GBF-OOI
Community White Paper

A Call For a Global Biogeochemical Fluxes Program for the Ocean Observing Initiative

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Relevance and Timeliness

The role of the oceans in modulating atmospheric CO_2 concentrations, and hence global climate, is related to their capacity to remove CO_2 from the atmosphere and sequester it in oceanic deep waters and in underlying sediments such that it remains out of communication with the atmosphere for hundreds to thousands of years. Two mechanisms by which CO_2 can be transferred to abyssal depths are via the so-called “solubility pump” and the “biological pump”. While the former can potentially be parameterized by developing accurate constraints on physical and physicochemical properties and ocean circulation, the latter is more complex, due to its tight coupling with biological processes throughout the entire oceanic water column, and is spatially and temporally heterogeneous.

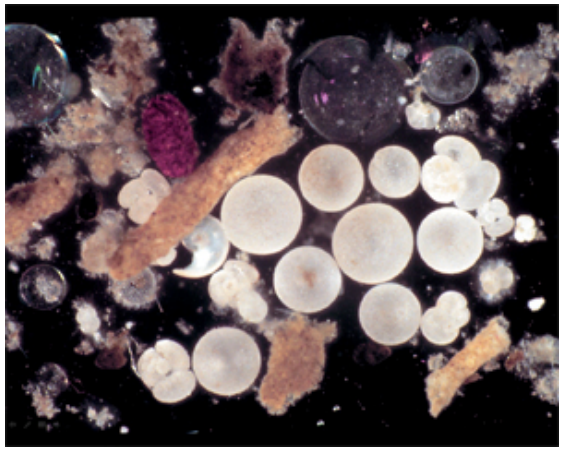

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Fig. 1. Settling particles: a low magnification photomicrograph of typical exported ocean particles intercepted by a mesopelagic TS-trap deployed in the carbonate ocean.

Characterization of the efficacy of, and variability in the biological pump is the subject of extensive prior and on-going research. In the past two decades, ocean biogeochemical cycles studies including the US-JGOFS and large international ocean observation programs have significantly deepened the our understanding of the underlying processes, and further established the concept of the “Biological Pump” originally proposed by Volk and Hoffert, 1985, as the interplay between ocean ecosystems and the Earth’s gravity (Fig. 1). A key facet of these studies was the extensive use of time-series sediment trap (TS-trap) and advanced mooring technology that supported export flux investigations. Syntheses of available observational data on the export of particulate organic carbon (POC) and other biogenic particle fluxes to the oceanic interior provided the first glimpse of the operation of the biological pump in specific ocean basins (e.g., Fischer et al., 2003) and the world ocean (e. g., Honjo et al., 2008).

Despite these prior or on-going export studies focused either on time-series observations in specific regions, or on more process-oriented investigations, critical gaps persist in our knowledge of the workings of the biological pump. For example, there are serious information gaps for certain regions that may be particularly prone to climate-driven shifts in oceanic productivity, or where mechanisms of carbon export are complex and difficult to quantify (e.g., adjacent to continental margins). Moreover, our understanding of the interactions and feedbacks between climate change and associated changes in ocean properties (e.g., ocean acidification) and marine biota remains so rudimentary that we are unable to confidently predict whether the biological carbon pump will increase or decrease in magnitude in response to the current anthropogenic perturbations in atmospheric CO_2.

We propose the initiation of a sustained, coordinated observation program to quantify critical biogeochemical fluxes and biological processes in key oceanic regions that span a broad geographic and latitudinal range, and encompass representative oceanic biomes and nutrient regimes by deploying arrays of advanced autonomous instrumentation. This observation program will profit from emerging technologies for observing ecosystem dynamics and constraining biogeochemical fluxes, and take advantage of recent advances in molecular biology and biogeochemistry in order to derive unprecedented insights into the underlying biogeochemical processes involved. In addition to providing constraints on key aspects of the oceanic biological pump, the observation program will provide a foundation for examination of a wide range of biogeochemical and ecological processes.

Another major objective of the GBF-OOI program is the provision of fundamental data and unique samples to the international ocean research and education community. Observational data and associated samples will be distributed to the community during the tenure of OOI-GBF following general OOI data/sample distribution policies.

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Forward

The Ocean Observatories Initiative (OOI) and other major international programs utilizing new ocean observing technologies are poised to revolutionize the way in which we explore the oceans and examine their role in the larger Earth system. Sustained, comprehensive, and in many cases, real-time observations emanating from these programs will provide unprecedented new insights into ocean processes over a range of spatial and temporal scales. A major overarching emphasis of the OOI is to assess the ocean's role in climate, and this question is being addressed within the coastal, regional and global components of OOI. The infrastructure that is currently planned for these sites will allow detailed characterization of underlying processes.

The Global OOI will also provide important insights into the exchange of carbon between the ocean and the atmosphere – a central issue in understanding controls on the Earth's climate system. However, there is a major void in this observation program with respect to two crucial aspects of the ocean's role in the global carbon cycle – the fixation of CO_2 by primary productivity in the surface ocean, and the removal of carbon to deep waters via the so-called "biological pump". Our understanding of these processes is sufficiently limited that we are presently unable to predict the future health of marine ecosystems in the face of a changing ocean environment, or how the biological pump will respond to, or participates in the changing boundary conditions of the Earth's climate.

The OOI infrastructure provides an extraordinary opportunity to implement a parallel, sustained biological and biogeochemical observation program to characterize two of the most poorly constrained and complex components of the Earth system - the primary productivity and the oceanic biological pump. The objective of this "White Paper" is to identify key elements to this Global Biogeochemical Flux (GBF) program, outline core observation and measurement strategies, highlight technological advances that will allow these objectives to be realized, and to stimulate interest and discussion amongst the ocean research community.

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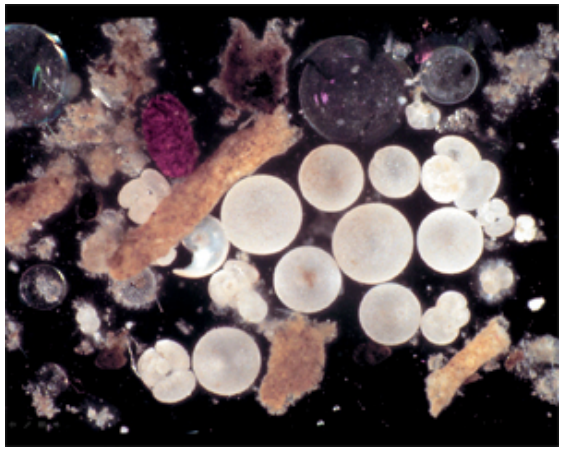

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Rationale: Current Knowledge and Motivation

The difference between export production (EP), the organic carbon export from the euphotic zone, and the flux of POC arriving at the top of bathypelagic zone (~ 1.5 to 2 km) corresponds to the amount of POC that is remineralized to dissolved inorganic carbon (DIC) or transformed to dissolved organic carbon (DOC) during its descent through the mesopelagic zone (Honjo, 2008). Globally, this difference between POC flux at the mesopelagic/bathypelagic boundary and EP indicates the total ?CO_2 that is stored in the world ocean. This corresponds to the ultimate impact of the oceanic biological pump and represents a critical component of the global carbon cycle. Based on our current rudimentary understanding of the biological pump, its capacity is estimated at 411 teramolC y^{-1}.

Greater than 90% of the POC flux is typically mineralized in mesopelagic waters. However, variability in flux attenuation is large, and caused by the extremely complex interplay between biological, biogeochemical and physical processes. POC mineralization stems from community metabolism of zooplankton and bacteria/archaea during its transit through mesopelagic zone. However, it is generally understood that zooplankton activity ceases between 1.5 to 2 km, whereupon ballasted POC settles toward the sea floor exclusively via gravitational forces ("terminal gravitational transport", Honjo et al., 2008) while attenuation of POC flux by microbial metabolism persists.

Our understanding of the rate of POC attenuation in the bottom boundary layer, as well as the lateral supply of POC within intermediate and bottom nepheloid layers, and associated changes in quality and quantity of organic matter, remains poor. Moreover, production of POC from DOC and DIC via deep-ocean microbial heterotrophy and autotrophy, respectively, may further complicate the picture. Attenuation and modification of POC flux continues upon arrival at the sea floor, mediated by diverse benthic organisms.

These complex processes must be characterized in order constrain the global burial rate of carbon and other biogenic/lithogenic elements. Despite the critical importance of constraining the overall gradient in POC flux throughout the world's oceans, remarkable uncertainty persists in these assessments due the complex, heterogeneous, and diverse processes involved.

To take the next major step forward in advancing our understanding of the oceanic biological pump, a global observation program is required that: (*i*) greatly improves constraints on global marine primary production (PP) as this represents a critical factor in understanding the global CO_2 cycle and is essential for developing accurate estimates of EP - the source of the biological pump; (*ii*) explores the spatiotemporal links between PP, EP, and the biogeochemistry of the oceanic interior, and the processes that attenuate POC flux; (*iii*) characterizes microbial community structure and dynamics both in the surface and deep ocean; (*iv*) develops a comprehensive picture of processes that take place from the surface ocean to the sea floor; (*v*) provides unique time-series samples for detailed laboratory-based chemical and biological characterization and tracer studies that will enable connections to be made to the operation of the biological pump in the geologic past.

The overarching goal is to provide high quality biological and biogeochemical observational data for the entire OOI research community. We believe the above-mentioned information will greatly advance our understanding of, and ability to characterize the oceanic biological pump, and will also satisfy a pressing need for fundamental studies of biological, biochemical and biogeochemical processes throughout the oceanic water column.

The US Joint Global Ocean Flux Study (JGOFS), which took place between 1989 and 1999 and was supported by the National Science Foundation (NSF), yielded critical new insights into the ocean's role in the global carbon cycle. This international program made unprecedented contributions to ocean science, and in particular helped establish "biogeochemistry" as a major genre of ocean and earth science. The program led not only to conceptual advances in our understanding of oceanic processes, but also to technological innovations in electro-mechanics, robotics and fluidics, enabling entirely new observations.

Currents global estimates of the attenuation of POC with depth incorporate critical uncertainties in (a) EP derived from modeled PP and POC export, (b) the global POC export flux to the deep ocean, and (c) the provenance and mode(s) of supply of POC to the deep ocean, as well as the processes acting upon this material. A second major knowledge gap concerns the biological community structure, both in surface waters and throughout the oceanic water column, and how this influences the efficacy of the biological pump, and its variation in response to climate forcing.

We suggest that the above uncertainties and information gaps can be greatly reduced through implementation of a concerted biogeochemical observation program aligned with the Global OOI. Specifically, more accurate and precise measurements of EP are possible by improving constraints on PP and by acquisition of synoptic measurements of fluxes and particle properties within the mesopelagic (Buesseler et al., 2007) and bathypelagic zones, and near the sea floor. Coupled with parallel observations of biological community variability, this program will greatly improve both our understanding of the overall controls on the biological pump, and our ability to predict how it may respond in the future.

