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Andersson, Andreas

Temporal and spatial variability in seawater carbonate chemistry on the Bermuda coral reef platform

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Monthly time-series seawater CO_2 system measurements from the Bermuda coral reef platform since 2007 and the Bermuda Atlantic Time-series Station (BATS) since 1983 reveal complex trends and controls on surface seawater pH, pCO_2 and aragonite saturation state (Ω_a). On the reef platform, seawater total dissolved inorganic carbon (DIC) increased 11.0±3.0 μmol kg^{-1}, pCO_2 increased 30.2±5.7 μatm, pH decreased -0.025±0.004, and Ω_a decreased -0.14±0.03. In contrast, trends at BATS during the same time period exhibited the opposite directionality. At BATS, seawater DIC decreased -2.4±2.5 μmol/kg, pCO_2 decreased -6.9±4.5 μatm, pH increased 0.008±0.004, and Ω increased 0.12±0.03 units. The observed trends on the Bermuda coral reef and at BATS can be accounted for by a combination of factors including the uptake of anthropogenic CO_2, seasonal oscillations in temperature and salinity, biological activity, and sub-decadal climate variability as dictated by the North Atlantic Oscillation (NAO). Shifts in the reef's metabolic activity towards increased net ecosystem calcification (NEC) and reduced net ecosystem production (NEP) in response to a negative NAO state appear to be responsible for the rapid acidification observed on the platform.

Archer, Stephen

Influence of ocean acidification on biotic controls of DMS emissions

Stephen Archer, Patricia Matrai, Peter Countway

Bigelow Laboratory for Ocean Sciences

The poster illustrates the aims and approaches of a recently NSF-funded project. Given the considerable **c**hanges in DMS concentrations that altered pCO_2 and pH causes, it appears essential to accurately include OA in any assessment of the influence of climate change on DMS emissions and potential feedbacks. Our strategy is to quantify the key state variables and processes governing DMS biogeochemistry in relation to predicted levels of change in pCO_2 and pH in three natural-water mesocosm experiments in warm-water environments. We will use the formulations included in a DMS-Ecosystem Model as the basis by which to interpret the experimental results in each mesocosm and then in relation to pCO_2 and pH for each experiment. Comparison between experiments will allow us to determine how the response of key processes varies between the different environments and microbial communities. This comparison will be extended to selected previous experiments, conducted in cold-temperate and polar environments, in order to develop a more comprehensive characterization of the DMS response to OA. We will use the comparison across latitudes and trophic environments to define 'universal' functional relationships that can then be incorporated in an Earth System Model to reassess the significance of the DMS response to OA in the context of changes to other multiple stressors associated with climate change.

Arnold, Thomas

Ocean acidification and potential for carbon sequestration by coastal seagrasses

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Seagrasses cover a global area of approximately 177,000 km^2 and provide ecosystem services worth an estimated $1.9 trillion per year. Their high rates of carbon assimilation may reduce local pCO_2 levels by >50% during daytime. As a result seagrasses sequester "blue carbon", storing as much as 19.9 Pg of organic carbon in the form of anaerobic, organic-rich loams. They are responsible for an estimated 10–18% of oceanic carbon burial. However, not all plant products have the same "sequestration potential" (SP). Plant phenolics, which in land plants tend over-accumulate under high CO_2 conditions, resist decomposition for long periods of time, compared to other plant products. Using Free Ocean Carbon Enrichment technology we tested the impact of high CO_2 / low pH conditions on seagrass phenolic substances and observed that OA triggered a 10x *decrease* in concentrations of small- and medium-sized phenolics in five populations of seagrasses, including four different species from three continents. These lost phenolics have bioactivity as anti-feedants and anti-microbials; we have observed corresponding increases in fish grazing and predict increased outbreaks of the seagrass wasting disease, both of which would compromise seagrass SP. On the other hand, we have traced the unused carbon to pools of insoluble polyphenols, including lignin and other compounds with high SPs. We hypothesize that OA will led to two opposing processes: (1) a short-term increase in above-ground carbon recycling via herbivory and disease and (2) a longer-term increase in the SP of plant tissues with enhanced lignification in marine sediments.

Baumann, Hannes

Effects of ocean acidification and hypoxia on fish early life stages

Hannes Baumann & Christopher Gobler

Anthropogenic ocean acidification coupled with increasing marine hypoxia has heightened the need to better understand the sensitivity of marine organisms to low pH and oxygen conditions. In contrast to juvenile and adult stages, fish embryos and larvae may be the most vulnerable; however, there's still an insufficient empirical basis for sound conclusions. Since 2012, our two groups from Stony Brook University have been conducting comprehensive NSF-funded series of experiments to further explore these issues. We use Inland and Atlantic Silversides (*Menidia beryllina* and *M. menidia*, respectively) as model species, because of their key role as forage fish in coastal and estuarine habitats and because of decades of expertise in experimental rearing methods. Our general objectives are to determine CO_2 and O_2 reactions norms in terms of larval growth and survival and test those for seasonal variability, parental effects, temperature- and food-dependency, as well as additive and/or synergistic effects of concurrent high CO_2 and low O_2 conditions. Furthermore, we are in the process of testing genomic approaches to determine the heritability, and transcriptomic approaches to explore the molecular mechanisms of larval fish CO_2 sensitivity. The poster gives a brief introduction to our project, our group and experimental approaches, as well as upcoming talks and publications.

Bednarsek, Nina

Is ocean acidification in the California Current Ecosystem driving coastal pteropod populations to decline?

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The ocean uptake of anthropogenic CO_2 has shoaled the aragonite saturation horizon (Ω_{ar}) in the California Current Ecosystem. Undersaturation exposure imposes adverse physiological and structural effects on many calcifiers, including pteropods. Upwelled corrosive waters (Ω_{ar}<1) reaching to within 100 m of the surface in the CCE are within the diel vertical migration zone of pteropods, implying a possible reduction of their favorable habitat due to ocean acidification. Forming a shell composed of aragonite, one of the more soluble forms of calcium carbonate, pteropods are particularly vulnerable to shell dissolution and even short-term exposures to near-saturated waters (Ω_{ar} ~1) can cause severe shell dissolution. Few studies to date have demonstrated widespread biological impacts of ocean acidification under conditions found in the natural environment. From a combined survey of chemical, hydrographic properties and biological sampling along the Washington-Oregon-California coast in August 2011 we determined that large portions of the shelf waters are corrosive to live pteropods. We show a strong positive correlation between the proportion of pteropods with severe dissolution and the percentage of the water column that is undersaturated with respect to aragonite in the upper 100 m. From this relationship, we were able to determine the extent of dissolution for the pre-industrial era, current (2011), and projections for year 2050. Our calculations show that dissolution has increased by 30% since the beginning of the industrial era, and could increase to 70% by 2050 in this region.

Breitburg, Denise

Breathless nights on acid: Effects of diel-cycling dissolved oxygen and pH on oyster disease dynamics

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Diel-cycling dissolved O_2 and CO_2 concentrations are driven by light-dark cycles of respiration and photosynthesis, and are exacerbated by anthropogenic nutrient loading and restricted circulation. We have been conducting laboratory and field experiments to examine the individual and combined effects of diel-cycling hypoxia and pH on the acquisition and progression of *Perkinsus marinus* (dermo) infections in the eastern oyster *Crassostrea virginica*. Recent experiments have used a LabView-controlled laboratory system that creates a variety of cyclical and constant conditions in aquaria fed with raw, flowing estuarine water. Our results indicate that diel-cycling hypoxia can increase the acquisition and progression of *P. marinus* infections but that pH cycling between 7.0 and 7.8 – 8.0 does not. In fact, diel-cycling pH increased phagocytosis by oyster hemocytes. In 2013 experiments, conducted at salinities of approximately 6.5 – 9.2, oyster growth in diel-cycling hypoxia, diel-cycling pH, and constant reduced pH (7.4) was similar to that in controls. Disease prevalence was higher when oysters were exposed to severe diel-cycling hypoxia (0.5 mg/L 5d/wk) and pH levels of 7.8 – 8.0, than when both dissolved oxygen and pH cycled. Our results suggest that the combined effects of these two commonly co-occurring stressors may be non-additive and difficult to predict from single stressor, constant-exposure experiments because of physiological and behavioral compensatory mechanisms.

Capson, Todd

The Northeast Coastal Acidification Network

Joseph Salisbury[1], Ru Morrison[2], Todd Capson (Presenter)[3], Dwight Gledhill[4], Bill Mook[5], Elizabeth Turner[6], Esperanza Stancioff[7], Mel Cote[8], Helmuth Thomas[9], Sylvain DeGuise[10]

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By nature of its cool temperatures and copious freshwater input, the coastal waters of the northeast U.S. and Canadian Maritimes are particularly sensitive to processes that cause ocean acidification. Despite this sensitivity, and despite recent events known to affect acidification such as ocean warming, hydrological intensification and variability in water mass origin, a comprehensive plan to monitor and study regional ocean acidification is still lacking. The Northeast Coastal Acidification Network (NE-CAN) represents a nexus of scientist, federal and state agency representatives, resource managers, and affected industry partners dedicated to coordinating and guiding regional observing, research, and modeling endeavors to better identify critical vulnerabilities, particularly with respect to regionally important and economically significant marine resources. NE-CAN serves as a necessary interface between research and industry interests, whereby state-of-the-science can be readily exchanged with regional interest groups and key data and information synthesis products can be specifically tailored and informed by user group needs and observations. Presently a NE-CAN steering committee has been formed which will ensure that efforts are coordinated with the Integrated Sentinel Monitoring for Climate Change in the Northeast Region initiative. An important prerequisite towards implementing NE-CAN is to first inventory and synthesize the current state-of-knowledge with respect to the known coastal biogeochemistry complexities of the region and identified biological sensitivities to changes in carbonate chemistry in response to both ocean and coastal acidification. During the talk we will discuss the status of ocean acidification observing and research in the Gulf of Maine (and elsewhere in the Northeast) and outline our nascent plan to improve both. We will also show research in the western Gulf of Maine highlighting acid variability attributable to the extreme temperature and hydrological events experienced during the last decade.

Carrington, Emily

Response of mussels to multiple environmental stressors: an ecomaterials perspective

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The performance of any organism in its natural environment is often constrained by its structural integrity. This physical constraint is clearly evident in coastal marine ecosystems, where shells and spines deter predators, body size, shape and flexibility influence hydrodynamic stress, and the strength of tethers and adhesives secure attachment to benthic substrates. It has been shown that ocean acidification can alter calcification rates as well as resource allocation to non-calcified tissues. How do these structural modifications at the organismal level affect ecological performance? This study builds on our previous work with mussel byssus, the collagenous fibers that tether these bivalve mollusks to hard substrates. Natural and farmed populations worldwide are prone to seasonal "fall-off" events, when increased storms coincide with weak attachment. To isolate which environmental conditions contribute to byssus weakening, we exposed the mussel *Mytilus trossulus* to a broad suite of environmental conditions (pCO_2, temperature, food supply) for several weeks in laboratory mesocosms and then quantified the material properties of the byssal threads produced. Threads were weaker in mussels held in elevated pCO_2 conditions, as well as in elevated water temperature. These results suggest multiple environmental stressors, including ocean acidification, can combine to critically compromise the structural integrity of mussels. In extending these findings to real world conditions, it will be important to consider the timing and magnitude of environmental fluctuations encountered by mussels in their natural environment.

Chambers, Chris

Ocean acidification effects in the early life-stages of summer flounder, *Paralichthys dentatus*

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Ocean acidification effects on fish are expected to differ across species, be subtle, and interact with other stressors. An experimental framework was implemented that assessed the early life stage (ELS) responses of summer flounder (*Paralichthys dentatus*), an important flatfish of the mid-Atlantic region of the USA, to a wide range of pH and CO_2 levels. Survival of embryos was reduced by 50% below local ambient conditions (7.8 pH, 775 ppm pCO_2) when maintained at the intermediate conditions (7.4 pH, 1860 ppm pCO_2), and another 50% when at the most acidic conditions (7.1 pH, 4,715 ppm pCO_2). Reduced survival of embryos at higher CO_2 levels was consistent among three females used as sources of embryos. Sizes of larvae were altered by elevated CO_2 levels with longer larvae in more acidic waters. Larvae were longer (but with less energy reserves) at hatching to midway through the larval period. Larvae from the most acidic conditions initiated metamorphosis earlier and at smaller sizes than those from more moderate and ambient conditions. Tissue damage was evident in older larvae from both elevated CO_2 levels. CO_2 affected cranial-facial features levels these effects changed with larval age. Skeletal elements of larvae from ambient CO_2 environments were comparable or smaller than those from elevated CO_2 environments when younger (14 d and 21-d post-hatching) but larger at older ages (28 d). The impairment of ELS of summer flounder by elevated CO_2 levels suggests that this species will be challenged by ocean acidification in the near future.

