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Title:	**Open-Ocean Observatories: Ocean Circulation and Biogeochemical Cycles**		
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Permission to post abstract on ORION Web site: **X** Yes ☐ No

Abstract: *(400 words or less)*

We propose a system of 16 open-ocean water column observatories that would uniquely enable a wide range of ocean research not possible with present means. A particular strength of the envisaged system and of the consortium that has come together, is that it truly catalyzes and allows cross-disciplinary integrated observations and analyses of linked processes in strategic or representatives locations of the world ocean. The disciplines working in concert that would carry out simultaneous measurements/interpretations of interdependent processes, events, and changes include: physical oceanography (water mass formation, transports, mode water processes), biogeochemistry (CO_2, O_2, nutrient, trace metal processes), ecology (primary production, zooplankton, fish regimes), and ecosystem modelling. In addition, we have linked up with the global air-sea flux and geophysics ORION consortia to identify a list of sites that are of common interest for all groups, and 11 of our 16 sites are the highest priority ones from a ranking by all three consortia. Thus, if implemented, it is very likely that the air-sea flux observations, which are critical for the watercolumn studies proposed here, would also be available. The high temporal resolution of the simultaneous observations over long time (and covering the water column vertically), will for the first time allow us to study and understand the effects of atmospheric and physical forcing (ranging from short-term or event-like to interannual variability) on the biogeochemistry and directly or indirectly on the ecosystem. Thus the causes and predictability of fluctuations from sudden blooms or anomalous CO_2 uptake, to regime shifts can be studied. The two-way telemetry will allowus to respond to events detected or expected, thus enabling adaptive interdisciplinary science on the global scale. In addition, the implementation of a real network spanning many ocean provinces and biogeographical regimes will allow us to study both differences and connections in the responses observed.

The network of sites will be embedded in the international OceanSITES project, to facilitate the coordination and sharing of operating a global observatory system. In particular the data management approach will capitalize on developments underway internationally, while remaining coherent with the DMAC plans of the US IOOS. Our consortium will also contribute to the education and outreach facility endorsed by previous ORION workshops on the topic.

Please describe below key non-standard measurement technology needed to achieve the proposed scientific objectives: (*250 words or less*)

To understand the global system, we need to be able to occupy the proposed network of site regardless of meteorological, wave, or ice conditions, in order to achieve coverage of the diverse ocean regimes. The ability to carry out multidisciplinary observations everywhere in the water column, near the surface and deep, with many, sometimes large, sensors is imperative. A profiling capability in the mixed-layer and euphotic zone all the way to the surface, as well as in the deep ocean, has many advantages, amoung them cost savings since the number of sensors can be reduced. At the same time, in most locations surface air-sea flux measurements from a companion proposal is highly desirable. This may lead to a need for 2 moorings at many sites, one with a surface buoy and fixed sensors, one with the profiling systems. Some parts of the profiling technologies are still under development. Data telemetry from all sensors will be required, and in some cases bi-directional sensor control would have benefits. For higher datarate systems, especially in the profiling platforms, this is not currently implemented. Easy integration of new sensors into the data stream (plug-and-play) would be desirable. Some sensors also need continued development (e.g. for some carbon parameters) along with general improvements on moored sensors (e.g. biofouling control).

Proposed Sites:

Site Name	Position	Water Depth (m)	Proposed Duration			Site-specific Comments
			Start Date	Deploy (months)	Revisits during deployment	
Peru Basin	18°S 85°W	4000	2007	48	4	
AAIW formation	55°S 55°S	4000	2010	12	1	
Brazil/Arg. basin	42°S 42°W	4000	2010	12	1	
Irminger Sea	60°N 39°W	4000	2007	48	4	
PIRATA	0° 23°W	4000	2008	36	3	
Edge subtr gyre	23°N 44°W	4000	2009	24	2	
HOT	22.7°N 158°W	4000	2010	12	1	
PAPA	50°N 145°W	4000	2008	36	3	
Arabian Sea	15°N 65°E	4000	2009	24	2	
NTAS	15°N 51°W	4000	2008	36	3	
B ATS	32°N 64°W	4000	2010	12	1	
Equat. Pacific	5°S 110°W	4000	2007	48	4	
S.Pacif. subtr.gyre	28°S 120°W	4000	2008	36	3	
BRAVO	57°N 53°W	4000	2009	24	2	
Porcupine Plain	49°N 16.5°W	4000	2009	24	2	
Station W	40°N 70°W	4000	2007	48	4	

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Open-Ocean Observatories: Ocean Circulation and Biogeochemical Cycles
An ORION Conceptual Proposal

1. Abstract and Summary

We propose a system of 16 open-ocean water column observatories that would uniquely enable a wide range of ocean research not possible with present means. A particular strength of the envisaged system and of the consortium that has come together is that it truly catalyzes and allows cross-disciplinary integrated observations and analyses of linked processes in strategic or representative locations of the world ocean. The disciplines working in concert that would carry out simultaneous measurements/interpretations of interdependent processes, events, and changes include: physical oceanography (water mass formation, transports, mode water processes), biogeochemistry (CO_2, O_2, nutrient, trace metal processes), ecology (primary production, zooplankton, fish regimes), and ecosystem modelling. In addition, we have linked up with the global air-sea flux and geophysics ORION consortia to identify a list of common sites that are of common interest for all groups, and 11 of our 16 sites are the highest priority ones from a ranking by all three consortia. Thus, if implemented, it is very likely that the air-sea flux observations, which are critical for the watercolumn studies proposed here, would also be available. The high temporal resolution of the simultaneous observations over long time (and covering the water column vertically), will for the first time allow us to study and understand the effects of atmospheric and physical forcing (ranging from short-term or event-like to interannual variability) on the biogeochemistry and directly or indirectly on the ecosystem. Thus the causes and predictability of fluctuations from sudden blooms or anomalous CO_2 uptake, to regime shifts can be studied. The two-way telemetry will allow us to respond to events detected or expected, thus enabling adaptive interdisciplinary science on the global scale. In addition, the implementation of a real network spanning many ocean provinces and biogeographical regimes will allow us to study both differences and connections in the responses observed.

The network of sites will be embedded in the international OceanSITES project, to facilitate the coordination and sharing of operating a global observatory system. In particular the data management approach will capitalize on developments underway internationally, while remaining coherent with the DMAC plans of the US IOOS. Our consortium will also contribute to the education and outreach facility endorsed by previous ORION workshops on the topic.

2. Preface

Long-term continuous open-ocean observations are required for quantifying and understanding interannual-to-decadal changes in ocean circulation, water properties, water mass formation, and ecosystems, for observing episodic events and their impact, for providing reference sites for atmospheric time series and quantifying air-sea fluxes, for quantifying the role of the oceans in the global carbon cycle, for improving images of the Earth's interior by completing a global network of geophysical observations, and for measuring global plate motions and lithospheric deformation.

This is one of three coordinated proposals being submitted for interdisciplinary observations at a select number of open ocean sites. The present proposal focuses on ocean circulation and physical processes, biogeochemical cycles, and ecosystem dynamics; the other proposals will address climate and air-sea fluxes (Weller et al), and earth structure and geodynamics (Detrick et al). Because of the high cost of operating and maintaining time series sites in open-ocean areas, at least initially there are likely to be only a limited number of global stations as part of ORION and those sites that serve the largest number of interdisciplinary interests will likely have a high priority. We have therefore worked with our colleagues in other disciplines to identify open ocean observatory sites with the broadest interdisciplinary interest that also contribute to studies of ocean circulation and biogeochemical cycles.

3. Program Rationale and Key Scientific Hypotheses

A. Rationale and need for a global network

The need for a sustained ocean observing system for research applications is widely recognized as a result of the growing awareness that the ocean is a key component of the global climate, weather, and ecosystem, a major source of living resources and biodiversity, and is central for shipping, offshore exploitation, tourism and coastal protection. The current focus of ocean and climate research is on change and variability, and the predictability thereof, and no longer on describing and understanding its mean state and functioning. The essential ability to detect and understand changes and events in the ocean, and to predict or mitigate their impact on climate, on global ecosystems, society, and the economy, has lead many nations to start or contribute to the development of or to contribute to the development of an Integrated Ocean Observing System – examples are the European GMES program, the US IOOS, and the global GEO (Group on Earth Observations) efforts. Such a system needs to be sustained, global, multidisciplinary, and the data made freely available to everybody.

The challenge of this observing system is formidable since the oceans are a vast and hostile environment, only a few parameters in surface waters are accessible with space-based remote sensing, the interplay of physical and biogeochemical parameters is important, and an extreme range of space and timescales (meters to thousands of kilometers, hours to decades) needs to be covered. In many respects however, we are ready to implement the required observing system – and work on the implementation of some elements of an integrated ocean observing system is already underway in the research and operational communities.

In the past, the natural way to observe changes or events has been with fixed (Eulerian) timeseries at a point, and most historical records are of this type (weather/climate/sealevel observations at established stations, ocean weather ships, repeat hydrography records like at Bermuda). Nonetheless, the overall ocean observing system needed now has to provide a global 4-D description of the oceanic variables of climatic and societal relevance. Fixed-point timeseries can provide unique 2-D cuts through this space (time and depth) for many variables at selected locations, resolving a wide range of temporal variability and sampling the water column from the surface to the bottom. They are an important complement to and fill a gap left by other components of the observing system, like remote sensing, profiling floats, surface drifters, sections with gliders and with vessels. For this reason, timeseries have been identified as an essential part of the Global Ocean Observing System (GOOS).

Timeseries techniques are well suited for regular observations of critical or hard-to-sample regions and periods, like straits, boundary currents, boundary layers, ice-covered areas, or storm seasons. They are also required for resolving rapid changes or processes, such as diurnal cycles or sudden events. In addition, due to the size and weight of many of the sensors, timeseries frequently are the only approach for observing multidisciplinary variability. This proposal presents the need of a global timeseries observatories network for ocean circulation, biogeochemical cycles and ecosystem research.

The need for a coordinated global network is compelling. There are an appreciable number of timeseries sites already that are being operated individually around the globe. However, as single sites the visibility and impact of many of them in the science community is relatively small. Their value and power would be multiplied by integrating them into a single system of ocean observatories. A major reason for the limited impact of timeseries sites is that large-scale or global issues are not yet being addressed in a coordinated approach. Many global change topics and operational applications require global systems, such as for the detection of patterns, the propagation of signals, thermohaline transport changes, observation of CO_2 uptake and release regimes, and ecosystem regime shifts. The different research and operational communities (CLIVAR, GOOS, IGCO, IMBER, SOLAS etc) are attempting within their fields to implement coordinated observing systems for such purposes, but frequently any one of them cannot muster enough critical mass for advocating or implementing a system of ocean observatories. Thus, at best, the result is a collection of largely single, PI-driven timeseries sites at locations of national or personal interest, and frequently a timeseries comes to an end when the individual runs out of resources or interest.

Implementing and maintaining a global network is only feasible if true sharing of resources (hardware, ships, expertise, funding, and technology) across communities (and countries) is invoked. This requires an effort on the scale of ORION, which in addition, needs to be tied into an international network, which for timeseries is the OceanSITES project (www.OceanSITES.org). Other projects such as ARGO have demonstrated that this is feasible. ORION and OceanSITES can provide the required network context, in terms of coordination, implementation, information exchange, visibility, and common advocacy. Having the mandate from several communities in turn gives more recognition and weight to the global system being built.

An overriding factor in reaching users and providing visibility is the existence of a coordinated and integrated data management system. Few users in the science community will look for data from timeseries sites that need to be accessed in different places and formats, that have no uniform and documented quality control, and whose existence and availability depends entirely on a single PI or project. The power and value of a single timeseries system comes from making access to the whole network possible as a single data set, in a standard format, and from a unique portal. This requires an organization like ORION, linking to the US Integrated Ocean Observing System (IOOS) and internationally to OceanSITES (which has initiated a suitable data infrastructure).

B. Need for observatories and OOI infrastructure

1) Co-located time series measurements of physical, and biogeochemical oceanographic properties and air-sea exchanges are needed:

The biogeochemical properties, processes, and changes in the ocean watercolumn depend strongly on the interplay with and forcing by the air-sea fluxes and physical processes. Moreover, the life of a given organism (or group of organisms) in the ocean depends on a complex interplay of those forcings, the chemical properties of the seawater, and the interactions with other organisms in the environment. Despite these clear relationships, most oceanographic research and data collection is strongly ”stovepiped“ by subdiscipline. While advancement in understanding of ocean processes has nevertheless been achieved in the last 50 years, continued progress will require a bridging of disciplinary observing boundaries. A program of interdisciplinary ocean observatories is presently the only feasible approach to do that, acquiring data which can reveal the multidisciplinary interactions and interdependent processes occurring on many timescales and over the depth dimension.

In addition, development of global coupled physical-biogeochemical (carbon cycling) models depends on the existence of simultaneous physical and biogeochemical timeseries measurements. While remotely-sensed data are very useful for this purpose, these data can tell us very little about what happens below the surface (one optical depth), about interactions occurring on time scales less than a day, and about properties not measurable from space (e.g. nutrients, carbon).

2) Existing time series have insufficient length or temporal resolution:

Observational oceanography conducted to date consists chiefly of one-time (or a small set of) cruise-based expeditions or moored programs involving installations at a handful of geographic sites for periods of a few years. Increasingly we are discovering that event-like processes or departures from the mean or annual cycle play a significant role in the ocean's evolution, and that these high-frequency and other processes are modulated on annual to decadal time scales. Both place important constraints on the sampling required to resolve all the variablity and shed light on its causes. Long-term measurement programs that sample frequently in time (perhaps under external control based on real-time assessments of the measurements – see below) are required.

3) Real time access to data is almost non existent:

In remote regions, access to the observatories is very restricted, and even for closer ones each ship visit is expensive. Data telemetry allows the science to be carried forward even in the absence of a visit, and improvements during each service visit can be prepared and optimized based on the data received previously. Telemetry also allows malfunctions to be diagnosed early and appropriate action to be planned for the subsequent visit. Detection of events may also trigger adapted sampling, either by the mooring itself or via a glider network around it. In case of catastrophic instrument loss, the data collected up to then are safeguarded with telemetry, and thus the investment is not completely lost. For education and outreach, data telemetry from ocean observatories has a huge attraction, allowing the public to follow changes and events in the deep ocean in real time.

4) Coordinated networks are needed, which single PI proposals cannot implement/maintain:

A small number of deep-ocean sites have been sampled regularly (in the upper ocean) for periods of up to 50 years (e.g. Hydrostation S off Bermuda, Ocean Stations M and P in the Norwegian Sea and eastern subpolar N. Pacific, respectively). The data from these programs has yielded vital information about decadal-timescale ocean variability as well as annual to mesoscale-frequency processes. These records are particularly notable because they have been continued under a series of short-term grants to a small number of dedicated individuals. Every few years, at grant renewal time, these time series are under threat of termination. Routine, regular, long-term sampling can be difficult to cast as exciting and so typically fares poorly in traditional peer review. This is particularly true when proposing initiation of a long-term sampling program. A community effort to collect long-term observations having broad interest, such as ORION, is required.

5) Few institutions have the capacity to operate open-ocean observatories over long time

There have never been a large number of technical groups in the U.S. able to deploy and maintain open-ocean moored systems over long time. In fact, this capability has been shrinking of late, making access to this capacity scarce in the community and even setting the stage for animosities to develop between those investigators having local access to technical support groups and those who do not. Therefore the existence of the OOI infrastructure will enable investigations that are otherwise not possible, both for individual PI's and for work with broad community involvement. A broadly-supported program of open-ocean observatories providing data to all will help eliminate conflicts.

C. Key scientific hypotheses to be tested with the proposed system

Data from the proposed multi-disciplinary open-ocean observatories will support investigations of numerous processes and test various scientific hypotheses, including:

- The intensity of water mass transformation (and thus volume and properties of newly-modified waters) can be determined (and ultimately predicted) from the atmospheric forcing and knowledge of internal ocean processes such as horizontal advection and eddy stirring and diapycnal mixing.

