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Do We Now Understand The Ocean's Biological Pump?

by Jorge L. Sarmiento, John Dunne and Robert A. Armstrong

A core problem for global carbon-cycle research is to explain the role of the oceanic "biological pump" in determining levels of dissolved inorganic carbon (DIC) in surface waters and the exchange of carbon between ocean and atmosphere. Surface nutrient concentrations are key to predicting this exchange because unused nutrients in the upper ocean allow associated carbon dioxide (CO_2) to escape into the atmosphere. What have we learned during the JGOFS era that can help us understand what controls the strength and efficiency of the biological pump?

A new paradigm of ecological systems in the surface ocean has emerged during the last several years, focused on the relative roles of the regeneration of nutrients versus their export. The regeneration system includes the smallest autotrophs, picoplankton that are generally only able to utilize ammonium; a microbial loop that consists of heterotrophic bacteria and the dissolved organic matter on which they live, and small protists that graze on bacteria and picoplankton. This system is ubiquitous and stable. It has a low *ef*-ratio, defined as the fraction of productivity that is supported by nutrients supplied from external sources such as the nutricline or the atmosphere.

The export pathway, on the other hand, comprises the classical diatom-based food chain, including copepods and other large zooplankton predators. It is opportunistic, responding rapidly to injections of nutrients, shoaling of the mixed layer or increases in irradiance. It is fundamentally unstable, disappearing rapidly when resources become limited, and has a high *ef*-ratio. We now think that a large fraction of oceanic variability in the *ef*-ratio depends upon whether a given region supports just the regeneration system or the export pathway as well.

Is knowledge of the relationship of *ef*-ratio to the structure of planktonic food webs either necessary or sufficient for understanding the biological pump? We would argue that it is neither.

A key concept for analyzing the biological pump is the distinction between its strength and its efficiency. We define the strength of the pump as the magnitude of the export of organic matter. For example, a location such as the Bermuda Atlantic Time Series (BATS) station in the Sargasso Sea where the export of organic matter is 4 moles of carbon per square meter per year (mol $C/m^2/yr$), has a stronger biological pump than one with an export of 2 mol $C/m^2/yr$, such as the Hawaii Ocean Time-series station (HOT) in the north Pacific oligotrophic gyre (Figure 1b).

The maximum possible strength of the biological pump at a given location is limited by the supply of macronutrients in the upwelling water and the stoichiometric ratio of carbon to nitrogen to phosphorus in the organic matter exported from the surface. Nitrogen fixation and aeolian fixed nitrogen also contribute, but to a lesser extent.

In contrast, we define the efficiency of the biological pump as a measure of its effectiveness in reducing surface nutrients relative to subsurface values. We define it more specifically as the average nitrate level at depths in the range of 100 to 200 meters, minus the average in the top 100 meters, divided by the average in the 100- to 200-meter range (Figure 1). We use nitrate observations in the upper 100 meters from summertime, when surface nutrients are at a minimum and the efficiency is at its maximum. Thus a region in which summer surface-layer nutrient levels are equal to deep nutrient levels has an efficiency of 0%, and one in which summer surface-layer nutrients are totally depleted has an efficiency of 100%.

Figure 2a shows that the strength of the biological pump and its efficiency are generally inversely related to each other. For example, the high-latitude regions of the Southern Ocean have a strong but inefficient biological pump. Conversely, the low-latitude subtropical gyres have a weak but efficient biological pump.

While the strength of the biological pump is important in determining the export of organic matter and thus the biological activity in the deep ocean, the efficiency of the biological pump is the key factor in determining the balance of carbon between the atmosphere and the ocean, at least in regions where the supply of nutrients and carbon from below is high. This is because it is ultimately the efficiency of the biological pump in stripping out as

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much carbon as possible from upwelling waters that determines how much of the excess carbon stored in the deep ocean can escape back into the atmosphere. In regions such as the Southern Ocean where the biological pump efficiency is low, CO_2 is able to escape from the deep waters that upwell there. Thus the average atmospheric concentration is higher than it would be if the efficiency of the pump were high.

What Governs Pump Efficiency?

What does the JGOFS-era paradigm of the surface ecosystem and its link to the *ef*-ratio tell us about biological pump efficiency? Given the relationship between the export pathway and high *ef*-ratios, one might expect high *ef*-ratio environments to have an efficient biological pump and vice-versa. In fact, most of the world ocean exhibits the opposite relationship (Figure 2b). For example, the Southern Ocean has a high *ef*-ratio but a low biological pump efficiency; the subtropical gyres, on the other hand, have a low -ratio but a highly efficient biological pump. Thus knowledge of the *ef*-ratio does not help us predict biological pump efficiency.

If the *ef*-ratio does not indicate the efficiency of the biological pump, what does? While ocean circulation plays an important role, efficiency is clearly modulated by other factors. The regions characterized by low biological pump efficiency in Figure 1d generally correspond to areas where the supply of nutrients from upwelling and deep wintertime mixing is high. However, there are areas of high biological pump efficiency that have extremely high nutrient supply, such as coastal regions.

As a result of JGOFS-era discover-

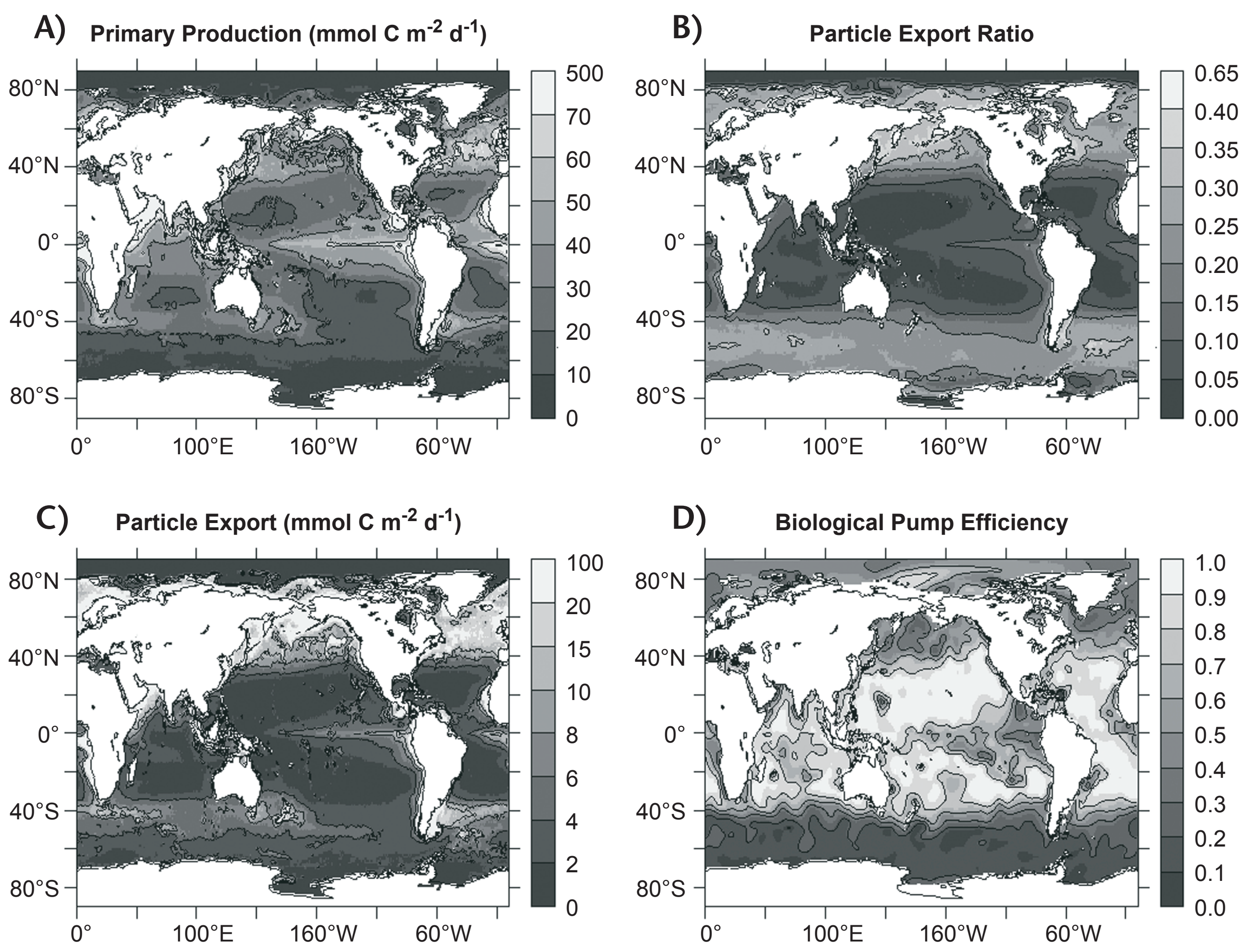

Figure 1: (a) Primary production estimated by a combination of empirical models using satellite-based estimates of chlorophyll. (b) Particle export ratio (particle export divided by primary production) estimated from satellite-based chlorophyll estimates and temperature distributions using an empirical model developed by John Dunne. (c) Particle export calculated by taking the product of the particle export ratio times the primary production. (d) Estimate of the efficiency of the oceanic biological pump calculated from climatic average nitrate observations. Efficiency is 100% when organisms deplete surface nutrients totally. It is 0% when no biological removal of upwelled nutrients occurs.

ies, we now generally believe that iron limitation plays a crucial role in limiting the uptake of nutrients, most particularly in the high-nutrient, low-chlorophyll areas that occur predominantly in the Southern Ocean and the Southern Hemisphere subtropics (Figure 3a) and in the North and equatorial Pacific (Figure 3b).

