OCB NEWS
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*Studying marine biogeochemical cycles and associated ecosystems in the face of environmental change*
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# Ocean Acidification or $CO_2$ Fertilization?

*by David Hutchins*

When I was a graduate student at U.C. Santa Cruz in the early nineties, like most young marine scientists I took a required Chemical Oceanography course. Although most of what I was taught about ocean biogeochemistry still applies today, one subject definitely has changed. One of the basic marine chemistry paradigms that we were taught back then is that the pH of the ocean remains nearly constant within fairly narrow limits, and simply can't change to any large degree. We've known that fossil fuel carbon is entering the ocean as far back as the 1950s, from pioneering work by people like Roger Revelle. Nevertheless, until very recently most of us believed that seawater is just too well buffered by the large amount of dissolved inorganic carbon it contains to be greatly affected by any reasonably expected human perturbation. We now know that this was wrong.

The problem is that we were greatly underestimating the ability of our species to dominate, distort and divert the Earth's natural carbon cycle. As we move into the new millennium, it has become increasingly clear that fossil fuel carbon dioxide ($CO_2$) invading the surface ocean is rapidly overwhelming the ability of the carbonate buffer system to bounce back. Unless we quickly change the way we produce energy to power our civilization, it is predicted that surface ocean pH will fall to 7.8 or so by the end of this century. Projections are that ocean pH will continue to decrease well into the subsequent centuries down to near-neutral levels, a situation that is totally unprecedented in the modern ocean. This unsettling subject was highlighted by an OCB scoping workshop held at Scripps Institution of Oceanography late last year, as well as by a number of other recent and upcoming international meetings. In fact, ocean acidification is now at the very forefront of environmental concerns in the international oceanographic community.

**Figure 1:** The nitrogen gas ($N_2$)-fixing cyanobacterium *Trichodesmium*—one of the main beneficiaries of a high-$CO_2$ ocean?

There is no reason to expect that most marine organisms, accustomed over the ages to living at pH 8 or above, are going to be especially happy about living in a dilute acid bath. Although many types of plankton are quite tolerant of pH values up to 9 or so—levels that can sometimes be reached in intensely photosynthesizing algal blooms—most have probably never in their recent evolutionary history been exposed to low pH conditions. A great deal of the research that has been done in the past few years on the biological consequences of an acidified ocean has focused on organisms that produce calcite or aragonite shells. There is definitely good reason for this concern. Multiple lines of evidence suggest that calcifying organisms ranging from corals to pteropods to coccolithophorids may be among the first casualties of ongoing seawater acidification.

The ecological ramifications of inhibiting marine bio-calcification are not fully understood, but clearly they could be large. Pteropods are a keystone group in high latitude marine food webs, and coccolithophores have a major influence on global ocean carbon and sulfur cycles. Coral reefs support much of the ocean's overall biodiversity, and their loss to acidification (alarmingly predicted by some models as soon as the latter half of this century) would be an environmental tragedy of monumental proportions.

However, it is important to realize that not all ocean life will fare badly in a low pH ocean. As with any comprehensive regime shift, both winners and losers will emerge over the course of this planetary-scale seawater chemistry change. One functional group that seems poised to benefit dramatically from rising seawater $pCO_2$ is the $N_2$-fixing cyanobacteria. Several recent studies suggest that nitrogen gas ($N_2$) fixation rates of *Trichodesmium* (Fig. 1) will increase significantly with increasing $pCO_2$, perhaps by 50% or more at end of the century $CO_2$ levels (~750 ppm) relative to today (Fig. 2). In effect, we now think that the growth and $N_2$ fixation of this biogeochemically critical genus is carbon-limited at present day $pCO_2$.

This would suggest that in the future this diazotroph (and possibly others) may account for an even larger fraction of the new N flux entering the ocean than is the case today. Potential repercussions of fertilizing marine $N_2$ fixers with $CO_2$ include increased anthropogenic carbon uptake by the biological pump, an increased tendency to drive the central gyre ecosystems towards phosphorus (P) or iron (Fe) limitation, basic shifts in the structure of microbial and metazoan communities, and perhaps even an increase in the overall fixed N inventory of the entire ocean. This $N_2$ fixation effect is just one example of the many possible ways that $CO_2$ enrichment could radically alter present day ocean carbon and nutrient cycles, with obvious potential for multiple feedbacks to atmospheric $pCO_2$ and global climate.

So it seems evident that if you're a pteropod what is happening is "ocean acidification," definitely a bad thing, but if you are a $N_2$-fixing cyanobacterium it is "$CO_2$ fertilization," a good thing. There is recent evidence that certain other algal groups, such as some harmful algal bloom flagellates, may also benefit disproportionately from a future warmer, high-$CO_2$ ocean. We expect that the phytoplankton groups that will directly benefit the most from rising $pCO_2$ are those that lack good high-affinity dissolved inorganic carbon concentrating mechanisms (CCMs), such as various DIC transporters and carbonic anhydrases. Although ongoing studies on these topics are now beginning to give us new insights into how inter-specific competition and succession patterns may be altered, the only thing that we can say for certain about biological communities in the coming greenhouse ocean is that they will be different from those of today.

Of course, one of the things that makes accurate predictions difficult is that ocean acidification is not occurring in isolation. Anthropogenic global change goes far beyond rising $pCO_2$ alone, encompassing many other concurrent changes in the environment that will all have profound interactive effects on ocean biology and biogeochemistry. Sea surface warming and freshening due to changing rainfall patterns and ice melting will almost certainly result in increased stratification and shoaling of mixed layer depths, especially in the mid- and high latitudes. This in turn will tend to greatly constrict supplies of major nutrients and iron from below, and at the same time will increase the average light intensity experienced by phytoplankton cells suspended in a shallower mixed layer. In effect, much more of the surface ocean may come to resemble the highly stratified oligotrophic central gyre systems of today. Future aeolian iron input rates and patterns will also likely be different from those of today, due to terrestrial climate and human land use shifts. So will top down control mechanisms on phytoplankton, as zooplankton assemblages contract or expand their biogeographic ranges in a changing ocean.

In short, along with rising $pCO_2$ and

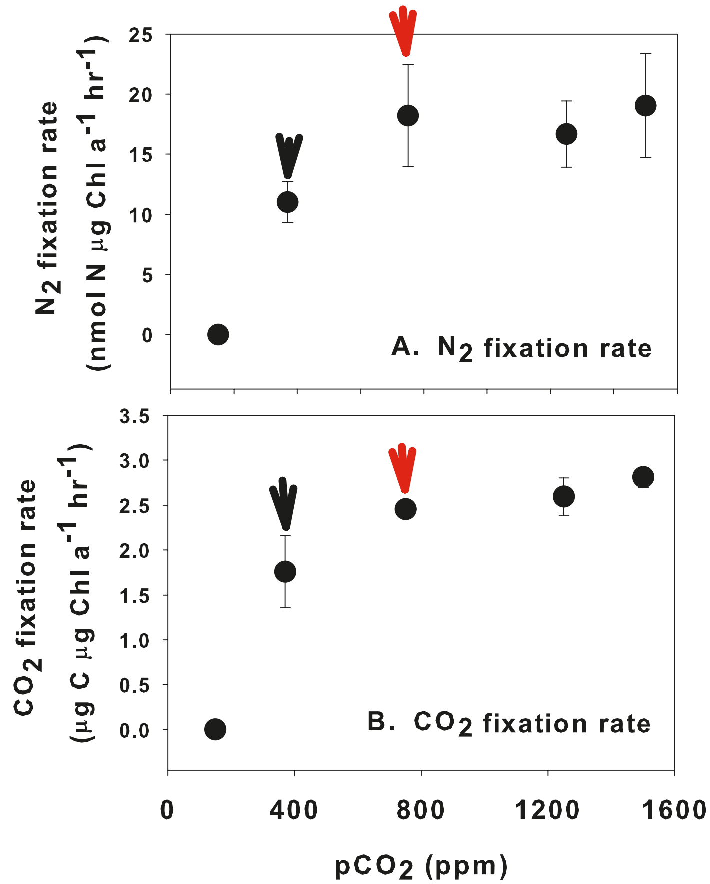


**Figure 2.** Effects of changing $pCO_2$ on A) $N_2$ fixation rates and B) $CO_2$ fixation rates of acclimated cultured *Trichodesmium*. The black arrow indicates present day $pCO_2$ and the red arrow indicates projected year 2100 $pCO_2$. In this experiment, $N_2$ fixation rates increase by ~60% and $CO_2$ fixation rates increase by ~40% over this $pCO_2$ range, but then remain relatively constant with further $pCO_2$ increases. *Trichodesmium* was unable to grow at all at 150 ppm, so rates for this $pCO_2$ treatment are zero.

