

OBSERVING BIOGEOCHEMICAL CYCLES AT GLOBAL SCALES WITH PROFILING FLOATS AND GLIDERS

PROSPECTS FOR A GLOBAL ARRAY

BY KENNETH S. JOHNSON, WILLIAM M. BERELSON, EMMANUEL S. BOSS,
ZANNA CHASE, HERVÉ CLAUSTRE, STEVEN R. EMERSON, NICOLAS GRUBER,
ARNE KÖRTZINGER, MARY JANE PERRY, AND STEPHEN C. RISER

ABSTRACT. Chemical and biological sensor technologies have advanced rapidly in the past five years. Sensors that require low power and operate for multiple years are now available for oxygen, nitrate, and a variety of bio-optical properties that serve as proxies for important components of the carbon cycle (e.g., particulate organic carbon). These sensors have all been deployed successfully for long periods, in some cases more than three years, on platforms such as profiling floats or gliders. Technologies for pH, $p\text{CO}_2$, and particulate inorganic carbon are maturing rapidly as well. These sensors could serve as the enabling technology for a global biogeochemical observing system that might operate on a scale comparable to the current Argo array. Here, we review the scientific motivation and the prospects for a global observing system for ocean biogeochemistry.

INTRODUCTION

The challenge of understanding the ocean's role in the global carbon cycle and its response to a changing environment requires an expanded scale of observation in both space and time. Traditional ocean sampling methods rarely achieve measurements on the spatial and temporal scales required to answer questions regarding such phenomena as the magnitude of the uptake of anthropogenic carbon dioxide and the severity of resulting ocean acidification (Sabine et al., 2004), ventilation of the thermocline in mode-water-formation areas and associated formation of preformed nutrients (e.g., Sarmiento et al., 2004), rate and spatial distribution of ocean deoxygenation (Stramma et al., 2008), transport of nutrients to the euphotic zone in nutrient-starved, stratified ocean regions (e.g., Jenkins and Doney, 2003), and mechanisms controlling the ocean's biological carbon pump (e.g., Ducklow et al., 2001).

Much of what we currently know about the temporal variability of biogeochemical processes comes from satellite ocean color measurements and a few, primarily ship-based, time series programs (e.g., Hawaii Ocean Time-series [HOT], Bermuda Atlantic Time-series Study [BATS], CARbon Retention In A Colored Ocean [CARIACO] in the Gulf of Mexico, and European Station for Time-Series in the Ocean Canary Islands [ESTOC]) where sampling is repeated roughly monthly (Ducklow et al., 2009). Ship-based sampling cannot resolve mesoscale and higher-frequency processes (e.g., eddies, tropical storms) and gives little sense of change over

broad areas. Satellite observations have helped to overcome this limitation, but the suite of observable biogeochemical parameters is constrained to ocean color during cloud-free periods in the upper one-fifth of the euphotic zone. The result is that we have only limited understanding of how ocean biogeochemistry is changing in response to natural climate variations such as El Niño or to anthropogenic climate changes driven by the accumulation of greenhouse gases in the atmosphere.

Observing ocean biogeochemistry at the proper spatial and temporal scales required to address driving scientific questions will require a revolution. Such a revolution in the observing technology is at hand (Johnson et al., 2007; see also the September 2008 *Limnology and Oceanography* special issue on Autonomous and Lagrangian Platforms and Sensors, and various white papers prepared for Ocean Obs 09, <http://www.oceanobs09.net>). Rapid progress is being made in the development of a suite of chemical and biological sensors that are low power, small in size, precise and accurate, and have long-term stability. Within the past five years, sensor technologies for oxygen, chlorophyll, particles, and nitrate have been refined. These sensors are now capable of deployment on long-endurance missions on autonomous platforms such as profiling floats and gliders. They represent the enabling technology for a global biogeochemical observing system that might operate on a scale comparable to the physically oriented Argo array (Roemmich et al., 2004, 2009).

This paper reviews the status of autonomous observing systems for

ocean biogeochemical properties and lays out a vision for the future. It was developed as the result of a US Ocean Carbon and Biogeochemistry Program (OCB) Scoping Workshop entitled "Observing Biogeochemical Cycles at Global Scales with Profiling Floats and Gliders." The workshop was held April 28–30, 2009, in Moss Landing, CA (<http://www.whoi.edu/sites/OCBfloatsgliders>) with support from the US National Science Foundation, National Aeronautics and Space Administration, and National Oceanic and Atmospheric Administration. The Scoping Workshop focused on assessing the path forward to a global sensor array that enables autonomous measurements of chemical and biological properties throughout the ocean.

AUTONOMOUS AND LAGRANGIAN PLATFORMS AND SENSORS

Observing the ocean over broad scales requires high-endurance and relatively low-cost sensors and platforms. Prospects for such capabilities were reviewed at the "ALPS: Autonomous and Lagrangian Platforms and Sensors Workshop" in 2003 (Perry and Rudnick, 2003a, b). In the six years since that workshop, the field has matured rapidly. We briefly review these developments below.

Platforms

In 2003, profiling floats were a relatively mature technology and gliders were rapidly developing. Since that time, the Argo array of profiling floats (Roemmich et al., 2004, 2009) has reached its design goal of 3000 floats in the ocean, while more than 100 gliders (Rudnick et al.,

2004) are now exploring the ocean. Both profiling floats and gliders cycle vertically in the ocean by changing their buoyancy. Platform density is changed by pumping oil stored in an internal reservoir into an external bladder to increase volume at constant mass (to ascend) or by deflating the bladder (to descend). Gliders can be programmed to sample along a predetermined path due to their ability to change internal weight distribution. Coupled with external wings that provide lift, the change in weight distribution allows gliders to move forward at speeds near 0.5 m s^{-1} as they cycle vertically. Floats drift with the currents at parking depths of (typically) 1000 m before ascending to the surface at programmed time intervals (hours to days). At the surface, both floats and gliders transmit their data to orbiting satellites using either Service Argos (most floats) or the Iridium system (some floats, all gliders). Many floats

in the Argo Program have operated for five years or more, while some types of gliders have survived for nearly one year, including extended operations under ice.

