Report For

The GBF-OOI Scoping Workshop

Ocean Carbon and Biogeochemistry (OCB) Scoping Workshop on a Biogeochemical Flux Program Aligned with the Ocean Observatories Initiative

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Note: Links to plenary presentations can be found at the workshop agenda page: http://gbf-ooi.whoi.edu/content/workshop-agenda; Links to Plenary Abstracts, Breakout Session Notes and other related documents can be found: http://gbf-ooi.whoi.edu/content/workshop-report-related-documents. Links to plenary talks point to abstracts when available. If not available, a link to the agenda is provided.

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I. GBF-Ocean Observatory Initiative Philosophy and OCB Workshop Motivation

I-1. Background: The Grand Challenge

The atmospheric inventory of carbon as CO_2 is currently estimated as 62.5 petamoles (pre-industrial values were 48.3 petamoles), and an increase of 0.28 petamoles/year has been witnessed in recent decades as a consequence of anthropogenic CO_2 emissions (0.44 petamolC yr^{-1}) (IPCC Report). The pelagic and coastal oceans, together with the Great Lakes, contain over 90% of the Earth's actively cycling carbon molecules ("bioactive C"), and these systems, including their ecosystems, thus exert a strong influence on the chemistry of the Earth's environment by modulating carbon flux and transformations between carbon pools. In particular, the reservoir of bioactive carbon stored in the deep ocean, estimated as 3,100 petamoles, is more than 60 times the amount of CO_2 held in the present atmosphere, and 80 times greater than the carbon held in terrestrial vegetation and soils combined, and hence represents by far the largest single inventory of the bioactive carbon on Earth (ICPP Climate Change-2007): (Plenary 1, Honjo). <http://www.whoi.edu/whitepaper/GBF-OOI>

A portion of the CO_2 is recycled from the ocean interior to the euphotic zone and the atmosphere by upwelling and other deep overturning processes associated with Global Thermohaline Circulation on a range of scales. This loss is counter-balanced by processes that transfer carbon to the ocean depths. An essential mechanism that replenishes this deep carbon reservoir, and modulates atmospheric pCO_2 and hence global climate, is the "Biological Pump." The Biological Pump starts by the photosynthetic fixation of inorganic C to particulate organic carbon (POC) as algal biomass in the euphotic zone. Marine Primary Production (PP) is estimated to be 4 petamolC yr^{-1} (Plenary 1, Chavez; Plenary 2, Yoder and Behrenfeld). Research undertaken during the JGOFS study and subsequent programs has clarified that a fraction of this bioactive carbon is rapidly transported directly to the ocean interior through a complex interplay of intricate processes involving phytoplankton, zooplankton and bacterioplankton (including bacteria, archaea, virus and other micro-organisms), as well as the Earth's gravity. Prior studies suggest that the annual flux of C removed from the atmosphere and transferred to the deep ocean reservoir via the biological pump is on the order of 0.04-petamolC yr^{-1} (Plenary 1, Honjo; Honjo and Eglinton, OCB News, 2011 <http://www.us-ocb.org/publications/OCB_NEWS_WINTER11.pdf>). In this way, a steady state is maintained between PP in the euphotic zone and export of bioactive carbon as POC to all deeper zones of the pelagic ocean.

Dissolved organic carbon (DOC) also forms an important of the oceanic carbon cycle, with global ocean inventories of semi-labile, semi-refractory and refractory (recalcitrant) DOC (r-DOC) recently estimated at 0.48, 1.15 and 52 petamoles, respectively (Plenary 1, Hansell). Turnover times for the first two DOC pools are on the order of a few years to a decade in the euphotic and mesopelagic zones. ^{14}C data suggest that the r-DOC reservoir is highly stable (Plenary 1, Hansell) and of a scale that is comparable to the total amount of carbon in terrestrial vegetation.

Over the past few decades we have gained critical insights into the role of biological processes in the Earth's carbon cycle, particularly with the recognition of the vital importance of the oceanic Biological Pump as a global phenomenon. These advances, which were marked by exciting and sometimes unexpected findings, resulted in new paradigms for the role of oceanic biological processes in modulating conditions conducive to the current balance of the ocean life. While the above observations highlight the advances in our appreciation of the role of the oceans in the global carbon cycle, we suffer from a lack of information and understanding that limits our ability to place these processes in a quantitative context, to determine their dynamics, or to assess how the ocean carbon will respond or contribute to climate change. Specifically, our limited mechanistic and quantitative understanding of the processes underpinning the biological pump prevents us from assessing its importance in modulating atmospheric CO_2, and hence climate, or to predict the future behavior of the biological pump.

I-2. Knowledge Gaps in Understanding the Global Biological Pump

Substantial knowledge gaps exist concerning biogeochemical processes within all zones and domains of the coastal and pelagic ocean. In the **euphotic zone**, or the "Phytoplankton Domain", accurate constraints on marine primary production, both in terms of absolute flux and the nature of the photosynthetic algal community, are of crucial significance. Satellite-based surface ocean color observations have made an enormous contribution to ocean biogeochemistry and have yielded the most spatially comprehensive view of global marine primary productivity (Plenary 2, Yoder and Behrenfeld). While satellite-based observations will be indispensable in future ocean observing efforts these measurements probe only the surface-most layer of the euphotic zone and do not capture empirical information on the diversity of organisms contributing to PP, or the fate of this photosynthetically derived carbon. There is a clear need to constrain carbon and bio-mineral production *throughout* the euphotic zone in high-resolution time-series, as well as to characterize the nature and dynamics of the primary producer community and to constrain autotrophic and heterotrophic processes *at all ocean depths* (Plenary 4, Taylor).

In the **mesopelagic zone** or **twilight zone,** zooplankton are understood to exert strong influences on biogeochemical processes, however, their impact on the net flux and composition of settling POC and of DOC remains poorly understood (Plenary 1, Benitez-Nelson, Honjo, Plenary 4, Benfield: Sosik). The role of bacterioplankton in the mesopelagic zone also remains uncertain (Plenary 1, Hansell; Plenary 2, Saito). Direct, continuous observation of zooplankton and microbial communities throughout the mesopelagic zone are required to evaluate their role in modulating the Biological Pump.

T**he bathypelagic zone** or "Bacterioplankton Domain**,** is an equally important layer to understand in the context of the oceanic carbon cycle and its response to Global Change, yet remains critically under-sampled (Plenary 1, German and Boetius). Here, at depths beyond the influence of migrating zooplankton, gravitational settling of ballasted particles ("Terminal Gravitational Transport": Plenary 1, Honjo) is considered the dominant POC supply mechanism. The deep ocean microbial community is responsible for remineralization of POC to $\sum CO_2$, but also may add new POC through autotrophic activity. Constraining the organic matter remineralization in the bathypelagic zone is indispensable for assessing fluxes to the deep-ocean reservoir of dissolved inorganic carbon. However, our knowledge of the diversity, dynamics and metabolic activity of deep ocean microbial organisms and communities responsible for this process remains rudimentary, as does our understanding of susceptibilities to climate change, including to the warming and deoxygenation of deep waters (Plenary 1, German and Boetius; Plenary 1, Hansell).

The dynamics of the bioactive carbon on the **ocean margins** are even far more complex than in the pelagic ocean, but are regions of high carbon productivity, export and burial. Characterizing processes on the continental margins is therefore a prerequisite for the development of a complete understanding of the Global Carbon Cycle, yet ocean margins remain strongly underrepresented in the global carbon databases and models (Plenary 1, Thunell).

Current estimates of "global fluxes" and "global inventories" of bioactive carbon generally stem from mass balance calculations using data acquired from diverse, and often asynchronous observations. These estimates are prone to considerable uncertainty due to sparse data coverage that may, for example, fail to capture seasonal variability or are geographically biased (Plenary 1, Honjo, Thunell). These deficiencies reflect both a lack of technology and sparseness of opportunity for the appropriate ocean experiment that is required to obtain precise, coherent observations of the Biological Pump on a temporal and spatial scale suitable for assessing links and sensitivity to global change.

I-3. Motivation for the OCB Scoping Workshop

The current pace of carbon accumulation in the atmosphere (0.28 petamolC yr^{-1}, IPCC) and other active reservoirs associated with global change is alarming. Ocean warming, acidification, deoxygenation are evidently proceeding at perceptible rates. Yet, the manner in which the oceanic Biological Pump will respond to these chances remains highly uncertain. This fundamental question can only be addressed via comprehensive observations of the biological processes and biogeochemical fluxes involved in the Biological Pump on a global scale. A complete understanding of global biological pump can only be developed through a combination of empirical measurement and model approaches and through the engagement of scientists spanning diverse disciplines. This is the motivation for, and concept behind, the initiation of a Global Biogeochemical Flux (GBF) Ocean Observatory Initiative. The goal of the OCB Scoping Workshop was to discuss the crucial elements of a GBF observatory and to explore potential synergy with the Ocean Observatories Initiative (OOI). In this context, the measurement strategies, technological challenges, and geographic emphases each require consideration.

I-4. Strategy to attack unknowns in the Global Biological Pump

A primary goal of the GBF Observatory plan is the implementation of advanced and reliable ocean engineering technologies and analytical methods that can yield precise measurements of key biogeochemical parameters at spatial and temporal scales relevant for constraining the characteristics of the biological pump (Plenary 4, Aubrey and all speakers of this session). The ultimate goal is to acquire data of sufficient composition, density and quality to construct models that empirically determine the capacity of the global ocean to take up anthropogenic CO_2 via the Biological Pump, and to assess whether and how this is affected by global changes in ocean ecosystems (Plenary 1, Chavez; Thunell; Plenary 2, Dunne; Chavez et al., 2010). This requires drastic improvements in data accuracy/precision, sustained observations with tight spatiotemporal control, and the synchronized measurement of a diverse suite of parameters (Plenary 4, Honjo; Honjo and Eglinton, OCB News, 2011: http://www.us-ocb.org/publications/OCB_NEWS_WINTER11.pdf). Armed with this information, and with the aid of rapidly advancing cyberinfrastucture and computing capacity (Plenary 3, Schofield), the proposed GBF-Ocean Observatory could establish a practical framework for understanding the magnitude and manner of future change in the Biological Pump, and how potential changes influence the well-being of our planet.

I-5. Technical Readiness

Autonomous observation of ocean properties represents a major new emphasis within the ocean science community. This is highlighted by the recent Ocean Observatories Initiative (OOI) that seeks to implement and sustain ocean observatories in coastal and open ocean settings (Plenary 3, Daly: Distinguished Lecture, Delaney) <www.oceanobservatories.org>. From the perspective of observing biogeochemical processes, the ability to constrain oxygen and potentially other important parameters (e.g., POC, NO_2) through the deployment of floats and gliders represents an important advancement in terms of providing global-scale coverage (Plenary 4, Sosik; Bishop, *Oceanography*, 2009; Johnson et al., *Oceanography*, 2009). However, in parallel to the sensor-based floats and other remote observation strategies (e.g., satellites), detailed sustained observations at a number of key sites, where a greatly expanded series of parameters can be documented, is crucial to constrain oceanic productivity and to fully understand the workings of the biological pump throughout the oceanic water column in the context of global change.

Past and emerging engineering developments in recent decades have paved the way for accessing all ocean realms and exploration of biogeochemical processes throughout the entire water column, extending into the sea floor. In particular, there have been marked advances of under-water micro-robotics, meso-/micro-fluidics, synthetic and metallic materials science, integrated IC-design, and the development of powerful instrument control software. These technologies enable new and highly efficient "sampler-based" and "imaging" instrumentation that are poised to greatly advance our understanding of the cycling of bioactive carbon in the world oceans <http://www.whoi.edu/whitepaper/GBF-OOI>. With these developments, it is both timely and feasible to design and implement global observatories dedicated to the goal of understanding the ocean biogeochemical fluxes and inventories and their links with global change.