Meta-analysis of ocean acidification experiments on the early life-stages of marine fishes

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National Marine Fisheries Service / Northeast Fisheries Science Center, National Oceanic and Atmospheric Administration (NOAA), [1] College of Natural Sciences, Forestry, and Agriculture, University of Maine, [2]Department of Natural Sciences, University of Maryland Eastern Shore

Marine fish early life-stages (ELS) have received increased attention regarding effects of ocean acidification (OA) because ELS are a recruitment bottleneck and are least likely to be resilient to physiological challenges associated with OA. Only a small number (< 50) of publications currently exist on the ELS responses to OA but this literature is expanding rapidly. A framework was created for collecting critical contextual data for the experiments (e.g., phylogeny of the study species; details of the experimental design). Such metadata establishes a means of standardizing data reporting for future experiments and provides the raw material for our second objective: perform a meta-analysis of data drawn from relevant publications on OA effects on marine fish ELS. The metadata included text, tabular, supplemental, and graphical components. The meta-analysis was reduced to six primary ELS response variables (survival, length, and mass; otolith size and area; and behavioral response to predator cues) and tested four null hypotheses: no differences in ELS responses to OA i) among fish due to phylogeny, ii) between fish from major biomes, iii) between fish with different egg habitats; and iv) between embryonic versus larval stages. A strong bias exists in the study species (phylogeny) and source locations (biomes). Initial analyses suggest a greater susceptibility in fish with tropical distributions and pelagic eggs. The embryonic stage appears more sensitive than more advanced stages to OA exposure. Future experiments should standardize reporting of carbonate chemistry parameters and fully report data from all response variables in order to standardized datasets.

Chandler, Cynthia

The Biological and Chemical Oceanography Data Management Office

Cynthia L. Chandler[1], Robert C. Groman[2], Molly D. Allison[2], Peter H. Wiebe[2], David M. Glover[1]

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Ocean acidification (OA) research, an interdisciplinary field of study, generates and requires access to a wide variety of measurements. The Biological and Chemical Oceanography Data Management Office (BCO-DMO) is funded by the Biological and Chemical Oceanography Sections of the National Science Foundation (NSF) Division of Ocean Sciences (OCE) and NSF Office of Polar Programs (PLR) Antarctic Organisms & Ecosystems Program (ANT) and is recognized in the 2011 Division of Ocean Sciences Sample and Data Policy as one of several program-specific data offices that support NSF OCE funded researchers.

Efforts at BCO-DMO focus on comprehensive data management activities that span the full data life cycle from "proposal through preservation". BCO-DMO staff members work in partnership with NSF-funded investigators from large national programs, medium-sized collaborative research projects, and researchers from single investigator awards to ensure that data from their respective research projects are available for reuse. NSF-funded ocean science researchers have been contributing data from recently funded projects to the BCO-DMO data system, creating a rich repository of ocean, coastal and Great Lakes research program data.

The BCO-DMO data system includes legacy data from several large ocean research programs (e.g. United States Joint Global Ocean Flux Study and United States GLOBal Ocean ECosystems Dynamics), and data from recently granted NSF OCE and PLR awards, including the Science, Engineering and Education for Sustainability (SEES) OA program. The BCO-DMO data system accommodates many different types of data including: in situ and experimental biological, chemical, and physical measurements; modeling results and synthesis data products.

Chen, Chen-Tung Arthur

Influence of changing seawater temperature on ocean acidification

Chen-Tung Arthur Chen and Hon-Kit Lui

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Conventional wisdom has it that global warming and seawater acidification are different manifestations of increased atmospheric CO_2, and even a small change in seawater temperature (T) or pH may cause large impacts on oceanic ecosystems. In this study, acidification rates from two open access time-series studies are compared with that of six published time series studies. The results show that reported rates of change in pH measured at *in situ* temperature (pH_{insitu}) differ from the expected rate of -0.0016~-0.0018 yr^{-1},assuming equilibrium with the atmospheric CO_2 . This indicates that the increased atmospheric CO_2 is not the sole factor controlling changes in seawater pH. Results by applying the Multiple-Linear-Regression (MLP) show that the average $\Delta pH_{insitu}/ \Delta T$ from five time-series is 7.7 ±1.2 times that expected under only the air-sea CO_2 equilibrium. Such a result provides an insight on how future climate change can alter the ocean acidification. Implications are that aquatic ecosystems suffering from ocean acidification could be affected sooner than expected when warming is considered along with increasing atmospheric CO_2.

Cohen, Anne

The coral reef response to ocean acidification: Insights from laboratory experiments and field data

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[abstract unavailable at time of printing]

Cooley, Sarah

Developing an Atlantic sea scallop integrated assessment model to explore ocean acidification and temperature rise

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The sea scallop (*Placopecten magellanicus*) is the nation's most valuable single-species fishery, providing $455 million in ex-vessel revenue in 2010, but this lucrative natural resource faces ongoing pressures including changing climate, increasing ocean acidification, continuing harvests, and fluctuating markets. Currently, the combined impact of these different factors is difficult to incorporate adequately into policy decisions. This project is developing an integrated assessment model (IAM) comprising reduced-form biogeochemical, population, and economic numerical submodels. The one-dimensional biogeochemical model including anthropogenic and natural factors has been developed for sea scallop habitats in Georges Bank and the Mid Atlantic Bight. The modeled environmental conditions for these two key scallop habitats feed into the population submodel that simulates sea scallop recruitment, growth, and harvest. Sea scallop harvests feed into the economic submodel, in which scallop fishing policies and market factors affect the ecosystem and biogeochemical models. Preliminary results indicate that the scallop submodel yields realistic harvest volumes, size class distributions, and temperature-dependent growth; the socioeconomic submodel yields realistic revenues, harvest controls, and catch limits; and the biogeochemical model parameterizes environmental conditions well. When the full IAM is complete, we will explore the sensitivity of the coupled natural–socioeconomic system to different scenarios involving scallop harvest levels, price fluctuations, fishery rules, environmental conditions (including the overlapping stressors of ocean acidification and temperature), and national and international demand.

Cordes, Erik

Different genotypes of the deep-water coral *Lophelia pertusa* have different responses to ocean acidification.

Erik Cordes

Lophelia pertusa is one of the most widespread and common deep-water corals in the world. In the deep Gulf of Mexico, it forms large reef complexes along with other species of corals; structures as extensive as any of the shallow-water reefs in the Gulf. Deep-water corals are expected to feel the impacts of ocean acidification sooner than shallow water corals because they inhabit depths much closer to the aragonite saturation horizon. Only recently have data on the carbonate system of the deep Gulf of Mexico been available, and they revealed that *L. pertusa* persists at some of the lowest saturation states ever measured over a coral reef (omega = 1.28 - 1.46, Lunden et al. 2013). Laboratory experiments demonstrate that *L. pertusa* is resilient to low saturation states, capable of positive net calcification at a pH of 7.75 and a saturation state just over 1.0. However, different genotypes of *L. pertusa* showed variable responses to low pH and saturation state, with some corals capable of positive growth only under more favorable conditions. This finding has implications for the interpretation of other ocean acidification experiments, and for the dynamics of coral populations in the future ocean.

de Carlo, Eric Heinen

Variability in the CO_2-carbonic acid system parameters across coral reef settings in Hawaii: Perspectives from multi-year records from NOAA/PMEL MAP-CO_2 buoys.

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A series of MAP-CO_2 buoys deployed in the coastal waters of Hawaii have produced multiyear high temporal resolution CO_2 records in four different coral reef environments of the island of Oahu, Hawaii. This study is part of an integrated effort to understand the factors that influence the dynamics of CO_2-carbonic acid system parameters in waters bathing Pacific high island coral reef ecosystems and subject to differing natural and anthropogenic stresses. The MAP-CO_2 buoys are located in backreef, lagoonal, and fringing reef sites, and measure CO_2 and O_2 in seawater and in the atmosphere. Other sensors on the buoys record physical and biogeochemical parameters (CTD, chl-a, turbidity, pH, nitrate). The buoy records, when combined with data from synoptic spatial sampling, have allowed us to examine the interplay between biological cycles of productivity/respiration and calcification/dissolution and biogeochemical and physical forcing on hourly to inter-annual time scales, including those of land runoff.

Our data demonstrate that coral reefs are subject to a wide range of pCO_2 both on short and long time scales, and significant differences in the CO_2-carbonic acid system dynamics across these various settings. We report that coral communities currently thrive in areas where the concentrations of CO_2 can range from extremes as low as 200 ppm to as high as 1000 ppm and can fluctuate by ~500 ppm on any given day. The data provide evidence that net ecosystem calcification currently occurs in the presence of levels of CO_2 predicted to occur well into the next century, although these coral reef ecosystems are only exposed to the extremes for short periods of time each day.

Deheyn, Dimitri

Changes in color and biofluorescence as early physiological markers of stress: application to OA issues

Dimitri D. Deheyn, Jenny Tu, Katie Barott, Martin Tresguerres

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Many marine invertebrates show specific patterns of coloration that often involve a complex mixing of pigments. In addition to giving a colored display, pigments can have diverse functions such as being antioxidants, by-product of physiological reactions, and/or being directly related to assimilation from the diet, and thus be good proxies to assess nature and quality of food supply for a given species in an ecosystem. Pigment abundance in tissues is often directly or indirectly affected by metabolic and environmental stress. Because these pigments absorb a specific wavelength of light (which gives them their inherent color), they often also have biofluorescence properties. Using optical and hyperspectral imaging techniques, we have studied whether color and biofluorescence of corals change upon exposure to different concentrations of pCO_2 in seawater. Our poster will relate our preliminary analysis from corals experimentally exposed for 31days to pH 7.6, 7.9, and 8.1 (control), thus corresponding to pCO_2 concentrations ranging from ~1,200 to ~500 μatm. These results will be discussed in relation to levels of reactive oxygen species, and to abundance of proton pumps proteins.

Drake, Jeana

Proteomic analysis of skeletal framework proteins from the stony coral, *Stylophora pistillata*

Jeana Drake, Tali Mass, Liti Haramaty, Ehud Zelzion, Debashish Bhattacharya, Paul G. Falkowski

It has long been recognized that a suite of proteins exists in coral skeletons that is critical for the oriented precipitation of calcium carbonate crystals, yet these proteins remain poorly characterized. Using liquid chromatography-tandem mass spectrometry analysis of proteins extracted from the cell free skeleton of the hermatypic coral, *Stylophora pistillata,* combined with a draft genome assembly from the cnidarian host cells of the same species, we identified 36 coral skeletal organic matrix (SOM) proteins. The proteome of the coral skeleton contains an assemblage of adhesion and structural proteins as well as two highly acidic proteins that may constitute a novel coral SOM protein sub-family. We compared the 36 SOM protein sequences to genome and transcriptome data from three other corals, three additional invertebrates, one vertebrate, and three single-celled organisms. This work represents the first extensive proteomic analysis of biomineralization-related proteins in corals from which we identify a biomineralization "toolkit" - an organic scaffold upon which aragonite crystals can be deposited in specific orientations to form a phenotypically identifiable structure.

Using the *Stylophora pistillata* genome and cell cultures to understand the mechanism of aragonite precipitation in corals.

Tali Mass, Jeana Drake, Liti Haramaty, Udi Zelzion, Debashish Bhattacharya, Yair Rosenthal and Paul Falkowski

Despite the broad interest in coral calcification and the potential for climate-driven adverse effects, the molecules and biophysical mechanism responsible for the precipitation of carbonates in corals are poorly understood. The lack of a mechanistic understanding of processes that lead to and control calcification limits our ability to predict the response of corals to increasing atmospheric CO_2. Using a draft genome assembly from the cnidarian host animal cells of the Indo-Pacific stony coral, *Stylophora pistillata* in combination with transcriptomic data from EST libraries and RT-PCR, we identified, cloned, and characterized four coral acid-rich proteins (CARPs), derived from expression of genes obtained from the common stony coral, *Stylophora pistillata*. Each of these four proteins can spontaneously catalyze the precipitation of calcium carbonate in vitro.

