OCEAN CARBON & BIOGEOCHEMISTRY SUMMER WORKSHOP
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POSTER ABSTRACTS

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***Better Practices for Management of Oceanographic Research Cruise Data**

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*This poster will be on display in Clark 507 for the duration of the workshop

The research cruise is the preeminent data gathering activity of many oceanographic research projects. As such, it is imperative that there be robust documentation of the research activities to ensure maximum value of data acquired during the cruise and their cogent first use, and also to support their accurate reuse. Decades of experience managing oceanographic data have yielded valuable insights into better practices for cruise data management. Staff members from the Biological and Chemical Oceanography Data Management Office (BCO-DMO) have written a manual outlining some important guidelines for shipboard data management. BCO-DMO personnel are part of a collaborative team from WHOI, LDEO and SIO proposing the Rolling Deck to Repository (R2R) initiative to help improve access to shipboard data acquired aboard UNOLS vessels in the US academic fleet. BCO-DMO and R2R recommend that investigators share the following four products as soon as possible following a research cruise: the basic cruise metadata including science party manifest and data inventory, the cruise operations report, the scientific sampling event log, and the navigation data (to generate the cruise track). Details about these products and other guidelines from the BCO-DMO manual will be presented.

SESSION 2. OCEAN ACIDIFICATION: FRONTIERS IN UNDERSTANDING PHYSIOLOGICAL AND ECOLOGICAL RESPONSES

M1. The development of a free-ocean-carbon-enrichment (F.O.C.E.) system for assessing the impact of ocean acidification on benthic organisms under otherwise natural conditions

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Since the industrial revolution the oceans have absorbed 450 billion tons of CO_2, approximately one third of the total emitted into the atmosphere since that time. The result is a reduction in ocean pH, by 0.1 units this century, and a reduced availability of dissolved carbonate ions (CO_3^{2-}), which are required by calcifying organisms to make calcium carbonate ($CaCO_3$) shells and skeletons. This ocean acidification (OA) is expected to disrupt growth of many types of corals, molluscs, calcifying reef seaweeds, and phytoplankton. On the other hand, OA increases CO_2 availability and may allow some species to become more productive; for example, mesocosm studies suggest that OA may increase sea grass productivity up to 400%, at least under saturating irradiances. However, there have been relatively few tests of these predictions in the lab or in the field.

To better characterize the response of shallow water benthic organisms to OA, I designed an automated free-ocean-carbon-enrichment (F.O.C.E.) system consisting of a unique surface buoy, which functions as an on-site seawater pumping and treatment station, and an array of open-top acrylic chambers secured within benthic communities. High CO_2, low-pH seawater is generated on demand by CO_2 injection in a 1.5-L CO_2 reactor and acidified seawater is then delivered to the underwater chambers. The desired conditions are maintained electronically via internal pH probes and operator controlled timing mechanisms. Power is provided by a combination of a 130-watt solar array and sealed 12 V AGM batteries, with inverter. During experiments, benthic organisms are secured inside open-top 0.5-m^2 diameter acrylic domes with attachment points, an inflow port, and adjustable exhaust vents at the top of each chamber. Chambers are secured to the bottom using a "sediment collar," a circular plastic sleeve that extends 15 cm into sediments.

Indoor testing verified that flow rates are sufficient to maintain positive pressures within open-top chambers, and to renew chamber volumes at 4-minute intervals. Field testing of the F.O.C.E. system occurred in spring 2009 in a mixed species sea grass bed near the Sanibel-Captiva Conservation Fund's Marine Laboratory in Tarpon Bay, FL. These tests confirmed that the system successfully lowered the pH of seawater over 0.5-m^2 sections of benthic habitats from ambient levels to those as low as 5.5 units, raising CO_2 levels and lowering the $CaCO_3$ saturation state. This F.O.C.E. system is currently in operation in the Chesapeake Bay (USA). These tests demonstrate that small-scale F.O.C.E.

systems can be deployed at near-shore locations, at relatively low cost, to quantify the impact of OA on a variety of marine organisms.

M2. Outflow of corrosive Arctic water to the North Atlantic: Saturation state of seawater for calcite and aragonite in Canadian Arctic Archipelago and the Labrador Sea

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Ocean acidification is predicted to impact the polar oceans first. We investigated saturation state with respect to calcite (Ω_{cal}) and aragonite (Ω_{arg}) in six sections in Canadian Arctic Archipelago (CAA) and the Labrador Sea using DIC and alkalinity measurements collected from 2003-2005. The study area includes Smith Sound, Barrow Strait, Baffin Bay, Davis Strait, Hudson Strait, and the Labrador Sea. Smith Sound and Barrow Strait are conduits for the Arctic outflow to the North Atlantic. Ω_{arg} in Arctic outflow was 1.23 with pH_{total}=8.15 in Smith Sound, and in Barrow Strait Ω_{arg} was 1.15 with pH_{total}=8.00. The saturation horizon was 150 m in Barrow Strait. This low saturation state water from the Arctic can be traced at the eastern part of Baffin Bay and Davis Strait sections. While outflow through Hudson Strait modifies this corrosive Arctic water, low saturation state water is still identified on the southern part of Labrador Shelf. Horizontal variation of saturation state is due to the circulation and water masses. Since circulation in Baffin Bay and the Labrador Sea are cyclonic, the western side of the basins where Arctic water flows out has lower saturation state than the eastern side in Baffin Bay, Davis Strait and the Labrador Sea. The saturation horizon is ~1000 m for calcite and ~300 m for aragonite on the western side of Baffin Bay, and it deepens as you travel northeastward. In Davis Strait, the aragonite saturation horizon shoals to 180 m on the western side of the section and deepens as you travel eastward. Limited water exchange due to sills in the northern and southern portions of the basin contributes to the low saturation state at depth in Baffin Bay and Davis Strait. In the central part of the Labrador Sea, ventilation ages of water masses, which are controlled by horizontal advective processes, influence depths of the saturation horizon of 2300 m. On the shelf regions, the low saturation state on the Labrador Shelf is due to the Arctic water outflow with Ω_{arg} =1.36 and pH=8.08, while Ω_{arg} is 1.77 and pH is 8.08 on the West Greenland Shelf. Rapid environmental changes such as retreating ice extent and hydrological cycles will influence the carbonate chemistry in the polar oceans in the near future. This study provides present saturation states of key areas in Canadian Arctic Archipelago and the northwest Atlantic. Since shelf regions where Arctic water flows out are biologically active and important for commercial fisheries, monitoring and investigation of biological response to ocean acidification in these areas is essential for prediction of future changes.

