Ocean Carbon and Biogeochemistry News

Studying marine biogeochemical cycles and associated ecosystems in the face of environmental change

Volume 7, Number 1 • Summer 2014

Twenty-five Years of Omics at BATS

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Today "omics" refers to a suite of methods – genomics, transcriptomics, proteomics, and metabolomics, that measure the structure and distribution of biomolecules (*1*). The prefix "meta" is added when the molecules come from an environmental sample with mixed populations rather than a cultured isolate. This short article provides a brief history of omics research at the Bermuda Atlantic Time-series Study (BATS) site, from the perspective of scientists involved in the BATS and related omics time-series projects. Today BATS is arguably the most heavily studied ocean site in the world from an omics perspective, although similar programs have arisen at globally distributed locations. Omics databases are rich, enduring, and can be plumbed repeatedly to address new research questions as they arise. For this reason, BATS is likely to continue to be a productive source of new discoveries that have a basis in omics science. Another factor that will propel further research at this site is the pronounced seasonality of BATS, which makes it a favorable location for studying impacts of climate change on ocean ecology (*2, 3*).

The early days

The omics revolution began in 1987 in the northwestern Sargasso Sea when postdocs from Norm Pace's lab, then at Indiana University, selected Hydrostation S (prior to the establishment of BATS) as a site to investigate new ideas about studying uncultured microorganisms by cloning and sequencing DNA from nature (4). Hawaii was the other site considered, but at that time there was no easy access to water samples at Station Aloha, without using the Deep Ocean Water in the Ocean Thermal Energy Conversion (OTEC) system. This option was ruled out because of concern that pipe wall biofilms would shed cells and compromise samples. So, instead, it was decided that short trips aboard the R/V *Weatherbird* (I) into the Sargasso Sea was the most

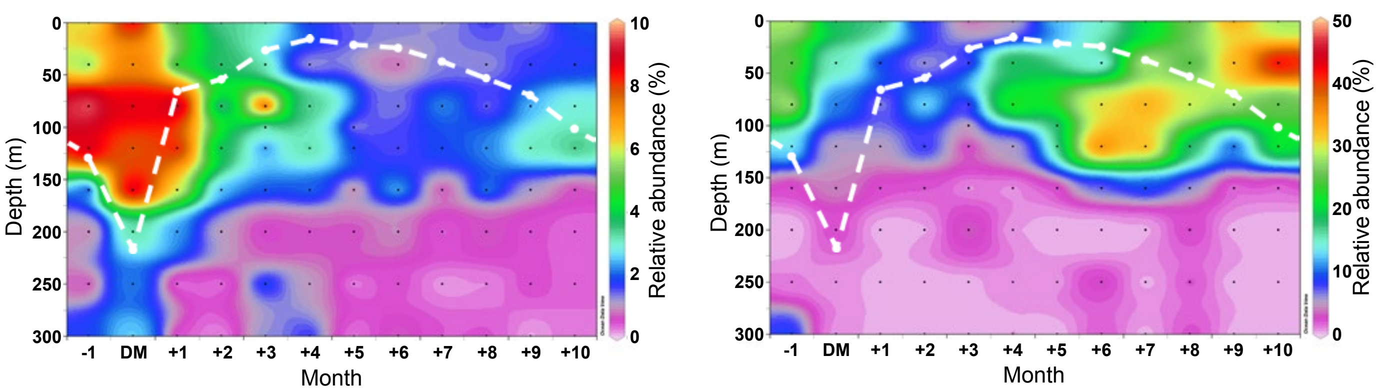

Figure 1. Average distributions of ribosomal RNA genes provide an "omics" perspective on seasonality at BATS. A) *Prochlorococcus* and *Synechococcus*, and B) all plastid rRNA genes. The data for each year were shifted on the temporal axis to align dates of deepest mixing (DM). The dashed white line represents the average mixed depth at this site. These data provide a clear view of eukarytotic dominance during the period of deep mixing, the shift of eukaryotic phytoplankton to the DCM during the summer, and the rise of cyanobacterial dominance during the stratified period. Reproduced and modified from (*33*).

viable option. This is how the first samples of plankton DNA were collected for DNA cloning, from whence came the “SAR” collection of 16S rRNA gene sequences, after which many bacterioplankton clades were named, including the notable alphaproteobacterium SAR11.

The first omics data from the northwestern Sargasso Sea was an outstanding success (5), but that would not become clear until some time later. The data revealed the presence of unknown microorganisms in surface seawater samples from BATS, supporting the hypothesis that the microbial world was populated with novel taxa that defied cultivation and were unknown to microbiologists, oceanographers or any scientists for that matter. Subsequently the first comparison of data from two ocean sites, BATS and Station ALOHA (6), established that many of the unknown organisms had a cosmopolitan distribution (7).

Supported by an early BATS ancillary project grant (1990 - 1993) from the National Science Foundation (NSF), the Giovannoni research group at Oregon State University began collecting time-series DNA and RNA samples from the surface and 200 meters, and occasional depth profiles at 0, 40, 80, 120, 160, 200 and 250 meters. This became the first ocean omics time-series.

Throughout this period, the project focused on producing a comprehensive system for classifying uncultured bacterioplankton diversity, and proving that microbial communities were stratified across the surface layer. Evidence that the newly discovered bacteria were present in stratified populations, and that similar patterns were found in the Atlantic and Pacific Oceans, was published in a series of early papers (8-13).

Another early observation first made at BATS that later became important was the surprising variation among closely related genes, which continues to be analyzed as a source of insight into the evolutionary processes that shape plankton diversity (5, 11, 14, 15). This research has recently assumed greater signifiance as concerns rise about the mechanisms organisms use to evolve in response to rapid environmental change.

Early omics research at BATS focused on bacteria, but plankton communities are diverse and later research expanded to include zooplankton (14), protists, and viruses. A number of these studies examined diversity in the context of the vertical structuring of plankton communities, with reports about both photosynthetic and non-photosynthetic protists (13, 16, 17). BATS was one of a

Strain designation	Taxonomic identification	GenBank accession number
HTCC2501	Robiginitalea biformata	CP001712.1
HTCC2503	Parvularcula bermudensis	CP002156
HTCC2506	Fulvimarina pelagi	DS022272.1
HTCC2516	Oceanicola granulosus	NZ_AAOT00000000.1
HTCC2559	Croceibacter atlanticus	CP002046.1
HTCC2594	Erythrobacter litoralis	NC_007722.1
HTCC2597	Oceanicola batsensis	NZ_CH724131.1
HTCC2601	Pelagibaca bermudensis	NZ_DS022276.1
HTCC2633	Oceanicaulis alexandrii	NZ_CH672428.1
HTCC2649	Janibacter sp.	CH672413.1
HTCC2654	Maritimibacter alkaliphilus	NZ_CH902578.1
HTCC5015	Unnamed Alphaproteobacteria	ABSJ00000000.1
HTCC7211	Candidatus ‘Pelagibacter ubique’	NZ_DS995298.1

Table 1. Bacterioplankton genomes from cultured organisms isolated from the Sargasso Sea by Oregon State University High Throughput Cultivation Laboratory (HTCL).

