Ocean Carbon and Biogeochemistry News

Studying marine biogeochemical cycles and associated ecosystems in the face of environmental change

Volume 4, Number 3 • Fall 2011

Improving Model Predictions of Ocean Biogeochemistry

by Curtis Deutsch (UCLA)

The global cycles of the major biologically active elements are strongly shaped by physical climate. In turn, the primary greenhouse gases are largely regulated by these elemental cycles, giving rise to a variety of potential long-term feedbacks between biogeochemistry and climate. The inclusion of these processes and feedbacks has driven the evolution of climate models to more complex Earth System models. The ability to test the resulting predictions for biogeochemical cycles remains limited by the time scales involved, which are typically longer than the observational record. Climate variability provides a natural laboratory to test the understanding of critical biogeochemical processes and their representation in models. This situation closely parallels that of the physical climate system, where methods for testing and quantifying feedbacks have been an active area of research, and provide a useful template for extension to biogeochemistry and the carbon cycle.

U.S. CLIVAR recently convened a joint meeting with Ocean Carbon and Biogeochemistry (OCB) to explore these themes and to identify areas of common interest. The presentations and discussions spanned a wide range of processes and scales from plankton metabolism to meridional overturning with regional foci from the North Atlantic to the Southern Ocean. Here I will summarize two case studies in which changes in ocean biogeochemistry have been linked to climate variability, and illustrate how methods that combine models and data might be used to better constrain the long-term changes in these elemental cycles currently being predicted by IPCC class models. Both examples are drawn from the tropical Pacific, where the rapidly evolving understanding of physical climate variability provides a solid foundation on which to improve our understanding of the links to biogeochemical cycles.

Air-sea CO_2 flux

The oceanic absorption of anthropogenic CO_2 represents a small residual difference between much larger rates of uptake and release that are conceptually associated with the "natural" CO_2 cycle. In this pre-industrial CO_2 cycle, the tropical Pacific represents the largest oceanic source of CO_2 to the atmosphere, owing to the upwelling and subsequent

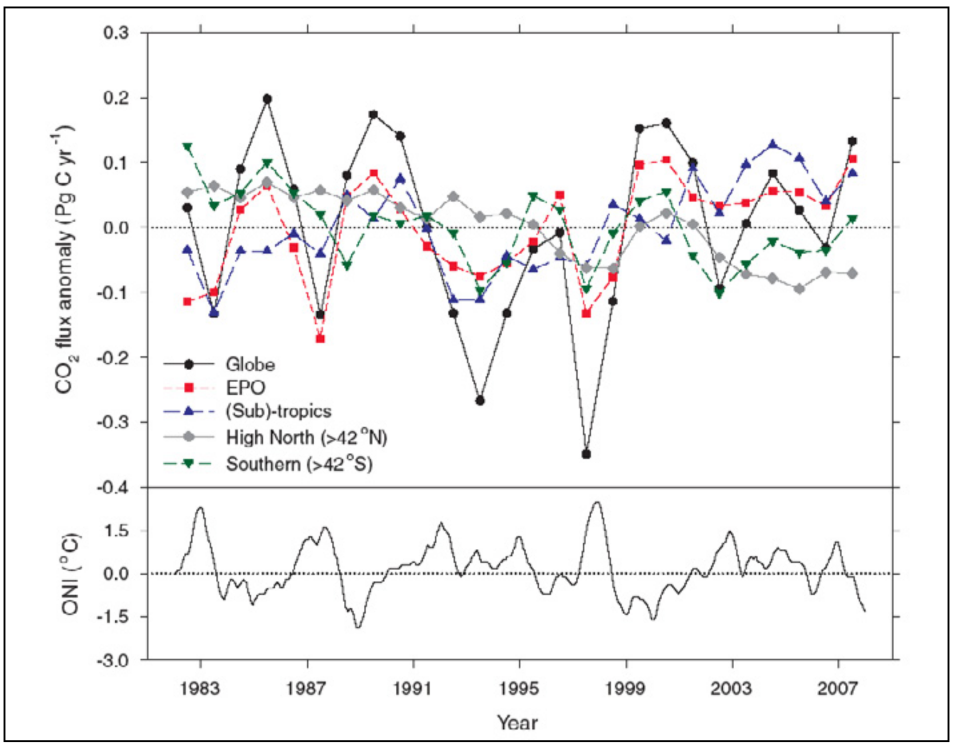

Figure 1. Global and regional air-sea CO_2 flux anomalies estimated from empirical relationships to SST, revealing the strong global influence of ENSO as indicated by the Oceanic Niño Index (ONI). EPO = Equatorial Pacific (10°N–10°S; 80°W–135°E). Figure from *Park et al.* (2010).

heating of cold, carbon-rich deep water. It is also the largest driver of interannual variability of air-sea CO_2 flux (Fig. 1), due to the effects of ENSO on both ocean and terrestrial carbon reservoirs. The tropical Pacific is among the most well-characterized regions of atmosphere-ocean carbon exchange based on time-series measurements on the TAO array, which have helped quantify seasonal and interannual variations in CO_2 flux. Generally, the stronger trade winds during a La Niña enhance the outgassing of CO_2 to the atmosphere via a larger flux of carbon upwelling from depth (a "thermodynamic" effect) and faster equilibration of this excess carbon with the atmosphere (a "kinetic" effect). The reverse anomalies accompany an El Niño, along with a reduced rate of plankton growth due to nutrient limitation, which opposes but does not reverse the anomalies from the kinetic and thermodynamic effects.

A rapidly growing body of research on tropical Pacific climate suggests that both the mean state of the equatorial circulation and its ENSO-related variability may change in a warmer climate. A long-term weakening of the equatorial trade winds (Walker circulation) is expected to reduce the rate of upwelling (*Vecchi et al.*, 2006), and this would reduce the mean source of CO_2 to the atmosphere, at least in a transient state. Changes in the zonal structure, frequency, and intensity of ENSO are also being actively debated (*McPhaden et al.*, 2011; *Yeh et al.*, 2009), but could affect the variability of the CO_2 source in both the ocean and terrestrial carbon cycles. In the ocean, model simulations suggest that the relative importance of kinetic and thermodynamic drivers of variability also varies systematically with longitude, with wind speed being more important in the eastern Pacific and upwelling explaining the flux anomalies in the central basin (*Doney et al.*, 2009). The effect of such changes on the CO_2 source from the tropical Pacific and its interannual variability is not known, and may extend well beyond the equatorial Pacific itself, since ENSO-related CO_2 flux anomalies are global in scale (Fig. 1). The process-level understanding of complex influences on equatorial Pacific CO_2 flux may also hold relevance in other upwelling regions such as the Southern Ocean, where climatic trends in wind-driven ocean CO_2 outgassing are currently being debated (*Lovenduski and Ito*, 2009).

Ocean hypoxia

While not directly involved in climate-carbon feedbacks, dissolved oxygen in the ocean plays a central role in fundamental biogeochemical processes, and in atmospheric constraints on anthropogenic CO_2 uptake by the terrestrial biosphere. The oceanic distribution of O_2 is largely a product of the ventilation of the ocean interior by O_2-rich surface waters from mid- and high latitudes. The decline of thermocline O_2 toward the tropics reflects the continual

Greetings from the OCB Project Office

Welcome to our newsletter, and thank you for reading!

We are quite busy in the OCB Project Office this fall! We received almost 30 nominations for the OCB Scientific Steering Committee (SSC) from the community this year, and current SSC members are now amidst discussions and voting. Keep an eye out for an announcement of the new OCB SSC members!

Please be sure to read the OCB Update to find important OCB meeting dates and links to new OCB workshop reports. We are still seeking community feedback on the 2012 OCB Summer Workshop. Please send us your ideas by **December 9, 2011**. The Update also includes detailed information about ongoing NACP/OCB Coastal Synthesis activities. Regional leaders are seeking community involvement!

OCB and U.S. CLIVAR

We had a very productive and stimulating summer workshop in Woods Hole this July (see article in this issue). One of the highlights of this year's workshop was a joint science session with U.S. CLIVAR, the goals of which were to explore overlapping scientific interests and identify initial high-priority research topics that may lead to joint activities between U.S. CLIVAR and OCB researchers over the next decade. The science pieces in this issue of *OCB News* are based on material presented during the joint plenary session. Scott Doney highlights potential scientific synergies between the two programs and summarizes common observational approaches and opportunities. Curtis Deutsch uses a combination of data and modeling to explores links between climate variability and ocean biogeochemistry, with case studies on air-sea CO_2 flux and ocean hypoxia. Based on existing observations and modeling approaches, Nicole Lovenduski describes the relationship between the Southern Annular Mode, a dominant mode of southern hemisphere extratropical climate variability, and carbon uptake in the Southern Ocean. These articles are also being published in the fall issue of the U.S. CLIVAR newsletter Variations.

Soon after the joint session, the OCB and CLIVAR offices worked with the joint session planners to draft an announcement of opportunity for joint working groups. We did receive prospectuses for joint working groups, and the U.S. CLIVAR and OCB scientific leadership are amidst discussions. We will announce respiratory consumption of O_2, yielding regions of very low (hypoxia) to no (anoxia) O_2. Such low-O_2 conditions directly influence numerous biological and chemical processes, including the production of the greenhouse gas N_2O, the loss of scarce bioavailable nitrogen, and the physiology of marine organisms. The ocean's oxygen content may respond sensitively to global ocean warming because as the ocean is heated from above, O_2 becomes less soluble in surface waters and is also less readily transported to depth in areas of increased thermal stratification (*Keeling et al.*, 2009). However, observed O_2 variance is dominated by interannual and decadal fluctuations superimposed on a much smaller, long-term trend, and there are few time-series from low-O_2 regions, where the effect of O_2 loss would have the greatest biogeochemical consequences.

Model simulations show large swings in the volume of low-O_2 water, consistent with patterns revealed by long time-series from the California coast (California Cooperative Oceanic Fisheries Investigations, or CalCOFI) (*Deutsch et al.*, 2011). The depth of the tropical and subtropical thermocline is the key modulator of anoxia, because it causes nonlinear changes in the rate of respiration that maintains thermocline hypoxia, despite replenishment by transport. Thermocline depth fluctuations in the low-O_2 zones of the eastern tropical Pacific are part of a basin-scale pattern of thermocline variability that is closely connected to Pacific climate. The principal spatial pattern of decadal variability in thermocline (13°C isotherm) depth across the entire Pacific Ocean includes a coherent shoaling and deepening of the thermocline throughout the eastern basin associated with cool and warm phases of the Pacific Decadal Oscillation, or PDO, respectively (Fig. 2). The sensitivity of low-O_2 zones to variations in thermocline depth highlights a potential mechanism for counteracting the expansion of some hypoxic zones due to warming, but the time scales over which this mechanism remains important are not presently known.

