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VARIATIONS

Climate and the Carbon Cycle

Mike Patterson, Director

U.S. CLIVAR has embarked on a long-term collaboration with the U.S. Carbon Cycle Science community to identify and foster the development of intersecting and complementary research interests. Given CLIVAR's focus on the role of the ocean in climate, the ocean aspects of the carbon cycle has emerged as a starting point for inter-program development.

A year ago, U.S. CLIVAR and the Ocean Carbon Biogeochemistry (OCB) programs co-convened a joint science meeting in Woods Hole to begin exploring common science issues, including how changes in ocean circulation and heat content affect the magnitude and distribution of ocean carbon sources and sinks, and how coupled physical/biogeochemical processes and feedbacks determine the future state of heat and carbon sources and sinks.

This issue of Variations presents a summary of and contributions from presenters from the joint meeting, highlighting the potential for jointly developed observing systems (Scott Doney), coupled feedbacks in Earth system models (Curtis Deutsch), and the appli-

IN THIS ISSUE

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

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 daylong 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

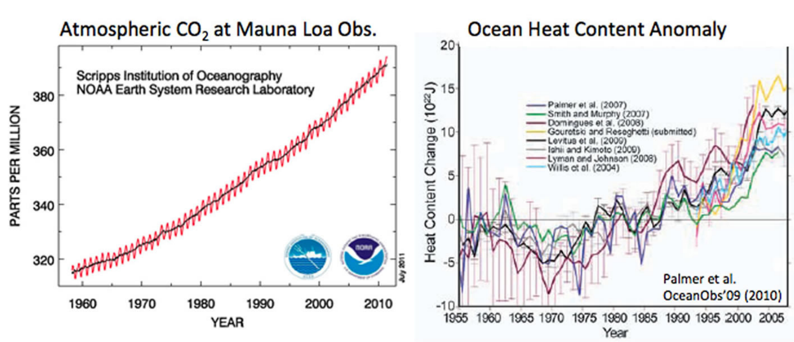

Figure 1: Observed trends for the last half-century in (left) atmospheric CO_2 & (right) global ocean heat content anomaly highlighting the impacts of human fossil-fuel CO_2 emissions and global warming.

cation of both observing systems and models to the climate and carbon-sensitive Southern Ocean region (Nicole Lovenduski).

The July 2011 meeting successfully launched the planning of two new Working Groups (WGs) that were selected for joint sponsorship by U.S. CLIVAR and OCB starting in March of this year.

The Southern Ocean WG, co-chaired by Joellen Russell and Igor Kamenkovich, explores this Ocean's important role in regulating atmospheric CO_2 and the global climate system by developing data/model metrics to quantify the mechanisms, processes and tendencies relevant to the role of the Southern Ocean in climate.

The second new WG on Ocean Carbon Uptake in CMIP5 Models, co-chaired by Annalisa Bracco, Curtis Deutsch, and Taka Ito, is focusing on the relative importance of ocean stratification and wind forcing in controlling air-sea CO_2 fluxes and oceanic carbon uptake in CMIP5 simulations. Both are three-year endeavors to culminate in a single community-wide workshop in 2014. More details on the WGs and their activities are provided on page 5 herein.

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VARIATIONS

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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 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.

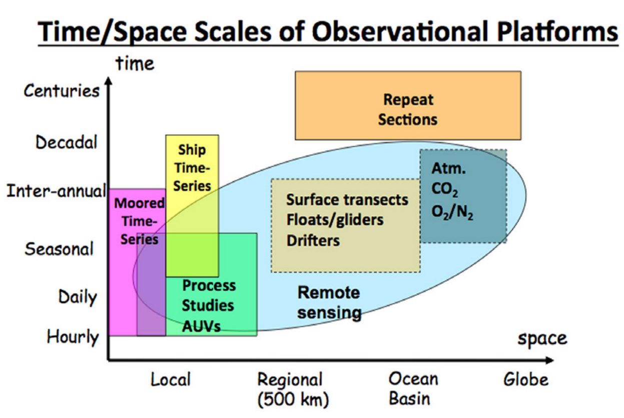

Figure 2: Schematic diagram illustrating the characteristic time- and space-scales sampled by different observing systems and networks.