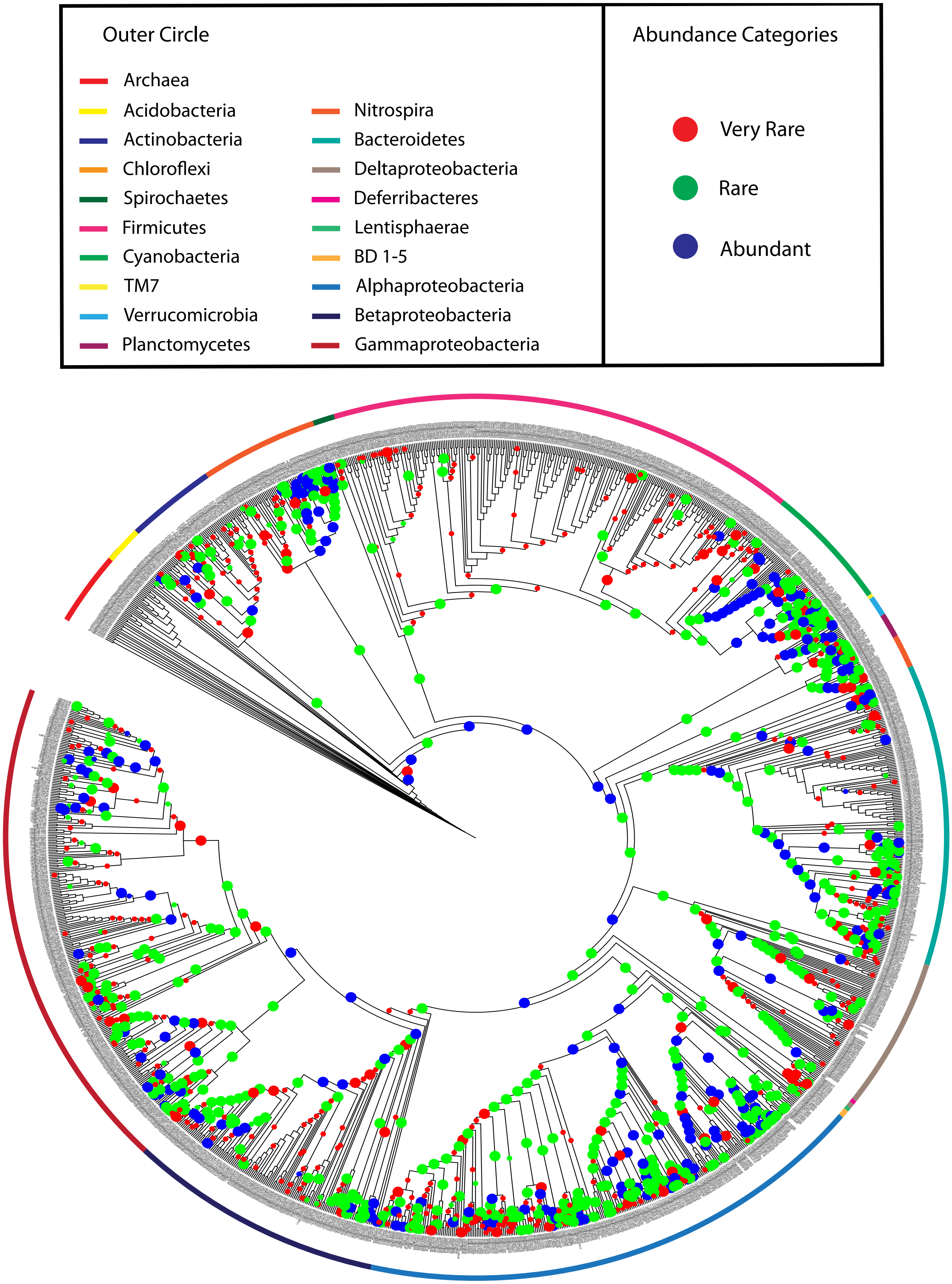

Figure 2. Evolutionary tree (Interactive Tree of Life plot) showing the diversity of bacterioplankton populations detected at BATS by DNA sequencing. Abundance is indicated by color (red – very rare, green – rare, and blue – abundant). Reproduced with permission from (37).

number of several sites at which the diversity of double-stranded DNA viruses (metaviromics) was studied with sequencing technology, revealing vast viral diversity (18). Single-stranded DNA phage diversity, which requires different methods, had also been investigated at BATS (19).

Carbon Cycling and the Microbial Observatory

Funding difficulties interrupted the BATS omics time-series in 1994, but the time-series resumed in 1997 with NSF support after refocusing attention on understanding microbial processes, controls of community structure and interactions between microbes and the carbon cycle. C. Carlson and D. Hansell at BIOS (formerly Bermuda Biological Station for Research) had elucidated annual patterns of dissolved organic carbon (DOC) variability and its contribution to export at BATS (20, 21). Because it was well known that plankton communities were stratified vertically and varied seasonally, an obvious direction to proceed was connecting the stratified microbial communities with variation in carbon cycle functions. This was the focus of three subsequent rounds of funding through NSF's Microbial Observatory program (1999 – present). Subsequent experimental and field work demonstrated that the DOC that accumulated in the surface layer was partially re-mineralized after export to the upper mesopelagic by deep mixing events (22), and that distinct mesopelagic bacterioplankton assemblages appeared to respond at depth to the recently exported DOC (23).

Many notable publications have relied on the BATS platform to study microbial interactions with DOM, as that science has followed the trail from DOC measurement processes at scales of tens and hundreds of meters, over seasons, to the interactions of individual plankton with the complex spectrum of dissolved organic matter (DOM) at fine scales of resolution. This work included studies of cloned hydrolase gene sequences (*24*) and measurements of the uptake of radioactively and stable isotopically labeled organic compounds, such as amino acids, sugars and DMSP, by specific microbial taxa (*25-27*).

Bacterioplankton Cultures and Genomes

In the early 2000's the advances in cultivation lead to the axenic culturing of many previously uncultured bacterioplankton allowing for genome sequencing and descriptions of many new taxa (Table 1). Cultured organisms with sequenced genomes proved important for identifying new geochemical activities of plankton, for example SAR11 methylovory (oxidation but not assimilation of C1 compounds, such as formate, formaldehyde, methanol and methylamine) was first described in culture followed by the demonstration of this new geochemical process at BATS (*28*). In another example, the thiamine precursor hydroxymethyl pyrimidine (HMP) was shown to be required by SAR11 cells produced by phytoplankton, and vertical profiles of this compound were quantitatively measured in the BATS water column (*29*). These examples further illustrate the interplay between laboratory studies and field research. Although this research depended on cultured isolates, genomes and metagenomes were a great advantage for the discovery of unknown types of metabolism that were then shown to be important processes in the oceans.

Venter's Metagenome

In 2004, J.C. Venter's team published a paper that was a landmark, not just for oceanographers, but for most biologists (*30*). They reported an analysis of 1.045 billion bases of environmental DNA sequence from BATS. It was by far the largest analysis of a metagenomic dataset ever reported. Interestingly, this report did not describe much new diversity at the level of deeply branching new taxa, because BATS and other ocean sites had already been so well studied by ribosomal RNA sequencing. However, for the first time, the richness of microbial diversity was fully on display, including the high level of variability between closely related microbial genomes, the incredible number of novel genes they harbored and the microbial community's metabolic potential.

Metaproteomics

Although the metagenome allowed the microbial oceanographic community to gain insight into metabolic potential, the implementation of metaproteomics allowed scientists to assess the realization of that potential. The first major application of metaproteomics to ocean science was reported in 2008 (*31*). Mass spectrometry of plankton protein showed that SAR11 populations in the high light, low nutrient summer surface microbial community at BATS were actively growing and devoted a large proportion of their protein synthesis activity to a small set of nutrient transport proteins (phosphorus transport in particular) and cell homeostasis proteins. This work also explored the taxonomic specificity of peptides.