What is the role of iron? Because of the inverse relationship between *ef*-ratio and export efficiency observed in our analysis, we suggest that the critical role of iron is not associated with its enhancement of the export pathway component of the ecosystem. Our analysis leads us rather to conclude that iron functions through Liebig's Law of the Minimum, where the ability of the phytoplankton to remove macronutrients at a given location is determined by the ratio of iron to the macronutrients, as originally proposed by the late John Martin.

The mean deep-ocean iron concentration of approximately 0.7 micromoles per cubic meter (µmol/m^3) is about half of what would be required to deplete the mean deep-ocean nitrate concentration of 30 mmol/m^3, given a representative iron-to-nitrogen ratio of 40 mmol Fe per mol N in phytoplankton. Model simulations, such as those performed by David Archer of the University of Chicago and Kenneth Johnson of the Monterey Bay Aquarium Research Institute (MBARI) in 2000 and reported in *Global Biogeochemical Cycles*, suggest that about three-quarters of the surface biological production is driven by iron supplied from below, with the remainder coming from atmospheric dust.

An inadequate supply of iron to the high-nutrient North and equatorial Pacific and the Southern Ocean is the most likely reason for the low biological pump efficiency in these regions (Figure 3). Applying this hypothesis to the global context, we find that the overall lower supply of iron to the ocean in the Southern Hemisphere may explain much of the remarkable difference between the waters of the Northern Hemisphere and those of the Southern Hemisphere in terms of biological pump strength, efficiency and *ef*-ratio (Figure 2). To confirm this hypothesis, we turn to seven major mesoscale iron fertilization experiments conducted during the JGOFS era.

These experiments demonstrate that iron fertilization can stimulate phytoplankton growth sufficiently to deplete surface-water nutrients in both the North and equatorial Pacific. For example, scientists observed a maximum drawdown of 15 mmol/m^3 of nitrate at the Subarctic Pacific Iron Experiment for Ecosystems Dynamics Study (SEEDS) site in the northwest Pacific and roughly 5 mmol/m^3 of nitrate during the IronEx II experiment in the equatorial Pacific. These results suggest that an increased iron supply from airborne dust would make it possible for phytoplankton growth to exhaust surface nutrients in these regions.

However, three separate Southern Ocean iron fertilization experiments were unable to stimulate nitrate drawdown by more than roughly 3 mmol/m^3. In an article in *Nature* in 2004, Kenneth Coale of Moss Landing Marine Laboratory and colleagues provide a compelling explanation of SOFeX results that ties in nicely with an hypothesis presented originally by Greg Mitchell of the Scripps Institution of Oceanography and his colleagues in *Limnology and Oceanography* in 1991. They pointed to light limitation on phytoplankton growth as the primary reason why nutrients are not depleted in the Southern Ocean, linking this finding in part to the deeper mixed layers of the region. Mitchell and his colleagues defined light limitation, not by the usual Sverdrup criterion of the threshold light supply necessary to get a bloom started, but rather by the light supply that is required to deplete nutrients completely.

Given deep summertime mixing, frequent cloudiness, phytoplankton self-shading and an extremely high nutrient supply, the Southern Ocean might never experience total depletion of nutrients in surface waters even if the iron supply were adequate. While it is well documented that Southern Ocean phytoplankton suffer from an insufficiency of iron, the evidence suggests that adding iron might only lead to a relatively modest drop in nitrate concentrations before light limitation becomes a major limiting factor.

Considering all the above observations and experiments, we conclude that the relative strength of the regeneration system versus the export pathway, as reflected in the relative abundances of small versus large phytoplankton, is not nearly as good a predictor of biological pump efficiency as is the ratio of macronutrients to other limiting factors, such as iron and, in the case of the Southern Ocean, light.

Ballast In The Export Flux

We have shown that knowing the relative strengths of the regeneration system and export pathway does not help us understand the efficiency of the biological pump. But this distinction is important to our understanding of another aspect of the biological pump. Ocean scientists have long recognized that inclusion of mineral material makes particles containing organic carbon heavy enough to sink. Only during the JGOFS era, however, did it become evident that there is a strong quantitative relationship between particulate organic carbon (POC) flux and the flux of

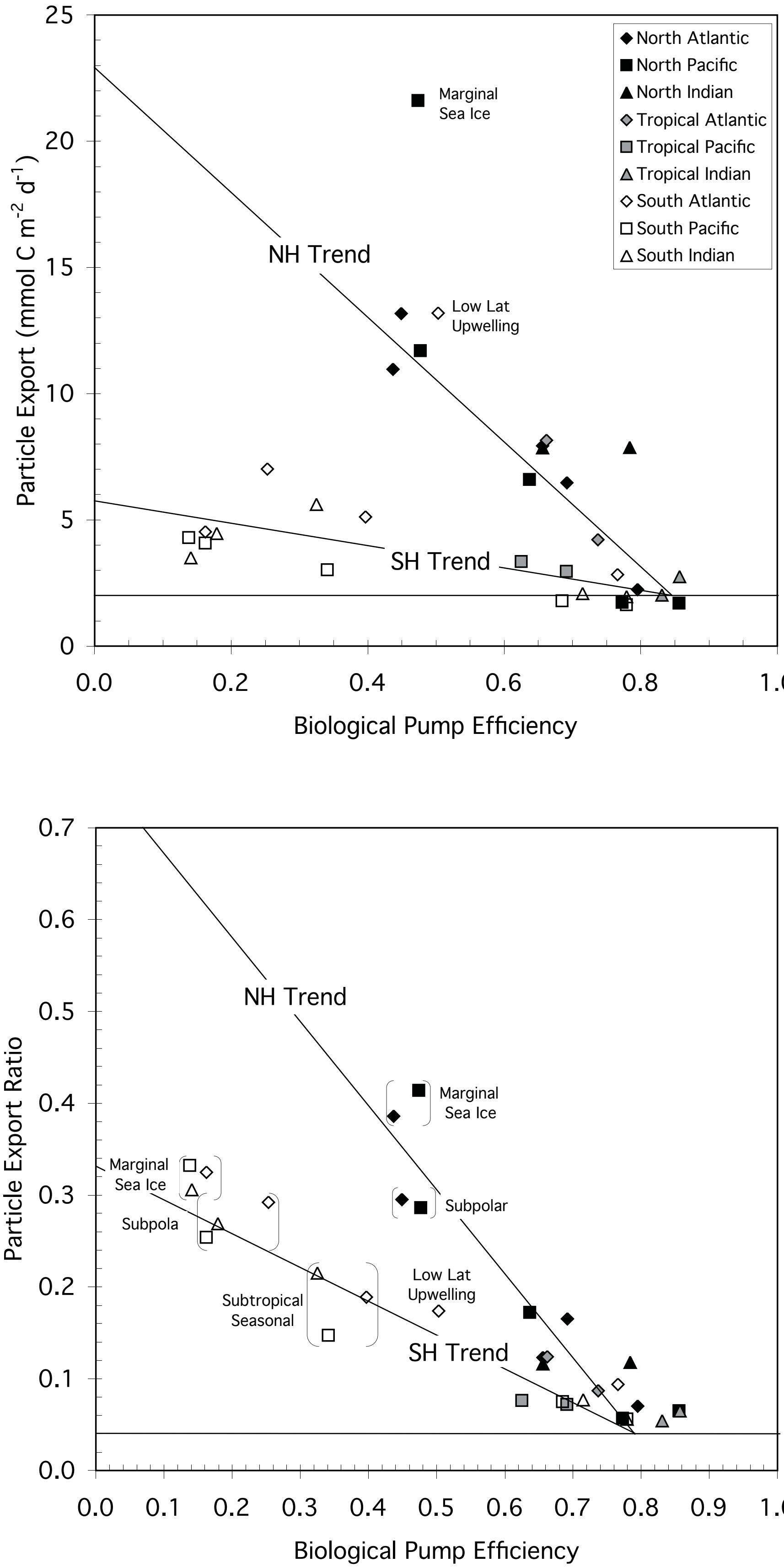

Figure 2: Top panel shows particle export in mmol C/m2/d plotted versus biological pump efficiency. Lower panel shows the particle export ratio (particle export divided by primary production) versus biological pump efficiency. Each symbol corresponds to the geometric mean over each of 33 biogeographical provinces based on six biome definitions: the marginal ice zone, the subpolar gyre region of downwelling, the subtropical gyre region of upwelling, the permanently stratified subtropical gyre, the tropics between 5°S and 5°N, and the low-latitude coastal upwelling regions. The data used to calculate biological pump efficiency are summertime observations in each hemisphere. The particle export ratio is calculated from annual mean satellite chlorophyll estimates and temperature observations using an empirical model developed by John Dunne and colleagues. The SH and NH lines shown in the diagrams illustrate the two major trends that separate primarily Southern Hemisphere observations (open symbols) plus the tropical Pacific (shaded squares) from Northern Hemisphere observations (filled symbols) plus the tropical Atlantic and Indian oceans.

mineral ballasts. By fitting a series of models to data from the U.S. JGOFS Equatorial Pacific Process Study, Robert Armstrong of Stony Brook University and his colleagues found that using total mineral material as a predictor of POC flux greatly increased the predictive power of both exponential and power-law ("Martin curve") remineralization profiles.