Our results demonstrate that coral acid-rich proteins (CARPs) not only bind Ca^{2+} stoichiometrically but also precipitate aragonite in vitro in seawater at pH 8.2 and 7.6, via an electrostatic interaction with protons on bicarbonate anions. Phylogenetic analysis suggests that at least one of the CARPs arose from a gene fusion. Similar, highly acidic proteins appear to have evolved several times independently in metazoans through convergence. Based purely on thermodynamic grounds, the predicted change in surface ocean pH in the next decades would appear to have minimal effect on the capacity of these acid-rich proteins to precipitate carbonates.

Frieder, Christina

Fertilization effects of reduced pH in temperate echinoids

Christina A. Frieder

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Some, but not all, species of echinoids have exhibited reduced fertilization at pH values within the range of ocean acidification scenarios and present-day variability. In this study, I explored the effects of pH on the fertilization ratio, the fraction of eggs fertilized, in four species of temperate echinoids; these species vary with extent of habitat overlap, depth distributions and relative genetic relatedness. Fertilization ratios were determined across a range of sperm-egg ratios at ambient, > 7.95, and low pH, < 7.55. All four species had reduced fertilization, but only within species-specific sperm:egg ranges. pH response curves were generated for two of the species, *Strongylocentrotus purpuratus* and *S. franciscanus*, by measuring the fertilization ratio at nine pH levels at a sperm-egg ratio that was shown to be sensitive to pH reductions. *S. purpuratus* maintained high fertilization across a broad range of pH. *S. franciscanus* had significant fertilization reductions at rather modest pH declines of 0.06 units from ambient pH 8.0. Further experimentation revealed changing sire identity resulted in variable fertilization ratios under decreased pH in *S. pupuratus* and *S. franciscanus*. Males with greater pH-tolerant gametes could become dominant sires with ocean acidification, representing a potential source of selection to pH stress. This information, in combination with ocean acidification predictions and understanding of how sperm-egg ratios and thus population densities regulate the magnitude of the pH response could be incorporated into management practices of the *S. franciscanus* fishery.

Evaluating ocean acidification consequences under natural oxygen and periodicity regimes: Mussel development on upwelling margins

Christina A. Frieder, Jennifer P. Gonzalez, Emily E. Bockmon, Michael O. Navarro, Lisa A. Levin

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Natural variation and changing climate on upwelling margins subject meroplanktonic organisms to broad ranges of pH and oxygen ([O_2]) levels. Semidiurnal fluctuations and upwelling events create excursions of 0.1 – 0.3 pH units and 50 - 100 µmol O_2 kg^{-1}. Here we explore in laboratory experiments the interactive effects of pH, [O_2], and semidiurnal pH fluctuations on the development and size of early life stages of two mytilid mussels, *Mytilus californianus* and *M. galloprovincialis*. Low pH at ~7.5 resulted in delayed transition from the trochophore to veliger stage, but this effect of low pH was absent when incorporating semidiurnal fluctuations in both species. Larval shells were smaller in low pH (< 7.6); this effect was absent when semidiurnal fluctuations of 0.3 units were incorporated at low pH for *M. galloprovincialis* but not for *M. californianus.* There was no effect on larval size of low [O_2] alone or in combination with pH. Larvae of the two mytilid species exhibited similar magnitudes of size reduction with reduced pH, and variation in the size response increased with decreasing pH. Early life stages of mytilid mussels appear largely tolerant to a broad range of [O_2] experienced in their environment. The results of this study reveal that incorporation of pH fluctuations characteristic of coastal settings into experimental studies of ocean acidification impacts on biological systems reduce the apparent negative consequences of declining pH. Furthermore, quantifying changes in variation of a response to pH stress can reveal early signs of perturbation to populations and potential resilience capacity.

Gagnon, Alexander

Mechanisms influencing coral biomineralization in a changing ocean

Alex Gagnon, University of Washington; Jess Adkins, Caltech; Jonathan Erez, Hebrew University Jerusalem

During biomineralization, organisms choreograph the flow of ions, manipulate aqueous speciation, and modulate surface chemistry through organic-mineral interactions. Due to differences in the intricate balance between these processes, marine calcifiers exhibit divergent sensitivities to ocean acidification. Furthermore, this response is often modulated by secondary environmental and biological factors, making the impact of ocean acidification on skeletal growth difficult to predict. A mechanistic understanding of biomineralization would resolve these problems, dramatically transforming our ability to predict and mange the impacts of ocean acidification.

We know that coral are particularly sensitive to ocean acidification through previous experiments on reef communities, mesocosms, and individual cultured specimens. Furthermore, we know that coral actively elevate the pH of the calcifying microenvironment, the extracellular space where skeletal growth occurs. Given that this biological control can override the chemistry of the surrounding seawater, how does ocean acidification impact coral growth? Furthermore, what key factors modulate this sensitivity? These questions can be answered in part through a geochemical approach to coral biomineralization. The geochemical approach harnesses compositional signatures recorded in skeletal material to generate and test biomineralization models. Specifically we have used a combination of high spatial resolution mass spectrometry, isotope labels, and coral culture to quantify ion transport dynamics and test how seawater chemistry impacts calcifying-fluid pH regulation – part of a systematic research program to identify the basic chemical rules governing calcification.

Garcia, Hernan

The U.S. National Oceanographic Data Center (NODC) Ocean Acidification Data Stewardship (OADS) project

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The US National Oceanographic Data Center (NODC), through its Ocean Acidification Data Stewardship (OADS) project, serves as the data management focal point for NOAA's Ocean Acidification Program (OAP). NODC provides scientific data management, archival, long-term preservation, online discovery, and access of ocean acidification (OA) and ocean carbon related data. OA observational and biological response rich metadata content are being developed using international standards (ISO 19115-2 and CF-compliant netCDF) to help ensure that the OA data can be utilized for optimal data discovery and interoperable online data service. While NODC's data are accessible via our Geoportal (THREDDS/OPeNDAP), we are developing a data access interface to of allow data searchers based on tailored user constrains (e.g., variables, data quality, temporal and spatial coverage, methods, instruments, data scales, standards, etc.). We are implementing computer automated data extraction scripts for archiving ocean carbon and other oceanographic data from Data Acquisition Centers such as Carbon Dioxide Information Analysis Center (CDIAC), CLIVAR & Carbon Hydrographic Data Office (CCHDO), and Biological and Chemical Oceanography Data management Office (BCO-DMO). NODC is exploring the challenges of coordinated data flow for diverse coastal and ocean monitoring, laboratory and field experiments, model output, data synthesis products, and other ocean acidification data. Additional information is available at our NODC OADS web page at http://www.nodc.noaa.gov/oceanacidification.

Garrison, David

NSF Ocean Acidification Program

Anna Manyak Davis, David Garrison

NSF Division of Ocean Sciences

National Science Foundation's Ocean Acidification Program supports basic research focused on the chemistry of ocean acidification and its interplay with fundamental biogeochemical, physiological, and evolutionary processes of organisms; the implications of these effects for ecosystem structure and function; and how the earth system history informs our understanding of the effects of ocean acidification on the present day and future ocean. Since its inception in 2009, the Program has provided approximately $43M to support nearly 50 ocean acidification-focused projects spanning the biological, chemical, and geological sciences. Funded projects have examined the effects of ocean acidification in marine environments from equatorial to polar waters and from estuaries to the open ocean. Physiological and evolutionary effects of ocean acidification have been examined on a range of calcifying and non-calcifying marine organisms, from phytoplankton to corals to fish. Now in its final year as a specifically OA focused announcement, the Ocean Acidification Program has an expected FY2014 budget of $11.25M and encourages interdisciplinary synthesis studies that use diverse approaches to answer innovative ocean acidification questions.

Grottoli, Andréa

Interactive effects of elevated pCO_2 and temperature on the physiology of four species of Pacific corals.

Andréa G. Grottoli, Mark E. Warner, Wei-Jun Cai, James Bauer, Verena Schoepf, Stephen Levas, Todd F. Melman, Kenneth D. Hoadley, Daniel T. Pettay, Xinping Hu, Yongchen Wang, Yohei Matsui

We measured the interactive effect of elevated pCO_2 (382, 607, 741 μatm) and temperature (26.5, 29°C) on coral physiology (calcification, energy reserves, organic carbon fluxes) on four species of corals: *Acropora* *millepora*, *Montipora monasteriata*, *Pocillopora damicornis*, and *Turbinaria reniformis.* Only *A. millepora* decreased calcification in response to increases in pCO_2. The other three species maintained calcification rates even when both pCO_2 and temperature were elevated. Coral energy reserves showed mixed responses to elevated pCO_2 and temperature, and were either unaffected or displayed nonlinear responses with both the lowest and highest concentrations often observed at the mid-pCO_2 level of 607 µatm. In addition, dissolved and particulate organic carbon (DOC, POC) fluxes were measured in two of the species (*A. millipora* and *T. reniformis*). Independent of temperature, DOC fluxes decreased significantly at elevated pCO_2 in both species, while POC fluxes increased at elevated pCO_2 in *T. reniformis* alone. Biweekly feeding and minimal DOC loses may have helped corals maintain calcification rates and energy reserves under these conditions. Temperature sometimes modulated the response of many aspects of coral physiology to OA, and both mitigated and worsened pCO_2 effects. Our findings show that coral energy reserves are generally not metabolized to sustain calcification under OA, which has important implications for coral health and bleaching resilience in a high-CO_2 world. Overall, these findings suggest that some corals could be more resistant to simultaneously warming and acidifying oceans than previously expected.

Hauri, Claudine

A revised view of the dynamics of carbon cycling in the Chukchi Sea

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Dynamic and complex physical and biological processes drive the carbon system chemistry of the shallow Chukchi Sea. The inflow of nutrient-rich Pacific water through the Bering Straight and sustained periods of solar radiation in summer turn this polar shelf into one of the most productive ecosystems in the world. High rates of primary production (~ 470 g C m^{-2} y^{-1}) and low pelagic grazing rates draw down pCO_2 at the surface and support large fluxes of organic carbon to a rich benthic ecosystem. Much of this carbon is remineralized, leading to elevated pCO_2 in bottom and subsurface waters, which are thought to be isolated from the atmosphere by strong stratification. Subsequent shelf to basin transport of remineralized carbon and organic matter into subsurface waters of the Arctic Ocean basin are believed to support this globally important CO_2 sink, as well as maintain high pCO_2 levels in bottom waters along their circulation-driven northward journey. Here, we document a new mechanism of carbon cycling in the Chukchi Sea that substantially reduces the net strength of this globally significant carbon sink and revises our knowledge of the dynamics of carbon cycling on this polar shelf. Surface pCO_2 measurements and wind analysis suggest that annually occurring storm-induced mixing events during autumn months disrupt water column stratification and mix remineralized carbon from subsurface waters to the surface, leading to strong outgassing of CO_2 to the atmosphere and decrease in surface pH. An improved understanding of the distribution and transport of carbon on the shelf is crucial to elucidate how the Chukchi Sea will respond to ongoing ocean acidification and climate change.

Hill, Victoria

Impact of climate warming and ocean carbonation on eelgrass (*Zostera marina* L.)

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Despite numerous successful adaptations to a submerged aquatic existence, seagrasses have high light requirements that make them vulnerable to anthropogenic disturbances. The paradoxical vulnerability results largely from their high reliance on dissolved aqueous CO_2 for photosynthesis. As with other impacts of climate change, increased concentrations of dissolved aqueous CO_2 [$CO_{2(aq)}$] in the oceans of the world will elicit both negative and positive responses among organisms, ultimately potentiating ecological losers and winners. We are exploring the response of eelgrass to increased $CO_{2(aq)}$ within the context of a warming coastal ocean using a combination of manipulative experiments, physiological/biochemical investigations and mathematical modeling. Experiments conducted during the summer of 2012 and 2013 revealed significant positive effects of CO_2 enrichment on eelgrass growth, accumulation of mobile sugar reserves, shoot survival and vegetative shoot propagation, despite prolonged exposure to water temperatures exceeding 30° C. Rising $CO_{2(aq)}$ appears to increase the high temperature tolerance of plants by improving the Q_{10} response of photosynthesis relative to respiration, thereby maintaining positive carbon balance that facilitates higher growth rates and improved survival of vegetative shoots at high temperature. The response of these Chesapeake Bay populations growing near the southern limit of eelgrass distribution on the Atlantic coast are helping us gain predictive insight into how climate change may alter the geographic distribution of this critically important species in other coastal environments that may be subjected to multiple stressors linked to climate change.

