NSF funded CRI-OA collaborative research initiative and was funded as an Ocean Acidification-Category 1, 2010 award. Over the course of this century, all tropical coral reef ecosystems, whether fringing heavily populated coastlines or lining remote islands and atolls, face unprecedented threat from ocean acidification caused by rising levels of atmospheric CO2. In many laboratory experiments conducted to date, calcium carbonate production (calcification) by scleractinian (stony) corals showed an inverse correlation to seawater saturation state OMEGAar), whether OMEGAar was manipulated by acid or CO2 addition. Based on these data, it is predicted that coral calcification rates could decline by up to 80% of modern values by the end of this century. A growing body of new experimental data however, suggests that the coral calcification response to ocean acidification may be less straightforward and a lot more variable than previously recognized. In at least 10 recent experiments including our own, 8 different tropical and temperate species reared under nutritionally-replete but significantly elevated CO2 conditions (780-1200 ppm, OMEAGar ~1.5-2), continued to calcify at rates comparable to conspecifics reared under ambient CO2. These experimental results are consistent with initial field data collected on reefs in the eastern Pacific and southern Oman, where corals today live and accrete their skeletons under conditions equivalent to 2X and 3X pre-industrial CO2. On these high CO2, high nutrient reefs (where nitrate concentrations typically exceed 2.5 micro-molar), coral growth rates rival, and sometimes even exceed, those of conspecifics in low CO2, oligotrophic reef environments. The investigators propose that a coral's energetic status, tightly coupled to the availability of inorganic nutrients and/or food, is a key factor in the calcification response to CO2-induced ocean acidification. Their hypothesis, if confirmed by the proposed laboratory investigations, implies that predicted changes in coastal and open ocean nutrient concentrations over the course of this century, driven by both climate impacts on ocean stratification and by increased human activity in coastal regions, could play a critical role in exacerbating and in some areas, modulating the coral reef response to ocean acidification. This research program builds on the investigators initial results and observations. The planned laboratory experiments will test the hypothesis that: (1) The coral calcification response to ocean acidification is linked to the energetic status of the coral host. The relative contribution of symbiont photosynthesis and heterotrophic feeding to a coral's energetic status varies amongst species. Enhancing the energetic status of corals reared under high CO2, either by stimulating photosynthesis with

inorganic nutrients or by direct heterotrophic feeding of the host lowers the sensitivity of calcification to decreased seawater OMEGAar; (2) A species-specific threshold CO2 level exists over which enhanced energetic status can no longer compensate for decreased OMEGAar of the external seawater. Similarly, we will test the hypothesis that a nutrient threshold exists over which nutrients become detrimental for calcification even under high CO2 conditions; and (3) Temperature-induced reduction of algal symbionts is one stressor that can reduce the energetic reserve of the coral host and exacerbate the calcification response to ocean acidification. The investigator's initial findings highlight the critical importance of energetic status in the coral calcification response to ocean acidification. Verification of these findings in the laboratory, and identification of nutrient and CO2 thresholds for a range of species will have immediate, direct impact on predictions of reef resilience in a high CO2 world. The research project brings together a diverse group of expertise in coral biogeochemistry, chemical oceanography, molecular biology and coral reproductive ecology to focus on a problem that has enormous societal, economic and conservation relevance.

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Program Information

Science, Engineering and Education for Sustainability NSF-Wide Investment (SEES): Ocean Acidification (formerly CRI-OA) (SEES-OA)