Greetings from the OCB Project Office (cont.)

the results of this joint call once final decisions have been reached.

Outreach and other activities

The Project Office has been quite busy with outreach activities this fall. In September, I did a presentation and hands-on demonstration on ocean acidification for the Woods Hole Oceanographic Institution Ocean Science Journalism Fellows. In mid-October, I visited with 36 7th grade students from Saint David's School in New York City as part of their weeklong trip to the Cape Cod Sea Camps in Brewster, MA. After a short presentation and Q&A session on ocean acidification, we spent a fun afternoon learning about pH and ocean acidification with hands-on experiments (see full article in Education and Outreach section).

In November, I am representing OCB at the Smithsonian Institution's MarineGEO workshop to discuss development of a global-scale network of ecological observatories dedicated to understanding changes in the structure and function of marine ecosystems. If you are attending the 2012 Ocean Sciences Meeting, I encourage you to see Kendra Daly's talk on the OCB Program in *Session 098: The Critical Importance of Community Building in the Ocean Sciences*.

Enjoy this issue of the OCB News, and if you would like to contribute to future issues, please don't hesitate to contact me.

All the best,
Heather Benway
(Executive Officer, OCB Project Office)

Future Directions

The intercomparison of climate models through the IPCC process has been a critical avenue for evaluating model biases and thus weighing the relative likelihood of wide-ranging climate projections. One promising approach is to exploit the relationship between climate feedbacks at different time scales, where the availability of observations on short time scales can be used to constrain behavior over longer time scales. The seasonal cycle has been shown to be a particularly powerful test case for feedbacks at longer time periods (*Hall and Qu*, 2006; *Knutti et al.*, 2006). These methods have not yet been applied to biogeochemical cycles in earth system models and the climate feedbacks they entail. To do so requires that we address at least two questions:

- ➔ For which processes, and at which time scales, is natural variability of the carbon cycle a useful analog for longer-term trends?
- ➔ What are the observational requirements to constrain the range of model behavior at shorter time scales (e.g., seasonal to interannual)?

The first question can be addressed using model analyses, while the second will likely require coordinated measurement efforts, some involving new or greatly expanded observational platforms.

The current phase of the IPCC Coupled Model Intercomparison Project (CMIP5) provides a consistent set of climate simulations using state-of-the-art global climate

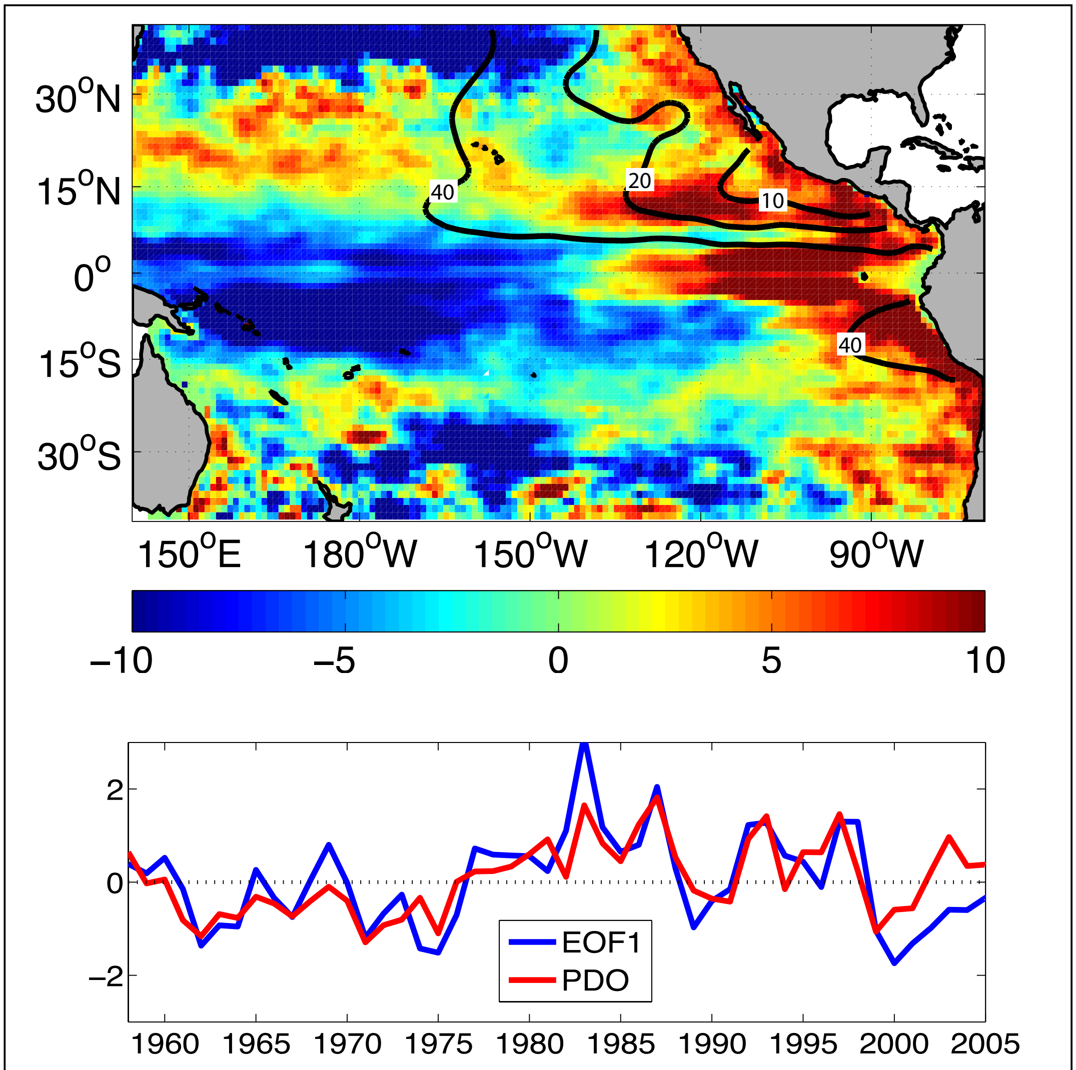

Figure 2. (a) Location of hypoxic water in the Pacific thermocline (300 m, contours) on top of the leading spatial pattern of thermocline depth (13°C isotherm, lying with the low-O_2 core) according to an EOF analysis of the Simple Ocean Data Assimilation (*Carton and Giese,* 2008). (b) Time-series of the thermocline depth EOF and the Pacific Decadal Oscillation (PDO). Figure adapted from *Deutsch et al.* (2011).

models with interactive carbon cycling components. These simulations represent a unique opportunity to explore how different amplitudes of variability are correlated across time scales in diverse model architectures. In the example of equatorial CO_2 fluxes, one might seek to establish whether the sensitivity of CO_2 outgassing to trade wind strength between ENSO cycles is correlated across models with regional trends in outgassing over the coming century, for example due to a weakening Walker circulation. Similarly, for ocean hypoxia the relationship between the extent of low-O_2 water and the depth of the thermocline at observable time scales may help to adjudicate the differing trends already evident in some earth system models.

Using these methods to narrow model uncertainties requires that the true degree of variation at observable time scales can be accurately estimated from data. For many such relevant processes, the ocean remains severely undersampled, even over the seasonal cycle. However, emerging observations of biogeochemical properties from autonomous profiling floats, together with ongoing ocean time-series and shipboard (e.g., repeat hydrography) measurement programs provide important opportunities to characterize seasonal to interannual variability that may help refine the representation of biogeochemical responses (and ultimately feedbacks) to climate change in the current generation of Earth system models.

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OCB and U.S. CLIVAR: Scientific Questions & Global Observing Capabilities

by Scott Doney (Woods Hole Oceanographic Institution)

As part of their 2011 summer meetings, the U.S. CLIVAR and Ocean Carbon and Biogeochemistry (OCB) communities came together for a day-long session to discuss opportunities for collaborative research. The relevant science questions span physical topics such as variability and trends in sea surface temperature (SST), ocean heat content, and the wind-driven and thermohaline components of ocean circulation to biogeochemical issues such as ocean carbon dioxide (CO_2) uptake, declining oxygen levels, shifts in rates of biological productivity, and changes in ecosystem patterns and structure. Here I address some of the scientific synergies across the two communities and common observational approaches, emphasizing ship-based and *in-situ* autonomous platforms.

There are natural linkages between the sets of physical and biogeochemical questions addressed by the CLIVAR and OCB research communities, respectively. The air-sea fluxes of momentum, heat, freshwater, CO_2, and other trace gases are modulated by similar kinetic processes such as winds, turbulence, and wave breaking. Ocean circulation, heat content, and marine biogeochemistry are coupled on seasonal to decadal time scales. A good example is the oceanic response to El Niño-Southern Oscillation (ENSO) in the tropical Pacific, in which reduced equatorial upwelling and relaxation of the east-west tilt of the thermocline during El Niño events lead to warmer SSTs and reduce outgassing of CO_2. In the extratropics, surface chlorophyll is correlated with SST, reflecting a combination of varying mixed layer depth (which affects the light environment experienced by the phytoplankton), nutrient supply, temperature-dependent physiological processes, and loss mechanisms.