*Ref: (Adapted from D.A. Hutchins et al., Limnol. Oceanogr. 52(4), 1293-1304 (2007).)*

falling pH, plankton communities in the euphotic zone will simultaneously have to deal with changes in almost every other important environmental parameter- light, temperature, major and micronutrient supplies, inter-specific competition, and grazing pressure. Some of these concurrent changes may reinforce the biological effects of acidification, while others will tend to negate them. An example of this type of interactive influence of $pCO_2$, light, and temperature on calcification of the coccolithophorid *Emiliania huxleyi* is shown in Fig. 3. It is evident that these multivariate interactions can be exceedingly complex, and both synergisms and antagonisms are likely. Realistic prediction of the net outcome of this complex network of global change variables is virtually impossible at this point. Obviously though, caution is needed when extrapolating from the results of experiments or models that vary only $CO_2$ and neglect other, perhaps equally important co-variables.

To make these kinds of accurate predictions a reality, we need to marshal all of the tools available to us from modern oceanography. Time series, remote sensing, instrumented moorings, and other observational efforts can help discern decadal-scale trends, although perhaps in some cases we may need to reassess some of their priority parameters and analytical emphases. Quantitative models are already helping us to formulate hypotheses about future changes, but still require a new generation of data inputs before they can hope to accurately capture the full complexities of the processes involved. The exponential expansion in the availability of new genetic, genomic and metagenomic tools also has almost unlimited potential to revolutionize this field, as it has done for many others in marine biology. Experimental manipulations represent another tool that can yield these types of needed insights, as the tremendous advances in the iron limitation field over the past twenty years have shown us.

Global change manipulative experiments can be divided into two general categories. As shown by the data in Figs. 2 and 3, one invaluable approach is to take biogeochemically and ecologically critical organisms, get them growing as isolated cultures in the lab, and then closely examine their physiological responses to simulated greenhouse ocean conditions. This type of approach has been extensively used for many years by a number of international research groups to answer questions about algal CCM physiology and responses to changing temperature, light and nutrient regimes. One major advantage of lab culture work is the ability to acclimate the organism to experimental conditions over many generations before sampling, and lab investigations are also amenable to relatively complex, multivariate experimental designs. Their obvious disadvantage is that they cannot realistically simulate the complex biological, physical and chemical matrices that real organisms experience in the ocean.

To deal with this last issue, several research groups have been conducting manipulative experiments with natural assemblages. My lab has used a shipboard continuous culture system to carry out global change experiments with communities that are growing under relatively steady-state conditions of altered $CO_2$, temperature,

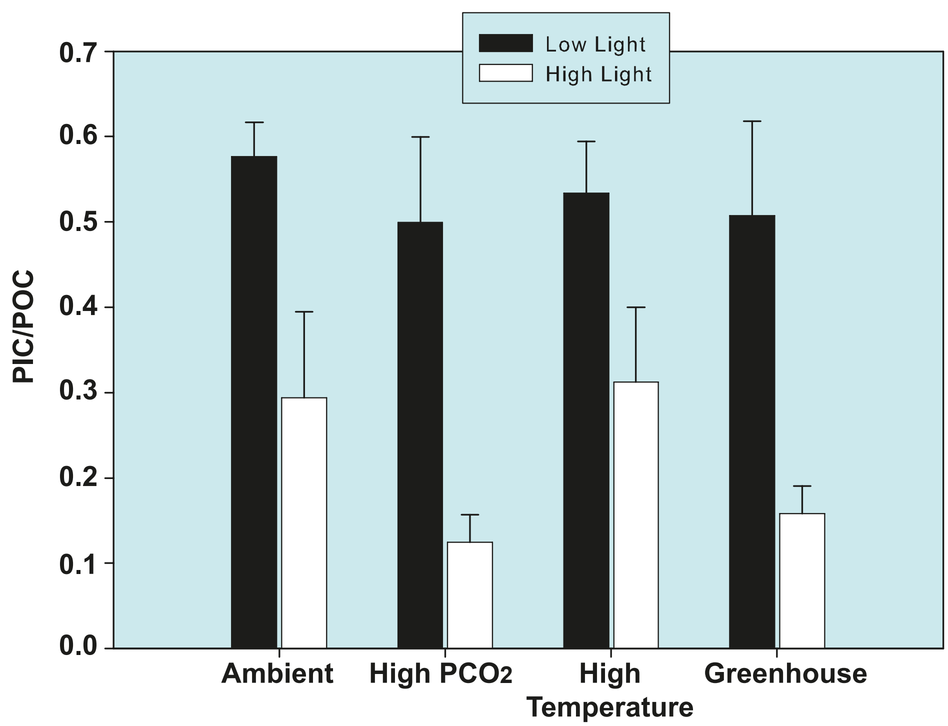


**Figure 3.** Results of an experiment examining the interactions between $pCO_2$, temperature and light as they affect calcification of acclimated cultures of the coccolithophorid *Emiliania huxleyi*. The degree of calcification is expressed as the cellular PIC/POC ratio (particulate inorganic carbon to particulate organic carbon). Treatments include an ambient control (20°C and 375 ppm $pCO_2$), high $pCO_2$ alone (750 ppm), high temperature alone (24°C), and "greenhouse" (both $pCO_2$ and temperature increased together). All four treatments were run at both high light (open bars) and low light (black bars). This experiment suggested that neither $pCO_2$, light, nor temperature affected cellular calcification at low light. However, increased light greatly decreased the PIC:POC ratio in all treatments, while increased $pCO_2$ further interacted with light to decrease calcification even more at high light.

*Ref: (From Y. Feng et al., Eur. J. Phycol. 43(1), 87-98 (2008)).*

light and iron availability. While no one would argue that ocean biology is really at steady state, the advantage of our experimental methods is that they allow us to acclimate the assemblage to the altered conditions over a period of weeks. The relative stability of the biomass, community composition and biogeochemistry in the continuous culture system also means that the physiological parameters we measure are meaningful, since the community has had a chance to adapt and reach some sort of equilibrium state.

Another method that has been used mostly by the Europeans to examine whole community responses is a large volume mesocosm experiment. A number of landmark papers by Ulf Riebesell and colleagues have come from $CO_2$ manipulations conducted at the Bergen mesocosm facility in Norway. The advantages of mesocosms are that they have fewer enclosure artifacts than smaller bottles, and the large volume of water can allow a better representation of the whole plankton community, including components like mesograzers that are typically not present in shipboard incubations. The experiments that have been published using this mesocosm method have all been "batch" type grow-out experiments, where the phytoplankton are allowed to grow through a lag phase, into exponential growth phase, and finally into stationary phase as the initial nutrients are exhausted. This batch type growth may be an effective way to simulate the course of a coastal phytoplankton bloom under high $CO_2$ conditions.

However, caution needs to be exercised in interpreting batch culture physiological and biogeochemical responses, since these are continually changing throughout the course of this type of non-steady-state experiment. In addition, none of the published European experiments have attempted to co-vary other parameters like temperature along with $pCO_2$.