Transcriptomics, an allied approach that measures messenger RNA instead of their translated products, proteins, was applied to study how the heterotrophic microbial community changes expression of its genes in response to DMSP addition. This work is leading to insights into the organisms and biochemical pathways that degrade DMSP in the Sargasso Sea (*32*).

Spatiotemporal Patterns

A series of papers began emerging from 2007 that involved analysis of the entire 12-year time-series of > 400 surface layer (0-300 m) samples with multivariate statistical tools. This work resolved four microbial communities: Upper euphotic zone (UEZ), deep chlorophyll maximum (DCM), spring bloom (SBL) and upper mesopelagic (UMP), and showed that they are tightly tied to seasonal cycles (*33*). An analysis of plastid 16S diversity in the data showed that previously unreported open-ocean prasinophyte blooms dominate eukaryotic phytoplankton during convective mixing at BATS, and eukaryotic phytoplankton turnover occurs in a pattern of seasonal succession (*34*).

The discovery of patterns of seasonal succession at BATS may be particularly relevant to understanding how ocean ecosystems will respond to climate change. BATS is a natural laboratory for understanding this process because of its pronounced seasonality and annual transitions from eukaryote-dominated primary production to cyanobacteria-dominated production (Fig. 1).

BATS researchers pioneered and continue to refine their understanding of fine-scale evolutionary diversity and its meaning. These ideas are now generally known as the ecotype concept. SAR11 was resolved first into three ecotypes, each with different seasonal and spatial distributions (*11, 35*), and later into 11 ecotypes (*36*).

Advances in DNA sequencing were exploited to study the distribution of rare bacterioplankton taxa at BATS (Fig. 2) (*37*). Rare taxa can be particularly important because of their role as a seed bank that repopulates communities that are dynamically changing, for example in response to seasonal forcing. This research showed that most rare bacterioplankton populations respond to depth and season, producing patterns similar to abundant taxa, suggesting a phenomenon that is referred to by ecologists as environmental filtering. We also reported that transport by mixing drives increased community diversity at BATS throughout most of the year, and that rare taxa bloom in episodic patterns, indicating they are adapted to exploit infrequent disturbances.

Mesoscale eddies, which periodically influence the physical and biogeochemical fields in the vicinity of BATS have also been studied with omics methods to understand how these features influence plankton communities (*38*).

Current Research

Research on interactions between bacterioplankton communities and DOM dynamics at BATS continues to be a mainstay of the authors' research, which is building on a foundation that long made cultures and systems biology a priority. Very large, new metagenomic and metaproteomic data sets are being analyzed to identify highly expressed plankton proteins, thereby laying the foundation for studying the flow of nutrients through food webs with isotopic tracers (metabolomics). The big omics data sets now available are a tremendous asset to biological oceanographers working at BATS, as well as other researchers around the world. The final test of these activities will be in their application to the discovery process.

Acknowledgments. Major support was provided by grants from the Marine Microbiology Initiative of the Gordon and Betty Moore Foundation grant GBMF607.01 to SJG and the NSF Microbial Observatory program grants MCB-0237713 & OCE-0802004 to SJG and MCB-0237728 & OCE-08001991 to CAC. The authors thank R. Parsons of BIOS for analytical and logistical assistance throughout the Microbial Observatory program and the Captains and crew of the *R/V's Weatherbird(I), Weatherbird II*, and *Atlantic Explorer* for sample collections.

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Integrating marine biogeochemistry and ecosystem research: From nutrients to fish

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*The following news piece is inspired by an article that appeared in 2013 in the Journal of Marine Systems entitled: "*Bridging marine ecosystem and biogeochemistry research: Lessons and recommendations from comparative studies*" by Salihoglu et al. (1) which summarized contributions and discussions held at the Workshop 2 of the* IMBER (Integrated Marine Biogeochemistry and Ecosystems Research) IMBIZO II meeting *October 10-14, 2010 in Crete, Greece (2).*

Why the need to integrate biogeochemistry with ecosystem science?

The flux of carbon and energy in the ocean is dominated, outside the merely physical realm, by organisms of great functional and taxonomic diversity, including phytoplankton and other microbes, as well as higher trophic levels. However, in most of the oceanographic literature, biogeochemical processes are considered in isolation from ecosystem processes, and vice versa, despite the apparent need to find a synergy between them to understand how global change will impact marine ecosystems, biogeochemical cycles and their interactions. While in principle addressing the same processes, biogeochemistry focuses on fluxes of elements and energy, while ecosystem science addresses diversity and function of organisms and their trophic interactions, spanning from primary producers all the way up to fish, birds, marine mammals and humans (Fig. 1).

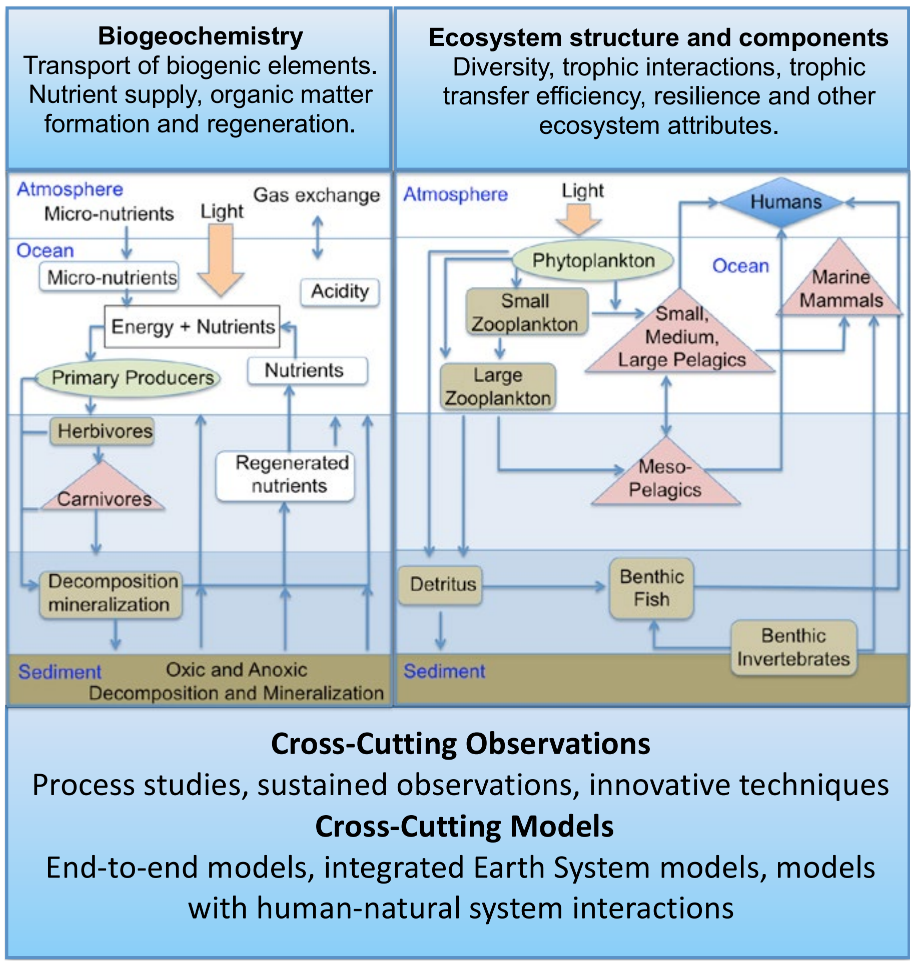

Figure 1. Modified from Figure 1 in (1). Biogeochemistry focuses on the flow of elements and energy through a system, whereas ecosystem processes encompass organism-based approaches and investigation of trophic interactions. Lower panel summarizes cross-cutting tools for comparison, both from the observational and modeling sides.