The above measurements are now within reach using a combination of existing and nascent mooring, time-series observation, and autonomous sampling technologies. Specifically, the deployment of several different types of time-series underwater instrumentation will provide crucial information on surface ocean primary production, the processes associated with export and remineralization of biogenic materials from the euphotic zone and to the deep ocean, and the flux and nature of materials settling to the ocean interior.

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Principal Elements of the GBF-OOI program

We envision array clusters comprised of 20 or more instruments on 4 dedicated, interacting biogeochemical flux moorings (Moorings A to D) located adjacent to each of the Global OOI mooring arrays. These moorings would be serviced on the same annual cruises to the Global OOI study sites. Each mooring is designed to serve a unique purpose, but could also be modified to accommodate a range of ancillary instrumentation in support of diverse biogeochemical studies. Below, we elaborate on the core suite of GBF-OOI instruments and data format and delivery status expected from each annual deployment. We demonstrate the feasibility of the proposed instrument configurations and illustrate the information they will provide in the following sections. We emphasize that such technologies are evolving rapidly, emphasizing that capabilities will likely be even greater by the time that the Global OOI array is fully commissioned.

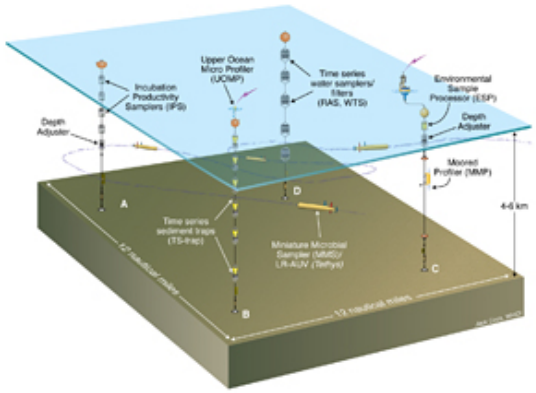

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Fig. 2. A 3D illustration of proposed GBF-OOI array, which consists of 4 moorings. Objectives, capabilities and technology of each mooring are detailed in section 3 and 4 of this white paper. MBARI's high endurance ROV Tethys with miniature microbial sampler has not been tested as of yet.

1. Accurate assessment of oceanic primary production
2. Constraining export fluxes of POC and other particulate material
3. Sustained observations of surface ocean microbial community structure

4. Provision of time-series water and suspended particle samples for biogeochemical tracer studies
5. Other potential components of the GBF-OOI
   a. Observation of biological and biogeochemical processes in the Mesopelagic Zone
   b. Sustained observations of biogeochemical processes occurring at or near the sea floor

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1. Accurate assessment of oceanic primary production

Quantifying global ocean primary production (PP) remains a formidable yet pressing challenge for our understanding of the role of the oceans in the Earth's carbon cycle. Constraining global PP is also urgently required in order to assess the capacity of the oceans to feed the rapidly growing human population. Many layers of difficulty confront ocean scientists seeking to derive an accurate global assessment of oceanic PP. We believe these hurdles can be surmounted, and that this scientific goal can be reached in the coming decade through the coupling of novel technologies for quantification of in situ PP with broader scale information on ocean productivity from remote sensing. Specifically, the combination of a novel autonomous time-series incubation device (here termed "Incubation Productivity System", IPS) (indices of technical abbreviations are available in Table 1) (Fig. 3) with *in situ* operating Rapid Repetition Rate fluorometers (FRR; Kolber et al., 1993) for tracer incubation and fluorometric assessment of net and gross primary production, which if deployed throughout the entire euphotic zone, would yield high-temporal resolution and depth-integrated assessments of primary productivity at the key ocean stations targeted by the Global OOI, (and potentially also at other ocean observation sites). Combining this contextual observational data with improved ocean color observation and modeling efforts (Werdell, 2009) would enable construction of robust model-based estimates of PP for the global ocean.

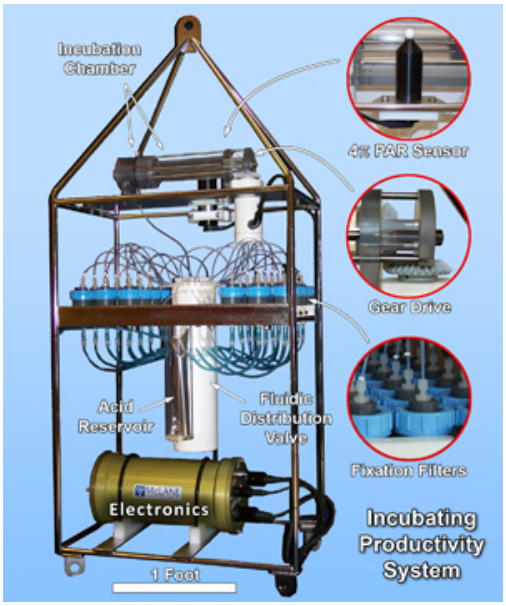

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Fig. 3. Photograph of a prototype of the incubating productive system (IPS).

Major improvements in the accuracy of EP are possible by coupling improved constraints on PP with increasing the intensity and frequency of flux and particulate measurements in the mesopelagic zone and by acquiring spatially comprehensive, synoptic measurements of organic carbon fluxes to, and through, the mesopelagic and bathypelagic ocean. Coupled with parallel observations of biological community variability, this will greatly improve both our understanding of the overall controls on the biological pump, and our ability to predict how it may respond in the future.

Related Files

Table 1: Abbreviations of GBF-OOI Major Instruments

Abbreviation	Full name	Objective	Mooring
ADA	Autonomous Depth Adjuster	Instruments depth adjustment	A, C
AMS	Automated Microbial Sampler	Discrete microbe, DNA collector	D
DOM	Advanced Deep Ocean Mooring	Support instruments	A, B, C, D
ESP	Environmental Sample Processor	In situ genomics assay	C
EM-Hose	Super-stretchable EOM EM-Hose	Stable deployment of ESP	C
EMP	Euphotic Micro Profiler	Daily profiling between 0-200 m	A
IPS	Incubation Productivity Sampler	Primary production incubation	A
LSB	Large-mass Steel Buoy	Large Steel Mass Flotation	C
MG-Buoy	MicroGrid power genetating Buoy	Power generators, sat. transmission,	C
MMP	Multi-purpose Moored Profiler	Deep water profiler, wire crawler	A
RAS	Remote Access Sampler	Time-series water sample caster	D
SFF	Larger Syntactic Form Flotation	Large Syntactic Form Flotation	A, B, D
TS-trap	Time-series sediment trap	Export flux measurement, programable	B
WTS	Water Transfer System	In situ suspended particle filtration	D

» Table 1

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An IPS system has been developed which enables time-series, *in situ* assessments of biological productivity via incubations with C, N and O stable isotopic labels (Taylor et al., 2010; in preparation) and that can be pre-programmed to operate at specific time intervals or triggered by independent sensor commands (e.g., in response to an increase in productivity as detected from satellite imagery). The IPS is currently capable of performing 48 discrete incubations during 12 months of unattended deployment. FRR fluorometers (commercial version, Chelsea Instruments) and a lower power, long term, mooring compatible version in development (Z. Kolber) can provide intercalibrated estimates of phytoplankton physiological state and primary production on a high resolution temporal basis.

Deployment of a vertical array of several synchronized IPS & FRR systems for up to one year, would provide depth-integrated, temporally-resolved assessments of epipelagic zone productivity every 15-days (incubation) or significantly less (FRR) spanning an annual cycle (Mooring A). Utilizing multi-isotopic tracers and the same time-course sampling technology, the IPS can also provide information on production rates of particulate inorganic carbon, PIC (i.e., $CaCO_3$ in coccolithophorids) and particulate silica, PSi (SiO_2 in diatom frustules). This information will be invaluable for investigating ocean alkalinity, acidification, and for assessment of the ballasting role of different inorganic phases in relation to the biological pump. A second development that is crucial for *in situ* measurements of surface ocean biological productivity, and for establishing links between field data and satellite-based ocean color observations, are mooring capabilities for precise deployment of instrumentation within the euphotic layer. New electro-mechanic technology (Automatic Depth Adjuster; ADA) is near completion that precisely (± 0.5 m) maintains instruments such as the IPS within 15 m of the ocean surface.

Kolber, Z. S., Prasil, O. and Falkowski, P. G. (1998) Measurements ofvariable chlorophyll fluorescenceusing fast repetition rate techniques: defining methodology and experimental protocols. Biochim. Biophys. Acta, 1367, 88–106.

Werdell, P. J., 2009. Global bio-optical algorithms for ocean color satellite applications. EOS Transactions AGU, 90,

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2. Constraining export fluxes of POC and other particulate material

The US Joint Global Ocean Flux Study (JGOFS), initiated in 1989 and supported by the National Science Foundation (NSF), established a critical research program to understand the global cycles of CO_2 and POC in the ocean. During the 15-years of this program and its international counterparts, unprecedented contributions were made to ocean science, and in particular to our understanding of the biogeochemistry of the oceans. This program not only led to conceptual advances, but also catalyzed technological innovations that yielded previously unattainable observational data. The latter included ocean mooring construction and instrumentation design (Fig. 5).

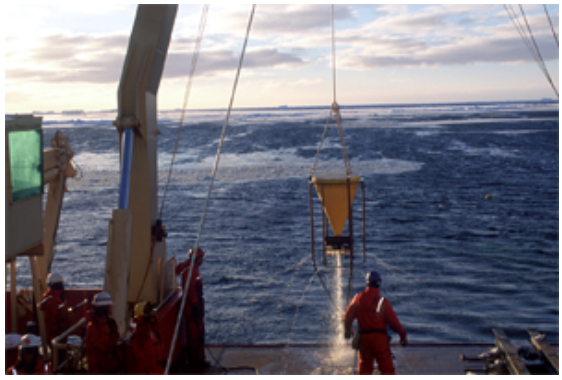

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Fig. 5. Recovery of a TS-trap from ice-floe filled Ross Sea, Soutern Ocean by the JGOFS mooring team from Oregon State University.

Estimates of the attenuation of POC with depth however, include critical uncertainties in estimates for EP derived from modeled PP and POC export, sparse observations of global POC export flux measured in the deep ocean, and a lack of constraints on the provenance and mode of supply of POC entering the deep ocean as well as the processes acting upon this material. A second major knowledge gap is with respect to the biological community structure, in surface waters and throughout the oceanic water column, how this varies in response to climate forcing, and in turn how this influences the efficacy of the biological pump. Understanding the role of the zooplankton community on ocean biogeochemistry remains a particularly important objective.