Both programs also are motivated, in part, by historical data from the past several decades, which indicate how the ocean and the Earth system as a whole evolve with time (Fig. 1). Well known examples include rising atmospheric levels of CO_2 and other greenhouse gases, increases in the heat content of the ocean thermocline, and reductions in the extent and thickness of sea ice in the Arctic and along the West Antarctic Peninsula. Detecting these long-term trends, which are often attributed to human actions and anthropogenic climate change, is challenging because the ocean exhibits substantial natural variability on sub-annual to multi-decadal time scales. Natural variability is of interest in its own regard. Surface temperatures and upper-ocean heat content are useful for extended-range weather and short-term climate forecasts, and ocean physical-biological variability is used for fishery applications and monitoring ecosystem health (e.g., potential for thermal coral bleaching events; harmful algal blooms). Observations, along with process studies and

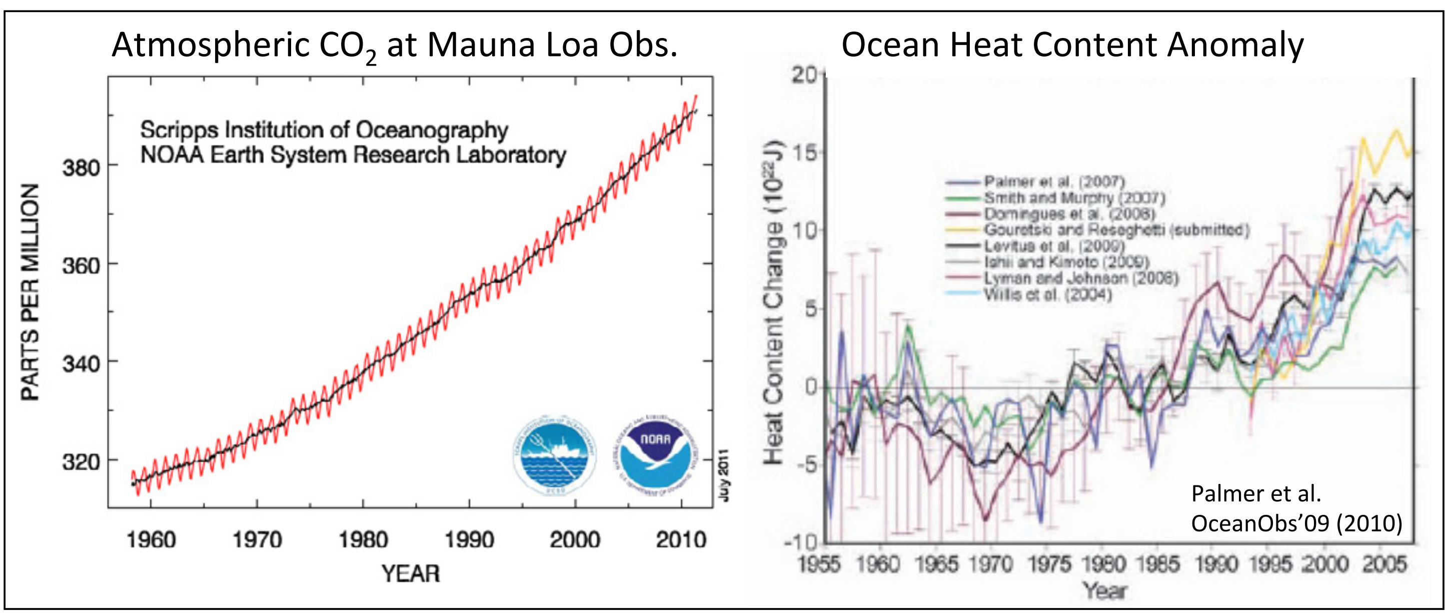


Figure 1: Observed trends for the last half-century in (left) atmospheric CO_2 and (right) global ocean heat content anomaly highlighting the impacts of human fossil-fuel CO_2 emissions and global warming.

models, are also essential for attributing the underlying causes driving both ocean variability and trends, in particular for teasing apart the effects of anthropogenic forcing from other internal and external factors.

Better projections of Earth's climate over the next several decades to centuries require a solid understanding of ocean physics and biogeochemistry. Uncertainties in climate projections can be divided roughly into three groups: uncertainties in emissions of CO_2 (and other greenhouse gases and aerosols) to the atmosphere associated with social, political, economic, and technological factors; for a specified emissions scenario, uncertainties in atmospheric CO_2 levels associated with land and ocean carbon sinks and climate-carbon feedbacks; for a specified atmospheric CO_2 level, uncertainties in the climate sensitivity to associated changes in clouds, ocean circulation, sea ice, land biophysics, etc.

The ocean slows climate change by storing excess heat and by removing CO_2 from the atmosphere. Temporal trends in ocean heat content, reconstructed for the last half-century from XBT and CTD profiles, show that most of the heating associated with global warming has occurred in the ocean with small contributions from melting of land ice. Data coverage has expanded greatly with the availability of routine satellite altimetry and the global Argo array of ~3200 profiling floats, which provide maps of temperature and salinity data over the upper 2000m every ~10 days (www.argo.ucsd.edu; argo.jcommops.org).

For the ocean inventory of anthropogenic CO_2, we rely primarily on water collected in conjunction with CTD profiles from research ships. Anthropogenic CO_2 cannot be measured directly, but can be estimated from dissolved inorganic carbon (DIC) and alkalinity data and ancillary information on hydrography, nutrients, oxygen, and other chemical tracers. The WOCE/JGOFS Global CO_2 survey in the late-1980s and 1990s provided a baseline for calculating anthropogenic CO_2 uptake from pre-industrial conditions and for tracking future changes. Current estimates indicate that the ocean takes up about a quarter of human CO_2 emissions, with the highest uptake rates occurring in areas of mode, intermediate, and deep water formation. The primary governing mechanisms are the thermodynamics of CO_2 dissolution into seawater and the kinetics of surface water exchange with subsurface waters.

The ocean CO_2 sink may become less effective in the future due to warming, increased vertical stratification, and altered ocean circulation, which would act to accelerate climate change. Strengthened westerly winds in the Southern Ocean, on the other hand, may lead to increased ocean uptake of anthropogenic CO_2, serving as a negative feedback. Current model estimates suggest that the climate-ocean carbon feedback is positive—less ocean CO_2 uptake under a warming climate—but with a wide range of magnitudes. Better constraints on the response of ocean circulation and biological productivity to changing climate could improve model estimates. Satellite observations indicate a coupling on interannual time scales between upper ocean heat content and phytoplankton biomass, and most future model projections show reduced productivity in the tropics and subtropics, because increased stratification limits nutrient supply, and neutral or increased productivity in subpolar and polar regions because of shallower mixed layers and reduced sea ice. Models also suggest that subsurface oxygen levels will decline due to altered circulation and biogeochemistry in a warmer world; these predictions are partially supported by historical data indicating an expansion in the spatial extent of oxygen minima.

Global ocean observing capabilities to address such coupling issues have improved with time due to the growth and coordination of international research ship surveys, volunteer observing ship networks, time-series and moorings, autonomous platforms with *in-situ* sensor technologies, and satellite remote sensing. Yet the ocean remains vastly undersampled for many key properties, especially for addressing biogeochemical and ecological questions.

No single observational approach can address all problems, in part because each platform (or network) has characteristic sampling time and space scales that must be matched to the phenomenon of interest (Fig. 2). For example, mooring records provide high temporal resolution for individual locations but lack spatial information. The global ship survey conducted for hydrography and CO_2 during the WOCE/JGOFS era took nearly a decade to complete and offers a window on large-scale, slowly evolving circulation and biogeochemical patterns. Other research networks such as underway and upper-ocean measurements from Volunteer Observing Ships (VOS) and the Argo profiling float array fill in intermediate time and space scales.

Individual platforms and networks also have their own specific limitation on the suite of properties that can be measured and on the accuracy and precision of the resulting data. Satellite remote sensing of ocean color, for example, allows for global coverage every few days (barring cloud cover), but only samples the upper tens of meters of the water column and requires algorithms to convert measured water-leaving radiances into useful biological properties (e.g., surface chlorophyll concentrations). A solution is to integrate multiple sampling approaches with models and process studies, but this requires an in-depth understanding of the relationship among observations and a substantial and growing infrastructure for data management and data assimilation.

Broadly speaking, we can estimate the ocean uptake of heat, CO_2, or any other property either by monitoring the rate of change in the ocean inventory or by quantifying the net air-sea exchange. Independent approaches are crucial, if possible, to minimize the impact of biases or limitations in any particular method. Ocean inventories change slowly with time, requiring high-quality measurements over extended periods of time. To characterize the marine inorganic carbon system, we need to measure at least 2 of 4 carbon parameters (DIC, alkalinity, pH, and the partial pressure of CO_2, pCO_2), as well as temperature and salinity. Present-day anthropogenic ocean carbon concentrations are ~50-60 μmol/kg in surface waters, only ~2% of natural DIC levels, decreasing with depth; concentrations through the thermocline are increasing over time by ~1-10 μmol/kg/decade. Because of the small signal and large natural variability, high precision and accuracy are required, and diagnostic techniques are needed to separate the imprint of rising atmospheric CO_2 versus variability in ocean circulation and biology.

The U.S. and international repeat hydrography programs (ushydro.ucsd.edu; go-ship.org) are reoccupying select hydrographic sections from the WOCE/JGOFS global survey on an approximate decadal schedule. A suite of full-depth physical, biogeochemical, and tracer measurements are being made. Early results for the Atlantic and Pacific basins include warming of bottom waters, continued invasion of chlorofluorocarbons into the thermocline and deep ocean, decadal shifts in oxygen distributions, and estimates of the decadal growth of anthropogenic CO_2.