Hopkinson, Brian

Mechanistic explanations for the effects of rising CO_2 on phytoplankton and coral

Brian Hopkinson[1], Wei-jun Cai[2], Bill Fitt[1], Christof Meile[1], Anna Tansik[1], Yuening Ma[1], and Qian Ding[1].

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It is clear that rising CO_2 and accompanying ocean acidification generally increase rates of photosynthesis and decrease rates of calcification in both phytoplankton and corals. Although these responses may appear to be readily predictable, since ocean acidification decreases the concentration of the carbonate ion required to precipitate calcium carbonate and increases the concentration of CO_2 required for photosynthesis, a more thorough consideration of the physiology of calcification and photosynthesis complicates the story. Photosynthesis and calcification are carefully regulated processes occurring intracellularly or in isolated extracellular compartments. My lab investigates the role that inorganic carbon processing plays in mediating the effects of ocean acidification on marine organisms. Our results show that the response of the CO_2 concentrating mechanism to high CO_2 in marine phytoplankton is likely responsible for increased rates of photosynthesis in most phytoplankton. We have begun investigating the role that inorganic carbon processing plays in mediating decreased calcification rates in corals. In an initial characterization of carbonic anhydrase activity in corals we have found an extracellular carbonic anhydrase, critical for photosynthesis, which may allow increased CO_2 influxes at high CO_2 and contribute to acidification of the calcifying fluid.

Johnson, Zackary

Dramatic variability of the carbonate system at a temperate coastal ocean site (Beaufort, North Carolina, USA) is regulated by physical and biogeochemical processes on multiple timescales

Zackary I. Johnson, Benjamin J. Wheeler, Sara K. Blinebry, Christina M. Carlson, Christopher S. Ward, Dana E. Hunt

Although mean ocean pH is expected to decrease by ~0.2 units over the next 50 years, there is substantial temporal variability in pH and other carbonate system parameters in many ocean regions. In order to develop predictions of the future impacts and nature of ocean acidification, there is a critical need to characterize the natural range and variability of the marine carbonate system and the mechanisms responsible for this variability, especially in coastal systems. Here we present pH and dissolved inorganic carbon (DIC) at time intervals spanning 1 hour to >1 year from a dynamic coastal, temperate marine system (Beaufort Inlet, Beaufort NC USA) to quantify variability of the carbonate system at multiple time scales. Daily and seasonal variability of the carbonate system is largely driven by temperature, alkalinity and the balance between primary production and respiration, but high frequency variability (hours to days) is further influenced by water mass movement (e.g. tides) and stochastic events (e.g. storms). Both annual variability (~0.3 units) and diurnal variability (~0.1 units) in coastal ocean acidity are similar in magnitude to long term projections associated with increasing atmospheric CO_2 and their drivers highlight the importance of characterizing the complete carbonate system (and not just pH). Short term variability of ocean carbon parameters may already exert significant pressure on some coastal marine ecosystems with implications for ecology, biogeochemistry and evolution and this shorter term variability layers additive effects and complexity, including extreme values, on top of long term trends in ocean acidification.

King, Andrew

Effects of ocean acidification on phytoplankton in cultures and field-collected assemblages

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The continuing rise in atmospheric carbon dioxide (CO_2) and its dissolution in the oceans, resulting in ocean acidification (OA), could have positive and/or negative consequences for different taxonomic groups of phytoplankton. Through the use of CO_2 manipulation experiments with semi-continuous unialgal cultures and natural phytoplankton assemblages from Vineyard Sound, MA, we are assessing how OA affects phytoplankton growth rates, lipids, fatty acids, and C, N, and P content – key factors that determine nutritional support for higher trophic levels. We also have begun using gene expression and protein assays to characterize physiological mechanisms underlying the observed responses to OA in diatom species. Further, we have conducted preliminary grazer/prey feeding experiments with eastern oyster larvae fed a haptophyte cultured under different CO_2 conditions.

Kline, David

Diel, monthly, and seasonal environmental and biogeochemical variability determine ocean acidification exposure severity on a high-latitude coral reef flat

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Increasing atmospheric carbon dioxide levels are leading to global oceanic pH declines, a process termed ocean acidification (OA). Changes in diel ranges in environmental and carbonate chemistry parameters coupled with seasonal changes in the mean conditions likely define periods during the year when the reef habitat is most exposed and sensitive to extremes in temperature and pH conditions. Here we present a 6 month time series from June through December 2010 of continuous and discrete data from the Heron Island

reef flat including temperature, pH, depth, current velocity, wind, rain, light (PAR), Dissolved Inorganic Carbon (DIC), total alkalinity (TA) and derived parameters such as pCO_2 and aragonite saturation state (Ω_{AR}). Our results suggest that diel pH variability on the reef flat can be as extreme as 7.7 – 8.5 or levels of pH more extreme than those predicted for the year 2100, with the most extreme changes occurring during low tides in July (austral winter). Diel ranges in temperature were greatest during August (austral winter) with the seawater warming from austral fall to spring along with an increase in PAR. When we analyzed the pH and temperature sensitivity, exposure and vulnerability we found that the Heron Island reef flat was most sensitive and vulnerable to pH in July (austral winter) with the greatest pH exposure in September (austral winter/spring). The greatest temperature exposure and vulnerability occurred in December (austral spring) and the greatest sensitivity was in June (austral fall/winter). The cumulative threat rank was greatest in December, largely driven by the temperature vulnerability, followed by July driven largely by the pH vulnerability. Periods of high temperature and pH vulnerability did not occur during the same time, which could have implications on overall reef habitat sensitivity and biological response to climate change.

Kübler, Janet

Who benefits from ocean acidification? Prediction of acidification effects on productivity of macroalgae

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The negative effects of changing ocean chemistry are documented for many calcareous species. Here, we estimate the relative effects of ocean acidification (OA) on noncalcifying macroalgae, based on the mechanisms of inorganic nutrient uptake and available data for photosynthetic and growth rate effects of changing dissolved inorganic carbon concentration [DIC]. Our analyses predicted two groups of seaweeds that are likely to have enhanced productivity under ocean acidification. The mechanisms of enhancement for the 2 groups are different. First, the non-bicarbonate using species have no mechanism of active uptake of dissolved inorganic carbon. Those species were predicted to increase productivity via direct alleviation of inorganic carbon limitation. Our model predicts a 50% increase in photosynthesis of CO_2-using seaweeds as pCO_2 rises from 400 to 460 µatm. The modeled rate of enhancement of photosynthesis declined with further increases in pCO_2. Increased pCO_2 will enhance productivity primarily at cooler temperatures (<15°C) and in light-saturated environments. In contrast, algal species with inducible inorganic carbon-concentrating mechanisms of the well described, *Ulva* type, were predicted to have enhanced growth without enhanced photosynthesis under OA via an indirect energetic benefit of elevated [DIC] progressively downregulating two modes of active uptake of bicarbonate. Changes in physiological performances of macroalgae may affect their demography, interspecific interactions and the composition of ecosystems via these enhancements of net productivity even in the absence of changes in net photosynthetic rate.

Kuffner, Ilsa

A calcification monitoring network in the Florida Keys

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Calcification rates of coral and crustose coralline algae (CCA) are expected to decline as the oceans continue to change as a result of warming, deteriorating water quality, and absorption of carbon dioxide. In 2009, we established a calcification-monitoring network to directly measure calcification rates using a weight-based approach. Our network includes five sites across 350 km of the Florida Keys Reef Tract (FKRT). Cement blocks were installed on the sea floor to house small colonies of transplanted corals, and algal-recruitment tiles were attached to the blocks to measure net calcification of the CCA community. *Siderastrea siderea* was the first coral species we monitored. We found that calcification rates were 48 percent higher in the remote

Dry Tortugas than at the other sites, and calcification rates were 53 percent higher in summer compared to winter across all sites (Kuffner et al. 2013). CCA calcification was not as clearly seasonal, but was highest at Sombrero Reef, which is directly offshore of the Seven Mile Bridge tidal pass. Also, CCA calcification rates normalized to 2D-surface area were more than an order of magnitude less than coral calcification rates. In 2013, we began monitoring *Acropora cervicornis* and *Montastraea faveolata* to see if patterns in coral calcification are similar for other coral species. We also recently published a report detailing the methods and materials we used to set up and maintain the calcification monitoring network (Morrison et al. 2013), allowing other groups to gather compatible baseline datasets on calcification rates for regional and global comparison.

Lawson, Gareth

Ocean acidification and pteropods in the northwest Atlantic and northeast Pacific

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Thecosome pteropods are a group of aragonite-shelled zooplankton widely distributed in pelagic ecosystems and thought to be particularly sensitive to ocean acidification. Two cruises were conducted along transects between 35 and 50°N in the northwest Atlantic (Aug 2011) and northeast Pacific (Aug-Sept 2012), capitalizing on differences in the carbonate chemistry of these regions as a natural experiment to gain insight into the response of pteropods to ocean acidification. Discrete samples of DIC, TA, and pH confirmed the different chemistry of the two basins (aragonite compensation depth (ACD) ca. 2500m at 50°N in the Atlantic and 135m in the Pacific). Comparisons to previous measurements along CLIVAR lines overlapping with the present transects (A20 and P17N) allow quantification of acidification rates, revealing anthropogenic carbon invasion in the two ocean basins in the past decade. Underway measurements of fCO_2 and pH indicated strong spatial variability. Multi-frequency acoustic measurements demonstrated significant variations in the diel vertical migrations of scattering layers between hydrographic regimes, while measurements with a new broadband echosounder allowed pteropod patches to be distinguished from other scatterers. Pteropod species composition and abundance from depth-stratified nets varied with latitude and basin. The extent of pteropod vertical migrations was reduced where the ACD was shallower, although low abundances of Pacific pteropods were also observed below the ACD. None of the pteropod species examined in shipboard experiments showed a significant effect of CO_2 level on metabolic rate, but a response to low O_2 and the interaction of low O_2/high CO_2 was evident in some species.

Levin, Lisa

Exploration of geochemical proxies for larval and embryonic exposure to low pH and oxygen

Lisa A. Levin, Christina A. Frieder, Michael O. Navarro

Center for Marine Biodiversity and Conservation, Scripps Institution of Oceanography, La Jolla, CA

As dissolved oxygen ($[O_2]$) and pH decrease with climate change, especially on upwelling margins, it will become increasingly useful to have geochemical proxies that reflect larval environmental exposure history. We explored the extent to which information about pH and $[O_2]$ exposure can be obtained from larval carbonate structures (shells, statoliths) that are retained after settlement in molluscs. Controlled lab experiments were conducted to investigate pH and $[O_2]$-induced variation in single and multi-element signatures in larval carbonates of the mussels *Mytilus californianus* and *M. galloprovincialis* and in embryonic statoliths of the market squid *Doryteuthis opalescencs*. Effects of present and future reduced pH and $[O_2]$ concentrations on geochemical signatures were investigated alone (low pH *or* low $[O_2]$) and in combination (low pHOx) relative to high pH *and* $[O_2]$ (high pHOx). U/Ca and Sr/Ca in both mussel species were found to

increase with decreasing pH. Noteably, all element ratios except U/Ca exhibited ontogenetic variation with larval size. U/Ca was also enriched in embryo statoliths exposed to low pHOx, relative to high pHOx, and in low DO alone relative to high pH alone. Squid embryos exposed to low DO alone were also enriched in Sr, Ba relative to those exposed to low pH alone. Multi - elemental signatures were only moderately useful in classifying low pHOx exposure of squid (60%), but could distinguish independent low pH from low O_2 exposure (93-94%). U/Ca is a potential geochemical proxy for pH exposure of planktonic mussel larvae, and merits further study as a hypoxia indicator in squid embryos.