One of the results of JGOFS (Fig. 5) has been the derivation of a total global export flux of POC through the base of the mesopelagic zone (~ 1.5 - 2 km) that is estimated as 36.2 ± 4.5 teramolC yr^{-1} based on results from 134 globally distributed TS-trap experiments between 1983 to 2007 undertaken by international ocean scientists (i.e. Honjo, et al., 2008). Estimates for the global export flux of $CaCO_3$ (Particulate Inorganic Carbon; PIC) that are derived mostly from coccolithophorids, (Fig. 6), planktonic foraminifera tests and pteropod shells, and biogenic SiO_2 (mostly diatom frustules, Fig. 7), radiolarian and silicoflagellate skeletons are similar, 33.8 ± 3.8 teramolCa yr^{-1} and 34.4 ± 2.6 teramolSi yr^{-1}, respectively. It was also found that there are distinct oceanic regions where the mol-ratio of the biogenic Si to PIC is >1, (north and south of the North Pacific Polar Front and the Antarctic Polar Front, respectively); whereas in other ocean areas this ratio is <1 (Fig. 8). Such observations are of critical importance for determining the factors influencing the attenuation in POC fluxes through the ocean water column, and for understanding the ocean's role in global geochemical cycles. They also shed light on seasonal variations in particle export within and between different oceanic regimes, and provide important context for interpreting down-core variations in oceanographic proxies recorded in underlying sediments.

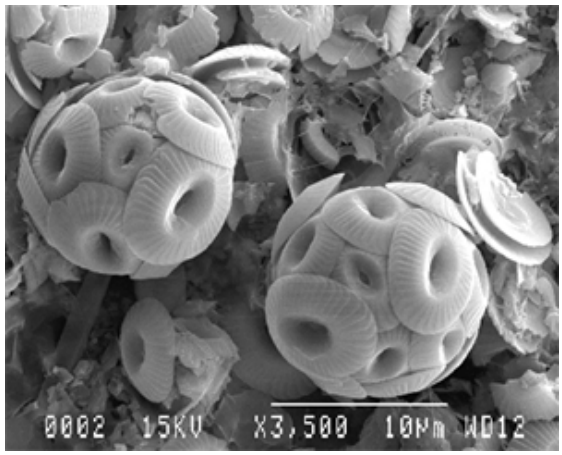

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Fig. 6. *Coccolithus pelagicus* in laboratory cuture.

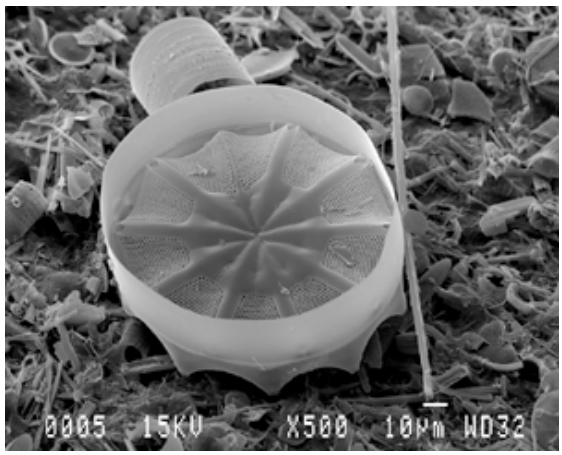

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Fig. 7. A frustule of a large *Asterolampra* diatom.

The depth and duration of TS-trap deployment in these prior studies was optimized in order to address specific questions and processes. Consequently, the resulting measurements were rarely synchronized in time, limited in spatial coverage, and with few exceptions, did not allow for examination of interannual variability in particle export. Thus, although these deep-ocean TS-trap experiments yielded highly valuable insights into the nature of the biological pump in different ocean regions, we are still far from arriving at a well-constrained global estimate for the flux of POC and other biogenic components to the bathypelagic zone/ocean floor.

For the duration of the OOI, at each site we propose deployment of six TS-traps (Fig. 9) with 24-periods at five key depths (Mooring B): two TS-traps at 500 m and 1000 m, within the mesopelagic zone (special traps may be added for the "twilight zone" experiments; Buesseler et al., 2007); a pair of TS-traps set 50 m apart in the upper bathypelagic zone (2000 m) where particles settle as a consequence of "terminal gravitational transport"

(Honjo et al., 2008) in order to derive high-temporal resolution (~ weekly) flux information (48 samples per deployment); a TS-trap within the bathypelagic zone (3000m), and a TS-trap within the benthic boundary layer (~ 100 mab). The settling particles intercepted by the TS-traps are amenable to detailed investigation using a broad suite of biogeochemical tracers in order to eludicate carbon sources and oceanic sedimentation processes.

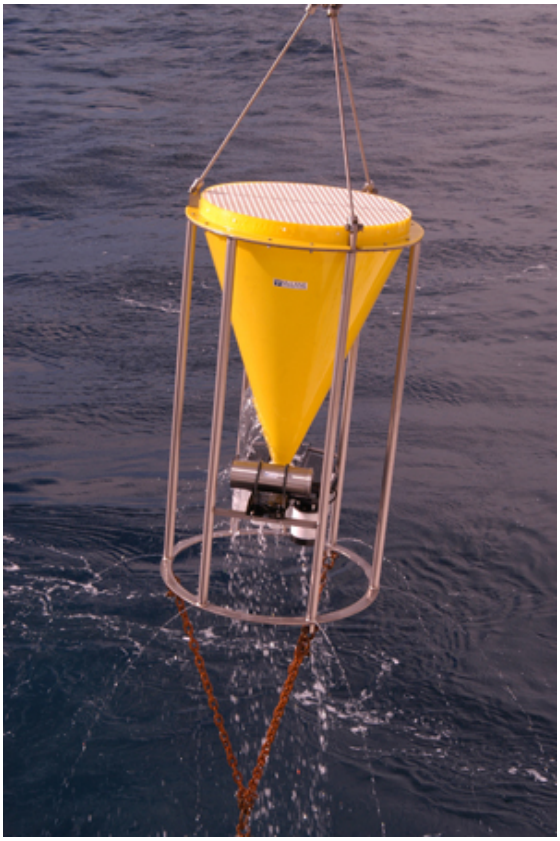

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Fig. 9. A TS-trap is made exclusively of innert palstic material and titanium in order to avoid contamination of samples during long term deployements in ocean environments.

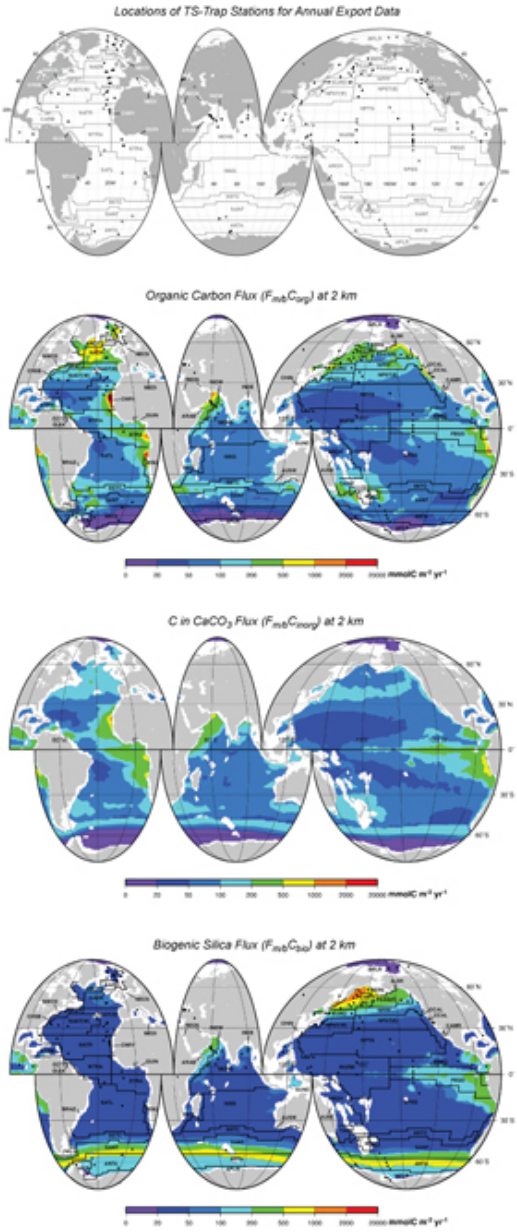

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Fig. 8. An outcome of the global JGOFS experiment: Distribution of POC, PIC and Biogenic Si (in mmolC m^{-2} yr^{-1}) parameterized from TS-traps deployed for a year from 134 stations (uppermost figure) during the period of 1983 to early 2000 (Honjo et al., 2008).

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3. Sustained observations of surface ocean microbial community structure

Innovations in molecular biology, and advances in the application of the ”omics” (e.g. genomics, transcriptomics, proteomics) are continuing at an extraordinary pace, and catalyzing breakthroughs in marine microbial biogeochemistry (Scholin et al., 2009). Our appreciation of the enormous influence of microbial community structure on the biological pump and associated biogeochemical processes has grown tremendously with the advent and increasing application of cultivation-independent molecular biological methods.

For example, the widespread occurrence and high abundance of Archaea in the oceanic water column was only recognized within the last two decades, and their metabolism and role in carbon and nutrient cycling are only now beginning to be understood. The role of viruses in the termination of plankton blooms is garnering increasing attention. It is clear that much greater emphasis should be devoted to assessing the influence of these and other microorganisms on the oceanic biological pump and related biogeochemical processes (Fig. 12).

In the laboratory, proteomic investigations on *Emiliania huxleyi* - the single most important photoautotroph controlling global ocean alkalinity, and a major source of ballast material to drive biological pump - are now opening up the opportunity to unravel the molecular mechanisms controlling *in vivo* calcification and their response to environmental forcing (Jones et al., submitted) (Fig.6). The availability of powerful and fast sequencing techniques and genomic protocols now makes it possible to monitor the changes undergone by organisms as they adapt to, for example, increasing temperature and pCO_2.

Extending genomic, transcriptomic and proteomic analysis to include ocean biomes is essential to understanding the living catalysts of the carbon cycle in the world ocean (e.g. Nowler et al, 2009; Delong et al., 2009). Such observations of microbial community structure, coupled with assessments of biological productivity are crucial if we are to develop a comprehensive understanding of the oceanic biological pump, and thus of pivotal importance to the OOI-GBF program. Emerging field-deployable devices that provide autonomous molecular biological assays offer new opportunities for assessing microbial community structure and function *in situ*, and in near real-time. In this context the Environmental Sample Processor, ESP, (Scholin et al., 2009), which utilizes new robotics and micro fluidics technology, represents a critically important emerging technology for ocean science (Fig. 11 & movie). Using an ESP in a moored configuration, Scholin et al. (2009) have demonstrated the feasibility of this concept by showing that changes in microbial community structure, abundance of functional genes and cell metabolites can be determined remotely (Fig. 13).