Ocean inventory changes can also be constrained from the global integral of air-sea exchange, though problems can arise because typically one is trying to find a small net imbalance between large positive and negative flux terms. Spatial mapping of surface water pCO_2 has been greatly facilitated by underway sampling on VOS research, commercial, and Antarctic resupply vessels (http://www.ioccp.org/UW.html). Air-sea CO_2 fluxes can be derived from the measured difference between ocean and atmosphere pCO_2, wind speeds from ship observations, atmospheric reanalysis, or scatterometers, and empirical gas transfer velocity relationships. Seasonal climatologies can be constructed globally from available data, but there remain substantial sampling gaps in some regions and seasonal biases in others (e.g., South Pacific; Southern Ocean). Internannual variability can be resolved for specific, high-traffic areas like the North Atlantic and Equatorial Pacific and estimated globally from regional pCO_2-SST regressions. Estimates of global ocean CO_2 uptake are broadly consistent across diverse methods including air-sea fluxes, ocean inventories, forward and inverse ocean models, and atmospheric CO_2 inverse models. Key insights on ocean CO_2 trends and biogeochemical dynamics have been derived from time-series

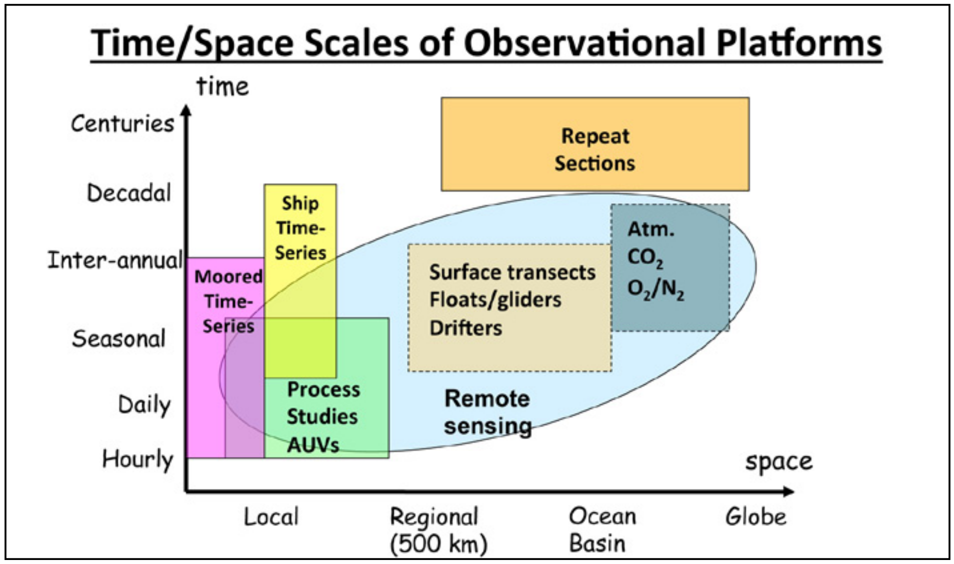


Figure 2: Schematic diagram illustrating the characteristic time- and space-scales sampled by different observing systems and networks.

stations, and biogeochemical capabilities could be incorporated on a broad collection of other existing time-series stations (www.oceansites.org).

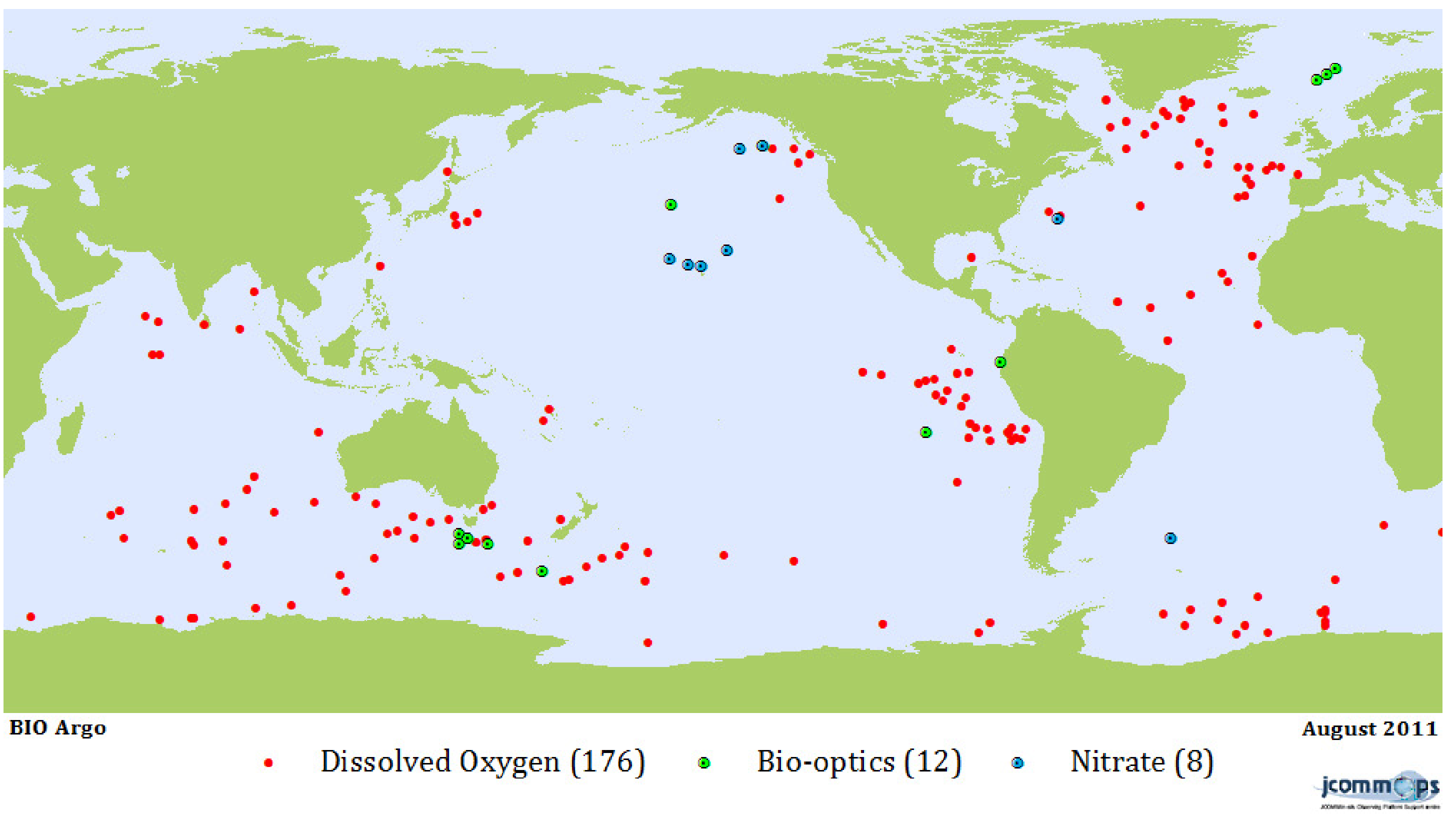
The physical oceanographic community has led the way in deploying autonomous observing platforms that can operate for extended periods of time, independent of a research ship. There are a variety of different available platforms, and a number of trade-offs need to be considered when developing a network of autonomous vehicles. Cost is an obvious factor, affecting the number of platforms that can be deployed and thus the density of sampling. Power influences a wide variety of vehicle attributes including the allowable sensor suite, the endurance (or range), and the number of cycles or vertical profiles. Platforms are often grouped into low-power systems (e.g., floats, gliders, drifters, and wave gliders) and high-power systems (autonomous underwater vehicles or AUVs, moorings, and cabled observatories). With the exception of cabled observatories, most autonomous platforms rely on satellite uplink to provide near-real time data transmission, often with limited bandwidth, though this is improving. The capability for two-way communication for many platforms allows for reprogramming of platform mission and sampling strategies. An important factor is whether the platform is expendable (e.g., most floats and drifters) or recoverable (at least in principle, if not always in fact) at the end of a mission (e.g., gliders, AUVs, moorings), which provides opportunity for post-calibration of sensors. Drifters and floats are Lagrangian sampling devices, following the flow of the water; AUVs and gliders are navigable, allowing sampling of specified features or along specified tracks.

Rapid progress is being made on *in-situ* biogeochemical sensors for Argo floats, opening up the possibility of a companion global biogeochemical array (Fig. 3). Currently available sensors include dissolved oxygen, nitrate, and bio-optics. Inorganic carbon system sensors are under development. There are compelling science questions that require sampling of the deep-ocean, which is currently only accessible via ship. This may change in the future with improved deep-water floats and extended range AUVs with the capability for water sample return. But there likely will remain a need for ship-based profiling for calibration, historical continuity, and exploratory measurements.

There remain significant logistical challenges across both communities in how to maintain sustained observations of the ocean. The current generation of climate-quality data records requires careful attention to sensor calibration and reference standards. Over time, observational programs, which have often been initiated at the level of individual investigator(s) to address specific scientific questions, may need to transition into sustainable, operational modes with a more secure funding model than available via the typical three-year, hypothesis-driven proposal process. The growing wealth of publicly available ocean data coming from observational networks provides a wonderful resource for the next generation of ocean scientists, but we may need to revisit the metrics and incentives we use evaluate the contributions of individuals in a more distributed and collaborative work environment.

In summary, the ocean-atmosphere system exhibits substantial variability across a wide range of time and space scales, and key challenges for the scientific community include partitioning the observed signals into contributions from natural variability versus secular change, and deciphering the underlying mechanisms and causes driving the physical, chemical, and biological dynamics. Arrays of autonomous platforms are already in wide use for physics applications and show great promise for biogeochemistry.

Figure 3: Map showing the locations of Argo floats with biogeochemical sensors (dissolved oxygen, bio-optics, and nitrate) as of August 2011. There are 196 floats with biogeochemical sensors out of a total Argo array of 3,234 active floats.