- Key biogeochemical parameters and conditions (CO_2 and oxygen uptake/release, nutrient supply, etc) of the water masses are set by the balance of horizontal and vertical processes in these regions.
- Key biogeochemical parameters and conditions are set by the nonlinear interactions across many time scales (e.g. interannual modulation of mesoscale eddies).
- The nutrient content of a watermass, established during the formation process, plays a critical role in establishing the subsurface nutrient reservoir and thus affects the temporal and spatial variability of primary productivity.
- The uptake and storage of anthropogenic CO_2 is controlled by local carbon chemistry at the ventilation sites as well as the formation and transport of watermasses in the watercolumn.
- Transient events, for example mesoscale eddies, internals waves, instability waves and weather phenomena (hurricanes, dust storms), contribute as much to the magnitude and variability of biogeochemical fluxes as do longer term processes such as seasonal variability, El Niño, the NAO and PDO.
- The ecosystem structure and evolution can be understood as a result of the above factors.
- Biogeographical ecosystem regimes and temporal switches between regime states are a result of the physical driving forces and unique, taxon-specific biological responses.
- Modelling/model development (hindcasting and prediction) of the relevant processes is possible with a sufficient data base of in-situ observations covering the temporal behaviour of biogeochemical variables in different regimes.

4. Scientific Objectives

Global-scale processes may change climate and ecological systems in unforeseen ways that could affect our political and economic stability. It is therefore imperative that we learn as much as possible about the causes and effects of such change. The magnitude of the natural fluctuations is similar to or larger than that predicted to result, initially, from human-induced perturbations to global climate, making it difficult to clearly identify the sources of ecosystem variability.

An important contribution of present time-series programs has been to document the temporal evolution of CO_2 in surface seawater and changing air-sea fluxes. These observations have clearly shown the effect of different modes of climate variability (e.g. ENSO, PDO) on CO_2 fluxes and water column biogeochemistry. Time series measurements have also shown that the uptake of anthropogenic CO_2 is variable over a wide range of time and space scales necessitating a sustained observing program to monitor the changes in ocean chemistry and CO_2 uptake efficiency in the future.

The present time series programs have also helped elucidate phytoplankton primary production in relation to climate perturbations. Phytoplankton occupy a central role in oceanic ecosystems, as their nutrient uptake, growth, and sinking mediate the biogeochemical fluxes of carbon and other elements between the atmosphere, surface ocean, and deep ocean. They also influence the penetration depth of solar energy and thus influence the ocean heat budget.

Because the atmosphere and oceans are physically coupled, climate exerts strong effects on the marine biogeochemistry and food web mediated by phytoplankton. Recent analysis indicates a tight correlation between phytoplankton abundance and fish production (Ware and Thomson, 2005) providing further support that large-scale regime shifts are regulated from the bottom-up (Chavez et al., 2003). However, we currently lack the necessary data to close this loop. A global array of ocean moorings would provide data to confirm such linkages.

An equally important goal of the time-series efforts is to provide basic physical, chemical, and biological context for a number of other studies. Investigations including such diverse topics as mid-water energy flow and benthic food webs, microbial recycling of nutrients, the formation of thin biological layers, natural iron fertilization of the ocean, and the development of harmful algal blooms can use build on the time-series programs.

The time series data, augmented with information from satellites and gliders, will span many scales of variability and permit construction of climatologies against which change can be quantified. The major focus in the early years will be the seasonal and spatial pattern of the physics, nutrient chemistry, and primary production. As the time series mature, the data will facilitate rigorous investigation of processes at longer time scales, such as the PDO and NAO.

As described above one of the most pressing issues facing society today is the extent to which global change will influence the biology and chemistry of the oceans. The effects of global change include the warming and acidification of the ocean resulting from absorption of anthropogenic CO_2 and atmospheric warming, the excessive exploitation of natural resources, and large-scale natural climate changes. The effects are seen on local, regional and global scales and they involve the interconnected physical, chemical, geological, and biological processes in the ocean. The distinction between local and global processes can often only be made by comparing simultaneous data from contrasting regions. To complicate matters further the effects may interact with each other in nonlinear or unpredictable ways. Given the societal importance of such large-scale changes, it is paramount that long-term observing stations throughout the global ocean are established.

The observing system will allow us to address the following scientific questions:

- What are the characteristics of ocean climate change variability in the different regimes about the globe and the physical links between global and regional systems? Do phenomena that originate in one part of the globe propagate to others?
- What are the relative roles of mesoscale versus basin-scale dynamics in forcing physical and ecosystem variability and biogeochemical cycling?
- By what processes does physical forcing regulate ecosystem structure and dynamics, biogeochemical cycling and bio-diversity at seasonal, interannual and multidecadal time-scales?
- How do ecosystem structure and biogeochemical cycling interrelate, and does this coupling change on seasonal, interannual and multidecadal time scales?

- How important is subtle multi-decadal physical variability in regulating ecosystem structure and how are the physical dynamics manifested in ecosystems and biogeochemical cycling?
- What is the quantitative impact of anthropogenic CO_2 uptake by the oceans on ecosystems and biogeochemical cycling?
- What additional human impacts on the ocean stratification/circulation and associated ecosystems and biogeochemical cycling are observable?

5. Experimental Design and Observing Requirements

A. Identifying a subset of the global network with maximum multidisciplinary interest

The CLIVAR and GOOS sponsored international interdisciplinary OceanSITES project coordinates the planning efforts of many of the groups interested in the science questions that can be addressed by the establishment of fixed timeseries sites in the open ocean (see http://www.OceanSITES.org). Its membership is multidisciplinary, including physical, biological, chemical, and geophysical scientists whose interests extend from the ocean bottom through the air-sea interface. They have identified a number of potential sites located at the intersection of regions of interest for multiple disciplines.

Starting from the site list developed by OceanSITES (see Appendix E of the National Research Council report *Enabling Ocean Science in the 21st Century*, 2003) and guided by past workshops and reports discussing the Ocean Observatories Initiative, the PIs from the three coordinated proposals mentioned in the Preface identified 30 sites of potential interdisciplinary interest for ORION's global network (all sites marked in fig.1). Then each of the four disciplines

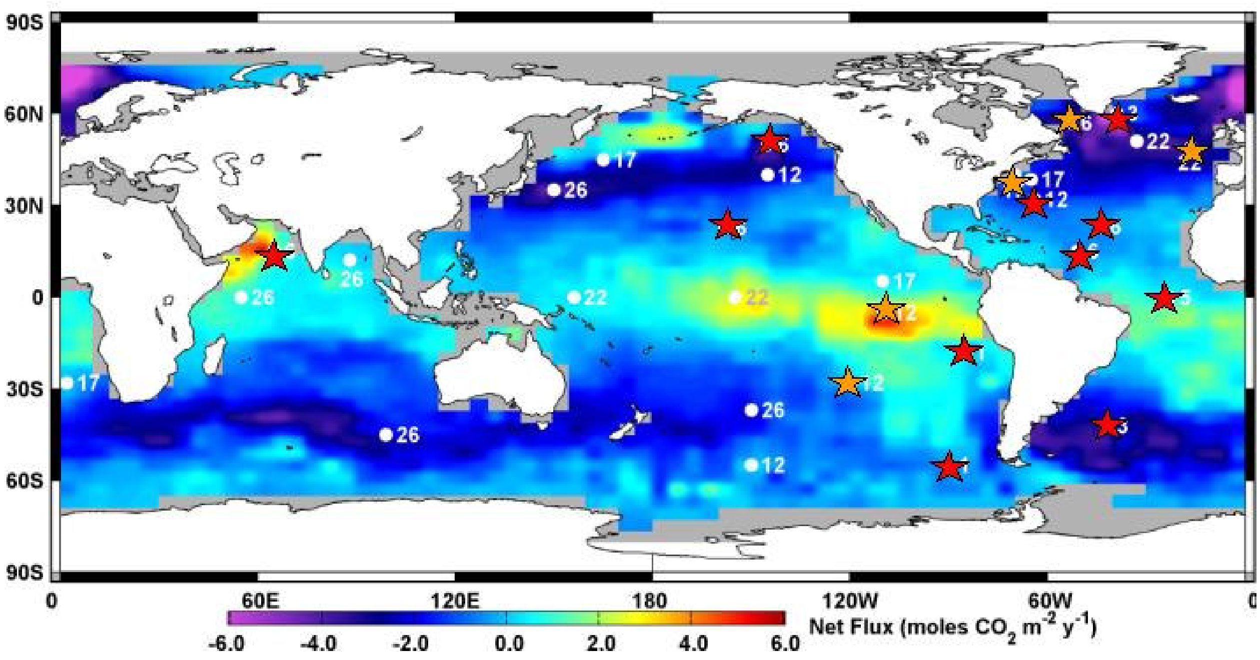


Fig.1: *All 30 sites of highest common interest to the 3 coordinated proposals (red stars and white circles). The red stars denote the 11 highest priority sites from this list; the orange stars are 5 additional sites of very high relevance for the current proposal.*

(air-sea flux, biogeochemistry, geophysics, and ocean circulation and climate) chose and ranked 15 high priority sites from the list of 30. Based on the combined disciplinary rankings of these 30 sites we identified eleven sites of highest interdisciplinary interest (Table 1, red stars in fig.1). All eleven sites are of interest to at least three of the four disciplinary groups. Amoung these sites, three of the four highest priority ones are in the southern hemisphere; and three sites are at latitudes of 50° or higher. They also include three established time series sites (BATS, HOT and Station Papa), but further add a number of sites in remote ocean areas that are rarely visited or studied. In addition to these eleven sites, we also have identified five other global sites of very high physical and/or biogeochemical priority (Table 2, orange stars in fig.1).

site #	*Location*	*Lat.*	*Long.*	*Priority for*	*Comments*
1	Pacific	18°S	85°W	A,B,C,G	Peru Basin; oxygen minimum zone, existing air-sea flux (stratocumulus) site, CO_2 upwelling
2	Pacific	55°S	90°W	A,B,C,G	Southern Ocean; AAIW formation; air-sea flux; anthropogenic CO_2 sink region;
3	Atlantic	42°S	42°W	B,C,G	Brazil/Argentine Basin; biogeochem; ocean circulation; large CO_2 flux region
4	Atlantic	60°N	39°W	A,B,C	southeast of Greenland; ocean circ., mode water, air-sea flux, biogeochem, ecosystem (calanus), fisheries, anthropogenic CO_2 sink region
5	Atlantic	0°	23°W	B,C,G	PIRATA mooring; equatorial Atlantic; biogeochem, CO_2 flux, ocean circ
6	Atlantic	23°N	44°W	A,B,G	Edge of subtropical gyre, air-sea flux; biogeochemistry (nutrients), ecosystem regime, CO_2 flux
7	Pacific	22.7°N	158°W	A,B,G	HOT (Hawaii Ocean Time Series) site; CO_2 history
8	Pacific	50°N	145°W	A,B,C,G	Station PAPA; NE Pacific; CO_2 history
9	Indian	15°N	65°E	A,B,C,G	Arabian Sea; monsoon regime, CO_2 upwelling
10	Atlantic	15°N	51°W	A,C,G	Existing Northwest Tropical Atlantic Station (NTAS), airsea flux, circulation (element of overturning array)
11	Atlantic	32°N	64°W	A,B,C	BATS (Bermuda Atlantic Time Series Site), subtrop. Gyre, CO_2 history

Table 1a: *List of 11 open-ocean observatory sites having strong common interest to the three consortia (watercolumn processes, air-sea interaction and geophysics).*

12	Pacific	5°S	110°W	B	Off equator, CO_2 flux maximum
13	Pacific	28°S	120°W	B	South Pacific subtropical gyre, nitrate minimum, CO_2
14	Atlantic	57°N	53°W	A,B,C	Labrador Sea, water mass formation, air-sea flux, CO_2 and O_2 dynanics
15	Atlantic	49°N	16.5°W	A,B,C	Porcupine Abyssal Plain, ocean circ., mode water, air-sea flux, biogeochem, anthropogenic CO_2 uptake
16	Atlantic	40°N	70°W	C	Station W, ocean circ, transport pair with BATS, CO_2

Table 1b: *List of an additional 5 open-ocean observatory sites of interest to the watercolumn processes consortium (this proposal).*

B. Scientific studies enabled by the network

The sites chosen can be roughly classified into three types of regimes and science applications.

1. *Key regions of strong vertical dynamics* where processes that govern the variability in ocean climate, in ecosystem dynamics, and in carbon cycle processes take place. Typically these are regions of water mass transformation, i.e. sites where intense vertical mixing is driven by surface buoyancy loss, or regions of upwelling, such as the equator. These areas are important sites for CO_2 fluxes and the uptake and storage of anthropogenic CO_2 (sites 2,3,5,9,12,14,15).
2. *Large, seemingly-homogeneous ocean provinces* in the physical and biological sense (such as the subtropical gyres), but which, as shown by time series at Bermuda and Hawaii, are far from stable and more productive than previously thought. Time series in such representative locations will allow understanding the processes representative of these regimes and contrasting, and possibly linking long-term changes in/between them (sites 1,4,6,7,8,11,13).
3. *Regions of important horizontal transports* and exchanges by major ocean currents and between ocean (sub)basins, including the fluxes of mass, heat, freshwater, carbon, nutrients and organisms (sites 4,10,11,16).

In all cases, the physical and the biogeochemical processes strongly interact and need to be observed simultaneously for an understanding of the processes, the governing factors, and the variability. In the following we outline selected research topics to be addressed by the consortium, using the proposed network of observatories and detail some of the specific instrumentation requirements.

a: ***carbon cycle / CO_2 flux processes***

Quantifying CO_2 exchange between the atmosphere and the oceans and understanding its controls and impact on ecosystems and biogeochemical cycling requires in-situ timeseries observations. Measurements of surface-ocean and atmospheric pCO_2 can now routinely be made on moored platforms. These measurements have already proved effective for quantifying the impact of the 1997-98 El Niño on the equatorial Pacific air-sea CO_2 flux. Measurements at BATS have documented the seasonal to interannual variability in CO_2 fluxes in an oligotrophic environment, and formed an integral part of the carbon chemistry measurement program at that site. Increasing the global coverage of pCO_2 sensors in a multidisciplinary observatory network will not only improve the accuracy of global CO_2 flux estimates (figure 2) – it will also enable important comparisons of the variability of fluxes between regions and the study of the interdepence with other physical, chemical and biological factors (see later figure 3).

Since December 1996, MBARI has collaborated with PMEL to maintain pCO_2 sensors on the TAO/TRITON moorings in the equatorial Pacific. During 2003, PMEL engineers worked with the MBARI group to take a similar MBARI designed pCO_2 system for a drifting buoy and modified it to work as a buoy based system. Together, MBARI and PMEL have 11 operating moored pCO_2 sensors in the North Pacific and North Atlantic. The PMEL/MBARI moored pCO_2 systems collect CO_2 and O_2 data from the marine boundary air and surface seawater. These

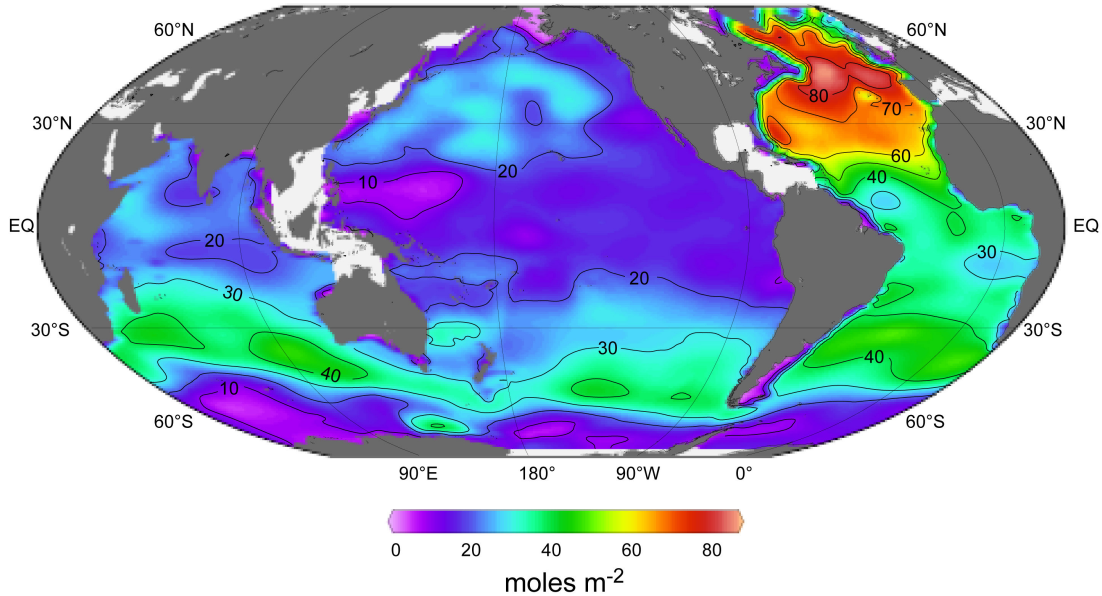


Fig.2: *Vertically integrated inventory of anthropogenic CO_2. Note that many of the16 sites proposed here cover the source regions in the North Atlantic and the Southern Ocean maxima east and west of South America (sites 2,3). The other southern ocean maxima in the Pacific and Indian sector would be occupied by others of the 30 sites of common interest in figure 1.*

systems are mounted on a surface buoy. The only pCO_2 sensor for subsurface mooring installations with any track record is the SAMI system manufactured by Sunburst. It has been used successfully on several year-long European observatory implementations, and allows deeper or profiling measurements of pCO_2. These two systems are bulky and heavy (using wet chemical analyses). A new technology for optical CO_2 measurements is now available (PSI CO_2-Pro by ProOceanus) and will be field-tested in the near future. It holds promise due to smaller size and power consumption.