Sensors

Oxygen sensors are now being deployed on floats for multiyear periods with little or no drift in sensor response (Körtzinger et al., 2004; Riser and Johnson, 2008). These long-term deployments are possible because these platforms spend much of their time at depth, in cold and dark waters. Consequently, biofouling is less of an issue than when sensors are permanently fixed in the upper ocean, for example, on moorings. Figure 1 shows the remarkable stability attained with an oxygen sensor deployed for nearly two years on a profiling float (Tengberg et al., 2006). As of June 2009, more than 200 floats had been deployed with oxygen sensors, with about 150 currently active. The

amount of oxygen data that is being delivered to national data centers from profiling floats is already nearly double that coming from ships. Gruber et al. (2007) address in detail the feasibility of deploying large numbers of oxygen sensors on profiling floats. Oxygen sensors have been deployed on gliders, also with excellent results (Figure 2; Nicholson et al., 2008; Perry et al., 2008).

Bio-optical sensor technologies have been refined so that they can now be deployed on autonomous platforms

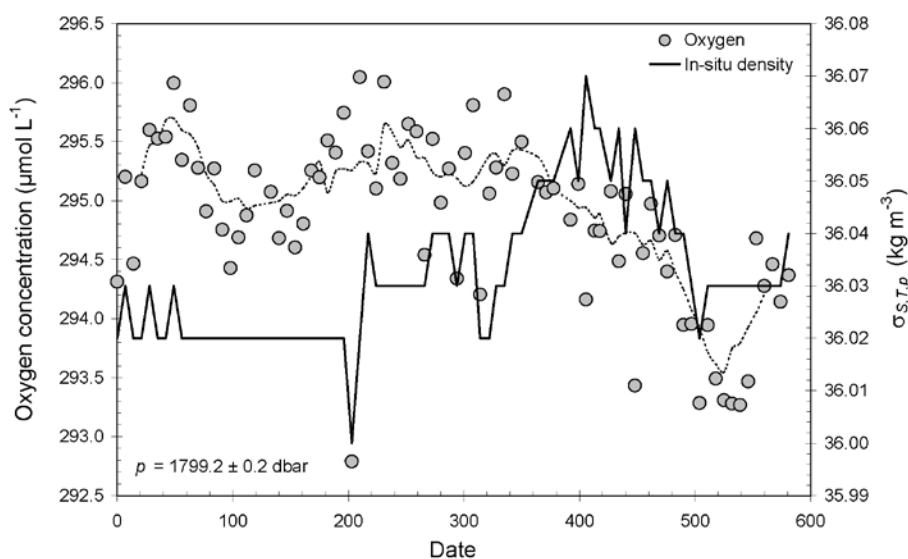


Figure 1. Oxygen and density data collected over 580 days from a free-drifting Argo float off the east coast of Canada in the Labrador Current, with oxygen readings as the float passed 1800-m depth. The average oxygen readings during the whole period were $295.0 \pm 0.7 \mu\text{mol L}^{-1}$. From Tengberg et al. (2006)

Kenneth S. Johnson (johnson@mbari.org) is Senior Scientist, Monterey Bay Aquarium Research Institute, Moss Landing, CA, USA. **William M. Berelson** is Professor, Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA. **Emmanuel S. Boss** is Associate Professor of Oceanography, University of Maine, Orono, ME, USA. **Zanna Chase** is Assistant Professor, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA. **Hervé Claustre** is Senior Scientist, Laboratoire d'Océanographie de Villefranche, Villefranche-sur-mer, France. **Steven R. Emerson** is Professor of Oceanography, University of Washington, Seattle, WA, USA. **Nicolas Gruber** is Professor of Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics, Eidgenössische Technische Hochschule (ETH), Zürich, Switzerland. **Arne Körtzinger** is Professor of Chemical Oceanography, Leibniz Institute of Marine Sciences, Kiel, Germany. **Mary Jane Perry** is Professor of Oceanography, Darling Marine Center, University of Maine, Walpole, ME, USA. **Stephen C. Riser** is Professor, School of Oceanography, University of Washington, Seattle, WA, USA.

(e.g., Bishop et al., 2002, 2004). Particle load is the main driver of water turbidity or transparency in the open ocean. Turbidity can be quantified by the measurement of the backscattering coefficient (backscattering meter), while transparency is measured by the particle attenuation coefficient (transmissometer). In open ocean waters, particulate organic carbon (POC) is the main source of particles, and both optical measurements can be converted to a concentration of POC with reasonable accuracy (e.g., Bishop and Wood, 2009). Boss et al. (2008) succeeded in observing chlorophyll fluorescence (proxy for phytoplankton) and light scattering (proxy for POC) in the upper 1000 m of the North Atlantic for three years (Figure 3). These observations resolved the annual cycle with no apparent sensor drift at depth, and they revealed remarkable events driven by mesoscale processes. Gliders are routinely deployed with bio-optical and chemical sensors for repeat observations along transects in the coastal and open ocean. Many of these time series have been sustained for years (Nicholson et al., 2008; Niewiadomska et al., 2008; Perry et al., 2008).