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 (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 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

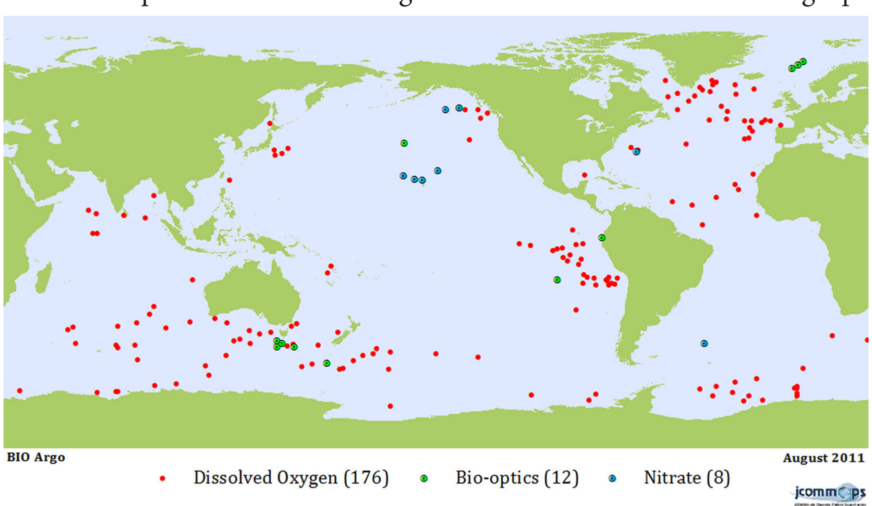

Figure 3: Map showing the locations of Argo floats with biogeochemical sensors (dissolved oxygen, bio-optics, and nitrate) as of August 2011. There are 196 floats with biogeochemical sensors out of a total Argo array of 3,234 active floats.

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.

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Two New Working Groups for U.S. CLIVAR & OCB

Jennifer Mays, U.S. CLIVAR Project Office

As a result of the joint meeting held in 2011, the U.S. CLIVAR and Ocean Carbon & Biogeochemistry research programs recently co-sponsored two new working groups: the Southern Ocean Working Group and the Ocean Carbon Uptake Working Group (WG). To date, both WGs have held several teleconferences and are planning their first in-person meetings in conjunction with the 2012 AGU Fall Meeting in San Francisco. Each WG will ultimately produce a white paper and/or journal article summarizing their findings and will co-sponsor an open workshop (planned for 2014).

The Southern Ocean WG's primary objective is to develop data/model metrics to refine climate projections with regards to the Southern Ocean's role in climate. These metrics will be drawn from a combination of theory, datasets and numerical modeling. In particular, the WG will focus on characterizing of the role of mesoscale eddies in heat and carbon uptake and defining the Southern Ocean's stratification, circulation and heat with regard to carbon uptake response in a changing climate.

The goals of the Ocean Carbon Uptake WG include advancing understanding of oceanic carbon uptake processes and how they are represented in CMIP5 model experiments. In doing so, they hope to promote communication between members of the OCB and U.S. CLIVAR community as well as between modelers and theoreticians. Coordinated analysis of CMIP5 model experiments will be focused on ocean stratification in the mixed layer, mixing parameterization schemes, and atmospheric wind forcing in the oceanic carbon uptake. The importance of multiple time scales and different ocean basins will guide the design of a common framework to analyze the model outputs. The WG will establish a list of physical and biogeochemical metrics for their model-model and model-data comparison.

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Climate Variability and Southern Ocean Carbon Uptake

Nicole Lovenduski, University of Colorado

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 multi-decadal variability over the past few decades. Coarse-resolution physical 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).