M3. Ocean acidification and global ecosystem services

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The decreasing oceanic saturation states of carbonate minerals resulting from ocean acidification have been associated with declining calcification rates of marine organisms that provide a range of ecosystem services. Calcification rates have been linked with delayed or stunted development of shells and skeletons, exposing planktonic larval calcifiers to a longer period of water-column predation, and possibly leaving insufficient energy for metamorphosis and reproduction. Calcifying organisms provide valuable income through harvests, coastal protection, tourism, and ecosystem support, all of which directly and indirectly benefit human communities. Damage to the services that these organisms provide would disproportionately affect developing nations and coastal regions. By 2050, both population increases and changes in carbonate mineral saturation will be greatest in low-latitude regions, multiplying the stresses on tropical ecosystems. Consequences of lost ecosystem services associated with ocean acidification and degraded marine environments could include protein shortages or even migration. Instituting adaptive strategies that might reduce pressures on marine ecosystems will require initial spending, but could lead to fewer long-term expenses than ignoring ocean acidification.

M4. Carbon cycling and carbonate chemistry in Santa Monica Bay, CA

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Time-series measurements of inorganic carbon, alkalinity, nutrients, and physical parameters were initiated in 2003 on a biweekly basis in the upper 300 m at a coastal site in Santa Monica Bay, CA. Our 6 years of DIC measurements reveal a complex seasonal pattern with a tendency for a maximum in late winter to late spring and a minimum in early summer. The spring-time DIC maxima are associated with episodic and short-lived upwelling events that are in general followed by a short period with a moderate to strong decrease in DIC due to both CO_2 outgassing and DIC uptake by phytoplankton. Our record also reveals a number of strong DIC drawdown events that occur in summer and fall, when nitrate is completely exhausted, for reasons not yet fully understood. Over the annual cycle, Santa Monica Bay is mostly undersaturated with respect to atmospheric CO_2, constituting a net sink on the order of 0.5 mol C m^{-2} yr^{-1}. Interannual variability in

the time-series record is mainly driven by the frequency and strength of the springtime upwelling events. Near surface alkalinity varies primarily in response to changes in surface salinity, while variations at depth reflect changes in water masses. The computed aragonite saturation horizon is less than 150 m deep and varies considerably on seasonal to interannual timescales, primarily in response to upwelling strength and intensity, which can lift the saturation horizon up to 30 m. This highlights the need for high temporal sampling to assess the impact of ocean acidification on marine ecosystems.

M5. Ocean acidification in estuaries and continental shelves of the Southeastern United States

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Calcium carbonate saturation state was studied in three estuaries (from September 2002 to May 2004) and the continental shelf (one cross-shelf transect, from July 2005 to May 2006) of the Southeastern United States. In the estuaries, aragonite saturation state was calculated from surface water DIC and pCO_2. For the onshore-offshore transect, aragonite saturation state was calculated from vertical distributions of DIC and pH. Results show that the saturation state of calcium carbonate on the east coast of the United States was much higher than that on the west coast (Feely et al., 2008). Aragonite saturation state on the east coast was always higher than 3 on the shelf during the sampling months. The lowest value occurred in the deep water along the continental slope, where aragonite saturation state approaches to 1.0-1.5 (200-600m depth). However, if CO_2 in the coastal ocean will increase as fast as that in the atmosphere, by the end of 2100, aragonite saturation state will approach undersaturation at the shelf break when upwelling takes place.

M6. Carbon cycling in the Arctic Archipelago: The export of Pacific carbon to the North Atlantic

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The Arctic Ocean is expected to be disproportionately sensitive to climatic changes, and thought to be an area where such changes might be detected. The Arctic hydrological cycle is influenced by runoff and precipitation, sea ice formation/melting, and the inflow of saline waters from Bering and Fram Straits and the Barents Sea Shelf. Pacific water is recognizable as low salinity water, with high concentrations of dissolved inorganic carbon (DIC), flowing from the Arctic Ocean to the North Atlantic via the Canadian Arctic Archipelago. We present DIC data from an east-west section through the Archipelago as part of the Canadian International Polar Year initiatives. The fractions of

Pacific and Arctic Ocean waters leaving the Archipelago and entering Baffin Bay, and subsequently the North Atlantic, are computed. The eastward transport of carbon from the Pacific, via the Arctic, to the North Atlantic is estimated.

Altered mixing ratios of Pacific and freshwater in the Arctic Ocean have been recorded in recent decades. Any climatically driven alterations in the composition of waters leaving the Arctic Archipelago may have implications for anthropogenic CO_2 uptake, and hence ocean acidification, in the sub-polar and temperate North Atlantic.