Nitrate sensors based on direct optical detection (Johnson and Coletti, 2002) are now deployed on profiling floats, and they have operated for more than 500 days. The power budget implies that they can operate over four years with 60 nitrate measurements from 1000 m to the surface at a cycle time of five days. Detection limits are on the order of 0.5 to 1 μM . Although not sufficient to measure euphotic zone nitrate concentrations in many regions, they can resolve annual cycles in mesotrophic,

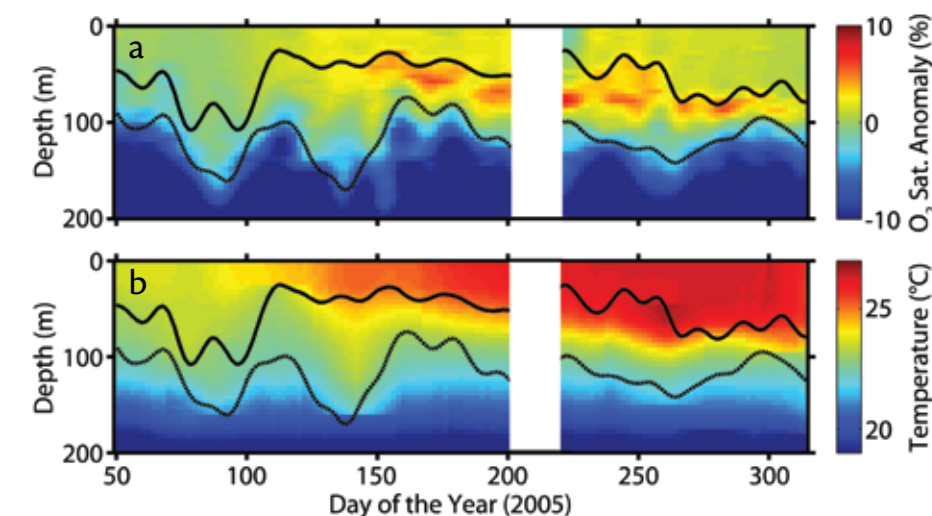


Figure 2. (a) Objective analysis-mapped O_2 -saturation anomaly (%) and (b) temperature ($^{\circ}\text{C}$) averaged over a 50-km x 50-km box in the upper 200 m near the Hawaii Ocean Time-series (HOT) station. The black line indicates mixed-layer depth and the dashed black line is the depth of $\sigma_{\theta} = 24.30$. From Nicholson et al. (2008)

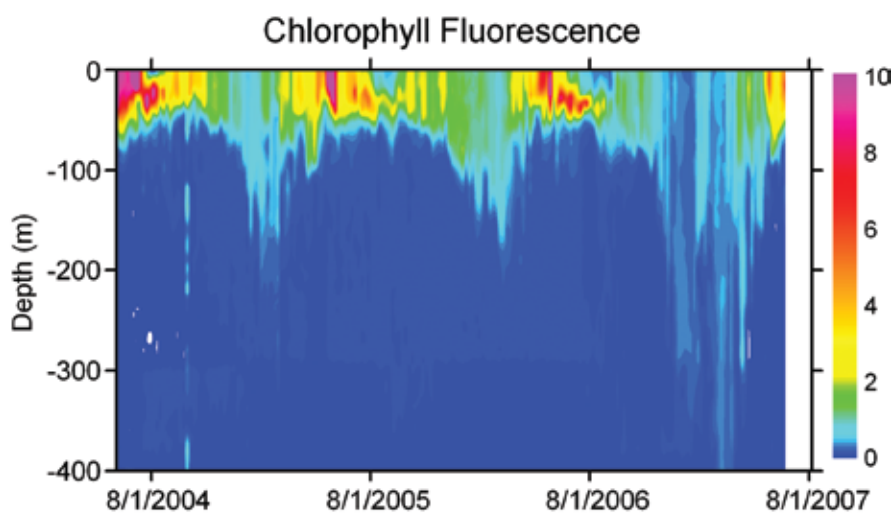


Figure 3. Chlorophyll estimated with a fluorometer deployed on a profiling float in the Labrador Sea region of the North Atlantic. Fluorescence data were converted to chlorophyll concentration using calibrations with both lab data and satellite-based chlorophyll (see Boss et al., 2008, for details). Figure adapted from data reported by Boss et al. (2008)

bloom-forming regions such as the North Atlantic (D'Asaro et al., 2008) or in high nitrate, low chlorophyll (HNLC) regions (Figure 4) and measure nitrate transport driven by mesoscale events. These nitrate sensors are also being adapted to gliders.

Other biogeochemical sensors have undergone preliminary deployments on floats or gliders. Measurements with gas tension devices (GTD; McNeil et al., 2006) can be combined with oxygen concentrations to determine the partial

pressure of molecular nitrogen (N_2) in seawater. These devices have been used on profiling floats deployed along hurricane trajectories to study gas exchange under extreme conditions (D'Asaro and McNeil, 2007). Measurement of N_2 concentration is essential to interpret oxygen concentrations in the mixed layer (Emerson et al., 2008), as the two gases share similar solubility, and to assess denitrification in low-oxygen zones. Prototype pCO_2 sensors have been tested on floats (author Körtzinger, *pers. comm.*, April 2009). The results are promising but limited so far by the comparatively long time constants of available pCO_2 sensor technology. Sensors for pH that are based on ion-sensitive field effect transistor (ISFET) technology, capable of low-power, long-term operation, are being tested in the laboratory and on surface moorings where they show exceptional long-term stability (recent work of author Johnson and Todd Martz of Scripps Institution of Oceanography). Modified ISFET pH sensors could be operated on floats and

gliders. Optical particulate inorganic carbon sensors are being developed with an eye toward deployment on profiling floats (Bishop, 2009).