Liu, Xuewu Sherwood

Integrated in situ DIC and pH sensors for comprehensive CO_2 system characterizations

Xuewu Liu[1], Robert H. Byrne[1], Lori Adornato[2] and Kim Yates[3]

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Comprehensive characterizations of ocean acidification impacts on marine systems require measurements of at least two compatible CO_2 system parameters. Sustained high frequency observations of dynamic biogeochemical processes in the coastal zone require the use of in situ instrumentation. Spectrophotometric procedures allow precise measurements of compatible CO_2 system parameters, pH and DIC, using a single type of integrated in situ instrumentation. Measurements of both DIC and pH are, in principal, calibration-free and do not require periodic post-deployment evaluations in the field. Here we report results of the first field trials of paired spectrophotometric DIC and pH sensors in biofouling-prone environments. The configuration and chemistry of the SEAS-DIC sensor effectively prevents biofouling in the sensor's optical and fluidic channels. The sustained performance of the sensor in biofouling-intensive environments is enabled by an optical system that does not come into contact with seawater and a fluidic system that experiences frequent rinsing with strong acid. The acidification of the DIC sensor, which is inherent to the measurement procedure as a means of converting DIC to dissolved CO_2, allows acidic seawater byproduct to also be used as a biocide for the pH measurement channel. The integrated instrument, pairing DIC and pH measurements, and acid cleaning of optical and fluidic channels, offers greatly improved prospects for sustained in situ operations. Preliminary results from deployments in Florida Bay show that coupled SEAS-DIC and SEAS-pH sensors allow high frequency observations of carbonate saturation states.

Maas, Amy

'RNA-seq'ing the effects of CO_2 on sea butterflies: physiology and gene-expression studies of thecosome pteropods

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Woods Hole Oceanographic Institution, Woods Hole, MA 02543

Thecosome pteropods are aragonite-shelled pelagic snails that are thought to be particularly sensitive to OA. Studies indicate that decreases in aragonite saturation state have significant impacts on both shell degradation and accretion. Metabolic experiments, however, often show no significant effect of CO_2 on oxygen consumption without the addition of other interactive stressors (i.e.: food deprivation, salinity or oxygen levels). In an attempt to understand the underlying processes being affected by CO_2 we have applied RNA-seq to assess transcriptome-wide effects of exposure to elevated CO_2 on the cosmopolitan species *Clio pyramidata*. Thecosome pteropods have no published transcriptome, requiring a *de novo* assembly prior to an assessment of differential gene expression. This new assembly provides information for a suite of candidate genes that can be used to investigate the effect of ecological perturbations such as ocean acidification studies,

as well as for other ecophysiological, biomaterials and phylogenetic studies. Although oxygen consumption rates were not affected by moderate-short term CO_2 exposure (~800 ppm, ~10 h), respiration rates and gene expression profiles varied greatly among individuals. Jackknife analysis of the dataset revealed transcripts, including C-type lectins, that were differentially expressed in a subset of individuals, but broader patterns were difficult to discriminate due to individual variability. Building off of this project, we are applying similar techniques in an ongoing study to experimentally explore the effect of CO_2 on the more sensitive species *Limacina retroversa* in the Gulf of Maine over a seasonal cycle and under more stressful conditions (800 or 1200 ppm, 1-14 days).

Mackey, Katherine

Effect of ocean acidification on marine *Synechococcus*

Katherine RM Mackey, Matt McIlvin, Dawn Moran, Bill Martin, and Mak A Saito

Anthropogenic carbon dioxide (CO_2) emissions are expected to double dissolved CO_2 levels and increase surface ocean acidity 150% by the year 2100, yet information on how these changes will affect different genera of phytoplankton is currently lacking. We cultured marine *Synechococcus* under CO_2 concentrations simulating preindustrial (190ppm), modern (400ppm) and projected future levels (750ppm, IPCC 2100 "business-as-usual" scenario), and compared growth rate, photosynthetic efficiency, and protein content among the treatments. The doubling time was 13% lower in preindustrial cultures (~20.5 hr/doubling) compared to cultures under modern or future scenarios (~17.9 hr/doubling). The dark-adapted photosynthetic efficiency, Fv/Fm, was also approximately 10% lower under preindustrial conditions than under modern or future levels of CO_2. Together these observations could suggest that *Synechococcus* is carbon limited under preindustrial CO_2 levels, but is saturated under modern and future levels. Proteome analysis revealed that certain proteins involved in photosynthesis, catabolism, carbon fixation, and carbon concentrating mechanisms responded to the CO_2 treatments, while others were insensitive to CO2 concentration. Future studies will further investigate the diversity of phytoplankton biochemical mechanisms for responding to ocean acidification.

Manahan, Donal

Separating nature and nurture for improved predictions of biological responses to ocean acidification

Donal T. Manahan, Scott L. Applebaum, Francis Pan, and Dennis Hedgecock

University of Southern California, Los Angeles

The foundations of evolution by natural selection are that (1) organisms have excess reproductive capacity and (2) individuals of the same species vary extensively. Some of this phenotypic variation is heritable (Phenotype = Genotype + Environment + G×E Interaction), so that, as the environment changes, natural selection modifies gene pools and generally improves physiological resilience over time ("adaptation"). Unfortunately, these principles of Darwinian biology are often difficult to apply in research directed at understanding the potential impact of global change on marine organisms because of the difficulties of measuring G×E Interactions. Considerable evidence suggests that future scenarios of ocean acidification (OA) will impact the metabolism of marine organisms. In this project, we are quantifying the bases of genotype-by-environment interactions in response to OA in the bivalve *Crassostrea gigas*, a species that has genetic and genomic resources that are unparalleled for most marine animals. Our findings highlight that major changes in rate processes at the biochemical level result in differential allocation of energy in response to OA. Biological variance in the ability of organisms to re-allocate energy usage suggests that some individuals have greater genetically determined physiological resilience to environmental stress. Understanding the genetic, cellular, and physiological mechanisms of this resilience will greatly improve abilities to predict potential to adapt to environmental change.

McClintock, James

Effects of reduced carbonate saturation state on early development in the edible sea urchin *Lytechinus variegatus* raised in artificial seawater

Roberta Challener, James McClintock, and Roberta Makowsky

Land-based aquaculture facilities often utilize additional bicarbonate sources to boost alkalinity in order to buffer seawater against reductions in pH. Despite these preventative measures, many facilities are likely to face periodic reductions in pH and corresponding reductions in carbonate saturation states due to the accumulation of metabolic waste products. We investigated the impact of reduced carbonate saturation states (Ω_{Ca}, Ω_{Ar}) on embryonic developmental rates, larval developmental rates, and echinoplutei skeletal morphometrics in the common edible sea urchin *Lytechinus variegatus* under high alkalinity conditions. Fertilized sea urchin eggs pooled from several adults were distributed among 5 x 1 liter glass beakers per treatment and maintained for 5 days without food. Rates of embryonic and larval development were significantly delayed in both the low and extreme low carbonate saturation state treatments relative to the control at a given time. Larvae reared under ambient control conditions had significantly greater skeletal postoral arm lengths and overall skeletal body lengths relative to skeletal body lengths than larvae grown under extreme low carbonate saturation state conditions, indicating that changes in the carbonate system can impact not only developmental rates but also larval skeletal morphology. Reduced rates of embryonic development and delayed and altered larval skeletal growth are likely to negatively impact larval culturing of *L. variegatus* in land-based, intensive culture conditions where calcite and aragonite saturation states are lowered by the accumulation of metabolic waste products.

Taking your research to the public: Leveraging a popular book to educate millions of people about ocean acidification and climate change

James B. McClintock

Authoring a popular book with an important environmental narrative can synergize opportunities to educate the general public that greatly exceed direct readership. In this poster, I convey how a friendship with EO Wilson encouraged me to author a book about my research and adventures in Antarctica set against a narrative of the ecological impacts of rapid climate change and ocean acidification. To maximize the book's educational outreach, I recruited internationally renowned authors, entrepreneurs, and scientists to contribute book jacket blurbs. This, in turn, facilitated interviews on NPR including the "Diane Rehm Show" and "On Point with Tom Ashbrook", along with book promotion tweets by Bill Gates, Al Gore, and Sylvia Earle. Media attention surrounding the book spawned book reviews in magazines including Smithsonian and Nature, and newspaper articles on climate change and ocean acidification. Invitations followed to write Op Ed pieces for the Birmingham News and the Huffington Post. An appointment to the Advisory Board of the E.O. Wilson Biodiversity Foundation resulted in the production of a video narrated by Harrison Ford based on a chapter of the book that describes the dramatic decline in Adelie penguins on the Antarctic Peninsula (the video is being featured in aquariums and zoos across America). In summary, while sales of the book are likely to number in the tens of thousands, in the larger picture the book has facilitated the education of several million Americans on the pressing issues of climate change and ocean acidification. Supported by an Endowed University Professorship to J.B.M.

McCorkle, Dan

Continuous, autonomous measurement of the CO_2 system in Waquoit Bay, MA

W.R. Martin[1], F.L. Sayles[1], D.C. McCorkle[2], and C. Weidman[3]

[1] Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, [2] Department of Geology and Geophysics, Woods Hole Oceanographic Institution, [3] Waquoit Bay National Estuarine Research Reserve

The chemistry and biology of coastal systems are impacted by processes occurring on tidal, diurnal, and seasonal cycles, as well as by unpredictable, discrete events. Continuous, autonomous measurements are essential for determining the impact of these processes on carbon cycling and seawater acidity. We deployed RATS, the Robotic Analyzer for the Total CO_2 System in Seawater, to make high-precision, in situ measurements of pH and TCO_2, with a sampling frequency of 2.5 hours and including on-board calibration, for 35 days in June / July, 2013, in Waquoit Bay, MA. We combined these measurements with continuous salinity, temperature, water depth, and O_2 measurements made by the Waquoit Bay National Estuarine Research Reserve and with additional WBNERR environmental data. There is a clear diurnal signal in TCO_2 and pH, whose intensity varies with incident radiation. The strongest signals in TCO_2 and pH are associated with photosynthesis and respiration: pH increased and TCO_2 decreased during the day, and the reverse at night. The daily ranges were as much as 600 µmol/kg in TCO_2 and a factor of 10 in $[H^+]$. Deviations from this signal, perhaps representing groundwater input, were apparent at tidal frequencies. The diurnal fluctuations of summertime TCO_2 and pH were as large as the observed seasonal variations in Waquoit Bay. Continuous, two-parameter carbonate system measurements will make it possible to quantify the natural variability in the carbon cycle in coastal waters, and to quantify the effects of anthropogenic perturbations of the carbon cycle, including eutrophication and ocean acidification, on coastal ecosystems.

McElhany, Paul

Ecological effects of ocean acidification along the U.S. west coast: Integrating experiments and models

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Predictions of the ecological effects of ocean acidification are essential for the development of effective adaptation, mitigation, and prevention strategies. Because large-scale ocean acidification experiments on intact marine ecosystems are generally impractical, ecological prediction typically relies on extrapolating results from small-scale laboratory studies on individual species to modeled effects on entire populations in the context of complex food webs. This process leads to inevitable uncertainties about ecosystem response. Using as an example the research at the NOAA Northwest Fisheries Science Center, which includes both laboratory experiments and ecosystem modeling, we explore the potential promise of and challenges in developing a comprehensive understanding of the ecological effects of ocean acidification in the California Current and its associated estuaries.

Mekik, Figen

Carbonate preservation in pelagic sediments: Developing a new aragonite preservation proxy

Figen Mekik

Grand Valley State University

Ocean acidification already impacts marine benthic and planktonic organisms where calcification waters are under-saturated with respect to aragonite and/or calcite. The further shoaling of the aragonite saturation horizon is expected to change the geographic distribution of organisms with aragonite shells, such as many corals and pteropods. While we can directly observe some of these changes in the modern ocean, reconstructing the marine saturation state of aragonite in the geological record and detecting paleo-ocean acidification/ alkalization events can only be accomplished with a proxy from marine sediments. There is an established calcite dissolution proxy (*G. menardii* Fragmentation Index-MFI) to identify past ocean acidification/alkalization events. We are currently developing another proxy tracing aragonite preservation in sediments under shallow and intermediate waters of Pacific, Atlantic and Indian Oceans using pteropod

shells. Ultimately, we will join our new aragonite preservation proxy with MFI to trace $CaCO_3$ preservation in sediments of all water depths. A reliable and quantitative indicator of aragonite preservation in deep sea sediments has many applications, such as [1] discerning geographic and hydrographic shifts in benthic and planktonic calcifier communities driven by ocean acidification or alkalization events, both now and in Earth's past; [2] gaining insights into ocean circulation changes and water mass boundary changes; [3] gaining insights into changes in ocean carbonate chemistry on glacial-interglacial timescales; and [4] identifying other factors that may cause dissolution of $CaCO_3$ unrelated to ocean carbonate chemistry, such as changes in fluxes of $CaCO_3$ and organic carbon to the deep sea.