SESSION 3. OBSERVING SYSTEMS AND TIME-SERIES

T1. Are reported trends in satellite primary production a sign of global warming?

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Recently reported trends in the 10-year record of SeaWiFS-derived chlorophyll and primary production have been attributed to climate change. Here we use output from the GFDL biogeochemical model to set the recent trends into a longer-term context. Trends from the SeaWiFS record are compared to trends in 10-year sections of the model output, and found to be greater than the modeled interannual variability only in small patches in high latitude regions. Analysis of the model trends suggests that decades-long time-series are required to detect trends above the 'noise' of natural interannual-decadal variability. The magnitude of trends and natural variability are spatially very patchy on a global scale. This implies that continuation of global monitoring over decadal timescales is required in order to detect the response of ocean biology to climate change.

T2. Spectral fluorometric assessments of phytoplankton community composition using the Algae Online Analyzer

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The size and taxonomic composition of marine phytoplankton communities determine rates of recycling and export of phytoplankton-derived carbon from the surface ocean. Size and functional group-based models of carbon export require information on phytoplankton community composition, but direct measurements require oceanographic cruises and provide only sporadic coverage. Ocean observing systems often characterize temporal variability in phytoplankton biomass with a chl-*a* fluorometer, but provide no information on taxonomic composition. Spectral fluorometers, however, which use multiple

excitation wavelengths targeted at specific photosynthetic pigments, provide information on both taxonomic composition and phytoplankton biomass, and can be used for continuous monitoring. We investigated the predictive capabilities of one commercially available spectral fluorometer, the Algae Online Analyzer (AOA; bbe Moldaenke, Germany) in both discrete sampling mode with natural phytoplankton communities and in continuous monitoring mode by installing it on a ferry that traverses an estuary several times daily. The AOA did a relatively good job of predicting phytoplankton community composition, but estimates of total phytoplankton biomass were ~1.2 to 3.4 times higher than direct determinations of chl-*a* by HPLC. The extent of the overestimate varied, but the sign of the inaccuracy was consistent between samplings and was related to diel variations in the ratio of fluorescence to chl-*a*, used as a conversion factor.

T3. A multi-year increase in shallow POC export is countered by enhanced mesopelagic POC attenuation in the Sargasso Sea

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Regional variability in the attenuation of particulate organic carbon (POC) flux with depth and the mechanisms controlling POC transfer efficiency have received renewed attention. We present data from the Bermuda Atlantic Time-series Study (BATS) indicating a coordinated increase in the magnitude of the biological carbon pump during the winter/spring period. Integrated epipelagic chlorophyll-a (Chl-a), primary production, suspended POC, and 150-m POC flux all increased by 30-86% from 1997 to 2007. These changes in the shallow biological carbon pump are associated with significant decreases in the relative abundance of diatoms and haptophytes and increases in *Synechococcus.* Over the same period, remineralization of POC flux between 150-300 m doubled such that the increase in the shallow biological pump did not increase the carbon flux to the mesopelagic. The increase in remineralization may be related to changes in the importance of zooplankton carbon demand. These findings document a disconnect between the shallow biological carbon pump and mesopelagic carbon sequestration in the oligotrophic oceans mediated by changes in plankton community structure.

T4. CARIACO: 14 years of ocean carbon and biogeochemistry on the continental margin of the southeastern Caribbean Sea

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The CARIACO (CArbon Retention In A Colored Ocean) ocean time-series program has been collecting measurements in the Cariaco Basin in the southeastern Caribbean Sea since October 1995. The time-series includes observations from 10.30º N, 64.40º W on a monthly or more frequent basis, which provide high temporal resolution data on biogeochemical and physical processes in a tropical setting, with the goal of understanding ocean variations in a changing climate. Some of the most important and relevant findings of the CARIACO Program include:

1. Hydrography of the Cariaco Basin is influenced mostly by wind-driven upwelling, which contributes to the exchange of waters in the upper 140 m.
2. Intrusion of oxygenated water has been observed episodically down to depths of more than 300 m.
3. Ocean currents in the upper 300 m of the Cariaco Basin are variable and are dependent on the Caribbean Current and transient eddies that cross the Caribbean Sea. Below this depth, current velocity is very small (< 5 cm/s).
4. River influence in the region is exerted mostly by local rivers, rather than the larger South American rivers (i.e. Orinoco and Amazon).
5. Concentrations of inorganic nutrients that support primary production fluctuate seasonally, driven mainly by the upwelling regime.
6. Dissolved organic carbon (DOC) accumulates in surface waters during the rainy season (concentrations of >80 μM); this carbon is laterally exported out of the basin during upwelling. Rivers are not a significant source of DOC.
7. Upwelling weakened between 1996 and 1998, and reached minima in 2005 when the Caribbean experienced a very warm year during the upwelling season (January-May).
8. Depth-integrated primary production is seasonally driven, with higher production measured during upwelling (~1900 vs. ~850 mg C m^{-2} d^{-1}, integrated to 100 m). An overall decline in primary production rates has been observed since the beginning of the time-series, in part linked to weaker upwelling.
9. No clear relationship has been observed between POC flux and primary production.
10. The remineralization rate of POC with depth is similar to that in open ocean environments, despite the anoxia that exists in the basin below 250 m.
11. Terrigenous material makes up >50% of the sediment flux. Lateral advection, particularly from the coast through nepheloid layers is thought to be an important mechanism of terrigenous particle transport.
12. Only about 4-8% of the settling material is composed of terrestrial organic carbon; most of the organic carbon measured in particle fluxes is of marine origin.