USING AUTONOMOUS PLATFORMS TO QUANTIFY KEY BIOGEOCHEMICAL PROCESSES

A global, biogeochemical observational array must be capable of delivering quantitative information on biogeochemical rates and standing stocks of important chemicals and biomass. A variety of preliminary studies using small numbers of deep-profiling floats, mixed-layer Lagrangian floats, and/or gliders to make quantitative estimates of biogeochemical rates have been completed. The next step is to extend these experiments to larger spatial and temporal scales.

Quantitative measurements of net community production can be achieved by tracking the time course of oxygen, nitrate, or dissolved inorganic carbon (DIC) concentrations. Recent studies of the seasonal buildup of oxygen in the sub-mixed-layer euphotic zone using

Argo float data (Riser and Johnson, 2008) and Seaglider measurements (Nicholson et al., 2008; Perry et al., 2008) demonstrate the potential to quantify net community production (NCP) using sensors. Euphotic zone studies of oxygen evolution are presently limited to observing the concentration changes below the mixed layer. The sensors do not yet have sufficient accuracy to quantify changes resulting from gas exchange with the atmosphere that are driven by the small difference between actual surface oxygen concentration and the values that would occur at atmospheric equilibrium. This level of accuracy should, however, be achievable using in situ calibration (see below). In HNLC regions, NCP can be assessed from the seasonal change in nitrate concentration and a suitable mixing model (Macready and Quay, 2001). Optical nitrate sensors now deployed on profiling floats are currently resolving these cycles at locations in the subarctic North Pacific (Figure 4) and in the Southern Ocean. These observations do

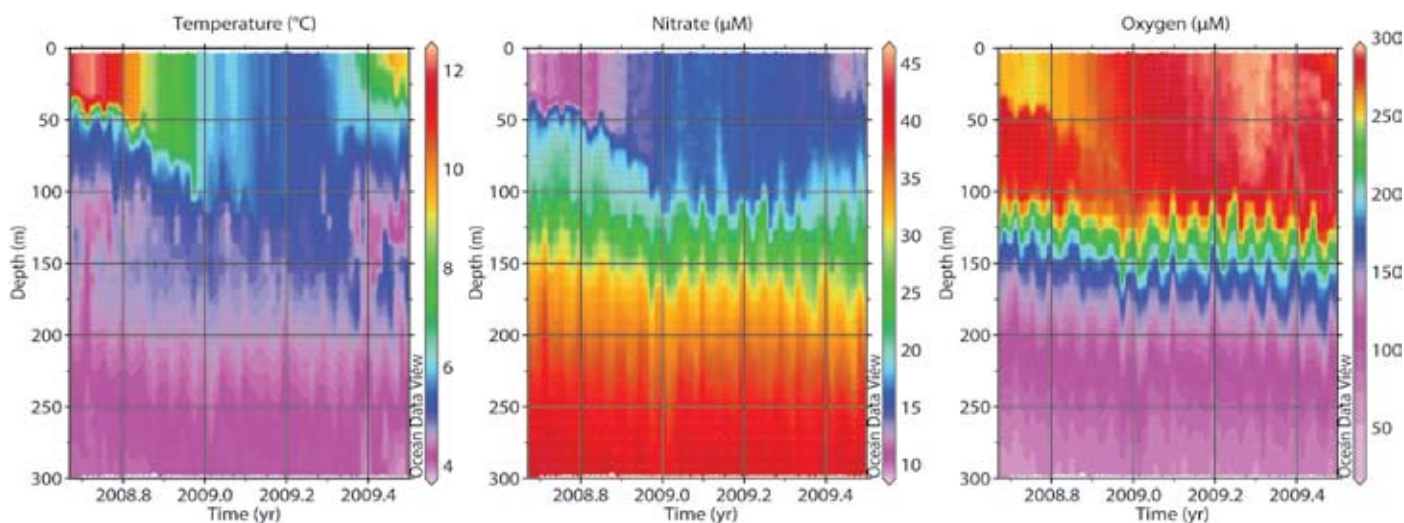


Figure 4. Temperature, nitrate, and oxygen measured at Ocean Station Papa in the North Pacific (50°N, 145°W) by Apex profiling float 5143, which is equipped with an ISUS nitrate sensor and Aanderaa oxygen optode. Data downloaded from www.mbari.org/chemsensor/floatviz.htm.

not suffer the complications that result from gas exchange, but they require knowledge of C:N in the plankton community. In the open ocean, optically detected POC concentrations show clear daily variations that are linked to the balance between production and losses.

zone is directly related to the oxygen-utilization rate in the mesopelagic region immediately below. This value has been determined by measuring the seasonal change in oxygen concentration from a series of Argo floats in the South Pacific (Martz et al., 2008). Because changes are

satellite observations and biogeochemical models with in situ sensor data. It provided quantitative assessments of net ecosystem production from oxygen evolution and nitrate drawdown, as well as the fate of the organic matter produced. It demonstrates how to extend information gained from Eulerian observatories (Körtzinger et al., 2008) to obtain a full three-dimensional picture.

“ THE CHALLENGE OF UNDERSTANDING THE OCEAN’S ROLE IN THE GLOBAL CARBON CYCLE AND ITS RESPONSE TO A CHANGING ENVIRONMENT REQUIRES AN EXPANDED SCALE OF OBSERVATION IN BOTH SPACE AND TIME. ”

Performing optical measurements at well-identified time periods of the day (e.g., sunrise, sunset) allows NCP to be estimated (Claustre et al., 2008).