We propose the deployment of an autonomous genomic sensor on a highly engineered mooring (Mooring C) that enables placement within the euphotic zone (20 m) for long duration, yielding TS-data which is complementary near-simultaneous to that derived from the IPS instrumentation.

This class of autonomous molecular biological sensors is maturing rapidly and will be both more powerful and widely available in the coming years. Coupled with chemical, physical and other biological information provided by OOI-GBF “core-measurements”, it will be possible to ascertain roles specific members of the microbial community play in biogeochemical cycling on a temporal scale in ways not possible previously (e.g., Bowler et al. 2009), and for locations that are inaccessible for much of the year. Examples include quantification of genes and gene products associated with carbon, nitrogen and phosphorus cycling to name but a few, as well as detection and quantification of specific taxa such as coccolithophorids

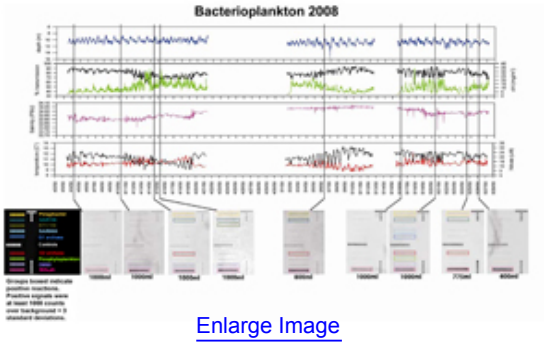

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Fig. 12. Example illustrating use of the ESP to detect groups of marine bacterioplankton in Monterey Bay spring, 2008.

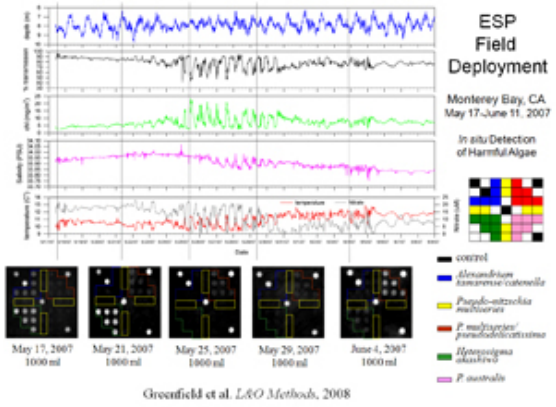

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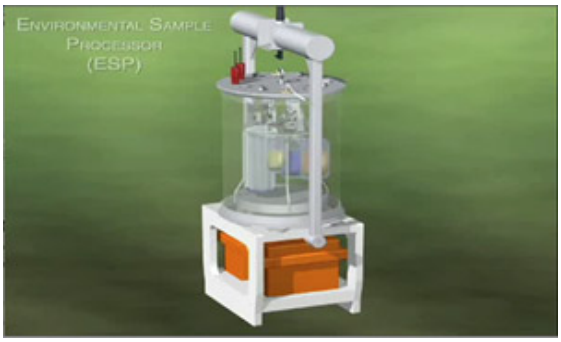
Fig. 13. An ESP assay in Monterey Bay, summer, 2007 on invertebrates and harmful algal toxin (domoic acid). For detail, see Fig. 11, *Oceanography* p. 162.

Enlarge Image

Fig. 11. The Environmental Sample Processor (ESP) is a device developed by MBARI that allows for autonomous, time-series sample acquisition, *in situ* application of DNA, RNA and protein probe arrays, and transmission of assay results in semi-real time. The linked Oceanography article (Scholin et al., 2009) summarizes the function, application and future development of this now commercially available ESP technology.

and diatoms that carry on the majority of POC and PIC productivity and provide ballast material for the oceanic biological pump. In addition to improving our understanding of the biological pump, sustained observations of microbial ecosystems are crucial for assessing responses to changing atmospheric and surface ocean carbon inventories.



Movie: Environmental Sample Processor (ESP)
Animation demonstrating the electro-mechanics and micro-fluvial movements of ESP through; 1.sample collection, 2.moving a sample pack to reaction, 3.taking photomicrograph of assay pattern, 4.scan-digitize the image for transmission. (Courtesy of Dr. Chris Scholin and MBARI)
» View Video (Quicktime)

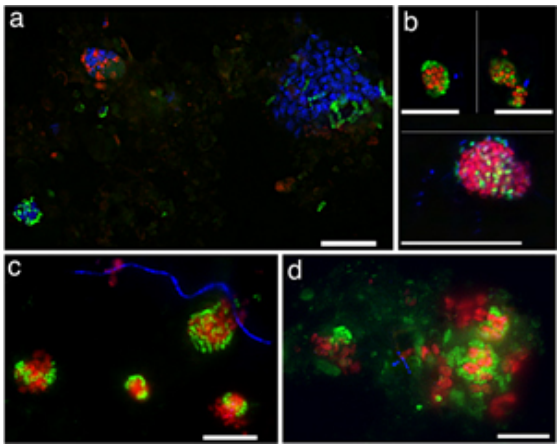


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Fig. 20. Fluorescence in situ hybridization (CARD-FISH) of Eel River Basin sediment. (a and b) Shown are oligonucleotide probes targeting archaeal ANME-2c (ANME2c_760, blue), Desulfosarcina (DSS_225, green), and Desulfobulbaceae (DBB_660, red) (a) and ANME-2 archaea (Eel_932, red), Desulfobacteriaceae (DSS_658, green), and Betaproteobacteria (Bet_42a, blue) (b Lower). Collage of two pictures. (b Upper) ANME-2 archaea (Eel_932, red) and Betaproteobacteria (Bet_42a, green) and a general DNA stain (DAPI, blue). (c and d) ANME-2 (Eel_932, red), Desulfobacteriaceae (DSS_658, green), and Alphaproteobacteria (Alpha_986, blue). (Scale bars, 10 ?m.)

(DeLong, E.F., Taylor. L. T., March, T.L. and Preston, C. M. 1999)

GBF-OOI

4. Provision of time-series water and suspended particle samples for biogeochemical tracer studies

Although the ability to undertake autonomous observations of biological and biogeochemical processes is continually improving, many crucial measurements require return of samples to the laboratory for in-depth characterization. However, marine science has been lacking technology to collect/preserve significant volume of discrete water and filtered suspended samples (*in situ*), in time and space. Ship-based sampling throughout the water column at open-ocean stations is impractical, and at best “snap shots” can be obtained using this approach. The combination of a time-series remote-access sampler (RAS) and water transfer system (WTS) (TS-RAS-WTS combined) fulfills this requirement . Discrete water samples, typically 500 ml, can be preserved with dissolved gas. The *in situ* pump can be configured to filter particulate matter from 10 liters of water with constant pressure, while maintaining preservative solution if necessary (Fig. 15). Discrete water samples can also be recovered using a modified RAS for microbial and DNA analysis (Automated Microbial Sampler; AMS; Fig. 17). We propose to deploy a mooring with time-series water and particle collectors in depth-series as a critical component of GBF-OOI program. (Mooring D).

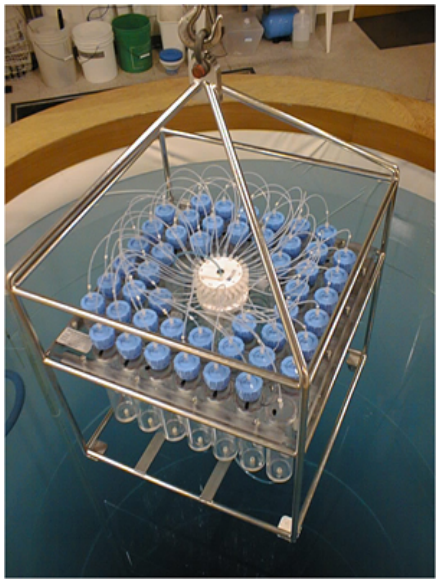

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Fig. 15. **a**: Water Transfer System (WTS) for time-series filter collection of particulate matter from up to 10 L of water that collected in aluminum foil/Tedlar bags to prevent loss of gaseous sample.

Enlarge Image

15b. RAS for time series collection of 500 ml whole water samples (or filtrates) with/without preservative.

This availability of water (dissolved) and particle samples (suspended particles) opens the door for the application of a broad range of geochemical and biogeochemical tracers and probes for characterization of the biological pump. New tracers have emerged that can provide constraints on both the proportion and provenance of materials supplied to intermediate or near-bottom depths, as well as to define overall contributions to the sinking flux. When coupled with the extensive hydrographic information available from adjacent OOI instrumented platforms, these tracers will yield a detailed picture of inputs and transport dynamics of biogenic and lithogenic materials, leading to refined estimates of carbon export at the study sites. For example, natural abundance radiocarbon measurements have proven to be a sensitive and effective means to quantitatively assess contributions of fresh and aged POC and DOC. Associated inorganic tracers (e.g., Al content, Nd isotopes) can provide complementary information on the abundance and provenance of lithogenic particles, and uranium-series radionuclides can place additional constraints on laterally- versus vertically-transported particles. Establishing the horizontal and vertical flux and character of carbon and other components is crucial for accurate parameterization of global models of the oceanic carbon cycle, as well as for paleoceanographic interpretation of underlying sedimentary records.

At a molecular level, specific organic compounds serve as effective tracers of biological source, and extent of organic matter transformation. The former, which primarily utilize lipids as marker molecules, span all three domains of life. Although less phylogenetically diagnostic than genomic markers (DNA), their structures retain a high degree of biological specificity, and have the benefit of persisting despite the overall attenuation in flux. As such, their signature can be traced from the precursor organism, through the water column, and into the underlying sedimentary. Moreover, the isotopic signatures carried by these molecules can provide a further layer of information, particularly regarding the environmental conditions experienced by the precursor organism during growth. The modified version of RAS, can also be used to collect and preserve discrete samples for DNA research (Automated Microbial Sampler, (Fig. 16, 17) enabling genomic studies on deep-ocean microbial populations .

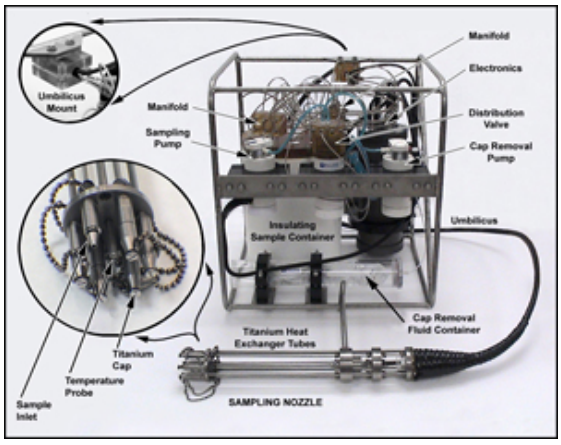

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Fig. 17. The Automated Microbial Sampler (AMS) is capable of obtaining discrete filtered microbial (e.g., phytoplankton, bacteria) samples via flow-through filter units and a sample preservation circuit that supplies chemical preservative to the filtered samples immediately following sampling.