Milke, Lisa

Physiological effects of elevated CO_2 on Atlantic surf clams

Lisa Milke[1], James Widman[1], Anne Cohen[2] and Dan McCorkle[2].

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The Atlantic surfclam, *Spisula solidissima,* is found from the Gulf of St. Lawrence to Cape Hatteras and the commercial fishery was worth $28.1million in 2010. Due to the surfclam's economic importance, and previous work demonstrating susceptibility of bivalve larvae to elevated CO_2 concentrations, a series of experiments were designed to examine 1) impacts of CO_2 concentrations on larval development and 2) interactions between CO_2 concentration and food quantity; i.e., if food availability has the ability to mitigate potential negative impacts of increased CO_2. Surfclam embryos were exposed to 380, 1200, or 2200 ppm CO_2 and fed 400 to 40,000 cell ml^{-1} of the microalgae *Isochrysis sp.* (Tiso). Sampling for growth, mortality and tissue biochemistry was conducted at various time points during five 3-15 day experiments conducted over the last three years. Preliminary results were variable across years. For example, after 6 days of development, smaller shell lengths are observed in animals exposed to 2200ppm in comparison to 380 or 1200ppm during the first year, but in year two, only animals exposed to 1200 ppm CO_2 exhibit reduced shell length in relation to those under ambient conditions. A third year of experiments was just completed, and analysis of growth and mortality data is underway. Samples for shell mass and tissue biochemistry are also being processed, with the intention that these metrics will further elucidate effects of CO_2 and nutrition on larval health.

Mooney, T Aran

CO_2 level-dependent effects of ocean acidification on squid early life history

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Early life stages of invertebrates may be particularly vulnerable to the influence of ocean acidification due to their developing, and often incomplete, physiological systems and critical life phases. Impacts to cephalopods are of concern because of the central role they play in many ocean ecosystems and because of their importance to global fisheries. These organisms' successful early development is largely dependent on the conditions of their surrounding environment. Our early work has shown Atlantic longfin squid (*Doryteuthis pealeii*), an ecologically and economically valuable taxon, raised under elevated pCO2 demonstrate significant developmental changes, including increased time to hatching and shorter mantle lengths. Aragonite statoliths, critical for balance and detecting movement, had significantly reduced surface area and were abnormally shaped, with increased porosity and altered crystal structure, in elevated pCO2-reared paralarvae. Our current research now incorporates multiple pCO2 levels along with detailed behavioral and metabolic assays. New evidence now suggests impacts are dependent upon pCO2 levels and significant impacts are found

across a range of levels. These developmental and physiological effects could alter squid paralarvae behavior and survival in the wild, directly and indirectly impacting marine food webs and commercial fisheries.

Early life stages of invertebrates may be particularly vulnerable to ocean acidification influences due to their developing, but often incomplete, physiological systems and critical life phases. Impacts to cephalopods are of concern because of the central role they play in many ocean ecosystems and because of their importance to global fisheries. These organisms' successful early development is largely dependent on conditions of the surrounding environment. Our early work has shown Atlantic longfin squid (*Doryteuthis pealeii*), an ecologically and economically valuable taxon, raised under elevated pCO_2 demonstrated significant developmental changes including increased time to hatching and shorter mantle lengths. Aragonite statoliths, critical for balance and detecting movement, had significantly reduced surface area and were abnormally shaped with increased porosity and altered crystal structure in elevated pCO_2-reared paralarvae. Our current research now incorporates detailed behavioral and metabolic assays. New evidence now suggests impacts are dependent upon pCO_2 levels and significant impacts are found across a range of levels. These developmental and physiological effects could alter squid paralarvae behavior and survival in the wild, directly and indirectly impacting marine food webs and commercial fisheries.

Morel, Francois

Effect of carbon dioxide on the carbon:nitrogen ratio of marine diatoms under nitrogen-limitation

Jenna L. Losh and François M. M. Morel

Department of Geosciences, Princeton University, Princeton, New Jersey 08544

Photosynthetic carbon fixation by marine phytoplankton and sinking of the biomass sequester CO_2 in deep seawater, helping to maintain low concentrations of atmospheric CO_2 and providing a potential feedback to the ongoing CO_2 increase. If nitrogen inputs to the surface ocean remain the same, a change in carbon export in N-limited ocean regions is possible only through a change in the C:N stoichiometry of the biomass. It has been shown that the C:N ratio of N-limited coccolithophores increases at high CO_2 concentrations and we confirmed this result with N-limited continuous cultures of *Emiliania huxleyi*. In similar experiments with the model diatoms *Thalassiosira weissflogii* and *Thalassiosira oceanica*, the C:N ratio of the biomass increased significantly at very low CO_2 across several growth rates. But at increasing concentrations of CO_2 up to 1000 ppm, the C:N ratio of the diatom biomass did not change significantly. Because diatoms are major contributors to the biological pump, these results, if confirmed, imply that little change should be expected in the stoichiometry of the sinking biomass as CO_2 increases in the oceanic regions that are limited by nitrogen. Unlike land plants, marine phytoplankton are unlikely to significantly increase the sequestration of CO_2 and provide a negative feedback to the ongoing increase in atmospheric CO_2.

O'Donnell, Michael

The west coast ocean acidification and hypoxia science panel

Michael J. O'Donnell, The California Ocean Science Trust

The West Coast Ocean Acidification and Hypoxia Science Panel (Science Panel) is a high-level panel convened to provide state-level decision makers with the knowledge needed to evaluate and develop action plans for this complex issue. The regional scope and membership of the Science Panel reflects the west coast-wide nature of the potential impacts of ocean acidification and hypoxia, and the unique drivers of ocean acidification and hypoxia along the California Current. The Science Panel consists of an interdisciplinary team of experts from California, Oregon, Washington and British Columbia.
The Science Panel will address core science questions identified by resource managers as critical to advancing their understanding of these issues:

1. What are the naturally occurring variations in acidification and hypoxia parameters in both space and time?
2. To what extent have, or are, we going to deviate from "naturally occurring variations" as identified in Q1?
3. How much do regional and local inputs affect the deviations identified in Q2?
4. What are the consequences of the deviations identified under Q2 for uses or ecological resources of our coastal oceans?
5. What research and monitoring would most efficiently fill critical information gaps encountered by the Panel in answering these questions?

The Science Panel will also identify the research and monitoring needed to contribute to a west coast-wide assessment of ocean acidification and hypoxia, and address information and data gaps critical to resource management decisions.

Orellana, Monica

A systems approach of diatom responses to ocean acidification

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[1]Institute for Systems Biology, USA. [2]University of Washington, USA.

Diatoms are important primary producers that play an critical role in the marine carbon cycle, and over geological times have influenced the global climate. Our goal is to understand and to predict the systems-wide responses of diatoms to environmental changes in the marine environment. We have conducted genome-wide transcription profiling of the model diatom *Thalassiosira pseudonana* during growth at two CO_2 levels: present day (400 ppm) and a doubling of the CO_2 level (800 ppm), reflecting the projected scenario for the 21st century. In this poster presentation we will focus on replicate analyses of the physiological and molecular modes associated with the cells state under the two CO_2 conditions. Our results show that most of the expressed genes associated with the difference in CO_2 growth are unknown, not annotated or hypothetical genes (800 genes). These genes changed in expression mostly under stationary phase, when nutrients were depleted from the media and the cells were undergoing starvation.

Real world, hands-on, inquiry- and systems-based high school ocean acidification curriculum through unique partnerships

Claudia M Ludwig[1], Mónica V Orellana[1,2], Nitin S Baliga[1, 2]

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Ocean acidification is a complex phenomenon with complex consequences. Understanding complexity and the impact of ocean acidification requires systems thinking and collaboration, both in research and in education. Scientific advancement will help us better understand the problem and devise more effective solutions, but executing these solutions will require widespread public participation to mitigate this global problem. We have translated current systems-level ocean acidification research into a classroom module, promoting conceptual development of standards based instructional outcomes.

A hands-on, interdisciplinary five week curriculum allows students to take on the roles of scientists and delegates as they investigate the consequences of the changing carbon cycle on the physics, chemistry, and biology of the oceans. They critically assess different pieces of information (news articles and real-time data from Puget Sound and oceans across the world) and combine their findings into a network diagram that interconnects key players of this system. Students probe the network for predicting effects of changing CO_2. They design experiments to test network properties and explore the consequences of increased CO_2 levels on pH of water, the integrity of seashells, and the lifecycle of diatoms. The module connects to other pertinent lessons (University of WA, the University of Hawaii C-MORE Program, NOAA, the Sea Urchin Ocean Acidification online simulation, and the NRDC developed video "Acid Test"). In the culminating activity, students act as delegates when reconvening to discuss the systems consequences of ocean acidification. They make recommendations for further research, policy-making, and lifestyle changes.

Passow, Uta

The effect of high CO_2 conditions on production, partitioning and fate of organic matter (NSF: OCE-1041038)

Anna James[1], Jan Taucher[3], Craig Carlson[1,2], Mark Brzezinski[1,2], Uta Passow[1]

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Increasing CO_2 concentrations are expected to alter pathways and processing of carbon through marine food-webs, and determine whether or not the ocean continues to be a sink for carbon. This project investigates potential effects of transient increases in CO_2 as experienced during upwelling on (i) the partitioning of carbon between the dissolved and particulate pools (DOC vs. POC) during phytoplankton growth. POC and DOC follow different paths through pelagic ecosystems: Whereas POC may be exported via sedimentation DOC is either recycled within the surface layer, or, if it is recalcitrant, may be exported by physical processes. Thus we also investigated (ii) if the bioavailability of DOC generated under different pCO_2 conditions is effected and (iii) if the microbial utilization of DOC is a function of pCO_2.

During exponential growth of the diatom *Thalassiosira weissflogii* POC production was a function of temperature only. In contrast, DOC production was elevated at increased pCO_2 levels (1000 ppm) compared to ambient (400 ppm) levels at 15°C, and less so at 20°C. The bioavailability of harvested DOC, which was investigated at ambient conditions using a natural bacterial community, showed distinct differences: At both temperatures more of the DOC produced under the high pCO_2 conditions was utilized, but less efficiently, compared to that produced within ambient pCO_2 treatments. Enhanced pCO_2 also had a direct effect on the processing of organic matter by naturally occurring bacterioplankton. Bacterioplankton respired more DOC and utilized it less efficiently if incubated at high (1500 ppm), compared to low pCO_2 conditions (250ppm).

Paytan, Adina

Reduced calcification and lack of acclimatization by coral colonies growing in areas of persistent natural acidification

Elizabeth D. Crook, Anne L. Cohen, Mario Rebolledo-Vieyra, Laura Hernandez, and Adina Paytan

As the surface ocean equilibrates with rising atmospheric CO2, the pH of surface seawater is decreasing with potentially negative impacts on coral calcification. A critical question is whether corals will be able to adapt or acclimate to these changes in seawater chemistry. We use high precision CT scanning of skeletal cores of Porites astreoides, an important Caribbean reef-building coral, to show that calcification rates decrease significantly along a natural gradient in pH and aragonite saturation (Ωarag). This decrease is accompanied by an increase in skeletal erosion and predation by boring organisms. The degree of sensitivity to reduced Ωarag measured on our field corals is consistent with that exhibited by the same species in laboratory CO2 manipulation experiments. We conclude that the Porites corals at our field site were not able to fully acclimatize enough to prevent the impacts of local ocean acidification on their skeletal growth and development, despite spending their entire lifespan in low pH, low Ωarag seawater.