There are critical questions that we believe can only be answered by integration of marine ecosystem and biogeochemistry research, for example:

1. How do primary producers (e.g., community composition, elemental composition) influence trophic transfer, and what are the consequences for biogeochemical cycles and the biological carbon pump?
2. What are the impacts of climate variability and change and other environmental stressors (e.g., ocean acidification, eutrophication, overfishing, etc.) on ecosystems (e.g., transfer of biomass to higher trophic levels) and marine biogeochemical cycles (e.g., the biological carbon pump)?

3. How does a change in biodiversity affect food web structure (e.g., trophic cascades) and biogeochemistry, and what are the implications of these changes for the marine ecosystem services upon which humans depend?

The above questions address overlapping components of ecosystems and human society under the influence of climate forcing. Ultimately, all components intersect in biogeochemistry and ecosystem science (Fig. 2).

Here, we illustrate examples of research and approaches that span biogeochemistry and ecosystem science by focusing on crosscutting observations and models (see lower panel in Fig. 1).

Crosscutting Observations

The challenge to understand biogeochemical and ecosystem responses to global change is profound, given the multitude of processes operating on different space and time scales. Crosscutting observations (i.e. integrated multidisciplinary studies) carried out in similar systems in a comparative fashion is a means of approaching this challenge. Examples of comparative studies have encompassed different oceanic environments such as upwelling margins (California vs. Canary Current Upwelling Systems (3)); subtropical gyres (subtropical north Atlantic vs. Pacific (4)); the subarctic (Barents vs. Chuckchi Seas (5)); equatorial Pacific vs. Atlantic (6), and the Southern Ocean (West Antarctic Peninsula vs. South Georgia (7)). The comparative framework in these studies relies on investigating the sensitivity of the system to a distinguishing biological or physical factor (such as temperature, currents, nutrient supply, or top predators). Studying the ecosystem's response can then provide insight to the sensitivity of the system to climate-induced changes or other stressors.

Sustained observations conducted at ocean time-series sites are particularly useful for these types of comparative studies, as these data sets provide adequately long time scales of observation to study biogeochemical and marine ecosystem expressions of key climate modes (e.g., El Niño-Southern Oscillation, or ENSO; Pacific Decadal Oscillation, or PDO; North Atlantic Oscillation, or NAO (8)). At the Bermuda Atlantic Time-series Study (BATS, 31°50' N, 64°10' W), shifts in the community composition of primary producers from larger to smaller cells was accompanied by an increase in overall phytoplankton standing stock and zooplankton biomass, as well as carbon export and remineralization below the euphotic zone (9,10). Those processes were thought to be linked to a shift

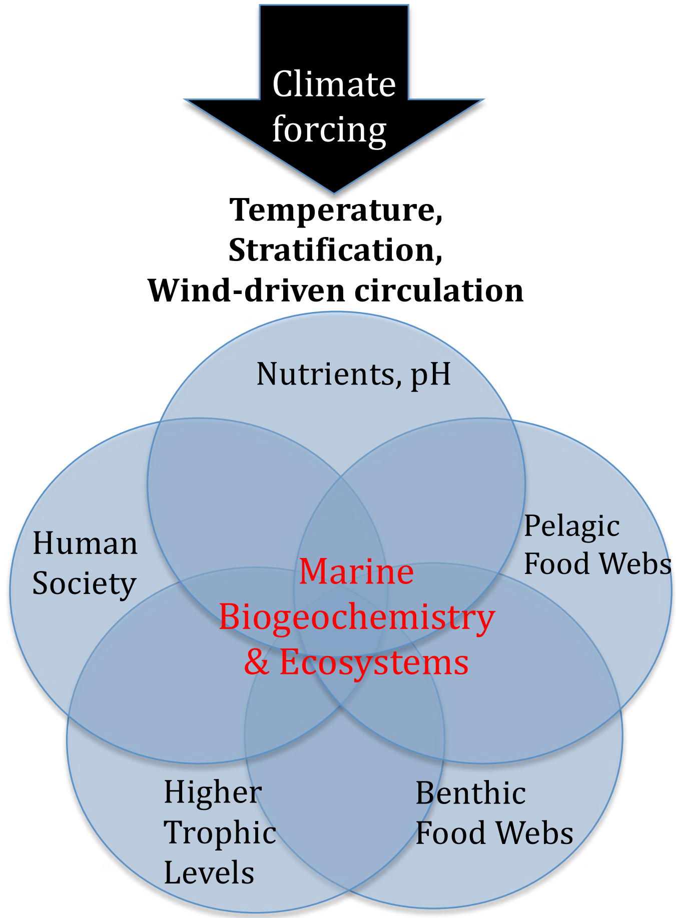

Figure 2. Venn diagram of components of natural and human systems and their interactions under the influence of climate forcing. The latter includes both natural climate modes (e.g., NAO, ENSO, PDO) and anthropogenic forcing. This forcing impacts the marine system through its influence on the physics and chemistry of seawater, which in turn impact structure, function, and productivity of benthic and pelagic food webs and higher trophic levels (e.g., distribution and recruitment of fish). Ultimately, marine ecosystems and biogeochemistry are located at the intersection of all components.

in the predominant mode of NAO influencing nutrient supply from below. Comparisons between BATS and the eastern subtropical time-series station ESTOC (ESTOC, European Station for Time-series in the Ocean, Canary Islands) revealed that the magnitude and mode of nutrient supply could influence not only the composition of primary producers and magnitude of carbon export, but also the remineralization of organic matter below the euphotic zone (11). The latter study also points to the role of higher tropic levels in carbon flux, which unfortunately could not be tested because of the lack of taxon-specific investigations of the pelagic animal communities at either station. The need to understand higher trophic level dynamics was also illustrated in studies at HOT (Hawaii Ocean Time-series), where nutrient-induced changes in phytoplankton biomass could increase the carrying capacity of mesozooplankton and with it, the export of particulate nitrogen (12,13).

It is apparent from the above examples that the composition of the consumers, as illustrated in the right hand panel of Fig. 1, cannot be ignored when trying to develop a holistic understanding of a marine ecosystem and the associated fluxes of carbon and other elements. It is important to note that none of the field-based comparative studies could be meaningfully conducted without the broader global context provided by remote sensing data sets such as variability in phytoplankton biomass, functional types and primary production, variability in the physical environment, etc.

Crosscutting Models

Hand in hand with observational strategies and insights outlined above, integrated numerical models are needed as tools to examine the postulated links between marine biogeochemical cycles and ecosystems (e.g., 1, *14, 15*). For example, these models are needed to study how changes in ocean physics and chemistry (bottom-up) compare with the influence of higher trophic levels (top-down) on phytoplankton productivity and carbon flux. Accurate representation of ocean physics is essential to reducing uncertainties surrounding ecosystem response. Furthermore, the study of the impacts of multiple stressors driven by natural and anthropogenic global change, and the feedbacks with the other components of the Earth system, requires integration of physical, biogeochemical and food web models.