The following is a preliminary vision for a stand-alone GBF-Observatory that is comprised of 4 moorings. This particular design was described in GBF-OOI Community White Paper <http://www.whoi.edu/whitepaper/GBF-OOI> for continuous open review by the oceanographic community, published in the spring of 2010, and subsequently presented at a number of national meetings including the 2010 AGU Fall Meeting and an OOI Workshop at Arizona State University, Tempe. The ultimate configuration of the GBF Observatory will be finalized at future GBF Observatory Workshops (refer p. 19 on the future plans of GBF Observatory Workshops), however the initial design involves the following elements: Basic particle flux measurements in the mesopelagic, bathypelagic zones are derived from time-series sediment trap deployments on a mooring spanning the entire water column (Plenary 1 and 4;

Mooring B in <http://www.whoi.edu/whitepaper/GBF-OOI>). Time-series sampling of water/suspended particle (for DOC, nutrients, organic and isotopic analysis, etc.,) and bacterioplankton (including archaeans) would be accomplished by deployment on instrumentation on a separate mooring (Mooring D). Advanced, robotic incubation technology is now available for time/depth-series studies of primary production at any ocean depth (including a hydrothermal vents) (Plenary 4) (Mooring A). State-of-the-art undersea holographic camera (Plenary 4), mounted on wire-crawling profilers or fixed-position instrumentation (Plenary 4) have the potential to greatly clarify the role of the vertically migrating zooplankton in the global biological pump (Mooring C), and new capabilities for autonomous DNA sequencing of samples throughout the water column at the sea floor will shed light on key microbial and zooplankton communities involves the biological pump (ecogenomic sensor, Plenary 4; Scholin et al., *Oceanography*, 2008; Mooring C). By combining this type of information with that emerging from newly developed RNA-preserving bacterioplankton sample collectors and RNA preserving zooplankton collectors (Mooring D), we are poised to make major strides in our understanding of "Genes in the Ocean". The range of technologies presented at the workshop provides strong evidence that the technical and methodological expertise is sufficiently advanced to meet the challenges and needs of an ocean biogeochemical flux observatory. The challenge is how to implement these technologies within a carefully coordinated global ocean observatory (Plenary 4, all presenters; Distinguished Lecture, J. Delaney).

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II. Workshop Format and Findings

II-1. The division and charges of breakout sessions

Following the plenary sessions during the first portion of the workshop, the participants engaged in discussions in breakout sessions designed to refine the goals of a GBF observatory and to explore potential activities that could be aligned with the OOI. **Three breakout sessions** were organized during the meeting, with a different charge being proposed prior to each session. Participants were asked to join one of **four groups** for these breakout sessions designed to encompass different aspects of ocean biogeochemical processes. These groups were selected such that each of the biogeochemical zones (Euphotic, Mesopelagic, Bathypelagic/Benthic) and ecosystem domains (phytoplankton, zooplankton, bacterioplankton) of the pelagic ocean in addition to continental margins were considered in detail:

(1) Upper ocean productivity and export flux
Discussion Leaders/Rapporteurs: R. Stanley; S. Neuer;

(2) Flux attenuation and respiration in the Twilight zone
Discussion Leaders/Rapporteurs: R. Keil; B. Van Mooy;

(3) Deep ocean/Seafloor processes
Discussion Leaders/Rapporteurs: R. Murray; G. Proskurowski;

(4) Continental margin fluxes and cross-shelf exchange
Discussion Leaders/Rapporteurs: C. Pilskaln; P. Coble.

During the first breakout session, the groups were provided the following charge:

• *What are the key questions and uncertainties in determining the role of surface ocean biological productivity, the oceanic biological pump, continental margin and deep ocean processes in the global carbon cycle and the Earth's climate?*

Following on from the initial discussions the charge for the second breakout session was

• *What needs to be done to meet these grand challenges within the framework of sustained time-series ocean observatories? How can biogeochemists take advantage of the OOI as a step towards this goal?*

A third breakout session carried no explicit charge, but participants were asked to consider the following topics:

• *Potential links to other science and technology programs; How to ensure that the observatory initiative has broad interest and support within the scientific community; potential partnerships that could be* *forged that would provide the broadest and strongest societal connections; potential topics for follow-up workshops.*

II-2. Summaries of Breakout Session 1

A. GROUP 1: Upper ocean (Leader/Rapporteur: R. Stanley/ S. Neuer)

The main uncertainty identified by the group was the magnitude and measurement of Net Community Production (NCP) as well as other production parameters and controls on their short-term variability. The role of community composition of primary producers and grazers and the composition and fate of NCP and settling organic matter were also identified as key questions. In order to get the global perspective the need for models and satellites was emphasized, but these need to be validated by the observed rates of production at specific locations. There is also a further need to identify the right spatial and temporal scales of observations to be able to capture relevant variability, to relate surface processes to particle flux, to close a carbon budget and to find a representative long-term trend for the observation region.

B. GROUP 2: Twilight Zone (Leader/Rapporteur: R. Keil / B. Van Mooy).

The "Twilight Zone" breakout group began by discussing the relative merits of constraining budgets versus elucidating mechanisms involved in carbon cycling within the mesopelagic ocean. There was a consensus that while budgets and fluxes are crucial for placing processes in the Twilight Zone within the context of the overall oceanic carbon cycle, it is essential to develop a mechanistic understanding of the underlying processes in order to model future variations. Two key questions in this regard that emerged were: 1) Where is the carbon coming from and where is it going (is it critical to know who made the carbon or what kind of carbon it is) and 2) What role does physics play? What processes (biological and abiological) lie behind particle settling? The roles of physical processes that range in scale from storms to microturbulence were discussed in the context of their influence on the cycling of carbon and associated elements in the twilight zone, and this raised questions concerning the balance between timescales of forcing, responses and measurements.

A second major challenge that was discussed was how to link organisms to mechanisms, inventories to rates, rates to budgets etc., that centered on how measurements should be coupled to answer these key questions. Moreover, the broader issue of how to use the parameters we can currently measure to answer these questions and to test/falsify the current hypothesis was raised.

Recommendations made at this stage of the discussion included: The need more measurement in a grid like fashion. The need for "smarter" measurements (if we have a measurement volume how do we get the ins and the outs?). The recognition that observatory studies can elucidate the mechanisms.
It was emphasized that the time scales under which different mechanisms come into play represents an important factor. One of the most important timescales is seasonality, but shorter-term variability such as deal migration rhythm of zooplankton is also important. The episodic nature in zooplankton responses was cited as a case in point. While advances in instrumentation were recognized, sampling rates may not match processes. It considered important to match timescales of observations with phenomena, a day to a season.

C. GROUP 3: Deep Ocean/Seafloor (Leader/Rapporteur: R. Murray/G. Proskurowski)

A key scientific question to be addressed within the GBF program should focus on the fate of organic carbon arriving at the deep sea floor in as many different environments as possible. How is carbon delivered to and across the sediment-water interface and what is the response of the seafloor to this delivery? More specific issues to be addressed in the context of time-series/observatory efforts should include an investigation into the time lag and level of attenuation of response at the seabed compared to "input" fluxes from event-like perturbations such as Spring blooms in the overlying upper ocean and lateral inputs from benthic storms. In pursuit of broader GBF objectives, such studies should not focus exclusively on geochemical studies (e.g. return flux of nutrients that are recycled at and beneath the seabed) but also include studies of activities and responses within benthic macro- and micro-biological communities.

A second important contribution that GBF Observatory could make would be to conduct a detailed characterization of the microbial communities present in deep ocean waters, at and above the seafloor to provide a global baseline data-set. Basic questions that remain to be addressed include (a) What species are present and with what abundances? And (b) which species are most active and what are their metabolisms?
A further important issue to be addressed by GBF Observatory concerns the input fluxes of organic carbon *from* the seafloor at sites of active fluid flow. In hydrothermal studies, early research focused almost exclusively on inorganic chemistry and geological controls of venting. But the past decade has seen an increasing recognition that the cycling of organic carbon together with microbial activity may play fundamentally important roles in regulating the impact of hydrothermal systems on whole-ocean biogeochemistry. The same may be even more true of the methane released along active margins associated with gas hydrates ± cold seeps. While some preliminary investigations have been conducted

studying fluxes from "steady state" systems, however, a particularly important question that remains outstanding asks how significant a proportion of the time-integrated whole, in terms of vent or cold-seep fluxes to the ocean may be associated with dramatic perturbation events such as a volcanic eruption or a major tectonic event.

Editorial Note: Specifically, the **Deep Ocean/Seafloor Processes** Breakout Group advocated that GBF Observatory data collection and research not only address the bathypelagic zone but also processes at the seafloor and in underlying sediments. An important issue raised by this group is the need to address carbon fluxes of organic carbon *from* the seafloor at sites of active fluid flow, and how this influences seafloor and pelagic microbial ecosystems. In hydrothermal studies, early research focused almost exclusively on inorganic chemistry and geological controls of venting. However, the past decade has seen an increasing recognition that the cycling of organic carbon together with microbial activity may play fundamentally important roles in regulating the impact of hydrothermal systems on whole-ocean biogeochemistry. The same may be even truer of the methane released along active margins associated with gas hydrates and cold seeps.

D. GROUP 4: Continental Margins and Coastal Regions (Leader/Rapporteur: C. Pilskaln; P. Coble)

The greatest uncertainty on the continental margin with respect to understanding the biological pump and the global ocean carbon cycle is the lack of a comprehensive quantification of cross-shelf carbon fluxes. Whether or not the margin-open ocean boundary is defined at 2 km depth or less, we do not have sufficient data sets to form a consensus on which margins are carbon retentive and which are advective relative to the adjacent open ocean. Contributing significantly to this uncertainty are persistent questions of the impact of terrestrial carbon input to the coast, water column and sediment-water interface respiration rates, impact of ocean acidification on shallow shelf water columns, and modern carbon accumulation rates in margin sediments. A secondary but significant uncertainty with regards to understanding ocean margin carbon budgets and dynamics is that we presently have minimal ability to effectively integrate the many regional ocean models (e.g., coupled biogeochemical-physical processes ROMs) with adjacent basin-scale global circulation models (GCMs). In order to provide the global context within which continental margin carbon fluxes may be assessed, we need to succeed at ROM-GCM integration.

II-3 Summaries of Breakout Session 2

A. GROUP 1: Upper ocean (Leader/Rapporteur: R. Stanley/ S. Neuer)

After review of the existing OOI list of sensors, the group pointed out that there are very few production relevant sensors. However, to accurately determine production terms in the upper ocean, the group put together a suite of off-the-shelf instruments to measure various production rates in concert: existing oxygen sensors need to be augmented by gas tracer measurements such as N2 using Gas Tension Devices (GTDs), in situ incubations need to be deployed in combination with FRRF (fast repetition rate fluorometers), shallow sediment traps are needed to measure flux and composition of sinking particulate organic matter, as well as imaging systems and DNA based molecular tools to determine plankton community composition. It was pointed out that the carbonate system can currently not be measured accurately, and pCO2 or DIC sensors are needed at the same depths as the existing pH sensors. Adaptive sampling strategy is considered important for biogeochemistry; in addition to in situ decision making by local instruments, communication with shore-based scientists is needed in combination with samplers with set sampling times. The OOI infrastructure would provide the physical platform for such interactive communication. The spatial extent of variability can be obtained by autonomous vehicles, satellites (altimetry, ocean color), ship based observations (when moorings are serviced) and ships of opportunity, as well as instruments on ARGO floats. Many of these components are current OOI technology and design. It was emphasized that the community needs to demonstrate the importance of BGF measurements in order to propose, in a timely manner, the next location of the Pioneer array and which new suite of instruments could be tested. In addition, new moorings should be considered in conjunction with existing time-series stations **(BATS, HOT).**

B. GROUP 2: Twilight Zone (Leader/Rapporteur: R. Keil / B. Van Mooy).

During the second breakout session, potential specific target locations and activities were discussed. For example, it was suggested that the Regional Scale Node, and potentially Station Papa within the Global array, might be appropriate to constrain NCP. A series of challenges were also identified in engaging observational biogeochemists and modelers in the OOI. It was recommended that it would be important for regional biogeochemical modes to be established over the OOI sites. Specific observational and measurement capabilities that will be required were also discussed. These included an array of technologies and approaches – some of these could only be undertaken on processes cruises that would complement the time-series observations/sampling. Approaches raised included camera systems, TS-sediment traps, gel traps and other velocity traps, as well as U-series isotope measurements.

There is a strong need for samples, for customized samplers, and for "plug-in" sensors. The RSN was recognized as the only cabled network that could help during the "test-bed" mode of the GBF Observatory. Recommendations were made for dedicated funding for instrumental development. In this context, "Smart" sampling of water, suspended particles and sinking particles and large living things and "smart" profiling instruments were seen as of particular importance.