In a related study, Christine Klaas and David Archer of the University of Chicago collected global data on POC flux and the fluxes of individual mineral ballasts. They then made a regression of POC flux versus fluxes of silicate minerals, carbonate minerals and dust. They found that this simple regression explained 85% to 90% of the variance in POC at depths greater than 2000 meters, whereas reliance on a single predictor, such as silicate, explained only 50-60% of the variance. In addition, they found that at these depths, silicate transported only 3% to 4% of POC (by mass), whereas carbonate and dust transported 5% to 6%.

If deep-water fluxes of POC are largely determined by their associated mineral ballasts, then the distinction between small phytoplankton, which do not make mineral ballasts, and larger phytoplankton, many of which do make mineral ballasts, is key to predicting the strength of these fluxes. However, this distinction may not be the whole story.

At a U.S. JGOFS Synthesis and Modeling Project conference on calcification in June 2002, field researchers presented evidence that half or more of the carbonate flux measured in deep traps is associated with foraminifera tests, not with coccoliths. This result challenges two tightly-held and somewhat contradictory views: that export from the euphotic zone is largely mediated by diatoms, and that export to the deep ocean is largely associated with calcium carbonate. These views could be reconciled if the foraminifera are found to consume sinking diatom aggregates on their way through the so-called "twilight zone" between 200 and 1000 meters.

In summary, the relative strength of the regeneration system versus the export pathway, as reflected in the relative abundances of large versus small phytoplankton, does not appear to explain the strength of the biological pump. We conclude, however, that it promises to be very useful in explaining the magnitude of POC delivery to the deep ocean and sediments and the depth scale of remineralization in the water column.❖

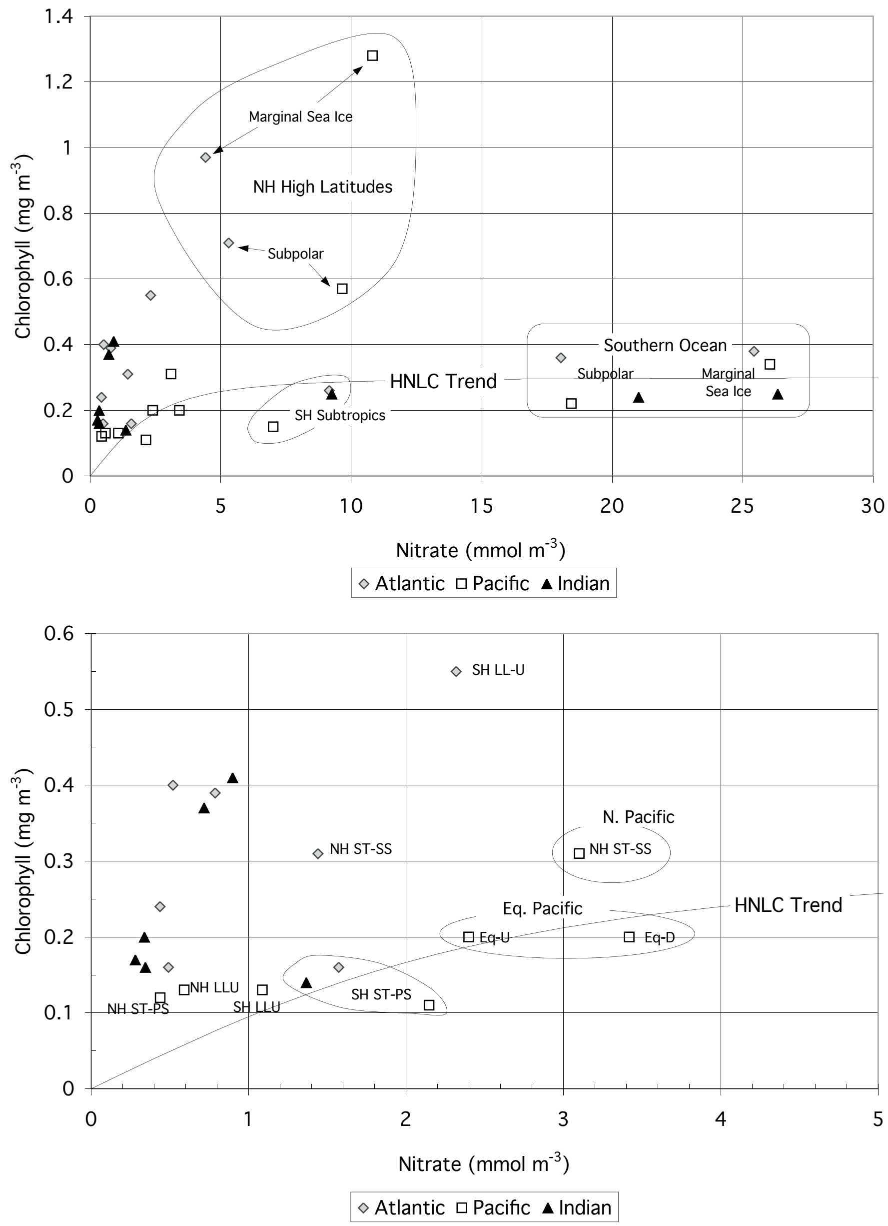

Figure 3: Geometric mean chlorophyll from Figure 1a plotted versus mean observed nitrate for each of the biogeographical provinces described in the caption to Figure 2. The lower panel is a blowup of part of the upper. The HNLC (high-nutrient, low-chlorophyll) trend lines are intended as a guide; they are not fits to the observations. The biogeographical provinces that sit on the HNLC trend line have low biological pump efficiencies and relatively low particle exports and particle export ratios (see Figure 2).

Phytoplankton And Heterotrophic Respiration In The Ocean

by John Marra

Some two and a half years ago, Richard Barber of Duke University and I were sitting in a pub in Bangor, Wales, puzzling over ocean productivity data based on carbon-14 (^{14}C), a radioactive isotope of carbon used to measure rates of photosynthetic carbon assimilation in aquatic systems. Dick and I had been using the ^{14}C method on JGOFS cruises to measure primary production. We were in Bangor for the Phytoplankton Productivity Conference at the University College of North Wales, organized by Peter J. leB. Williams and his colleagues there.

It had been 50 years since Einer Steemann Nielsen of the University of Copenhagen introduced the ^{14}C method to biological oceanography, the event that the Bangor conference was organized to celebrate. And here we were, still perplexed about the data. Dick and I had done the standard incubations for ^{14}C incorporation devised by JGOFS, but with the added wrinkle of separate dawn-to-dusk and 24-hour incubations. We were therefore able to measure the loss of the isotope overnight.

Dick pointed out an interesting feature of the data; the overnight loss seemed not to depend on where the measurements took place. Further, loss of carbon overnight seemed to be a roughly constant percentage of daytime assimilation. If it was a respiratory loss, why wasn't there a dependence on temperature? We left the conference with the matter unresolved but agreed to go back to our respective labs and think darkly.

As part of my contribution to the Bangor Phytoplankton Productivity Conference and book (*Phytoplankton Productivity: Carbon Assimilation in Marine and Freshwater Habitats*, edited by Williams, David N. Thomas, and Colin S. Reynolds and published by Blackwells), I had reviewed the published productivity data from JGOFS, including the data from oxygen-18 (^{18}O) and (light-dark) oxygen (O_2) incubations. The ^{18}O method should measure gross primary production, where respiratory losses are not subtracted, while (light-dark) O_2 incubations can estimate both net and gross primary production.