Climate Variability and Southern Ocean Carbon Uptake

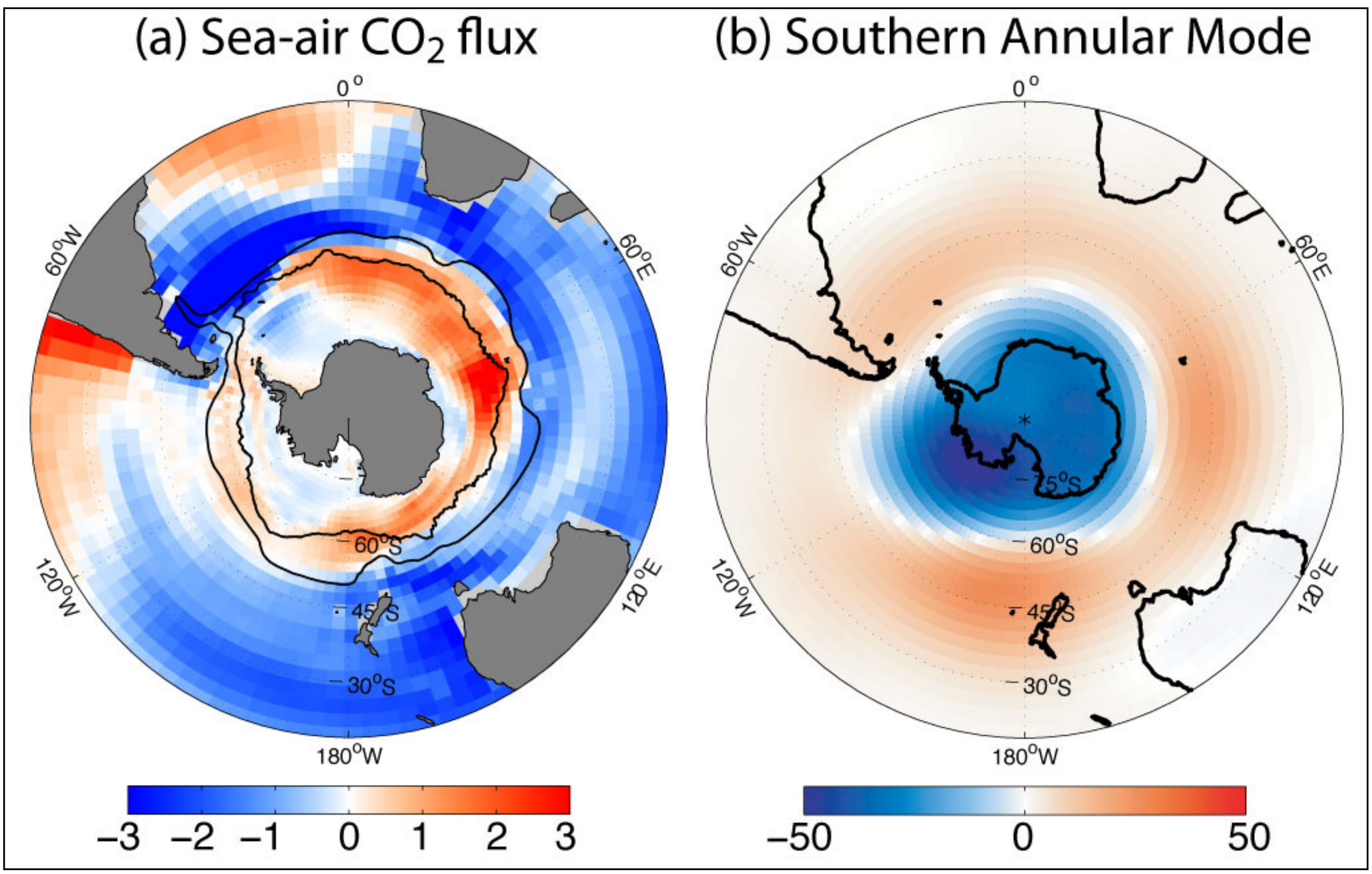
*by Nicole Lovenduski (*University of Colorado, Boulder)

Since the beginning of the industrial revolution, anthropogenic emissions of carbon dioxide (CO_2) have increased atmospheric CO_2 concentrations, driving increases in global atmospheric temperature. Only about half of the anthropogenic CO_2 emissions have remained in the atmosphere, while the remainder have been absorbed by natural carbon sinks: the ocean and the terrestrial biosphere. Modeling studies suggest that nearly half of the global oceanic anthropogenic CO_2 uptake has occurred in the Southern Ocean (*Mikaloff Fletcher et al.,* 2006). As such, the Southern Ocean is an important regulator of atmospheric CO_2 and the global climate system.

The physical circulation of the Southern Ocean governs the exchange of CO_2 across the air-sea interface. South of the Antarctic Circumpolar Current (ACC), the circulation is characterized by divergence and upwelling of deep water to the surface. The upwelled deep water is enriched in dissolved inorganic carbon (DIC), and given the inefficient DIC uptake via the biological pump, the high latitude Southern Ocean tends to lose natural CO_2 to the atmosphere (Figs. 1a, 3; *Mikaloff Fletcher et al.,* 2007). North of the ACC, subduction and mode water formation lead to substantial oceanic uptake of natural carbon from the atmosphere. This pattern of oceanic release and uptake of natural carbon is overlain by a pattern of uptake of anthropogenic CO_2, which is largest north of the ACC (*Khatiwala et al.,* 2009). The resulting pattern of the contemporary CO_2 fluxes is thus the superposition of these two component fluxes, with reduced outgassing south of the ACC relative to pre-industrial times, and enhanced uptake north of the ACC (*Gruber et al.,* 2009).

The Southern Ocean sink for atmospheric CO_2 has exhibited significant interannual to multidecadal variability over the past few decades. Coarse-resolution physical

Figure 1. (a) Annual-mean observed sea-air CO_2 flux (mol m^{-2} yr^{-1}). Positive values indicate CO_2 outgassing. Data from Takahashi et al. (2009). Black contours indicate the position of the Antarctic Polar Front and Subantarctic Front, the two main cores of the ACC. (b) Regression of 700 mb geopotential height anomalies onto the SAM index (m).



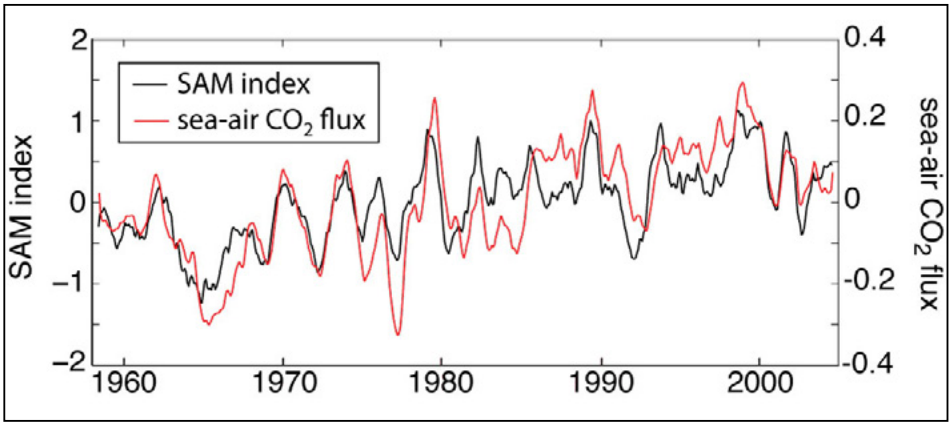


Figure 2. Integrated Southern Ocean (<35°S) sea-air flux of natural CO_2 (red; Pg C yr^{-1}), as estimated by a coarse-resolution ocean GCM, and the standardized SAM index (black). Both time series have been smoothed with a 12-month running average. Adapted from *Lovenduski et al.* (2007).

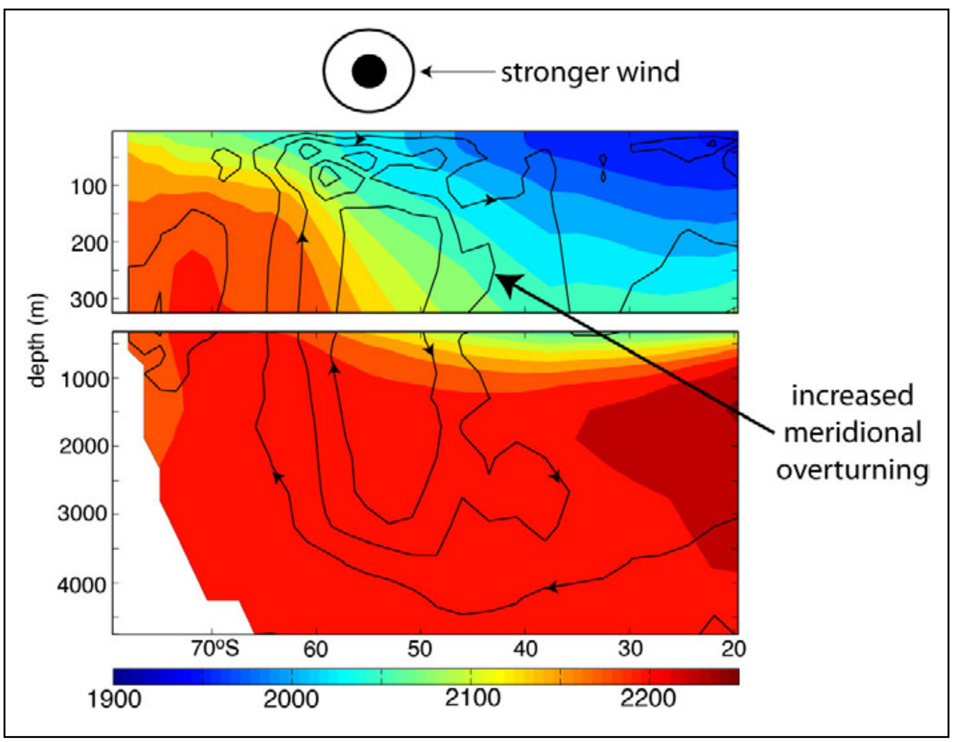
and biogeochemical ocean models yield large interannual variability in high-latitude sea-air fluxes of natural CO_2 (Fig. 2; *Lenton and Matear,* 2007; *Lovenduski et al.,* 2007; *Verdy et al.,* 2007). Studies based on ocean models (*Lovenduski et al.,* 2008) and the inversion of atmospheric CO_2 data (*Le Quéré et al.,* 2007) have revealed a significant multi-decadal trend in sea-air fluxes of natural CO_2 over the past 30 to 50 years (Fig. 2) that has substantially weakened the Southern Ocean's capacity to absorb CO_2 from the atmosphere. It has been suggested that a large fraction of this variability is driven by the Southern Annular Mode (SAM).

The SAM is the dominant mode of atmospheric climate variability in the extratropical Southern Hemisphere, and is characterized by an oscillation of atmospheric mass between the mid- and high latitudes. Positive and negative phases of the SAM are associated with meridional shifts in the westerly winds (Fig. 1b; *Thompson and Wallace,* 2000). Observations show a positive trend in the SAM over the past 30 years, synchronous with a poleward intensification of the westerly winds (*Thompson et al.,* 2000).

A substantial component of Southern Ocean circulation and sea-air CO_2 flux varies in phase with the SAM. Positive phases of the SAM (poleward-intensified westerlies) are correlated with an increase in northward Ekman transport and meridional overturning, inducing anomalous upwelling of water in the region south of the ACC (Hall and Visbeck, 2002). Since these upwelled waters are enriched in natural DIC, model-based studies show enhanced outgassing of natural CO_2 from the Southern Ocean during a positive SAM (Fig. 2; *Lovenduski et al.,* 2007), while anthropogenic fluxes remain largely unchanged. Simulations of coarse-resolution ocean general circulation models (GCMs) suggest that the multi-decadal trend in the SAM has led to a long-term increase in the rate of meridional overturning, driving an increase in the upwelling and equatorward transport of DIC-rich waters, and a trend toward outgassing of natural CO_2 (Figs. 2, 3; *LeQuéré et al.,* 2007; *Lovenduski et al.,* 2008) while again, the anthropogenic CO_2 fluxes appear not to be affected.