13. A strong seasonal fCO_2 cycle has been observed, with higher fCO_2 variability during the upwelling season (~389 ± 28.5 μatm).
14. High chemoautotrophic production occurs near the oxic/anoxic interface, equivalent to ~70% of surface production.
15. Heterotrophic carbon demand near the interface almost always exceeds delivery; presumably, carbon and energy demand are met by *in situ* chemoautotrophic production.

T6. Relating *in-situ* observations of biological, chemical and physical properties to plankton population dynamics

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Ocean-observing systems promise to deliver unfathomable quantities of biogeochemical data. A challenge lies in interpreting these data in terms of fundamental biogeochemical processes, such as rates of carbon export or net community production. To address this challenge, I have been combining small boat surveys with laboratory measurements of plankton growth and grazing rates in a coastal fjord in Washington State. Water column properties were recorded with a SeaBird 19+ CTD with meter-scale resolution at up to 15 stations in the 10-km fjord. Water samples from discrete depths were collected with a horizontally mounted Niskin bottle to quantify inorganic macronutrient and Chl-*a* concentrations, dominant phytoplankton taxa, phytoplankton photosynthesis and heterotrophic protist grazing rates. Phytoplankton distributions were frequently patchy, with phytoplankton concentrated within vertically thin, horizontally extensive (km-scale) layers. Even large tidal exchanges did not eliminate plankton layers within the fjord. Some layers persisted for days; a dense diatom bloom (>20 μg Chl-*a* l-1) lasted three weeks. Layer communities were often dominated by single phytoplankton taxa, including dinoflagellates, diatoms and prymnesiophytes. Dissolved macronutrient concentrations remained high, irrespective of phytoplankton concentrations or growth rate. The CTD-based fluorescence data (Wetlabs WetStar) was in good agreement (r^2 >0.6) with extracted Chl-*a* concentrations and microscopy-derived phytoplankton carbon biomass. Both within and outside layers, photosynthetic potential and phytoplankton growth rates were frequently high (~1 division/day). Grazing rates by heterotrophic protists were mostly lower than phytoplankton growth rates. The highest grazing rates measured were from within phytoplankton layers. Predation pressure changed significantly as a function of dominant phytoplankton taxa present. Because dominant taxa had a measurable effect on biological dynamics, there was no deterministic relationship between physical or chemical properties of the water column and the magnitude of biological rates observed. Thus, acquisition of some taxonomic resolution and preservation of the spatial structure of phytoplankton distributions will be an asset to autonomous ocean-observing systems that aim to reproduce growth and grazing rates within the system and thus their biogeochemical consequences.

T7. Making the invisible visible: Molecular tools to identify the contribution of small phytoplankton as contributors of particle export

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The biological carbon pump plays an important role in the global carbon cycle, but little is known about the contribution of specific taxa to the downward particle flux. Recently, small pico- and nanoplankton have been identified as potentially important players in export flux, but this is difficult to test experimentally. We are now able to use molecular techniques to identify specific taxonomic groups not only from the water column, but also from DNA isolated from shallow trap material. Here we present results from the application of different molecular techniques to identify protist and cyanobacterial communities in sinking material at two time-series stations in the subtropical North Atlantic. Small subunit ribosomal DNA sequences were amplified from each sample using either universal eukaryotic (18S rDNA) and cyanobacterial (16S rDNA) primers. Molecular clone libraries and denaturing gradient gel electrophoresis (DGGE) were then applied to compare plankton communities from various depths in the euphotic zone with sequences recovered from the surface-tethered particle traps. This enables us to assess the relative importance of different taxonomic groups to particle flux. We can show, using these molecular tools, that small protists as well as cyanobacteria can indeed be significant contributors to the community recovered from shallow particle traps. This confirms the importance of pico-and nanoplankton in carbon flux, especially in low productivity oceans.

T8. Satellite retrieval of phytoplankton community size structure in the global ocean

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Phytoplankton cell size is important to biogeochemical and food web processes and can be optically differentiated. The feasibility of retrieving phytoplankton community structure was investigated by isolating the effect phytoplankton cell size had on varying spectral remote sensing reflectance in the presence of other optically active constituents. This was achieved through the use of optical and radiative transfer models that were linked in an off-line diagnostic calculation to monthly output of a global biogeochemical/ecosystem/circulation model. This revealed important implications with regard to when and where the satellite standard algorithms will overestimate/underestimate chlorophyll concentration due to remote sensing reflectance being significantly affected by phytoplankton size. Global monthly maps of phytoplankton size structure for the first ten years of the SeaWiFS mission (September 1997 - August 2007) were retrieved from satellite imagery of remote sensing reflectance. The spatial and temporal patterns of phytoplankton size structure that emerged agreed well with *in situ* observations. Spatial and temporal patterns of phytoplankton size

structure in relation to chlorophyll concentration were investigated and revealed there were scales at which these parameters were not directly linked. These results point to the importance of considering phytoplankton cell size in investigations of primary production, biogeochemistry, carbon flux, and cycling.

T9. The challenges of modeling depth-integrated marine primary productivity over multiple decades: A case study at BATS and HOT

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The performance of 36 models (22 satellite-based models and 14 biogeochemical ocean circulation models (BOGCMs)) that estimate depth-integrated marine net primary productivity (NPP) was assessed by comparing their output to *in situ* ^{14}C data at the Bermuda Atlantic Time-Series (BATS) and the Hawaii Ocean Time-series (HOT) over nearly two decades. At both sites, more than 90% of the models underestimated mean NPP, with the BOGCMs on average having a negative bias that was nearly twice that of the satellite-based models. However, the difference in overall skill between the best BOGCM and the best satellite-based model at each site was not significant. These models, unlike most others, overestimated mean NPP and underestimated NPP variance. On average, the BOGCMs estimated the variance of NPP more accurately than the mean, thus their relatively lower skill was driven by bias. Satellite-based models typically performed equally in terms of variance and bias.