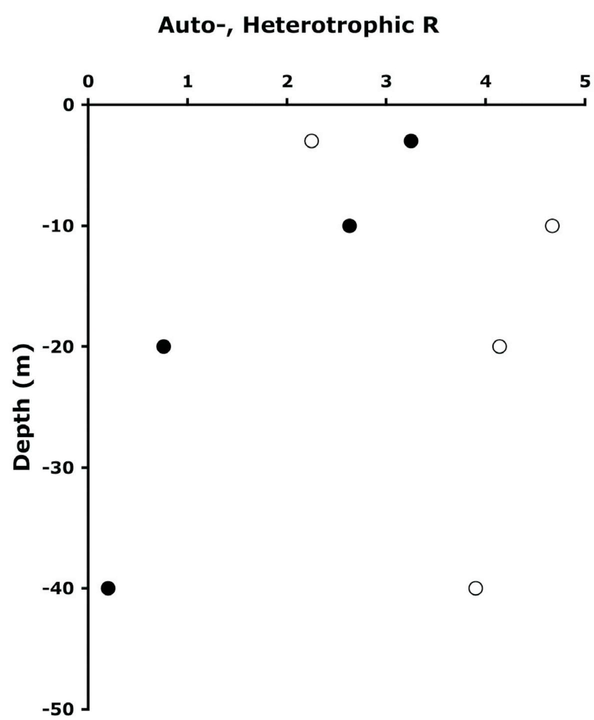

Figure 1: Components of respiration calculated from productivity data from the North Atlantic Bloom Experiment (NABE) at 47°N/20°W, for the productivity measurements done on May 2, 1989. The filled circles are estimates of phytoplankton respiration; the open circles are estimates of heterotrophic respiration (bacteria, protozoans and microzooplankton).

It was clear from comparisons with the oxygen methods that ^{14}C uptake estimates net production more closely over 24 hours. Published analyses based on the theory of isotopic incorporation, however, concluded that ^{14}C should measure gross production, not net. The resolution of this apparent paradox was to hypothesize that carbon dioxide (CO_2) originating from mitochondrial respiration was re-fixed in photosynthesis before it could exit the cell. There was laboratory evidence to support this idea.

If the above resolution is correct, then carbon uptake will always be less than gross O_2 production because there is a source of CO_2 from within the cells. In effect, photosynthesis is using more water molecules in photosynthesis (to produce O_2) relative to carbon because there is an internal source of carbon from mitochondrial respiration. Re-fixation of carbon during photosynthesis satisfies both the observational evidence and the earlier conclusions from isotopic theory.

Thus we had two issues occupying our minds that spring and summer. First, it appeared that, after 12 hours, ^{14}C behaves like ^{12}C, a stable isotope of carbon. It is not preferentially retained in the cells. The isotopes are at metabolic equilibrium.

Second, the analysis of the JGOFS productivity data

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The Microbial World At Macrobial Scales: Bacteria in JGOFS

by Hugh W. Ducklow

I procrastinated after the editor asked me to write about "what we learned in JGOFS" for this final issue of U.S. JGOFS News, in part because it is pretty hard to address such a question in a small space (but see the article by Jorge Sarmiento, John Dunne and Robert Armstrong in this issue). So I decided to write about bacteria. They don't take up much space, and they're what I did in JGOFS.

Hugh Ducklow

The View Before JGOFS

Heterotrophic bacteria in the ocean are less than 1 micron long and utilize dissolved organic matter (DOM) for energy and biomass. In the early 1980's when JGOFS was conceived, ocean scientists were just realizing the role and importance of bacterioplankton, following introduction of several new methods in the previous 10 years, principally by John Hobbie of the Marine Biological Laboratory and Jed Fuhrman, then a student at Scripps Institution of Oceanography. Not surprisingly, nearly all the observations were taking place near shore-based laboratories or on those few cruises where a bacteriologist or two were allowed to participate.

Bacteria are very numerous (millions per milliliter) in estuarine and coastal waters and very active. These regions often receive high levels of nutrient inputs from the land and have high levels of photosynthesis, the source of the DOM for the bacteria. Early syntheses suggested that bacteria are highly efficient, commandeering upwards of 50% of all the organic matter produced by phytoplankton. But there had been almost no observations in the open sea.

What are the bacteria doing out there, where organic inputs are lower, but where about 80% of the marine photosynthesis takes place? JGOFS provided the means to find out.

The JGOFS Era

In the summer of 1985 I was involved in a post-field study synthesis of the Warm Core Rings project at Woods Hole Oceanographic Institution (WHOI) with James McCarthy of Harvard University, David Nelson of Oregon State University and Terrence Joyce of WHOI. The initial Global Ocean Flux Study (GOFS) workshop had taken place in Woods Hole the summer before with no microbiologists involved, although Bruce Frost of the University of Washington had illustrated the foodweb consequences of bacterial DOM usage in an elegant talk at that meeting.

U.S. JGOFS was in the early stages of development as a formal program under the leadership of Peter Brewer of WHOI, then chairman of the new program's scientific steering committee (SSC). Jim took me over and introduced me to Peter, and I rambled on about wanting to learn about the large-scale variations in the ocean's smallest inhabitants. Shortly thereafter John Marra of Lamont-Doherty Earth Observatory, Sharon Smith, then of Brookhaven National Laboratory, and I joined the US JGOFS SSC, adding our perspective as biologists to the nascent program.

Around that time, I also began working with Michael Fasham of Southampton Oceanography Centre on a model of ocean plankton dynamics that incorporated a simple bacterial-DOM component. This model embodied the concept I sketched above and formed a strong rationale for including core measurements of bacteria in JGOFS. And so began a long run of bacterial investigations in the JGOFS process studies and in both the Bermuda Atlantic Time-series Study (BATS) and the Hawaii Ocean Time-series (HOT) Study.

I was fortunate to have three great graduate students during JGOFS. A hard-won BATS grant supported Craig Carlson's doctoral research. By that time there was a lot of interest in dissolved organic carbon (DOC), and Craig instituted core DOC measurements in the BATS program.

Craig's work provided an early realistic estimate of the efficiency with which bacteria convert DOC into biomass (less than 30%), and it demonstrated that export of DOC via vertical mixing is an important part of the annual carbon budget in the surface waters of the region. The annual export via mixing resets the DOC inventory at the BATS study site in the Sargasso Sea, keeping surface levels more or less stable in the long term. I consider this to be one of the Top 10 JGOFS Discoveries and our biggest contribution to the program.

Later, Matthew Church worked in the HOT Program, co-advised by David Karl of the University of Hawaii and me. Matt showed that, in contrast to the situation at the BATS site, DOM is accumulating over decadal time scales in the North Pacific gyre.

Untangling the physical and biological processes generating these contrasting patterns is still helping us to understand the intricacies of carbon cycling in the open sea. Craig and Matt went on to stints directing the BATS and HOT observational programs, respectively, illustrating the role of JGOFS in training and employing new generations of oceanographers.

Meanwhile, we went on to contribute bacterial abundance and productivity observations to the North Atlantic Bloom Experiment (NABE), the Equatorial Pacific Process Study (EqPac), the Arabian Sea Process Study and the Antarctic Environment and Southern Ocean Process Study (AESOPS), collaborating along the way with David Kirchman of the University of Delaware and Farooq Azam of Scripps Institution of Oceanography and their students.

In the North Atlantic and the Ross Sea in the Antarctic, bacterial dynamics are strongly influenced by annual spring phytoplankton blooms, breaking free from grazer control, blooming themselves and consuming semi-labile DOC. In the equatorial Pacific, bacteria are tightly controlled by the balance between DOC supply and removal by protozoan grazers. Their numbers and production rates are remarkably constant over time.

The Arabian Sea experiment yielded a regional and seasonal view of bacterial variability. We saw both bloom-like patterns reminiscent of the North Atlantic in the coastal upwelling province and a low, uniform "background" state resembling that of the equatorial Pacific in the oligotrophic central Arabian Sea. I was ably assisted in the field and laboratory in all these studies by Helen Quinby, who has probably counted more bacteria than any other single human being.

We achieved a better understanding of these patterns at a mechanistic level during the iron enrichment studies. These large-scale manipulative experiments were not part of JGOFS per se, but they were conceived by the late John Martin while he was active in U.S. JGOFS, and they were strongly influenced by JGOFS.

My third JGOFS doctoral student Jacques Oliver participated in the U.S. Southern Ocean Iron Experiment (SOFeX) in 2002 and showed how bacteria responded to the increased DOC flux stimulated by the iron additions sufficiently to escape grazer control. Variations on these patterns were also observed during two international iron experiments, the Southern Ocean Iron Release Experiment (SOIREE), conducted in antarctic waters south of Australia in 1999, and the Subarctic Ecosystem Response to Iron Enrichment Study (SERIES), conducted in the northeast Pacific in 2002. Using genomic techniques, Jacques demonstrated that iron enrichment not only affects bulk bacterial properties but also leads to changes in community composition at the species level.