Logistically, multiple variable experiments are not an easy thing to accomplish in a mesocosm facility. With both the advantages and limitations of large volume experiments in mind, the need for a state-of-the-art mesocosm facility for global change experiments in the U.S. was a prominent topic of discussion at the OCB ocean acidification workshop. The possibility of doing other types of manipulative high-$CO_2$ experiments, perhaps using the methods pioneered for in situ experiments by iron limitation researchers, was also on the table but was acknowledged to present exponentially greater logistical difficulties.

Finally, there is an issue that always comes up when discussing any type of global change manipulation experiments. How representative are these perturbation experiments of the types of biological shifts that will happen over the next century or two, when by necessity the experiments must subject the communities to much more abrupt, short-term changes? How important are adaptation and evolution at both the species and community level in determining the nature and magnitude of future assemblage changes? This issue certainly needs more attention than it has received. Probably the only way to really get a handle on adaptation processes, though, is to go back to the acclimated laboratory culture approach described above, especially when coupled with a sophisticated array of physiological, biochemical and molecular tools. Natural plankton communities simply cannot be maintained in enclosed experiments (of any size) long enough to allow meaningful assessments of adaptation and evolution.

**"So it seems evident that if you're a pteropod what is happening is 'ocean acidification,' definitely a bad thing, but if you are a $N_2$-fixing cyanobacterium it is '$CO_2$ fertilization,' a good thing."**

So, does this mean that relatively short-term global change manipulative experiments are not worth doing? Emphatically, no! They remain the only tool we currently have that can provide us with plausible, testable hypotheses about future biological responses to acidification and other variables. These hypotheses can then be validated or negated by other methods, like models and long-term observations. Short-term experimental manipulations obviously cannot tell us if and how organisms will be able to adapt to longer term global change effects, but they certainly can suggest to us which organisms in today's communities are already "pre-adapted" to take advantage of future changes. At any rate, it is not clear to what extent evolution can keep pace with the rapid rate of anthropogenic change in the ocean. A century is, after all, only a brief moment of time on an evolutionary timescale. It is entirely possible that the current ocean biology will simply not have enough time to fully adapt to rapidly falling seawater pH in the decades ahead.

No matter what we decide to do about designing experiments and observations to understand the impacts of ocean acidification and global change, one thing is clear. By continuing to burn fossil fuels, our species is currently conducting a massive, uncontrolled experiment on the entire ecosystem of the planet, including of course the oceans. Unfortunately, we don't have a "control Earth" for comparison! Whatever the strengths and weaknesses of the various proposed research approaches to ocean acidification, clearly the only one that is completely unacceptable to all of us is to do nothing at all.

# MS PHD'S join OCB at WHOI:
## *An Auspicious Assembly of Acronyms!*

The MS PHD'S, or Minorities Striving and Pursuing Higher Degrees of Success in Earth System Science initiative was developed by and for under-represented minorities with the overall purpose of facilitating increased participation in Earth system science. This program offers networking and mentoring opportunities with federal agency program officers, professional society representatives, peers, researchers, and educators from different institutions across the country. It provides its members with professional development opportunities and exposure to various earth system science and engineering fields via participation in community activities and scientific conferences like the Ocean Carbon and Biogeochemistry (OCB) Workshop, held July 23-26, 2007 at the Woods Hole Oceanographic Institution. Each year, OCB works with the MS PHD'S program to select candidates with an interest in oceans and climate to visit Woods Hole for one week as part of their overall MS PHD'S experience. This year, OCB hosted three graduate students working in the fields of environmental science, microbiology, and terrestrial geology.

Phaedra Thomas, Porché Spence, and Hovey Clifford (left to right) deploying a surface sediment grab sampling device.

"I am a Ph.D. student in the Soil Science Department at North Carolina State University. Currently my research focuses on characterizing the influence of residential lawn management on nitrogen losses via biogenic trace gas emissions and overland runoff. I have been a member of MS PHD'S since Fall 2006. Through the program, I recently had the opportunity of attending and presenting a poster at the Ocean Carbon and Biogeochemistry Workshop in Woods Hole, MA. I was able to network with oceanographers and learn more about marine science. I had the opportunity to participate in a day trip aboard the R/V *Tioga*. During the cruise we collected ocean sediment and water samples and learned about shipboard navigation. I also visited several marine labs in Woods Hole. Overall, the OCB workshop expanded my networking base and contributed to my professional development."

*—Porché Spence, MS PHD'S 2007/ North Carolina State University*

"I am a Biology graduate student at the University of South Florida in Tampa, Florida, and my research involves marine/freshwater microorganisms and the $CO_2$-fixing enzyme of Form IC RubisCO (ribulose-1,5-bisphosphate carboxylase/oxygenase). This topic fit well with the carbon theme of the OCB workshop in Woods Hole. I was able to present a poster at this meeting and interact with other researchers in the field. The activities in Woods Hole were well organized and well worth it. I participated in a day trip aboard the R/V *Tioga*, which allowed me to further understand the responsibilities and meticulous work that goes into sampling seawater and sediments. The aquarium and different lab tours let us see first-hand the impact of our research and how there is a definite need for it. This experience has enriched my academic and professional life and I am grateful to the MS PHD'S initiative, my OCB mentor Dr. Lihini Aluwihare, and the people of WHOI for the opportunity."

*—Phaedra Thomas, MS PHD'S 2007/ University of South Florida*

"Coming from a terrestrial geology background, I am pleased to say the workshop was not only intellectually stimulating, but provided an excellent opportunity to explore my interests as they would be applicable within another discipline. My current studies in terrestrial weathering, rates of nutrient release to the environment, and application of models to elucidate field observations seems to mimic the research of many in the field of ocean biogeochemistry. My OCB science mentor, Debbie Steinberg, introduced me to several individuals with whom I am sure I would never otherwise have met. In addition, I met a fellow 'Penn Stater,' Ray Najar. How funny to travel so far to meet a scientist who resides in your own backyard. Participating in the Breakout Session on "Riverine


Participants of the MS PHDS R/V *Tioga* day trip: Front (left to right): Nicole Benoit (WHOI), Porché Spence (NC State), Jennifer Zan Williams (Penn State), Ian Hanley (WHOI); Back (left to right): Hovey Clifford (WHOI), Bruce Tripp (WHOI), Ken Houtler (WHOI), and Phaedra Thomas (USF); Missing from photo: Andrew McDonnell (WHOI).

Fluxes and Near Coastal Environments" was an insightful preview to my future and I enjoyed the productivity of a brainstorming session. As an added bonus, our MS PHD'S activities included an aquarium tour, a day trip on the R/V *Tioga*, a mass spectrometry lab tour, and a tank tour of some current research at MBL on camouflage response of cuttlefish. I enjoyed the R/V *Tioga* trip most. I am a graduate of New Mexico State University, a landlocked institution which did not provide the opportunity to study or experience ocean science research. What a treat the *Tioga* experience was! If the opportunity arises for me to collaborate on or initiate a study that includes an ocean component, I will certainly participate! Thanks for a great workshop and the hospitality of Woods Hole!"

*—Jennifer Zan Williams, MS PHD'S 2007/ Pennsylvania State University*

## Welcome from OCB Project Office

Welcome to the inaugural newsletter of the Ocean Carbon and Biogeochemistry (OCB) Program. Ocean biogeochemistry and related aspects of marine ecology are central to the workings of our planet and to pressing scientific challenges such as human-driven climate change. Unresolved questions include, for example: How much fossil-fuel carbon dioxide does the ocean remove currently and how may that change in the future? How will marine ecosystems respond to global warming and ocean acidification and will this result in feedbacks on climate change?

The scope of many of these biogeochemical questions is large, spanning ocean chemical, physical, and biological disciplines. The solutions often require a hierarchy of approaches from individual studies to integrated, community efforts for field research, remote sensing, data management, and synthesis and modeling. With this in mind, the NSF, NASA, and NOAA created the OCB Program to foster better communication and coordination within the U.S. research community and with our international partners.