The systems are calibrated with WMO traceable CO_2 standards so their measurements are compatible with the global atmospheric CO_2 monitoring network. The wet chemistry systems have been shown to be accurate to ±2 ppm based on laboratory studies and in situ comparisons with shipboard systems. The systems are currently programmed to run every three hours and transmit a summary file each day. With the ORION moorings, a much more ambitious and flexible schedule can easily be developed. With two way communications, a system could be designed to recognize when pCO_2 values are changing rapidly and adapt the sampling schedule to properly capture the temporal signal. Placing CO_2 systems on the ORION mooring network will provide a critical contribution to a global climate observing system.

b: *oxygen and nutrients*

The gross carbon and oxygen exchanges between the atmosphere and the ocean are strongly influenced by the ocean's biological pump. Much was learned about the factors controlling these fluxes during the Joint Global Ocean Flux Study (JGOFS). However, it was quantified in only a few of the process-study and time-series locations. The role of atmospheric iron input was determined to be important, but was not evaluated globally (see below). In order to predict how the ocean's biological pump will respond to global climate change, we must quantify present biological fluxes in a wide variety of ocean areas and understand why they differ. Satellite ocean color measurements have been used to estimate both ocean primary production (~gross daily biological oxygen production) and biological carbon export (~ net annual oxygen production); however, these estimates are presently calibrated by in situ measurements in only four areas of the oceans--the present ocean time series sites and the equator.

The number of locations where biological oxygen (and carbon) fluxes and internal dynamics are known could be dramatically expanded by making in situ measurements of oxygen on moorings designed for air-water interface flux and watercolumn studies in the ORION mooring network. To do this requires some understanding of the behavior of oxygen in the surface ocean. Oxygen accumulates in surface water until it reaches a steady state where production by photosynthesis is balanced by losses due to gas exchange, respiration and transport. Below the thermocline, oxygen accumulates to form the "shallow oxygen maximum" that is characteristic of the late summer in oligotrophic systems, where it is a direct tracer of primary production (Shulenberger and Reid, 1981). With this knowledge, it has been shown that nearly continuous measurements of oxygen using in situ sensors on moorings can be used to determine: (a) gross daily biological oxygen production via diurnal changes and (b) net annual biological oxygen production via the flux to the atmosphere and seasonal build up below the mixed layer. These oxygen fluxes are stoichiometrically related to carbon fluxes. However, a large component of the biological oxygen flux from the upper ocean is across the air-water interface to the atmosphere. Evaluating these vertical fluxes requires determinations of the surface und subsurface ocean concentrations and factors that influence gas exchange rates (wind speed, wave height, surface roughness, etc.). We would carry out these studies using the ORION mooring network and satellite measurements. A range of oxygen sensors is available now, including a new promising optical sensor (optode), which can easily be installed on observatory systems.

Nitrate is an essential nutrient element that is required to support new primary production in the ocean. Measurement of nitrate would provide understanding of a key parameter that limits rates of primary production, the food chain, and the biological pump (figure 3). It is now possible to measure nitrate concentrations directly in seawater by measuring the UV absorption spectra, which contains a band due to light absorption by nitrate (Johnson and Coletti, 2002). ISUS (In Situ Ultraviolet Spectrophotometers) nitrate sensors have been deployed on surface moorings for year-long time periods in the euphotic zone with only modest drift due to biofouling. Such systems could also be incorporated into profiling floats, adding only 500 g of mass to the float if integrated into the pressure housing. It will not be feasible to directly detect nitrate concentrations in the mixed layer of oligotrophic ocean regions by this technique, because of the low ambient nitrate concentrations. However, the seasonal cycle of nutrients in equatorial and subpolar regions can be easily monitored. In addition, a widely dispersed observing system would provide important constraints on the impacts of episodic processes such as mesoscale eddies (McGillicuddy et al., 1998) or Rossby waves (Sakamoto et al., 2004) that periodically inject nitrate into the euphotic zone and increase primary production.

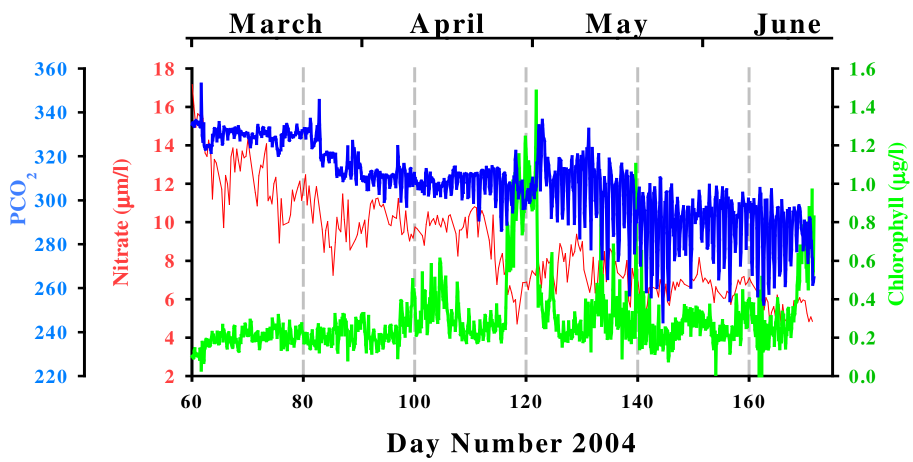


Fig.3: *pCO_2(blue), nutrients (nitrate, red), and chlor phyll (green) at 40m depth from an observatory mooring in the N.Atlantic (area of sites 4, 15) over a 4-month period. It allows to relate and investigate the biological drawdown of pCO_2, the nutrient availability and consumption, and the growth of chlorophyll, on diurnal, event and seasonal time scales. Longer such deployments would reveal causes for interannual changes and regime shifts.*

c: *primary production*

Quantifying integrated water column primary productivity requires knowledge of phytoplankton biomass, physiological condition (growth rate), and light-dependent changes in production with depth. Importantly, these three central parameters all have significant signatures in submarine optical properties. Recent work has shown that the carbon biomass of phytoplankton can be derived from optical measurements of particulate beam attenuation (Behrenfeld & Boss 2003). This relationship is strongest in Case I waters where the particle size distribution is most conserved. The significance of this development is that it allows changes in pigment concentration that are independent phytoplankton biomass to be related (through the Chl:C ratio) to variability in physiological status (Behrenfeld & Boss 2003). Measurements of stimulated fluorescence provide an optical approach to assessing pigment concentration. Finally, the light-limited reduction in productivity in the lower euphotic zone can be accounted for to first order with a mixed layer measurement of diffuse attenuation (e.g., a simple underwater PAR sensor) and an above surface measurement of incident irradiance. Combining these 4 core measurements enables the characterization of phytoplankton biomass, growth rates, and vertical light attenuation and thereby facilitates the routine monitoring of variability in integrated water column productivity to an accuracy not possible using satellite-based data and models.

Chlorophyll can be measured on a mooring with accuracy and precision equivalent to *in situ* techniques (see figure 3 in [Chavez *et al.*, 1999]) using fluorescence or diffuse attenuation coefficients of downwelling irradiance derived from pairs of radiometers [Morel and Maritorena, 2001]. Phytoplankton carbon biomass (PC) can be calculated from beam attenuation coefficients (beam-c, C_p), measured with a transmissometer. This relationship appears to vary between oceanic provinces [Gardner *et al.*, 2003], but is easily quantified. Particulate backscatter coefficients (b_b) provide an additional index of phytoplankton biomass and, together with C_p , can provide a sensitive index of changes in the characteristics of the particle assemblage.

Our consortium would carry out a range of biogeochemical studies enabled even by crude profiles of beam attenuation, fluorescence and backscatter on moorings. Many of the scientific hypotheses could be tested and various objectives addressed in this way. The minimum technology needed is to incorporate a miniaturized combined fluorescence/backscatter (flr/b_b) sensor into the housing of a transmissometer. WET Labs currently makes small 'puck' flr/b_b sensors which have been deployed on profiling floats in the Labrador Sea (http://flux.ocean.washington.edu/argo/homographs/TP/0005.html). We estimate that a combined flr/b_b/C_p instrument could be produced for <$10K. The transmissometer would require a pump and antifoulant protective sleeve, but in the interest of power conservation, the pump could be shared with an oxygen sensor such as the SBE43, in which case the SBE43 data could be powered and logged by the flr/b_b/C_p controller. The flr/b_b sensor would require an antifouling shutter/wiper mechanism. For a sampling interval of 15 minutes, and excluding the pump, we estimate that the shutter/wiper, transmissometer, fluorescence and backscatter measurements would require 24 mAh day^{-1}, with a data rate of ~1 kb day^{-1}. A minimum set of depths would be one near surface (<10m), three in the vicinity of the subsurface chlorophyll maximum (SSCM) and one below the SSCM. For example, in the central equatorial Pacific where the SSCM peaks at ~50m, an ideal suite of depths might be 10m, 30m, 50m, 70m and 100m. For coastal systems, where the chlorophyll maximum is essentially at the surface, a suitable spacing might be 5m, 10m, 20m, 30m, 50m. Assuming the surface expression of the buoy will have an irradiance sensor, the subsurface light profile could be determined from the chlorophyll profile or one to three subsurface radiometers. It seems feasible that simple radiometers could be incorporated into the flr/b_b/C_p sensor.

d: <u>Trace metals</u>

In recent years, there has been a growing appreciation of the role that some key trace metals play in marine phytoplankton nutrition and regulation of ocean biogeochemical cycles. The most familiar perhaps is the role of iron in limiting biological growth in "high nutrient low chlorophyll" environments such as the Antarctic, equatorial Pacific, and subarctic North Pacific (e.g. Martin and Fitzwater, 1988 and many other subsequent papers). But we known that other trace metals occur at very low concentrations yet are essential to photosynthetic activity and metabolism (e.g. Zn and Co, Morel et al., 2004), while other metals can inhibit the growth of some phytoplankton (e.g. Cu, Mann et al., 2002) and control their vertical distribution. Relatively little is known about the variability of trace metals in the upper ocean, and we need to have a much better understanding of these processes in order to model ocean biogeochemical cycles.

Trace metals with atmospheric sources and surface ocean residence time less than a few years (such as iron, lead, zinc, copper, and cobalt) show substantial spatial and temporal variability in the near-surface ocean due to seasonal cycles and erratic weather/ eddy/ bloom events (Boyle et al., 1986; Boyle et al., 1994; Jickells, 1995; Jickells et al., 1994; McGillicuddy and Robinson, 1997; McGillicuddy et al., 1998; Prospero, 1996; Tersol et al., 1996; Saito and Moffett, 2002). Pb and Fe are particularly interesting in this regard because Pb sources are dominantly anthropogenic and evolving on a decadal scale, and Fe is believed to limit biological growth and nitrogen fixation in significant oceanic regions (Coale et al., 1996; Martin and Fitzwater, 1988; Falkowski, 1997; Michaels et al., 1996)). Lead is decreasing in the thermocline of the eastern and western Atlantic as lower-Pb surface waters replace older high-lead waters. Iron shows very short term variability in the upper ocean (Boyle et al., 2005). It has been suggested that Fe should show longer-term decadal signals in response to changing aerosol fluxes (Michaels et al., 1996; Prospero, 1995; Prospero and Nees, 1977; Bates and Hansell, 2004), and in turn may limit biological activity.

If we are to understand and predict the evolution of natural and anthropogenic trace metals such as Pb and Fe in response to anthropogenic perturbations, we must learn more about the mechanisms determining spatial and temporal variability within the ocean. Overall, the trace element observations that we propose to carry out from the ORION observatories would allow addressing these issues.

e: ecosystem regimes and changes

In the 1990s a series of papers reported on Pacific climate, ocean and ecosystem variability with periods of 40-70 years (Ebbesmeyer et al., 1991; Francis and Hare, 1994; Mantua et al., 1997; Miller et al., 1994; Trenberth and Hurrell, 1994). A formal definition of the PDO was given in Mantua et al., (1997) and is based on sea surface temperatures in the North Pacific north of 20°N. More recently (Chao et al., 2000) show that this variability is also present in the South Pacific and is roughly symmetrical north and south of the equator. Almost ten years earlier a Japanese scientist (Kawasaki, 1983) had found synchronous variations in the landings of sardines off Japan, California, Peru, and Chile. Populations flourished for 20 to 30 years and then practically disappeared for similar periods. Periods of low sardine abundance were marked by dramatic increases in anchovy populations. The variability was later shown to extend to the Atlantic (Lluch-Belda et al., 1989) and to have occurred in pre-industrial times as evidenced by reconstructions from sediment cores (Baumgartner et al., 1992; Schwartzlose et al., 1999).

The mechanism responsible for the global variations in sardines and anchovies has been linked to the large-scale atmospheric and oceanic changes described in the 1990s (figure 4). Retrospective analysis suggests that from around 1925 to 1950 the Pacific was on average warm and dominated by sardines. A cool period from about 1950 to 1975 where anchovies dominated followed. Since 1975 the Pacific had been warm again until a recent cooling proposed for the late 1990s (Mantua and Hare, 2002; Chavez et al., 2003). Oceanographers have referred to the periods of rapid change between the warm and cool periods as regime shifts, a term coined by Isaacs (1975). As a result of the early response of ocean biota, it has been suggested that a regime or climate shift may even be best determined by monitoring marine organisms rather than climate

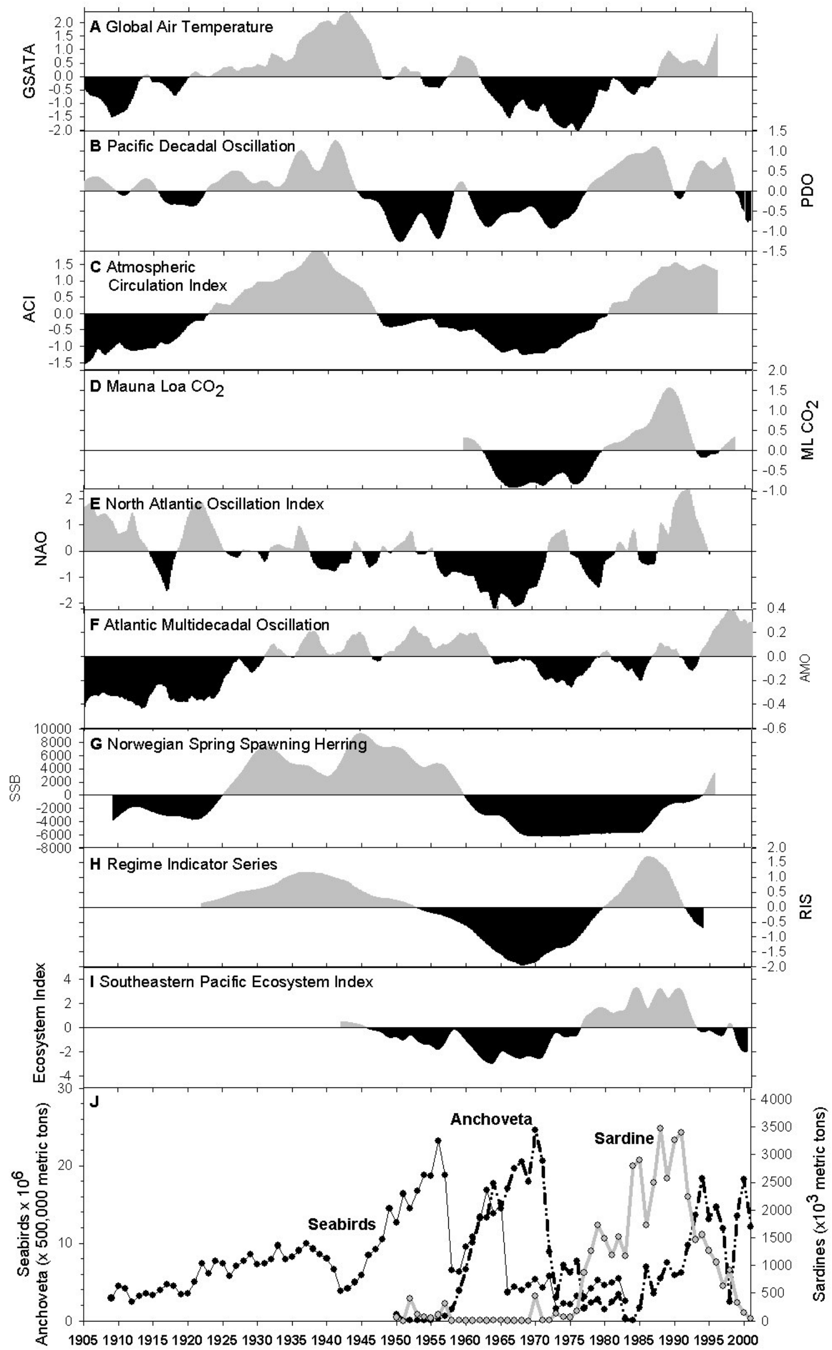


Fig.4: *The relations between global atmospheric, oceanographic, and ecosystem states shown in this figure could be investigated in terms of forcing and underlying processes with the proposed observatory system. A) detrended global air temperature (Jones et al., 1999), B) the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997), C) the Atmospheric Circulation Index (ACI) (Klashyatorin, 2001), D) detrended atmospheric CO2 measured at Mauna Loa (Keeling et al., 1989), E) the North Atlantic Oscillation (NAO), F) Atlantic Multidecadal Oscillation, a 10 year running average of the detrended Atlantic sea SST anomalies north of the equator (Enfield et al., 2001), G) anomalies in the Norwegian spring herring spawning biomass (Toresen and Ostvedt, 2000), H) Regime Indicator Series (RIS) that integrates global sardine and anchovy fluctuations (Lluch-Belda et al., 1997), I) the Southeastern Tropical Pacific ecosystem (STPE) index based on: J) seabird abundance, anchoveta and sardine landings from Peru used to construct the STPE index. Series have been smoothed with a 3-year running mean. (Chavez et al, 2003)*