Genomic probes were just beginning to be used widely toward the end of JGOFS. They represent the next frontier in marine bacterial ecology. The ability to follow species-level dynamics of oceanic bacteria puts microbial ecology about where phytoplankton science was a century ago, when oceanographers in Germany and the United Kingdom routinely discussed diatom and flagellate blooms.

Since the end of the process studies, we have been synthesizing our observations and contributing a unified data set to the U.S. JGOFS database. With Thomas Anderson of Southampton Oceanography Centre, we have been working on models to follow the flows of carbon through bacterial consumers as part of the U.S. JGOFS Synthesis and Modeling Project (SMP). Tom's models show that oceanic bacterial production has to be less than about 15% of the simultaneous primary production unless subsidized by stored or imported DOC.

In a follow-on to our SMP work, we are working with Dennis Hansell of the University of Miami to explain the variability of DOC concentrations and their role in supporting net heterotrophy in the open sea. Dennis's global-scale observations of DOC concentrations show how basin-scale transports of DOC constrain estimates of ocean metabolism. Thus at the end of JGOFS we have achieved a good mechanistic picture of the regional- and global-scale regulation of bacteria and can explain quantitatively their roles in the carbon cycle.

Finally, I would like to acknowledge the central role JGOFS has occupied in my career. I'm grateful to the National Science Foundation's Chemical Oceanography and Biological Oceanography programs and the Office of Polar Programs for 20 years of generous support to do this work. And I've been especially fortunate to have wonderful students and colleagues. It goes without saying that this work would not have been possible without them.❖

(Editors's note. Hugh Ducklow of the Virginia Institute of Marine Sciences wrote to us from R/V Laurence M. Gould *on his way home from Palmer Station in Antarctica in mid November. Hugh served terms as a member and chairman on both the U.S. JGOFS Scientific Steering Committee (SSC) and the JGOFS SSC.)*

U.S. JGOFS Legacies: The Value Of Central Planning And Data Management

by Ken O. Buesseler

Ken Buesseler

I am truly a "son of JGOFS," having been fortunate enough to participate in every U.S. JGOFS field study from the 1989 North Atlantic Bloom Experiment on before becoming executive scientist of the U.S. JGOFS Planning and Data Management Office (PDMO) at Woods Hole Oceanographic Isntitution (WHOI). From both of these perspectives, I want to reflect on the value for a major ocean program of centralized planning and data management.

From the inception of what was then the Global Ocean Flux Study (GOFS) in the mid 1980s, Neil Andersen at the U.S. National Science Foundation and many other program managers at the federal agencies worked with members of the U.S. JGOFS scientific steering committee (SSC) to set program priorities and data-quality standards. They demanded the timely submittal of results and promoted the broadest use of these data by the ocean sciences community. This may not seem revolutionary in retrospect, but these defining characteristics of U.S. JGOFS, I would argue, have contributed to the program's many successes and increased greatly the scientific impact of individual studies.

Where does one see this impact?

Anyone who goes to a large national or international meeting that includes ocean biogeochemistry and/or carbon-cycle science will undoubtedly find JGOFS data being presented in some talk or poster.

Why is this so common?

The scientific community knows the value of high-quality, well-organized and readily available data. These data are essential, as many of the cutting-edge questions in ocean sciences today demand supporting results to interpret the work of individual investigators or to develop a new model of how the ocean works.

For those of us who grew up with the JGOFS open data system, it is hard to imagine going back to the days of individual data sets held by each investigator, to be found only partially in a table or appendix to a paper or perhaps even deposited in a data repository, but certainly not available online with supporting documentation. Most often such data were only obtainable in useful form by contacting each and every investigator for his or her part of the larger scientific story one was trying to weave.

What is the price of this often underappreciated activity?

At its busiest, the U.S. JGOFS PDMO was supported at a level equivalent to 4% to 8% of total program costs. This included support for more than 56 topical meetings leading to 44 reports, publication of 48 issues of U.S. JGOFS News, initiation of a common web-based system for sharing data and information, organization and sponsorship of 36 SSC meetings, two or three participants' meetings after each process study and annually during the Synthesis and Modeling Project, and production of brochures and articles for education and outreach. I'd argue this was money well spent.

We are at an important crossroads in studies of the ocean carbon cycle. Individual projects and small-scale experiments are underway that are designed to test important post-JGOFS themes: the role of mesoscale eddies in the ocean cabon cycle, the effects of nitrogen and phosphorus cycling on phytoplankton growth, the importance of iron and other

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U.S. JGOFS Statistics

- 272 principal investigators
- Scientists at 75 institutions involved in U.S. JGOFS
- 73 Scientists have served on the U.S. JGOFS Steering Committee
- U.S. JGOFS grants to scientists in 26 states and the District of Columbia, plus Bermuda, Canada, France, Germany and the United Kingdom
- Scientists from 22 countries collaborated on U.S. JGOFS projects
- More than 300 undergraduate and graduate students supported on U.S. JGOFS grants
- 1,053 scientific publications to date
- 21 special issues of *Deep-Sea Research II* with 2 more underway
- 343,000 nautical miles of ocean explored on research cruises (almost 16 times around the globe)
- 3,040 days at sea (8+ years) conducting U.S. JGOFS field studies

Data collected by the U.S. JGOFS Planning and Data Management Office as of October 2004

U.S. JGOFS Data Management: Then And Now

by Cynthia L. Chandler

Data management has been an integral part of U.S. JGOFS since the program was launched. It is exciting to look back and see how far we have come in 15 years.

George Heimerdinger, then Northeast liaison officer for the National Oceanographic Data Center, got the ball rolling in 1989 when data gathered aboard R/V *Atlantis II* during the North Atlantic Bloom Experiment (NABE) began to arrive at his office at the Woods Hole Oceanographic Institution (WHOI). George received the data, typically in the form of ASCII files on 5 1/4-inch floppy disks, and worked diligently with the contributors to collect metadata information and complete quality assurance testing.

At the same time, Glenn Flierl of the Massachusetts Institute of Technology, James Bishop, then at Lamont-Doherty Earth Observatory (LDEO), David Glover of WHOI and Satish Paranjpe of LDEO developed a new object-oriented distributed database system that provided access to the growing collection of data. A series of workshops were organized to introduce scientists to the database system and to provide training.

By the end of 1992, the database had grown to 16 megabytes and included observations from both NABE and the Equatorial Pacific Process Study. Christine Hammond, who joined the U.S. JGOFS Data Management Office (DMO) at WHOI in 1994, took advantage of the emerging Internet and developed a World Wide Web browser interface for the U.S. JGOFS database. This approach provided online, on-demand access to the growing collection of U.S. JGOFS data and metadata.

Dave Gray

Cynthia Chandler

By 1996, the Arabian Sea cruises had been completed, and the Southern Ocean cruises had begun. U.S. JGOFS was increasingly able to promote the exchange of data and information among investigators and the sharing of the growing database with scientists worldwide who were interested in cross-disciplinary biogeochemical research.

David Schneider joined the DMO in 1996 to work primarily on data from the Arabian Sea and Southern Ocean field studies. In 2000, Glover became director of the DMO, and Cynthia Chandler took over as data manager when Hammond moved to another position at WHOI.

Synthesis and Modeling Project (SMP) results started coming online in 1999, thanks to efforts by Joanie Kleypas of the National Center for Atmospheric Research. The data policy developed for the SMP, like the one for the field studies, emphasized the need to provide investigators with timely access to results as well as tools to facilitate interdisciplinary research and the successful interaction of field researchers and modelers.

The nature of the SMP results, which included gridded output from large-scale model simulations, required a new interface. Data managers and SMP coordinators started to look into interactive data access systems, including the Distributed Ocean Data System (DODS) and the Live Access Server (LAS).

In 2000, DMO staff members began working with a team of software engineers at the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory and the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington. The goal was to create a customized LAS interface capable of serving gridded data from SMP projects as well as the merged data products that DMO staff members were planning to put together from selected process study data.

By the end of 2000, nearly 80% of the data from the four U.S. JGOFS process studies had been submitted, and the DMO launched a synthesis effort of its own. CTD and bottle profile data from all cruises within a single process study were combined in new data products organized by sampling device (CTD or bottle type). The most complex of these products was the Southern Ocean Niskin bottle data set, which came from 11 cruises and included 158 different data variables in addition to the metadata parameters.

By the end of 2002, the DMO was serving some 98% of the process study data, along with the growing collection of results generated by SMP investigators, at **http://usjgofs.whoi.edu/jg/dir/jgofs** . The initial volume of a final data report was published on CD-ROM and distributed first to participants at the final JGOFS Open Science Conference, held in May 2003 in Washington, D.C.