5. Other potential components of the GBF-OOI

The elements of the GBF-OOI outlined in the preceding sections are designed to provide key information that we consider crucial for defining the characteristics of the biological pump, including its magnitude and variability. The array of moorings and instrumentation would both provide direct access to various lines of information in quasi-real time, enable *in situ* experiments to be performed, as well as to recover water and particle samples for return to the laboratory and detailed biogeochemical studies. It is envisioned that the GBF-OOI infrastructure would provide a template for other important biological and biogeochemical observation platforms and experiments, including detailed investigations of processes in the epipelagic, mesopelagic and bathypelagic zones, as well as at the sea floor. Sensor technology is evolving rapidly, and it is anticipated that an array of optical, physico-chemical, biochemical and acoustic instruments would be capable of providing complementary information to that described above. The following sections highlight two areas that clearly warrant increased attention and are poised for technological advances.

a. Observation of biological and biogeochemical processes in the Mesopelagic Zone
b. Sustained observations of biogeochemical processes occurring at or near the sea floor

GBF-OOI

a. Observation of biological and biogeochemical processes in the Mesopelagic Zone

The largest gradients in POC flux as well as bacterial and zooplankton abundance and activity in the oceanic water column occurs in the mesopelagic zone, yet this is also the layer where there are presently only sparse measurements. The limited available data suggest that seasonal variations in export efficiency and POC flux attenuation within this 'twilight zone' may be as large as regional variability (Buesseler and Boyd, 2009). Time-series measurements within this zone and at each location will be important to constrain the overall flux attenuation and the underlying processes responsible for this attenuation. This can be achieved through TS measurements of fluxes (TS cylindrical traps), and of particle abundances and properties (profiling optical particle/plankton recorders), from the base of the euphotic zone to the base of the mesopelagic zone (Mooring B or Mooring C). The traps provide both quantitative flux information, and can be used to characterize particle sources as well as their size and abundance by parallel collection in polyacrylamide gels (e.g., Waite and Nodder, 2001). Great strides have been made in measuring POC abundances and size using optical systems. For example, the Villefranche UVP profiling camera system deployed on CTDs can rapidly capture both the size spectrum of detrital and biogenic particles, as well as zooplankton abundances (Guidi et al., 2009). Variations on this type of device are currently under development for deployment on moored profilers (MMP; Fig. 18) and autonomous underwater vehicles (AUV).

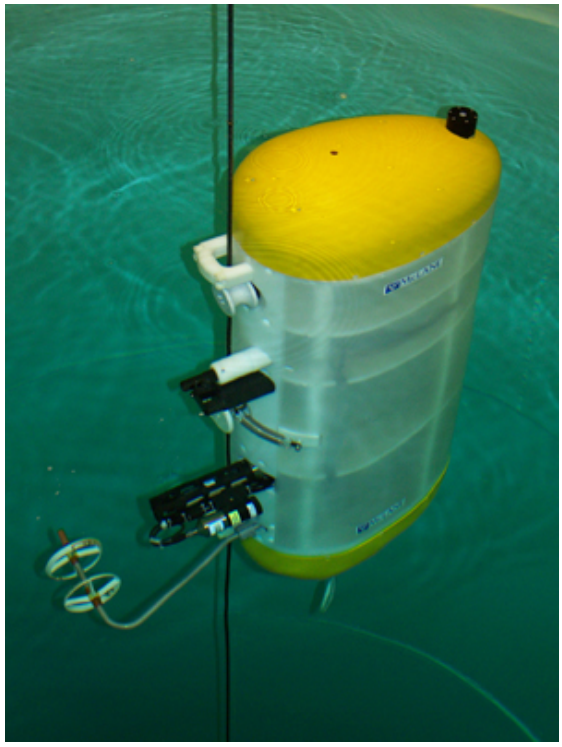

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Fig. 18. Updated wire-crawling moored profiler (MMP) equipped with a new high precision currrent sensor MARV (lower left).

The zooplankton community is considered to be a key factor in the biological pump. Their influence includes attenuating flux, repackaging of particles, or directly facilitating transport of fresh POC and DOC from the euphotic to the mesopelagic zones via diel and seasonal zooplankton migration. Together with the microbial community, zooplankton are the major contributors to remineralization of POC to TCO_2. Conversely, zooplankton mortality by bacterial or and viral attack contributes to POC export. The *in situ* dissolution of the aragonite shells of pteropods within the mesopelagic zone may also be important in terms of export of alkalinity and PIC biogeochemistry. While the exact processes and rates of zooplankton migration are still the subject of debate, there is a consensus that the grazing influence of migrating and non-migrating zooplankton can extends to 1.5 to 2 km depth, beyond which terminal gravitation transport takes over. It is vital that we obtain a greater understanding of this transition between biological and gravitational influences on POC cycling at the meso/bathypelagic boundary.

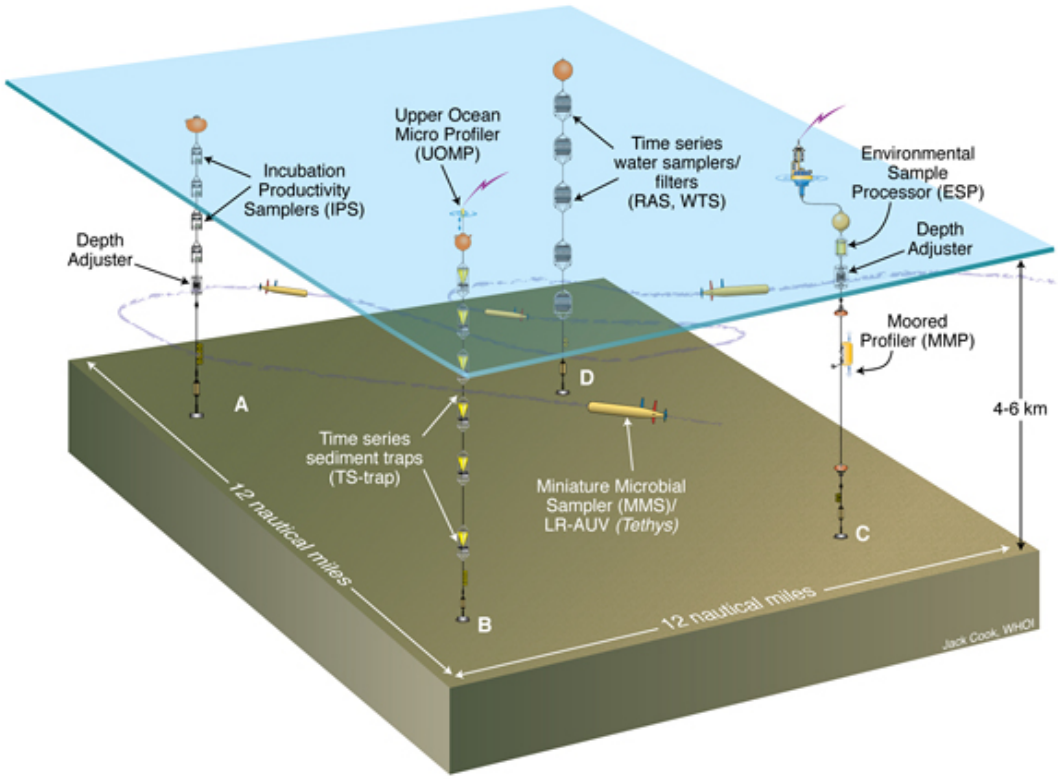
Future development and integration of plankton video-recorder (PVR) technologies (Benfield et al., 2007) with a power-enhanced, wire-crawling moored profiler vehicles (e.g., Mooring C) would realize this goal, particularly if these systems were partnered with automated zooplankton collector (ZPC) devices deployed at specific depths within the mesopelagic zone. Zooplankton collected by a ZPC can be preserved without mechanical damage, therefore and in a condition amenable to molecular biological investigation. Overall, the GBF-OOI moorings would, for the first time, provide a platform for sustained TS-observations of particle abundances and fluxes in the mesopelagic zone, and as well as information on the biological and biogeochemical processes that control export efficiencies.

Waite, A. and S. D. Nodder. 2001. The effect of in situ iron addition on the sinking rates and export flux of Southern Ocean diatoms. Deep-Sea Res. I, 48(11-12), 2635-2654.

GBF-OOI

Mooring and Instrument Technology

Crucial to the realization of the GBF-OOI is the development of reliable mooring systems capable of precise and controlled placement of sophisticated biogeochemical sensors, experimental systems and sampling devices at a wide range of depths, including in close proximity to the sea surface. Some of these moorings require significant electrical power and must be capable of transmission of instructions and data. Moreover, in order to be compatible with Global OOI field program, the endurance of the moorings and instrumentation must be at least 12 months so they can be serviced during the annual cruises to each location. These moorings would be maintained and subject to constant improvement and expansion for the duration of the OOI program, potentially as long as 25 years - a time-span that will enable detailed characterization of intra-annual and inter-annual variability in the ocean biological pump. (Table 2)



Mooring A: Primary Productivity Array

Mooring B: Deep Ocean Biogeochemical Flux Array

Mooring C: Oceanic Microbial Genomics Platform

Mooring D: Time-Series Water/Suspended Particle Sampling Array

Mooring design, construction and turn-around

GBF-OOI

b. Sustained observations of biogeochemical processes occurring at or near the sea floor

Given that more than 90% of the POC flux from the upper ocean is mineralized in the mesopelagic zone then the question arises: How important might local sources of deep “new” production be, within the bathypelagic zone, compared to the remaining surface ocean-derived POC flux descending across the mesopelagic/bathypelagic boundary?

Some evidence suggests that deep pelagic Archaea are capable of autotrophic carbon fixation (reference?), and thus represent an additional source of POC. Moreover, it has been estimated that 25 petamolC of organic carbon is associated with the oceanic deep sub-sea floor biosphere (compared, for example, to 47 petamolC estimated to reside in all terrestrial plant matter) (Whitman et al., 1998). Understanding the significance of deep ocean microbial activity on global biogeochemical C cycles requires assessment of the rates of exchange between them. With respect to inputs from the seafloor, two obvious “type-locality” settings would be those associated with active fluid flow from the seafloor – at cold seeps (Hydrate Ridge) and hydrothermal vents (Axial Seamount) that are a focus of study of the Regional Scale Node of the OOI offshore of the Pacific Northwest.