The OCB is designed as a bottom-up program open to broad community input and involvement in identifying and developing new research activities. Last summer we established an annual OCB science workshop, and in the Fall we started a series of OCB scoping workshops to target more specific research challenges and opportunities. The first scoping workshop on ocean acidification was a great success, which I hope will develop into a full-fledged new research program within OCB.

The OCB Program depends on the energy and creativity of individual scientists. I encourage you to get involved through participating in or organizing an OCB meeting and developing plans for future research programs.

Sincerely,

Scott Doney

# An Introduction to the Biological & Chemical Oceanography Data Management Office (BCO-DMO)

The BCO-DMO (www.bco-dmo.org) was created to serve PIs funded by the NSF Biological and Chemical Oceanography Sections as a facility where marine biogeochemical and ecological data and information developed in the course of scientific research can easily be disseminated, protected, and stored on short and intermediate time frames. The Data Management Office (DMO) also strives to provide research scientists and others with the tools and systems necessary to work with marine biogeochemical and ecological data from heterogeneous sources. To accomplish this, two data management offices, the former U.S. Joint Global Ocean Flux Study (JGOFS) DMO and the U.S. GLOBal ocean ECosystems dynamics (GLOBEC) DMO, have been united and enhanced to provide a venue for contribution of electronic data/meta-data and other information for open distribution via the World Wide Web.

The BCO-DMO will manage existing and new data sets from individual scientific investigators, collaborative groups of investigators, and data management offices of larger multi-institutional projects. The office staff will work with principal investigators on data quality control; maintain an inventory and program thesaurus of strictly defined field names; generate metadata (e.g., Directory Interchange Format (DIF)) records required by Federal agencies; ensure submission of data to national data centers; support and encourage data synthesis by providing new, online, Web-based display tools; facilitate interoperability among different data portals; and facilitate regional, national, and international data and information exchange.

**The Data and Information Management System**

The BCO-DMO uses the JGOFS/GLOBEC Client/Server distributed data management software to serve data and information to researchers via Web browser clients (e.g. Firefox, Safari, Internet Explorer, Netscape, etc). In addition, development of a machine-to-machine application programming interface (API) to allow interoperability between Web-based data systems is underway. The existing data management system is being modified to support the larger scope of the BCO-DMO effort and to address the ultimate goal of data system interoperability. The new BCO-DMO data management system that will ultimately provide a way to exchange data with other data systems is based on a philosophy of data stewardship, existing and evolving data standards, public domain software, and open access to the data. The data server system is designed to help researchers view, manipulate, and retrieve data with the ultimate goal of providing improved access to collections of ocean science data.

In the new BCO-DMO data system, project and data set metadata records designed to support re-use of the data are stored in a relational database (MySQL) and the data are stored in or made accessible by the JGOFS/GLOBEC object-oriented, relational, data management system. Data access is provided via any standard Web browser client, either through a geospatial interface (MapServer) or through a tabular, text-based directory listing of available data sets. The data server supports a variety of Web-based data displays; typically data are organized hierarchically and actual data values are shown. In addition, data can be graphed and displayed as X-Y plots or downloaded in several formats including plain text or Matlab or as compressed zip or tar files. In an effort to maximize data system interoperability in the future, data will also be available via Web Services; and data set descriptions will be generated that comply with a variety of metadata content standards.

Data can be contributed to the system in a variety of forms, including but not limited to, tabular listings, spreadsheets, and Matlab files. Images and movies can be served, subject to file size and resolution constraints. Data can also be served directly from other data management systems, such as Oracle, and other systems that support Internet access and the SQL interface.

For details on how to access and/or contribute data, please visit www.bco-dmo.org.

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# Linking Watersheds to Coastal Systems: A Global Perspective on River Inputs of N, P and C

*by Sybil P. Seitzinger and Emilio Mayorga*

The inputs of nutrients, carbon and freshwater from land to the coastal ocean have been markedly altered by anthropogenic activities. As a result, carbon production, ecology, and circulation in the coastal ocean have been altered in ways that are still being discovered. Addressing this challenge will require improved understanding of the linkages between human activities in watersheds, delivery of nutrients and water inputs to coastal systems, and the effects of those changes on coastal systems, in addition to continued studies on natural controls.

Uneven spatial distribution of human population, agriculture, and industrial activity leads to spatial differences in the anthropogenic alterations of nutrient inputs to coastal ecosystems. While many site-specific studies have documented river transport of nitrogen (N), phosphorus (P), carbon (C) and silicon (Si) to coastal systems, there are many more rivers for which there are no measurements; sustained monitoring of temporal changes in exports is rarer still. In order to provide regional and global perspectives on changing nutrient transport to coastal systems throughout the world, an international work group (Global NEWS —Nutrient Export from WaterSheds, www.marine.rutgers.edu/global news) has developed a spatially explicit global watershed model that relates human activities and natural processes in watersheds to nutrient inputs to coastal systems throughout the world. Global NEWS was formed in spring of 2002 as an interdisciplinary workgroup of UNESCO's Intergovernmental Oceanographic Commission (IOC, www.ioc.unesco.org) focused on understanding the relationship between human activity and coastal nutrient enrichment. The first version of the NEWS model is based on mid-1990s conditions and was published in a special section of Global Biogeochemical Cycles (1-5). This model is now being used to provide hindcasts and forecasts under a range of scenarios portraying changes in nutrient, carbon and water inputs to coastal systems. In this article we briefly describe the NEWS model and present highlights from the published results corresponding to mid-1990's conditions, focusing on river exports and fate in the coastal zone. Our goal is to stimulate collaborations with the oceanographic community addressing the coupled impacts of marine processes and riverine inputs on carbon, biogeochemistry and ecosystem functioning on the continental shelf.

**NEWS Model Basics**

NEWS is a multi-element, multi-form, spatially explicit global model of nutrient (N, P and C) export from watersheds by rivers (Table 1). The model output is the annual export at the mouth of the river (essentially zero salinity). Because the relative bioavailability of different nutrients and nutrient forms (dissolved vs. particulate, inorganic vs. organic) can influence ecosystem response, multi-element, multi-form approaches are needed to predict ecosystem vulnerability or response. The NEWS model uses consistent global databases to predict riverine nutrient export by form as a function of natural and anthropo-

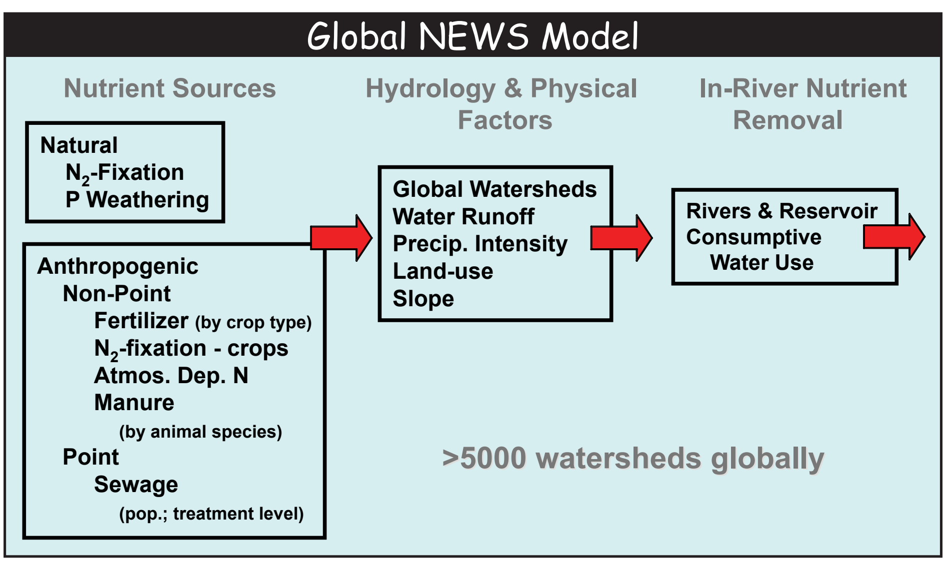



Figure 1. Schematic of some of the major inputs and controlling factors in the Global NEWS model.

| | Dissolved Inorganic | Dissolved Organic | Particulate |
|---|---|---|---|
| N | DIN | DON | PN |
| P | DIP | DOP | PP |
| C | **DIC** | DOC | POC |
| Si | **DSi** | | |

Table 1. Nutrient forms modeled in Global NEWS. DIC and DSi sub-models (in bold) are currently under development.

genic characteristics, including point and non-point watershed sources, hydrological and physical factors, and removal within the river system (Figure 1). In addition, it can estimate the relative contribution of each watershed source to export at the river mouth, by form (5). NEWS builds on an earlier model of dissolved inorganic N (DIN) export (6) as well as other models of biogeochemical exports—such as particulates (7)—developed by the community over the last decade.