Between 1989 and 2006-2007, *in situ* NPP at BATS and HOT increased by an average of ~2% per year. At BATS, the trend was driven by an increase in productivity in the upper 40 m, whereas at HOT, the increase in productivity was greatest between 45-75 m and was associated with increasing surface and deep (100 m) temperatures. Thus the anticipated low-latitude inverse relationship of increasing temperatures coupled to decreasing production was not observed at this site. The majority of satellite-based models resolved NPP trends consistently (regardless of time period, i.e. extended versus SeaWiFS time period) when chlorophyll-*a* was derived from high-performance liquid chromatography (HPLC), rather than fluorometric or SeaWiFS data. Overall model performance, however, was not affected by chlorophyll source. This is because model-data misfit among satellite-based models was consistent through time when HPLC chlorophyll-*a* was used, whereas the misfit computed using fluorometric or SeaWiFS chlorophyll-*a* was low in the early time-series and increased through time. Among BOGCMs, only two individual models successfully resolved the increasing trends of NPP (one model at each site). We caution the use of models that use SeaWiFS chlorophyll-*a* to assess changes in subtropical NPP, or at least in marine ecosystems similar to the BATS and HOT stations; satellite-based model estimates of NPP trends might improve if high quality HPLC chlorophyll-*a* time series were available.

T10. Seasonal variability of dissolved inorganic carbon and surface water pCO_2 in the Scotian Shelf region of the Northwestern Atlantic

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The seasonal variability of inorganic carbon in the surface waters of the Scotian Shelf region of the Canadian northwestern Atlantic Ocean is investigated. Seasonal variability is assessed using hourly measurements covering a full annual cycle of the partial pressure of CO_2 (pCO_2), and hydrographic variables obtained by an autonomous moored instrument. These measurements are complemented by frequent shipboard sampling of dissolved inorganic carbon (DIC), total alkalinity (TA), and pCO_2 at the mooring site and over the larger spatial scale. Biological processes, and advection are found to be the main factors controlling DIC in the surface waters and mixed layer, while the competing effects of temperature and biology influence surface pCO_2 in roughly equal magnitude. Annual mixed layer net community production (NCP) and the air-sea fluxes of CO_2 are estimated; the region acts as a moderate net source of CO_2 to the atmosphere on the annual scale, with a reversal of this process occurring only during the spring bloom, when a rapid undersaturation of the surface waters is reached for a short period. Supersaturation is ongoing throughout the year, despite persistent biological production, due to the magnitude of the temperature control on pCO_2 in this coastal region.

T11. Measurements of air and water CO_2 flux in the Gulf of Trieste

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Coastal marine regions such as the Gulf of Trieste (GOT) in the Northern Adriatic are strongly influenced by changes in climate and may play an important role in biological productivity and the global air-sea CO_2 flux. These regions serve as a link between carbon cycling on land and the ocean interior, and because the carbon dynamics are not studied in many coastal regions, their role in the global carbon cycle is highly uncertain. To date, in-depth studies of carbon cycling in coastal waters have been mostly limited to coastal transects that provide interesting snapshots of carbon dynamics. No CO_2 flux data are currently available in the GOT.

The Northern Adriatic is one of the most productive regions in the Mediterranean, and is affected by freshwater input, eutrophication, and large changes in air-sea exchange during Bora high wind events, which makes this region an excellent study site for investigations of air-sea interaction and changes in biology and carbon chemistry.

Here we present the first measurements of air and water CO_2 flux in the GOT. Water pCO_2 was measured at the Coastal Oceanographic buoy VIDA, Slovenia using the SAMI-CO_2 sensor during four deployments in spring and summer/fall 2007, and spring/summer and fall of 2008. pCO_2 measurements were combined with hydrological and biological observations to evaluate the processes that control carbon cycling in the region. The results indicate that the GOT was a net sink for atmospheric CO_2. Although some of the interannual and seasonal variability in aqueous CO_2 can be explained with changes in SST, our data also suggest a significant influence by fresh water input from rivers, biological production associated with high nutrient input, and gas exchange during high wind events.

T12. Bank-driven nutrient fluxes in a stratified shelf sea

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Patches of increased chlorophyll (chl) concentrations within the thermocline were observed over the slopes of several banks in the Celtic Sea. Supply of nitrate, the product of the nitrate gradient and the vertical diffusivity at the base of the thermocline, from the bottom mixed layer into the thermocline was enhanced over the slope of bank, compared to over a flat seafloor (5–23 mmol m^{-2} day^{-1} and 2 mmol m^{-2} day^{-1}, respectively). We hypothesize this increase in available nitrate to be the cause of the high chl signal, by promoting phytoplankton growth. The increased nitrate supply was forced by locally generated internal mixing through lee wave formation and dissipation. The apparent persistence of the biological signal associated with the banks and the large number of shelf sea banks suggests that this feature is of importance in new primary production in global shelf seas.