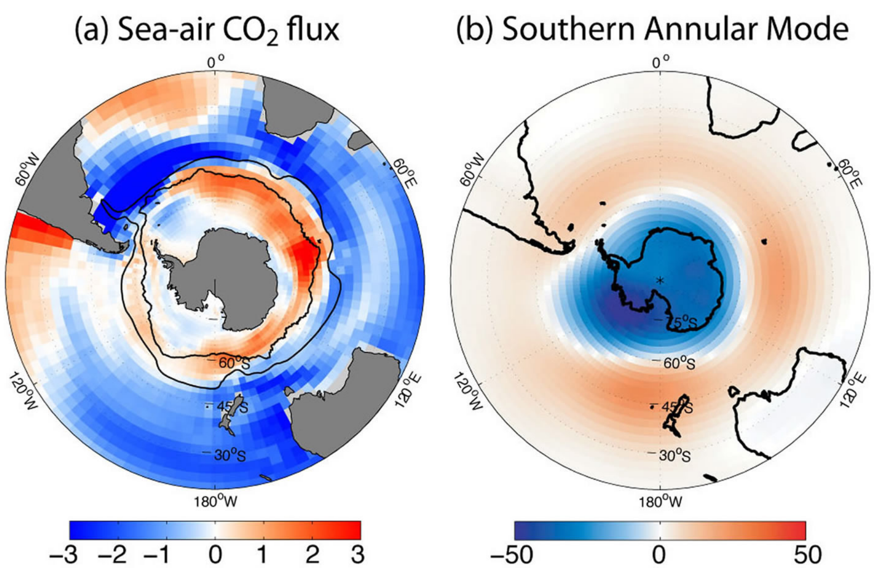
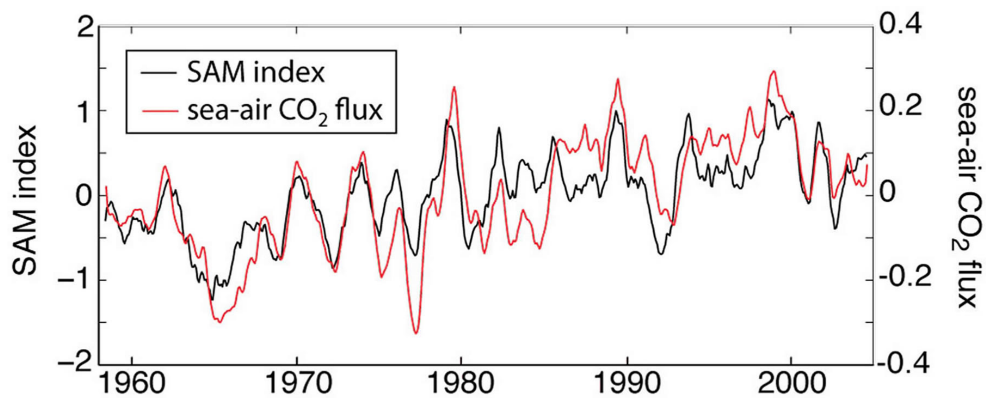


Figure 1. (a) Annual-mean observed sea-air CO_2 flux (mol m-2 yr-1). Positive values indicate CO_2 outgassing. Data from Takahashi et al. (2009). Black contours indicate the position of the Antarctic Polar Front and Subantarctic Front, the two main cores of the ACC. (b) Regression of 700 mb geopotential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

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

Figure 2. Integrated Southern Ocean (<35oS) 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).



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. During 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.

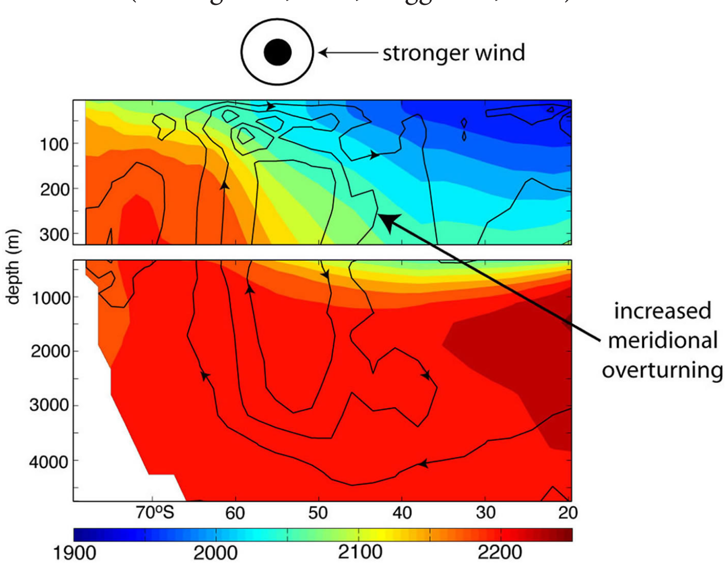


Figure 3. Annual-mean, zonal-mean DIC concentration (colors; mol kg-1), and the 30-year trend in the meridional overturning streamfunction (contours), as estimated by a coarse-resolution ocean GCM. Adapted from Lovenduski et al. (2008).

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

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Ocean Carbon Biogeochemistry and U.S. CLIVAR Joint Meeting Summary

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Atmospheric emissions of CO_2 not only contribute to warming our climate, but are expected to have a significant impact on ocean circulation, biogeochemistry and ecosystem structure. Those changes will then feedback onto the atmosphere.