Recent literature questions whether coarse-resolution ocean GCMs can simulate an appropriate Southern Ocean meridional overturning circulation (MOC) response to the SAM (*Böning et al.,* 2008; *Hogg et al.,* 2008). Mesoscale eddies, believed to play a central role in Southern Ocean heat and momentum balance, are not explicitly resolved, but rather are parameterized in such models. Dur-

Figure 3. Annual-mean, zonal-mean DIC concentration (colors; mmol kg^{-1}), and the 30-year trend in the meridional overturning streamfunction (contours), as estimated by a coarse-resolution ocean GCM. Adapted from *Lovenduski et al.* (2008).



ing positive phases of the SAM, the Ekman-driven increase in the strength of the MOC may be compensated by a wind-induced increase in the southward eddy fluxes, such that there is little net change in the residual MOC. If SAM variability has only a moderate impact on the rate of meridional overturning, one would expect only a small anomaly in CO_2 outgassing during positive phases of the SAM. Similarly, the trend in natural sea-air CO_2 flux (Fig. 2) would likely be substantially reduced relative to that predicted by coarse-resolution models. Resolving this issue will require improved parameterization of eddy advection in coarse-resolution ocean GCMs (*Farneti and Gent,* 2011; *Gent and Danabasoglu,* in press), eddy-resolving simulations of the Southern Ocean carbon cycle (*Lovenduski et al.,* in prep.), and enhanced physical and biogeochemical observations of the Southern Ocean.

Relatively sparse sampling of physical and biogeochemical properties in the Southern Ocean has hampered the investigation of circulation and carbon uptake variability from an observational perspective. However, a few studies of long-term biogeochemical changes have recently emerged in the literature. Using historical measurements of the partial pressure of CO_2 in the surface ocean, *Metzl* (2009) and *Takahashi et al.,* (2009) documented a multi-decadal decrease in Southern Ocean CO_2 uptake rates. On the basis of historical radiocarbon measurements in Drake Passage, *Sweeney et al.* (in prep.) provide evidence for a positive trend in the rate of meridional overturning over the last three decades. While these results appear to support those produced from coarse-resolution modeling studies, there remains a critical need for additional observational studies in this region.

The future evolution of the Southern Ocean carbon sink will depend on the future state of the climate system, which remains difficult to quantify. Simulations of future climate from coupled models consistently predict a positive trend in the SAM, warmer surface ocean temperatures, and enhanced precipitation in the Southern Ocean region over the coming century (*Meehl et al.,* 2007). While the SAM trend is likely to lead to more vigorous overturning (*Sigmond et al.,* 2011), the warming and freshening of the Southern Ocean surface is expected to increase stratification (*Sarmiento et al.,* 1998). Accurate predictions for the future evolution of the Southern Ocean carbon sink therefore require understanding how both SAM and stratification changes impact carbon cycling and sea-air CO_2 exchange in this region (*Lovenduski and Ito,* 2009).

Given the importance of the Southern Ocean for the global carbon cycle and climate system, it is critical that we develop a sustained physical and biogeochemical observational program for the Southern Ocean, and that we continue to improve modeling efforts in this region.

Acknowledgments

The author thanks N. Gruber for comments and suggestions that greatly improved this article. This work was supported by NOAA grant NA08OAR4320893.

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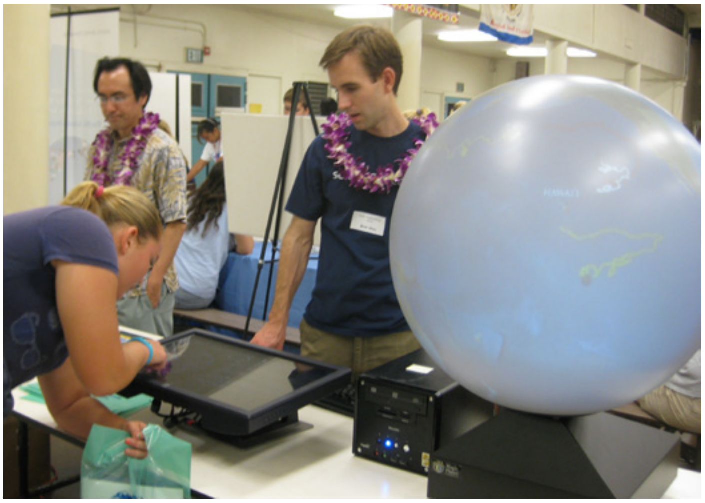
C-MORE hosts its first Ocean and Earth Science Career Night at Kailua Intermediate School

by Michelle Hsia, Education Specialist (C-MORE)

The Center for Microbial Oceanography: Research and Education (C-MORE), a National Science Foundation-sponsored Science and Technology Center based at the University of Hawaii at Manoa (UHM), held its first Ocean and Earth Science Career Night on October 27th at Kailua Intermediate School (KIS). Representatives from private businesses, federal and state government agencies and the UHM shared information and hands-on activities about local career opportunities in the earth and ocean sciences. Participating organizations included: C-MORE, Pacific Tsunami Warning Center, National Oceanic and Atmospheric Administration (NOAA) Fisheries, Department of Land and Natural Resources (DLNR), Papahanaumokuakea Marine National Monument, Hawai'i Institute of Marine Biology, UH Marine Center, UH Geology and Geophysics Department, Hui o Ko'olaupoko, Humpback Whale Marine Sanctuary, Makai Ocean Engineering, Oceanit, and the United States Coast Guard. Event sponsors included the National Science Foundation, Maui Jim Sunglasses, Aaron's Dive Shop, Oceanic International, Wave Riding Vehicles and Bob's Pizzeria.

The goal of the evening was to increase awareness of – and stimulate students' interest in pursuing – exciting local career opportunities in the earth and ocean sciences. The event was geared toward intermediate school students and their families, but community members attended the event as well. Students and parents learned about conservation techniques being implemented to protect humpback whales, coral reefs, and fish stocks. They also learned the basics of thermodynamics and generation of electricity from the ocean, microscopic plankton at the base of the marine food web and their importance to climate regulation, and the difference between convergent and divergent boundaries in plate tectonics. Students also learned to tie various knots used aboard research vessels, feel the difference between an assortment of rock formations, and smash barbs off fishing hooks to create a barbless circle hook that would prevent post-hooking injuries to fish and other animals that may end up caught in the line.

C-MORE hosts its first Ocean and Earth Science Career Night at Kailua Intermediate School (cont.)



During the event, students, parents, and various community members approached the science teacher that helped organize the event to express their excitement about the activities that each organization showcased and their appreciation for this opportunity to learn about what these local organizations were doing in the community. Community members were impressed at the amount of science knowledge and interest the KIS students possessed.

The C-MORE program plans to hold additional science career events on Oahu and neighboring islands in the future.

C-MORE Supports Graduate Student's Cutting-Edge Research on Marine Microbes

by Jamie Becker (MIT/WHOI Joint Program)

Massachusetts Institute of Technology (MIT)/Woods Hole Oceanographic Institution (WHOI) Joint Program student Jamie Becker, whose research is being supported by C-MORE and the Gordon and Betty Moore Foundation, recently published an article in WHOI's outreach publication *Oceanus*. The article features his research on the variety of organic carbon compounds produced by marine autotrophs and how these compounds link autotrophic and heterotrophic microbial communities.

The full article is available at http://www.whoi.edu/oceanus/viewArticle.do?id=118149&sectionid=1020.

OCB hosts three C-MORE Science Kits in Woods Hole

OCB is now hosting three C-MORE Science Kits: Ocean acidification, marine mystery, and ocean conveyor belt.

Ocean acidification kit (grades 6–12)

This two-lesson kit familiarizes students with the causes and consequences of ocean acidification: Lesson 1 includes a simple hands-on experiment, a short PowerPoint, and optional readings with worksheets. In Lesson 2, students conduct a more in-depth experiment with electronic probes to simulate the process of ocean acidification. Learn more about this kit.

Ocean conveyor belt kit (grades 8–12)

This four-lesson kit introduces students to some fundamental concepts in oceanography, including ocean circulation, nutrient cycling, and variations in the chemical, biological, and physical properties of seawater through hands-on and computer-based experiments. Learn more about this kit.

Marine mystery kit (grades 3–8)

Students learn about the causes of coral reef destruction by assuming various character roles in this marine murder-mystery. As they determine who killed Seymour Coral, students learn the basics of DNA testing. Suspects include global warming, sedimentation, and other threats facing coral reefs today. Learn more about this kit.

To Request a Kit

Teachers along the eastern seaboard may use these kits for free. To reserve a kit, please submit a request at: http://cmore.soest.hawaii.edu/education/teachers/science_kits/requestform.htm

Recent OCB Meetings

A Biogeochemical Flux Program Aligned with the Ocean Observatories Initiative

The Seventh Ocean Carbon & Biogeochemistry Scoping Workshop
Woods Hole, Massachusetts, May 23–25, 2011
by Heather Benway

The purpose of this scoping workshop was to explore the potential for development of a biogeochemical flux program aligned with the philosophy of the Ocean Observatories Initiative (OOI). The workshop convened 65–70 people, including academic, public, and private sector representation from the ocean science and engineering communities. The meeting opened with an overview of a proposed global biogeochemical flux observatory (based on a community white paper distributed in Spring 2010), followed by a series of plenary talks on biologically mediated fluxes (e.g., primary productivity, export flux of dissolved organic carbon) and ocean realms (e.g., coastal margins, mesopelagic, benthic) that are critical to characterizing and quantifying the biological pump. Afternoon talks and discussions focused on remote sensing data, biogeochemical modeling, and molecular approaches that would complement and inform the development of an in-water observatory. Close collaboration between the OOI and a GBF Observatory on technological, observational, infrastructural, and social outreach elements were also discussed. The final plenary session of the workshop opened with a description of the infrastructural vision for a global biogeochemical flux observatory, based on multiple globally distributed clusters consisting of four complementary biogeochemical moorings, each outfitted with sensors and instrumentation dedicated to a particular flux or ocean depth. A series of plenary talks then focused on newly emerging technologies, including fluorometry, imaging, bio-optics, and genomic sensors, all of which could help quantify ocean carbon fluxes associated with the biological pump.

