Science Background

A revolution in ocean observing is developing that will transform our understanding of ocean chemistry and biology. Today, our primary sources of information on temporal variability of biogeochemical processes within the ocean come from a few, ship-based time series programs at single points (e.g. HOT, BATS, CARIACO, ESTOC) and from satellite ocean color measurements. In addition, a few programs, such as the Atlantic Meridional Transect (AMT), involve repeat transects over broad regions at near annual scales. Ship-based sampling at time series sites is generally monthly at best, which misses high frequency processes. Satellites excel at providing global coverage at higher frequencies in cloud-free areas, but ocean color data is generally limited to one optical depth and the data do not resolve vertical structure. The result is that we have little understanding of how ocean biogeochemistry is changing in response to natural climate oscillations such as El Niño and Pacific Decadal Oscillation or to anthropogenic climate changes driven by burning fossil fuels. Even the processes that control regular, annual events such as the spring bloom are not always well understood.

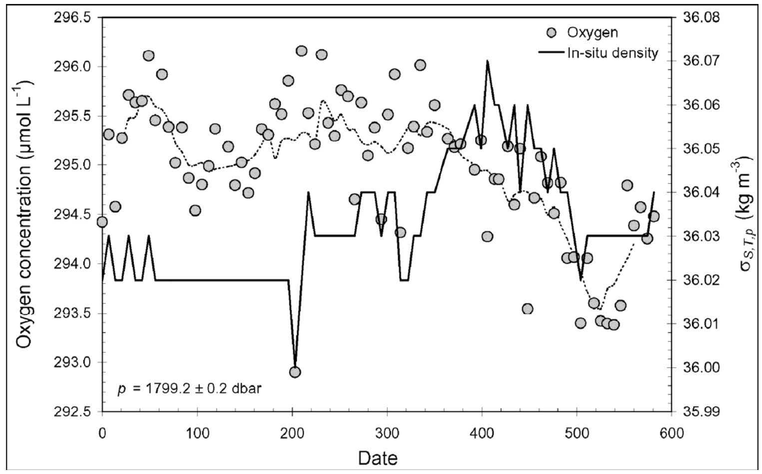

Figure 1. Oxygen measurements made at 1800 m depth over 600 days from an Apex profiling float (Kortzinger et al., 2005).

With only a few exceptions, the biogeochemistry community has not had sensors or platforms that were capable of providing long-term records over large areas and that could be used to resolve climate processes. However, there has been a remarkable transformation in our observing capabilities in the past decade using in situ chemical and optical measurements on moorings, and mobile platforms such as profiling floats and gliders.

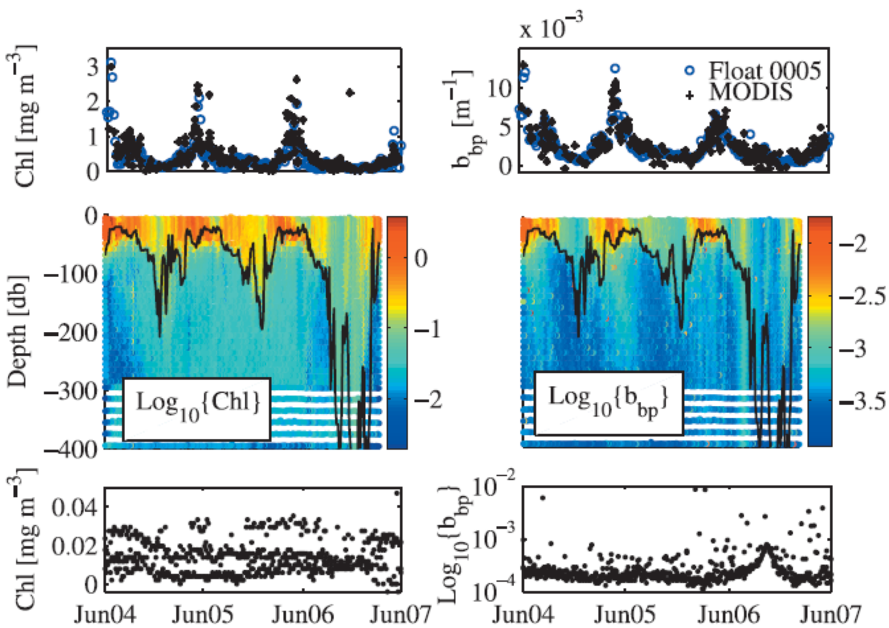

Fig. 2. Time series of (left) chlorophyll concentration and (right) particulate backscattering coefficient. (top panels) Near-surface float and Moderate Resolution Imaging Spectroradiometer Aqua satellite data, (middle panels) midwater column float data, and (bottom panels) float data below 950 meters (note log scale for particle backscattering). For satellite chlorophyll concentration and backscattering coefficient, we use NASA's inversion products OC3 and GSM, respectively (http://oceancolor.gsfc.nasa.gov/DOCS/MSL12/MSl12_prod.html).