The vertical flux of POC, which is a critical component of the biological carbon pump, can be determined by several methods. Qualitative changes in carbon export have been documented using transmissometers deployed on profiling floats (Bishop et al., 2004; Bishop and Wood, 2009). Particles accumulate on the optics while the float is parked at constant depth, and light attenuation by these particles is measured after some time interval with the float at constant depth. The particles are then washed from the optics with a pump and the cycle can be repeated. This sensor can provide a high-resolution record of relative changes in particle flux, but an absolute calibration is not yet possible. Carbon flux from the euphotic

a small fraction of the O_2 standing crop in this region and horizontal advection is an important and unknown variable, the method is most sensitive in the shallow mesopelagic.

Many of the capabilities discussed above were used in a demonstration experiment to study the North Atlantic spring bloom during 2008 (D’Asaro et al., 2008). This experiment occurred near the location of the 60°N Joint Global Flux Study (JGOFS) North Atlantic Bloom Experiment conducted from 1989–1991. Although this site had been well studied, preliminary results demonstrated a novel perspective on processes during the bloom. The 2008 experiment used an array of gliders and Lagrangian mixed-layer floats equipped with bio-optical and chemical (oxygen and nitrate) sensors to monitor the temporal evolution of the spring bloom. The work was also designed to integrate

NEXT-GENERATION, REGIONAL-SCALE EXPERIMENTS

One of the goals of the Scoping Workshop was to consider potential topics for these next-generation experiments of multiyear endurance over large ocean regions. A summary of these discussions is presented here as examples of multiyear float and glider experiments focused on questions that have global-scale implications. They are not, however, intended to represent the full complement of research issues that can be addressed using in situ sensors coupled with glider and float technology. In addition, longer-term follow-on studies to the North Atlantic experiment mentioned above were discussed.

Quantifying the Role of Biology in the Drawdown of CO_2 at the Subtropical-Subpolar Boundary in the North Pacific

An important oceanographic problem that can be successfully addressed using remote sensors is the study of net biological oxygen production at the boundary between the subarctic and subtropical gyres in the Pacific Ocean. The seasonal drawdown of pCO_2 at this boundary creates a carbon sink from atmosphere to ocean that is roughly equal to the

source observed in the equatorial Pacific (Takahashi, 2002). Ship observations have identified a maximum in biological carbon export at this boundary (recent work of author Emerson and Paul Quay, University of Washington), but the importance of biological processes to the

global-scale implications. However, the processes that maintain OMZ and control their dynamics are not well understood. There is great concern that these zones will enlarge in the future due to ocean deoxygenation, continuing a trend that has already been observed

the ocean uptake of anthropogenic CO₂ (Sabine et al., 2004). They are the most significant source of oxygen to intermediate depths, and they modulate the strength of the globally significant Peru-Chile oxygen minimum zone (Meissner et al., 2005). Subantarctic mode water is the main source of nutrients to the ocean's thermocline, and it supports a large fraction of biological production north of 30°S (Sarmiento et al., 2004). The nutrient properties of SAMW, which are set through biogeochemical processes in the subantarctic zone, are thus critical in determining ocean productivity.

There is evidence for freshening of intermediate waters and warming of mode waters over the past 10 to 20 years, with an overall increase in mode water production, consistent with models of anthropogenic climate change (Banks et al., 2000). The nutrient content of SAMW, set by biological processes within its formation region, is also sensitive to climate change (Sarmiento et al., 2004). Determining the biological processes that set the nutrient and oxygen properties of SAMW and detecting (and predicting) interannual and longer-time-scale changes in these properties are important priorities for studies of ocean biogeochemistry. These questions are well suited for addressing by sustained observations using floats or gliders.

THE PATH FORWARD

Over 200 floats in the Argo Program have been equipped with dissolved O₂ sensors (Figure 5a), and many gliders are now equipped to measure oxygen. Dozens of floats and gliders are equipped with bio-optics, primarily chlorophyll fluorometers and particle backscatter sensors (Figure 5b). Funding is now

“ THE CORE OF A GLOBAL BIOGEOCHEMICAL OBSERVING SYSTEM IS BEING DEVELOPED, ALBEIT IN A LARGELY AD HOC FASHION. ”

pCO₂ drawdown, and the mechanisms responsible for these observations, are not clear. Because of the dramatic seasonality of the pCO₂ drawdown, understanding its origin requires observations over complete annual cycles, a prospect difficult to achieve from ships. A study using floats and gliders would be capable of resolving the annual cycle of NCP and carbon export across the Pacific in the region between the subarctic and subtropical gyres.

Oxygen Minimum Zone and Nitrogen Cycle Studies

Oxygen minimum zones (OMZs) are regions of important biogeochemical reactions, such as denitrification and formation of the potent greenhouse gas nitrous oxide. At very low oxygen concentrations, nitrate becomes an alternative electron acceptor in respiration and is consumed. This significant feedback loop may regulate ocean productivity and climate over millennial time scales (Altabet et al., 2002). Although small in size, OMZs thus have

(Stramma et al., 2008). If these low-oxygen water masses were to extend into coastal regions, the impact on coastal water quality and coastal marine life would be severe.

Mapping and monitoring changes in OMZ oxygen concentration is now possible given the number of floats and gliders that sample these intermediate waters. Floats and gliders also provide a tool that helps link POC fluxes from the upper ocean to reactions in the ocean's interior. With N₂ sensors (GTDs) soon available for routine use on Lagrangian platforms, and oxygen, nitrate, and sulfide detection already proven, there is a window opening to study low-oxygen water masses, denitrification, and a suite of other processes in a manner that would never be feasible using standard shipboard approaches.