Phillips, Jennifer

CO_2-induced acidification of the Laurentian Great Lakes

Jennifer C. Phillips[1], Galen A. McKinley[1], Val Bennington[1], Harvey A. Bootsma[2], Darren J. Pilcher[1], Robert W. Sterner[3], Noel R. Urban[4]

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A number of studies indicate that air-water equilibration is the dominant control on pCO_2 in several Great Lakes at annual timescales or longer. Assuming this is the case across all lakes at present and into the future, we show that pH will decline by 0.3-0.4 units through 2100 under a business-as-usual CO_2 emission scenario. In a survey of the Great Lakes scientific community, 87% of respondents indicate that CO_2-driven acidification is likely. The available pH data do not support these predicted trends, but limited sampling in an environment characterized by significant spatio-temporal variability, as well as significant measurement uncertainty, cast doubt on the ability of the historical pH record to resolve the predicted trends. Evaluation of the current sampling strategy using eddy-resolving numerical models of Lake Superior and Lake Michigan are key evidence that the current monitoring strategy is inadequate. In order to track long-term pH change and assess whether atmospheric CO_2 will affect the Great Lakes like the oceans, a new approach to Great Lakes pH monitoring is required. Ecological impacts of CO_2 acidification have not been studied for the Great Lakes, but potential effects can be gleaned from the literature. In addition, our qualitative and quantitative survey results suggest that processes such as fish recruitment, dreissenid mussel growth, and nutrient cycling may be sensitive to pH, but there is lack of consensus about the magnitude and overall significance of these effects.

Reisdorph, Stacey

The dynamic controls on carbonate mineral saturation states in a glacially dominated estuary: Glacier Bay, Alaska

Stacey C. Reisdorph and Jeremy T. Mathis

Recently, a number of studies have shown that the intrusion of anthropogenic carbon dioxide (CO_2) into the ocean has created an acidification effect leading to the reduction in carbonate mineral concentrations. However, the uptake of atmospheric CO_2 is not the only climate-induced phenomenon that leads to a reduction of carbonate mineral saturation states (Ω). Over the past ~250 years, Glacier Bay, AK (GLBA) has experienced rapid deglaciation leading to an increase in the amount of freshwater entering the marine ecosystem. This excess freshwater discharge is low in total alkalinity and reduces the buffering capacity of surface waters, while enhancing the vulnerability of the estuary to further reductions in pH. The suppression of Ω provides the potential for these waters to become corrosive to shell-building organisms. To better understand these processes, we collected monthly samples within GLBA that show the variability in Ω throughout the water column. Low Ω's were well correlated to maximum glacial discharge rates and most prominent within the two regions where tidewater glacial discharge was highest. The saturation state of aragonite reached a minimum of 0.40 during the summer of 2011 before rebounding to a maximum value of 3.26 in the spring of 2012. Aragonite was undersaturated at the surface throughout the entire bay during fall months (Sept. and Oct.). Here, we present results from a year long study designed to better understand the effects of glacial freshwater discharge on the marine carbonate system and discern the primary controls on Ω in this pristine estuarine environment.

Robbins, Lisa

Approximately 20% of Canadian Basin surface waters are undersaturated with respect to aragonite

Lisa L. Robbins[1], Jonathan G. Wynn[2], Paul O. Knorr[1], John Lisle[1], Robert H. Byrne[3], Taro Takahashi[4], Bogdan P. Onac[2], Kim K. Yates[1], Kumiko Azetsu-Scott[5], Xuewu Liu[3], and Mark C. Patsavas[3]

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Models project that the Arctic Ocean will become undersaturated with respect to carbonate minerals such as aragonite (CaCO3) in the next decade. Recent field results indicate that in August-September when ice melt is at its greatest extent 20% of the Arctic Ocean is already undersaturated with respect to aragonite. Causal factors of this undersaturation have recently been explored and likely involve feedbacks associated with environmental changes in the region, including increasing atmospheric pCO2, changes in sea surface temperature, increased terrestrial freshwater runoff and reduction of the extent, thickness, and duration of sea-ice cover. Arctic Ocean marine ecosystems and associated organisms are projected to respond to these rapidly changing environmental conditions.

In order to establish a baseline that fills critical information gaps concerning saturation state of the Arctic, we collected high-resolution measurements of pCO2, pH, total dissolved inorganic carbon (DIC), total alkalinity (TA), and carbonate ([CO3-2]) from the Canada Basin, up to 88.45'N during August through September of 2010, 2011 and 2013. We supplemented ecosystem-wide stable oxygen isotope data and biological data with carbonate chemical data to demonstrate the effects of increased freshwater derived predominantly from sea-ice melt (fSIM). These data document dramatic differences in aragonite undersaturation and pCO2 over surface waters of the Canada and Makarov Basins in the Western Arctic Ocean. Based on the limited available data, summer surface Ωaragonite in this area decreased at an estimated rate of 2.1% yr-1 since August 1997.

Runge, Jefferey

Effects of ocean acidification on reproductive processes of the marine planktonic copepod *Calanus finmarchicus*

Preziosi, B[1]., Runge, J.[1*], Christensen, J.[2] and Jones, R[3].

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Calanus finmarchicus is a dominant copepod species in the North Atlantic and a fundamental link in marine food webs across its range. This project investigated whether higher CO_2/lower pH at expected future levels will cause a significant decrease in *C. finmarchicus* egg hatching success. Eggs were exposed to seawater of varied pH ranging from 8.0 (ambient) to 6.7. A series of experiments were conducted, each of which consisted of a control and up to 5 treatments maintained by bubbling a gas mixture of O_2, N_2, and CO_2 at a predetermined rate. The calculation of pH is based on measurements of titration alkalinity, total CO_2, salinity and nutrients in control and treatment tanks. Females were sorted from the catch of zooplankton from nearby Gulf of Maine coastal waters and incubated to obtain eggs. Replicate batches of eggs were placed into dishes with 80-μm mesh lids to allow for water exchange in control and treatment tanks. Experiments were conducted at 6°C and at 15°C. The latter temperature is near the upper thermal limit for *C. finmarchicus* hatching success, in order to simulate the combined stress of temperature and pH in surface waters of the Gulf of Maine, where the species has been very productive historically. Results indicate that there was no significant effect of higher CO_2/lower pH on egg hatching success across treatment levels at either experimental temperature.

Sabine, Chris

Autonomous ocean carbon monitoring using a moored dissolved inorganic carbon sensor

Andrea Fassbender, Christopher Sabine, Christian Meinig, Noah Lawrence-Slavas

The ocean plays a major role in the global carbon cycle, and thus in global climate, through the uptake and redistribution of atmospheric carbon dioxide (CO_2). Since industrialization, the ocean has reversed its role from a small global source of CO_2 to the atmosphere to a major atmospheric CO_2 sink. This role reversal has resulted in measurable ocean chemical changes, including a decline in seawater pH termed ocean acidification. Most of the CO_2 stored in the ocean accumulates as dissolved inorganic carbon (DIC), but we do not have good observations quantifying temporal DIC variability on regional scales. To address this, we have developed a prototype autonomous DIC sensor that can be deployed on moorings. Building off of the NOAA PMEL moored pCO_2 system ($MapCO_2$; now commercially available through the Battelle Memorial Institute) the DIC instrument has been adapted to recirculate a fixed volume of initially-CO_2-free air through ~1mL of acidified seawater. At equilibrium, the CO_2 concentration of the gas stream is measured using infrared detection and the quantity of CO_2 evolved from the sample is determined using the ideal gas law. This fast and efficient technique is similar to techniques that have been used reliably on shipboard underway DIC systems, but has not previously been adapted for long term, moored DIC measurements. Preliminary tests in the lab and under *in situ* conditions using Puget Sound water at the Seattle Aquarium illustrate that this system will be useful for ocean acidification studies.

Seibel, Brad

On the measurement and interpretation of whole-animal metabolic rates in ocean acidification studies

Brad A. Seibel

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Organismal metabolism, typically measured as a rate of oxygen consumption, is a complicated metric that includes the sum costs of all energy intensive processes and activities. It may be a sensitive indicator of organismal stress but the interpretation of changes in metabolism is not straightforward. Here I provide information on the factors known to influence metabolism, synergism between those factors, the direction of the expected response, and the mechanisms leading to a response. I review important methodological requirements for the measurement of metabolism. I provide examples of metabolic changes that result from synergistic effects of temperature, oxygen, feeding history, body size, environmental history and acidification. In particular, I focus on recent work in polar pteropods, showing that feeding history can mask the effects of CO_2 on whole-animal metabolism, and oceanic squids that become oxygen-limited due to a highly pH-sensitive respiratory protein in the blood. Both cases result in reductions in metabolism with increasing CO_2, in contrast to the elevation in metabolism often predicted to result from increased costs of ion transport under ocean acidification scenarios.

Shadwick, Elizabeth

Vulnerability of polar oceans to anthropogenic acidification: Comparison of Arctic and Antarctic seasonal cycles

Elizabeth H. Shadwick[1], Thomas W. Trull[1,2], Helmuth Thomas[3], and John A. E. Gibson[1]

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Polar oceans are chemically sensitive to anthropogenic acidification due to their relatively low alkalinity and correspondingly weak carbonate buffering capacity. Here, we compare unique CO_2 system observations covering complete annual cycles at an Arctic (Amundsen Gulf) and Antarctic site (Prydz Bay). The Arctic site experiences greater seasonal warming (10 vs 3°C) and freshening (3 vs 2), has lower alkalinity (2220 vs 2320 ⌠mol/kg), and lower summer pH (8.15 vs 8.5), than the Antarctic site. Despite a larger uptake of inorganic carbon by summer photosynthesis, the Arctic carbon system exhibits smaller seasonal changes than the more alkaline Antarctic system. In addition, the excess surface nutrients in the Antarctic may allow mitigation of acidification by lowering CO_2 with enhanced summer production driven by iron inputs from glacial and sea-ice melting. These differences suggest that the Arctic system is more vulnerable to anthropogenic change due to lower alkalinity, enhanced warming, and nutrient limitation.

Siedlecki, Samantha

Ocean acidification of the coastal waters of the Pacific Northwest: A modeling study

Siedlecki, S.A., Hermann, A., Bond, N., Alin, S., Feely, R., Hales, B., Newton, J.

A regional oxygen model of the Washington and Oregon shelves (Siedlecki, S.A., Banas, N., Davis, K.A., Giddings, S., P. MacCready, Connolly, T., & B. Hickey. Seasonal Oxygen variability on the continental shelves of Washington and Oregon, in prep) is combined with the empirical relationships between the carbonate system, oxygen and temperature (Alin et al, in prep) to simulate the carbonate chemistry in this region. A model hindcast for 2009 is compared to local observations of oxygen, and aragonite saturation. The model is able to reproduce the seasonal change in oxygen observed on the Oregon shelf. Challenges of this approach are discussed. The volume of hypoxic and undersaturated water increases over the upwelling season, occupying more of the water column later in the upwelling season. This results in increasingly stressful conditions over most of the water column for biota on the shelf as the upwelling season progresses. Spatial variability in the volume of undersaturated water in the region will be discussed.

Schnetzer, Astrid

Short-term changes in overall community structure and diversity within a marine natural protistan assemblage in response to changed pCO_2 concentration assessed by high-throughput sequencing

Schnetzer A., Jones AC., Tatters AO., Fu F., Lie AYA., Hutchins DA. and Caron DA.

Little is known about the impact of ocean acidification on marine protistan communities. This lack of knowledge is partly due to the difficulties entailed in assessing community structure within microbial eukaryote assemblages, which are highly complex and diverse. However, an understanding of how changed pCO_2 affects species composition within algal and protozoan communities, main primary producers and important secondary consumers in marine systems, is required if we aim to predict how global climate change can implicate energy transfer within planktonic systems and affect ecosystem function. We employed high-throughput sequencing (targeting the V4 and V9 region of the ribosomal 18S) to investigate responses to changed pCO_2 (190, 380 and 750 ppm) within a natural protistan assemblage from Southern California coastal waters.

Stillman, Jonathon

Physiological responses of the porcelain crab *Petrolisthes cinctipes* to simultaneous exposure to increased variability of pCO_2, temperature and emersion.

Adam W. Paganini, Nathan A. Miller, and Jonathon H. Stillman.

Romberg Tiburon Center and Department of Biology, San Francisco State University.