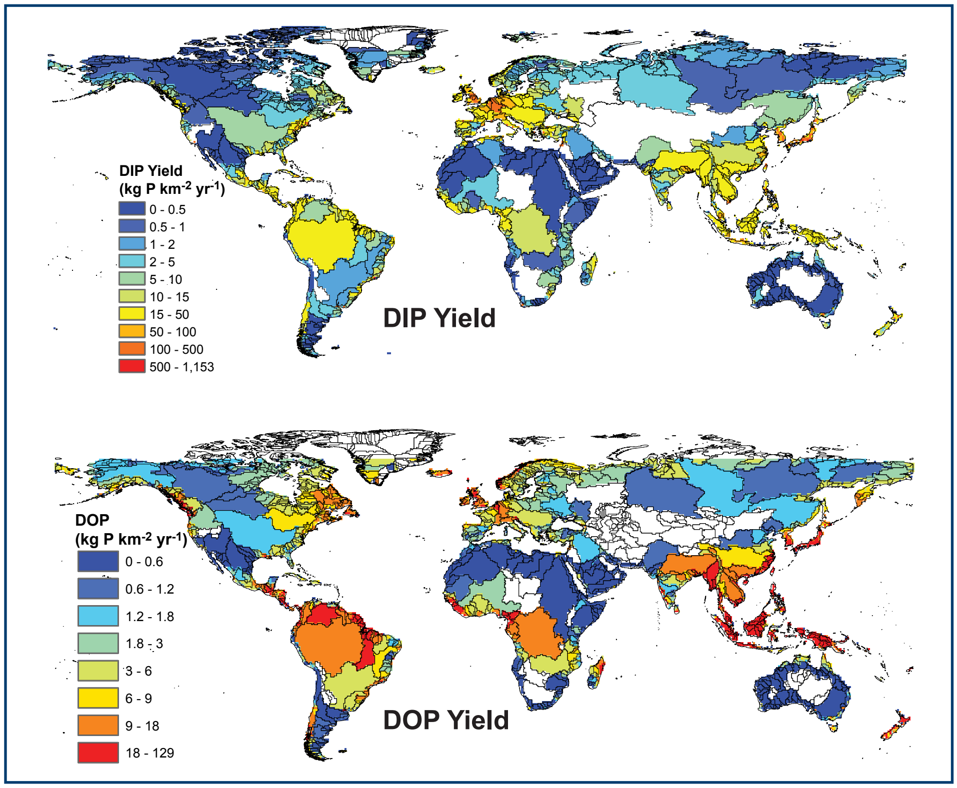



Figure 2. Basin yields of dissolved inorganic and organic phosphorus (DIP and DOP). The amount of P exported at the river mouth is expressed as the watershed average export in kg P per $km^2$ of watershed per year; total mass export or load equals yield times watershed area.

**Contemporary River Nutrient Exports: Forms and Spatial Distributions**

There are large spatial variations in river export of elements and elemental forms to the coastal zone. This is illustrated by the watershed yields of dissolved inorganic P (DIP) and dissolved organic P (DOP) (Fig. 2). Yields of DIP and DOP show large variations among watersheds within regions as well as at larger spatial scales. Furthermore, the spatial patterns and range of yields of these two P forms differ. These differences among rivers in both the amount and the form are driven by contrasts in the relative importance of the various sources and controlling factors in the watersheds (5).

There are also important differences between the patterns of N and P river export. The relative magnitude of the various forms of N and P differ (Fig. 3). At the global scale, approximately equal fractions (~40%) of total N (TN) river export are in the form of DIN and particulate N (PN), with dissolved organic N (DON) accounting for ~20%. In contrast, ~80% of total P (TP) export is as particulate P (PP), with relatively small amounts as DIP or DOP. This has important implications for linking nutrient inputs to coastal ecosystem biogeochemistry, as the different forms of N and P have different reactivities. For example, while most of the P is exported as particulate P, only a small portion of that is readily exchangeable into a form (e.g., DIP) that can be rapidly used by phytoplankton.

The latitudinal distribution of river nutrient export to the coast shows strong patterns. Aggregation of the NEWS model output by latitude emphasizes the importance of tropical and subtropical latitudes in N, P and C export. 70-75% of the global river TN, TP and total organic C (TOC) is exported into tropical and subtropical coastal waters (30˚S to 30˚N; Fig. 3). This region also dominates all global particulate fluxes (Fig. 3) due to the occurrence of high runoff and tectonically active mountain ranges in both large rivers (*e.g.*, Amazon, Mekong, Ganges-Brahmaputra) and small mountainous rivers. The former generally discharge into passive, wide shelves, while the latter discharge into active, narrow shelves, with consequences for the sequestration of exported particulates.

Nutrient ratios in coastal systems not only affect nutrient limitation but can also affect phytoplankton species composition. The NEWS model output suggests that the ratio of TN:TP in river export to coastal systems varies widely (Fig. 4). However, TN and TP river exports are only one part of the story. While the NEWS model predicts the individual forms of N and P, determining the bioavailability of each N and P form remains a major scientific challenge. Furthermore, rapid transformations of the different nutrient forms occur in coastal waters and modify the nutrient concentrations and ratios. Nevertheless, a preliminary comparison of the spatial distributions of NEWS N and P exports and *Prorocentrum minimum* (a high-biomass species that forms harmful algal blooms) observations suggests a global relationship between blooms and anthropogenically enhanced dissolved nutrient exports (unpub. data).

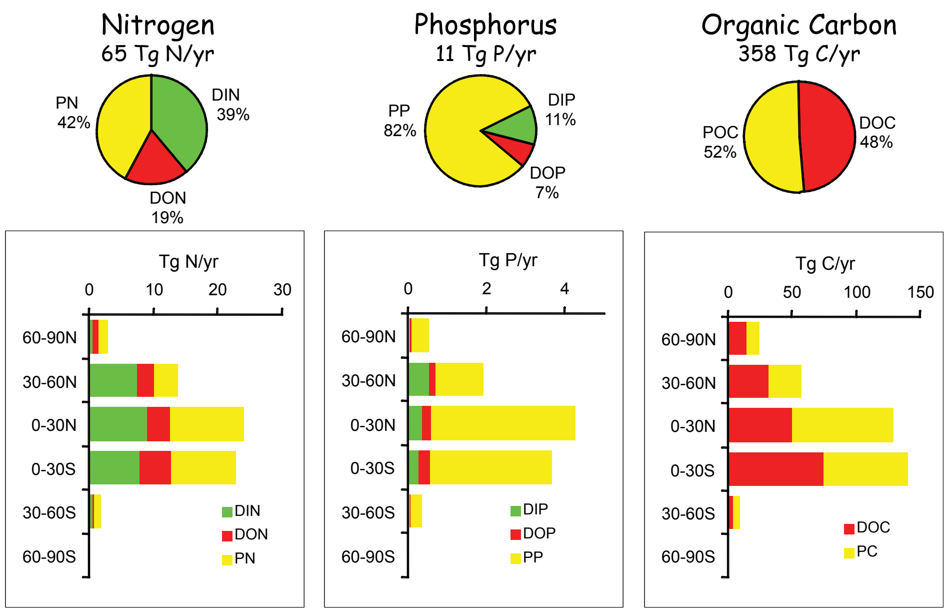



***Figure 3.*** Global and latitudinal partitioning of N, P and C river export to the oceans by nutrient form. For particulates, Global NEWS calculates particulate organic carbon (POC) and total (inorganic + organic) particulate N (PN) and P (PP) forms. PN and PP are typically dominated by organic and inorganic forms, respectively.