So far, more than 800 copies of the first volume of the U.S. JGOFS data report have been mailed to libraries, institutions and researchers worldwide. Volume one includes all of the data acquired during the four U.S. JGOFS process studies between 1989 and 1998. A second volume, also published on CD-ROM, includes a selection of SMP results. It was first distributed in July 2004 at the final SMP investigators' workshop. The DMO is preparing additional SMP results for a third volume, which will be published on DVD-ROM.

International Collaboration

U.S. JGOFS data managers benefited from participation in the JGOFS Data Management Task Team (DMTT). Through collaboration with data managers from seven other national JGOFS programs, DMO staff members were able to facilitate the contribution of U.S. JGOFS results to the international data collection effort and to ensure data availability and free and open communication of results. The DMTT published inventories of all JGOFS cruises, a dictionary of core JGOFS parameters and several international data collections on electronic media.

As U.S. JGOFS nears completion, the DMO is continuing to serve the needs of the program. The DMO, largely through the efforts of Jeff Dusenberry of WHOI, will continue to work with SMP investigators to complete the online inventory of data and results. The data server will continue to provide access to the field study data as well as SMP results as long as there is continued funding from the U.S. National Science Foundation (NSF).

The final step toward preserving the U.S. JGOFS data legacy will be to transfer information and materials from the planning office and DMO to the WHOI data library and archives. Data from the two U.S. JGOFS time-series programs, the Hawaii Ocean Time-series (HOT) study and Bermuda Atlantic Time-series Study (BATS), will continue to be served from the University of Hawaii and the Bermuda Biological Station for Research respectively. Data from the U.S. JGOFS Global Survey of Carbon Dioxide (CO_2) in the Oceans is available online at the Carbon Dioxide Information and Analysis Center (CDIAC).

In spite of the extraordinary advances in technology that have occurred over the last decade and a half, the basic principles for managing data articulated by the JGOFS Working Group on Data Management in 1988 are still valid today.

They are:

- Scientists will generate data in a format useful for their needs.
- Oceanographic data sets are best organized in terms of metadata.
- Data managers should avoid use of coded data values.
- Users should be able to obtain all the data they require from one source and in a consistent format.
- Data interchange formats should be designed for the convenience of scientific users.

The working group also recognized the special challenges presented by biological oceanographic data, specifically the lack of universally agreed-upon definitions for important terms such as "biomass" and "production." This is still true today.

Finally, it has been enlightening to search through the folders of communications records going back to 1989 and NABE. One is reminded how crucial it is to have dedicated data personnel working with investigators to gather complete and accurate geographical, temporal and methodological metadata.

This is an exciting time to be working in the field of ocean informatics. Data and information management will continue to be recognized as essential components of any scientific endeavor. U.S. JGOFS participants and other interested scientists are most fortunate that the U.S. NSF recognized the importance of data management early on and supported it throughout the program. And we of the DMO are most fortunate to work with such an extraordinary community of scientists and managers.❖

Internet addresses for U.S. JGOFS data and information
Home page **http://usjgofs.whoi.edu**
Data server **http://usjgofs.whoi.edu/jg/dir/jgofs**
SMP home page **http://usjgofs.whoi.edu/mzweb/syn-mod.htm**
SMP LAS **http://usjgofs.whoi.edu/las**
HOT and BATS data **http://usjgofs.whoi.edu/research/timeseries.html**
CO_2 survey **http://cdiac.esd.ornl.gov/**
JGOFS Open Science Conference **http://usjgofs.whoi.edu/osc2003.html**
U.S. JGOFS final data report **http://usjgofs.whoi.edu/publications/FinalDataRpt.html**

Final U.S. JGOFS SMP Workshop Marks End Of An Era

by Scott C. Doney

An era came to an end last summer with the final U.S. JGOFS Synthesis and Modeling Project (SMP) science workshop, which took place at Woods Hole Oceanographic Institution (WHOI) in mid July. Beginning in 1996, the SMP has hosted summer meetings each year to highlight research advances and outstanding science questions in marine biogeochemistry and modeling. While the format and participants have changed with time, the informal atmosphere and stimulating discussions have remained as hallmarks of these gatherings.

The final SMP workshop was smaller than most of its predecessors, with only about 50 participants. Events included a series of plenary research presentations, posters from individual SMP groups, open discussions and the final SMP clambake and volleyball game. Many now-familiar science themes were woven through the talks and posters presented at the workshop. Highlighted topics included the effects of iron fertilization on ocean biology and the marine carbon cycle, projected biogeochemical responses to future climate change, and the development and testing of more sophisticated marine ecosystem models.

Validation of marine ecosystem models is difficult and often incomplete because of the lack of information on key stocks and rates, even from the most data-rich field sites. John Steele of WHOI and Edward Laws of the University of Hawaii presented plenary talks on two different approaches for optimizing model parameters against data, one with the objective of maximizing ecosystem resiliency and the other with minimizing the aggregate flows between model compartments. The approaches and thus the underlying assumptions about how ecosystems function can generate strikingly different behavior from the same observational data. Perhaps the best quote of the meeting came from Steele, who mused on how we can avoid generating “false models tested by inadequate data.”

A second set of presentations emphasized the role of ocean physics in structuring marine biogeochemistry. William Jenkins of WHOI discussed the so-called “subtropical nutrient spiral.” This new hypothesis proposes that vertical mixing in western boundary currents such as the Gulf Stream provides a pathway for resupplying nutrients from the mid and lower thermocline to the upper ocean to support biological productivity in the subtropical gyres.

In a nicely complementary talk, Jorge Sarmiento of Princeton University highlighted the similar global-scale role of the Antarctic Circumpolar Current and Subantarctic Mode Water formation in transporting nutrients from the deep sea to the thermocline. Irina Marinov, also of Princeton, showed modeling results suggesting a decoupling of atmospheric carbon dioxide (CO_2) and biological export because of the limited exchange between two distinct circulation cells, mid-depth North Atlantic Deep Water flow and deep Antarctic Bottom Water flow.

While the main focus of the SMP has been on the open ocean, as was true of the U.S. JGOFS field programs, there is growing evidence for the global importance of continental shelf and margin systems. Three of the plenary talks presented interesting new results from regional coastal carbon-cycle and ecosystem models. Katja Fennel of Rutgers University suggested that nitrogen losses from sedimentary denitrification on the shelf and margin along the U.S. East Coast may exceed the regional nitrogen input from rivers. Fei Chai of the University of Maine and Nicolas Gruber of the University of California at Los Angeles presented

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Tom Kleindinst

Participants in the final SMP workshop in July 2004.

The Future Of Ocean Biogeochemical Research

by Scott C. Doney

Although our basic understanding of ocean biogeochemistry has improved dramatically over the last decade and a half during the JGOFS era, many critical questions remain unresolved. Some of these questions would sound very familiar to the planners of the earliest JGOFS projects.

For example, considerable uncertainty still exists about the seasonal-to-interannual variability in the air-sea flux of carbon dioxide (CO_2). Also, we do not yet know how the oceanic uptake of CO_2 from the atmosphere is likely to evolve over the next several centuries as ocean circulation and ecological systems change with greenhouse warming and other global environmental perturbations.

Other problems, not necessarily all new, are currently receiving more attention. These include the ecological responses to higher CO_2 and lower pH in surface waters, biogeochemical transformations in the mesopelagic ocean, coastal eutrophication, interaction between open ocean systems and those of the continental margins, and the scientific underpinnings for deliberate carbon mitigation strategies such as CO_2 injection and iron fertilization.


Tom Kleindinst

Scott Doney

Addressing these questions requires integrated research efforts on a variety of fronts, ranging from monitoring the temporal evolution of the ocean inorganic carbon inventory to innovative process studies of poorly understood biological and chemical dynamics. In a break with the past, the design of field experiments should, from the start, build on a backbone of long-term ocean observing system elements, satellite remote sensing, advanced numerical models and data assimilation.

Several recent scientific planning documents have explored these issues in detail. They include the "Ocean Carbon Transport, Exchanges and Transformations (OCTET)" report, produced in 2000 by Cindy Lee and colleagues with support from the National Science Foundation **(http://www.msrc.sunysb.edu/octet/)**; "A Large-Scale CO_2 Observing Plan: In Situ Oceans and Atmosphere (LSCOP)," produced by Michael Bender and colleagues in 2002 as a National Oceanic and Atmospheric Administration special report; and the "United States Surface Ocean - Lower Atmosphere Study (U.S. SOLAS) Workshop Report and Recommendations" **(http://www.aoml.noaa.gov/ocd/solas)**, produced by Rik Wanninkhof and colleagues in 2002.