From Boss et al., (2008a)

Oxygen sensors are now being deployed for multi-year periods with little or no drift in sensor response (Kortzinger et al., 2005; Johnson et al., 2007). These sensors are being used to study ocean ventilation (Kortzinger et al., 2004), the balance of net community production in oligotrophic regions (Riser and Johnson, 2008; Nicholson et al., 2008), and carbon export (Martz et al., 2008). Figure 1 shows the remarkable precision attained with an oxygen sensor deployed for two years on a profiling float (Kortzinger et al., 2005). Oxygen sensors deployed on gliders are used to study spatial and temporal variability over the period of a year near the HOT time series station (Nicholson et al., 2008). A white paper that addresses in detail the feasibility of deploying large numbers of oxygen sensors on profiling floats is available (Gruber et al., 2007).

Bio-optical sensor technologies have also advanced rapidly. There have now been a number of studies using sensors on profiling floats (Mitchell, 2000; Bishop et al., 2002; 2004). The data reported by Boss et al. (2008a; 2008b) show measurements of chlorophyll fluorescence from 1000 m depth to the surface in the North Atlantic for three years (Figure 2). These observations clearly resolve the annual cycle with no apparent drift at depth and show remarkable events driven by mesoscale processes. Gliders are routinely deployed with bio-optical and chemical sensors for time-series studies in the coastal and open ocean (Sackmann, 2007; Nicholson et al., 2008; Niewiadomska et al., 2008; Perry et al., 2008). An example is shown in Fig. 3.

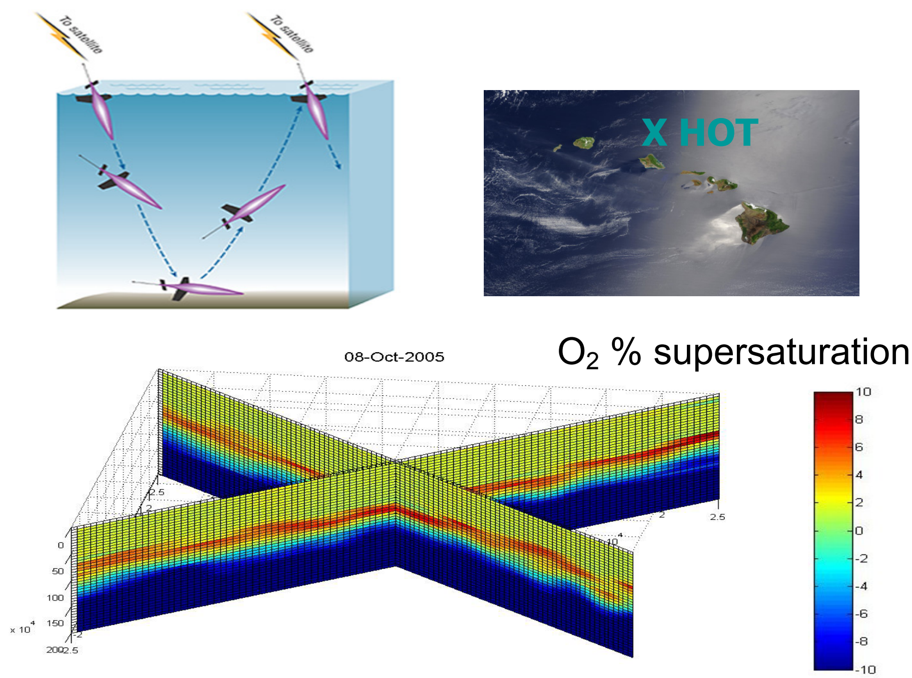

Fig. 3. Oxygen measured from a glider profiling near the HOT station in the North Pacific (Nicholson et al., 2008).