(Hare and Mantua, 2000). The pattern in SST anomalies associated with the multi-decadal changes is surprisingly similar to that observed during ENSO with an enhancement of high latitude anomalies relative to the tropics. The observing system described in this proposal will provide data that allow us to study the physical and biogeochemical forcing factors and processes in the different biogeographical regimes underlying these important variations with dramatic ecological consequences. In particular, measurements that can detect fluctuations in the abundance and approximate size class distributions for zooplankton and fish will be useful. Such data are best obtained by a combination of optical counting techniques like the Laser Optical Plankton Counter (LOPC) and acoustic backscatter methods (multi-frequency echosounders).

f: water property variability in "stable regimes"

The subtropical gyres cover a major fraction of the surface area of the oceans, and they include unique ecosystems. The old paradigm of a simple one-dimensional (vertical) balance between time-mean advection and diffusion has given way to a time-varying, fully three-dimensional balance where eddies are no longer simply lumped in with other unresolved processes and labelled "diffusion" (Karl et al., 2001). Episodes of strong surface flux forcing and Ekman pumping, modulated by interannual climate variability, entrain nutrients and other upper pycnocline properties into the surface layer. These pycnocline properties are set by air-sea interactions in remote locations and advected into the gyre, subject to variability at their surface sources as well as to variable advection (Lukas, 2001). Mesoscale eddies not only perturb the vertical velocity field and the depth of the pycnocline, with subsequent impacts on productivity (Letelier et al., 2000), but they also enhance vertical mixing and they also result in long-range transport of water properties even up property gradients (e.g., Lukas and Santiago-Mandujano, 2001). The proposed network of global observatories will be used in conjunction with spatial coverage by floats and gliders and with the aid of numerical models, to deconvolve these processes where they are simply superimposed, and to understand the essential nonlinear interactions among the various physical and biogeochemical processes.

An example of an ORION process study that is enabled by the OOI infrastructure is to separate the influences of along-isopycnal eddy transports of ecologically important properties from their influence via vertical advection and mixing. This will require the spatial coverage that can only be provided by gliders, in conjunction with the multi-variate high resolution observations at observatory sites. Using state-of-the-art data assimilation techniques and high-resolution ocean circulation models, gliders would be directed to sample eddy genesis regions that are most likely to produce the features that will impact the observatory site. Following these eddies over time and along their pathway with gliders will quantify their interaction with their environment. As they arrive at the observatory site, their ecological impacts will be quantified in a comprehensive manner. To do this work successfully will require research in predicting mesoscale eddy movements, and will require numerous cases to provide high statistical confidence in the results. This absolutely requires the sustained ocean observatory infrastructure.

g: <u>water mass formation</u>

Mixed layer deepening and erosion is a ubiquitous process in the ocean, but only certain conditions lead to persistent deep mixed layers and well-defined water masses. Given their origin in surface mixed layers, these so-called mode waters (large volumes of water with narrowly-defined properties) have many special characteristics (such as weak vertical stratification, high dissolved oxygen and low nutrient content) that influence their subsequent evolution and the biogeochemical processes within them. The transformation of water properties in the surface mixed layer is intimately related to air-sea interaction and the ocean's heat and fresh water budgets. Creation of large volumes of homogenized water frequently involves deep convection driven by surface buoyancy loss. But not all mode water formation sites are coincident with surface buoyancy forcing; formation of Antarctic Intermediate Water in the SE Pacific (figure 5) for example appears to be controlled strongly by surface Ekman convergence. Data from open-ocean observatories in key areas of water mass transformation will lead to a better understanding of the processes involved in generating and maintaining mode waters. Specific research themes include the heat and salt budgets and the regional circulation of mode water formation regions, the processes of internal restratification and mixing below the seasonal pycnocline, and contrasting warmer low-latitude regimes from colder higher latitude regimes.

But mixed layer processes are also important for setting the subsurface nutrient reservoir. The supply of nutrients to the euphotic zone, which fuels the biological pump, has traditionally been attributed to vertical processes: Wind-driven upwelling [*Mann and Lazier*, 1996], diapycnal diffusion [*Lewis et al.*, 1986], wintertime convection [*Gruber et al.*, 2002; *Lewis et al.*, 1988; *Menzel and Ryther*, 1961] and, more recently, eddy heaving [*McGillicuddy and Robinson*, 1997; *Oschlies and Garcon*, 1998] have all been examined for their contribution to the vertical flux of nutrients. However, a recent analysis of historical hydrographic and time series data [Palter et al., 2005] has revealed that Eighteen Degree Water (EDW), the subtropical mode water of the North Atlantic, plays an important role in setting the nutrient reservoir of the subtropical gyre. According to this study, the advection of EDW injects a wedge of low nutrient water beneath the seasonal thermocline in the North Atlantic subtropical gyre. The presence of the nutrient-depleted water mass then damps the biological response to each of the vertical processes that transports nutrients upwards throughout the subtropical gyre. This study suggests that efforts to understand the spatial and temporal variability of marine primary productivity must account for the variability in the subsurface nutrient supply; a supply dependent upon the spatial distribution of the watermasses within each basin.

With data from the proposed network of ocean observatories, we will be able to assess the linkage between water transformation in the surface mixed layer and the subsurface nutrient supply, which in turn is expected to be linked to surface productivity. Specifically we will investigate the time scales associated with the biological depletion of inorganic nutrients during water mass formation, the nutrient concentration of watermasses upon subduction, and how the formation of watermasses impact the downstream nutrient reservoir and vertical nutrient fluxes that fuel local primary productivity?

The required upper ocean sensors are temperature-salinity probes and acoustic doppler current meters (ADCP), plus the biogeochemical sensors mentioned before. The sites of particular interest are those that reside within the subtropics (Bermuda (BATS), south Pacific subtropical gyre), in the subpolar regions (Labrador Sea (BRAVO); Station PAPA ; South Pacific AAIW formation region) and at the transitional boundaries of these gyres (edge of Atlantic subtropical gyre; Station W; Brazil/Argentine Basin).

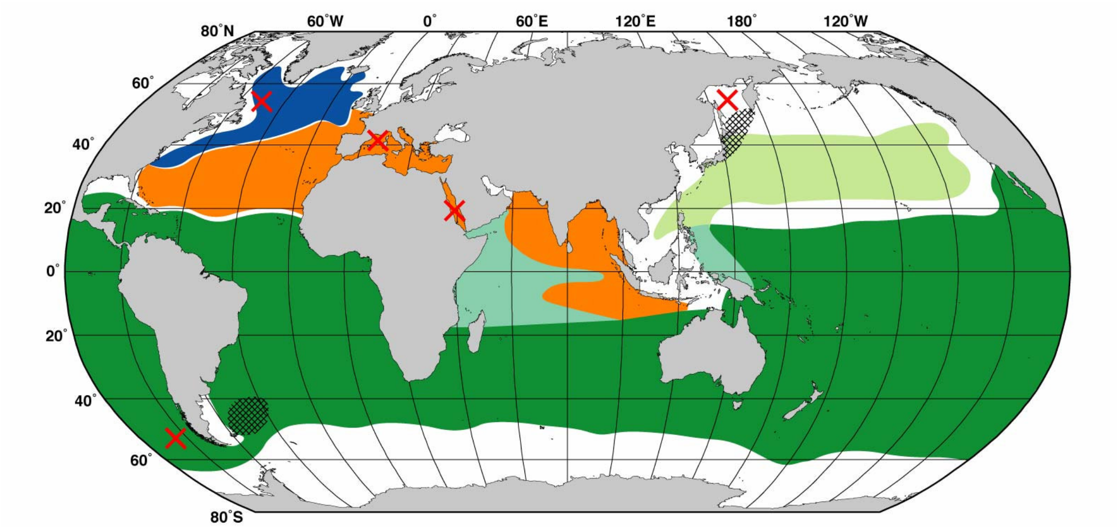


Fig.5: *Distribution of low and high salinity intermediate waters. The large green volume is AAIW, formed west and probably also east of South America (cross and hatching). These locations with evidently global influence could not be observed continuously until now with timeseries approaches due to adverse weather conditions, thus important understanding is lacking. They would be occupied by the proposed sites 2 and 3. Note also the Labrador Sea Water formation area (red cross), corresponding to site14.*

h. circulation regimes

Deep ocean moorings have shed new light on the character of the oceans' circulation variability on two scales: local and gyre. Arrays of moored instruments spanning a particular circulation feature are capable of returning time series of the total current transport and transport by water mass class, the accompanying stratification changes, and the associated fluxes of water properties and organisms. These estimates derive from direct measurement of velocity and the water properties. Such so-called coherent arrays have also been used to investigate ocean dynamics. Past examples of understanding derived from moored array programs include the works by Schott et al. (1988), Klink and Nowlin (2001) and Johns et al (1995). In contrast, assemblages of individual, widely-spaced moorings have been used to investigate gyre-scale transport variability. As opposed to the local array scheme of direct measurements, gyre-scale circulation variability estimates invoke the geostrophic balance between horizontally integrated transport and pressure differences. Thus time series of dynamic height and sea level (or bottom pressure) differences between sites may be related to the net horizontal transport between the stations. Time series from multiple sites have also proven valuable for documenting the propagation speed of climatic water property variations within ocean basins. The studies by Curry et al. et al (1998) and Curry and McCartney (2001) that analyzed time series data from Bermuda and the Labrador Sea to quantify variability in the N. Atlantic circulation are representative here. Both sampling schemes have proven useful for documenting the nature of ocean variability as well as providing input and/or validation data for numerical models.

Conventional moored current meters, temperature/salinity sensors spanning the water column and bottom pressure gauges are required to investigate circulation and stratification variability; additional water property sensors as detailed previously will also be useful for distinguishing transient water mass signals and transports of biogeochemical quantities. The proposed measurement sites in the Pacific and North Atlantic will provide valuable information about gyre-scale variability. For example, the group: Labrador Sea, Station W, Bermuda, Porcupine Abyssal Plain, and the site off Greenland will quantify variability in the Atlantic's subpolar and subtropical gyre circulations and track the propagation of climate anomalies around the basin. Similarly, the HOT and PAPA stations provide information about the NE Pacific circulation variability. Arrays of instruments off Greenland and Woods Hole will further return time series of deep boundary current transport, a key element of the Atlantic's overturning circulation.

i: Biogeochemical Modelling

Models provide the means to investigate hypotheses, analyze and extrapolate data both in space and time, help gather data efficiently through observational system simulation experiments, and last, but not least, identify crucial gaps to be filled by new observations and research to reduce uncertainties in our knowledge. To achieve such interactions, a synthesis and modeling framework must be set up and active from the beginning of OOI/ORION to integrate knowledge and to refine the implementation strategy.

The development of three dimensional numerical models has exploded over the last several decades as scientists have seen the need to synthesize the large and disparate amount of ocean observations. This is true for physical as we all as for biological and chemical oceanography. This explosion has made it abundantly clear that the accuracy of the models is directly tied to the available observations. A critical aspect of the modelling effort for the OOI global array proposed here will be the ecosystem model.

The ecosystem NPZ models typically consist of somewhere between 10 and 20 compartments. One such biogeochemical model consists of 12 compartments describing two size classes of phytoplankton (P1, P2) and zooplankton (Z1, Z2), detrital nitrogen (DN) and detrital silicon (DSi), silicate (Si(OH)4), total CO2 and two forms of dissolved inorganic nitrogen: nitrate (NO3) and ammonium (NH4), which are treated separately, thus enabling division of primary production into new production and regenerated production, oxygen (O2), and phosphate (PO4). Below the euphotic zone, sinking particulate organic matter is converted to inorganic nutrients by a regeneration process similar to the one used by Chai et al. (1996), in which organic matter decays to ammonium and then is nitrified to NO3. The flux of particulate material is specified using an empirical function determined from sediment trap observations.

Development of models capable of predicting marine ecosystem response to environmental change is a prerequisite for quantifying important feedbacks involving the global carbon cycle. However, models used for these types of analyses typically include large numbers of poorly known parameters that are difficult to measure. One solution to this problem is to invoke data assimilation techniques, which have been quite successful in other fields such as meteorology and physical oceanography.

Assimilation of the data acquired from the network of proposed OOI observatories into biogeochemical models will reveal which ecosystem models and which specific model formulations are most appropriate within each oceanographic regime. By comparing the performance of multiple ecosystem models in distinct oceanographic regimes, we will be able to determine which model formulations for biological processes such as photosynthesis, grazing, etc…. are most successful in each particular region, and also determine how much detail can be included in these biogeochemical models, without requiring a set of model parameters so large that it is impossible to place meaningful constraints on their values. By conducting both intra-site and inter-site model comparisons, we will be able to reformulate existing ecosystem models so that they are better able to simulate the underlying processes that generate the variability inherent in biogeochemical data sets collected from multiple oceanographic regimes

D. Overall observing requirements:

There presently exist two limitations to collecting long-term, autonomous and continuous time series in the global ocean. The first are the resources (human, facilities, infrastructure, financial) to maintain an array of moorings, each capable of supporting a large instrument suite with real-time telemetry, with off-the-shelf instrumentation. The second are the resources to develop new measurement systems able to collect data at high vertical resolution and potentially reduce the cost of instrumentation by either profiling or pumping water from multiple depths to a single instrument complex.

a: ***<u>Measurement platforms</u>***

Open-ocean observatories supporting physical and biogeochemical measurement programs will be constituted using a variety of technologies including surface and subsurface moorings and autonomous vehicles. The specific mix of instrumentation will be guided by the (funded) scientific goals and technological constraints of each observatory station.

Mooring technology, both surface and subsurface, is quite mature now. Subsurface moorings (able to support instruments at depths from ~50 m below the surface to the bottom) may be deployed anywhere in the world today with an endurance of at least 2 years (with 5 year missions in development). Several schemes to provide real-time data from subsurface moorings have been fielded and/or are in development now involving data capsules, underwater winch systems or autonomous vehicles. Thus observatories based on subsurface mooring technology will be able to jump start the ORION program and begin returning data while the more complex systems are being engineered and fielded.

Surface moorings for the temperate oceans are also a mature technology, and offer complementary capability/limitations to subsurface moorings. The surface buoyancy element of these moorings provides a natural platform for boundary layer meteorological measurements (see companion proposal authored by Weller et al.) and makes real-time telemetry relatively straightforward. However, active forcing of the mooring by wave action and sensor performance degradation over long time periods currently limits endurance to around 1 year (although the NDBC is achieving multi-year deployments). For many of the sites targeted for occupation by this proposal, present surface mooring technology is viable for initial data collection.