Southern Ocean Ventilation

Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) are key players in global biogeochemical cycles. They contribute significantly to

available to increase the number of floats with nitrate sensors from the present set of four (Figure 5b) to 40. The core of a global biogeochemical observing system is being developed, albeit in a largely ad hoc fashion. Moving forward with integrated, regional-scale experiments using autonomous platforms and multiple biogeochemical sensors as a model for a global observing system requires three significant developments.

First, we must demonstrate that sensors can generate climate-research-quality data. This standard means that results from sensors on different platforms must be intercomparable. For example, oxygen measurements should be made with a precision and accuracy of better than $\pm 0.5\%$ in order to avoid significant biases in biological rate estimates due to atmospheric oxygen exchange. They also must be highly accurate in order to be useful for determining seasonal to long-term trends in the ocean's oxygen content. Oxygen sensors can meet this requirement in terms of their precision (Figure 3), but very often factory calibrations do not produce accuracy at this level (e.g., Körtzinger et al., 2005; Riser and Johnson, 2008), limiting the opportunity to compare data across platforms. There are opportunities to make significant advances in calibration, but these will require both laboratory development and field testing. For example, optode O_2 sensors can be recalibrated using atmospheric pO_2 measurements when the floats surface (Körtzinger et al., 2005). Delayed-mode calibration of oxygen sensors may also be possible, as is now done for Argo salinity sensors, by using existing and newly developed oxygen climatologies at depth. Such standardized procedures

need to be developed and implemented at data centers for oxygen and other biogeochemical properties.

Second, we must demonstrate the operation of completely integrated observing systems that combine in situ sensors deployed on long-endurance platforms with satellite sensors and data-assimilating, biogeochemical-ecological models. In particular, data assimilation into models is essential to interpret the

large amounts of data in their spatial and temporal context, and to turn concentration measurements into quantitative rate estimates over large regions of the ocean. To date, there are relatively few efforts to assimilate biogeochemical data into models (e.g., Gregg, 2008), and achieving an integrated system will require substantial effort in this area. Some of the proposed pilot studies would represent ideal test beds for making rapid progress.

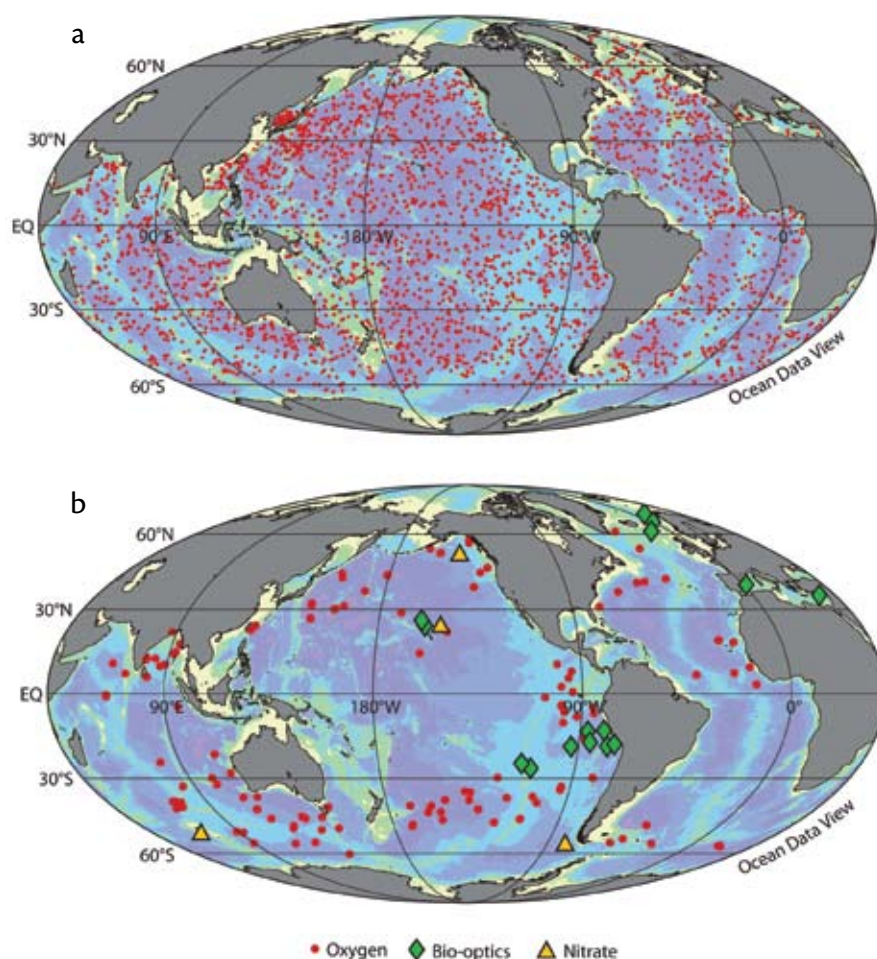


Figure 5. (a) All Argo floats reporting from June 9–16, 2009. (b) All Argo and Argo-equivalent floats equipped with oxygen sensors (red circles), bio-optical sensors (green diamonds), and nitrate sensors (yellow triangles) and reporting from June 9–16, 2009. Data were downloaded from the Argo Coriolis Data Center (<http://www.coriolis.eu.org/cdc/argo.htm>), except the nitrate float locations, which were downloaded from www.mbari.org/chemsensor/floatviz.htm. The census of Argo oxygen floats misses a number of active systems that are currently profiling under Antarctic ice and will not report until the next austral summer.