Traditionally, lower and higher trophic level (i.e. fish) models have been developed separately, and only recently have begun to be integrated. To date, most models are developed for a specific scientific purpose and focused only on a particular subset of the ecosystem (see Fig. 2 in (*1*)), either the plankton (e.g., NPZD-type models, see overview in (*16*)) and fish community components, or a selection of trophic levels (*17, 18*). Recently, with the need for models with forecast abilities and for ecosystem-based management, end-to-end models are being developed. A general description of an end-to-end model was given by (*19*) and further expanded by Rose (*20*). According to these authors, an end-to-end model represents the entire food web and the associated abiotic environment, and should include multiple species or functional groups at each of the key trophic levels in the system. An end-to-end model requires the integration of physical and biological processes on different time and space scales and implements two-way interaction among ecosystem components. It should also include dynamic representation of key forcings associated with climate, ocean physics, human activities (e.g., fishing). This end-to-end approach will be necessary to effectively address the questions posed at the beginning of this article.

Detailed information, often specific to region and/or trophic level, needs to be included at different levels of an integrated model. For example, high-resolution physics improves the quality of the forcing fields for lower trophic levels. Models must be able to resolve seasonal primary production patterns and shifts in phytoplankton and zooplankton species in response to natural and anthropogenic stressors. However, these models are constrained by the availability of data on physiology of phytoplankton and zooplankton aggregated groups. At higher trophic levels, individual variability and life history details become increasingly important, requiring structured population models and even individual-based models. Once again, data availability constrains the complexity of these models, but increased complexity is required to include organism behavior and species adaptability.

Anthropogenic pressures (warming, acidification, eutrophication, fishing) represent ongoing challenges that are affecting the productivity and structure of marine ecosystems. Observations often focus on specific trophic levels with limited resolution in space and time. However, oceanic systems are integrated across space and time scales that are impossible to resolve with observations, and include complex interactions among and within diverse communities, all with implications for biogeochemical cycling. Comparative modeling (both temporal and spatial comparisons) offers a means to improve our understanding by bringing attention to the critical processes that differentiate one system from another and result in differences in ecosystem response to a changing ocean system. For example, several studies (*21, 22, 23*) focused on understanding the combination of climate change and fishing pressures, and showed that these pressures have compounded effects that can be manifested differently in different regions. These studies suggest that differentiating the dominant drivers is the main challenge. Such comparative modeling studies offer a unique opportunity to isolate and quantify the effects of individual drivers.

The use of models to carry out comparisons of different ecosystems includes the application of a specific model to different ecosystems as well as the application of different models to a particular ecosystem (e.g., (*24*)). In addition, there are socio-economic and management models that can be effectively evaluated within a comparative framework (e.g., Ecopath with Ecosim). Application of models provides invaluable opportunities to understand the connections within and between ecosystems. A good example is the application of NEMURO.FISH, which was used to investigate geographical differences in oceanographic conditions on herring growth in several regions of the North Pacific, while maintaining the same climate forcing. One promising result was that despite having the same forcing and species, the modeled ecosystem responses were dependent upon regional oceanographic conditions (25).

Cross-ecosystem, multi-model comparisons are difficult to conduct. They often require substantial computational power and extensive scientific effort. However, this approach is essential to evaluate the robustness of ecosystem responses to climate change and anthropogenic forcing, and will require ongoing coordination, collaboration, and support across disciplines and regions.

Moving Forward

Salihoglu et al. (*1*) suggest guidelines for comparative studies that focus on sources, fluxes, and fates of primary production in the water column and sea bed (see their Table 3), and that should be implemented in new programs or added to existing studies. Those include simple measures from bulk parameters such as chlorophyll *a* to functional groups and trophic interactions. Model development needs to happen in parallel, and models should be used to test the hypotheses ahead of data collection to guide observational programs. One of the major roles of end- to-end models will be to identify critical observational parameters that span climate, physics, biogeochemistry, lower trophic levels, fish, and humans, which will ultimately result in better models with reduced uncertainties and improved predictive capabilities.

Well designed comparative analyses will help us better understand and predict the response of marine ecosystems and biogeochemical fluxes to global change, which will result in well informed, more effective management strategies. These analyses need to be based on closely coordinated observations, as well as end-to-end models that help in identifying key processes and potential ecosystem responses. Bridging ecosystems and biogeochemistry is an approach that also needs to be reflected in the education of our future generation of ocean scientists, not only in terms of shared expertise, but also in a mutual desire to overcome 'disciplinary silos'.

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Important Dates

July 21-24, 2014: OCB Summer Workshop (Woods Hole, MA) - plenary sessions include:
The Coupled North Atlantic-Arctic System: Processes and Dynamics
The Biological Pump: Transport Mechanisms and Mesopelagic Processes
Advances in our Understanding of the Role of Sea Ice in the Global Carbon Cycle
August 19-21, 2014: NACP/OCB Coastal CARbon Synthesis (CCARS) Community Workshop (Woods Hole, MA)

OCB Leadership Changes

New OCB Scientific Steering Committee (SSC) members

In 2014, six new members were elected to serve a 3-year term on the OCB Scientific Steering Committee: Mark Brzezinski (UCSB), Kristen Buck (USF), Adrian Burd (UGA), Bethany Jenkins (URI), Susanne Neuer (Arizona State Univ.), Michael Roman (UMD/HPL). Jeremy Mathis (U. Alaska, Fairbanks/NOAA/PMEL) was elected to serve another term. David Siegel (UCSB) and Kendra Daly (USF) transitioned to *ex officio* status. Craig Carlson (UCSB) assumed the chair position in 2014, and SSC members elected Matthew Church (Univ. Hawaii) as vice-chair.

We wish to thank outgoing members Andreas Andersson (SIO), Tom Bianchi (Univ. Florida), Lisa Levin (SIO), Tatiana Rynearson (URI), and Mak Saito (WHOI) for their dedication and service.

For more information about the OCB SSC, including its charge, terms of reference, and a list of current and previous members, please visit http://www.us-ocb.org/about/committees.html.

New OCB Ocean Time-Series Advisory Committee (OTSAC) members

In spring 2014, two new OCB Ocean Time-Series Advisory Committee members were elected: Mike DeGrandpre (Univ. Montana) and Richard Lampitt (National Oceanography Centre). Members of the subcommittee elected Susanne Neuer (Arizona State Univ.) as the new chair. We wish to thank outgoing member Ken Johnson (MBARI) for his dedication and service as member and chair of OTSAC for many years.

For more information about the OCB OTSAC, please visit http://www.us-ocb.org/about/subcommittees.html.

Meetings and Activities

International North Atlantic-Arctic Planning Workshop

April 14-16, 2014 (Arlington, VA)
By Heather Benway (OCB/WHOI), Eileen Hofmann (ODU), Mike St. John (Danish Tech. Univ.)

The North Atlantic-Arctic system is highly susceptible to climate-driven changes in circulation, biogeochemistry, and marine ecosystem dynamics, including commercially important fisheries, and is critical to the health and socioeconomic well being of North America and Europe. Ongoing U.S. and international activities (e.g., Overturning in the Subpolar North Atlantic Program (OSNAP)) are expanding the knowledge base necessary to understand the Atlantic Meridional Overturning Circulation (AMOC), which is an important foundation for addressing ecosystem services such as carbon cycling and fisheries. Initial results highlight the strong need for investment in the study of biogeochemical and ecosystem processes and how they interact with physical processes over a range of time and space scales.