A variety of other sensors are in various stages of development. Optical nitrate sensors (Johnson and Coletti, 2002) are currently deployed on floats and have operated successfully for >160 days (Figure 4). The power budget implies that they can operate for 4 years with 60 nitrate measurements from 1000 m to the surface at a cycle time of 5 days. These nitrate sensors are being adapted to the Spray gliders as well. Plans to deploy pCO_2 sensors on floats are under way (Kortzinger, personal communication). Optical particulate inorganic carbon sensors are in development with an eye towards deployment on profiling floats (Guay and Bishop, 2002).

Floats with multi-spectral radiometers and other bio-optical sensors are also being deployed at a variety of locations in the ocean (Claustre, personal communication).

Many of the capabilities described above are now being used in a demonstration experiment to study the North Atlantic spring bloom (http://bloom.apl.washington.edu/). This experiment is utilizing an array of gliders and floats equipped with bio-optical and chemical (oxygen and nitrate) sensors to monitor the temporal evolution of the spring bloom in the North Atlantic. The experiment will terminate in summer 2008. It is designed to assess many of the concepts discussed above, particularly integration of in situ observations, satellite observations and biogeochemical models. A next step will be to extend this type of experiment from studying one season to a sustained system that operates for several years.

Workshop Objectives and Products

A 2.5 day meeting will be held to address the four workshop objectives noted above. A notational format for the meeting is provided below. However, we expect that the format of the meeting would be refined following discussions amongst the planning committee and with the OCB office.

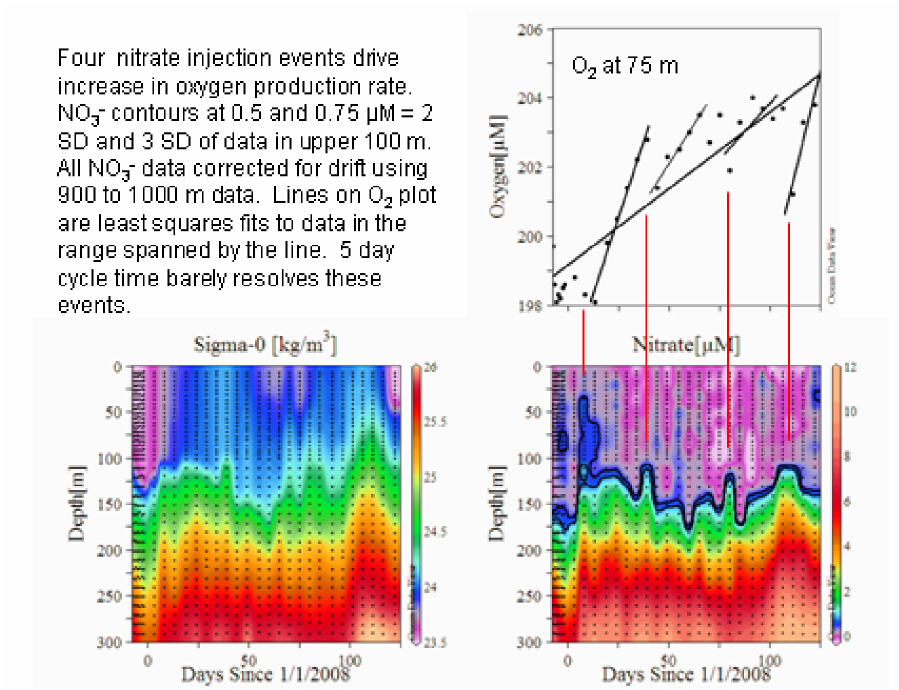

Figure 4. Nitrate and oxygen measurements made on an Apex profiling float near the HOT time series station.

1. Critically review currently existing technologies, their strengths, their weaknesses, and expected developments for long-term (years to decades) applications. A set of plenary talks will be made in the first morning of the meeting to address this topic. A reading list that includes both published papers and descriptions of planned technology developments will be circulated in advance of the meeting. The talks would focus on capabilities and limitations of chemical and biological sensors and operating platforms, as well as issues related to operating and sustaining large scale networks such as Argo.