Moored water column measurement systems fall into two basic categories: discrete sensors at fixed depth and profiling systems. Both have strengths and weaknesses, and so a mix of technologies is proposed for the open-ocean OOI program. Fast-temporal sampling for long time-periods is most effectively achieved with individual sensors mounted at discrete depths on a mooring. This traditional approach is well proven and is the core technology we propose for the open-ocean observatories. Shortcomings to this approach include the limited vertical resolution capable with discrete sensors, absolute and intercalibration of multiple sensors and the costs to acquire and maintain numerous sensors. Profiling technology in which a single suite of sensors is moved vertically through the water column addresses many of these issues. Three types of profiling technologies are available or in development: underwater winches, devices that move themselves up and down a mooring wire, and free vehicles. But the limited speed, endurance, and payload of these devices and the fact that a single moving device is more prone to failure than multiple fixed sensors means that they cannot fully replace the conventional technology. Thus a mix of technology is proposed for the open-ocean observatories.

We therefore propose that the fully multidisciplinary observatories addressing all the needs of air-sea flux measurements, physical and biogeochemical water-column observations, and geophysical ocean-bottom instrumentation, will ultimately need to consist of two co-located moorings plus a spatial sampling system:

- One mooring would carry the profiling systems. Two complimentary techniques for this merged into one mooring seems to be ideal and technically feasible within a few years. The surface layer (upper 150m or so) could be covered with an underwater winch, like the one just funded by NSF for development. This system can profile all the way to the surface and can accommodate a large suite of commercially available sensors, e.g. CTD, biooptics, nutrients, CO_2, O_2, pH, LOPC, and establishes data telemetry when at the surface (but also avoid the surface when too rough or ice-covered). The full ocean depth below 150m could be covered with a system propelling itself up/down the mooring wire, like e.g. the Moored Profiler (Doherty et al., 1999; Morrison et al., 2000; 2001). The device currently commercially available from McLane Research Instruments, Inc. has been interfaced to a CTD (temperature, conductivity, depth) - dissolved oxygen sensor, acoustic current meter (ACM), fluorometer and optical backscatter sensor (OBS). Data telemetry capability is supported with an inductive model used to relay information from the Profiler through the plastic-jacketed wire mooring rope. For OOI applications, these data will be assembled by a controller mounted at the subsurface floatation and would be fed into the winch module for transmission to shore.

- Where air-sea flux observations are desired, or sensors sampling rapidly at fixed depths, or samplers that are too large to incorporate into any profiling system, or where continuous data transfer and possibly power delivery down the mooring wire is needed, a surface mooring needs to be added to the observatory. The fully multidisciplinary observatory would have this as a second mooring for various surface-layer and atmospheric observations (see Weller et al proposal), include acoustic instrumentations (ADCP, zooplankton/fish echosounders) and trace metal water samplers in the watercolumn, support AUV docking stations, and provide power and data connections to the seafloor and the AUV dock.
- As mentioned in several places above, the temporally well-resolved observations at the single locations of the moored installations need to be put into a spatial context, in order to quantify the representativeness and gradients around the observatory site. Underwater gliders and autonomous vehicles are an exciting emerging technology that holds promise for providing this complementary information. The current suite of gliders and autonomous vehicles are somewhat limited by endurance, speed and the sensors they can carry. By the time the OOI will be installed, gliders are likely to have reached an endurance of 1 year, allowing them to be recovered and redeployed during mooring services. The ability now in development for an AUV to dock with a mooring to exchange data and recharge batteries will significantly address some of the remaining constraints. In addition, the global ARGO float network will provide larger-scale spatial background information, and in regions where floats are expected to remain in the vicinity of an observatory for extended periods, it may be worthwhile to equip them with additional multidisciplinary sensors in support of the observatory site.

b: <u>time and work schedule</u>

We propose a phased implementation of the sites described in the current proposal, guided by ORION and community needs and feedback, by international contributions and cooperations, and by funding considerations. A gradual ramping up of sites seems necessary for various reasons, since the OOI infrastructure cannot and should not be installed all at once. The capacity for implementation and operation needs to be developed over time. While various sites can be built with available technologies, the combination of many of them into a single observatory will require step-wise approaches and demonstration with fewer intial sites before expanding the network. The new capabilities to be developed for high latitudes and high bandwidth/power need time for testing and gaining experience. Working with the proposed 16 sites therefore, we anticipate implementation of 4 sites per year over a 4-year period, starting with the ones that are more ready and easiest to initiate.

6. Program Management Considerations

Our consortium plans to exploit the bandwidth and two-way capabilities of the new observatories. Variability and episodic events will be analyzed and responded to via a link between the data management team and the science operators. Data users such as particiants in ongoing process studies, and those involved in the development, validation, and verification of models and remote sensing methods, will be supplied data in near real time.

A science panel will be formed that includes all PIs for the consortium work and is open to colleagues who later propose additional water column studies using the global array. The panel will work with the global array operators (those funded by ORION to build and deploy the elements of the Global Array) to organize the deployment of the sensors on moorings. It will maintain a dialog with their peer groups from the air-sea flux and geophysics consortia planning to propose projects using the Global Array infrastructure and will liaise with the ORION Project Office, the ORION Management structure, national science programs (CLIVAR, SOLAS, for example) and international partners via OceanSITES to coordinate submission of collaborative proposals and selection and scheduling of global sites to be occupied. The science panel will encourage the communication between investigators and the ORION project to ensure sensors and instruments will plug into the hardware and software provided by the ORION project. Some of the PI's institutions have their own mooring design, fabrication, and deployment capacities; and it is anticipated that these resources would be offered, either in the form of a proposal to build and operate elements of the Global Array or as subcontractors to the Global Array operator(s).

The science panel will coordinate the integration of the many sensors and technologies by bringing together technical staff from among the investigators. It is planned that through cross-training and interaction, we can evolve a shared group of trained technical expertise that minimizes people committed to each cruise, spreads the work load, and makes the operation and maintenance of a global array practical and efficient. In the same way we would train a core group to monitor the telemetered data streams as part of the data management team and alert specific investigators as issues arise; this will eliminate duplication of effort and make good use of the collection and distribution service to be provided by the DAC and the ORION project.

The science panel will host an annual meeting of the water column investigators. This meeting will be a forum for program management and also provide both an opportunity for individual science progress reports and the growth of collaborative partnerships to further pursue science objectives. To minimize travel costs, these meetings should take place in conjunction with national scientific or ORION meetings where possible. In addition, we propose that one member from the water column group serve on the ORION executive committee.

7. Data Management Considerations

The prime paradigm for the data management and dissemination efforts is that all observatory data are publicly available without restrictions, both in real-time and in delayed-mode. Our data management plan will follow the broad outlines of the Data Management and Communications (DMAC) plan of the U.S. Integrated Ocean Observing System (IOOS; Hankin *et al*., 2005, http://dmac.ocean.us/dacsc/imp_plan.jsp). We will operate as a consortium of investigators making watercolumn timeseries observations from the global array. Our goal, consistent with that of the overall IOOS, will be to acquire data from the global array, create a secure and accessible archive, and deliver real-time and delayed-mode observations to a variety of users (e.g., researchers, educators, students, modeling centers). Descriptive information about the data (metadata) will be integrated into the data stream and will stay with the data during archiving and distribution. The data management plan will make data and derived data products readily accessible via a web interface and provide tools, or be compliant with available tools, for locating and retrieving data and metadata. We will, wherever possible, follow the conventions and use the data management infrastructure of the international OceanSITES (http://www.OceanSITES.org) program (see below), which shares data from time series stations around the global ocean. This will allow users to complement ORION Global Observatory data sets with time series from other long-term sites. The OceanSITES data sharing element is lead by Sylvie Pouliquen of IFREMER/CORIOLIS. OceanSITES is an action group of the JCOMM (WMO/IOC Joint Commission for Oceanography and Marine Meteorology) DBCP (Data Buoy Cooperation Panel), and our partnering with OceanSITES data management will ensure full international exposure to diverse users.

A. Data Streams

Real-time

There will be two types of data flow from the Global Array: Real-time and delayed mode. Real-time data will include complete data from some sources (e.g. slowly sampling chemical sensors) and partial or averaged data from other sources (acoustic or optical imaging data). These data will come directly to shore from surface or surfacing buoys, using satellite telemetry. Real-time data will be immediately archived and made available on a web site in its raw form, and simultaneously forwarded to a national or global timeseries data center (see below). Obviously, the appeal of the real-time data will be the short delay (~1hr), and we will ensure that these data are made available to regional observing centers, modeling centers, or any other groups that may be interested in derived products that depend on data from our array. The drawback of real-time data for the non-expert user will be the lack of quality control or value-added processing. As a result, these data are likely to be of the most interest to project researchers and technicians who are monitoring instrument performance, developing integrated data products, or implementing adaptive sampling strategies, or to operational modelling and forecasting centers which are aware of the data quality and the limitiations of automated real-time quality control.

Delayed-mode

Delayed-mode data will encompass a broad range of data that either could not be exported in real time due to bandwidth or to the need for analysis or processing. This means that instruments need to be recovered first and/or data (or samples) analyzed and quality controlled on land. Generally, the newer measurement methods used for the non-physical variables will require greater scrutiny, post-processing, and quality control to produce data products for sharing and archiving. Delayed-mode quality control can take 6-12 months.

Bi-directionality

Two-way communication will allow a response to events, adaptive sampling, and triggering other sensors depending on events detected. For ease of incorporation of sensors into such sensor networks, a recent ORION workshop organized by A. Chave for moored buoy use scenarios and technological requirements, recommended to equip each sensor with an internet IP protocol interface for standardized addressing. There are also emerging efforts for advancing the standardization to a plug-and-play level. The exact infrastructure and logic behind such plans still needs to be developed within ORION.

B. Metadata

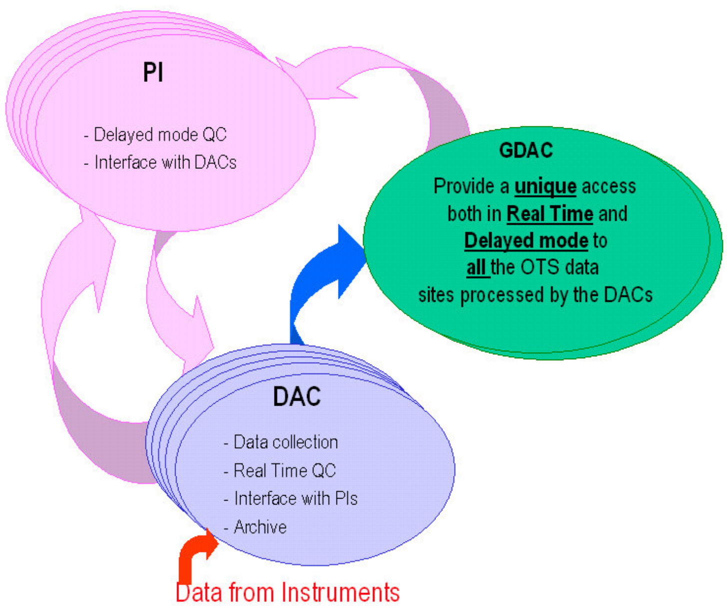
In the case of both the physical and non-physical variables, an important aspect of the data management will be the desire to carry forward to the user the supporting data sets, metadata, and technical information that establishes the credibility of the Global Array time series. In particular, we will collect the shipboard observations made at the times of deployments and recovery and the laboratory and field pre- and post-deployment calibration information that as a body establish the accuracy of the observatory data. This is a critical component of the total effort, and in-situ comparisons of shipboard and moored sensors need to be documented. We will provide metadata descriptions for our observatory components and their data products. We expect that the format, content, and vocabulary of such descriptions will be specified for each entire observatory, to assure consistency across all participants, and that it will follow established conventions in the US and international community.

C. Data Format

A format for timeseries data has been drafted by the international OceanSites program (see above). It is in Netcdf format, and was built by adapting to mooring data the format developed for Argo and Gosud (Global Ocean Surface Underway data), and including elements of the US DMAC plan. The format is now being adopted by some of the global timeseries operators. Here is a quote from the chairman of the US DMAC program about the OceanSITES data format: "The OceanSITES standard is a very sensible standard to support. While it is not possible to make a strict promise that OceanSITES will be the last time series standard that you will ever be asked to address, I can say that it looks like the best prospect for a stable standard that is available today. Neither IOOS nor Orion/OOI are mature enough to have provided concrete guidance (though both have helped to raise awareness of how severely hampered the community is today by inadequate data standards). The lack of agreed-upon, modern standards for the data interchange is particularly acute for time series data. Time series have fallen through the cracks as standards have been developing in the GIS world and the modeling world alike. The new OceanSITES standard has the virtue that it is nearly a proper subset of the emerging 4d standards for model data (the netCDF "CF" conventions). As a result there is high promise that compatibility with both IOOS and Orion will come "for free" (assuming that you install freely available OPeNDAP data servers for your OceanSITES netCDF files and that one of the multiple concurrent efforts to harmonize CF and GIS bear fruit). In other words, if you have to choose a single time series standard to support, OceanSITES is the most promising choice today."

D. Data Centers

When some sites in the OceanSITES network have started to provide data in the new format, the the next step is to set up two international timeseries Global data centres (GDACs) as entry portals: CORIOLIS in France, COADS in USA. The GDACs will provide a unique access to the data from the OceanSites data providers. These institutions will put their data in the defined format and either transfer them to one of the two GDACs or, where available, link to them in distributed manner using OPeNDAP technology. The GDACs will synchronize periodically to be sure to provide to users access to the same datasets. For the time being most of the OceanSites data are handled by individual PI's. It would be probably better if at a national level data assembly centres (DACs) were set up, similar to ARGO, to handle a large part of the data management task necessary within the OceanSites network. The consortium of the current proposal, through ORION, would work toward setting up a US DAC. The adjacent figure sketches a possible organizational structure.



E. Data Distribution

Data distribution methods will be developed to meet the needs of data users. The DAC will liaise with the user community (e.g., model, satellite, oceanography) and climate programs (e.g., CLIVAR, GOOS, GODAE) to determine which products are needed by each community. User needs are anticipated to differ among the research and operational communities and we plan to adjust our distribution systems accordingly. In addition, we will actively pursue new users.

Distribution of the quality-assured meteorological data will primarily be achieved through on-line technology. The shortest possible delay from receipt of the data to release of a quality assured version will be developed. Data will also be made available on digital media (e.g., CD, DVD, exabyte tape) upon request from users. The DAC will work to expand user access through collaboration with ongoing national/international data infrastructures (e.g., Distributed Oceanographic Data System [DODS], Live Access Server [LAS]) and by feeding the global OceanSITES data centers. The DAC will also actively participate in the Ocean.US Integrated Ocean Observing System - Data Management and Communications System (IOOS-DMAC) initiatives.

F. Quality control

Quality control is the most important process that can be applied to collected data. With good quality control, the data will be considerably more useful to other scientists. It is fairly well agreed that good quality control requires a visual review by a domain expert, so the emphasis of the data management effort is to support the domain experts needs. The typical observatory quality control scheme, to be run on every data stream or data set, in real-time and delayed-mode will include:

- data existence, validity, and operational consistency checks (check for gross malfunction)
- tailored bounds, spike, and variation checks
- summary statistics and plots delivered to domain expert for review
- all points of concern are appropriately flagged, not removed (QC histories remain tied to data set)

Common QC procedures both in real time and delayed mode at least for the core parameters will be developed, building on and being coherent with what has been/is being defined by other groups when the parameters are the same (i.e., with Argo for subsurface temperature and salinity measurements). Automated QC will be applied on the real-time data stream, while delayed-mode procedures usually need months to be applied and validated by experts or the PIs.

G. Merging and Integration

In its simplest form, we need to be able to take data from a particular area and time, and merge it with other data from that area that has the exact same time base. At a slightly more complicated level, we must be prepared to interpolate some data so that a single result can be created with a common time base. There are many issues and challenges in this kind of merging, and the intent of this task is to focus on what is possible in the short term. While we can implement these features as one-off solutions, the results will not have the community support that is desired and beneficial, and we encourage an approach that will build on the tools and expertise of existing data centers. In particular the global GDACs have experience at this, and the QC procedures, formats, and metadata that will be implemented for OceanSITES will facilitate this since they are consistent with the same for many other in-situ oceanographic data that already exist at such centers.

Future efforts will expand the types of data integration supported, in particular using distributed data systems and other elements of the US IOOS.

8. Education and Public Outreach

In parallel to conceptualization of ocean science research experiments using the OOI, efforts are underway to design infrastructure to maximize the education and public outreach (EPO) potential of coastal, regional and global-scale observatories. The Education Working Group at the January 2004 ORION Workshop made six major recommendations regarding the infrastructural requirements of the ORION education program (ORION Workshop Report, Chapter 5), three of which were included in the ORION science plan as constituting the core goals of the ORION Education and Public Awareness Plan.