**Fate of N in Coastal Systems Linked to C**

Denitrification is one microbial process that not only decreases the amount of fixed N in an ecosystem, but also decreases the N:P ratio. Denitrification is very effective at removing N in estuarine and continental shelf ecosystems. Based on a spatially explicit model of denitrification in global coastal systems (8), we estimate that of the approximately 65 Tg/yr of TN exported globally by rivers, ~20 Tg are rapidly removed by denitrification in estuarine sediments (Fig. 5). That leaves approximately 45 Tg of N that reaches continental shelves either by large rivers that discharge directly to the shelf (e.g., Mississippi River) or riverine N that is not denitrified in the estuary and is flushed out of the estuary to the shelf. The model suggests that essentially all of that 45 Tg N is denitrified in the shelf sediments.

However, before this N can be denitrified, it must first be incorporated into the C cycle. It is through deposition of organic matter to the sediments, followed by organic matter decomposition that releases the organic N as ammonia, which is then nitrified and denitrified, that most of the river N enters the denitrification pathway. Alternate pathways of $N_2$ production, such as anaerobic ammonia oxidation, also can occur in coastal sediments; the magnitude of those pathways is an area of active research.

While rivers represent a major pathway for the transfer of nutrients from land to ocean, an additional amount of terrestrially derived N enters the ocean via atmospheric deposition (9). This N is likely ultimately denitrified either in oxygen-minimum zones or transported back on to the shelf. In fact, the continental shelves are a major sink not only for riverine N, but for N derived from $N_2$-fixation occurring in oceanic waters. Total denitrification on continental shelves may exceed 100 Tg N/yr with contributions from riverine N, atmospheric N and marine $N_2$-fixation.

The impact of river inputs on the C cycle involves both direct C fluxes and nutrient fluxes that impact ecosystems on continental margins, and hence C production (and potentially, burial). How does the amount of organic carbon delivered by rivers compare to the amount of organic carbon that could be produced from, for example the DIN supplied by rivers to coastal waters? Assuming Redfield stoichiometry, the amount of organic C (OC) delivered by rivers equals about 2-3 times the amount of OC that could be produced from the DIN delivered by rivers (Fig. 6).

**Future Nutrient Exports**

Continued economic and population growth are expected to result in rapid increases in anthropogenic nutrient inputs to watersheds and human alterations of the hydrological cycle, in addition to climate change driven

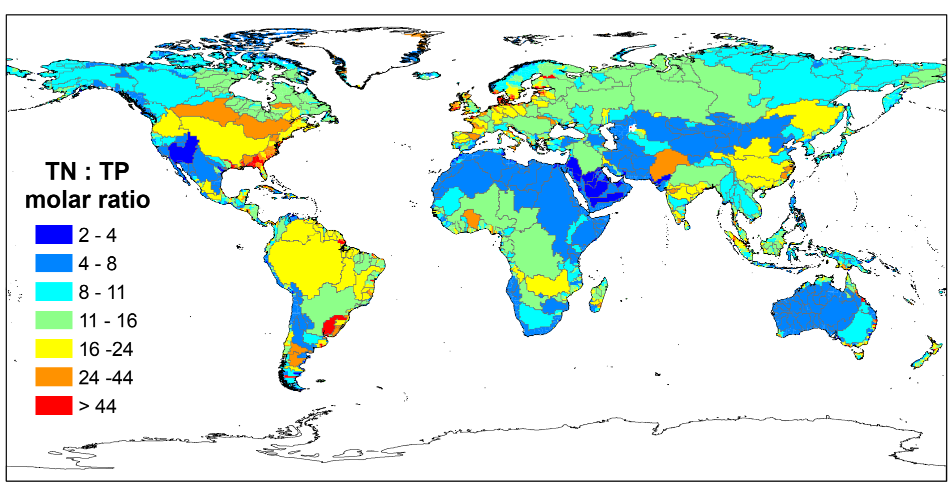



***Figure 4.*** Molar ratio of total N to total P (TN:TP) in river basin exports.

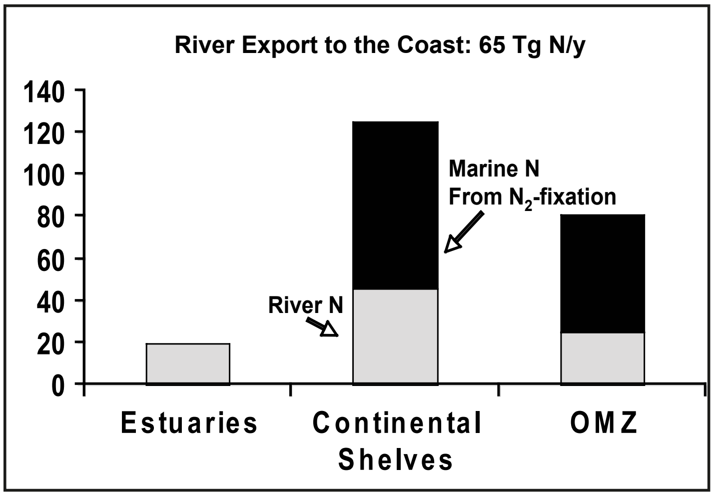



**Figure 5.** Global denitrification of N in estuaries, continental shelves, and oxygen-minimum zones (OMZ) from land-based (gray) and marine (black) sources (modified from (8)).

by the emission of greenhouse gases. We are applying the NEWS model to global scenarios of future conditions in order to develop a scientific basis for actions to reverse these trends and sustain riverine and coastal ecosystem health. The magnitude and spatial patterns of those changes will depend on many social, economic, policy, climate, and biogeochemical factors. Earlier results (10) for the year 2050 under a business-as-usual scenario indicated that between 1990 and 2050 the global DIN export by rivers would more than double; by 2050, 90% of river export would be considered anthropogenic. Currently, we are examining nutrient export trajectories under the Millennium Ecosystem Assessment scenarios (www.maweb.org/en/Scenarios.aspx) (11) for 2030 and 2050. Preliminary results show contrasting patterns of export among scenarios, regions, and nutrient forms. When completed, this work may help guide policy decisions related to nutrient mobilization.

## Evolution of NEWS

The initial model developed by the Global NEWS workgroup is serving as a starting point for ongoing and future enhancements, and for collaborations with other Earth System and policy efforts. Coastal degradation is a global-scale problem that requires the promotion of regional expertise. With support from UNESCO-IOC and the Global Environmental Facility (GEF), we have carried out training workshops for scientists from developing countries and countries with economies in transition, fostering capacity building through the transfer of advanced methods, practices and tools for coastal nutrient management.

In addition to the Millennium Ecosystem Assessment scenario thrust, we are extending the model to sub-basin and sub-annual scales in a project funded by NASA and led by the University of New Hampshire's Water Systems Analysis Group (WSAG, www.wsag.unh.edu). Gaps in nutrient form coverage are being filled in through the development of sub-models for dissolved silica (DSi) and dissolved inorganic carbon (DIC). To directly link human activities on land to coastal responses, we are developing relationships between river nutrient inputs and quantitative indicators of coastal ecosystem health, at regional to global scales. Integration of these Global NEWS activities with other terrestrial and oceanographic efforts will be greatly facilitated by our participation in the recently launched Community Surface Dynamics Modeling System (CSDMS, www.csdms.colorado.edu), which is focusing on interoperability among models spanning the transport of water, sediments and constituents from the land surface to the continental shelf.