Following the plenary sessions, a series of three breakout sessions took place. Each of the breakouts was divided into four groups to ensure that all marine biogeochemical zones and ecosystem domains were represented: Group 1) upper ocean productivity and export flux; Group 2) flux attenuation and respiration in the twilight zone; Group 3) deep ocean/seafloor processes; and Group 4) continental margin fluxes and cross-shelf exchange. The first breakout session focused on identifying fluxes and/or processes in each biogeochemical realm that should be made a high observational priority to better characterize the ocean biological pump. In the second breakout session, participants proposed observational approaches, including both existing OOI and new infrastructure, for addressing key questions surrounding the biological pump, particularly those processes and fluxes highlighted during Breakout 1. The final breakout session focused on identifying potential links to relevant scientific and observational efforts, how to integrate and synthesize data from multiple sources, and how to engage with the public in a meaningful and effective way. For more information about the workshop, please visit the workshop website at http://gbf-ooi.whoi.edu/.

The full workshop report includes detailed community recommendations from the plenary and breakout sessions. The report also describes a potential collaborative opportunity with the Axial Seamount Regional Scale Node (RSN) of OOI based on preliminary discussions that took place at the Oct. 2011 Axial RSN Science Workshop.

Observing and modeling our changing marine ecosystems

The Sixth Annual Ocean Carbon & Biogeochemistry Summer Workshop
Woods Hole, Massachusetts, July 18–21, 2011
by Heather Benway

This year's summer workshop convened 116 participants at the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts.

A plenary session on *Trends, Thresholds, and Tipping Points in Marine Ecosystems* included presentations that described different types of ecosystem responses (linear vs. nonlinear; reversible vs. irreversible) to natural and anthropogenic stressors, and illustrated the complexity introduced by multiple environmental variables operating simultaneously. Highlights included a broad characterization of regime shifts based on stressor type (natural vs. human), spatial scale, and management potential; a multi-stressor, whole ecosystem approach to understanding and predicting regional impacts of ocean acidification; a model-based exploration of Arctic sea-ice response to warming; and an examination of fish population response to North Pacific climate and circulation indices.

A joint science session with the U.S. Climate Variability and Predictability (CLIVAR) Program convened OCB and CLIVAR scientists to explore common

NACP/OCB Coastal Synthesis Activities Gain Momentum

Since the initial community workshop in December 2010 (San Francisco, CA), the Coastal Synthesis activities are moving forward. Community workshops and meetings over the course of the year, including the 3rd NACP All-Investigators Meeting (Jan/Feb 2011) and the 2011 OCB Summer Workshop, have provided opportunities for the PIs to provide updates and gather feedback on the coastal synthesis activity. Regional leaders are currently developing small teams, assigning tasks, and planning small (10–20 people) regional team meetings ~1.5–2 days in duration that will occur over the next ~6 months to focus on refining regional budgets.

The past several issues of OCB News have highlighted coastal synthesis activities, including the current status of regional carbon budgets (see below). Even if you do not want to attend yet another meeting, you can still contribute to the development of these budgets. Regional team members will be doing extensive literature searches and modeling exercises to help quantify carbon fluxes across key boundaries, including land-ocean, air-sea, sediment-water, and cross-shelf, as well as biological fluxes such as photosynthesis and respiration. If you can contribute data or modeling expertise in any of the regions, please get in contact with the regional leads (see below). I also encourage you to read the recent newsletter articles and visit the Coastal Carbon Wiki for regional updates. You can also add to the regional spreadsheets of data and modeling resources that we started to develop at the community workshop in December (regional spreadsheet links below, each includes both data and modeling tabs).

East coast

- Leaders: Wei-Jun Cai, Marjy Friedrichs, Ray Najjar
- Current status
- OCB Newsletter article
- Regional spreadsheet
- Three sub-regions (Gulf of Maine, Mid-Atlantic Bight, South Atlantic Bight)
- Regional team meeting to occur **Jan. 19–20, 2012** at VIMS (Gloucester Point, VA)

West coast

- Leaders: Simone Alin, Burke Hales
- Current status

The Sixth Annual Ocean Carbon & Biogeochemistry Summer Workshop (cont.)

scientific interests that may lead to joint community activities. The session opened with science overview talks that described: existing ocean observing capabilities across multiple platforms; the utility of molecular and genomic tools for mapping biogeochemistry; and the importance of bridging disparate physical and biogeochemical spatial scales. With collective expertise in physical circulation, climate dynamics, biogeochemistry, and biology, plenary speakers addressed cross-cutting topics such as the impacts of global overturning circulation and Southern Ocean climate variability on carbon storage, tropical air-sea interaction and upwelling impacts on oxygen and carbon cycling, and high-frequency physical-biological interactions on submeso- to mesoscales. A call for joint OCB/CLIVAR working groups was issued in early September and prospectuses are currently under review by the US CLIVAR and OCB SSCs.

A session entitled *Toward the Implementation of a Global Autonomous Biogeochemical Observing System* opened with a description of GLOBE (GLobal Ocean Biogeochemical Experiment), an emerging community initiative to deploy a global network of biogeochemical sensors on profiling floats and gliders. Other presentations highlighted gaps in existing global data sets and products and provided concrete examples of modeling and data assimilation techniques that could inform critical questions surrounding ocean carbon cycling and marine ecosystem health. One speaker described current oxygen sensor capabilities, including calibration, drift, and data-quality issues. Another speaker presented a comprehensive vision for cross-calibration of autonomous sensors, citing examples from the 2008 North Atlantic Bloom Experiment. The session concluded with an overview of international autonomous observing activities and a community discussion of regional science drivers to begin formulating a vision for an autonomous observing system.

For further information, please visit the workshop website at http://www.whoi.edu/workshops/ocb-workshop2011/.

NACP/OCB Coastal Synthesis Activities Gain Momentum (cont.)

West Coast (cont.)

- Regional spreadsheet
- Four sub-regions (Gulf of Alaska, Northern California Current System, Southern California Current System, Central American Isthmus)
- Rough draft of an outline for sub-regional carbon budget papers

Gulf of Mexico

- Leader: Paula Coble
- Current status
- Newsletter article on Gulf of Mexico carbon budget
- Newsletter article on synthesis of Chromophoric Dissolved Organic Matter (CDOM) data
- Regional spreadsheet
- Regional team meeting to take place within next ~4–6 months at/near Univ. of South Florida (St. Petersburg, FL)

Arctic

- Leader: Jeremy Mathis
- Current status
- Newsletter article
- Regional spreadsheet
- Three sub-regions (Gulf of Alaska, Bering Sea, western Arctic Ocean)

Great Lakes

- Leader: Galen McKinley
- Current status
- Newsletter article
- Regional spreadsheet
- Papers being developed for Lake Superior (McKinley)
- McKinley et al. to start new modeling project on Lake Michigan carbon cycle
- Seeking colleagues who are doing carbon cycle research on the other Great Lakes

Community Resources

Publications and reports

- Pre-publication version of NRC report Assessing Requirements for Sustained Ocean Color Research and Operations
- 2011 U.S. Carbon Cycle Science Plan
- USGCRP Strategic Plan 2012–2021 open for public comment until November 29, 2011
- Conservation International's Science to Action Guidebook
- New book on Ocean Acidification (Jean-Pierre Gattuso and Lina Hansson (Eds.), 326 pages, Oxford University Press)
- IMBER Data Management 'Cookbook' — A Project Guide to Good Data Practices (now available in Spanish)
- IPCC Report Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)

Data and Research

- Surface Ocean CO_2 Atlas (SOCAT) version 1.5 publicly released
- Submit fCO_2 data for Surface Ocean CO_2 Atlas (SOCAT) version 2 by December 31, 2011
- New version of Ocean Data View (v. 4.4.2) now available for download
- The IOC, with the endorsement of SCOR and IAPSO, adopts TEOS-10 as the official description of seawater and ice properties in marine science
- Inter-laboratory comparison experiment for sea water CO_2 measurements planned for 2012

OCB Publications and Reports

- OCB Scoping Workshop Report: The molecular biology of biogeochemistry: Using molecular methods to link ocean chemistry with biological activity (November 2010, Los Angeles, CA)
- OCB Meeting Report: OCB/NACP Coastal Synthesis Workshop (Available in Eos Trans. American Geophys. Union 92 (23)). (December 2010, San Francisco, CA)
- OCB Meeting Report: OCB Ocean Acidification Principal Investigators' Meeting (March 2011, Woods Hole, MA)
- OCB Scoping Workshop Report: A Biogeochemical Flux program aligned with the Ocean Observatories Initiative (May 2011, Woods Hole, MA)

Community Resources (cont.)

- CO2SYS for MATLAB updated to v1.1 (available for download at CDIAC)
- LDEO Database version 2010 is now available at CDIAC
- NASA Aquarius yields first global salinity image

Communication and Outreach

- OCB scientists Feely and Doney publish ASLO e-lecture on ocean acidification
- IMBER launches new website

Important OCB Dates

- **January 19–20, 2012:** East coast regional team meeting for the OCB/NACP coastal synthesis activity (VIMS, College of William and Mary)
- **July 16–19, 2012:** OCB Summer Workshop (Woods Hole Oceanographic Institution, Woods Hole, MA)

OCB Informational Resources

- OCB Policies and Procedures: A community guide on OCB's programmatic mission, objectives, and operating procedures
- Coastal Synthesis Activity - join a regional email list, visit the coastal synthesis wiki site or the initial (Dec. 2010) coastal synthesis workshop website
- OCB Ocean Acidification Website
- OCB Ocean Fertilization Website
- Subscribe or post to the OCB email list
- Submit a paper to the OCB publications list

Impressions of the Summer 2011 Ocean Acidification Course at UW Friday Harbor Labs

The graduate course at the University of Washington's Friday Harbor Laboratories on *Experimental Approaches to Understanding Ocean Acidification* took place in June–July 2011. In an effort to expand the growing U.S. ocean acidification research community and facilitate the training of young scientists, OCB provided travel support for several U.S. students to participate in the Friday Harbor course. The last issue of *OCB News* included brief bios of each of these students. Below are some of their impressions of and reflections on the FHL course.