C. GROUP 3: Deep Ocean/Seafloor (Leader/Rapporteur: R. Murray/G. Proskurowski)

A first important goal should be to include a significant benthic component to all aspects of the GBF Observatory program – including recruitment of the appropriate specialists who were not necessarily present at the OCB scoping workshop but who were active previously, for example, under the JGOFS program. Even in their absence, we can predict that an important contribution to the GBF whole would be to introduce a program that combines deep coring (piston & giant piston cores) at each location to be established under GBF Observatory as well as temporally repeated multi-core sampling to investigate the ocean/sediment interface on multiple occasions and under varying conditions. In parallel with this sediment and pore-water based approach, we would also recommend further benthic intervention either in the form of lander and/or benthic crawler technologies. Key goals here would be to conduct both pre-programmed and informed active-response investigations at and across the seafloor using a combination of (a) in situ probes – e.g. to track changing pore water conditions; (b) incubation approaches – to study rates of oxygen consumption/respiration; (c) discrete sampling for water, particle and microbial analyses – e.g. using a combination of existing and/or emerging GBF Observatory technologies such as ESP, RAS/FF2-RNA samplers. While one set of such technologies, combination of robotics and micro-fluidics, could be implemented on a pre-programmed basis to collect fresh data at fixed time-series intervals (e.g. weekly) at 12 month deployment cycles, what would be particularly valuable would be to also include a capability to image the seafloor at all locations to be investigated within the GBF Observatory program so that event-response sampling and data collection could also be implemented. Even from remote (mooring-based) installations, telemetry and bandwidth sufficient to transmit one image of the seafloor per day would be extremely valuable in this regard. To characterize the deep ocean (water column) microbial communities at each GBF Observatory site the way forward is quite simple to propose. We should simply duplicate the capability to conduct the same programs envisaged at the seafloor but to conduct such sampling by Mooring D, for example, in concert with conventional deep sediment trap deployments (Mooring B, for example in Technology: WWW.whoi.edu/whitepaper/GBF-OOI/). And, additionally, discrete sampling for water column geochemical analysis.

For sites of active fluid flow, there is clear benefit to be gained from coordination with work that is already proposed in the OOI-RSN that will provide power and communications infrastructure to a mid-ocean ridge hydrothermal field (at Axial Volcano, western edge of Juan de Fuca Plate) and an active margin cold seep site (Hydrate Ridge). While current provisions allow for monitoring of key parameters at the seafloor, however (e.g. vent-fluid temperatures and key concentrations at Axial) what the GBF program would be well placed to contribute would be the most detailed characterization yet achieved of the biogeochemical cycling and export fluxes to the deep ocean that arise associated with these dynamic seafloor systems (Plenary 4: Scholin).

A particularly important goal that can only be achieved from sustained (decadal) observations will be to discern what proportion of the total impact on the oceans comes from the steady state fluxes that have most typically been observed at sites of seafloor fluid flow and what proportion, instead, is associated with the catastrophic events such as major earthquakes which may only recur over century-long time-scales (using tsunami-records as proxies for seismicity in the Pacific North West) or for seafloor volcanic eruptions where recurrence times are on the order of a decade (i.e. much shorter than observatory-scale durations and potentially imminent at Axial volcano). To capture steady stat fluxes, we can envisage an array of instrumentation including profiling sensors and time-series sediment traps, coupled with physical oceanographic instrumentation, arrayed radially around vent and cold-seep sites, to track and sample material exported from the seafloor to the surrounding ocean. In the case of major "event"-related discharges (e.g. exhalation of a subsurface hydrothermal cell ahead of a volcanic eruption, destabilization and degassing of gas hydrates associated with a tectonic event) it is unlikely that a fixed sampling/monitoring array could adequately predict the height in the water column nor the dispersion direction that any material released into the ocean might follow.

For this reason, therefore, we consider it extremely important that any GBF Observatory activity associated with these goals should include provision of suitably mobile platforms (e.g. AUVs) that can not only locate and track dispersing plumes of effluent that are released into the ocean but are also equipped with a suitable combination of sensors and sampling equipment that can detect how the material released to the ocean is cycled and evolves (Plenary 1: German). While the prime driver for the inclusion of such mobile assets within our GBF Observatory planning would be to ensure that the biogeochemical significance of such time-critical "events" is not missed (and noting that according to plate tectonic theory, at least one such event should be guaranteed within the next few years), it should also be noted that such AUVs – if power delivery is considered a tractable problem within any cabled observatory system - would also be able to use their in situ sensing capabilities to also add value to the "steady state" investigations at each site considered, for example flying missions across and around the perimeter of active vent and seep sites between routine servicing periods.

D. GROUP 4: Continental Margins and Coastal Regions (Leader/Rapporteur: C. Pilskaln; P. Coble)

The OOI time-series framework includes two continental margin installations—the Mid-Atlantic Bight Pioneer Array and the Washington Shelf Endurance Array. To address the uncertainties identified in breakout session 1, the margin group unanimously agreed that measurements of particle characterization and particle processes must be included on the continental margin OOI installations. This could be accomplished by the addition of quantitative particle/plankton imaging systems and discrete particle sampling instruments to the moored arrays (Plenary 4: Sosik). Additionally, the existing OOI observatories have minimal instrumentation for characterizing carbon system properties with only shallow depth pCO2 sensors and full-depth pH measurements. It is recommended that DIC sensors be added to the existing moorings and that every effort is made to collect time-synchronous profiles (by the suite of profiler-mounted instruments) at the mooring sites in order to maximize the synoptic nature of the measurements needed for gradient and flux estimates.

II-4 Summaries of Breakout Session 3

A. GROUP 1: Upper ocean (Leader/Rapporteur: R. Stanley/ S. Neuer)

The group felt that GBF Observatory needed to show a significant advance beyond JGOFS, in particular to emphasize the importance of ecosystem structure, the roles of margins and the response of the ocean to climate change. It seems appropriate at this time to leverage the existing OOI platforms and infrastructure, but to have a long-term goal specific to GBF. To engage with the wider scientific community we strongly endorsed an Oceanography article as an output from the workshop, as well as town hall meetings at national conferences. We should also consider tapping other funding sources (e.g. private foundations/companies). GBF Observatory would do well to link strongly to other observing platforms such as ARGO, existing times series stations, and Voluntary Observing Ships (VOS). In particular, the technology needed for GBF Observatory would be appropriate for these other platforms: we could, for instance envisage gliders with GBF sensors at the time series sites. New programs, such as BIOTRACERS Program would be good programs to link to as well.

It will be important to have public support for this initiative. We discussed ways to engage the public's interest: presenting "solutions", rather than just expounding on crises. The need for observing systems to aid in fisheries (e.g. Salmon and their prey) and aquaculture (e.g. oysters and their sensitivity to water pH) will be helpful in this regard. Connections to, for instance, Southwest Fisheries Science Center (NOAA) would be useful. Topics such as oxygen minimum zones, global hydrological cycles, harmful algal blooms, and El Nino could potentially be addressed by such observing systems.

Going forward the group suggested:

1. A timely modeling component to help with system design and optimal locations;
2. Clarification on existing OOI mooring components and OOI technological requirements for new instruments;
3. Integration with other international programs and other organizations, and
4. A small subgroup to explore ideas of outreach.

B. GROUP 2: Twilight Zone (Leader/Rapporteur: R. Keil / B. Van Mooy).

The third breakout session of the Twilight Zone group asked the question: How do we go from “bugs-to-behavior-to-biogeochemistry”? The group recognized the exciting developments in optical imaging methods (e.g., holography, spectral imaging), but considered that at present it is difficult to place observations from optical methods in the context of biogeochemical processes. Emerging autonomous zooplankton collectors preserve RNA of the individual samples (Mooring D, for example). However, by leveraging such technologies, it was anticipated that the community could ultimately move beyond primitive parameterizations of carbon attenuation based on the Martin curve. The GBF Observatory networks could enable us to move from empirical models to more mechanistic models. In particular, a key strength (and distinguishing aspect) of the GBF Observatory plan is the coupled observations of epi-, meso-, and bathy-pelagic processes in order to fully deconvolute the workings of the biological pump.

Potential connections to other programs such as BASINS and CALCOFI were discussed. The group also emphasized the need to continue to balance time-resolving and space-resolving programs. It was considered that the ideal GBF would involve the deployment extensive suites of floats and gliders equipped with sophisticated biogeochemical sensors, but this remains far from reality at present. There is a clear and strong need for a mooring-based GBF determine connections between glider-based sensor surveys and the underlying mechanisms. The GBF Observatory and instrumentation technology is essential as ultimately some of the key phenomena may not be resolvable without access to samples to characterize in detail.

C. Combined GROUP 3: Deep Ocean/Seafloor (Leader/Rapporteur: R. Murray/G. Proskurowski) and GROUP 4: Continental Margins and Coastal Regions (Leader/Rapporteur: C. Pilskaln; P. Coble).

The combined coastal ocean and deep ocean seafloor groups unanimously agreed that the most significant and obvious research component missing from the existing program is a lack of observations on benthic processes at the sediment-water interface. This leaves a substantial void in our ability to understand and quantify rates of ocean sequestration of carbon. Thus it was suggested that benthic biogeochemical process measurements by a variety of sensors (e.g., quantitative imaging systems, O_2 and pH electrodes, etc.) be placed at the sediment-water interface, on benthic landers and on benthic rovers, and that such measurements should represent a major cornerstone of the future GBF Observatory program. Additionally, benthic biogeochemical studies should be supported at coastal as well as global OOI sites. Significant discussion focused on the placement of GBF Observatory sites and whether the existing OOI Global Observatory sites are the most appropriate for the long-term vision and goals of the GBF community.

This group agreed that Station PAPA represents an important global site for GBF Observatory interests due to the long time-series data sets that exist for the location, the significant impact of ocean acidification on the North Pacific, the linkage between climate change and Pacific ENSO cycles, and the potential incorporation of Station PAPA into the GEOTRACES program. The group also noted that the Coastal and RSN OOI sites could be relatively easily instrumented for benthic studies to address specific process-oriented questions and that the competition for the Pioneer Array re-location in 5 years should have a prominent focus on benthic/sedimentary geochemistry.

There was extensive discussion and suggestions regarding scientific and operational links of a GBF Observatory program to other agency-funded research and technology programs such as NASA's Carbon Cycle and Ecosystems Program which includes large scale carbon monitoring efforts and a variety of ocean-atmosphere and terrestrial-coastal ocean flux products, the North American Carbon Program (terrestrial and ocean carbon budgets), GEOTRACES, OceanSITES, CLIVAR Repeat Sections, InterRIDGE, INDEEP, C-DEBI and SCOR Climate Change initiatives. To ensure broad scientific and public interest as well as political support for a future GBF Observatory program, it is important to maintain our focus on climate change as the primary driver of GBF research and as the key linkage to other data gathering and carbon monitoring programs.

We must be able to integrate GBF data sets with carbon monitoring data to address societal concerns of how climate change may be influencing the increase in the extent and duration of harmful algal blooms, the growth of hypoxic/anoxic zones on the margins, and decreasing fisheries stocks worldwide. Suggested future workshops involving the GBF community and other researchers/carbon programs were a joint NASA-GBF workshop to interface our scientific objectives and integrate key carbon system measurements, a GBF technology development workshop to critically review the state-of-the-art and what key technology jumps are needed in the near future by the GBF community, and a modeling workshop focused on integrating regional ocean models (ROMs) and global circulation models (GCMs) sooner vs. later to greatly improve our ability to provide margin-to-open ocean forecasting of biogeochemical cycles and budgets.

II-5. General Discussion

A strong, coherent message that emanated from participants of the open-discussion Breakout Sessions was the need for high-quality, rigorously coherent biogeochemical data sets of bioactive carbon fluxes from all realms of the ocean environment. Discussions focused on specific realms of activity, including the air-sea interface to the seafloor, coastal to pelagic environments and all zones, domains of the Global Ocean. It was recognized that a global GBF Observatory array comprised of existing and newly developed or emerging time-series instruments can serve such an objective <www.oceanobservatories.org/>.

The potential for synergy with the existing OOI programs was discussed extensively, particularly by the Continental Margin and Upper Ocean Groups <OOI Data Products Table http://gbf-ooi.whoi.edu/sites/gbf-ooi.whoi.edu/files/data_poster_OOI_2011-05-10_ver_0-09.pdf >. It is clear from these discussions that there would be clear benefits to the implementation of GBF Observatories as part of the current OOI, however there are several significant hurdles that render this challenging at present. The GBF Observatory requires far heavier moorings for its automated sampling/measurement/incubation systems from the ocean surface to the abyssopelagic seafloor and vent systems. Autonomous instruments are deployed at specific depths throughout the entire water column and with synchronized sampling in a manner that is incompatible with current OOI mooring configurations. In addition, the criteria for selection of mooring sites differ from those of the current OOI. An exception is the Regional Scale Node (RSN), which represents a potentially ideal oceanographic setting for an initial test bed program.

A sentiment that emerged from the Breakout Sessions was that any non-time-series measurement with specific, stand-alone instruments could utilize infrastructure of the OOI program. On the other hand, the moorings of a GBF Observatory could, within ballast and size constraints, offer many alternatives for sensors and samplers whose specifications are incompatible with OOI infrastructure (e.g., incorporation of smaller, cylindrical instruments within frames supporting TS sediment traps on Mooring B, <http://www.whoi.edu/GBF-OOI/page.do?pid=41504>

Many breakout session participants were supportive of the Global floating sensor programs (Bishop et al. 2009; Johnson et al., 2009; reference details in p. 6) and glider operation programs that enable ocean basin-scale biogeochemical observations. Consensus was that such observation strategy is highly complementary to that emanating from the GBF Observatory approach.