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Mooring A: Primary Productivity Array

Mooring A is a fully submerged, bottom-tethered suspended mooring with no surface expression (Fig. 4, Table 3-A). The unique mooring design enables the position of the uppermost IPS to be maintained at 15 m and others at specified depths in the euphotic zone (tentatively proposed as 30, 50, 80 and 120m). Deployment and precise maintenance of instruments at such shallow depths (15 m ± 0.5 m) for extended time periods on a mooring that extends to, and is tethered at abyssal depths, is not feasible using traditional methods. The essential feature of Mooring A (and Mooring C) is an Automated Depth Adjuster (ADA) located at 150 m that maintains overlying instruments, including the IPS array, precisely at the designated depth. This configuration allows the upper portion of the mooring (supporting the IPS instrumentation) to move horizontally but limit vertical oscillation. An acoustic transponder on the instrument float communicates with a neighboring mooring (Mooring C; Table 3-C) to send the precise depth sensor readings of the float and other operational information of the 15 m IPS.

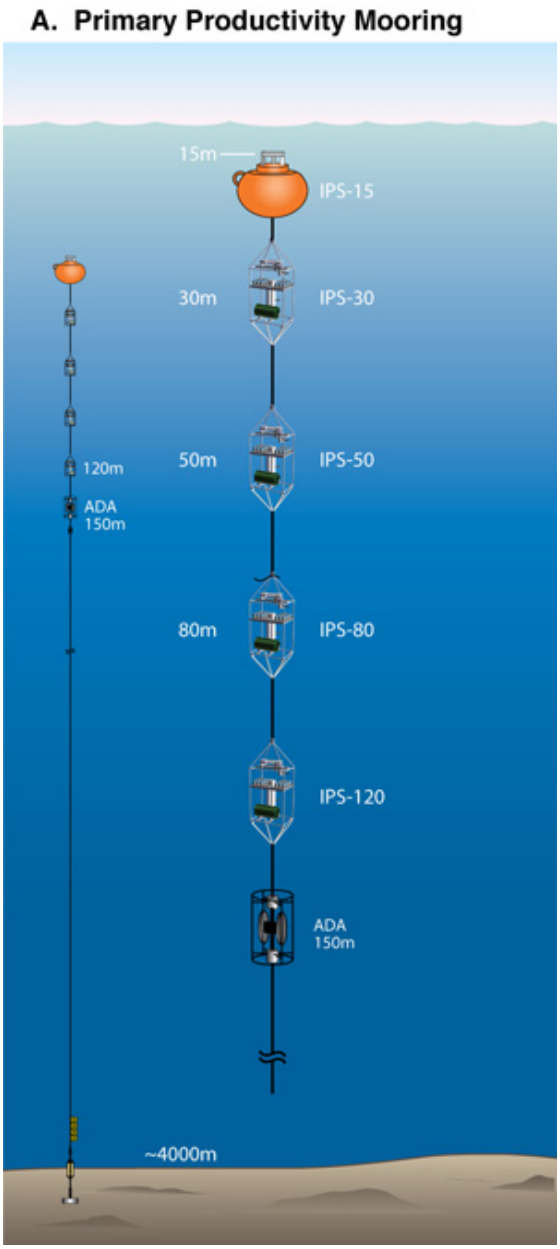
The time-series operation programs of all IPS instruments are precisely synchronized. The primary productivity assessment at 15 m deep is critical for comparison with satellite ocean color imagery, and for building robust algorithms of global primary productivity based on the latter. During the course of the OOI program, it is anticipated that there will be a demand to deploy many new sensors at this depth. In order to accommodate such future demand, the top Syntactic underwater buoy of Mooring A is configured such that it can serve as an *in situ* laboratory. The incubator deployed at 15 m (including an anti-biofouling device and a 4? PAR sensor) is completely exposed to the sunlight at the top the syntactic sphere. The remainder of the 15 m IPS mechanism is secured inside of the Syntactic buoy, protecting it from damage due to wave hit, fish bite, nesting or biofouling. The operation of the 15 m IPS is powered by a large storage battery to allow variety of specific studies such as isotope labeling or *in situ* dissolution experiments. An IPS can be programmed for 48 incubation cycles using ^{13}C, ^{15}N and ^{18}O stable isotope tracers. Other non-radioactive tracers (e.g., Ca and Si isotopes) may also potentially be applied to examine primary productivity of coccolithophores and diatoms.

Related Files

Table 3-A: Primary Production Mooring

Depths	*Instruments*	*Appearances*	*Sample Quantity*
15 m	IPS-15 incubator Syntactic 60" Buoy IPS-15 microfluvial mechanism, Productivity auto-lab, Power storage	4pai exposure housed in the syntactic sphere 100 Ah battery NO2 sensor	48 cycles: each 14C, 14N, 18O; total 144 incubations
30 m	ISP-30	SS weldment	48 cycles total 144 incubations
50 m	ISP-50	SS weldment	48 cycles total 144 incubations
80 m	ISP-80	SS weldment	48 cycles total 144 incubations
120 m	ISP-120	SS weldment	48 cycles total 144 incubations
150 m	**Auto depth adjuster** Electric rock system	SS weldment	
180 m	MMP parking station	rubber tire	
3-4km Stretch	**MMP**	5/16" coated wire	
150 m ab	MMP parking station	rubber tire	
100 m ab	Release		
Ocean Floor	Recoverable Anchor	(weight undecided)	
	Total samples	*At 7 depths*	*240 cycles, 720 incubations*

» Table 3-A
Primary Production, Mooring A.



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Mooring A. Primary productivity mooring showing vertical arrangement of IPS. An Automated Depth Adjuster (ADA) maintains the top of the Syntactic foam float at depths as shallow as 15 m. (See Table).

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Mooring B: Deep Ocean Biogeochemical Flux Array

The Mooring B (Table 3-B) design represents a typical TS-trap array that was successfully utilized during JGOFS (US), HiLat (Japan), and Indo-German Arabian Sea Experiment studies, corresponding to more than 100 deployments each of ~12 months duration. There is extensive experience in advanced mooring design and full-ocean-depth deployments associated with decades of sea-going activities. We propose deployment of 6 TS-traps, each of which would collect settling particles for 24 periods per 12 month deployment. In addition to TS-traps within the mesopelagic and bathypelagic layers, 2 TS-traps are deployed at the mesopelagic/bathypelagic boundary (2000 m) and configured to operate sequentially (yielding higher temporal resolution; with 48 periods) for more detailed examination of the rate of POC export via the terminal gravitational transport. The open-close cycles of all TS-traps will be synchronized with each other as well as with other TS instruments (e.g., IPS, ESP, and RAS) deployed on adjacent moorings.

A unique feature envisioned for Mooring B is the addition of a "Surface Ocean Micro-profiler" (under development). The uppermost buoy (67" diameter, syntactic foam Fig. 19) that provides the major buoyancy of . Mooring B also serves as the launching base for a pressured gas-driven probe with a miniaturized CTD and 4? PAR sensor that operates between 200m and the ocean surface to support the IPS deployment at Mooring A. This probe shuttles through the euphotic layer once a day, and the compressed low-power signals are burst-transmitted to a global communication center on the surface buoy of Mooring C, and relayed from there to shore laboratories.

Related Files

Table 3-B: Export Flux Mooring

Depths	*Instruments*	*Appearances*	*Sample Quantity*	*Transmission*
0 - 200 m	Euphotic Balcon Profiler Micro-CTD Optical pakage Burst transmitter	HP-gas driven surface sensing Micro Buoy	360 shuttles/day	Once/day relayed via C-mooring
200 m	Syntactic 67" Buoy SCP luncher	Inductive gas feeder P-Radar, flush lights		
Twilight Zone	Particle intrecepters			
500 m	TS-trap 500	Titanium weldment Internal camera tiltmeter, compass	24 + 1	
1000 m	TS-trap 1000	Titanium weldment Internal camera tiltmeter, compass	24 + 1	
2000 m	TS-trap 2000 x2 resolution	Titanium weldment Internal camera tiltmeter, compass	48 + 2	
3000 m	TS-trap 2000 x2 resolution	Titanium weldment Internal camera tiltmeter, compass	24 + 1	
200 m ab	TS-trap NL AMS	Titanium weldment Internal camera tiltmeter, compass	24 + 1	
100 m ab	Release			
Ocean Floor	Recoverable Anchor	(weight undecided)		
	Total samples	*at 5-depths*	*144 each 15-days yr.*	

» Table 3-B
Export Flux Mooring Table

B. Export Flux Mooring

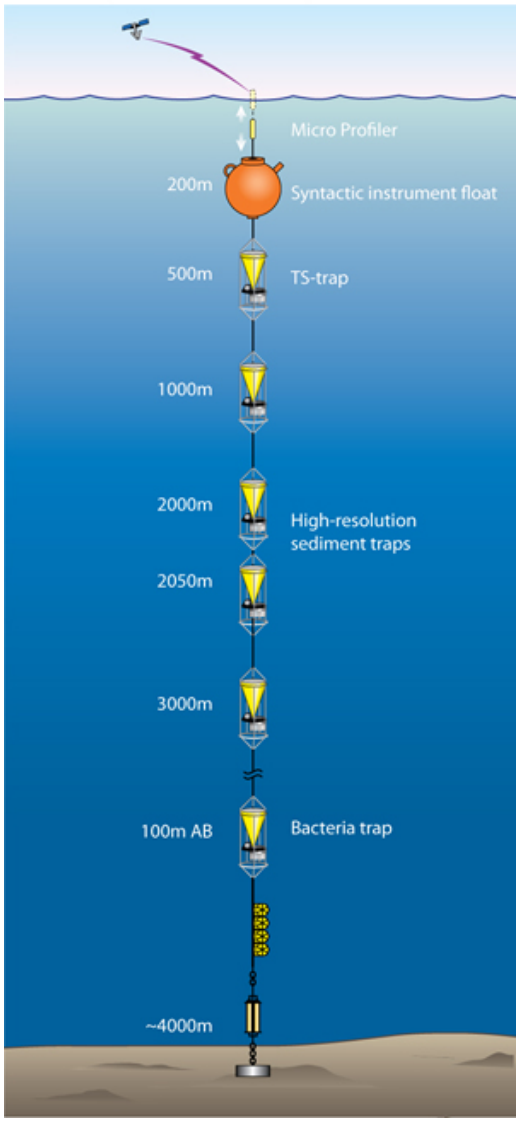

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Fig. 10. **Mooring B**. Export flux mooring showing a syntactic instrument float that houses an epipelagic micro-profiler and supports an array of TS-traps. The deployment configuration in the upper mesopelagic layer is flexible.

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Fig. 19. An example of Syntactic underwater floatation that was just recovered on board R/V *Mirai* in 2004 with the cooperation of WHOI engineers. Instrument wells on Mooring A and B provide fully exposed platform for IPS-15 m (Fig. 4) and a launching/garage facility for the epipelagic micro-profiler (Fig. 10).