T13. Spatial and temporal variations in carbon fluxes in the tropical oceans: Comparisons of the Pacific and Atlantic Oceans

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The tropical oceans play a very important role in the global carbon cycle because they are the dominant natural oceanic source of CO_2 to the atmosphere. Global carbon cycle modeling studies indicate that the tropical oceans contribute the largest fraction of the interannual variability of the global ocean-atmosphere CO_2 flux. However, there are considerable discrepancies among different approaches (*e.g.,* observations, ocean carbon models, and inverse models), and large uncertainties in the estimates of the carbon fluxes at basin scales. Here, we present a basin-scale study employing satellite data and validated regional biogeochemical models to address a number of key issues leading to a better understanding of the large-scale temporal and spatial variability of carbon fluxes in the tropical oceans. Our study indicates that there are considerable differences in the carbon cycle between the tropical Pacific and Atlantic Ocean, including seasonal,

interannual and decadal variability in the carbon fluxes between the upper ocean and deep ocean, and between the tropical oceans and the atmosphere. While the surface chlorophyll concentration is generally higher in the tropical Atlantic than in the Pacific, the carbon biomass is similar in both regions due to lower carbon to chlorophyll ratio in the tropical Atlantic relative to Pacific. In the tropical Pacific, the interannual variability, driven by the El Niño/Southern Oscillation (ENSO) cycle, is dominant, followed by modest seasonality and decadal variability. However, the tropical Atlantic shows relatively weaker interannual variability but stronger seasonality in the carbon fluxes.

T14. Simultaneous spectrophotometric measurements of the CO_2 system parameters in seawater

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We have developed new technologies to make simultaneous and autonomous measurements of pH, carbon dioxide fugacity (fCO_2), and total dissolved inorganic carbon (DIC). The multi-parameter measurements of the seawater CO_2 system are based on spectrophotometric determinations of solution pH at multiple wavelengths using sulfonephthalein indicators. The spectrophotometric pH measurements use a long path length PEEK optical cell (10-15 cm) and a continuous sample-indicator-mixing flow design. The fCO_2 optical cell consists of Teflon AF 2400 (DuPont) capillary tubing sealed within the borehole of a PEEK rod. This Teflon AF tubing is filled with a standard indicator solution with a fixed total alkalinity, and forms a liquid core waveguide (LCW). The LCW functions as both a long pathlength (~15 cm) optical cell and a membrane that equilibrates the internal standard solution with external seawater. fCO_2 is then determined by measuring the pH of the internal solution. DIC is measured by determining the pH of standard internal solutions in equilibrium with seawater that has been acidified to convert all forms of DIC to CO_2. We integrated these technologies to develop a fully automated Multi-parameter Inorganic Carbon Analyzer (MICA), which makes simultaneous flow-through underway measurements of pH, fCO_2 and DIC with a sampling frequency of ~7 samples (21 measurements) per hour. The MICA have been used in the CLIVAR/CO_2 Repeat Hydrography program and several coastal CO_2 studies. MICA measurements show excellent field precision and accuracy, all of which are comparable to state-of-the-art conventional measurements of the CO_2 system parameters.

We also integrated the spectrophotometric pH measurement into the Spectrophotometric Elemental Analysis System (SEAS), an *in situ* sensor system for measurements of multiple chemical species (nutrients and trace metals) in aquatic environments. The SEAS-pH sensor is capable of making *in situ* high-resolution and high-precision water column pH profiles and time-series measurements at a fixed location. Other spectrophotometric measurements of the CO_2 system parameters will be adapted to the *in situ* sensors suited for various *in situ* measurement platforms, particularly profilers, and AUV/ROV/gliders, with a primary goal of enabling high spatial and temporal resolution studies within ocean observing systems.

T15. Sustaining climate-quality satellite ocean color radiometry measurements

James Yoder (Chair) and Venetia Stuart (Executive Scientist)

International Ocean Colour Coordinating Group (IOCCG)

Recent publications indicate that phytoplankton chlorophyll/carbon concentrations in large regions of the ocean (primarily in the mid-ocean gyres) are decreasing, possibly owing to climate change affecting ocean stratification. However, the SeaWiFS record began in 1997, and thus the early part of the record is heavily influenced by the impact of one of the largest ENSO events of the past 100 years that began in 1997 and had a major impact for several years on near-surface chlorophyll/carbon concentrations in many regions of the global ocean. Thus, there is not yet a sufficiently long record of calibrated satellite ocean color radiance to differentiate interannual variability (such as that associated with ENSO) from climate change impacts. Yet, neither NASA nor NOAA has an approved mission for a satellite sensor that can sustain ocean color radiometry (OCR) imagery of the quality achieved by SeaWiFS and MODIS-Aqua. Sustaining that time-series of climate-quality data for the U.S. and international research community will require unprecedented cooperation among space agencies.

The Committee on Earth Observation Satellites (CEOS) adopted the concept of "virtual constellations" as a mechanism for further encouraging cooperation among agencies launching similar sensors. The IOCCG proposed an Ocean Color Radiometry-Virtual Constellation (OCR-VC), which was recently approved by CEOS. The OCR-VC can be used as a mechanism to improve international cooperation, and should thus help the science community obtain and sustain a time-series of climate-quality ocean color radiances beyond the lifetime of MODIS-Aqua. The organizers of OceanObs '09 accepted a white paper describing the OCR-VC and its potential significance for sustaining a time series of climate quality OCR data for the research community. The paper will be presented and discussed at the September 2009 OceanObs '09 meeting.