In February 2013, the European Union (EU)-U.S. Joint Consultative Group held a meeting on Science and

Technology Cooperation, which focused on developing the knowledge and technologies that can foster economic growth, create jobs, and help solve shared challenges, such as in health, climate change and food security. To facilitate this process, the Group explored how to advance cooperation in transatlantic marine, maritime and Arctic research, transport research, health research and materials science. This meeting resulted in the Galway Statement on Atlantic Ocean Cooperation, which is an agreement that was signed in May 2013 between the U.S., European Union, and Canada to join forces on Atlantic research. The goals of this cooperative agreement are to better understand the Atlantic Ocean, promote the sustainable management of its resources, and study the interplay of the Atlantic Ocean with the Arctic Ocean, particularly with regard to climate change. This agreement recognizes that Atlantic research will be more effective if coordinated on a transatlantic basis. One of the key suggestions of the Galway Statement was to convene an international meeting of the scientific community and funding agencies to develop an international science plan to help focus future research activities.

With funding from the National Science Foundation, the European Commission, and the European Union Delegation to the U.S., OCB organized a planning workshop on April 14-16, 2014 in Arlington, VA to discuss the state of North Atlantic-Arctic science and begin planning the next phase of interdisciplinary research, with an emphasis on mechanisms to facilitate international collaboration. Participants included invited scientists from the U.S., Canadian and European research communities, as well as representatives from relevant National funding agencies, with a mission to identify critical research questions that will advance understanding of the North Atlantic-Arctic system, with particular focus on:

- ***Gateways:*** Implications of changes in communication between Arctic-North Atlantic, as well as between the shelves and the open ocean for biogeochemical cycling, marine ecosystems and their services
- ***Circulation:*** Role of large-scale (e.g., AMOC) versus meso- to sub-mesoscale processes (e.g. eddies, fronts) in different parts of the Atlantic-Arctic system and feedbacks to biogeochemistry and ecosystem structure and function
- ***Bloom dynamics:*** Interactions between physical, biogeochemical, and ecological processes involved in the initiation, evolution, and termination of blooms and associated sensitivities to climate and circulation changes
- ***Sustainable fisheries:*** Collective impacts of fishing pressures, climate, and ocean circulation changes on key North Atlantic fisheries, including the interactions with lower trophic levels and ecosystem restructuring that these activities cause;
- ***Marine ecosystem health:*** Sensitivity of marine biodiversity and ecosystem resilience to climate and circulation changes
- ***Prediction:*** Development, validation, and application of advanced earth system models (climate-physical oceanographic-ecosystem) able to capture the adaptive nature and evolution of key biogeochemical and ecosystem players, thereby furthering our ability to predict future changes and inform decision-making

To highlight key aspects of North Atlantic-Arctic science and stimulate thoughtful discussion among participants, the workshop included crosscutting plenary talks on small- and large-scale circulation, biogeochemistry, ecosystem dynamics, and links to human populations. A series of smaller group breakout discussions helped inform key elements of a science plan, including development of overarching questions and identification of specific research and observational priorities within the key disciplines of ocean physics and climate dynamics, biogeochemical cycling, food webs and community structure, ecosystem health and biodiversity, interactions between humans and natural systems, and management and adaptation strategies. Participants also broke into groups to compile information on current and planned observing and research activities in the North Atlantic-Arctic system for the U.S., EU, and Canada. Throughout the discussions at the workshop, participants also identified several research foci that cut across disciplines and are ripe for trans-Atlantic collaborative research investigations.

Representatives from U.S. (NSF, NASA, NOAA, DOE), Canadian, and European funding agencies attended the workshop and provided information on current and planned North Atlantic-Arctic investments, with cross-agency dialog providing the opportunity to discuss and synergize near-term funding opportunities to facilitate international collaboration. Near-term U.S. funding will be competed through existing core programs. In Europe, a series of funding opportunities are available via the Horizon 2020 Blue Growth Calls *Blue Growth: Unlocking the potential of Seas and Oceans*.

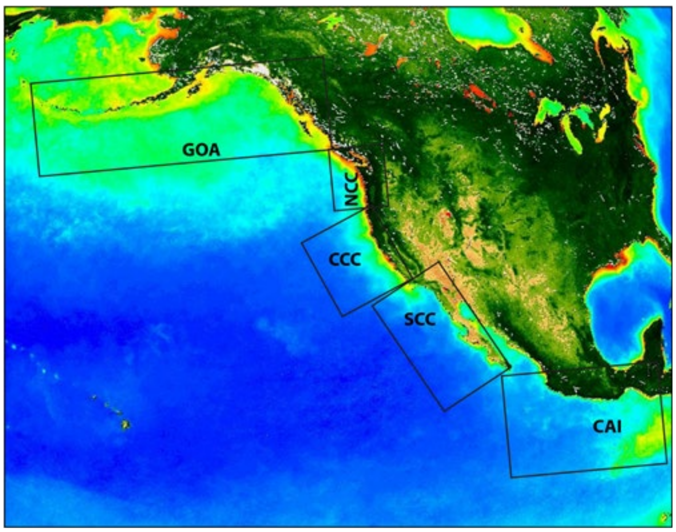
A meeting report has been submitted to *Eos*, and a draft of the science plan will be released for community input later this summer with plans to finalize in early 2015. For more information, please visit
http://www.whoi.edu/website/NAtl_Arctic/home

Coastal CARbon Synthesis (CCARS): West Coast Carbon Synthesis Workshop

March 19-20, 2014 (Seattle, WA)

by Simone Alin (NOAA/PMEL) and Samantha Siedlecki (UW)

The West Coast represents the longest coastline in North America, stretching from Panama all the way northward to the Aleutians. The West Coast synthesis team divided the coast up into sub-regions based on differences in oceanographic drivers of coastal carbon cycling. Sub-regions include the Gulf of Alaska, the Central American Isthmus, and the California Current System (CCS), which is further subdivided into northern, central, and southern sectors.



The West Coast Carbon Synthesis Workshop took place March 19-20, 2014 in Seattle, WA and convened 17 researchers. The primary focus of the workshop was the northern, central and southern sectors of the CCS. The group identified key advances that have been made since the North American Continental Margins report (Hales et al., 2008), notably the convergence of models and observations on air-sea fluxes; more sophisticated coastal carbon cycle models; and increased observational coverage in space and time, allowing for more data synthesis and model-data comparison. Remaining gaps that make it difficult to quantify west coast carbon fluxes include lack of information on estuarine processing and transfer to the coastal ocean; lack of winter observations; missing net community production (NCP); and lack of observational coverage in the Gulf of Alaska and Central American Isthmus sub-regions.

The group identified the following priorities for advancing West Coast carbon cycle research:

- More mining and synthesis of long-term data sets (e.g. CalCOFI, IMECOCAL)
- More cross-platform data synthesis
- More model-data and model-model intercomparison work
- Prioritize modeling and observational efforts needed to close C budgets (e.g., winter data, estuarine data, missing NCP)
- Improve understanding of how coastal carbon budgets are affecting ocean interior
- Time-series observations with water column profiles
- Improved understanding of how coastal carbon cycles will change in the future, which will require models to make predictions and process studies to test hypotheses generated by them

Outcomes of this workshop will include an overview carbon budget synthesis paper that summarizes knowns and unknowns across all sub-regions and more detailed synthesis papers on air-sea fluxes, water column metabolism, and terrestrial inputs. The findings of this workshop will also feed into community discussions at the upcoming CCARS workshop in August.