II-6. Broader Impacts, Public Outreach and Socio-Economical Contributions

Discussion was initiated on the subject of how to best serve the broader US community through the implementation of a clear, visible public outreach program during all phases of the Ocean Observatory Program. The potential to reach beyond the academic community through development of strong links with existing and emerging ocean industries, collaborating during both R&D and production phases, was discussed. The following highlights emerged:

1. Acquiring fundamental data on the cycling of bioactive carbon and ecology of organisms in the ocean from the very surface to the deep ocean bottom is of direct value to the US and the global society, and for our ability to assess and predict the economic and cultural consequences of changing Global Climate and particular industries as fisheries as an example.

2. Advocating for an Ocean Observatory – with a mission that is equally large in scope and fascinating in complexity to some high-profile space/astronomy programs has the potential to garner the interest of young population of the US and the World as well as to yield crucial scientific data.

3. A GBF Observatory program of the magnitude envision could generate significant employment opportunities in the US private, advanced technology manufacturing sectors through large-scale production of ocean observing/research and analytical instruments and mooring/platform systems as well as Observatory turn-around service firms. Thus an observatory program sustained over decades could create a stable business environment for small, local high-tech firms and ship service industries.

4. Again analogous to space exploration programs, technological innovations resulting from labor-intensive processes necessary for development and implementation of advanced instrumentation and software for a GBF Observatory could result in substantial advances that permeate well beyond the ocean science community. For example, micro-fluidic, micro-robotic, advanced imaging technologies and genomic sample collection capacity, highly precise sample analytical systems may be of value to many other industries, creating new, stable employment opportunities.

III. Workshop Summary and Recommendations

In order to gain true predictive capability of the role of the oceans in the dynamics of global climate change, we must fully understand the global biological pump that exerts a major control on the inventory and fluxes of bioactive carbon in the ocean. To achieve this ultimate goal, we must gain comprehensive datasets, acquired in a sustained manner, which will enable us to constrain biogeochemical and biological processes with far greater precision than has been achieved in the past. This must be accomplished via consistent time-series observations manner continuously over the coming decades, at all depth domains of the pelagic ocean and on oceanic margins. There was strong support at the 2011 Spring OCB Scoping workshop for this overarching objective and for the application of emerging ocean instrument and platform technologies in order to better understand ocean biogeochemical processes and their impact on a global scale.

The eleven excellent lectures of Plenary 2, 3 and 4 as well as John Delaney's distinguished lecture highlighted both the scientific challenges that lie ahead, as well the cutting-edge technologies and methodologies (e.g., microfluidics, robotics and new electro-optics as well as power-supply/high-speed, large volume communication systems) that can now be implemented and coordinated through global cyberinfrastructure and computing power to meet these challenges. While these technologies, both individual or collectively, were of great interest to the meeting participants, there was insufficient time to discuss them in detail. Data and sample analysis and archiving protocols and practices for the huge numbers of time-series measurements envisioned to emanate from instrument arrays represents another topic that is critical to the success of a GBF Observatory program, but which was not addressed in this preliminary workshop. These individual subjects should be discussed by additional workshops.

Potential for collaborative research at the Axial Seamount Regional Scale Node

In discussions during the SSC meeting that immediately followed the OCB workshop, the Regional Scale Node of the OOI (Distinguished Lecture by Delaney) was identified as a potentially excellent *candidate* for the initiation of a pilot GBF Observatory. This assessment was made based on the infrastructure (hardware, power, communications) supplied by the cabled array that would facilitate testing of engineering readiness of moorings and sensors to study the bioactive carbon cycle in open ocean conditions where the idea of OOI initiated. In addition, the recent eruption of axial volcano highlights the value of full water column bacterioplankton sampling. A number of GBF Observatory SSC members and scientists participated in the Axial al RSN Science Workshop in Seattle, in early October 2011 to further explore potential synergy between programs. <http://sites.google.com/site/axialrsnscienceworkshop/>

Additional Workshops

Technology readiness workshop. Although the Scoping Workshop provided an opportunity to highlight critical technological needs for a GBF Observatory in order to constrain ocean biogeochemical processes, there is clearly a need to further discuss the proposed technology with, and to hear more demands from, the scientific community. In particular, the technological capacity of the proposed Observatory, both as a complete observation system and in the contest of individual samplers/sensors, requires much more thorough discussion in the context of specific scientific objectives. Recommended actions would include: (1) Development of a more comprehensive description of the GBF Observatory methodology/technology, with a solicitation for community input on a follow-up White Paper, and (2) Dedicated workshops and ad hoc discussions focusing on specific technologies (e.g., GBF mooring platforms: <http://www.whoi.edu/GBF-OOI/page.do?pid=41502>).

Laboratory analysis and sample/data archiving workshop. A workshop focusing on the need for *centralized analytical and sample archiving capabilities* for biogeochemical and microbial, molecular biological measurements is recommended. Such a workshop should include detailed discussions on (1) how to achieve and maintain the required accuracy & precision for data germane to biogeochemical flux calculations and modeling in a high sample-throughput fashion; (2) how [and where] to archive samples for future biogeochemical and molecular biological study.

Workshop on modeling of biogeochemical fluxes. An important goal of this workshop would be to perform exercises to determine optimal spatial coverage for an observation array, as well as to assess the accuracy and precision of measurements is needed to constrain/inform models.

Contribution to *Oceanography* magazine

We plan to submit an article to Oceanography magazine that conveys the philosophy, objectives and technical readiness of a GBF Observatory program that highlights key issues discussed during the OCB Scoping Workshop. The manuscript will be drafted by the Executive Committee as soon as possible and reviewed by SSC members and OCB office prior to the submission.

Appendices

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Agenda
OCB Scoping Workshop on GBF-OOI

(Global Biogeochemical Fluxes Program for the Ocean Observatories Initiative)

May 23 – 25, 2011

Clark Laboratory Rm. 507, Woods Hole Oceanographic Institution

MONDAY A.M.

08:00 *Registration & Continental Breakfast*

08:30 **Workshop Introduction: Goals and Format** (*T. Eglinton*)

08:50 **Plenary 1: Scientific objectives and observational priorities of a GBF Program** (*Chairs: K. Daly and C. Benitez-Nelson)*

- 08:55 GBF-OOI Overview: Rationale, Objectives, and Design (*S. Honjo)*
- 09:25 Primary Productivity in a Changing Ocean (*F. Chavez)*
- 09:50 Dissolved Organic Carbon in Ocean Export Production (*D. Hansell*)

10:15 *Coffee break*

- 10:30 Ocean Twilight Zone (*C. Benitez-Nelson*)
- 10:55 *Ocean Margins: Production, Flux and Remineralization of Particulate Organic Matter (R. Thunell)*
- 11:20 The Role of Deep Ocean Processes in Global Biogeochemical Cycles (*C. German and A. Boetius*)
- **11:45** **Community Discussion**

12:15 *Lunch*

MONDAY P.M.

13:00 **Plenary 2: Assessing Primary Productivity and Biogeochemical Fluxes from the Global Ocean to Molecular Scale** *(Chair: A. Bracher)*

- 13:10 Integrating Remotely Sensed and Direct Observations of Surface Ocean Productivity and the Biological Pump (*J. Yoder and M. Behrenfeld*)

13:35 Measurement Strategies to Inform Global Ocean Biogeochemical General Circulation Models and Vice Versa (*J. Dunne*)

14:00 Oceanic Molecular Biological Models (*M. Saito*)

14:25 Community Discussion

15:05 Coffee Break

15:20 Plenary 3: The OOI and Prospects for a GBF Program (*Chair: C. Pilskaln)*

15:25 OOI Elements and Technological Capabilities: Biogeochemical Cycles and Fluxes (*K. Daly*)

16:00 OOI Cyberinfrastructure: Data Acquisition, Synthesis, Broader Impacts and Public Outreach (*O. Schofield*)

16:30 Community Discussion

17:00 Reception & Poster Session

18:00 Dinner & Distinguished Lecture *(J. Delaney)*

Tuesday A.M.

08:00 Continental Breakfast

08:30 Plenary 4: GBF-OOI Technology (*A. Aubrey*)

08:35 GBF-OOI Technology, Platform, Sensors and Samplers (*S. Honjo*)

09:05 In Situ Measurements of Surface Ocean Productivity (*C. Taylor*]

09:30 Fast Repetition Rate Flourometry (Z. Kolber)

09:55 Coffee Break

10:15 Bio-optical Technologies *(H. Sosik)*

10:40 Imaging Technologies for Water Column Observations (M. Benfield)

11:05 Ecogenomic Sensors (*C. Scholin*)

11:30 Community Discussion

12:00 Charge to Breakout Groups

12:10 Lunch

Tuesday P.M.

13:15 **Breakout Session 1:** How can the current and proposed observatories be optimized to improve our understanding of the global carbon cycle and our predictive capacity for global environmental change?

14:30 *Coffee Break*

15:00 **Breakout Session 1 Reporting**

15:30 **Breakout Session 2:** How can the proposed GBF-OOI Ocean Observatory be best utilized to contribute to furthering your individual research goals? How would such advancement at your individual level of research contribute to an improved understanding of global carbon flux, the overarching goal of the GBF-OOI?

17:00 ***Reception & Poster Session***

Wednesday A.M.

08:00 *Continental Breakfast (Steering Committee meets in 509)*

08:30 **Breakout Session 2 Reporting**

09:00 **Synthesis of Day 2 Discussions**

09:15 **Charge to Breakout Session 3: Synthesis, Integration and Public Engagement**

09:30 **Breakout Session 3** (until 11:00)

11:00 *Coffee Break*

11:15 **Breakout Session 3 Reporting**

11:30 **Wrap-Up and Discussion of Next Steps**

12:00 *Boxed Lunch and Adjourn*

13:00 – 15:00 **GBF-OOI Scientific Steering Committee Meeting**

Plenary 1: Abstracts

Scientific objectives and observational priorities of a GBF Program

Co-Chairs: K. Daly and C. Benitez-Nelson

The Ocean Twilight Zone

Dr. Claudia Benitez-Nelson, University of South Carolina
Dr. Ken Buesseler, Woods Hole Oceanographic Institution

Abstract:
Sinking particles play a critical role in the transport of material from surface waters to depth, influencing not only carbon biogeochemistry, but also mesopelagic and benthic organism community structure, and the geochemical cycling of particle reactive elements, such as heavy metals. Yet our knowledge of the magnitude and spatial and temporal variability of this transport is confounded by the complexities associated with sinking particle flux measurements as well as how we parameterize this flux relative to other known indices, e.g, depth horizon versus light level. These problems are exacerbated by a lack of detailed temporal and spatial measurements that can only be captured using high density measurements. The purpose of this talk is to therefore discuss the strengths and weaknesses of current and emerging particle flux measurement techniques and to provide insight into how using a *combination* of methods is key for over constraining particle flux. We further highlight the importance of how one defines and conceptualizes sinking particle fluxes; as this influences our mechanistic understanding of the physical and biological processes that impact particle composition and thus remineralization rates through the mesopelagic. We end our presentation with a brief discussion of other processes, such as zooplankton migration, that influence the transport of material from surface water to the deeper ocean, and emerging mooring technologies that may be used to capture these processes with higher temporal and spatial resolution.

Dissolved Organic Carbon in Export Production

Dennis A. Hansell, University of Miami

Abstract:
Holding 662 PgC, marine dissolved organic carbon (DOC) is a very large and reactive pool of carbon that plays an important role in the cycling of carbon and the biological pump. DOC is exported to depth at a rate of ~2 PgC yr-1 following two pathways: convergence within the subtropical gyres and overturning, thermohaline circulation at higher latitudes, largely in association with mode water formation. Our work (Hansell, C. Carlson, R. Schlitzer) indicates that there exist at least 3 fractions of exported DOC, each defined by unique reactivity character. Knowing the distribution and concentrations of each fraction along with its reactivity (removal rates) allows for modeling the integrated rates of exported DOC removal within the ocean interior. Rates of DOC removal at depths >130 m reach ~1.5 mol C m-2 yr-1, with the highest export occurring in subtropical gyres and in the northern North Atlantic. In these convergence zones, DOC export can equal or exceed export of particulate organic carbon (POC). In divergence zones, such as coastal and equatorial upwelling systems, POC export dominates and DOC export is miniscule. These findings are consistent with expectations: DOC export follows the circulation to depth (convergence zones and overturning circulation), while POC export is located in regions of upwelling and new nutrient additions. An important linkage between POC and DOC export is established in the divergent systems as well: it is where POC is exported, and net community production is positive, that net DOC production occurs. So the divergence zones produce the DOC that is ultimately exported elsewhere in the system.