SESSION 4. NACP/OCB COASTAL INTERIM SYNTHESIS ACTIVITIES

T16. Seasonal evolution of carbon sources and sinks along the western continental margin of North America

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Using monthly climatologies of remotely sensed sea surface temperature and chlorophyll as inputs, we applied the artificial neuronal network approach of Saraceno et al. (2006) to

objectively define biogeochemical regions along the west coast of North America from British Columbia through Central America. Monthly climatologies reveal strong meridional variation in SST and strong variation across the continental shelf in chlorophyll, with pronounced seasonal variation in both variables. The resulting self-organizing map (SOM) delineated 18 biogeochemical regions, which break up the western North America continental shelf into roughly three domains—the U.S. west coast, Baja California, and Central America south of Baja —as would be expected on the basis of physical oceanographic conditions. Along the U.S. west coast, the dominant structure evident in the SOMs reflects the influence of wind-driven upwelling, with strong across-shelf differentiation of biogeochemical regimes. Along Baja, winds are weaker and the shelf is wider, with weaker upwelling as a result. In Central America, the predominant mode of variability is associated with wind jets through mountain passes and the resulting upwelling in the Gulfs of Panama, Papagayo, and Tehuantepec.

With SOM in hand, all pCO_2 observations (n = 237,418) were assigned to the appropriate region, depending on the month and location in which the measurement was taken. Within each region, a mechanistic prediction algorithm based on remotely sensed parameters was fitted to allow the extrapolation of pCO_2 values across the region and the creation of monthly pCO_2 maps. We then generated CO_2 flux maps of the study region using published parameterizations for gas transfer velocity (k) as a function of wind speed (U_{10}) and SST.

Monthly pCO_2 and flux maps indicate that most of the Pacific coast of North America to 50°N acts as a weak to moderate sink for CO_2 for most of the year. Strong sinks occur along the coast north of ~40°N from May to Nov. Locally strong sources of CO_2 are associated with the mountain gap wind jets in Central America, beginning in the north in Nov. and tapering off in the south in Apr. with moderately strong sinks forming in the shadow of the dissipating wind jets. More diffuse source conditions appear offshore of southern Mexico in the spring and travel north off Baja through the summer before returning to the south and dissipating in the late fall. Finally, the Gulf of California appears to be a weak to moderate CO_2 source for most of the year. Overall, this analysis suggests that the magnitude of the western North American continental shelf carbon sink is roughly twice as large as estimated in the *State of the Carbon Cycle Report* synthesis (~30 vs. 13 Tg-Cyr^{-1}), which was based on approximately 1/3 as much data. However, significant sampling gaps remain in areas that may substantially influence net exchange estimates for the entire area (*e.g.*, Central American wind jet hotspots).

T17. Data synthesis and modeling along the Gulf of Mexico coast: Two case studies in Texas estuaries

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Photosynthesis carried out by primary producers is the most important mechanism by which organic carbon is assimilated; two major variables that affect primary productivity

are light and nutrient availability, the latter being the focus of this work. All living things require nutrients for sustenance. However, as human populations and concomitant environmental pressures increase, nutrients delivered to rivers and estuaries from contributing basins also increase, leading to nutrient over-enrichment, the unbalancing of nutrient cycles, and shifts in the structure and function of ecosystems. The present work synthesized and analyzed historical and short-term experimental nutrient data, primarily nitrogen and phosphorus, developed nutrient budgets, and modeled the estuarine ecosystem response to varying nutrient loads. Land use/land cover change analyses were performed in contributing river basins to determine spatial and temporal effects on nutrient concentrations and loads. This work is being conducted in estuaries along the central Texas Gulf coast, including the Lavaca-Colorado, Guadalupe, Mission-Aransas and Nueces Estuaries. The two case studies presented here include findings from the Guadalupe Estuary and Oso Bay, a secondary bay in the Nueces Estuary. The Guadalupe Estuary drains the Guadalupe and San Antonio River Basins, two very distinct, yet adjacent geographic regions exhibiting differences in land use/land cover composition, river flow, population densities, permitted industrial and municipal point source discharges, therefore nutrient concentrations, loads, and ecosystem response. The Guadalupe River Basin exhibits signs of a nonpoint source-dominated system, while the San Antonio River Basin exhibits signs of a point source-dominated system. Oso Bay is a shallow, secondary bay that drains a watershed dominated by agriculture, urbanization, and municipal and industrial permitted discharges. We studied the effects of a storm-derived nutrient pulse on water quality in Oso Bay, the sources of these nutrients, and the role they play in the biogeochemical processes in the bay. The exchange of water, salinity and nutrients between Oso Creek, Oso Bay and Corpus Christi Bay was examined during a one-week period that included a tropical storm event using the Land Ocean Interaction in the Coastal Zone (LOICZ) approach. This work is the first attempt at modeling nutrient loads using a comprehensive basin approach in Texas estuaries and will provide the foundation necessary to fulfill a pressing state need to develop nutrient criteria and freshwater inflow recommendations for bays and estuaries. The effects of nutrients in carbon assimilation at local estuary scales can have cumulative effects on regional and global, Gulf and oceanic scales, therefore making this work essential.

T18. U.S. Eastern Continental Shelf carbon cycling (USECoS): Modeling, data assimilation, and analysis

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Although the oceans play a major role in the uptake of fossil fuel CO_2 from the atmosphere, there is much debate about the contribution from continental shelves, because many key shelf fluxes are not yet well quantified: the exchange of carbon across the land-ocean and shelf-slope interfaces, air-sea exchange of CO_2, burial, and biological processes including productivity. The goal of the USECoS (U.S. Eastern Continental Shelf Carbon Cycling) project is to quantify these carbon fluxes along the eastern U.S. coast using models quantitatively evaluated by comparisons with observations, and to establish a framework for predicting how these fluxes may be modified as a result of climate and land use change. This study builds on results from our earlier NASA-funded study of carbon cycling, which resulted in development of a coupled biogeochemical-ocean circulation model configured for the U.S. eastern continental shelf. This model was extensively evaluated with *in situ* and remotely sensed data. Results indicated that reduction in uncertainties in the shelf component of the global carbon cycle required 1) increased resolution of the physical model via nesting, 2) refinements to the biogeochemical model, and 3) quantitatively evaluating these via assimilation of biogeochemical data (*in situ* and remotely sensed). These model improvements will be described and the consequences of these for simulation of carbon cycling on the U.S. east coast continental shelf discussed. The resultant model provides a framework for better understanding and reducing estimates of uncertainties in current and future carbon transformations and cycling in continental shelf systems.