OCB Scoping Workshop: Improving predictive biogeochemical models through single cell-based analyses of marine plankton physiological plasticity, genetic diversity and evolutionary processes

May 28-30, 2014 (East Boothbay, ME)

Submitted by: Workshop Steering Committee
Mike Lomas, Bigelow Laboratory for Ocean Sciences
Ben Twining, Bigelow Laboratory for Ocean Sciences
Ramunas Stepanauskas, Bigelow Laboratory for Ocean Sciences
Adam Martiny, University of California Irvine
Steve Giovannoni, Oregon State University
Stephanie Dutkiewicz, Massachusetts Institute of Technology
Susanne Neuer, Arizona State University
Alison Taylor, University North Carolina – Wilmington
Adrian Marchetti, Duke University

The global ocean is currently undergoing significant changes, from the acidification of surface seawater to expansion of mid-water oxygen minimum zones to changes in vertical stratification and nutrient inputs. Understanding these changes and enabling the prediction of their impact on global biogeochemical processes requires detailed information at the level of the individual organism, such as their physiological traits, characteristics, rate processes and plasticity to respond to environmental change. 'Omics' measurements can provide detailed information on intra- and inter-specific diversity, presence/absence of particular genes and if they are transcribed and translated. However, these powerful techniques have limited ability to provide quantitative information on rate processes desired in current biogeochemical models. Similarly, geochemical rate measurements constrain important processes but generally do not resolve the known role of biodiversity and physiological plasticity. How do we combine these very different measurements to improve our understanding and ability to model ocean biogeochemistry?

Forty-eight marine scientists spanning from Ph.D. students to late-career researchers and program managers participated in an OCB scoping workshop *Improving predictive biogeochemical models through single cell-based analyses of marine plankton physiological plasticity, genetic diversity and evolutionary processes* at Bigelow Laboratory for Ocean Sciences from May 28-30, 2014 to tackle this and related questions. The meeting agenda was centered around three general topics: 1) Microbial traits and tradeoffs; 2) taxon- and single-cell specific biogeochemistry; and 3) genetics and evolution in the context of biogeochemistry and global change. Three plenary speakers – Drs. Elena Litchman (MSU), David Hutchins (USC), and Tatiana Rynearson (URI) – set the stage for detailed breakout group discussions on the following questions:

- What are the single cell-specific and population-level traits required for parameterizing microbial "plasticity" in marine biogeochemical models of the current ocean?
- Do genetic diversity, evolution and physiological plasticity have similar or different impacts on ocean biogeochemistry, particularly the production and export of particulate organic matter from the surface ocean?
- What roles do taxonomic diversity and physiological plasticity play in controlling the response of microbial communities to current and future environmental stressors (e.g., expanding oxygen minimum zones, ocean acidification, ocean warming, stratification and changing nutrient concentrations or supply rates)?

Biodiversity has at least three functional roles to play in the context of marine biogeochemistry. The first is the well known inter-phylum diversity (e.g., diatoms vs. Cyanobacteria). In many cases, this level of biodiversity is partially captured in many models, whether through allometry or involvement in a specific process (e.g., nitrogen fixation). The second role is intra-specific variability derived from genetic differences (e.g., ecotypes) or finer dissection within the same population that allows for occupation of multiple ecological niches, or a continuum of niches. The third role is physiological plasticity derived from changes in expression levels of different genes and proteins, rather than differences in genetic content. It is currently recognized that some groups of organisms, even if similar in size, are more plastic and less genetically diverse (*Croccosphaera*), compared with those that have limited plasticity but are very genetically diverse (*Prochlorococcus*). A first step might be to continue discovering which levels of biodiversity are most important for those organisms involved in a specific biogeochemical function, or those organisms occupying a particular biogeographical province (or perhaps better defined as a biogeochemical province). This would involve a combination of laboratory studies with ecologically relevant isolates in order to constrain degrees of physiological plasticity under varying environmental conditions, as well as field studies to examine the genetic diversity of particular groups within and between natural populations.

Another important theme at this workshop is that we cannot look at each process in isolation. Changes in temperature, pH, and nutrient availability are all happening at once. Thus, microorganisms are facing multiple stressors simultaneously. However, we currently have limited knowledge (primarily via a few culture experiments) of how different environmental factors interact in shaping the physiology and biogeochemical roles of marine microorganisms. Thus, we need new types of experimental designs to address this important issue in natural populations.

This meeting synopsis is just the first of several tangible products that are envisioned to arise from the scoping workshop and move this research field forward. Those products include (in no particular order):

- A formal workshop report in the form of a white paper that communicates the vision and forward-looking priorities for this research
- An article for *Eos* highlighting the workshop conclusions and vision at a higher level for broader audiences in an effort to better connect with and engage other disciplines
- Identification of key topics and possible speakers for a special session at an upcoming Ocean/Aquatic Sciences meeting, and potentially to include a town hall meeting to discuss the outcomes of the meeting and future research avenues

This topical area is one of great interest to many ocean scientists and is developing rapidly. For more information about the meeting, please visit http://www.whoi.edu/website/taxon-specific-biogeochemistry/.

OCB Publications

- Benway, H. M., Doney, S. C. (2014). Scientific outcomes and future challenges of the Ocean Carbon and Biogeochemistry Program. *Oceanography* 27(1): 106-107.
- Benway, H. M., Coble, P. G. (Editors), 2014. Report of The U.S. Gulf of Mexico Carbon Cycle Synthesis Workshop, March 27-28, 2013, Ocean Carbon and Biogeochemistry Program and North American Carbon Program, 67 pp. (workshop website).
- Benway, H. M., Doney, S. C. (2013). Addressing biogeochemical knowledge gaps. *International Innovation* (North America, June 2013), 12-14.

How Can OCB Help You?

- Looking to **publicize a recent paper**? Add it to the OCB peer-reviewed literature list, contact the Project Office about doing a science feature on the OCB website, or submit to the OCB Newsletter
- Want to **share news** about education and outreach resources, jobs, field opportunities, relevant upcoming meetings and special sessions, etc.? Post to the OCB email list
- Looking for **international travel support**? The OCB Project Office has limited funds for U.S. participation in international workshops and meetings that advance the programmatic mission of OCB. The OCB SSC reviews travel support requests three times a year: March, July, and November

Ocean Acidification

Studying ocean acidification's effects on marine ecoystems and biogeochemistry

Ocean Acidification Resources

- IAEA Ocean Acidification International Coordination Centre and Bibliographic Database
- New website: Ocean Acidification: Bringing information on ocean acidification to scientists, policymakers and the public
- SOLAS IMBER Working Group on Ocean Acidification (SIOA) and the Ocean Acidification International Coordination Centre (OA-ICC) have developed a set of 10 slides for communicating on ocean acidification to non-scientific audiences
- 20 Facts about Ocean Acidification
- Strategic Plan for Federal Research and Monitoring of Ocean Acidification developed by the Interagency Working Group on Ocean Acidification

Community Announcements

Science planning

- NASA currently seeking feedback on draft Strategic Science Plan for EXPORTS
- The National Research Council seeking community input on NSF's science priorities for Antarctic and Southern Ocean (deadline: November 1, 2014)
- Review latest SCOR working group proposals by **Aug 1, 2014**