2. Identify important oceanographic problems that can be addressed only with in situ remote measurements and develop experiments (perhaps international in scope) that could be implemented to solve them. This topic may include a series of short presentations solicited from

attendees in advance of the meeting about potential experiments of several years duration. These presentations could be grouped by process (e.g. nutrient supply, oxygen balance, carbon export) or by region (e.g., North Atlantic, Subarctic Pacific, Southern Ocean). The remainder of the afternoon will be used for an open discussion by participants of the pros and cons of various classes of experiments. The morning of the second day could then be used for persons interested in the various experiments to form break-out groups and address issues raised in the previous afternoon's discussion. The break-out groups could report back to the whole in a plenary session at the end of the morning. We hope that this will result in a constructive dialog that will lead to active pursuit of multi-year experiments.

Examples of experiments utilizing autonomous observing systems deployed over several years and which could be targeted at the workshop for development into proposed field programs include:

a) North Pacific carbon flux. The boundary between the subarctic and subtropical gyre in the Pacific Ocean is a location of intense CO_2 draw-down in the winter. The CO_2 influx to the ocean in this location is one of the most important in the global air-sea carbon exchange; it is about the same as the CO_2 efflux from the Pacific Equatorial region and occurs entirely in the winter months (Takahashi et al., 2002). While part of this CO_2 invasion to the ocean in this region is caused by thermodynamics of the carbonate system following cooling of the waters in the Kuroshio Extension as it flows the Northeast, another part is caused by intense biological production at the gyre boundary in the winter months (Takahashi et al., 2002). We have very little knowledge of the reasons for this intense productivity. A study of the mechanisms behind the process requires depth dependent measurements of metabolic tracers of the biological carbon cycle. This can be done from research ships, but it is absolutely infeasible to derive more that a section or two at single crossings on time scales of 5-10 years by this method because of the expense and scientist's time required. The only way to derive a comprehensive investigation the net biological production and the nutrient dynamics responsible for this extremely important ocean-atmosphere CO_2 flux over different locations and seasons is to deploy a set of Argo floats equipped with oxygen, nitrate and bio-optical sensors in the western part of the subtropical front. From there they will profile the front as they drift eastward.

b) Interannual variation in low oxygen biogeochemistry. There is significant interest in changing oxygen content of the ocean, particularly apparent increases in the intensity of oxygen minimum zones (Stramma et al., 2008). These changes in oxygen may directly impact rates of denitrification and there is some evidence of large interannual changes in denitrification rates (Codispoti et al., 1986). An array of profiling floats and gliders equipped with oxygen and nitrate sensors in a region such as eastern Pacific could be used to assess non-Redfieldian changes in nitrate and oxygen stocks. Broecker (1974) introduced a tracer called $NO = 9*NO_3^- + O_2$. NO can be used in a manner similar to tracers such as N* to identify regions where denitrification may be removing nitrate. A float array equipped with nitrate and oxygen provide an interannual record of changes in NO while a glider array would bound spatial variations in pools of nitrate and oxygen deficient zones. Adding bio-optics to the array might be utilized to understand the impacts of particle export on control of the oxygen and nitrate balance.

c) Southern Ocean carbon export. One of the outcomes of the set of open ocean iron fertilization experiments is an understanding of impacts of short-term changes in mixed layer depth on primary production and carbon export (de Baar et al., 2005). Iron fertilization experiments in areas of low winds and shallow mixed layers lead to much larger blooms and carbon export. How do such processes operate in the ocean with natural iron concentrations? This question is difficult to study at high latitudes because of infrequent satellite coverage and lack of in situ measurements of mixed layer depth and biomass. Moorings are difficult to utilize because of extreme weather conditions. Such a topic could be readily addressed in High Nitrate, Low Chlorophyll waters using an array of Lagrangian platforms equipped with nitrate sensors and bio-optics. Nitrate drawdown tracks net community production. Bio-optics tracks particle production and export.

3. Assess the potential to create a long-term observing system based on in situ sensors, satellites and data-assimilating models to monitor biogeochemical processes on a global scale. In the afternoon of the second day, it would be very interesting to have a round table discussion with an Argo representative, an observational carbon cycle scientist, a biogeochemical modeler and a funding agency representative on their assessments of the opportunities, limitations and unmet requirements related to an in situ biogeochemical sensor network.

4. Unmet needs for sensors and sensor quality, platforms, and other issues that may arise. The last morning of the meeting will focus on this topic. These discussions will be informed by the items discussed in the previous afternoon.

Products of the meeting will include a meeting report and an EOS article, planning groups to implement one or more multi-year experiments, and groups organized to develop proposals that might address unmet needs that are identified in the meeting report.