Recent advances in autonomous sensors and platforms, including floats, gliders, underwater vehicles and cabled observatories, are likely to alter the field of ocean biogeochemistry over the next decade in fundamental ways, providing data at much higher temporal and spatial densities than has been available from ship-based studies. Similarly, the application of new molecular and genomic techniques to the ocean is driving a scientific revolution in marine microbiology. Discoveries range from previously unknown groups of organisms and novel metabolic pathways to a deeper appreciation of the fundamental genetic and functional diversity of oceanic microbes.

Many of the needed research components are already in place as part of ongoing ocean carbon observing programs (see accompanying box). Following the dramatic success of the satellite-mounted SeaWiFS ocean

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Ongoing Ocean Carbon Observing Programs

CLIVAR/CO_2 Repeat Hydrography Program **(http://ushydro.ucsd.edu/)**

VOS Underway pCO_2 Program **(http://www.pmel.noaa.gov/co2/uwpco2/)**

Hawaii Ocean Time-series (HOT) study **(http://hahana.soest.hawaii.edu/hot/hot_jgofs.html)**

Bermuda Atlantic Time-series Study (BATS) **(http://www.bbsr.edu/cintoo/bats/bats.html)**

Carbon Retention in a Colored Ocean (CARIACO) time-series study **(http://imars.usf.edu/cariaco/index.html)**

Monterey Bay time-series study **(http://www.mbari.org/bog/Projects/CentralCal/intro.htm)**

Open Questions After JGOFS:

Winter Chlorophyll Levels In The Two Subpolar HNLC Regions

by Karl Banse

One question that persists after JGOFS is why offshore phytoplankton chlorophyll is almost as high in winter as it is in summer in two subpolar regions, the subarctic Pacific and the subantarctic ring of water around Antarctica between the Subtropical Convergence and the Polar Front. These regions are situated at low latitudes north and south (roughly between 45° and 60°). Both are high nutrient-low chlorophyll (HNLC) regions, characterized by scarcity of iron and a general absence of spring phytoplankton blooms.

Open-sea iron fertilization experiments of the last decade in the HNLC regions have focused our interest almost entirely on dramatic phytoplankton blooms of large species inside the fertilized patches. The mechanisms underlying these blooms seem to be analogous to those in the adjoining coastal regions or near the ice edge. In contrast, little attention has been paid to data from the control areas outside the patches, beyond using them for contrast. Such data could answer the question: How do the subpolar HNLC regions, more than one tenth of the entire ocean, work in their natural state?

Several puzzles remain to be resolved. First, the chlorophyll in the two regions is much higher in winter than it is in the North Atlantic with its deep mixed layers or in the Antarctic zone proper, almost as high as summer levels. Although the carbon-to-chlorophyll ratio is probably higher in summer, I doubt that the phytoplankton carbon concentration in summer is twice that of winter.

Second, during the solstices, underwater irradiance and therefore phytoplankton cell division rate appear to play almost no role, given that we see no relationship between pigment levels and mixed-layer depths down to 250 meters, as I have shown in a 1996 article in *Progress In Oceanography*.

Third, the strongly changing incident irradiance in the two HNLC regions leads to markedly changing integrated photosynthetic rates from one season to the next, yet the chlorophyll changes little. We know that lack of iron prevents blooms of the large phytoplankton species during spring and summer. But why do the small phytoplankton, which exhibit relatively high division rates even under iron stress, not accumulate more biomass during the summer?

In an article in *Biological Oceanography* in 1985, G.T. Evans and J.S. Parslow presented a simple analytical model on annual plankton cycles. This model suggests that, if high food supply during the winter keeps enough zooplankton around, the spring bloom will be suppressed when Sverdrup's critical depth theorem would predict it.

We now know that in HNLC regions the very small phytoplankton that can cope with low iron levels are controlled by protozoans with about the same division rates as their prey. We also believe that truly deep mixed layers in winter would negate phytoplankton growth. But why do we find in the two subpolar HNLC regions overall about as much chlorophyll in winter as in summer, in spite of the reduced underwater irradiance and cell division rates? Conversely, since there seem to be enough small zooplankton around to suppress the spring bloom and control the phytoplankton concentration during the summer, why does wintertime grazing not depress pigment levels to the low values seen in the North Atlantic and the Antarctic proper?

Finally, why does grazing keep phytoplankton concentrations at observed levels rather than reducing them to, say, a third of these levels in the vast regions of the warm open sea, which also exhibit little seasonal change of phytoplankton, but because of scarcity of available nitrogen and phosphate? How does the oligotrophic ocean really work?❖

(Editor's note: Karl Banse is in the School of Oceanography at the University of Washington.)

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This is the final U.S. JGOFS News.

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New International Study To Focus On Trace Elements And Isotopes In The Ocean

by Robert F. Anderson and Gideon M. Henderson

Since the late 1990s, marine geochemists have been working to develop a comprehensive global study of the ocean biogeochemical cycles of trace elements and their isotopes. These efforts have evolved into an international program called GEOTRACES.

Creation of GEOTRACES was motivated by the dual realization that trace elements and their isotopes play critical roles in the ocean, but that our incomplete understanding of their cycles limits our ability to address problems in many areas of ocean science. For example, distributions, sources and sinks of trace elements serving as essential micronutrients are known so poorly that their sensitivity to global change, as well as their role in marine ecosystems and the ocean carbon cycle, cannot be predicted or modeled in a meaningful way. The removal of many dissolved trace elements from the surface ocean via sinking particles was discovered decades ago, yet we still lack quantitative rates and a mechanistic understanding of many removal processes.

Paleoceanographic records demonstrate striking correlations between elemental and isotopic distributions and independent indicators of climate variability. However, our ability to exploit these records to reconstruct processes and conditions in the past is limited by incomplete characterization of their biogeochemistry in the modern ocean. Quantification of past changes in ocean biogeochemistry provides vital constraints on ocean models and therefore on our ability to forecast future changes.

Marine geochemists are poised to make significant progress in trace element biogeochemistry. Advances in clean sampling protocols and analytical techniques provide unprecedented capability for measurement of a wide range of elements. New analytical methodologies that permit sampling at high density and new modeling strategies, applied successfully during the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS), make this the right time to mount a major international research program to study the global marine biogeochemical cycles of trace elements and their isotopes.

GEOTRACES has two principal goals: to determine global oceanic distributions of selected trace metals and their isotopes, and to evaluate the sources, sinks and internal cycling of these elements and thereby characterize the physical, chemical and biological processes regulating their distributions.

Studies will be organized under two themes. Theme 1 will focus on modern cycling of trace elements and their isotopes by quantifying fluxes at the principal ocean interfaces (the atmosphere, the continental margins and the mid-ocean ridges) and by determining rates of internal cycling within the ocean through biological uptake, chemical scavenging and physical transport. Theme 2 will focus on trace elements that serve as paleoceanographic proxies in order to improve our understanding of the factors controlling proxy distributions in the water column and in sediments.

GEOTRACES is intended to be global in scope, with ocean sections complemented by regional process studies. Sections and process studies will involve close cooperation among field and laboratory investigators and modelers.

The sections will cross regions that provide the most information about sources, sinks and internal cycling of trace elements. Although no commitments have yet been made to particular sections, priority will be assigned to regions of prominent sources or sinks, such as dust plumes, major rivers, hydrothermal plumes and continental margins. Sections will also sample principal water masses as well as the major biogeographic provinces.

The resources needed for this global ocean survey will require international cooperation. An international program will also allow intercalibration and standardization of methods used in the analytically-challenging measurement of trace elements as well as their transfer among national programs.

Numerical models will offer opportunities to combine and evaluate physical and biogeochemical processes and allow us to infer fluxes and source/sink rates from a comparison of simulated trace element fields with measured distributions. GEOTRACES will make use of a hierarchy of models, including coupled physical/biogeochemical general circulation models, box models, chemical speciation models and inverse models.

Recent advances in data assimilation and inverse modeling now allow direct data utilization methods not yet applied for determination of trace element fluxes. Inverse models promise to be an important part of ongoing and future studies of ocean circulation. Expanding these approaches to assimilation of trace element distributions offers a strategy for quantifying fluxes, including the uptake and regeneration of trace elements by sinking particles.

Formal planning of GEOTRACES began with an international workshop in Toulouse, France, in April 2003 that brought together 85 scientists from 15 nations. The Toulouse meeting was followed by regional and national planning workshops in Europe, North America and Japan. Planning is underway for similar workshops in Canada, China and elsewhere.

In 2003 the Scientific Committee on Oceanic Research (SCOR) agreed to provide oversight of the planning for GEOTRACES. The planning group organized under SCOR sponsorship to prepare a science plan held its first meeting in June 2004 in Oxford, United Kingdom. A draft of the science plan will be released for public comment early in 2005, and comments will be incorporated into a revised document at the second planning group meeting in May 2005. After the science plan has been completed, a scientific steering committee (SSC) will be formed to oversee implementation of the program.