- Form an education and communications coordination office.
- Establish a data management and content translation facility.
- Establish a community of educator leaders who coordinate, sustain, and support local education leadership in their science education improvement initiatives.

The science plan asserts, "Educational programs designed for the OOI infrastructure will be ground-breaking in the way they… integrate the huge volume of real-time and near-real-time data and imagery, the diverse types of data and information products, and an ever-growing reservoir of archived data". The key infrastructural component necessary to realize this vision is a *data management and content translation facility* focused on the educational applications of ORION data products.

Such a facility is essential, for while the institutional infrastructure and personnel (in the form of established labs and data management facilities associated with large projects) exist to support scientific data management, no such entities or teams of personnel exist to create effective mechanisms for using observatory data in an educational context. Recent articles in the ORION Newsletter have emphasized the value of scientist-educator collaboration, called for the development of mechanisms to identify and share "effective practices" concerning ocean observing system EPO (McDonnell, 2005), and discussed the design of educational portals to observatory data based on educators' needs (Matsumoto and Bell, 2005).

The data management and content translation facility will provide the essential infrastructural underpinnings for all E&O activities associated with OOI/OION. Without focused needs-assessment, piloting and evaluation of how we can best use OOI data – the educational tools and products we generate will fall short of the transformation in ocean science education that we envision for this large project. This facility will have several key functions: 1) It will serve as the critical link between those coordinating scientific data management and the critically important education user groups; 2) It will provide the requisite guidance for the appropriate use of OOI data in a wide variety of contexts, including school curricula, undergraduate education, exhibits and programs created at science centers, museums and aquariums, educator professional development programs (K-16), multi media productions and public communications, including communicating with policy makers; 3) It will provide tools and services to support the other two core elements of the Education and Public Awareness Plan (i.e. the coordination office and the community of educator-leaders). The facility will truly serve as the keystone in the bridge between the research and education communities for ORION. We propose to contribute to such a facility with staff and infrastructure.

9. Summary

As argued here, the need for a coordinated global network of ocean observatories supporting a wide range of multidisciplinary investigations is compelling. The present proposal represents one element of such a program: study of water column processes. We note however the close scientific ties with the Weller *et al.* companion proposal to investigate air-sea interaction, the strong potential for logistical and data-communication ties with the companion geophysics proposal by Orcutt *et al.*, and tight relationships with several specific-site open-ocean observatory proposals. The present consortium of investigators looks forward to interacting with this larger group to refine the ORION science and measurement plans.

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APPENDICES: Budget information and CV's

Instrument	number per site	Unit cost	size	Weight (water)	Power	Data volume rate	Service interval
<u>SENSORS</u>							
ADCP longranger	1	$45K	100x40cm	55kg	1.5W, 20-60VDC	50kB/day	2y
CTD sensor	5	$10K	50x15cm	3kg	50mA, 7-16V	20kB/day	2y
Acoustic current meter	1	$10K	Included….	…..in….	……..deep……………	….profiler….	2y
Dissolved oxygen sensor	2	$5K	30x7cm	1kg	60mW, 7-14V	1kb/day	1y
Fluorometer/backscatter/ attenuation "puck"	2	$10K	25x7cm	0.1kg	24mAh/day, 7-15VDC	2kb/day	1y
Multi-spectral radiance	1	$8K	7x15cm	0.5kg	40mA	1kb/day	1y
Multi-spectral irradiance	1	$8K	7x15cm	0.5kg	40mA	1kb/day	1y
Nitrate sensor	2	$25K	60x15cm	1kg	0.5A, 12V	<1kb/day	
pCO2 sensor	2	$20K	60x20cm	4kg	400mA, 12V	<1kb/day	1y
pH sensor	2	under	development			1kb/day	
Laser optical plankton counter (LOPC)	1	$40K	49x25x10cm	6kg	Tbd	Tbd	1y
Dual frequency zoo-plankton /fish echosounder	2	$50K	50x35cm	15kg	35W	12MB/day	1y
Trace metal water sampler	1	$60K	6'x22 "	0kg	50Wh per sample	n.a. (sample collection)	1y
<u>OTHER</u>							
Inductive modems	5	$6K	internal		10mA, 9V	9600baud	n.a.
Underwater gliders /AUV	1	$70K	n.a.	n.a.	n.a.	n.a.	n.a.
<u>PLATFORM/VEHICLE</u>							
Upper ocean profiler (e.g. winch)	1	$130K	Under development	n.a.	Tbd	n.a.	1y
Deep profiler (e.g. MMP) Only platform, no sensors	1	$45K	130x50cm	0 kg.	200 mA, 8-11V (when profiling)	1 MB/day	1y

Table A-1 : *Instrument specifications*

Budget Item	Year 1 (2007) Install 4 new sites Acquire 2 swap-out	Year 2 (2008) Service 4 old sites Install 4 new sites Acquire 1 swap-out	Year 3 (2009) Service 8 old sites Install 4 new sites Acquire 1 swap-out	Year 4 (2010) Service 12 old sites Install 4 new sites Acquire 1 swap-out	Year 5 (2011) Service 16 sites
Personnel **(in person-months)**					
Sr. Scientist	24 @ 14.3K	36	48	60	60
Sr. Engineer	48 @ 11.2K	48	48	48	48
Jr Scientist	60 @ 7.8K	80	100	120	120
Grad student/tuition	120 @ 3.6K	180	240	240	240
Data manager	12 @ 8.2K	18	24	24	24
Outreach	12 @ 7.3K	12	12	12	12
Technician (lab)	48 @ 6.7K	60	80	96	96
Technician (sea)	16 @ 6.7K	32	48	64	64
Total Salaries and Benefits	$ 2,395,600	$3,287,200	$4,295,600	$5,046,900	$5.223.500
Equipment **(see Table A-1)**	6x $780K = $4,680K	5x $803K = $4,015K	5x $827K = $4,135K	5x $852K = $4,260K	0
computing	$200K	$200K	$200K	$200K	$200K
Expendable Supplies					
Batteries,antifouling,etc	$80K	$160K	$240K	$320K	$320K
Lab and cruise supplies	$90K	$130K	$170K	$210K	$210K
Travel science	$110K	$110K	$110K	$110K	$110K
Cruises	$56K	$112K	$168K	$224K	$224K
Communication	$90K	$170K	$250K	$330K	$330K
Transport /Shipping	$32K	$64K	$96K	$128K	$128K
Total Direct Costs	$7,733,600	$8,248,200	$9,664,600	$10,828,900	$6,745,500
Indirect Costs	$1,424,400	$2,001,900	$2,643,000	$3,209,500	$3,305,700
Total	**$9,158,000**	**$10,250,100**	**$12,307,600**	**$14,038,400**	**$10,051,200**
Ship time (da) (on site; excl. transits)	**12 da**	**24 da**	**36 da**	**48 da**	**48 da**

Table A-2 : *Budget Overview*

Budget explanation :
Salaries and instrument costs assume an appreciation of 3.5% per year. Indirect costs are assumed to be 54.5% of all items except equipment and student tuition.

Salaries :

We will be working in 10 teams covering the following scientific and technical expertises in terms of scientific analysis and sensor implementation, service, deployments :
(1) water mass formation processes, (2) transport observation; variability in homogeneous regimes, (3) CO_2 fluxes and carbon cycle, (4) oxygen and nutrient processes, (5) primary productivity, (6) zooplankton, fish, ecosystem variability, (7) trace metals, (8) 1-D ecosystem model development and assimilation, (9) ecosystem models coupled to full GCMs, (10) glider observations. These teams are not necessarily located at a single institution - in general several consortium members will contribute to one such team and share the work/collaborate.

Each team will require 0.5 FTE of senior researchers/PI's for project and science supervision, 1.0 FTE of junior scientists (1/3 postdoc, 1/3 assistant, 1/3 associate level) for scientific analysis work. The 8 observational teams further each need on average 1.0 FTE for technical work on instrumentation, 0.5 FTE of senior development engineers for sensor adaptation into the observatory and telemetry. In addition, technical staff is needed for at-sea work during the deployment/service cruises: each year each site needs to be visited once with an average cruise length of 3 weeks and 5 technicians need to participate (plus overtime), which gives 0.33 FTE per site. Graduate students should be supported as 2 per team.

Salaries are futher requested for development and maintenance of the data management effort described (2 FTE), including the contribution to a national timeseries DAC, and for outreach activities as proposed above (1 FTE EPO contributing the facility).

Computing:

This covers workstations, desktop PCs, and software (databases, visualization, analysis) for the data management ($50K per year), the education and outreach facility ($100K per year), and for the scientific analysis work ($50K per year).

Expendable Supplies:

Each site carries approximately 25 different sensors, plus the profiling systems. The supplies needed for servicing these, including batteries, antifouling systems, spare parts, are estimated at $20K per site. Lab supplies are estimated at $5K per team per year, cruise supplies at $10K per cruise.

Travel:

ORION meetings domestic:

2 per team/year @ $2K = $40K/year.

Scientific meetings and conferences:

domestic 2 per team/year @ $2K = $40K/year ,

international 1 per team per year @ $3K = $30K/year.

Field work (cruises) 7 per site/year (5 technical, 2 scientists) @ $2K = $14K/year /site

Communication:

This mainly includes satellite telemetry (e.g. Iridium) costs of $20K per site/year, plus $1K per team for telephone etc.

Transport/Shipping:

Each team is expected to ship equipment between manufacturers, labs, observatory integration facility, start/end ports of cruises. We estimate 1 surface and 1 air shipments per observational team per year and per site @ $0.5K each,

Ship time:

We estimate each site will require 3 day on location.

SUMMARY PROPOSAL BUDGET

Year 1

FOR ORION USE ONLY

ORGANIZATION	PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
______			
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR ______	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted (If Different)
1. Sr. Scientist	__	__	__	$ 343,200	$______
2. Sr. Engineer	__	__	__	$ 537,600	______
3. Jr. Scientist	__	__	__	$ 468,000	______
4.	__	__	__		______
5. ______	__	__	__	______	______
6. (___) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	__	__	__	______	______
7. (___) TOTAL SENIOR PERSONNEL (1-6)	__	__	__	______	______
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (___) POSTDOCTORAL ASSOCIATES	__	__	__	______	______
2. (___) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	__	__	__	$ 614,800	______
3. (___) GRADUATE STUDENTS				$ 432,000	______
4. (___) UNDERGRADUATE STUDENTS				______	______
5. (___) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				______	______
6. (___) OTHER				______	______
TOTAL SALARIES AND WAGES (A + B)				$ 2,395,600	______
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				______	______
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$ 2,395,600	______
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) ______					
TOTAL EQUIPMENT				$ 4,880,000	______
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				$ 80,000	______
2. FOREIGN				$ 86,000	______
F. PARTICIPANT SUPPORT 1. STIPENDS $ ______ 2. TRAVEL ______ 3. SUBSISTENCE ______ 4. OTHER ______					
TOTAL NUMBER OF PARTICIPANTS (______) TOTAL PARTICIPANT COSTS				______	______
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$ 170,000	______
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				______	______
3. CONSULTANT SERVICES				______	______
4. COMPUTER SERVICES				______	______
5. SUBAWARDS				______	______
6. OTHER (Communication & Transport/Shipping)				$ 122,000	______
TOTAL OTHER DIRECT COSTS				$ 292,000	______
H. TOTAL DIRECT COSTS (A THROUGH G)				$ 7,733,600	______
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) ______ ______					
TOTAL INDIRECT COSTS (F&A)				$ 1,424,400	______
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$ 9,158,000	______
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)				______	______
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 9,158,000	$_____

M. COST SHARING: PROPOSED LEVEL $______	AGREED LEVEL IF DIFFERENT: $______		
PI/PD TYPED NAME AND SIGNATURE*	DATE	**FOR ORION USE ONLY** INDIRECT COST RATE VERIFICATION	
ORG. REP. TYPED NAME & SIGNATURE* ______	DATE ______	Date Checked	Date of Rate Sheet	Initials-ORG

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.C)

SUMMARY PROPOSAL BUDGET

Year 2

FOR ORION USE ONLY	
ORGANIZATION ______	PROPOSAL NO.	DURATION (MONTHS) Proposed / Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR ______	AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted (If Different)
1. Sr. Scientist	__	__	__	$ 532,820	$______
2. Sr. Engineer	__	__	__	$ 556,420	______
3. Jr. Scientist	__	__	__	$ 645.840	______
4.	__	__	__		______
5. ______	__	__	__	______	______
6. (___) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	__	__	__	______	______
7. (___) TOTAL SENIOR PERSONNEL (1-6)	__	__	__	______	______
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (___) POSTDOCTORAL ASSOCIATES	__	__	__	______	______
2. (___) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	__	__	__	$ 881,440	______
3. (___) GRADUATE STUDENTS				$ 670,680	______
4. (___) UNDERGRADUATE STUDENTS				______	______
5. (___) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				______	______
6. (___) OTHER				______	______
TOTAL SALARIES AND WAGES (A + B)				$ 3,287,200	______
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				______	______
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$ 3,287,200	______
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) ______					
TOTAL EQUIPMENT				$ 4,215,000	______
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				$ 80,000	______
2. FOREIGN				$ 142,000	______
F. PARTICIPANT SUPPORT 1. STIPENDS $ ______ 2. TRAVEL ______ 3. SUBSISTENCE ______ 4. OTHER ______					
TOTAL NUMBER OF PARTICIPANTS (______) TOTAL PARTICIPANT COSTS				______	______
G. OTHER DIRECT COSTS				______	______
1. MATERIALS AND SUPPLIES				$ 290,000	______
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				______	______
3. CONSULTANT SERVICES				______	______
4. COMPUTER SERVICES				______	______
5. SUBAWARDS				______	______
6. OTHER (Communication & Transport/Shipping)				$ 234,000	______
TOTAL OTHER DIRECT COSTS				$ 524,000	______
H. TOTAL DIRECT COSTS (A THROUGH G)				$ 8,248,200	______
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) ______ ______					
TOTAL INDIRECT COSTS (F&A)				$ 2,001,900	______
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$ 10,250,100	______
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)				______	______
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$______	$______

M. COST SHARING: PROPOSED LEVEL $______	AGREED LEVEL IF DIFFERENT: $______	
PI/PD TYPED NAME AND SIGNATURE* ______	DATE ______	**FOR ORION USE ONLY** INDIRECT COST RATE VERIFICATION
ORG. REP. TYPED NAME & SIGNATURE* ______	DATE ______	Date Checked / Date of Rate Sheet / Initials-ORG

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			FOR ORION USE ONLY		
SUMMARY PROPOSAL BUDGET		**Year 3**			
ORGANIZATION ______			PROPOSAL NO.	DURATION (MONTHS)	
				Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR ______			AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted (If Different)
1. Sr. Scientist	__	__	__	$ 735,290	$______
2. Sr. Engineer	__	__	__	$ 575,900	______
3. Jr. Scientist	__	__	__	$ 835,560	______
4.	__	__	__		______
5. ______	__	__	__	______	______
6. (___) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	__	__	__	______	______
7. (___) TOTAL SENIOR PERSONNEL (1-6)	__	__	__	______	______
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (___) POSTDOCTORAL ASSOCIATES	__	__	__	______	______
2. (___) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	__	__	__	$ 1,223,310	______
3. (___) GRADUATE STUDENTS				$ 925,540	______
4. (___) UNDERGRADUATE STUDENTS				______	______
5. (___) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				______	______
6. (___) OTHER				______	______
TOTAL SALARIES AND WAGES (A + B)				$ 4,295,600	______
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				______	______
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$ 4,295,600	______
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) ______					
TOTAL EQUIPMENT				$ 4,435,000	______
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				$ 80,000	______
2. FOREIGN				$198,000	______
F. PARTICIPANT SUPPORT 1. STIPENDS $ ______ 2. TRAVEL ______ 3. SUBSISTENCE ______ 4. OTHER ______					
TOTAL NUMBER OF PARTICIPANTS (______) TOTAL PARTICIPANT COSTS				______	______
G. OTHER DIRECT COSTS				______	______
1. MATERIALS AND SUPPLIES				$ 410,000	______
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				______	______
3. CONSULTANT SERVICES				______	______
4. COMPUTER SERVICES				______	______
5. SUBAWARDS				______	______
6. OTHER (Communication & Transport/Shipping)				$ 346,000	______
TOTAL OTHER DIRECT COSTS				$ 756,000	______
H. TOTAL DIRECT COSTS (A THROUGH G)				$ 9,664,600	______
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) ______ ______					
TOTAL INDIRECT COSTS (F&A)				$ 2,643,000	______
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$ 12,307,600	______
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)				______	______
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$_____	$_____