Two important unknowns must be overcome to make progress in understanding DOC export dynamics. First, the exported DOC can be removed by both biotic and abiotic processes, but we do not know when or where each occurs. Nor do we know the active agents of removal. Second, DOC removal observed in the deep ocean are net rates. There are processes, such as solublization of sinking particles, that can add DOC to a water mass undergoing net DOC loss. Proofs of such additions include: i) the net accumulation at 200 m at the BATS site (unpublished), in association with increased export and remineralization at that depth; ii) the accumulation of fluorescent and colored dissolved organic matter in the very high AOU waters of the deep northern North Pacific (Yamashita and Tanoue, 2008); iii) the accumulation of RubisCO in the deep North Pacific under zones of high export production (Orellana and Hansell, unpublished); and iv) the accumulation of DOC in deep equatorial waters of the Pacific and Atlantic, suggestive of solublization of the sinking POC (unpublished). The difference between the net and gross rates of DOC removal is unknown as we do not know the quantitative significance of the inputs terms; we know only that they exist.

To understand the role of DOC in the biological pump more fully, studies have to target the appropriate ocean regions where each step of the process dominates. For net DOC production in surface waters, look in high productivity systems. For DOC production as residue of exported particles, look under high productivity systems. For DOC export, look to the convergence zones globally, and deep water formation in the North Atlantic.

Ocean Margins: Production, Flux and Remineralization of Biogenic Material

Robert Thunell, University of South Carolina
Collaborators: Claudia Benitez-Nelson, University of South Carolina; Frank Muller-Karger, Laura Lorenzoni and Enrique Montes, University of South Florida; Gordon Taylor and Mary Scranton, Stony Brook University; Yrene Astor and Ramon Varella, Fundacion LaSalle (Venezuela)

Abstract:
Ocean margins are very dynamic regions marked by complex interactions between terrestrial, marine and atmospheric carbon reservoirs. Ocean margins can be characterized in many different ways including: upwelling dominated margins, river dominated margins, sediment starved margins, shelf dominated margins, slope dominated margins, active margins and passive margins. Most attempts to model the marine carbon cycle have not fully integrated the ocean margins in large part because of this complexity and because of the paucity of observations and data for the margins. While the magnitude and variability of carbon fluxes are often much higher in coastal oceans than in open ocean environments, the existing data for ocean margins is relatively limited and as a result it is difficult to quantify the role that ocean margins play in controlling the ocean carbon cycle. The air-sea exchange of CO2 is a good example of where there is a very limited database for ocean margins. Are margins net sources or sinks for atmospheric CO2? Cai and others (2006) synthesized the limited data on CO2 fluxes along ocean margins and found that there is a tendency for the low latitude margins to be sources of CO2 and the higher latitude margins to be sinks. However, the number of observations is small with little data for the Southern Hemisphere.

There have been several attempts to synthesize data on carbon fluxes and burial for the global ocean and to evaluate the importance of ocean margins in the global carbon budget. Using ocean color data, Muller-Karger and others (2005) estimated net primary production along margins to be ~9 Pg C yr-1 or about 20% of the global ocean total. They also estimated that approximately 40% of the organic carbon being buried in the oceans takes place on the margins. Most recently, Jahnke (2010) estimated that net primary production on ocean margins is about 9.8 Pg C yr-1, very similar to that determined by Muller-Karger et al. (2005). Jahnke (2010) also estimated that the ocean are a net sink for atmospheric CO2, taking up about 0.29 Pg C yr-1, with most of this occurring in polar and subpolar regions. Furthermore, Jahnke (2010) estimated that 0.19 Pg C is buried each year on ocean margins, with this being nearly half of the global ocean burial.

The Cariaco Ocean Time Series provides a good opportunity to evaluate the production, flux and remineralization of organic matter in a highly productive ocean margin setting, and to see how this ecosystem is changing in response to changes in climate forcing. The long term mean primary production in Cariaco Basin is ~1.3 gC m-2 d-1. In terms of the org C flux, about 5% of the PP makes it to 230 m and this decreases to 2.7% at 1200 m. Between the base of the euphotic zone at 50 m and the 230 m trap, we find that opal and org C fluxes decrease by an average of 80-85%, while carbonate decreases by about 70%. This remineralization effects the elemental composition of the sinking particles. For example, while the coupling between C and N remains very strong at all depths, the C:N ratio increases with depth, with most of the change occurring in the upper 400 m. The C:N ratio increases from 7.2 to 8.3 between 150 m and 400 m. Similar depth-dependant changes occur for C;P and N:P.

From 1995 to 2010, we find that SST in Cariaco Basin has increased by ~0.1 C yr-1 and that there has been a significant decrease in upwelling over this same period. In response to this, primary production has been steadily declining at a rate of about 1.5% yr-1. Such a decline in production is consistent with the work of Behrenfeld et al. (2006), which demonstrated that global ocean production has been deceasing since the late 1990's due to surface warming and enhanced stratification. As part of this decline in primary production, we observe a significant change in the Cariaco plankton community. Changing hydrographic conditions have resulted in an ecosystem shift away from a highly productive system dominated by diatoms to one where calcifiers are more important. We hypothesize that warming of the tropics is causing a northward migration of the ITCZ. Such a shift would result in the changes we observe in Cariaco Basin, specifically reduced trade winds and upwelling and consequently lower productivity.

If there is to be a global biogeochemical fluxes component to the ocean observing initiative it should address the need for more observations on ocean margins. Ocean margins are underrepresented in the global ocean carbon database. More time series are needed to document climate-driven changes in biogeochemical cycling along ocean margins.

Plenary 2: Summary & Abstracts

Assessing Primary Productivity and Biogeochemical Fluxes

Chair: Astrid Bracher

The scope of this plenary was to cover in three talks and consecutive discussions the needs for the correct assessment of primary productivity and resulting biogeochemical fluxes with the integration of in-situ and surface observations into models. It was discussed how to use observations in global ocean primary production models and biogeochemical general circulation models by improving their parameterization, including small scale physiological processes, and how to get from models and satellite information knowledge on choosing the right observation strategies and sites for long-term sampling.

Integrating Remotely Sensed and Direct Observations of Surface Productivity and the Biological Pump

Jim Yoder, WHOI
Mike Behrenfeld, Oregon State

Summary:

In the talk by **Jim Yoder (WHOI)** and **Mike Behrenfeld (Oregon State University)** on **"Integrating Remotely Sensed and Direct Observations of Surface Productivity and the Biological Pump"** it was emphasized that ocean color starting with CZCS in 1978 revolutionized the assessment of global ocean biomass and primary production. While global estimates of net primary production (NPP) based on 14C measurements from the 1950s to 1980s ranged from around 20-56 Pg C/year (the highest numbers coming up when the first ocean color data became available), the numbers raised in the empirical approaches using satellite chl-, SST and PAR data from 1990s up to today to 40-65 PgC/year. Already these global NPP estimates have been used to study changes due to global physical or chemical variability; e.g. it was shown by Behrenfeld et al. (Science, 2001) that the NPP increased by 6 Pg during the transition from 1997 El Niño to 1999 La Niña. There have been attempts to develop C-based primary production estimates and the variability of C-based versus Chl-based models showed an annual NPP averaged 67 Pg C yr^{-1} for the C-based model and 60 Pg C yr^{-1} for the Chl-based model over the 1997 to 2002 period. Far more dramatic are the spatial and seasonal differences in NPP between models. The carbon model yielded 40% and 49% higher annual NPP for the central Atlantic and central Pacific regions.

Still, the numbers of all attempts to globally estimate marine primary production using satellite information are quite diverging, and the missing piece for the global primary production assessment are global data on phytoplankton physiology. In addition to that, the validation of satellite primary production due to missing long-term in-situ studys is so far limited. Future perspectives are the current semi-empirical algorithm developments in respect to derive insight on phytoplankton physiology via additionally retrieved products, such as inverse techniques to get chl-a, CDOM, particulate carbon, fluorescence for the physiological state, growth rates and carbon-based (via the back-scattering signal) primary production. New developments on retrieving satellite-based products such as cell size, taxonomic classification and CDOM will help to imply the state of the biological pump. Unfortunately, the upcoming NASA VIIRS sensors (with launch date in 2011 and 2014) will have less bands than SeaWiFS and MODIS and the financing to produce high quality ocean color products is still unsecure. The discussion of this talk emphasized that

- GBF-OOI has to put recommendations (pressure) to NASA to ensure that VIIRS will at least to fulfill the requirements that similar to SeaWiFS ocean color products can be extracted.
- the data policy between NASA and ESA has to ensure free (and rapid) data access to the ESA ocean color sensors MERIS (operating since 2002) and the upcoming Sentinel-3 OLCI sensor (launched 2013 and 2015)
- the upcoming PACE NASA mission is becoming that strength through the validation possibilities via the GBF-OOI program and through the extra-polation of GBF-OOI data into the global spatial context by incorporation the satellite ocean products (ocean color, SST, salinity, SSH, winds, …)
- the OOI-GBF-sites, where primary production is directly measured continuously, are established to serve as a vicarious calibration site for satellite-based primary production estimates, similar to what the MOBY buoy measurements for the vicarious calibration of water leaving radiances of the SeaWiFS and MODIS mission.

Measurement Strategies to Inform Global Ocean Biogeochemical General Circulation Models (OBGCM) and Vice Versa

John Dunne, NOAA

Summary:

The second talk by **John Dunne (Biospheric Processes Group, Geophysical Fluid Dynamics, NOAA)** focused on **“Measurement Strategies to Inform Global Ocean Biogeochemical General Circulation Models (OBGCM) and Vice Versa”**. There are many global OBGCMs currently in use and OBGCM fluxes are global in their scope, but highly variable between models. The following questions to which OBGCMs are applied, have been raised:

- “How much anthropogenic carbon uptake has occurred?”
- ”How will anthropogenic carbon uptake change under climate change?”,
- “How will the natural carbon cycle change under climate change?”
- “How will ecosystems change under climate change?”

Currently, the clearest uncertainty in the OBGCMs’ answers to the above questions lies in our ability to represent the ocean circulation and its sensitivity to change. The biogeochemical uncertainties include mechanistic controls on

- euphotic zone rates of nutrient consumption and degree of residual nutrients
- controls on POM/DOM passive and active transport
- deviations in stoichiometry from Redfield (e.g. N_2 fixation)
- remineralization scales through the twilight zone

The process level understanding of these mechanistic controls constrains the model algorithms. It is claimed to develop for measurement strategies ecological and biogeochemical testbeds (e.g. JGOFS program, intercomparison of satellite-based primary production by Friedrichs et al. 2007). These testbeds should be suitable to answer if:

- the physical, chemical and biological system is comprehensively resolved

- the uncertainty is small enough to falsify a bad model
- this are the appropriate measurement strategies necessary for data assimilation

and these testbeds should

- have a concept how the new information stands against previous work?
- resolve how models need to change to represent the process
- help to judge if the reduction in bias/uncertainty of the parameterized process is globally significant (>0.1 PgC/year)?

An example for a globally powerful testbed is the modest measurement strategy used to derive the Martin Curve (Martin et al. 1987).

In physical oceanography, global data assimilation is used for state estimation and short term forecasting (recently up to a year). For parameter estimation, e.g. for the carbon cycle, data is commonly used for initialization, but data assimilation has mostly been restricted to regional state estimation and parameter tuning. The central challenges are data sparseness and their physical or biological attribution (e.g. pCO_2). So to judge why observations do not match the model, several reasons might exist: The pressure history is different, there is a physical bias in temperature and salinity and a chemical bias in Alk, DIC, NO_3, the wind speed parameterization is incorrect and there are unresolved features, like an eddy or a front.

Also the power of OBGCMs informing for measurement strategies was discussed. OBGCMs can give hindsight, fill measurement gaps for a more comprehensive picture and give foresight by OBGCMs for Observation System Simulation Experiments for detection and attribution and other sensitivity experiments.

To what modeling questions is a GBF-OOI particularly well-suited?