The feedback is likely to be positive, resulting in a decrease in the rates at which the ocean takes up and stores atmospheric carbon dioxide, further enhancing global warming. However a quantification of its strength and importance is still missing and its investigation requires an interdisciplinary approach and a broad collaboration between scientists working in different disciplines.
On July 19, 2011, the Ocean Carbon and Biogeoechemistry (OCG) Group and the U.S. CLIVAR Scientific Coordination Committees and Panels met in Woods Hole, MA for a Joint Science Session. Approximately 200 people participated for a full day of scientific presentations spaced by community discussions. The agenda and all presentations are available at www.whoi.edu/page.do?pid=50536.

The major objective of the meeting was to identify priority research topics for collaboration between U.S. CLIVAR and OCB researchers over the next decade and to insure a better coordination of the projects aiming at characterizing the oceanic carbon-climate feedback. Problems identified as crucially important include quantification of the ocean's role in setting future atmospheric concentrations of carbon dioxide, methane, and other carbon-containing greenhouse gases; an improved understanding of the interplay between the physical processes in the ocean, the oceanic heat content and the magnitudes and distributions of ocean carbon sources and sinks on seasonal to centennial time scales; and the identification the coupled physical/biochemical processes that influence the present and future state of heat and carbon sources and sinks and ecosystem structure.

The scientific presentations included a detailed analysis of present global observing capabilities, limitations and observational approaches at different scales (S. Doney). This allowed for exploring synergies between the two communities, and pointed to the necessity of integrating observations, forward and inverse model results for the detection and attribution of trends in CO_2 air-sea fluxes. Modeling challenges that are inherent when addressing intrinsically coupled problems were then identified. These challenges span a multitude of scales and processes, from molecular diffusion to the global overturning circulation on the physical side, and from the intra-cellular metabolic network to global biogeography in the biogeochemical realm (M. Follows). Specific attention was given to the representation of mesoscale and submesoscale processes, their relative importance in mediating variability in both physical and biological fields and their contribution to localized upwelling events and impacts on biogeochemical processes (A. Mahadevan). The impact of the overturning circulations, shallow within the ocean gyres, intermediate in the North Atlantic and North Pacific, and deep in the North Atlantic and around Antarctica, on the oceanic heat and carbon transport, and their variability were discussed in detail (A. McDonald). This presentation highlighted the multiplicity of open questions that need to be addressed to understand the interplay between oceanic physical and biological and chemical processes, on time scales from months to centuries, in a changing climate.

A more detailed look at the complexity and variety of processes that impact the air-sea exchange of CO_2 in the Southern Ocean followed (N. Lowenduski). Here large uncertainties plague observationalists, modelers and theoreticians when trying to quantify the mean state of CO_2 fluxes, let alone their variability or future changes, as few observations, strikingly different model outputs and contrasting theories on role of eddies on CO_2 uptake and transport limit scientific advancement. Finally, an overview of the variability in the carbon and oxygen cycling in the Pacific Ocean and its linkage to climatic forcings, from ENSO to the PDO and NPGO, to the Walker circulation (C. Deutsch) allowed for discussing future scenarios of CO_2 outgassing/uptake and ocean deoxygenation.

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Improving Model Predictions of Ocean Biogeochemistry

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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 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

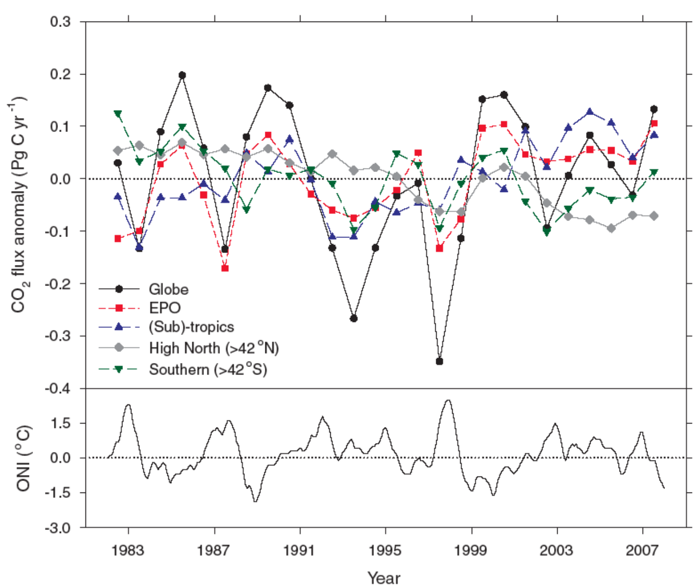

Figure 1. Global and regional air-sea CO_2 flux anomalies estimated from empirical relationships to SST, revealing the strong global influence of ENSO as indicated by the Oceanic Niño Index (ONI). EPO=Equatorial Pacific (10°N–10°S; 80°W–135°E). Figure from Park et al. 2010.