Mooring C: Oceanic Microbial Genomics Platform

Mooring C (Fig. 14; Table 4) is designed primarily to support long-term ESP experiments, but also to accommodate other instruments critical to the success of the OOI-BGF program. Deployment of the ESP at 20 m is proposed as optimal in terms minimizing physical stresses while capturing surface ocean microbial community structure, and yielding information complementary to that emanating from the ISP experiments. Because the ESP contains electro-mechanical robotics and precision micro-fluidic mechanisms (Scholin et al., 2007) it is critical that excessive motion (e.g., by surface wave action) is avoided. New Autonomous Depth Adjuster (ADA) mooring technology developed at WHOI can overcome this problem whereby the surface instrumented buoy is connected to the "underwater-mass" a steel buoy via a highly stretchable (max. 175%) electro-mechanical hose. An ESP is hung from this steel buoy, and the entire mooring system is tethered to the anchor (and acoustic release) via low-stretch steel wire. Prior deployments have demonstrated that this method effectively damps any movement caused by waves up to 9 m in amplitude.

Since an ESP consumes much more energy compared to conventional oceanographic instruments, we propose to deploy a so-called Micro-Grid Power Buoy (MGPB) (Fig. 14). The onboard wind generator and photovoltaic cell combination generates up to the 60 w/hr of electricity on average, which is used to replenish a 200A storage battery installed at the base of the MGPB. In this way, ample electricity can be supplied for quasi-permanent operation of the ESP, contextual underwater and in-air sensors, global broadcasting of resulting data, and for maintenance of a local data network between Mooring C and Moorings B/D. The performance and cost of satellite data transmission is improving at a rapid pace, and there will likely be much greater band-width and flexibility in data transfer by the time that the Global OOI program is fully commissioned. These data will be submitted to data centers and distributed to the research community according to OOI protocols.

Related Files

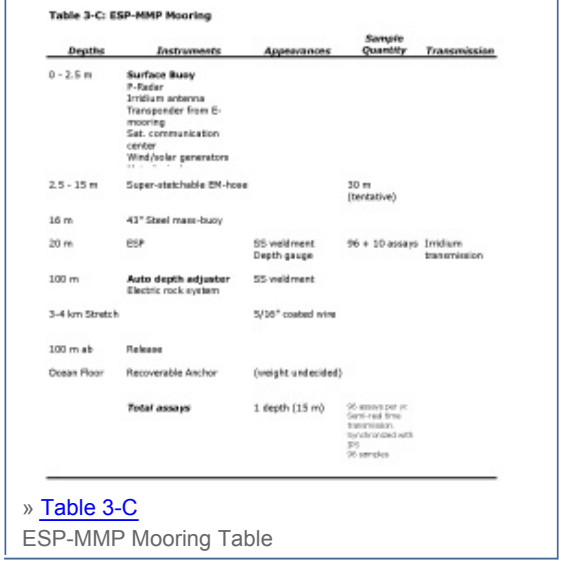

Table 3-C: ESP-MMP Mooring

Depths	Instruments	Appeavances	Sample Quantity	Transmission
0 - 2.5 m	Surface Buoy F-Radar Iridium antenna Transponder from E-mooring Sat. communication center Wind/solar generators			
2.5 - 15 m	Super-stretchable EM-hose		10 m (tentative)	
16 m	43" Steel mass-buoy			
20 m	ESP	SS weldment Depth gauge	96 + 10 assays	Iridium transmission
100 m	Auto depth adjuster Electric rock system	SS weldment		
3-4 km Stretch		5/16" coated wire		
100 m ab	Release			
Ocean Floor	Recoverable Anchor	(weight undecided)		
	Total assays	1 depth (15 m)		

» Table 3-C
ESP-MMP Mooring Table

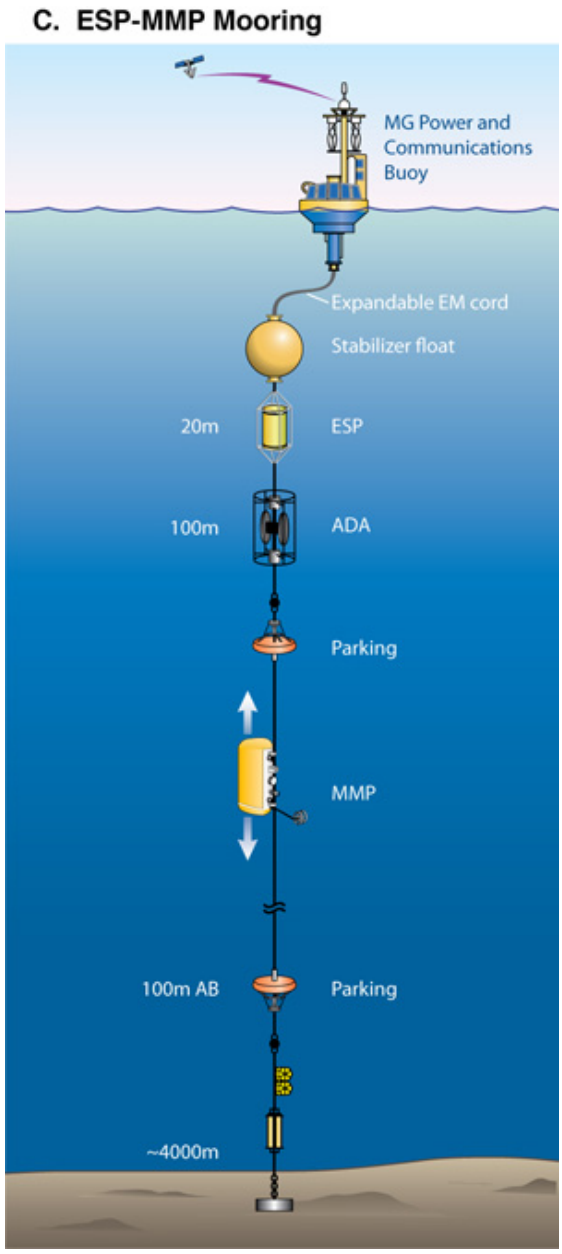

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Fig. 14. Mooring C. ESP and wire-crawling moored profiler (MMP) mooring scheme. An ESP is deployed at 20 m via an Autonomous Depth Adjuster (ADA). Power to operate the ESP and enable data transmission is supplied by the Micro Grid buoy via a flexible EM cable and a steel stabilizer float. MMP shuttles between lower epipelagic zone and benthic layer to collect contextual data.

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Mooring D: Time-Series Water/Suspended Particle Sampling Array

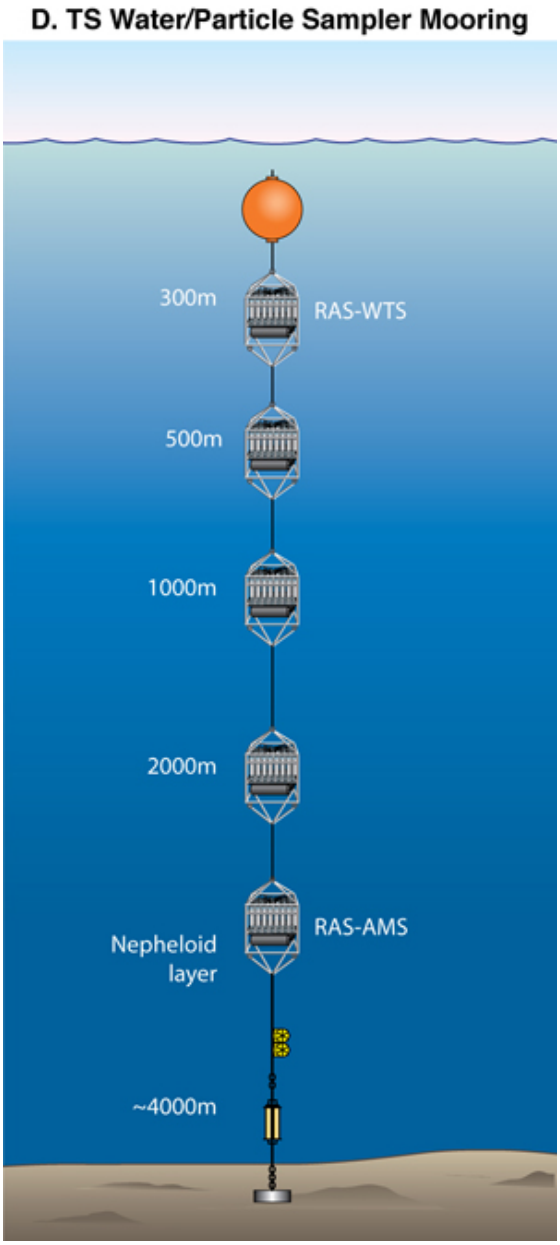
Capabilities now exist for autonomous time-series collection of up to forty-eight discrete 500 ml water samples (using a Remote Access Sampler, RAS) and 48 suspended particle samples by filtration of 10-L of water (Water Transfer System, WTS) at pre-programmed intervals. We envision Mooring D (Table 2-D) would be equipped with RAS/WTS positioned at depths equivalent to those of the TS-traps. These water and suspended sediment samples are vital for examining temporal and vertical variability in specific tracers, isotopes, nutrients, DOC and related substances. Autonomous systems for collection and preservation of particles specifically for genomic analysis (Automated Microbial Sampler, AMS; Fig. 17) could also be deployed on this mooring, with the operation schedule of each system carefully synchronized. (Table 3-D)

Related Files

Table 3-D: TS-Water/Particle Sampling Mooring

Depths	*Instruments*	*Appearances*	*Sample Quantity*
100 m	50" Syntactic sphere buoy	P-Radar, flush lights tiltmeter, compus	
200 m	RAS-WTS 200	SS weldment Depth guage	48 x 500 ml water 24 x 10L on 47 mm-filtrs
500 m	RAS-WTS 500	SS weldment	48 x 500 ml water 24 x 10L on 47 mm-filtrs
1000 m	RAS-WTS 1000	SS weldment	48 x 500 ml water 24 x 10L on 47 mm-filtrs
2000 m	RAS-WTS 1000	SS weldment	48 x 500 ml water 24 x 10L on 47 mm-filtrs
200 m ab	RAS-WTS Nepheloid	SS weldment	48 x 500 ml water 24 x 10L on 47 mm-filtrs
100 m ab	Release		
Ocean Floor	Recoverable Anchor (weight undecided)		
	Total samples	*5 depths*	*250 500 ml water samples Total of 125 Ltr.* *120 filter samples each represents 10 ltr., filtering total of 1.2 tons of water*

» Table 3-D
Time Series Water/Particle Sampling Mooring Table



Enlarge Image

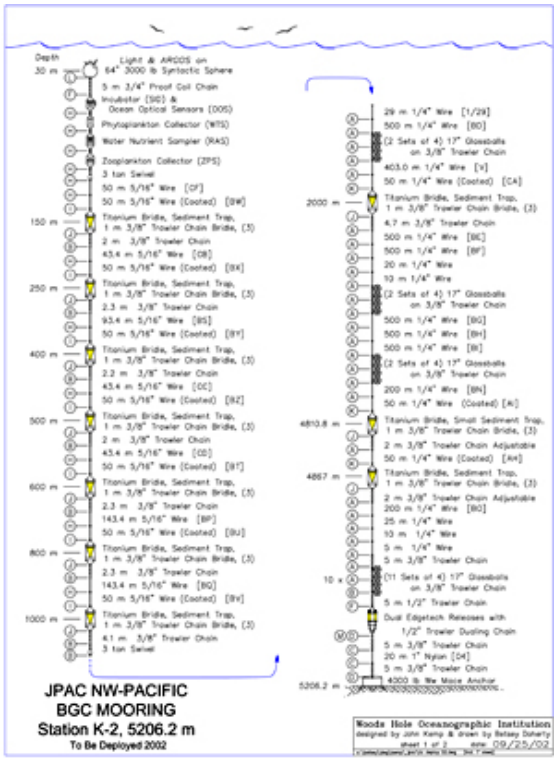
Fig. 16. **Mooring D.** This mooring supports time-series acquisition of discrete suspended particle and deep water samples for biogeochemical or microbial investigation. Sampling will be synchronized with the rest of instruments on other moorings.