Early tasks for the GEOTRACES SSC, in preparation for the main field program, include formulation of a data submission policy and management strategy, the development and distribution of standard reference materials, and the organization of intercalibration exercises. An international planning office will be set up and managed under SCOR oversight. GEOTRACES will be conducted in close collaboration with other international ocean research initiatives and modeling programs to ensure synergy between programs and to avoid unnecessary duplication of effort.❖

(Editor's note: Robert Anderson, co-coordinator of the U.S. JGOFS Antarctic Environment and Southern Ocean Process Study, is at Lamont-Doherty Earth Observatory. Gideon Henderson is in the Department of Earth Sciences at Oxford University.)

Legacies–from page 9

micronutients, the transformations to sinking fluxes in the mid water column, and the exchanges at the ocean boundaries. On one hand, the JGOFS style of interdisciplinary field and modeling work continues.

On the other, without centralized planning, there are few organized workshops with project investigators, outside experts and modelers to evaluate and utilize data to their fullest. There is also no home for the "orphaned" data sets that are now accumulating on hard drives, rather than being organized into a common and quality-controlled format and served up freely via a continually improving web-based system.

In the post-JGOFS era, self-selected groups of investigators are moving ahead to tackle important questions related to the ocean carbon cycle. But they have lost, hopefully only temporarily, the many benefits that were brought to us through centralized planning and data management in JGOFS.

It is only appropriate that we acknowledge in this last issue of *U.S. JGOFS News* our debt to these underappreciated aspects of conducting science. Scientists today reap the benefit of the heroes who worked behind the scenes, not collecting new data or writing new research papers but making it easier for the rest of us to do so. It is to this group, the staff members who have worked over the past 15 years in the PDMO and the scientists who have served on the SSC, that I want to offer my sincerest appreciation. Thanks to these individuals and to robust support for these activities from the federal agencies, JGOFS is more than the sum of its parts. I hope this lesson is not lost as we move ahead on the next generation of ocean science studies.❖

SMP Workshop–from page 12

simulation results for the eastern boundary upwelling system along the U.S. West Coast, where plankton bloom dynamics are strongly influenced by synoptic wind events, mesoscale eddies and topography.

The U.S. JGOFS Synthesis and Modeling Project ends officially in spring 2005. A variety of SMP activities are continuing with about a dozen funded research projects still underway. A third SMP special volume of Deep-Sea Research II is in the works, with an expected publication date of late 2005. The Regional Ecosystem Modeling Test-Bed Project, led by Marjorie Friedrichs of Old Dominion University, plans to hold a workshop in early 2005.

Many of the synthetic data products and numerical simulations produced by SMP investigators are currently available online via the U.S. JGOFS web page (**http://usjgofs.whoi.edu/mzweb/data.html**), and more are being posted regularly. This resource will be maintained as long as possible online, and a subset will be preserved on discs (DVDs) by the U.S. JGOFS Data Management Office.❖

(Editor's note: Scott Doney, Woods Hole Oceanographic Institution, has served as co-chairman, with Jorge Sarmiento of Princeton University, of the U.S. JGOFS Synthesis and Modeling Project since 1997.)

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U.S. JGOFS Final Data Report: Volume 1 (CD-ROM), Process Study Data (1989-1998); Volume 2 (CD-ROM), Synthesis and Modeling Project, part 1; Volume 3 (DVD-ROM), Synthesis and Modeling Project, part 2.

JGOFS International Collection of CTD, XBT and SeaSoar Data, Arabian Sea Process Study (1990-1997) CD-ROM. German JGOFS Data Management Office, Kiel, Germany.

JGOFS International Collection DVD, Volume 1. Discrete Datasets (1989-2000).

Deep-Sea Research II Volumes

Copies of a number of special issues of ***Deep-Sea Research, Part II*** on JGOFS programs are available from the U.S. JGOFS Planning Office as well. All are free unless otherwise noted:

Murray, J.W., guest editor. ***A U.S. JGOFS Process Study in the Equatorial Pacific.*** Volume 42, nos. 2-3. 1995.

Murray, J.W., guest editor. ***A U.S. JGOFS Process Study in the Equatorial Pacific, Part 2.*** Volume 43, nos. 4-6. 1996.

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Smith, Walker O. Jr. and Robert F. Anderson, guest editors. ***U.S. Southern Ocean JGOFS Program (AESOPS), Part II.*** Volume 48, nos. 19-20. 2001.

Doney, Scott C. and Joan A. Kleypas, guest editors. ***The U.S. JGOFS Synthesis and Modeling Project: Phase II.*** Volume 50, nos. 22-26. 2003.

Siegel, D.A., A.C. Thomas and J. Marra, guest editors. ***Views of Ocean Processes from the Sea-viewing Wide Field-of-view Sensor (Sea WiFS) Mission: Volume 1.*** Volume 51, nos. 1-3. 2004. $40

Requests for publications should be made to:
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Future–from page 13

color sensor, data are now available from the MODIS instruments and other sensors. In the future, ocean color data will become an operational product from the NPOESS satellite-mounted instruments.

A series of targeted, mid-sized ocean biogeochemical process studies have been completed or are underway, and plans are in place for deploying an extensive new ocean observing infrastructure as part of the NSF-sponsored Ocean Research Interactive Observatory Networks (ORION) **(http://www.orionprogram.org/)**. ORION is likely to include a regional cabled network, coastal observatories and open-ocean mooring systems.

Collectively, these efforts represent a tremendous investment by the U.S. government agencies and the scientific community in studying the ocean carbon system. They form the base for a much needed, coordinated large-scale ocean biogeochemical program to follow on the successes of JGOFS.

Building on the many previous community discussions, I recently led a working group of scientists in developing just such a multi-agency implementation strategy for U.S. ocean carbon research. Earlier this year, we issued our report, titled "Ocean Carbon and Climate Change (OCCC): An Implementation Strategy for U.S. Ocean Carbon Cycle Science **(http://www.carboncycle-science.gov/occc-report.html)**. Related efforts are underway internationally through SOLAS and the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) study under the auspices of the International Geosphere-Biosphere Programme.

Oceanic responses to changing climate conditions and the feedbacks between ocean and atmosphere are of more than academic interest. With OCCC, I hope that we have provided a blueprint for addressing pressing societal concerns and research questions for ocean biogeochemistry in the future.❖

Phytoplankton–from page 6

suggested that ^{14}C uptake measures net production. A third ingredient took more of a leap, and that was to assume that phytoplankton respiration is the same during the day as at night. Thus, if there is metabolic equilibrium overnight, and if respiration is equivalent both day and night, together with the observation that ^{14}C estimates net or net primary production during the day, then phytoplankton respiration can be calculated to be twice the dark loss of carbon overnight.

We tested this hypothesis using data from the JGOFS North Atlantic Bloom Experiment (NABE) and from two cruises during the U.S. JGOFS Arabian Sea expedition. It was only on two of these cruises that both 12-hour and 24-hour ^{14}C incubations and ^{18}O gross production measurements were done. The ^{18}O incubations and analyses were carried out during NABE by John Kiddon and Michael Bender, then at the University of Rhode Island (URI), and by Bender and Mary-Lynn Dickson (also URI) for the Arabian Sea cruises.

For both data sets, twice the dark loss of carbon overnight, when added to the daytime uptake, was equivalent to gross production (after applying the photosynthetic quotient). This suggests that twice the dark loss of carbon is a good estimate of phytoplankton respiration. From there, the heterotrophic respiration, that is, from bacteria, protozoans and microzooplankton can be calculated from the difference between phytoplankton respiration and community respiration.

In the accompanying figure, I have plotted the depth distribution of phytoplankton and heterotrophic respiration for a station during NABE. This is the first time that we can see the distribution of the components of respiration in the plankton.

While heterotrophic respiration is more or less constant with depth, the autotrophic respiration of the phytoplankton declines. From what we know, this makes sense. Heterotrophic respiration is unlikely to be directly dependent on solar radiation, but it is more closely related to the autotrophic biomass. The steep decline of autotrophic respiration is consistent with the idea that it is composed of respiratory energy used for growth combined with respiration used for maintaining basal cellular metabolism.

The analyses we have completed are only a beginning. There remain several issues to resolve for a more complete test of the hypothesis, such as the effect of microzooplankton grazing on carbon assimilation, other sources of respiration, the value of the photosynthetic quotient and the temperature dependence. Those interested in the topic can contact Barber or myself for reprints of published work.❖

(Editor's note: John Marra, who is at Lamont-Doherty Earth Observatory, served as chief scientist on U.S. JGOFS cruises in the North Atlantic, Arabian Sea and Southern Ocean.)

Photo courtesy of Mary Zawoysky

A fond farewell from the U.S. JGOFS team: Clockwise from left, Cyndy Chandler, Ken Buesseler, Mardi Bowles, Mary Zawoysky, and Dave Glover.

U.S. JGOFS

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