- Process level characterization of the twilight zone.
- Characterization of variability in poorly sampled but biogeochemically critical regions like the Southern Ocean, Labrador and Nordic Seas
- Resolving fine scale biological response to physical perturbations like storms, entrainment, detrainment
- Resolving biological response to natural iron fertilization events and other biological perturbations
- Serving as a testbed for instrument and method development

To summarize, there are currently many global OBGCMs in use. To critically inform these models will require measurement strategies to either be globally representative or reduce the regional uncertainties with global significance. The measurements can also change how these models are built (i.e. microbial loop, ballast). On the process level information should be fully resolve the phenomenon, including physical drivers, constrain a mechanism as it applies globally and reduce uncertainty/bias >0.1 PgC/yr. On the other hand, models can help to optimize experimental design of the measurements taken via the GBF OOI.

In the discussion it was claimed to take (more) into account the biology (e.g. zooplankton type dependent flux rate which determines BGC flux down to the ocean floor strongly) for assumptions made in the OBGCMs. Again, it was strongly recommended to ensure the intercomparison of the

OBGCMs, then use those to identify key sites for GBF-OOI and vice versa ensure sensible (what temporable resolution) sampling with GBF-OOI sites, so this data will enable improved parameterizations in these models. Generally, the ocean margins and coastal oceans seem not be well resolved in the OBGCMs. In order to improve those, regional models have to take the coastal GBF-OOI data to get improved the regional methods and feed this knowledget back to improve the parameterizations made in the global OBGCMs regarding the marginal ocean. Limitations regarding computational or costs restrictions for improving the capabilities of these models, only apply to the ones with high spatial resolutions (JOHN please give a number here, or examples?), but the question is whether these resolutions are necessary on a global level. The GBF-OOI data set might illucidate that there fundamental changes necessary in the parameterizations of OBGCMs.

Measurement strategies to inform global ocean biogeochemical general circulation models (OBGCMs) and vice versa

John P Dunne, NOAA Geophysical Fluid Dynamics Laboratory

Abstract:

Global ocean biogeochemical general circulation models (OBGCMs) are coupled simulations that solve both the primitive equations of geophysical fluid dynamics for the ocean circulation as well as tracer circulation and biogeochemical and ecological interactions necessary to represent the carbon and related cycles. The current state of OBGCMs is such that a variety of climate supercomputing centers around the world have been running such models at relatively coarse resolution (100-400 km scale) in order to represent the broad circulation and biogeochemical features of equatorial upwelling, subtropical gyre, subpolar gyre and polar systems. OBGCM fluxes are global in scope, and highly variable between models with a great deal of uncertainty and bias present in both the physical and chemical representations as the targeted focus of many research efforts.

Some of the big questions to which OBGCMs are being applied include: How much anthropogenic carbon uptake has occurred? How will anthropogenic carbon uptake change under climate change? How will the natural carbon cycle change under climate change? And, how will ecosystems change under climate change? Currently, the clearest uncertainty in these OBGCM answers is in our ability to represent the ocean circulation and its sensitivity to change. Biogeochemical uncertainties include mechanistic controls on: euphotic zone rates of nutrient consumption and degree of residual nutrient; controls on POM/DOM passive and active transport; deviations in stoichiometry from Redfield (e.g. N2 fixation); remineralization scales through the twilight zone

There are a variety of measurement strategies that are key to supporting the continuing development of OBGCMs, including: determination of biogeochemical rates, their variability and controls to improve process-level understanding; testbeds providing the physical and biogeochemical context to compare alternative representations to detailed observations; globally synoptic observational programs such as ARGO and WOCE that constrain the entire scope of real world variability, and data assimilation efforts that utilize such globally synoptic observations to infer underlying biogeochemical cycling.

In order for an observational strategy to be successful in improving process-level understanding, it should be able to stand up to the following set of questions: Will the process be comprehensively resolved? Will possible variation in the process be known? How will the new information stand against previous work? How will models need to change to represent the process? Will the reduction in bias/uncertainty be globally significant (>0.1 PgC/year)? A classic example of a modest observational strategy that proved invaluable to the development of OBGCMs was the VERTEX program which led to the development of the 'Martin curve (Martin et al., 1987). Several factors went into making this effort so successful. First, the sediment trap approach that they used was well characterized in its utility. Second, they applied the approach in a regime that the approach was well-suited – that is, exposed to shearing currents less than 10 cm/s. Third, they chose a regime that could reasonably assumed to be under a quasi steady state, and finally, they collected samples that resolved both the depth and offshore dependence of the flux variability in order to deterministically interpret the observations in a single semi-mechanistic/semi-empirical framework. The key to empirical description in its applicability to OBGCMs is in their ability to capture regional and temporal variability in a mechanistically justifiable way. Such was a detriment in the Lutz et al (2002) study which, though providing a comprehensive statistical scope for variability, did not afford an OBGCM of representing that variability within it. This is in contrast to the very successful efforts by Armstrong et al. (2001), Francois et al (2002) and Klaas and Archer (2002) which together interpreted the observations into a comprehensive description of deep ocean particle dynamics.

In order for an observational strategy to develop into a successful ecological/biogeochemical testbed, it should be able to stand up to the following set of questions: Is the physical, chemical and biological system comprehensively resolved? The contrasting efforts to observe the North Atlantic Spring Bloom over the years provide an instructive set of examples in this regard. Sverdup's (1953) 'Critical Depth Hypothesis' could only be tested in a quantitative way due to the existence of the Weather Ship 'M' observational record that sampled physical and ecological conditions both throughout the winter to provide initial conditions as well as throughout the spring to summer transition to falsify inferior models of the phytoplankton response. This early, temporally comprehensive observational strategy contrasts with the JGOFS North Atlantic Bloom Experiment that focused on an intensive suite of process measurements during the bloom, but missed the transition from winter conditions making model initialization impossible. While valuable for calibrating processes like model recycling efficiency, the effort serves as a missed opportunity for testing how/when/why the bloom began. Both of these contrast again with the recent 2008 effort (e.g. Bagniewski et al, 2010) that depended heavily on new autonomous technologies in order to get a combination of extensive temporal and spatial coverage with a punctuated suite of intensive ship based observations to broaden the context. With its high resolution lagrangian platform, it proved even more powerful than the classic weathership for testing hypotheses for bloom initiation. As was demonstrated in the recent Regional Ecosystem Model Testbeds project (Friedrichs et al., 2007), such frameworks for comparing observations with alternative model implementations can be quite powerful in enabling comparative fidelity and portability assessment. However, such idealized frameworks depend on the physics being very well constrained and the ecological responses being synoptically sampled.

In order for an observational strategy to provide synoptic global properties, the property or flux must be globally observable from a logistic perspective, unbiased, and with certainty good enough to falsify alternative models. A variety of biogeochemical syntheses are available with variable comprehensiveness in coverage. The most comprehensive and definitive for fidelity assessment include: NOAA/NODC World Ocean Atlas 2009 (T, S, NO_3, PO_4, SiO_4, O_2); DoE GLODAP/CDIAC DIC, Alk, Anth CO_2, CFCs, ^{14}C; NASA Satellite Ocean Color for chlorophyll POC and composition; NOAA Copepod Database 2007 for mesozooplankton ; and Takahashi/LDEO pCO_2 database. More sparse but globally extensive and powerful for validation include: Honjo et al (2008) deep sediment traps; Jahnke (1996) sediment respiration; Jahnke (1996) and Seiter (2002) and accumulation; Parekh/Moore dissolved iron databases; Dennis Hansell's DOC database; and Jenkins/Schlosser $^3H/^3He$ database.

Another way in which measurement strategies inform OBGCMs is through data assimilation. In physical oceanography, global data assimilation is used for: sState estimation, short term forecasting (recently up to a year), and parameter estimation. For the carbon cycle, data is commonly used for initialization, but data assimilation has mostly been restricted to regional state estimation and parameter tuning. The central challenges are data sparseness and physical/biological attribution. This challenge of attribution is illustrated nicely through consideration of pCO2 biases in a data assimilation framework, and determining a single course of corrective action for the model to take when observations do not match the model without being able to distinguish whether the bias is because: the pressure history is different; there is a physical bias in T, S; there is a chemical bias in Alk, DIC, NO3; the wind speed parameterization is incorrect; or there is an underlying unresolved feature (eddy/front). Some biogeochemical state estimations have been conducted that assume steady state by Ganachaud and Wunsch (2002), Schlitzer (2006) and Kwon and Primeau (2006), but time-varying assimilation is still far off.

OBGCMs can provide valuable support for measurement strategies both in terms of providing hindsight with respect to filling measurement gaps and foresight in Observation System Simulation Experiments (OSSEs) to scope out the viability of a proposed measurement strategy in its ability to adequately detect and attribute the phenomenon of interest. Such biogeochemical OSSE's were conducted by Robbie Toggweiler in support of the JGOFS EqPac Process Study (Murray et al., 1992) and McCreary et al. (1996) in support of the JGOFS Arabian Sea Process Study. There are many global OBGCMs currently in use. To critically inform these models will require measurement strategies to either: be globally representative, reduce regional uncertainties with global significance, change how models are built (i.e. microbial loop, ballast). Process level information should: fully resolve the phenomenon, including physical drivers, constrain a mechanism as it applies globally, reduce uncertainty/bias >0.1 PgC/yr. Models can help optimize experimental design.

The modeling questions to which a GBF-OOI may be particularly well-suited include: process level characterization of the twilight zone, characterization of variability in poorly sampled but biogeochemically critical regions like the Southern Ocean, Labrador and Nordic Seas, resolving fine scale biological response to physical perturbations like storms, entrainment, detrainment, resolving biological response to natural iron fertilization events and other biological perturbations, and serving as a testbed for instrument and method development.

Oceanic Biochemical Approaches: Proteomic Measurements of Enzymes – A New Biogeochemical Tool

Mak Saito, WHOI

Summary:

The third talk by **Mak Saito (WHOI)** focused on **"Oceanic Biochemical Approaches: Proteomic Measurements of Enzymes – A New Biogeochemical Tool"**. Tracing the quantity of certain macro molecules, specifically enzymes, enables to identify what and where certain biochemical reactions are occurring and identifying their relevance in key BGC processes. With the insight of these enzymes turnover rates, controls on their activity, e.g. what is conducting and what is catalyzing, it can be derived how those trace elements influence primary productivity and BGC. With the help of modeling regions of limitation can be predicted, e.g. intermediate depth processes (e.g. denitrification, anammox, remineralization) or the expansion of Oxygen Minimum Zones. The potential of the application of proteomics to OOI-GBC and GEOTRACES was discussed. The advantages are direct measurement of the enzymes responsible for biogeochemical reactions which with calibration should enable to obtain estimates of reaction rates, the analysis of many targets simultaneously is possible (not primer-specific) and the systems are amenable to GEOTRACES and automated sample collection with later storage at ambient temp. Disadvantages are that large seawater volumes (10-200L) are necessary and that further identification/calibration of biomarkers and the development of high-throughput capabilities and optimized sampling platform is necessary.

Plenary 3: Abstracts

The OOI and Prospects for a GBF Program

Chair: C. Pilskaln

OOI Elements and Technological Capabilities: Biogeochemical Cycles and Fluxes

Kendra Daly, University of South Florida

The Ocean Observatories Initiative (OOI) is a long-term, NSF-funded program to provide 25-30 years of sustained ocean measurements to study climate variability, ocean circulation, ecosystem dynamics, air-sea exchange, seafloor processes, and plate-scale geodynamics. The OOI will enable powerful new scientific approaches for exploring the complexities of Earth-ocean-atmosphere interactions, thereby accelerating progress toward the goal of understanding and predicting our ocean environment. The OOI also will foster new discoveries that will, in turn, move research in unforeseen directions.

The OOI will deploy three integrated facilities: (1) global arrays at four high latitude sites in the north and south Pacific and the north and south Atlantic, (2) coastal observatories, which include the Pioneer array in the mid-Atlantic Bight and the Endurance Array off of Washington and Oregon, and (3) a high power (10 kv) and bandwidth (10 Gb/s) regional cabled component offshore of Washington and Oregon. The cabled component integrates the Oregon line of the Endurance Array with a hydrate deposit site on the shelf slope, a site in the core of the California Current at the base of the shelf slope, and sites adjacent to and in Axial Seamount on the outer edge of the Juan de Fuca plate. Final commissioning of the OOI will occur during 2014.

This presentation will provide information on the core sensors (49 types measuring physical, chemical, biological, and geological parameters) and infrastructure provided by the NSF's Major Equipment and Facilities Construction (MREFC) account at all of the OOI sites. The variability of carbon parameters at all OOI sites will be presented to encourage science discussions. In addition, some examples of climate driven variability in the north Pacific and biogeochemical questions that can be supported by the cabled array will be described. In particular, the cabled component will be able to support many different types of complex ecosystem sensors that can be proposed as part of individual or community experiments. The cabled component also will be able to support event detection and adaptive response science strategies through remote control of instrumentation and platforms.