Intertidal zone organisms experience daily, dramatic, fluctuations in temperature and pH. These fluctuations are expected to increase along the California coast under future climate scenarios. How intertidal organisms respond to variability in temperature and pH has not been previously examined, even though an accurate understanding of how coastal organisms will respond to ocean warming and acidification must include consideration of realistic current and future levels of habitat variability. We investigated performance of the porcelain crab, *Petrolisthes cinctipes*, under interactive conditions of variation in temperature and pH. Adult *P. cinctipes* were exposed to three temperature spikes during a simulated daytime low tide (11°C, 25°C or 30°C), or were held submerged at 11°C. At night the crabs in each treatment were exposed to three pH levels: constant pH (8.1), or pH spikes to 7.6, or 7.15. Following two weeks of acclimation, we measured respiration rates at 11°C and 18°C and upper thermal limits of cardiac performance (CT_{max}). Metabolic depression was observed in crabs that experienced aerial daily heat spikes, and the depression was stronger in low pH acclimated individuals. CT_{max} was elevated with acclimation temperature, and the elevation was higher under low pH acclimation, suggesting elevated basal maintenance costs. Our results indicate that there are interactive effects of pH and temperature variability on the temperature sensitivity and thermal limits of these intertidal zone crabs, and that the combination of low pH with elevated temperature causes a metabolic state that is likely not ecologically sustainable for these crabs.

Tresguerres, Martin

Coral cellular physiology: mechanisms for CO_2/pH sensing, calcification, carbon concentration and metabolic pathways

Martín Tresguerres, Dimitri Deheyn, Megan Barron, Lauren Linsmayer, Sidney Pérez and Katie Barott

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Understanding and predicting potential effects of OA on organisms requires that we first understand their basic cell biology. We have focused on four essential physiological processes in corals: CO_2/pH-sensing and signal transduction, calcification, carbon concentrating (CC) for zooxanthellae photosynthesis and balance between aerobic and anaerobic metabolic pathways. We have identified and characterized the evolutionarily conserved acid/base-sensing enzyme soluble adenylyl cyclase (sAC); our results suggest that sAC regulates calcification, CC and gene expression via the cAMP-signaling pathway. Immunolocalization revealed that proton pumps are highly abundant in the symbiosome membrane of gastrodermal cells and respirometry experiments confirmed proton pumps are essential for photosynthesis of the symbiotic zooxanthella. Additionally, proton pumps are present in the basolateral membrane of aboral gastrodermal cells, suggesting a role in calcification. The sodium/potassium ATPase is abundantly present in calicoblastic cells, which also suggests a role in calcification. There were some differences in the cellular localization and abundance of these proteins between two species of corals (*Acropora yongei* and *Stylophora pistillata*), indicating species-specific mechanisms and therefore potential differential responses to OA. Finally, we are attempting to biochemically characterize aerobic and anaerobic metabolic pathways in corals and their relative contributions during day (light) and night (dark). These types of results are essential to be able to interpret results from shotgun genomic, transcriptomic, and proteomic analyses, understand the effects of OA, and develop monitoring tools based on mechanistic models.

van Hooidonk, Ruben

Creating ocean acidification products

Ruben van Hooidonk

NOAA AOML, Miami

Currently at AOML we are improving an experimental monitoring product that maps ocean acidification (OA) variables in the Caribbean and Gulf of Mexico using remote sensing to provide now-casts of the sate of OA in the region. By leveraging of the current OA programs that take in-situ measurements we can BOTH validate and tune the empirical algorithms that calculate the required variables to calculate aragonite saturation state and other PERTINENT parameters of the carbonic acid system. Here we present the preliminary results of of our new remote sensing product and show comparisons to in-situ data.

To assess the risks of ocean acidification to marine life on longer time scales, accurate models are required to make forecasts. To accomplish this an ensemble of fully coupled global climate change models that include a bio-geochemical component have been used to model future ocean acidification. Ocean acidification trajectories have been modeled for four emission scenarios included in IPCC AR 5. Here we present results relevant to coral reef ecosystems, including effects on calcification rates. We also present a product, in the form of a Google Earth tool, developed to aid stakeholders such as managers of coral reefs to interpret ocean acidification impacts and describe to community members the need for actions to reduce stress to reefs.

Wang, Zhaohui Aleck

Coastal ocean acidification in the Gulf of Maine: Potential drivers and impacts

Zhaohui Aleck Wang[1], Cynthia H. Pilskaln[2], Amy Maas[3], Kazuhiro Hayashi[2], and Gareth L. Lawson[3]

[1] Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, [2] School for Marine Science and Technology, University of Massachusetts Dartmouth, [3] Biology Department, Woods Hole Oceanographic Institution

Recent studies indicate that the Gulf of Maine (GoME) may be more susceptible to ocean acidification than has previously been thought due to its low buffer capacity, low pH, and low calcium carbonate saturation. Our latest measurements in the deep Wilkinson Basin suggest that the subsurface waters of the GoME, especially in the benthic nepheloid layer, have an in-situ pH level of ~7.7 and are already experiencing under-saturation with respect to aragonite, potentially on a seasonal basis. In situ pH, DIC, and TA in these waters varied greatly with depth. The corrosive condition in the GoME is likely multi-factored, involving multiple driving forces. Low aragonite saturation and pH at depths seem to be related to semi-enclosed nature of the GoME and coupled with high surface production, followed by rapid remineralization processes. Other natural and anthropogenic factors, such as rising atmospheric CO_2 level and variability in adjacent slope water inflows, may also play a role. The consequences of the corrosive condition to the pelagic ecosystem are not well understood but preliminary lab experiments suggest that the local species of thecosome pteropod *Limacina retroversa* is metabolically affected by high CO_2. Distributions of carbonate chemistry, such as pH and aragonite saturation, potentially have important and long-term effects on GoME geochemistry, biology and ecology, as the acidification may become worse in the coming decades. A comprehensive characterization of seasonal and inter-annual variability in the carbonate chemistry system and particle biogeochemistry of the GoME, and associated impacts on pelagic and benthic calcifying organisms remains lacking but would provide key insight into the drivers and impacts of coastal ocean acidification in this important region.

Waldbusser, George

Understanding the mechanisms of larval bivalve sensitivity to ocean acidification

Waldbusser, G.G., B. Hales, C.J. Langdon, B.A. Haley, E.L. Brunner, and M. Gray

Larval bivalves have been identified as a particularly sensitive organism and life history stage to ocean acidification. During the larval period of development from a fertilized egg to metamorphosis bivalves must overcome several developmental and physiological hurdles. In coastal zones bivalves are subjected to acidification in multiple ways, eutrophication, freshwater input, and anthropogenic CO_2; combined these drivers can decouple the marine carbonate chemistry parameters such as P_{CO2} and saturation state. Additionally, fundamental understanding of organismal physiology and of winners and losers in a high CO_2 world requires exploration of what carbonate system parameters bivalves are responding to. We have been carrying out experiments and studies of early larval bivalve development, growth, feeding, and respiration under naturally variable conditions and under unique carbonate chemistry manipulations, across several species. By altering total dissolved inorganic carbon and alkalinity we have been able to reproduce a suite of experimental conditions that have different combinations of saturation state, P_{CO2} and pH. To date our results have found acute effects of saturation state but not P_{CO2} or pH on shell development, growth, and feeding. Initiation of feeding has shown no response to any carbonate system parameter, while feeding rate and gut fullness are positively related to saturation state. Limited experimental work on respiration has shown only a minor effect of elevated P_{CO2} and very low saturation state on respiration. We will highlight some differences among experimental species, as well as some detailed studies on the dynamics of early shell formation.

Wieczorek, Daniel

Experimental exposure system designed to study the effect of multiple variables associated with ocean acidification on the early life stages of marine species

Wieczorek D., J.C. Samson, M.E. Poach, R.C. Chambers, B.A. Phelan

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To address the growing concerns of the possible impacts ocean acidification may have on marine organisms in their vulnerable, early life stages NOAA/NMFS/JJ Howard Marine Lab at Sandy Hook, NJ has designed and implemented a large scale flow through experimental system. Conducting ocean acidification research in a laboratory setting can present many unique obstacles related to facility location, water supply, water quality, ambient conditions, and experimental variables. These obstacles are often compounded when attempting to create ecologically/biologically relevant experimental conditions while still achieving standardized pH/pCO2 levels proposed by the ocean acidification research community. The system we have designed is customizable to a number of distinct variables, in different combinations. Our system can be used for experimentation on shellfish, crustaceans, and both pelagic and benthic finfish at multiple life stages. Utilizing a large scale flow through design the system has the ability to manipulate carbonate chemistry, temperature, salinity, flow rates, dissolved oxygen, as well as biogeochemicals like ammonium and sulfide if needed, all while meeting the specific needs of sensitive life stages of multiple species. The system is continuously monitored by both automated instruments and discreet sampling. In experiments run to date, the system maintained distinct pCO2 and pH values ranging from 300 to 4000ppm pCO2 and pH of 8.0 to 7.1 with temperatures ranging from 4 to 21 degrees C. We evaluated the performance of this system in terms of the stability of the parameters of the inorganic carbonate system in all experimental vessels and in the representation of conditions found in local coastal waters.

White, Meredith

Coccolithophore growth, photosynthesis, calcification, and culture dynamics in response to increased pCO_2

Meredith M. White, David T. Drapeau, Laura C. Lubelczyk, Bruce Bowler, William M. Balch

In an effort to further understand the effects of ocean acidification on coccolithophore photosynthesis and calcification, we exposed two species (*Pleurochrysis carterae* and *Emiliania huxleyi*) to three pCO2 conditions: 280 (pre-industrial), 380 (~present day), and 750 (projected for the year 2100) ppm and measured photosynthetic and calcification rates via the ^{14}C-microdiffusion technique. We additionally measured cell size and growth, and characterized the carbonate chemistry of the culture media. We found that that calcification increased significantly with increasing pCO_2. Moreover, in studies of the variability of carbonate chemistry through the diurnal cycle, we found that pH varied by as much as 0.3 pH units at 750 ppm pCO_2 (lowest pH predictably was at night). Furthermore, the saturation state for calcite was just above 1.0 at the end of the dark period at 750 ppm. There also was significant variability in cell size over the diurnal cycle, which we are investigating in relation to the cell cycle for division as well as calcification. Finally, our evidence indicates that two species of coccolithophores, *P. carterae* and *E. huxleyi,* exert different biological control on the culture water chemistry, with photosynthesis of *P. carterae* driving the pH up at high cell densities, and calcification of *E. huxleyi* driving pH down at high cell densities.

Wilcox Freeburg, Eric

The shape of things to come: Ocean acidification effects on fish earstone mineralogy

As the oceans acidify in response to CO_2 incorporation, carbonate series concentrations are changing. This change in carbonate series has a direct effect on calcifying organisms. Impacts on external calcifiers, such as corals, bivalves, etc, has been the subject of intense scrutiny. However, the impact to organisms with internally calcified structures, such as fish and their inner earstones, has only recently begun to be discussed. To more thoroughly understand the impacts of OA on fish, we studied the Clark's clownfish, *Amphiprion clarkii*, otolith mineralogy under a range of acidified conditions. SEM imagery of isolated otoliths were scored for dominant mineral, mineral cover, and core development characteristics. Significant effects were found in core development with respect to pH, showing an increase in visible core protrusion with decreasing treatment pH. We attribute this change in core development to physiological blood pH maintenance mechanisms. The ramifications of such core development change is yet unknown, but coupled with recent density studies, may show a significant impact in otolith functionality. Further study is necessary to more fully understand the ramifications of enhanced core mineralization.

Williamson, Phil

Overview of the UK Ocean Acidification Research Programme

Phil Williamson[1], Carol Turley[2] & the UKOA research community

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The £12m UKOA research programme (2010-2015) involves over 120 scientists in 26 research laboratories across the UK, working closely with European partners and other relevant international activities. Seven multi-institute consortium projects address: observation and synthesis; upper ocean biogeochemistry; OA impacts on benthic ecosystems; commercially important species and socio-economic implications; effects of palaeo- OA events; and regional and global modelling of OA processes and future impacts. Ship-based fieldwork, now complete, has included research cruises in European shelf seas (2011), the North East Atlantic and Arctic (2012), and the Southern Ocean (2013), and studies of cold-water corals (2011, 2012). UKOA outreach and knowledge exchange includes work with UNFCCC, CBD and other international bodies.