GBF-OOI

Mooring design, construction and turn-around

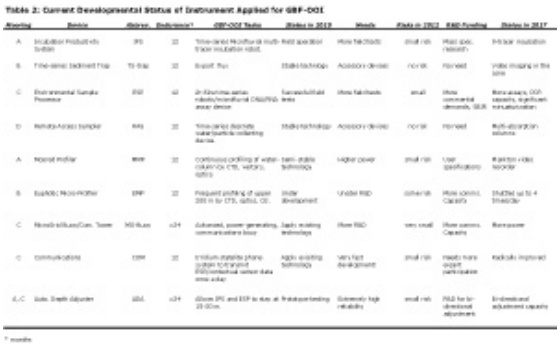
The US OOI engineering community includes several highly experienced groups of sea-going technologists who have previously successfully executed large biogeochemical flux studies (e.g., JGOFS) For example, the HiLat program successfully handled very large, highly-engineered moorings (Fig. 20). Groups with many expert mooring engineers and highly trained technicians are currently active at several institutions including U. Washington, Oregon State University and WHOI. Some of them have already committed to other OOI elements. Their participation, including on computer simulations, mechanical tests, manufacturing, and onboard command software design will be crucial for the design and construction of the GBF-OOI mooring arrays. All moorings will be supported by large syntactic foam (internally structured) buoys, except the Mooring C where a heavy steel buoy will be used. The basic deployment/recovery scheme adopts the anchor-last method using 2 electronically-controlled traction winches on board large ocean-class research vessels of the type that will be used to service the global OOI mooring arrays. In order to minimize environmental impacts, the mooring design and deployments will be optimized to minimize waste and for recovery and maximize re-use of of mooring components.

Related File



» Fig. 20

Fig. 20. An example of complex, heavily instrumented mooring deployed as part of the JAMSTEC/MIO HiLat Program. This highly engineered mooring system, which was designed and operated by the WHOI Bouy Lab was successfully deployed at three North Pacific Stations (K-1, 2, and 3). The mooring array proposed for OOI-GBF is significantly lighter and less complex, with the exception of new requirements for shallow deployment of IPS and ESP instruments.



» Table 2

Current Developmental Status of Instruments for GBF-OOI.

GBF-OOI

Distribution of Data and Samples Emanating from the OOI-BGF program

In the spirit of the OOI, the goal of the BGF program will be to disseminate data emanating from the observation platforms as quickly as possible. For some instrumentation (e.g. ESP), this will occur in quasi real-time. However, not all instrumentation will yield data instantly - an important and necessary departure from the concept of the OOI. Several types of measurements require return of samples to the laboratory for detailed analysis. A key facet of the OOI-BGF program will be the unprecedented degree and breadth of autonomous sampling in order to provide access to diverse biogeochemical and biological questions associated with the oceanic biological pump. We envision centralized analytical facilities, both in the US and abroad, for generation of core biogeochemical data. In accordance with the OOI date handling protocols, all digital data will be distributed promptly. Similarly, analytical data will also will be submitted and posted according to the OOI data protocols, and samples would be accessible to the general oceanographic community.

GBF-OOI

Impact on Ocean Research and Education

The proposed OOI-Global Biogeochemical Flux program will provide an unparalleled capacity to investigate biological activity in the ocean, biologically-mediated export of carbon to the deep ocean, and the role of the oceanic biological pump in the global carbon cycle. The comprehensive, coherent time-series data sets from key oceanic regimes emanating from this concerted observation program will allow major advances in our understanding of ocean biogeochemistry in the context of the Earth system. It will connect microbially-mediated processes to ocean-wide fluxes, combine genomic-level studies with assessments of elemental budgets, and allow extrapolations to the global ocean through remote sensing. This program will catalyze further innovations in ocean instruments and observation platforms, and will serve as a broad template for both ocean science research and education.

The proposed BGF-OOI program is shaped by the urgent need to understand the ocean's capacity to take up anthropogenic CO_2. In addition to constraining productivity in and export from the surface ocean, this program will provide key constraints on organic carbon consumption with depth and remineralization rates that influence CO_2 generation and storage in the world ocean. There are other pressing reasons to initiate this study. For example, grave concerns exist over global food availability in the near future, and whether ocean productivity can sustain the fisheries essential for many cultures. Accurate assessments of present and future ocean productivity are crucial for making robust predictions, and the observations proposed here are essential for calibrating remote sensing data in order to develop global assessments of ocean productivity.

Partnering with other elements of the OOI program will lead to an overall strengthening of educational and outreach efforts while affording considerable cost savings due to minimal additional ship time requirements. We will also take advantage of OOI Cyber-Infrastructure and adhere to OOI's policy for data distribution and publication.

GBF-OOI
Supporting Materials

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Tables

Figures

Fig. 1. Settling particles a low magnification photomicrograph of typical exported ocean particles intercepted by a mesopelagic TS-trap deployed in the carbonate ocean. A variety of zooplankton fecal pellets, several species of planktonic foraminifer tests, pteropod shells, large diatom frustules, and coccospheres are seen. Amorphous aggregates (marine snow flakes are loaded by coccoliths (not resolved under this low magnification). The fecal pellet at the mid-left of the photo is approximately 150 micrometer long. Biogeochemical investigation of the exported particles uses the mole values of the majority of elements from total export particles, POC, PIC ($CaCO_3$) and Biogenic Si (SiO_2).

Fig. 2. A 3-D illustration of proposed GBF-OOI array, which consists of 4 moorings. Objectives, capabilities and technology of each mooring are detailed in section 3 and 4 of this white paper. MBARI's high endurance ROV Tethys with miniature microbial sampler (Poster 1) has not been tested as of yet.

Fig. 3. Photograph of a prototype of the Incubation Productivity Sampler (IPS). The IPS is an autonomous micro-laboratory that will conduct multiple *in situ* end point (t_0, t_1) or time course (e.g., t_0, t_1, t_2, t_3) time series incubations for up to 1 year to obtain ^{13}C primary production, ^{15}N nitrogen fixation, ^{18}O gross production, respiration values.

Fig. 4. Mooring A, Primary productivity mooring. showing vertical arrangement of IPS. An Automated Depth Adjuster adjusts the top of the Syntactic foam float at depths as shallow as 15 m. (Table 1).

Fig. 5. Recovery of a TS-trap from ice-floe filled Ross Sea, Soutern Ocean by the JGOFS mooring team from Oregon State University.

Fig. 6. *Coccolithus pelagicus* in laboratory cuture.

Fig. 7. A frustule of a large *Asterolampra* diatom.

Fig. 8. An outcome of the global JGOFS experiment. Distribution of POC, PIC and Biogenic Si in mmolC m^{-2} yr^{-1} parameterized from TS-traps deployed for a year from 134 stations (uppermost figure) during the period of 1983 to early 2000 (Honjo et al., 2008).

Fig. 9. A Time-Series (TS) Sediment Trap A TS-Trap is made exclusively of innert palstic material and titanium in order to avoid contamination of samples during long term deployements in ocean environments. In fact, the TS-trap in this photo has been used for several 12-month-deployement cycles yet looks brand new!

Fig. 10. Mooring B. Export flux mooring showing vertical arrangement of an epipelagic micro-profiler and an array of TS-traps. The deployment plan in the upper mesopleagic layer can be changed.

Fig. 11. The Environmental Sample Processor (ESP) is a device developed by MBARI that allows for autonomous sample acquisition and application of DNA, RNA and protein probe arrays *in situ* and transmit the assay results on semi-real time. The linked Oceanography article (Scholin et al., 2009) summarizes the function, application and future development of the ESP technology. ESPs are commercially available.

Fig. 12. Example illustrating use of the ESP to detect groups of marine bacterioplankton in Monterey Bay spring, 2008. The bottom panel shows arrays developed and imaged by the ESP. Changes in the microbial rRNA pool were observed, most notably was the appearance and disappearance of Marine G2 Euryarchaea (red boxes). In contrast, MAlph was present on all arrays developed.

Fig. 13. An ESP assay in Monterey Bay, summer, 2007 on invertebrates and harmful algal toxin (domoic acid). For detail, link Fig. 11, p. 162.

Fig. 14. Mooring C. ESP and MMP mooring scheme. An ESP is deployed at 20 m via ADA. Power to operate ESP and data transmission is supplied by the Micro Grid buoy via flexible EM cable and a steel stabilizer float. MMP shuttles between lower epipelagic zone and benthic layer to collect contextual data.

Fig. 15a. Water Transfer System (WTS) for time series filter collection of the particulate fraction from up to 10 L of water that collected in aluminum foil/Tedlar sandwich bags to prevent loss of gaseous sample. **b**: RAS for time series collection of 500 ml whole water samples (or filtrates) with/without preservative.

Fig 15b. Remote Access Sampler (RAS) for time series collection of 500 ml whole water samples (or filtrates) with/without preservative.

Fig. 16. Mooring D. This moring supports sample acquisition of water, suspended particle and descrete deep water samples for microbial study in time-seres syschoronized with the rest of instruments on other morrings, for subsequent chemical and biological analyses.

Fig. 17. Automated Microbial Sampler (AMS) is capable of obtaining descrete filtered microbial (e.g., phytoplankton, bacteria) samples via flow through filter units & a sample preservation circuit to that will permit the active chemical preservation of the filtered samples within seconds of completion of sampling.

Fig. 18. Fluorescence in situ hybridization (CARD-FISH) of Eel River Basin sediment.

Fig. 19. An example of Syntactic underwater floatation that was just recovered on board R/VMirai in 2004 with the cooperation of WHOI engineers. Instrument wells on Mooring A and B provide fully exposed platform for IPS-15 m (Fig. 4) and a launching/garage facility for the epipelagic micro-profiler (Fig. 10).