In Situ Measurements of Surface Ocean Productivity

Craig Taylor
Woods Hole Oceanographic Institution
ctaylor@whoi.edu

Critical to advancing our understanding of the oceanic biological pump, will be the application of experimental approaches that greatly improve global estimates of marine primary production (PP) and more accurate estimates of the spatiotemporal links between PP, export production (EP) and the biogeochemical processes that impact particulate organic carbon (POC) flux.

Our laboratory, in collaboration with McLane Research Laboratories have focused on the *in situ* tracer incubation as one tool for quantifying microbial rate processes in general, PP in particular. Biological tracer incubation studies are advantageous in that they directly quantify physiological or metabolic response of the resident microbial population to their environment. However, they also tend to be rather labor intensive operations and typically require an on-shore or ship-based laboratory setting for their execution. Hence, the temporal resolution of such studies tends to be controlled as much by experimental or financial logistics as by the temporal dynamics of the physico-chemical environmental variables impacting the activities being measured. Critical biological data can be aliased by seemingly random events that can have an impact on critical measures such as regional seasonal or annual depth integrated PP rates. Illustrated in a study by our laboratory at stations ~13 km (N10) and ~28 km (N04) off the coast of Massachusetts (**Figure 1**)

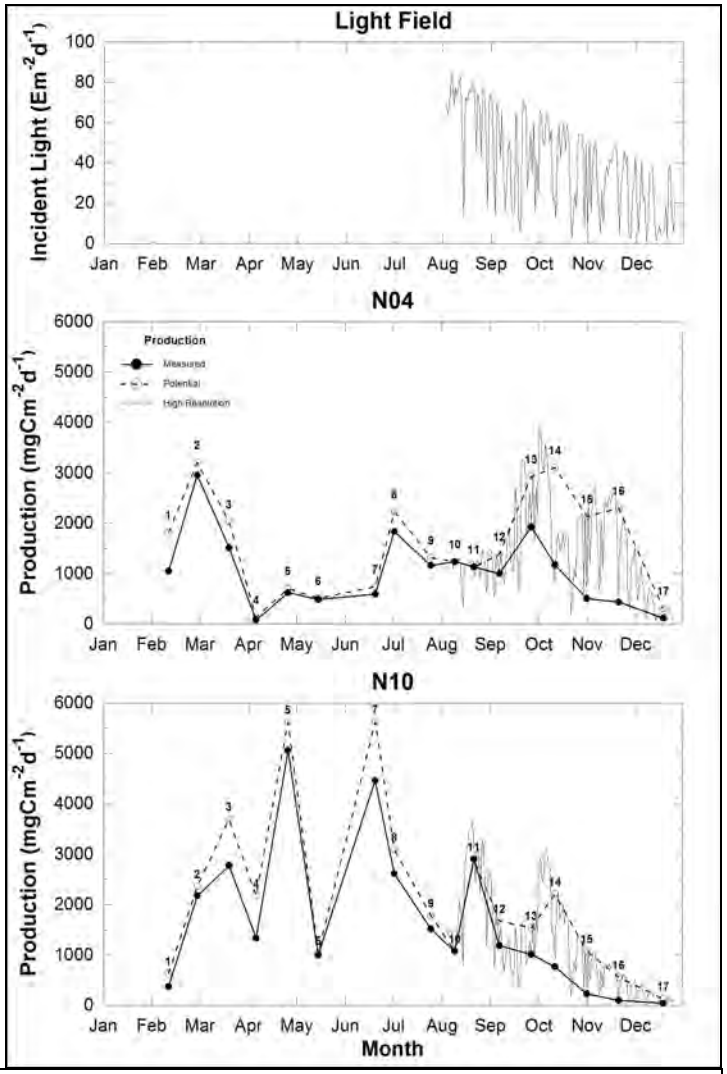

Figure 1. Effect of sample aliasing on critical rate process measurements. Solid line, PP at the incident light on the day of the cruise; dashed line, PP at cloudless day incident light for that day of the year; fine solid line, daily PP calculated from measured incident light and between cruise averaged photosynthetic properties centered on the day of the cruise.

Graphed PP calculated from chl specific P vs. I parameters, measured in samples collected at 5 depths, water column chla measurements, depth-dependent water column light attenuation, daily production obtained by integration of production calculated at each depth from incident light measured every 15 min on that day & those PP values integrated over depth.

the magnitude of the fall bloom was underestimated by ~36% & ~42% (N10, N04, respectively) when *day of cruise* integral production was compared with production estimated by temporal integration of the high resolution data; all because the cruise dates (planned long in advance) throughout the fall bloom happened to occur on cloudy days (compare bold solid lines, production at day of cruise light intensities, the dashed line, production were that day sunny & the fine solid line, probable daily production given the light field of that day). Annual depth integrated production would have been underestimated by non-trivial ~19% & 27% (N10, N04, respectively) had the *day of cruise* data been the sole source of the PP data as is often the case in time series studies of this sort.

To reduce the labor intensity of microbial tracer incubation studies and increase the temporal resolution of time series of the sort illustrated in **Figure 1**, we have developed robotic micro-laboratories (Time Series-Submersible Incubation Device, TS-SID; Incubating Productivity System, IPS) that are able to conduct in situ biological tracer incubation experiments under conditions that accurately simulate the environment and require no involvement of the investigator other than the analysis of sample at the end of a given deployment (**Figure 2**).

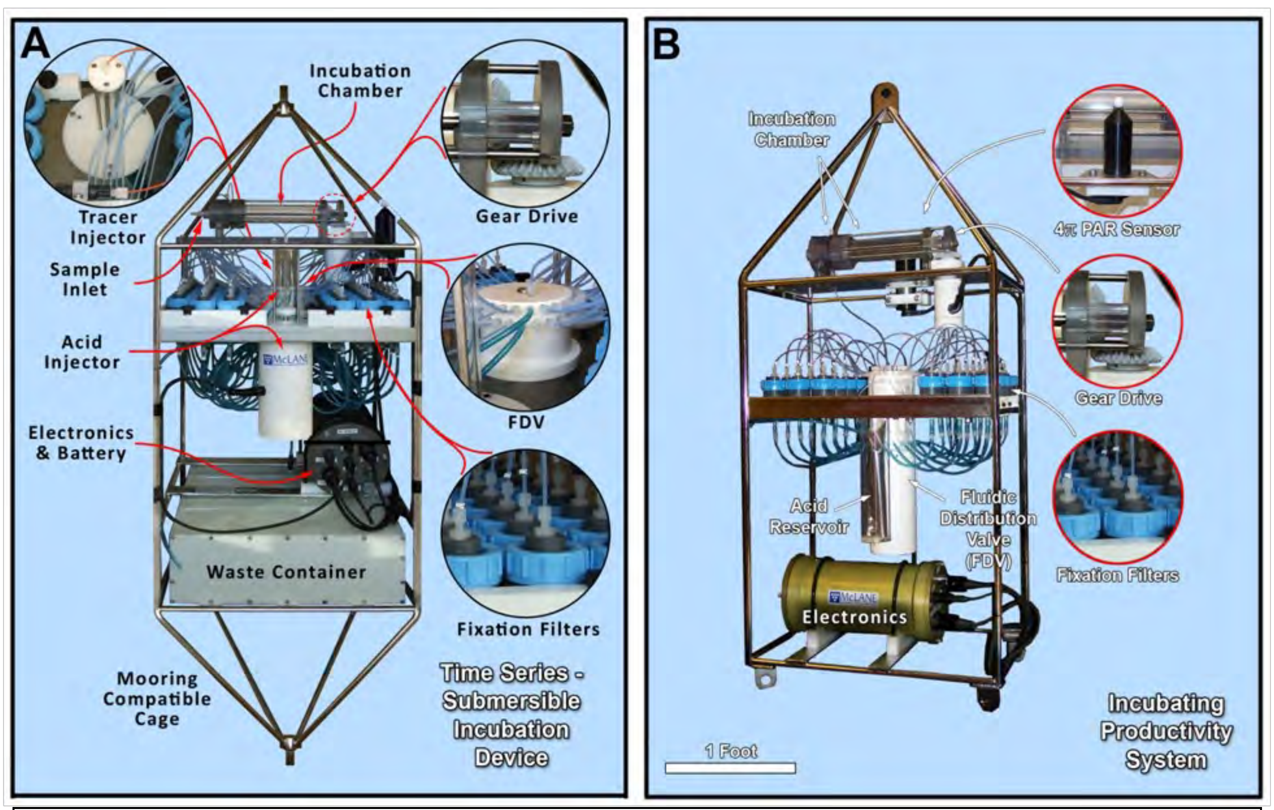

Figure 2. The Time Series-Submersible Incubation Device (TS-SID) & Incubating Productivity System (IPS). The TS-SID can collect & preserve 48 incubated samples, the IPS a smaller footprint version capable of collecting & preserving 24 incubated samples.

The modular instruments consist of a 400-4000 mL gear-driven syringe like incubation chamber, a Fluidic Distribution Valve (FDV) for directing incubated samples to one of 24 or 48 in line Fixation Filter Units (FFU), possesses mechanisms for the introduction of tracer (Tracer Injector, TS-SID), (FDV, IPS), possesses internal (acid cleaning) and external (mechanical)

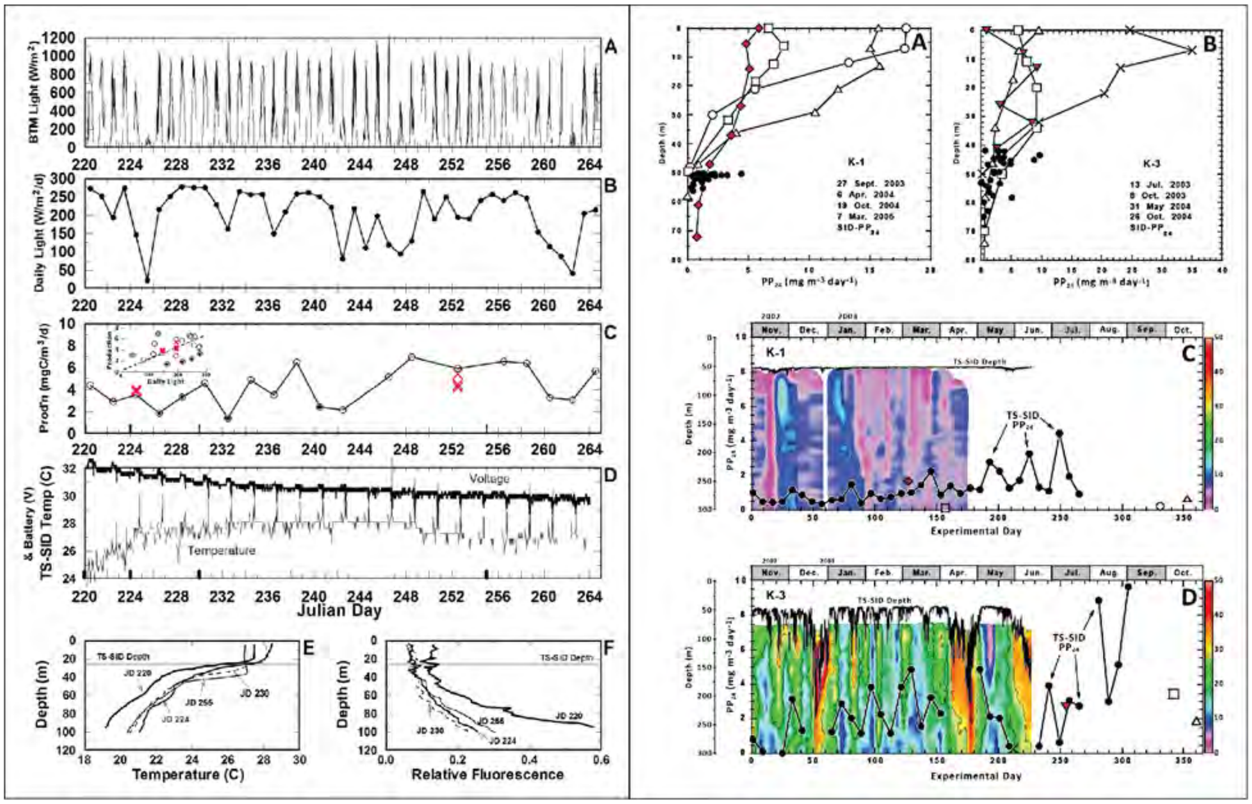

Figure 3. Comparison of moored TS-SID primary production measurements with measurements conducted by the Bermuda Atlantic Time Series (BATS) program (left panel) and during a 10 month deployment the N. Pacific stations K-1 (51°20' N, 165°12' E & K-3) & K-3 (39°10' N, 160°01' E) (right panel). Ship based measurements at BATS, K-1, K-2 at the same time/depth the TS-SID incubations were conducted are indicated by red symbols.