Website: http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503477

Coverage: global

NSF Climate Research Investment (CRI) activities that were initiated in 2010 are now included under Science, Engineering and Education for Sustainability NSF-Wide Investment (SEES). SEES is a portfolio of activities that highlights NSF's unique role in helping society address the challenge(s) of achieving sustainability. Detailed information about the SEES program is available from NSF (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504707). In recognition of the need for basic research concerning the nature, extent and impact of ocean acidification on oceanic environments in the past, present and future, the goal of the SEES: OA program is to understand (a) the chemistry and physical chemistry of ocean acidification; (b) how ocean acidification interacts with processes at the organismal level; and (c) how the earth system history informs our understanding of the effects of ocean acidification on the present day and future ocean. Solicitations issued under this program:NSF 10-530, FY 2010-FY2011NSF 12-500, FY 2012NSF 12-600, FY 2013NSF 13-586, FY 2014 NSF 13-586 was

the final solicitation that will be released for this program. PI Meetings:1st U.S. Ocean Acidification PI Meeting(March 22-24, 2011, Woods Hole, MA)2nd U.S. Ocean Acidification PI Meeting(Sept. 18-20, 2013, Washington, DC) 3rd U.S. Ocean Acidification PI Meeting (June 9-11, 2015, Woods Hole, MA – Tentative) NSF media releases for the Ocean Acidification Program: Press Release 10-186 NSF Awards Grants to Study Effects of Ocean Acidification Discovery Blue Mussels "Hang On" Along Rocky Shores: For How Long? Discovery nsf.gov - National Science Foundation (NSF) Discoveries - Trouble in Paradise: Ocean Acidification This Way Comes - US National Science Foundation (NSF) Press Release 12-179 nsf.gov - National Science Foundation (NSF) News - Ocean Acidification: Finding New Answers Through National Science Foundation Research Grants - US National Science Foundation (NSF) Press Release 13-102 World Oceans Month Brings Mixed News for Oysters Press Release 13-108 nsf.gov - National Science Foundation (NSF) News - Natural Underwater Springs Show How Coral Reefs Respond to Ocean Acidification - US National Science Foundation (NSF) Press Release 13-148 Ocean acidification: Making new discoveries through National Science Foundation research grants Press Release 13-148 - Video nsf.gov - News - Video - NSF Ocean Sciences Division Director David Conover answers questions about ocean acidification. - US National Science Foundation (NSF) Press Release 14-010 nsf.gov - National Science Foundation (NSF) News - Palau's coral reefs surprisingly resistant to ocean acidification - US National Science Foundation (NSF) Press Release 14-116 nsf.gov - National Science Foundation (NSF) News - Ocean Acidification: NSF awards $11.4 million in new grants to study effects on marine ecosystems - US National Science Foundation (NSF)

Ocean Carbon and Biogeochemistry (OCB)

Website: http://us-ocb.org/

Coverage: Global

The Ocean Carbon and Biogeochemistry (OCB) program focuses on the ocean's role as a component of the global Earth system, bringing together research in geochemistry, ocean physics, and ecology that inform on and advance our understanding of ocean biogeochemistry. The overall program goals are to promote, plan, and coordinate collaborative, multidisciplinary research opportunities within the U.S. research community and with international partners. Important OCB-related activities currently include: the Ocean Carbon and Climate Change (OCCC) and the North American Carbon Program (NACP); U.S. contributions to IMBER, SOLAS, CARBOOCEAN; and numerous U.S. single-investigator and medium-size research projects funded by U.S. federal agencies including NASA, NOAA, and NSF. The scientific mission of OCB is to study the evolving role of the ocean in the global carbon cycle, in the face of environmental variability and change through studies of marine biogeochemical cycles and

associated ecosystems. The overarching OCB science themes include improved understanding and prediction of: 1) oceanic uptake and release of atmospheric CO2 and other greenhouse gases and 2) environmental sensitivities of biogeochemical cycles, marine ecosystems, and interactions between the two. The OCB Research Priorities (updated January 2012) include: ocean acidification; terrestrial/coastal carbon fluxes and exchanges; climate sensitivities of and change in ecosystem structure and associated impacts on biogeochemical cycles; mesopelagic ecological and biogeochemical interactions; benthic-pelagic feedbacks on biogeochemical cycles; ocean carbon uptake and storage; and expanding low-oxygen conditions in the coastal and open oceans.

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Funding

Funding Source	Award
NSF Division of Ocean Sciences (NSF OCE)	OCE-1041052
NSF Division of Ocean Sciences (NSF OCE)	OCE-1041106

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