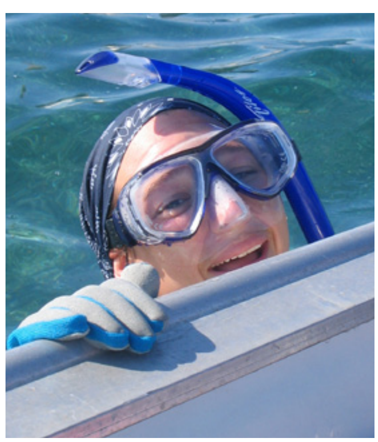
Emily Bockmon
(Scripps Institution of Oceanography)

Emily Bockmon
Scripps Insitiution of Oceanography

"The Ocean Acidification course at Friday Harbor Labs was a great experience and very beneficial. The opportunity to complete our own ocean acidification experiment from start to finish was particularly unique and interesting. Julie Schram and I examined the impacts of mussel biomass load and seawater flow rate on the carbonate chemistry of an experimental aquarium. I especially value the relationships formed with my peers in the ocean and fresh water sciences community."

Laura Enzor
(University of South Carolina)

"Overall, I found the Ocean Acidification course at FHL to be an invaluable experience. I think learning the intricacies of carbonate chemistry from Dr. Andrew Dickson was one of the highlights of the course. Dr. Dickson was always more than happy to discuss specific research problems or answer any questions we came up with. Another highlight for me was being able to work with Dr. Michael "Moose" O'Donnell and the system he built for experimental generation of pCO_2 levels. I have built a similar system for my major professor, Dr. Sean Place, for his research project examining the effects of ocean acidification on Notothenioids in Antarctica. Being able to work with Moose and ask specific questions about the system was a great help. Additionally, I found it helpful to use this system for my independent project, in which I examined how biological filtration and feeding can add error to carbonate chemistry measurements. The data I collected can be applied not only to my own research but to the project in Antarctica as well. I also think Dr. Terrie Klinger's knowledge of local currents, tides and underwater topographic features was particularly helpful for the class. During the course, we were able to characterize local water carbonate chemistry using water samples gathered aboard the R/V Centennial. *Terrie's input was extremely useful in drawing conclusions from our data."*



Laura Enzor
University of South Carolina

Lydia Kapsenberg
(University of California, Santa Barbara)

Lydia Kapsenberg
University of California, Santa Barbara

"The Ocean Acidification class at Friday Harbor Laboratories is the first class I have taken that is 100% applicable to my own research. The most valuable portion was Dr. Andrew Dickson's instruction on seawater carbon chemistry. The combination of lecture and laboratory work following the Guide to Best Practices for Ocean CO_2 Measurements (Dickson et al., 2007) strengthened my laboratory and field seawater carbon chemistry understanding ten fold. The outstanding boating resources at Friday Harbor Laboratories made it possible for us to conduct independent field

studies and characterize carbon parameters around the San Juan Islands for the first time. Additionally, the class presented a great opportunity to meet other graduate students in the field of ocean acidification. The variety of scientific backgrounds sparked countless scientific discussions and set the stage for future collaborations. I hope the Ocean Acidification class will be offered in the future, as it creates great baseline knowledge for graduate students studying ocean acidification through laboratory-based experiments."

Carlie Pietsch
(University of Southern California, Los Angeles)

Carlie Pietsch
University of Southern California, Los Angeles

"The five weeks I spent in the brand new Friday Harbor ocean acidification course were inspirational and fun! The course was structured to give an introduction to the concepts and chemistry behind ocean acidification, followed by experiences using analytical equipment and developing field experiments. The problem of ocean acidification requires the collaboration of the fields of biology, ocean science, and chemistry. I think that the varied expertise of the instructors and the recruitment of students with different backgrounds contributed to the course's success. Together we executed short but high-impact research projects that literally "tested the waters" around the marine lab, establishing baselines for future observations and experiments on the effects of ocean acidification.

I gained confidence and technical skills working with the sensitive instrumentation of a field that is different from my own. I think as a group we discovered how important collaboration and good communication between the disciplines can be. Courses and conferences that bring researchers together can be extremely productive, as ours was. Together we were able to focus on the most important questions, develop efficient methods, and produce interesting results. All the while we had a lot of fun. The library was right next to the harbor and we learned to drive the Friday Harbor boats and use them to collect our research samples. Some even spotted the famous San Juan Island Orcas.

I would definitely recommend taking a course at Friday Harbor that is within or even parallels your research interests. Thanks to the exposure that the course provided, I am approaching my research on the paleoecology of mass extinctions with new perspectives, considering the impact that past acidification events may have had on ancient life."

Chelsea Vaughn
(Smith College '09)

"Ocean acidification is a topic worthy of a full college course to cover the principles alone, not to mention the practical lab applications and independent projects. However, in five weeks at Friday Harbor Lab, we covered it all! The first few weeks featured full days of classroom discussions and lectures, followed by hands-on lab time to implement what we had learned. Moose and Terrie did a great job leading the group – they provided a rich learning experience that should be required of everybody, novice or veteran, entering the field of ocean acidification. We were also fortunate to have many guest lecturers; Andrew Dickson played a huge role in making ocean acidification a tangible concept.

Chelsea Vaughn
Smith College

After learning in the classroom and lab, we put our understanding into action, conducting several small experiments around the labs and finally gathering data for our group projects. My group, referred to as "The Retentives", compared carbonate chemistry among bodies of water with varying levels of retention within the San Juan Archipelago. We wrapped up the class with presenting our findings to the Friday Harbor Labs community, at which point we received a tremendous amount of support for and interest in our research.

The entire experience was wonderful: The OA students were an amazing group of people, the scientific community knowledgeable and helpful, and the island one of the most beautiful settings I have ever visited for conducting research. Thank you to Friday Harbor Labs for the experience and to all of the supporting organizations that made the summer course possible!"

Spreading the word about ocean acidification:

A journey to the Cape Cod Sea Camps

by Heather Benway

Images courtesy of: Jorge Roman

With a carload of cups, straws, seawater, red cabbage juice, bleach, lemon juice, seashells, yeast packets, and other miscellaneous items, I drove to the Cape Cod Sea Camps in Brewster, MA on a rainy day in mid-October to teach 36 7th graders from the Saint David's School in NYC about ocean acidification. The inquisitive students proved to be quick studies and great sports, as they performed various experiments that demonstrated the concepts of pH and ocean acidification. We started with a brief presentation and Q&A session on ocean acidification and then broke into smaller groups that visited different "stations" around the room. At the "pH Demonstration" station, students used red cabbage juice, a natural pH indicator, to compare the pH of seawater with that of different household solutions such as bleach, vinegar, seltzer water, and lemon juice. At the "Ocean Acidification in a Cup" station, students used straws to bubble their exhaled CO_2 into seawater and freshwater samples containing red cabbage juice pH indicator, watching the pH change right before their eyes. The "Yeast Experiment" station provided yet another opportunity to simulate ocean acidification. The students activated the yeast with warm water and sugar. Half of the group used a CO_2 probe to directly monitor the CO_2 being given off by the organisms, and the other half bubbled that CO_2 gas into water and used a pH probe to monitor changes in the water pH. At the "Biological Impacts" station, students compared mollusk shells that had been soaked in just seawater (control) vs. acidified seawater. They looked at the shells under a microscope and also made observations of shell texture and brittleness. Students determined how many heavy books it took to break the control vs. acidified shells.

Materials and experiments were modified from the OCB ocean acidification lab kit and the C-MORE ocean acidification kit, which is available in the OCB Project Office for local teacher use.

OCB Calendar

2011	
Nov. 29–Dec. 2:	Earth observation for ocean-atmosphere interactions science – A joint ESA-SOLAS-EGU conference (Frascati, Italy)
Dec. 5–9:	2011 American Geophysical Union Fall Meeting (San Francisco, CA)
2012	
Jan. 19–20:	NACP/OCB Coastal Synthesis Activity: East coast regional team meeting (Virginia Institute of Marine Science of the College of William and Mary)
Feb. 19–24:	2012 Ocean Sciences Meeting (Salt Lake City, UT)
March 26–29:	Planet Under Pressure: new knowledge towards solutions (London, UK)
April 22–27:	International Polar Year 2012 From Knowledge to Action (Montréal, Canada)
April 24–27:	OCEANS OF CHANGE 2nd ICES/PICES Conference for Early Career Scientists (Majorca Island, Spain)
May 7–10:	SOLAS Open Science Conference (Cle Elum, WA)
May 7–11:	44th International Liege Colloquium on Ocean dynamics remote sensing of colour, temperature and salinity - New challenges and opportunities (Liege, Belgium)
May 15–19:	2nd International Symposium: Effect of climate change on the world's oceans (Yeosu, Korea)
July 9–13:	12th International Coral Reef Symposium (Cairns, Australia)
July 16–19:	OCB Summer Workshop (Woods Hole, MA)
July 23–28:	IMBER ClimECO3 Summer School (Ankara, Turkey)
Sept. 3–6:	Bjerknes Centre open science conference: Climate change in high latitudes (Bergen, Norway)
Sept. 24–27:	Third Symposium on the Ocean in a High-CO_2 World (Monterey, CA)
2013	
January 28–31, 2013:	IMBER IMBIZO III: The future of marine biogeochemistry, ecosystems and societies (Goa, India) - Please submit your ideas of potential workshop topics to Lisa Maddison by **15 November 2011**

OCB-RELEVANT FUNDING OPPORTUNITIES

- **November 15, 2011:** NSF Dynamics of Coupled Natural and Human Systems (CNH) proposal deadline
- **November 30, 2011:** Partnerships for Enhanced Engagement in Research (PEER) proposal deadline
- **December 1, 2011:** Burroughs Wellcome Fund deadline for collaborative research travel grants
- **December 5, 2011:** NSF Science, Engineering and Education for Sustainability Fellows (NSF SEES)
- **December 15, 2011:** NOAA Ocean Acidification LOI deadline (LOIs required)
- **January 6, 2012:** NSF Ocean Acidification proposal deadline; Please note opportunity to develop US-UK collaborations between ocean acidification researchers
- **January 30, 2012:** NOAA Ocean Acidification proposal deadline
- **February 15, 2012:** NSF Biological and Chemical Oceanography proposal targets
- **February 15, 2012:** NSF Ocean Technology and Interdisciplinary Coordination
- **May 15, 2012:** NSF Partnerships for International Research and Education (PIRE)

OCB News

is an electronic newsletter that is published by the OCB Project Office. Current and previous issues of OCB News can be downloaded from: www.us-ocb.org/publications/newsletters.html

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