Because assimilation of biogeochemical data requires detailed knowledge about the physical setting of the observations, tight collaboration is required with the rapidly developing physical ocean data assimilation community (see, for example, Brasseur et al., 2009).

different sampling intervals. Future sensor developments, including pH, $p\text{CO}_2$, and possibly acoustic sensors for zooplankton, would enrich the system. These future developments are not essential, however, to begin regional-scale experimentation with a system that

“...A NOVEL BIOGEOCHEMICAL OBSERVING SYSTEM COULD BE DEVELOPED, PERMITTING US TO ADDRESS SOME KEY SCIENTIFIC QUESTIONS IN AN INNOVATIVE MANNER.”

Finally, an integrated data management system must be available for a biogeochemical observing system. Most of the data collected by profiling floats are delivered to a single data management system, which makes it relatively easy to access (Figure 5). Glider data are not handled in this manner, and this situation must be remedied.

With these efforts, a novel biogeochemical observing system could be developed, permitting us to address some key scientific questions in an innovative manner. We envision two strategies to move forward with the implementation beyond the regional-scale experiments. For some biogeochemical sensors (e.g., oxygen; Gruber et al., 2007), a collaboration could be set up to add the sensors directly to the existing Argo platforms. Such collaboration requires funding to offset the full marginal costs of adding sensors. More complex sensor arrays might best be deployed as a mission separate from Argo, especially when they require

could provide significant and quantitative information on the carbon cycle and related biogeochemical properties in the ocean. In particular, the existing and proven optical and chemical sensor set would be sufficient in many areas to document temporal changes in the biological carbon pump and seasonal to long-term changes in oceanic oxygen. 

REFERENCES

- Altabet, M.A., M.J. Higginson, and D.W. Murray. 2002. The effect of millennial-scale changes in Arabian Sea denitrification on atmospheric CO_2 . *Nature* 415:159–162.
- Banks, H.T., R.A. Wood, J.M. Gregory, T.C. Johns, and G.S. Jones. 2000. Are observed decadal changes in the intermediate water masses a signature of anthropogenic climate change? *Geophysical Research Letters* 27:2,961–2,964.
- Bishop, J.K.B. 2009. Autonomous observations of the ocean biological carbon pump. *Oceanography* 22(2):182–193.
- Bishop, J.K.B., and T.J. Wood. 2009. Year-round observations of carbon biomass and flux variability in the Southern Ocean. *Global Biogeochemical Cycles* 23, GB2019, doi:10.1029/2008GB003206.
- Bishop, J.K.B., R.E. Davis, and J.T. Sherman. 2002. Robotic observations of dust storm enhancement of carbon biomass in the North Pacific. *Science* 298: 817–821.
- Bishop, J.K.B., T.J. Wood, R.E. Davis, and J.T. Sherman. 2004. Robotic observations of enhanced carbon biomass and export at 55°S. *Science* 304:417–420.
- Boss, E., D. Swift, L. Taylor, P. Brickley, R. Zaneveld, S. Riser, M.J. Perry, and P.G. Stratton. 2008. Observations of pigment and particle distributions in the western North Atlantic from an autonomous float and ocean color satellite. *Limnology and Oceanography* 53:2,112–2,122.
- Brasseur, P., N. Gruber, R. Barciela, K. Brander, M. Doron, A. El Moussaoui, A.J. Hobday, M. Huret, A.-S. Kremer, P. Lehoudey, and others. 2009. Integrating biogeochemistry and ecology into ocean data assimilation systems. *Oceanography* 22(3):206–215.
- Claustre, H., Y. Huot, I. Obernosterer, B. Gentili, D. Tailliez, and M.R. Lewis. 2008. Gross community production and metabolic balance in the South Pacific Gyre, using a non intrusive bio-optical method. *Biogeosciences* 4:463–474.
- D'Asaro, E.A., and C.L. McNeil. 2007. Air-sea gas exchange at extreme wind speeds measured by autonomous oceanographic floats. *Journal of Marine Systems* 66:92–109.
- D'Asaro, E.A., C. Lee, M. Perry, K. Fennel, E. Rehm, A. Gray, N. Briggs, and K. Gudmundsson. 2008. The 2008 North Atlantic Spring Bloom Experiment I: Overview and strategy. *Eos, Transactions, American Geophysical Union* 89(53), Fall Meeting Supplement, Abstract OS24A-08.
- Ducklow, H.W., D.K. Steinberg, and K.O. Buesseler. 2001. Upper ocean carbon export and the biological pump. *Oceanography* 14(4):50–58. Available online at: http://www.tos.org/oceanography/issues/issue_archive/14_4.html (accessed July 15, 2009).
- Ducklow, H.W., S.C. Doney, and D.K. Steinberg. 2009. Contributions of long-term research and time-series observations to marine ecology and biogeochemistry. *Annual Review of Marine Science* 1:279–302.
- Emerson, S., C. Stump, and D. Nicholson. 2008. Net biological oxygen production in the ocean: Remote in situ measurements of O_2 and N_2 in surface waters. *Global Biogeochemical Cycles* 22, GB3023, doi:10.1029/2007GB003095.
- Gregg, W. 2008. Assimilation of SeaWiFS ocean chlorophyll data into a three-dimensional global ocean model. *Journal of Marine Systems* 69:205–225.
- Gruber, N., S. Doney, S. Emerson, D. Gilbert, T. Kobayashi, A. Körtzinger, G. Johnson, K. Johnson, S. Riser, and O. Ulloa. 2007. The Argo-oxygen program: A white paper to promote the addition of oxygen sensors to the international Argo float program. Available online at: http://www.imber.info/C_WG_SubGroup2.html (accessed July 13, 2009).
- Jenkins, W.J., and S.C. Doney. 2003. The subtropical nutrient spiral. *Global Biogeochemical Cycles* 17(1110), doi:10.1029/2003GB002085.