M. COST SHARING: PROPOSED LEVEL $______	AGREED LEVEL IF DIFFERENT: $______			
PI/PD TYPED NAME AND SIGNATURE*	DATE	FOR ORION USE ONLY		
		INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE* ______	DATE ______	Date Checked	Date of Rate Sheet	Initials-ORG

OOI Form 1030 (10/99) ***Supersedes All Previous Editions*** *SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.C)

	FOR ORION USE ONLY		
SUMMARY PROPOSAL BUDGET **Year 4**			
ORGANIZATION ______	PROPOSAL NO.	DURATION (MONTHS)	
		Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR ______	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	Funded Person-months			Funds Requested By Proposer	Funds Granted (If Different)
	CAL	ACAD	SUMR		
1. Sr. Scientist	__	__	__	$ 951,280	$______
2. Sr. Engineer	__	__	__	$ 596,050	______
3. Jr. Scientist	__	__	__	$ 1,037,760	______
4.	__	__	__		______
5. ______	__	__	__	______	______
6. (___) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	__	__	__	______	______
7. (___) TOTAL SENIOR PERSONNEL (1-6)	__	__	__	______	______
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (___) POSTDOCTORAL ASSOCIATES	__	__	__	______	______
2. (___) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	__	__	__	$ 1,503,870	______
3. (___) GRADUATE STUDENTS				$ 957,940	______
4. (___) UNDERGRADUATE STUDENTS				______	______
5. (___) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				______	______
6. (___) OTHER				______	______
TOTAL SALARIES AND WAGES (A + B)				$ 5,046,900	______
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				______	______
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$ 5,046,900	______
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) ______					
TOTAL EQUIPMENT				$ 4,460,000	______
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				$ 80,000	______
2. FOREIGN				$ 254,000	______
F. PARTICIPANT SUPPORT 1. STIPENDS $ ______ 2. TRAVEL ______ 3. SUBSISTENCE ______ 4. OTHER ______					
TOTAL NUMBER OF PARTICIPANTS (______) TOTAL PARTICIPANT COSTS				______	______
G. OTHER DIRECT COSTS				______	______
1. MATERIALS AND SUPPLIES				$ 530,000	______
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				______	______
3. CONSULTANT SERVICES				______	______
4. COMPUTER SERVICES				______	______
5. SUBAWARDS				______	______
6. OTHER (Communication & Transport/Shipping)				$ 458,000	______
TOTAL OTHER DIRECT COSTS				$ 988,000	______
H. TOTAL DIRECT COSTS (A THROUGH G)				$ 10,828,900	______
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) ______ ______					
TOTAL INDIRECT COSTS (F&A)				$ 3,209,500	______
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$ 14,038,400	______
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)				______	______
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$_____	$_____

M. COST SHARING: PROPOSED LEVEL $______	AGREED LEVEL IF DIFFERENT: $______			
PI/PD TYPED NAME AND SIGNATURE*	DATE	FOR ORION USE ONLY		
		INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE* ______	DATE ______	Date Checked	Date of Rate Sheet	Initials-ORG

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FOR ORION USE ONLY

SUMMARY PROPOSAL BUDGET

Year 5

ORGANIZATION ______			PROPOSAL NO.	DURATION (MONTHS)	
				Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR ______			AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted (If Different)
1. Sr. Scientist	__	__	__	$ 984,580	$______
2. Sr. Engineer	__	__	__	$ 616,910	______
3. Jr. Scientist	__	__	__	$ 1,084,090	______
4.	__	__	__		______
5. ______	__	__	__	______	______
6. (___) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	__	__	__	______	______
7. (___) TOTAL SENIOR PERSONNEL (1-6)	__	__	__	______	______
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (___) POSTDOCTORAL ASSOCIATES	__	__	__	______	______
2. (___) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	__	__	__	$ 1,546,460	______
3. (___) GRADUATE STUDENTS				$ 991,460	______
4. (___) UNDERGRADUATE STUDENTS				______	______
5. (___) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				______	______
6. (___) OTHER				______	______
TOTAL SALARIES AND WAGES (A + B)				$ 5,223,500	______
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				______	______
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$ 5,223,500	______
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) ______ ______ ______					
TOTAL EQUIPMENT				$ 200,000	______
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				$ 80,000	______
2. FOREIGN				$ 254,000	______
F. PARTICIPANT SUPPORT 1. STIPENDS $ ______ 2. TRAVEL ______ 3. SUBSISTENCE ______ 4. OTHER ______					
TOTAL NUMBER OF PARTICIPANTS (______) TOTAL PARTICIPANT COSTS				______	______
G. OTHER DIRECT COSTS				______	______
1. MATERIALS AND SUPPLIES				$ 530,000	______
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				______	______
3. CONSULTANT SERVICES				______	______
4. COMPUTER SERVICES				______	______
5. SUBAWARDS				______	______
6. OTHER (Communication & Transport/Shipping)				$ 458,000	______
TOTAL OTHER DIRECT COSTS				$ 988,000	______
H. TOTAL DIRECT COSTS (A THROUGH G)				$ 6,745,500	______
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) ______ ______					
TOTAL INDIRECT COSTS (F&A)				$ 3,305,700	______
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$ 10,051,200	______
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)				______	______
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$______	$______

M. COST SHARING: PROPOSED LEVEL $______	AGREED LEVEL IF DIFFERENT: $______			
PI/PD TYPED NAME AND SIGNATURE*	DATE	FOR ORION USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. TYPED NAME & SIGNATURE* ______	DATE ______	Date Checked	Date of Rate Sheet	Initials-ORG

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*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.C)

CUMULATIVE PROPOSAL BUDGET

FOR ORION USE ONLY		
PROPOSAL NO.	DURATION (MONTHS)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
______

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
______

A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates List each separately with name and title. (A.7. Show number in brackets)	Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted (If Different)
1. Sr. Scientist	__	__	__	$ 3,547,170	$______
2. Sr. Engineer	__	__	__	$ 2,882,880	______
3. Jr. Scientist	__	__	__	$ 4,071,250	______
4. ______	__	__	__	______	______
5. ______	__	__	__	______	______
6. (___) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)	__	__	__	______	______
7. (___) TOTAL SENIOR PERSONNEL (1-6)	__	__	__	______	______
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (___) POSTDOCTORAL ASSOCIATES	__	__	__	______	______
2. (___) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	__	__	__	$ 5,769,880	______
3. (___) GRADUATE STUDENTS				$ 3,977,620	______
4. (___) UNDERGRADUATE STUDENTS				______	______
5. (___) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				______	______
6. (___) OTHER				______	______
TOTAL SALARIES AND WAGES (A + B)				______	______
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				______	______
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				$ 20,248,800	______
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) ______ ______ ______					
TOTAL EQUIPMENT				$ 18,090,000	______
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				$ 400,000	______
2. FOREIGN				$ 934,000	______
F. PARTICIPANT SUPPORT 1. STIPENDS $ ______ 2. TRAVEL ______ 3. SUBSISTENCE ______ 4. OTHER ______					
TOTAL NUMBER OF PARTICIPANTS (______) TOTAL PARTICIPANT COSTS				______	______
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$ 1,930,000	______
2. PUBLICATION/DOCUMENTATION/DISSEMINATION				______	______
3. CONSULTANT SERVICES				______	______
4. COMPUTER SERVICES				______	______
5. SUBAWARDS				______	______
6. OTHER ______				$ 1,618,000	______
TOTAL OTHER DIRECT COSTS				$ 3,548,000	______
H. TOTAL DIRECT COSTS (A THROUGH G)				$ 43,220,800	______
I. INDIRECT COSTS (F&A) (SPECIFY RATE AND BASE) ______ ______					
TOTAL INDIRECT COSTS (F&A)				$ 12,584,500	______
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				$ 55,805,300	______
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECT SEE GPG II.D.7.j.)				______	______
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 55,805,300	$_____

M. COST SHARING: PROPOSED LEVEL $______	AGREED LEVEL IF DIFFERENT: $______		
PI/PD TYPED NAME AND SIGNATURE*	DATE	FOR ORION USE ONLY INDIRECT COST RATE VERIFICATION	
ORG. REP. TYPED NAME & SIGNATURE* ______	DATE ______	Date Checked | Date of Rate Sheet	Initials-ORG

OOI Form 1030 (10/99) ***Supersedes All Previous Editions***

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPG III.C)

CURRICULUM VITAE: Francisco P. Chavez

Monterey Bay Aquarium Research Institute (MBARI)
7700 Sandholdt Road, Moss Landing, CA 95039-9644
Voice: 831-775-1709, FAX: 831-775-1620, Email: chfr@mbari.org

Education:

PhD	Duke University	Botany	1987
BS	Humboldt State University	Oceanography	1977

Professional Background:

2000-present	Senior Scientist, MBARI
2000-present	Faculty (courtesy), Stanford University
1996-2000	Associate Scientist (III), MBARI
1992-1996	Associate Scientist (II), MBARI
1990-present	Research Associate, University of California, Santa Cruz
1987-1992	Assistant Scientist, MBARI

Selected Professional Activities

Member JGOFS time series oversight committee
Reviewer, Chilean Oceanographic Program, Peruvian Fisheries and Oceanography Program
NSF Alan Waterman award committee (2003-2005)
NSF Advisory Committee for the Geoscience Directorate (2003-2005)
Board of Directors, Center for Integrated Marine Technologies (2002-)
Board of Govenors, Pacific Coastal Ocean Observing System
Science Team for Global Eulerian Observations (2002-)

Current Research Interests:

Biology and chemistry of the ocean in relation to natural climate variability and global change. Global carbon cycle. Instrumentation and systems for long-term ocean observing. Satellite remote sensing.

Graduate Advisor:

Richard T. Barber

Graduate Students:

Rafael A. Olivieri (UCSC), M. Celia Villac (Texas A&M), Jonathan Phinney (UCSC), Elena Mauri (MLML).

Post-Doctoral Advisor for:

Chris Scholin, Raphael Kudela, Peter Strutton, Russell Hopcroft, John Ryan, Carmen Castro, Brad Penta, Victor Kuwahara, Kevin Mahoney

Collaborators:

Fei Chai (University of Maine), Niki Gruber (UCLA), Richard Dugdale (SFSU), Don Croll (UC Santa Cruz), Adina Paytan (Stanford), Dennis Hansell (University of Miami), Curt Collins (NPS), Ken Johnson (MBARI).

Synergistic Activities:

Served on a number of ORION/OOI and IOOS committees
Moved MBARI development to moorings of the TAO array

5 Most Relevant Publications

Chavez, F.P. and J.R. Toggweiler (1995). Physical estimates of global new production: the upwelling contribution, In *Upwelling in the Ocean: Modern Processes and Ancient Records.* Summerhayes, C.P., Emeis, K.C., Angel, M.V., Smith, R.L., and Zeitzschel, B., (eds.), J. Wiley & Sons, Chichester.

Chavez, F.P., J.T. Pennington, R. Herlien, H. Jannasch, G. Thurmond and G.E. Friederich (1997) Moorings and drifters for real-time interdisciplinary oceanography. Journal of Atmospheric and Oceanic Technology **14,** 1199-1211.

Chavez, F.P., P.G. Strutton, G.E. Friederich, R.A. Feely, G.A. Feldman, D. Foley, and M.J. McPhaden. (1999) Biological and chemical response of the equatorial Pacific Ocean to the 1997 and 1998 El Niño. Science **286**, 2126-2131.

Chavez, F.P., D. Wright, R. Herlien, M. Kelley, F. Shane and P.G. Strutton (2000) A device for protecting moored spectroradiometers from bio-fouling. Journal of Oceanographic and Atmospheric Technology, **17**, 215-219.

Chavez, F.P., J.P. Ryan, S. Lluch-Cota and M. Ñiquen C. (2003) From anchovies to sardines and back-Multidecadal change in the Pacific Ocean. Science **299**, 217-221.

5 Additional Publications

Johnson, K.S., F.P. Chavez and G.E. Friederich (1999) Continental shelf sediment as a primary source of iron for coastal phytoplankton. Nature **398**, 697-700.

Chavez, F.P. and C.A. Collins (2000) Studies of the California Current System: present, past and future. Deep-Sea Research II, **47**, 761-763.

Chavez, F.P, C.A. Collins, A. Huyer, and D. Mackas eds. (2002) El Niño along the west coast of North America. Progress in Oceanography, **54**, 1-6.

Strutton, P.G. and F.P. Chavez (2004) Biological heating in the equatorial Pacific: Observed variability and potential for real-time calculation. Journal of Climate, **17**, 1097-1109.

Chavez, F.P. (in press) Biological consequences of interannual to multidecadal variability. Chapter 17 In Volume 13 of The Sea. A. Robinson and K. Brink (eds.).

Biographical Sketch
Steven R. Emerson

Address: School of Oceanography, Box 357940
University of Washington
Seattle, Washington 98195-7940
Date of Birth: 19 November, 1947
Citizenship: U.S.

Telephone: (206) 543-0428
Fax: (206) 685-3351
e-mail: emerson@u.washington.edu

Education

College of Wooster (Cum Laude), Wooster, Ohio, Geology, B.A., 1969
Columbia University, New York, Geochemistry, Oceanography, Environmental Sciences, Ph.D., l974
Swiss Federal Institute of Technology, Zurich, Switzerland, Aquatic Chemistry, Postdoctoral Research, 1974-1976

Employment

1986-present	Professor, School of Oceanography, UW
1982-1986	Associate Professor, School of Oceanography, UW
1980-1982	Assistant Professor, School of Oceanography, UW
1976-1979	Research Assistant Professor, School of Oceanography, UW

Research Interests

Cycling of oxygen and inert gases and isotopes in the ocean surface waters; organic carbon dynamics at the deep-sea sediment water interface; calcium carbonate preservation in the sea; sediment pore water chemistry the effect of anoxic conditions on solubility of metals in seawater

Five Publications Most Closely Related To This Research

Hamme, R and S. Emerson (2005) The effects of bubble dynamics and mixing on dissolved gases: Implications for productivity measurements at station ALOHA, *J. Mar.Res* . (in press)

Hamme, R and S. Emerson (2004a) Measurement of dissolved neon by isotope dilution quadrupole mass spectrometry, *Mar. Chem.,* 91, 53-64.

Hamme, R and S. Emerson (2004b) The solubility of neon, nitrogen and argon in distilled water and seawater, *Deep-Sea Res. I*, 1517-1528.

Hamme, R and S. Emerson (2002) Mechanisms controlling the global distribution of the inert gases Ar, N_2, and Ne in the ocean, *Geophysical Research Letters,* 29, doi: 0.1029/2000GL015273.

Emerson, S., C. Stump, B. Johnson, and D. Karl (2002) Autonomous determination of oxygen and nitrogen concentrations in the Ocean, *Deep-Sea Research I*, 49, 941-952.

Five Other Publications

Abell, J., S. Emerson and R. Keil (2005) Using preformed nitrate to infer decadal changes in DOM remineralization in subtropical North Pacific, Glob. Biogeochem. Cycles, 19, 1008, doi: 10.1029/2004GB00285

Emerson, S., T. W. Watanabe, T. Ono and Sabine Mecking (2004) Temporal trends in Apparent Oxygen Utilization in the upper pycnocline of the North Pacific: 1980-2000, *Jour. Oceanogr.*, 60, 139-147.

Emerson, S. and J. I. Hedges (2004) Sediment Diagenesis and Benthic Flux, In: Treatise on Geochemistry,V. 6, *The Oceans and Marine Geochemistry*, (H. Elderfield, ed.), Elsevier, Amsterdam, 646 p.

Emerson, S., C. Stump, D. Wilbur, and P. Quay (1999) Accurate measurement of O_2, N_2, and Ar gases in water and the solubility of N_2, *Marine Chemistry*, 64, 337-347.

Emerson, S., P. Quay, D. Karl, C. Winn, L. Tupas and M. Landry (1997) Experimental determination of the organic carbon flux from open-ocean surface waters, *Nature*, 389, 951 -954.