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].

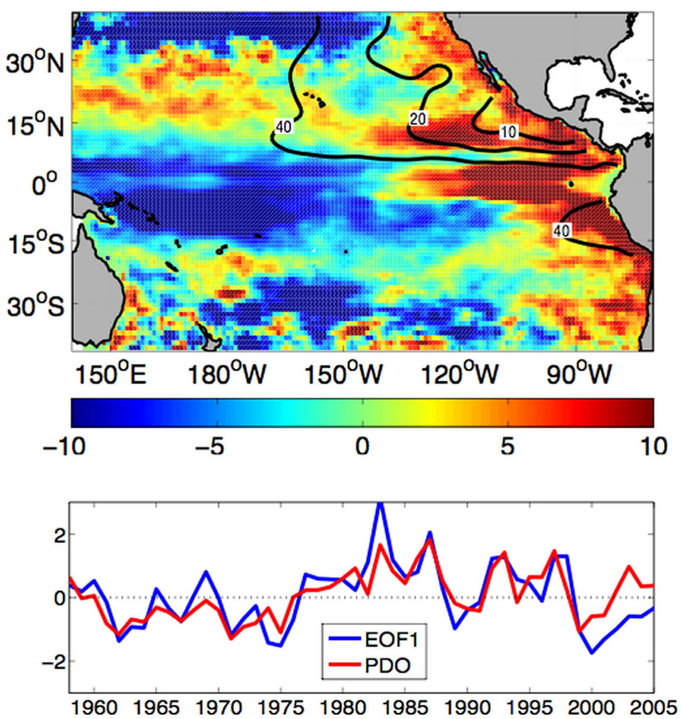

Figure 2. (a) Location of hypoxic water in the Pacific thermocline (300 m, contours) on top of the leading spatial pattern of thermocline depth (13°C isotherm, lying with the low-O_2 core) according to an EOF analysis of the Simple Ocean Data Assimilation [Carton and Geise, 2008]. (b) Time-series of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

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 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.

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:

1. For which processes, and at which time scales, is natural variability of the carbon cycle a useful analog for longer-term trends?

2. 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 models with interactive carbon cycling components. These simulations represent an 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 across 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 changes 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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Calendar of CLIVAR-Related Events

for further details, visit: www.usclivar.org/calendar

International Conference on North Atlantic Climate Variability

Sept. 24-26, 2012
Hamburg, Germany

WCRP WG on Coupled Modeling & WCRP WG on Seasonal to Interannual Prediction Sessions

Sept. 24-26, 2012
Hamburg, Germany
By invitation

20 Years of Progress in Radar Altimetry Symposium

Sept. 24-26, 2012
Venice, Italy

Argo Science Workshop

Sept. 27-29, 2012
Venice, Italy

9th Meeting of the CLIVAR/ IOC-GOOS Indian Ocean Panel

Oct. 15-20, 2012
Cape Town, South Africa
By invitation

NOAA's 37th Climate Diagnostics and Prediction Workshop

Oct. 22-25, 2012
Fort Collins, CO

Integrated Ocean Observing System (IOOS) Summit 2012

Nov. 13-16, 2012
Herndon, VA

GSOP Ocean Synthesis and Air-Sea Flux Evaluation Workshop

Nov. 27-Dec. 1, 2012
Woods Hole, MA
By invitation

AGU Fall Meeting

Dec. 3-7, 2012
San Francisco, CA

93rd AMS Annual Meeting

Jan. 6-10, 2013
Austin, TX

U.S. CLIVAR ENSO Diversity Workshop

Feb. 6-8, 2013
Boulder, CO

ASLO 2013 Aquatic Sciences Meeting

Feb. 17-22, 2013
New Orleans, LA

Email Jennifer Mays to include your event in our upcoming edition of Variations and the U.S. CLIVAR website.

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