We are grateful for the financial and institutional support provided by UNESCO-IOC, GEF, NSF, NOAA, NASA and the individual institutions represented by Global NEWS participants. We look forward to opportunities to interface our work with the OCB community.

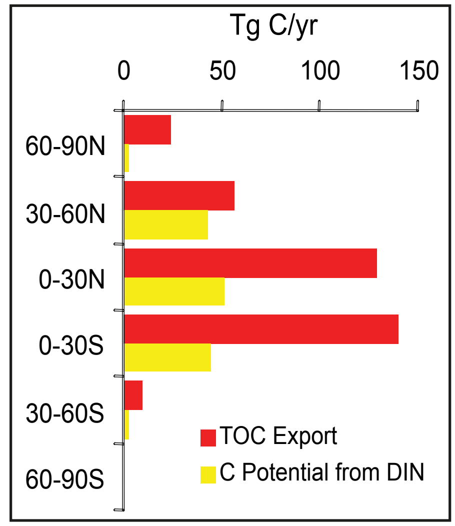



**Figure 6.** Latitudinal distribution of total organic carbon (TOC) delivered by rivers to the oceans, compared to the amount of organic carbon that could be produced from river DIN exports assuming Redfield stoichiometry.

### References

1. *A. H. W. Beusen, A. L. M. Dekkers, A. F. Bouwman, W. Ludwig, J. Harrison, Global Biogeochem. Cycles 19, GB4S05, doi:10.1029/2005GB002453 (2005).*
2. *E. Dumont, J. A. Harrison, C. Kroeze, E. J. Bakker, S. P. Seitzinger, Global Biogeochem. Cycles 19, GB4S02, doi:10.1029/2005GB002488 (2005).*
3. *J. A. Harrison et al., Global Biogeochem. Cycles 19, GB4S03, doi:10.1029/2004GB002357 (2005).*
4. *J. A. Harrison, N. Caraco, S. P. Seitzinger, Global Biogeochem. Cycles 19, GB4S04, doi:10.1029/2005GB002480 (2005).*
5. *S. P. Seitzinger, J. A. Harrison, E. Dumont, A. H. W. Beusen, A. F. Bouwman, Global Biogeochem. Cycles 19, GB4S01, doi:10.1029/2005GB002606 (2005).*
6. *S. P. Seitzinger, C. Kroeze, Global Biogeochem. Cycles 12(1), 93-113 (1998).*
7. *W. Ludwig, J. Probst, S. Kempe, Global Biogeochem. Cycles 10, 23-41 (1996).*
8. *S. P. Seitzinger et al., Ecol. Applications 16(6), 2064-2090 (2006).*
9. *R.A. Duce et al., Science (In Press).*
10. *S. P. Seitzinger et al., Estuaries 25(4b), 640-655 (2002).*
11. *S. Carpenter, P. Pingali, E. Bennett, M. Zurek, Eds. (Island Press, 2005), vol. 2: Scenarios. Findings of the Scenarios Working Group, In Millennium Ecosystem Assessment Series.*

# OCB Update

**OCB Scientific mission**

To establish the evolving role of the ocean in the global carbon cycle, in the face of environmental change, through studies of marine biogeochemical cycles and associated ecosystems.

**Overarching scientific themes**

1) Oceanic uptake and release of atmospheric $CO_2$ and other greenhouse gases
2) Climate sensitivities of biogeochemical cycles and interactions with ecosystem structure.

**Current scientific priorities**

- Ocean acidification
- Terrestrial/coastal carbon fluxes and exchanges
- Climate sensitivities of and change in ecosystem structure and associated impacts on biogeochemical cycles
- Mesopelagic ecological and biogeochemical interactions
- Benthic-pelagic feedbacks on biogeochemical cycles
- Ocean carbon uptake and storage

The scope of OCB-related activities encompasses a variety of ongoing programs including the Ocean Carbon and Climate Change (OCCC) program and the North American Carbon Program (NACP); U.S. contributions to IMBER (Integrated Marine Biogeochemistry and Ecosystem Research), SOLAS (Surface-Ocean Lower Atmosphere Study), and CARBOOCEAN; numerous U.S. single- and multi-investigator research projects funded by NASA, NOAA, and NSF; and critical ocean observing efforts, such as the HOT (Hawaii Ocean Time-Series), BATS (Bermuda Atlantic Time-Series), and CARIACO (CArbon Retention In A Colored Ocean) time-series, Repeat Hydrography $CO_2$ surveys, satellite remote sensing, and ORION (Ocean Research Interactive Observatory Networks). A key objective of OCB is to coordinate and enhance interactions among these various activities.

The role of OCB is to promote, plan, and coordinate collaborative, multidisciplinary research opportunities within the U.S. and with international partners. OCB will support any project at the request of the PI(s) that falls within our broad scientific priorities; projects can be already underway or in the planning stage, and the scope can be from an individual scientist to multi-scientist teams. Support from OCB could include helping to publicize upcoming field opportunities, facilitate collaboration from different research teams, disseminate research findings, data sets and model products, and develop and share educational and public outreach material. OCB does not approve or endorse any particular research project---that is the role of the peer review process and the federal science agencies. Instead, OCB will make recommendations on research topics and priorities within the framework of ocean biogeochemistry and related ecological science.

The OCB Project Office, currently based at Woods Hole Oceanographic Institution, maintains the OCB webpage, which serves as a venue for publicizing meetings and workshops; posting scientific planning documents, white papers, and workshop reports; meeting/workshop logistics; posting relevant current events; OCB PI project information; and data archiving.

Current OCB projects include a combination of individual PI grants and mid-sized projects (multiple PIs), with a view toward larger coordinated studies. OCB is also promoting new research initiatives. As of FY08 (February 15 target), NSF Chemical Oceanography has up to $3 million/year for new OCB-related research. OCB-related proposals can also be submitted to NSF Biological Oceanography. NSF OCE is especially encouraging new proposals to do ocean acidification research. Funding opportunities for OCB-related science are also available through the NASA Research Opportunities in Space and Earth Sciences (ROSES) and the NOAA Global Carbon Cycle Programs.

In addition to its larger annual summer science workshop, which focuses on broad cross-cutting themes, OCB supports smaller, more focused scoping workshops that target specific OCB research priorities, providing a public venue for research planning and multidisciplinary collaborations. Solicitations for scoping workshop proposals are routinely distributed to the OCB community. The first scoping workshop on Ocean Acidification took place in October 2007. Planning is currently underway for the next scoping workshop on Terrestrial and Coastal Carbon Fluxes and Exchanges in the Gulf of Mexico, which is scheduled for May 6-8, 2008 in St. Petersburg, FL. A new scoping workshop solicitation has been released, and the proposal submission deadline is June 15, 2008.

**OCB establishes Ocean Time-Series Advisory Committee**

OCB SSC member Debbie Bronk (VIMS) is the chair of the recently formed Ocean Time-Series Advisory Committee (OTSAC), which was convened to review existing ocean biogeochemical time-series (e.g., HOT, BATS, CARIACO), develop recommendations to improve the effectiveness and intercomparability of these time-series, and interface with the OCB research community to identify and communicate the needs for existing and future time-series sites. The other members of OTSAC include Craig Carlson (UCSB), Steve Emerson (UW), Ken Johnson (MBARI), Dennis McGillicuddy (WHOI), and Chris Sabine (NOAA/PMEL). At the end of August 2007,

## OCB Update

OTSAC distributed a questionnaire to PIs for three U.S. biogeochemical ocean time-series (BATS, HOT, and CARIACO). The questionnaire was designed to 1) Collect information on a wide array of chemical, physical, and biological parameters that were currently being measured, as well as what was proposed in the 2007 renewal submissions to NSF; and 2) Identify the needs of the time-series sites. Based on the responses to the questionnaire, OTSAC members submitted an initial summary report to the OCB SSC. The report includes a tabular summary of measurements being made at each time-series site (HOT, BATS, CARIACO) as they relate to core measurements specified by the 1996 JGOFS Time-Series Oversight Committee. The report also highlights specific data inter-comparability issues among the three sites for future consideration.