BATS Deployment: Panel A, Light sensor readings from the MET package on the BTM surface float. Panel B, daily average light. Panel C, production measured at 26 m depth by the TS-SID over a 9 hr period centered on solar noon (open circles, covering >92% of the photoperiod). Inset, plot of production vs. daily incident light. Panel D, internal temperature of the TS-SID electronics case and battery pack voltage. Panels E & F, BATS CTD profiles of temperature and relative chlorophyll fluorescence on the days indicated. TS-SID depth indicated by gray horizontal lines. Julian days 220-244 correspond to Aug. 8 - Sept. 1, 1997. BTM data were obtained from web site: http://www.icess. ucsb.edu/opl /btm.html.

N. Pacific Deployment: Primary production at Stations K-1 (Panel A, 51°20' N, 165°12' E) and K-3 (panel B, 39°10' N, 160°01' E). *In situ* TS-SID Primary Production (TS-SID PP24) measurements are shown as closed circles. As shown in the McLane Moored Profiler (MMP, John Toole, WHOI) measurements, the more northerly station, K-3, experienced substantial winds and currents approaching 50 cm/sec, which leaned over the mooring and occasionally plunged the TS-SID below the euphotic zone to depths of ~250 m (black lines, Panels C, D; these data not used). Simulated *in situ* 13C ship-based measurements were made during cruises at both stations (open symbols; red symbols, ship incubations done at the time the TS-SID was recovered). The TS-SID was nominally located at the base of the euphotic zone at ~50 m (shallower depths were not possible given winter sea

means for control of biofouling of the incubation chamber & Electronic Controller/Battery Pack permitting deployments of up to 1 year. The TS-SID can work with both radioactive and heavy tracers (hence, waste container); the IPS heavy tracers only.

Each autonomous *in situ* incubation involves a flushing cycle to condition the incubation chamber to the environment, procurement of the sample to be incubated with simultaneous introduction of tracer and the collection/chemical preservation of filtered incubated samples, another flushing cycle for removal of tracer from the incubation chamber. At user determined intervals the interior of the incubation chamber is acid cleaned; establishment of an external biofilm is prevented by the repeated wiping of the chamber outer surface during normal SID operations.

TS-SID performance (**Figure 3,** previous page) was tested on the Bermuda Test Bed Mooring (BTM) for comparison with classic ship-based measurements made by the Bermuda Atlantic Time Series (BATS) team at the same depth and time (red crosses) and in 10 month deployments in the N. Pacific at Stations K-1 & K-3. The ship-based and robotic measurement approaches favorably agreed with one another.

Presently under construction is the Submersible Incubation Device-In Situ Microbial Sampler (SID-ISMS, **Figure 4**), a robotic micro-laboratory that will integrate heavy isotope tracer incubation studies with microbial sampling for phylogenetic identity of the organisms in the environment at the time of the incubations. The instrument possesses a 2L incubation chamber which will permit simultaneous time series measurements of ^{13}C-PP and ^{15}N-N_2 nitrogen fixation rates for up to a year. This instrument will collect and chemically preserve up to 48 incubated samples and permit use of multiple tracers (e.g., incubations measuring ^{13}C-PP with ^{15}N-nitrogen fixation; ^{13}C-PP with ^{15}N-nitrification rates, etc). Microbial samples ranging in size between 500 ml whole water samples to several liter filtered and chemically preserved samples will be possible (via micro-gear pump). A newly developed FFU will permit *in situ* chemical preservation (e.g., RNAlater) of filtered samples rapidly enough for gene function (mRNA) studies. This filter unit will have general application for *in situ* preservation of microbial samples from the environment as well as of incubated samples during tracer studies. The instrument will possess a suite of additional sensors (4π par sensor, CTD, transmissometer, fluorometer or

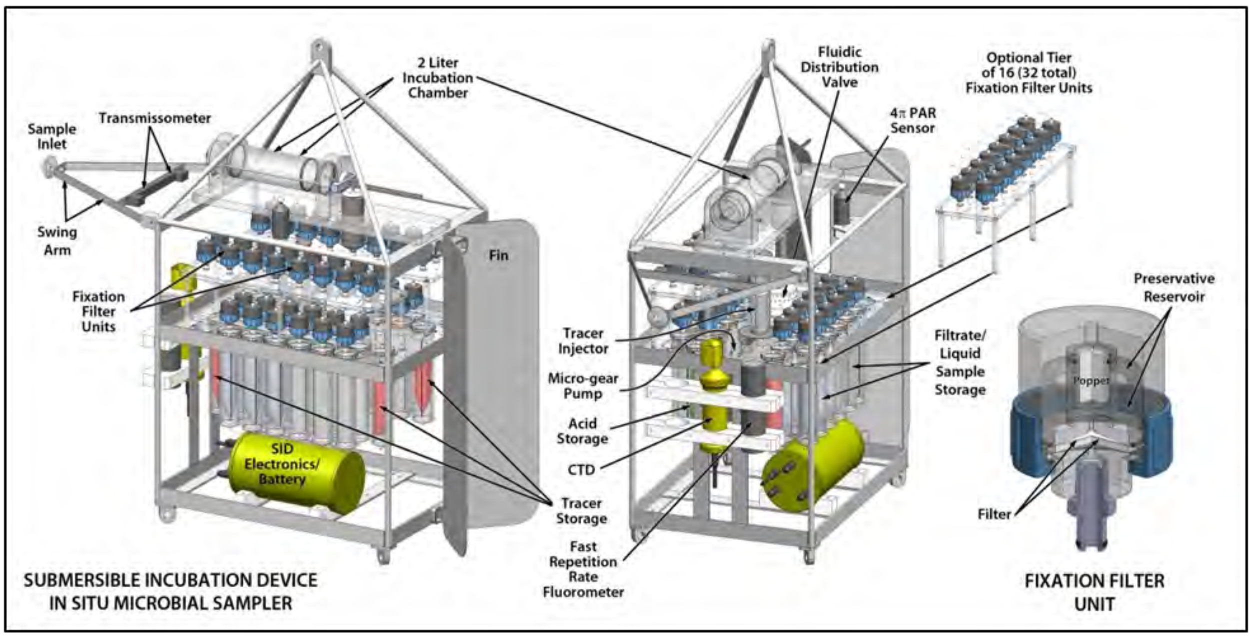

Figure 4. Submersible Incubation Device-In Situ Microbial Sampler (SID-ISMS). This instrument integrates tracer incubation studies with *in situ* microbial sampling. Inset, new prototype Fixation Filter Unit that is capable of chemically preserving (RNAlater) filtered samples quickly enough for gene function studies (mRNA). Preservative delivery is via laminar convection driven by the density contrast between the preservative (e.g., RNAlater) and sample (seawater). The passive poppet prevents preservative loss during filtration, permitting

Fast Repetition Rate Fluorometer [FRRF, developed by Z. Kolber]).

In a recently funded project we, in collaboration with S. Sievert, WHOI, will be developing a version of SID (Vent-TS-SID, **Figure 5**) that will permit: 1) The time series measurement of ^{13}C chemosynthesis rates & ^{15}N nitrate reduction rates (or other biological rate measurements) within warm water hydrothermal vent fluids, at emanating vent fluid temperatures and elevated temperatures emulating conditions deeper within the vent ecosystem (heating of chambers require ~5 -13 W power, depending upon maintained temperatures). 2) Acquisition, filtration and chemical preservation (RNA*later*) of vent fluid microbes present in the vent fluids and/or at the beginning and end of a given incubation. 3) Collection & preservation of samples for subsequent *Fluorescent In situ Hybridization* (FISH) studies. 4) Acquisition into metalized polyethylene bags & $ZnCl_2$ chemical preservation of filtrate samples for subsequent analyses of the nitrate reduction products ^{15}N-N_2 & ^{15}N-NH_4, hydrogen sulfide (preserved as zinc sulfide) upon return of the instrument (or investigator choice of preservative).

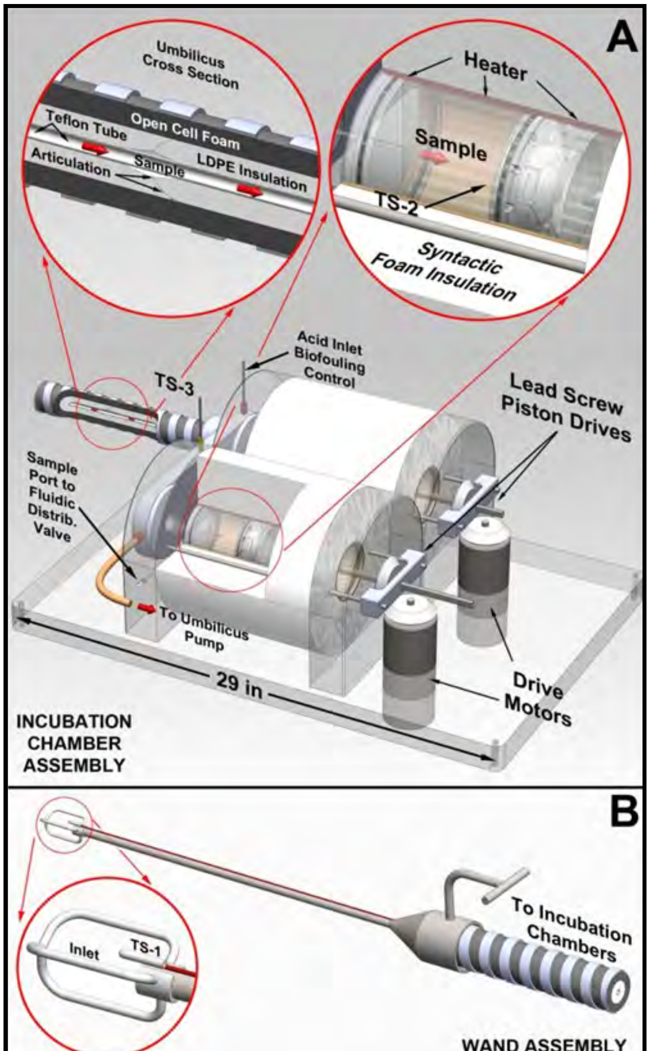

Figure 5. Propose heated Vent-TSSID Twin Incubation Chambers to be developed. Panel A, Incubation chamber assembly; Panel B, sampling wand. Red encircled insets, cross section views of umbilicus & heated incubation chamber & wand inlet. An umbilicus pump draws vent fluid as shown by the red arrows. Temperature within the incubation chambers are maintained by a waterproof Nichrome heater. Incubating sample is gently stirred by a solid state magnetic stirrer potted within the incubation chamber piston. For biofouling control, an acid injector mixes acid with seawater pumped by the umbilicus pump (in reverse direction) to prevent biofilm buildup within the sample tube in the umbilicus. Similarly, acidic water can also be drawn into the incubation chambers for biofouling control. TS-1, TS-2 & 4 (incubation chambers, 4 not shown) and TS-3, inlet manifold temperature sensor.

The above selected suite of measurements will provide a quantitative measure of microbial rate processes, concentration & changes in the main sources of energy & electron acceptors, and phylogenetic and/or gene function information in support of the tracer incubations within a given vent over time or between different vents.

For GBF-OOI this instrument will provide among the first *in situ* measures under *in situ* physico-chemical conditions of organic carbon input into deep waters from vents.

As illustrated in **Figure 1** there is potential for substantial variability in PP at a given location in response to a suite of environmental variables, including light field, lateral transport of phytoplankton populations, changes in physiological state in response to stochastic, seasonal changes in nutrient status, etc. Acquisition of 48 evenly distributed incubated samples during year long moored deployments affords a temporal resolution of ~8 days between incubations; while more frequent than ship-based studies there is still potential for sample aliasing. Combining the unique capabilities of the FRRF (Z. Kolber) & SID-ISMS, however, may afford time series PP measurements that are more temporally resolved and accurate than either instrument is likely to provide independently. The FRRF provides a window into phytoplankton physiological state, changes in capacity/efficiency of Photosystem II (PSII) in response to changes in the environment and a measure of the passage of electrons from PSII to Photosystem I (PSI). Because these fluorescence measures can be transmitted to the laboratory via satellite, the information can also be used to trigger adaptive sampling by other moored instrumentation such as the SID-ISMS, water samplers, etc.

From the above active fluorescence measures an estimate of PP is possible, but the algorithms involved require external calibration from independent measurements of production, a parameter that the SID-ISMS can provide at sufficient temporal resolution, particularly if adaptive sampling is implemented. The instrument combo may permit, during GBF-OOI deployments, continuously calibrated year long time series measures of PP at daily or perhaps hourly intervals.