Publications and web resources

- 3rd U.S. National Climate Assessment report and toolkit are now available
- International North Atlantic-Arctic research planning website
- Future Earth website now available
- ABoVE (Arctic-Boreal Vulnerability Experiment) Concise Experiment Plan released
- Open access e-Book Western Pacific Air-Sea Interaction Study (W-PASS)
- EPA report *Climate Change Indicators in the United States: 2014*
- New special issue in *Progress in Oceanography* from IMBER IMBIZO II
- Special issue on Changing Ocean Chemistry (2014). *Oceanography* 27(1).
- Contribute to a special issue of *Marine Chemistry* on 'Biogeochemistry of trace elements and their isotopes' **(Submission deadline: October 31, 2014)**

Research tools

- Call for transnational access to FixO3 observatories (Fixed-point Open Ocean Observatories). Objective of this call is to offer free-of-charge access to fourteen ocean surface, water column and seafloor observatory installations and one shallow water test site (OBSEA). **(Deadline: July 31, 2014)**
- Participate in Primary Production Algorithm Round Robins (PPARR)-5 on Arctic Ocean
- GEOTRACES Intermediate Data Product
- New Community Earth System Model (CESM) tools and datasets:
    - CESM1(CAM5) Large Ensemble Community Project
    - Climate Variability Diagnostics Package (CVDP)
- The new LDEO Database V2013 is published at CDIAC: http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/

center for microbial oceanography: research and education

C-MORE *linking genomes to biomes*

Ecological Dissertations in the Aquatic Sciences

Ecological Dissertations in the Aquatic Sciences (Eco-DAS) is an NSF-sponsored symposium series designed to facilitate interdisciplinary collaboration between new aquatic scientists. The initial Eco-DAS award funded three biennial symposia held in 2008, 2010 and 2012. In addition to presenting their own work, participants interacted with representatives of funding agencies and private foundations, gained vital career skills from guest speakers and mentors, and worked in self-assembled author teams to design and write significant contributions to the peer-reviewed literature. The previous Eco-DAS symposia have led to the production of three e-Books with a total of 21 chapters, two articles published in the *Limnology and Oceanography Bulletin*, and one article published in *Limnology and Oceanography: Fluids and Environments* (see the ASLO website for more information: www.aslo.org).

Eco-DAS is designed to create collaboration, but the symposia still take place two years apart and produce cohorts of participants who may never have met individuals from the other symposia. Two workshops were held recently to build connections between cohorts. The first took place immediately following the Ocean Sciences Meeting held in Honolulu Hawaii, in February 2014. The second took place immediately following the Joint Aquatic Sciences Meeting held in Portland Oregon in May 2014.

About half of the past Eco-DAS participants were able to attend at least one of the reunion workshops. The primary focus of both workshops was on effective communication. They employed a combination of 3MT-style presentations (3MT = Three Minute Thesis 3MT®, developed by the University of Queensland; see their website at http://www.uq.edu.au/grad-school/three-minute-thesis), and "speed dating" short conversations among the participants. By all accounts, the one-day reunion workshops were a success, even coming at the end of a long meeting week!

Eco-DAS 2.0 was recently funded, and will continue the series with symposia to be held in 2014, 2016 and 2018. As with previous symposia, the goal is to build connections among new PhDs, and one of the primary tools will be the production of peer-reviewed publications by self-assembling author teams. We're looking forward to an exciting series, and to meeting another 100+ of the next generation of aquatic scientists.

Paul Kemp

With thanks to Lydia Baker, manager of the Eco-DAS 2010/2012 e-Books and co-organizer of the recent reunion workshops with Elisha Wood-Charlson, to all the mentors and guest speakers for the previous symposia, and to all of the amazing participants!

OCB hosts three C-MORE Science Kits in Woods Hole

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

Calendar

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

2014	
July 6-11:	Gordon Research Conference Ocean Global Change Biology (Waterville Valley, NH)
July 7-18:	3rd International Marine Phytoplankton Taxonomy Workshop (Plymouth, UK)
July 8-11:	US CLIVAR Summit (Denver, CO)
July 21-24*:	2014 OCB Summer Workshop (Woods Hole, MA)
July 21-August 2**:	Second IOCCG Summer Lecture Series (Villefranche-sur-Mer, France)
July 26-27:	Gordon Research Seminar on Microbial Stress (South Hadley, MA)
August 4-8**:	Training Course on pH Sensor Best Practices (La Jolla, CA)
August 4-9**:	IMBER ClimEco4 Summer School - Delineating the issues of climate change and impacts to marine ecosystems: Bridging the gap between research, assessment, policy and management (Shanghai, China)
August 19-21*:	NACP/OCB Coastal CARbon Synthesis (CCARS) Community Workshop (Woods Hole, MA)
August 26-29:	2014 PICES Summer School End-to-End Models for Marine Resources Management and Research (Gangneung-Wonju National University (GWNU), Republic of Korea)
September 8-11:	Challenger Society for Marine Science Conference 2014 (Plymouth, UK)
September 9-11:	US AMOC Science Team Meeting (Seattle, WA)
September 20-27:	Autumn School Data Assimilation in Biogeochemical Cycles (Trieste, Italy)
September 24-27:	Short Course on Environmental Economics (Rhodes Business School) (Grahamstown, South Africa)
October 12-16:	World Conference on Marine Biodiversity (Qingdao, China)
October 27-30:	8th European Conference on Ecological Modeling Beyond boundaries: next generation modeling (Marrakech, Morocco)
October 28-31:	Earth Observation for Ocean-Atmosphere Interactions Science 2014 Responding to the new scientific challenges of SOLAS (Frascati (Rome), Italy)
November 17-21:	2nd International Ocean Research Conference One Planet, One Ocean (Barcelona, Spain)
December 15-19:	2014 Fall American Geophysical Union (AGU) Meeting (San Francisco, CA)

2015	
January 26-29:	5th North American Carbon Program (NACP) Principal Investigators Meeting (Washington, DC)
March 23-27:	Third International Symposium on Effects of climate change on the world's oceans (Santos, Brazil)
May 18-21:	7th International Symposium on Gas Transfer at Water Surfaces (Seattle, WA)
September 7-11:	SOLAS Open Science Conference 2015 (Kiel, Germany)

Upcoming Funding Opportunities

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

Rolling Submissions

- NSF Research Coordination Networks (RCN)
- NASA ROSES Rapid Response and Novel Research in Earth Science
- NASA ROSES Fellowships for Early Career Researchers (current fellows)
- NASA ROSES Topical Workshops, Symposia, and Conferences

2014	
January-June:	Wendy Schmidt Ocean Health X Prize Registration open (early-bird registration ends in March)
July 30:	NASA ROSES Ocean Salinity Field Campaign proposal deadline
July 31:	Belmont Forum Collaborative Research Action: Arctic Observing and Research for Sustainability proposal deadline
July 31:	Wendy Schmidt Ocean Health XPrize Entry Submission Form deadline
July 31:	Group on Earth Observations (GEO) Appathon registration deadline
August 1:	Simons Collaboration on Ocean Processes and Ecology (SCOPE) proposal deadline
August 15:	NSF Chemical Oceanography and Biological Oceanography proposal targets
September 25:	NASA ROSES Science Team for the OCO Missions proposal deadline
October 20:	NSF Arctic Research Opportunities proposal deadline
November 3:	NASA ROSES Remote Sensing Theory for Earth Science proposal deadline
November 18:	NSF Dynamics of Coupled Natural and Human Systems (CNH) proposal deadline

2015	
February 15:	NSF Chemical Oceanography and Biological Oceanography proposal targets
February 15:	NSF Ocean Technology and Interdisciplinary Coordination proposal deadline
October 2:	NSF Coastal SEES proposal deadline