In addition to core measurements at the time-series sites, OTSAC has identified the role of moorings at the time-series sites as a high-priority issue to pursue, and discussed this and several other big picture issues at the ASLO/Ocean Sciences meeting in March via a special session on time-series (Time-series Observations of Biogeochemical Processes and Their Long Term Trends), which included a review of the time-series program and the goals of OTSAC, as well as an overview talk by the PI from each of the time-series sites. There was also an Ocean Time-Series Town Hall to discuss future needs and issues of the time-series program.

**OCB Website: request for Projects and Links**

We are currently building on the project list for the OCB webpage and invite you to send us information and/or links to any of your projects that you feel address the broad scientific themes of OCB. We are also including a designated heading for "Upcoming Field Opportunities" on the OCB webpage to help scientists in the OCB community gain access to potential data collection opportunities and build new collaborations. Please be as specific as you can when advertising or seeking to participate in upcoming field opportunities (e.g., cruise dates, locations, measurement capabilities, etc.). Please send all information about OCB projects and upcoming field campaigns to hbenway@whoi.edu.

## OCB Workshops

**2007 Summer Science Workshop**

The second annual OCB summer science workshop sponsored by the National Science Foundation took place July 23-26, 2007 at the Woods Hole Oceanographic Institution in Woods Hole, MA, convening 155 participants. Plenary sessions focused on three broad interdisciplinary themes: 1) Interplay between biotic structure and biogeochemical cycles, 2) Changing ocean biogeochemistry: The prediction challenge, and 3) Terrestrial/coastal ocean cross-boundary fluxes. Workshop participants also held smaller daily breakout sessions addressing high-priority subtopics within each workshop theme to identify important knowledge gaps, brainstorm effective observational and modeling strategies, and define OCB's role in forging ahead. To access live webcasts and presentations from the meeting, please visit www.us-ocb.org/OCB_webcast_2007.html. To download the workshop report that was published in Eos, visit www.us-ocb.org.

**Ocean Acidification Scoping Workshop**

OCB's first scoping workshop, which focused on ocean acidification, took place October 9-11, 2007 at Scripps Institution of Oceanography, convening 93 participants. In addition to plenary talks focusing on various aspects of ecosystem response to ocean acidification, participants divided into four ecosystem focus groups: Coral reefs, Coastal/estuarine regions, High-latitude pelagic, and Low-latitude pelagic. Each focus group devised research implementation strategies on a 10-year timeline involving a mix of field observations, manipulative experiments and modeling to investigate potential impacts of ocean acidification on key ecosystem processes and organisms. A brief workshop report has been submitted to Eos for publication and a detailed report is currently in preparation and will be posted on the OCB website when available www.us-ocb.org.

**Upcoming Scoping Workshop: Terrestrial and Coastal Carbon Fluxes and Exchanges in the Gulf of Mexico**

OCB will sponsor its second scoping workshop May 6-8, 2008 in St. Petersburg, FL. The meeting will be co-hosted by the USGS Florida Integrated Science Center and the College of Marine Science, University of South Florida. The goal of this workshop is to bring together researchers to discuss potential integrated research projects relating to carbon fluxes and exchange in the Gulf of Mexico that support the OCB mission. The scope of the workshop will be developed by the workshop Steering Committee with input from both terrestrial and ocean carbon research communities. Drs. Lisa Robbins and Paula Coble are organizing the workshop and logistics and registration will be posted on the workshop website: www.whoi.edu/sites/GMxCarbon.

# OCB Activities Calendar

## OCB ACTIVITIES

***May 6-8, 2008:*** OCB scoping workshop – "Terrestrial and coastal carbon fluxes and exchanges in the Gulf of Mexico," U.S. Geological Survey Florida Integrated Science Center, St. Petersburg, FL www.whoi.edu/sites/GMxCarbon

***June 15, 2008:*** OCB scoping workshop proposal submission deadline

***July 21-24, 2008:*** OCB summer science workshop, Woods Hole Oceanographic Institution, Woods Hole, MA, www.whoi.edu/sites/ocbworkshop2008

## OCB-RELATED ACTIVITIES

***April 3, 2008:*** "Marine plankton: From cells to ecosystems," Plymouth, UK, www.holligan-fest.org

***April 13-18, 2008:*** European Geosciences Union (EGU) General Assembly, Vienna, Austria, meetings.copernicus.org/egu2008/

***May 18-22, 2008:*** 10th International estuarine biogeochemistry symposium, Xiamen, China, mel.xmu.edu.cn/meeting/10th_iebs

***May 19-23, 2008:*** "The effects of climate change on the world's oceans," Gijón, Spain, www.pices.int/meetings/international_symposia/2008_symposia/Climate_change/climate_background_3.aspx

***June 2-6, 2008:*** "Eastern boundary upwelling ecosystems: integrative and comparative approaches" Canary Islands, Spain, www.upwelling-symposium.org/

***June 23-26, 2008:*** "Advances in marine ecosystem modeling" Research Symposium, Plymouth, UK, www.amemr.info/default.asp?page=2008Symposium

***July 8-11, 2008:*** International Symposium: "Coping with global change in marine social-ecological systems," FAO Headquarters, Rome, Italy, www.peopleandthesea.org/

***September 9-11, 2008:*** "Linking carbon storage in terrestrial ecosystems with other climate forcing agents," Santa Barbara, CA, Contact: Jim Randerson (jranders@uci.edu)

***October 5-10, 2008:*** DISCO XXI (chemical oceanography, www.disco-symposium.org) and PODS V (physical oceanography, Symposia for new PhDs, Honolulu, HI

***October 6-8, 2008:*** "2nd Symposium on the ocean in a high-$CO_2$ world," Musée Océanographique, Monaco, www.confmanager.com/main.cfm?cid=975

***October 6-10, 2008:*** Ocean Optics XIX, Il Ciocco, Tuscany, Italy, oceanopticsconference.org

***October 11-16, 2008:*** Eco-DAS Symposium (Ecological Dissertations in the Aquatic Sciences, formerly DIALOG) for new PhD's in ecological oceanography and limnology, University of Hawai'i at Manoa, cmore.soest.hawaii.edu/eco-das/Eco-DAS2008.pdf Applications due April 30.

***November 6-7, 2008:*** International Ocean Carbon Coordination Project (IOCCP) Time-Series Workshop, Scripps Institution of Oceanography, La Jolla, CA

***November 9-13, 2008:*** IMBER IMBIZO: "Biogeochemical and ecosystem interactions in a changing ocean," Miami, FL, www.imber.info/IMBIZIO.html

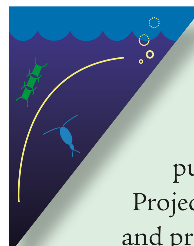
***September 13-19, 2009:*** International Carbon Dioxide Conference, Jena, Germany, Contact: Martin Heiman

***September 21-25, 2009:*** Ocean Obs 2009: "Ocean Information for Society: Sustaining the Benefits, Realizing the Potential," Venice, Italy, www.ocean-obs09.net

## FUNDING OPPORTUNITIES

***June 2, 2008:*** NASA Research Opportunities in Space and Earth Sciences (ROSES), Ocean Biology and Biogeochemistry Program proposal submission deadline

***August 15, 2008:*** NSF Chemical Oceanography and Biological Oceanography proposal submission targets



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