- Johnson, K.S., and L.J. Coletti. 2002. In situ ultra-violet spectrophotometry for high resolution and long term monitoring of nitrate, bromide and bisulfide in the ocean. *Deep-Sea Research Part I* 49:1,291–1,305.
- Johnson, K.S., J.A. Needoba, S.C. Riser, and W.J. Showers. 2007. Chemical sensor networks for the aquatic environment. *Chemical Reviews* 107:623–640, doi:10.1021/cr050354e.
- Körtzinger, A., J. Schimanski, U. Send, and D. Wallace. 2004. The ocean takes a deep breath. *Science* 306:1,337.
- Körtzinger, A., J. Schimanski, and U. Send. 2005. High quality oxygen measurements from profiling floats: A promising new technique. *Journal of Atmospheric and Oceanic Technology* 22:302–308.
- Körtzinger, A., U. Send, R.S. Lampitt, S. Hartman, D.W.R. Wallace, J. Karstensen, M.G. Villagarcia, O. Llinás, and M.D. DeGrandpre. 2008. The seasonal pCO₂ cycle at 49°N/16.5°W in the northeastern Atlantic Ocean and what it tells us about biological productivity. *Journal of Geophysical Research* 113, C04020, doi:10.1029/2007JC004347.
- MacCready, P., and P. Quay. 2001. Biological export flux in the Southern Ocean estimated from a climatological nitrate budget. *Deep-Sea Research Part II* 48:4,299–4,322.
- Martz, T.R., K.S. Johnson, and S.C. Riser. 2008. Ocean metabolism observed with oxygen sensors on profiling floats in the Pacific. *Limnology and Oceanography* 53:2,094–2,111.
- McNeil, C.L., E. D'Asaro, B.D. Johnson, and M. Horn. 2006. A gas tension device with response times of minutes. *Journal of Atmospheric and Oceanic Technology* 23:1,539–1,558.
- Meissner, K.J., E.D. Galbraith, and C. Volker. 2005. Denitrification under glacial and interglacial conditions: A physical approach. *Paleoceanography* 20, PA3001, doi:10.1029/2004PA001083.
- Nicholson, D., S. Emerson, and C. Erickson. 2008. Sub mixed-layer oxygen production determined from Seaglider surveys. *Limnology and Oceanography* 53:2,226–2,236.
- Niewiadomska, K., H. Claustre, L. Prieur, and F. d'Ortenzio. 2008. Submesoscale physical-biogeochemical coupling across the Ligurian current (northwestern Mediterranean) using a bio-optical glider. *Limnology and Oceanography* 53:2,210–2,225.
- Perry, M.J., and D.L. Rudnick. 2003a. Observing the ocean with autonomous and Lagrangian platforms and sensors (ALPS): The role of ALPS in sustained ocean observing systems. *Oceanography* 16(4):31–36. Available online at: http://www.tos.org/oceanography/issues/issue_archive/16_4.html (accessed July 15, 2009).
- Perry, M.J., and D.L. Rudnick, eds. 2003b. ALPS: Autonomous and Lagrangian Platforms and Sensors. Workshop Report, 64 pp. Available online at: http://www.geo-prose.com/pdfs/alps_report.pdf (accessed July 13, 2009).
- Perry, M.J., B.S. Sackmann, C.C. Eriksen, and C.M. Lee. 2008. Seaglider observations of blooms and subsurface chlorophyll maxima off the Washington coast, USA. *Limnology and Oceanography* 53:2,169–2,179.
- Riser, S.C., and K.S. Johnson. 2008. Net production of oxygen in the subtropical ocean. *Nature* 451:323–326.
- Roemmich, D., S. Riser, R. Davis, and Y. Desaubies. 2004. Autonomous profiling floats: Workhorse for broadscale ocean observations. *Marine Technology Society Journal* 38:31–39.
- Roemmich, D., G.C. Johnson, S. Riser, R. Davis, J. Gilson, W.B. Owens, S.L. Garzoli, C. Schmid, and M. Ignaszewski. 2009. The Argo Program: Observing the global ocean with profiling floats. *Oceanography* 22(2):34–43.
- Rudnick, D.L., R.E. Davis, C.C. Eriksen, D.M. Fratantoni, and M.J. Perry. 2004. Underwater gliders for ocean research. *Marine Technology Society Journal* 38:73–84.
- 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, and others. 2004. The oceanic sink for anthropogenic CO₂. *Science* 305:367–371.
- Sarmiento, J.L., N. Gruber, M.A. Brzezinski, and J.P. Dunne. 2004. High-latitude controls of thermocline nutrients and low latitude biological productivity. *Nature* 426:56–60.
- Stramma, L., G.C. Johnson, J. Sprintall, and V. Mohrholz. 2008. Expanding oxygen-minimum zones in the tropical oceans. *Science* 320:655–658.
- Takahashi, T., S.C. Sutherland, C. Sweeney, A. Poisson, N. Metzl, B. Tillbrook, N. Bates, R. Wanninkhof, R.A. Feely, C. Sabine, J. Olafsson, and Y. Nojiri. 2002. Global sea-air CO₂ flux based on climatological surface ocean pCO₂, and seasonal biological and temperature effects. *Deep Sea Research Part II* 49:1,601–1,622.
- Tengberg, A., J. Hovdenes, H.J. Andersson, O. Brocandel, R. Diaz, D. Hebert, T. Arnerich, C. Huber, A. Körtzinger, A. Khripounoff, and others. 2006. Evaluation of a lifetime-based optode to measure oxygen in aquatic systems. *Limnology and Oceanography: Methods* 4:7–17.