Synergistic Activities

a. Development of Curriculum materials for courses in:
   - Chemical Oceanography
   - Chemical Kinetics
   - The Carbon Cycle and Greenhouse Gases

b. Chairman of the 2001 Chemical Oceanography Gordon Conference

c. Thesis advisor for 9 Ph.D. and 3 Masters-degree students since 1980

Collaborators (other than at U.W. in the past 48 Months)

Ariel Anbar, University of Rochester
David Archer, University of Chicago
Nicolas Caillon, LSCE, Saclay, France
Dave Karl, University of Hawaii
Craig McNiel, University of Rhode Island
Jennifer Morford, Franklin and Marshall College
Jeff Severinghaus, University of California, San Diego
Toshiahiro Saino, Nagoya U., Nagoya, Japan
Yutaka Watanabe, Hokkaido U., Hokkaido, Japan

Graduate and Postdoctoral Advisors

W. S. Broecker, Ph.D. advisor
Werner Stumm, Post Doctoral advisor

Thesis Advisor and Postgraduate-Scholar Sponsor (last 5 years)

Jeff Abell, Earth Sciences, Utrecht U., Utrecht, Netherlands
Erin Breckel, Environmental Consulting, San Diego, CA
John Dunne, GFDL, Princeton, N.J.
Curtis Deutch, U. of Washington, Seattle, WA
Roberta Hamme, Scripps Institute of Oceanography, La Jolla, CA
Julia Linton, Private Education Consultant, San Francisco, CA
Jennifer Morford, Franklin and Marshall College, Lancaster, PA

CURRICULUM VITAE

Christopher L. Sabine:

a. Professional Preparation

Texas A&M University	Marine Science	B.S. 1986
University of Hawaii	Oceanography	Ph. D. 1992
Postdoctoral Institutions:		
Princeton University	Oceanography	1992-1994

b. Appointments

Oceanographer	NOAA Pacific Marine Environmental Laboratory	2002-present
Affiliate Assistant Professor	Department of Oceanography, University of Washington	1999-present
Research Scientist	Joint Institute for the Study of the Atmosphere and the Ocean, University of Washington/ NOAA PMEL	1999-2002
Research Staff	Program in Atmospheric and Ocean Sciences, Department of Geosciences, Princeton University	1994-1999
Research Associate	Program in Atmospheric and Ocean Sciences, Department of Geological and Geophysical Sciences, Princeton University	1992-1999
Graduate Research Assistant	Hawaii Institute of Geophysics, University of Hawaii at Manoa.	1987-1992

c. Publications

5 related to proposed research

Sabine, C.L., R.M. Key, R.A. Feely, and D. Greeley, Inorganic carbon in the Indian Ocean: Distribution and dissolution processes. *Global Biogeochem. Cycles*, 16, 4, 1067, doi: 10.1029/2002GB001869, 2002.

Gloor, M., N. Gruber, J.L. Sarmiento, **C.L. Sabine**, R.A. Feely, and C. Rödenbeck, A first estimate of present and preindustrial air-sea CO_2 flux patterns based on ocean interior carbon measurements and models. *Geophys. Res. Lett.,* 30, 1, 1010, doi: 10.1029/2002GL015594, 2003.

Sabine, C.L., M. Heimann, P. Artaxo, D. Bakker, C.-T.A. Chen, C.B. Field, N. Gruber, C. LeQuéré, R.G. Prinn, J.E. Richey, P.R. Lankao, J. Sathaye, and R. Valentini, Chapter 2: Current status and past trends of the global carbon cycle. *Toward CO_2 Stabilization: Issues, Strategies, and Consequences*, C.B. Field and M.R. Raupach (eds.), Island Press, Washington D.C., 17-44, 2004.

Sabine, C.L., R.A. Feely, Y.W. Watanabe, and M.F. Lamb, Temporal evolution of the north Pacific CO_2 uptake rate. *J. Oceanogr.*, 60(1), 5–15, 2004.

Sabine, C.L., R.A. Feely, N. Gruber, R.M. Key, K. Lee, J.L. Bullister, R. Wanninkhof, C.S. Wong, D.W.R. Wallace, B. Tilbrook, F.J. Millero, T.-H. Peng, A. Kozyr, T. Ono, and A.F. Rios, The oceanic sink for anthropogenic CO_2. *Science*, 305(5682), 367–371, 2004.

Selected additional publications

Sabine, C.L., F.T. Mackenzie, C.W. Winn, and D.M. Karl, Geochemistry of carbon dioxide at the Hawaii Ocean Time-series station, ALOHA, *Global Biogeochem. Cycles*, 9, 637-651, 1995.

Sabine, C.L., R.M. Key, K.M. Johnson, F.J. Millero, A. Poisson, J.L. Sarmiento, D.W.R. Wallace and C.D. Winn, Anthropogenic CO_2 inventory of the Indian Ocean, *Global Biogeochem. Cycles*, 13, 179-198, 1999.

Sabine, C.L., R. Wanninkhof, R. M. Key, C. Goyet, F. J. Millero, Seasonal CO_2 Fluxes in the Tropical and Subtropical Indian Ocean, *Mar. Chem.*, 72, 33-53, 2000.

Orr, J.C., E. Maier-Reimer, U. Mikolajewicz, P. Monfray, J.L. Sarmiento, J.R. Toggweiler, N.K. Taylor, J. Palmer, N. Gruber, **C.L. Sabine**, C. Le Quere, R.M. Key and J. Boutin, Global oceanic uptake of anthropogenic carbon dioxide as predicted by four 3-D ocean models, *Global Biogeochem. Cycles*, 15, 43-60, 2001.

Feely, R.A., **C.L. Sabine**, T. Takahashi, and R. Wanninkhof, Uptake and storage of carbon dioxide in the oceans: The global CO_2 survey, *The Oceanography Magazine*, 14 (4), 18-32, 2001.

Sabine, C.L., R.A. Feely, R.M. Key, J.L. Bullister, F.J. Millero, K. Lee, T.-H. Peng, B. Tilbrook, T. Ono, and C.S. Wong, Distribution of anthropogenic CO_2 in the Pacific Ocean, *Global Biogeochem. Cycles*, 16, 4, 1083, doi: 10.1029/2001GB001639, 2002.

Key, R.M., A. Kozyr, **C.L. Sabine**, K. Lee, R. Wanninkhof, J.L. Bullister, R.A. Feely, F.J. Millero, and T.-H. Peng, A global ocean carbon climatology: Results from GLODAP. *Global Biogeochem. Cycles*, 18, GB4031, doi:10.1029/2004GB002247, 2004.

Chung, S.-N., G.-H. Park, K. Lee, R.M. Key, F.J. Millero, R.A. Feely, **C.L. Sabine**, and F.G. Falkowski. Postindustrial enhancement of aragonite undersaturation in the upper subtropical and tropical Atlantic Ocean: The role of anthropogenic CO_2, *Limnology and Oceanography*, 14(2):1-7. 2004.

d. Synergistic Activities

Participated in 24 oceanographic cruises in Atlantic, Pacific, Indian, and Southern oceans.

1998-present	Member of CARbon dioxide IN the Atlantic (CARINA)
2000-2003	Member of IGBP Integrated Global Carbon Observing (IGCO) theme team
2001-2004	Member of US CLIVAR Southern Ocean panel
2001-present	Member of International CLIVAR/CLIC Southern Ocean panel
2001-present	Scientific Steering Committee member for IGBP/IHDP/WCRP Global Carbon Project
2001-present	Working Group for the Implementation of the North American Carbon Program (NACP)
2002-present	Member of PICES Working Group 17: Biogeochemical Data Integration and Synthesis
2002-2004	Working Group for the Implementation of Ocean Carbon and Climate Change (OCCC) Program
2003-present	Lead author for IPCC Special Report on carbon dioxide capture and storage

e. Collaborators & Other Affiliations

Collaborators

B. Balch (Bigelow Laboratory), N.R. Bates (BBSR), W. Berelson (USC), J. Bullister (NOAA/ PMEL), R.H. Byrne (USF), K. Caldeira (LLNL), A. Dickson (Scripps), S. Doney (NCAR), R.A. Feely (NOAA/ PMEL), N. Gruber (UCLA), S. Hankin (NOAA/PMEL), G. Johnson (NOAA/ PMEL), R. Key (Princeton U.), A. Kozyr (CDIAC), K. Lee (Pohang U., Korea), F.J. Millero (U. of Miami/RSMAS), J.C. Orr (IPSL, France), T.-H. Peng (NOAA/ AOML), J. Sarmiento (Princeton U.), R. Sonnerup (U. of Washington), T. Takahashi (LDEO), B. Tilbrook (CSIRO, Australia), R. Wanninkhof (NOAA/AOML)

Graduate and Postdoctoral Advisors

Graduate Advisor: F. Mackenzie; Postdoctoral Sponsor: J. Sarmiento

BIOGRAPHICAL SKETCH

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PROFESSIONAL PREPARATION
University of Sussex, Astronomy, M.Sc., 1980
University of Southampton, Oceanography, M.Sc., 1982
Scripps Institution of Oceanography, UCSD, Oceanography, Ph.D., 1988
Universitaet Kiel, Institut fuer Meereskunde, Habilitation (German qualification for full professorship), 1995

APPOINTMENTS

2003- Professor
Scripps Institution of Oceanography,
University of California, San Diego

1998-2003 Professor (tenured C3)
Institut fuer Meereskunde
Universitaet Kiel

1995-1998 Associate Professor (C2)
Institut fuer Meereskunde
Universitaet Kiel

1989-1995 Assistant Professor (C1)
Institut fuer Meereskunde
Universitaet Kiel

FIVE RELATED PUBLICATIONS

Send, U., F. Schott, F. Gaillard and Y. Desaubies, 1995: Oberservation of a deep convection regime with acoustic tomography. *J. Geophys. Res.* , 100 (C4), 6927-6941.

Send, U., C. Eden, and F. Schott, 2002: Atlantic Equatorial Deep Jets: Space/Time Structure and Cross-Equatorial Fluxes. *J. Phys. Oc.* 32 (3), 891-902.

Send, U., T. Kanzow, W. Zenk and M. Rhein, 2002: Monitoring the Atlantic Meridional Overturning Circulation at 16°N. *Exchanges*, 7 (3/4), 31-33.

Send, U, P. F. Worcester, B. D. Cornuelle, C. O. Tiemann, and B. Baschek, 2002: Integral measurements of mass transport and heat content in straits from acoustic transmissions. *Deep-Sea Res.*, 49 (19), 4069-4096.

Macrander, A., R.H. Kaese, U. Send, H. Valdimarsson, and S. Jonsson, 2005: Dynamic Relations in the Denmark Strait Overflow verified by velocity and hydrographic observations. *Geophys. Res. Letters* (in print)

FIVE OTHER PUBLICATIONS

Send, U. and J. Marshall, 1995: Integral effects of deep convection. *J. Phys. Oceanogr*., 25 (5), 855-872.

Send, U., G. Krahmann, D. Mauuary, Y. Desaubies, F. Gaillard, T. Terre, J. Papadakis, M. Taroudakis, E. Skarsoulis, and C. Millot, 1997: Acoustic observations of heat content across the Mediterranean Sea. *Nature*, 385, 615-617.

Send, U., and R. Kaese, 1998: Parameterization of Processes in Deep Convection Regimes. In E.Chassignet and J.Verron (eds.): *Ocean Modelling and Parameterization*. Kluwer Academic Publishers, p.191-214.

Send, U., and B. Baschek, 2001: Intensive ship-board observations of the flow through the Strait of Gibraltar. *J. Geophys. Res*., 106 (C12), 31,018-31,032.

Schmidt, S., and U. Send, 2005: Timing, Origin and Composition of Seasonal Labrador Sea Freshwater., *J. Phys. Oceanogr.*, in print.

SYNERGISTIC ACTIVITIES

- Session Convenor at various EGS assemblies and American Acoustical Society Conference
- Member, ARGO International Science Team and ARGO Data Management Team
- Member, Clivar Global Synthesis and Observations Panel
- Co-Chair, OceanSITES Steering Team
- Development of a data telemetry system for moorings
- Initiation of a European collaboration and initiative for establishing multidisciplinary deep-ocean timeseries observatories

COLLABORATORS WITHIN THE LAST 48 MONTHS (other than those above)

W.Zenk, M.Rhein, M.Visbeck, A.Chave, R.Lampitt, D.Wallace, A.Clarke, J.Lilly

ADVISORS

M.Sc. advisor: I.Robinson (Southampton)
Ph.D. advisor: C.Winant (SIO), R.Beardsley (WHOI)

GRADUATE STUDENTS ADVISED

Diploma students:
Michael Reich (2001), Daniela Weber (2001), Lutz Helmbrecht (2002), Lars Boehme (2003), Hauke Schmidt (current), Jochen Koenig (current), Christian Begler (current)
Ph.D. students:
Torsten Kanzow (2004), Andreas Macrander (2004), Tom Avsic (current), Matthias Lankhorst (current), Sunke Schmidt (current)

John Merrill Toole

Physical Oceanographer
Senior Scientist
Department of Physical Oceanography
Woods Hole Oceanographic Institution

B.A., University of Maine, 1975

Sc.D., Massachusetts Institute of Technology–Woods Hole Oceanographic Institution Joint Program, 1980

Physics Laboratory Instructor, University of Maine, 1974–1975

Summer Student Fellow, 1974, Woods Hole Oceanographic Institution

National Research Council Postdoctoral Research Associate, 1980–1982, Pacific Marine Environmental Laboratory

Graduate Research Assistant, 1975–1980, Postdoctoral Investigator, 1980, Assistant Scientist, 1982–1986, Associate Scientist, 1986–1996, tenure awarded, 1990; Senior Scientist, 1996–present, Woods Hole Oceanographic Institution

Member, Phi Beta Kappa, Phi Kappa Phi, Sigma Phi Sigma

Fellow of the American Geophysical Union, 2004

Columbus O'Donnell Iselin Chair for Excellence in Oceanography, WHOI, 2005-2009

U.S. Patents

No. 5,869,756: Moored water profiling apparatus. Inventors: K.W. Doherty, J.M. Toole and D. E. Frye, Feb. 9, 1999.

No. 5,665,909: Free-fall, wire-guided hydrographic profiler. Inventors: K.W. Doherty, J.M. Toole, and R.C. Millard, Sept. 9, 1997

Research Interests: The physics of ocean mixing including the nature of finescale and microscale velocity, temperature and salinity fluctuations and the relationships between them. Global oceanic heat and fresh water budgets, water mass formation and circulation. Low-latitude ocean circulation, El Niño. Annual to multi-decadal variability of ocean water properties, stratification and circulation, ocean time-series stations. Oceanographic instrument development.

Author or co-author of 62 refereed scientific publications

Recent Publications

Wijffels, S. E., J. M. Toole and R. E. Davis, 2001. Revisiting the South Pacific subtropical circulation: A synthesis of World Ocean Circulation Experiment observations along 32°S. *Journal of Geophysical Research*, **106**, 19,481–19,513.

St. Laurent, Louis C., John M. Toole, and Raymond W. Schmitt, 2001. Buoyancy forcing by turbulence above rough topography in the abyssal Brazil Basin. *Journal of Physical Oceanography*, **31**, 3476–3495.

DiMarco, S. F., P. Chapman, W. D. Nowlin, Jr., P. Hacker, K. Donohue, M. Luther, G. C. Johnson and J. Toole, 2002. Volume transport and property distributions of the Mozambique Channel. *Deep-Sea Research II*, **49**(7-8), 1481–1511.

Polzin, K. L., E. Kunze, J. M. Toole, and R. W. Schmitt, 2003. The partition of finescale energy into internal waves and subinertial motions. *Journal of Physical Oceanography*, **33**, 234–248.

Donohue, K. and J. Toole, 2003. A near-synoptic survey of the Southwest Indian Ocean. In: Topical Studies in Oceanography: Physical Oceanography of the Indian Ocean: from WOCE to CLIVAR, Fritz Schott, editor. *Deep-Sea Research II*, **50**, 1893–1932.

Toole, J. M., H.-M. Zhang, and M. J. Caruso, 2004. On the time-dependent internal energy budgets of the tropical warm-water pools. *Journal of Climate*, **17**, 1398–1410.

Nash, J. D. E. Kunze, J. M. Toole, and R. W. Schmitt, 2004. Internal tide reflection and turbulent mixing on the continental slope. *Journal of Physical Oceanography*, **34**, 1117–1134.

Schmitt, R.W., J.R. Ledwell, E.T. Montgomery, K.L. Polzin and J.M. Toole, 2005. Diapycnal mixing by salt fingers in the main thermocline of the tropical Atlantic. *Science*, **308**, 685-688.

Schmitt, Raymond W., Robert C. Millard, John M. Toole and W. David Wellwood. A double-diffusive interface tank for dynamic-response studies. *Journal of Marine Research*, **63**, 263-289.

Thurnherr, A. M., L. C. St. Laurent, K. G. Speer, J. M. Toole, and J. R. Ledwell. Mixing Associated with Sills in a Canyon on the Mid-Ocean Ridge Flank. *Journal of Physical Oceanography*, in press.