T19. Facilitating synthesis activities in the North American Carbon Program

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The central objective of the North American Carbon Program (NACP), a core element of the U.S. Climate Change Science Program, is to quantify the sources and sinks of carbon dioxide, carbon monoxide, and methane in North America and adjacent ocean regions. The NACP consists of a wide range of investigators at universities and federal research centers. Although many of these investigators have worked together in the past, many have had few prior interactions and may not know of similar work within knowledge domains, much less across the diversity of environments and scientific approaches in the Program.

Coordinating interactions and sharing data are major challenges in conducting NACP. The Google Earth Collection on the NACP website (www.nacarbon.org) provides a geographical view of the research products contributed by each core and affiliated NACP project. Other relevant data sources can also be browsed in spatial context with NACP contributions. Each contribution links to project-oriented metadata, or “project profiles,” that provide a greater understanding of the scientific and social context of each dataset and are an important means of communicating within the NACP and to the larger carbon cycle science community. Project profiles store information such as a project's title, leaders, participants, abstract, keywords, funding agencies, associated intensive field campaigns, expected data products, data needs, publications, and URLs of associated data

centers, datasets, and metadata. Data products are research contributions that include biometric inventories, flux tower estimates, remote sensing land cover products, tools, services, and model inputs/outputs.

Project leaders have been asked to identify these contributions to the site level whenever possible, either through simple latitude/longitude pair, or by uploading a KML, KMZ, or shape file. After post-processing, research contributions are added to the NACP Google Earth Collection to facilitate discovery and use in synthesis activities of the Program.

T20. Nutrient loadings and subsequent ecosystem responses during and after storm events in the Mission-Aransas National Estuarine Research Reserve, Texas, USA: A modeling study

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Precipitation patterns in the south central United States are highly variable and tele-connected with ENSO-driven climate events. As a consequence, the frequency, timing, duration, and magnitude of river inflows to coastal waters of the western Gulf of Mexico are highly variable. This variability leads to dramatic changes in salinity, nutrient, and organic matter dynamics in estuaries of the western Gulf. While the variability in river inputs to the western Gulf is more extreme than many other coastal systems, understanding watershed/estuary dynamics in this region will help us anticipate effects of changing climate regimes on coastal systems more generally. We developed a 6-component ecosystem model embedded in a box model in order to investigate effects of changing environmental conditions on water quality and phytoplankton dynamics. The model was implemented with data sets collected from the Mission-Aransas National Estuarine Research Reserve (NERR) during and after three major storm events in 2007 and 2008. The Mission-Aransas NERR is one of seven major estuarine systems along the Texas Gulf Coast. Two rivers flow directly into the Mission-Aransas NERR, the Mission and Aransas. These rivers specifically flow into Copano Bay. Preliminary results reveal that: 1) pulsed storm events deliver high amounts of freshwater and nitrogen loadings to estuaries; 2) both newly exported and regenerated nitrogen fueled local phytoplankton blooms; 3) the fate of newly produced phytoplankton nitrogen (carbon) was dissolved organic nitrogen (carbon). We also present implications of 'what-if' scenarios (IPCC, 2007) of increasing frequency and intensity of storms in the estuarine and coastal ecosystem responses. We hope upcoming results will provide a basis for the understanding of the impacts of climate variability and change (*e.g.,* extreme weather events), and/or land use/land cover change (*e.g.,* urbanization) on the biogeochemical cycles of coastal ecosystems.

T5. Colored dissolved organic matter and dissolved organic carbon in the water column and in the bottom nepheloid layers of the Cariaco Basin, Venezuela

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Colored dissolved organic matter (CDOM) and dissolved organic carbon (DOC) were sampled in the water column of the Cariaco Basin (SE Caribbean Sea) and in the nepheloid layers of the adjacent continental margin in the fall of 2008 and spring of 2009 in an attempt to characterize the concentrations and distribution of these variables and establish potential links between the coast and the open basin. The Cariaco Basin is a semi-enclosed basin in the Southeastern Caribbean Sea, which is permanently anoxic below ~250 m. CDOM concentration in the deep basin increased dramatically below 250 m, reaching a maximum of 0.136 m^{-1} at 1310 m. CDOM Excitation emission matrix spectroscopy (EEMS) revealed that below 250 m protein-like peaks accentuated, suggesting production of new material, attributed to the high bacterial activity measured in the Cariaco Basin. Below this depth the apparition of peaks corresponding to humic substances suggested that the nature of the dissolved organic matter in the bottom of the basin is more complex. DOC concentrations in the deep basin are ~10 μM higher than in bottom waters of the adjacent Caribbean Sea, supporting the idea that refractory and semi-labile DOC is allowed to accumulate in this environment.

The role of CDOM and DOC contribution by Bottom Nepheloid layers (BNL) originating in the adjacent continental margin was also examined. Observations in other BNL have suggested that these may be regions of high DOC concentration, potentially contributing to DOC export from the shelves to the open ocean. However, DOC concentrations in the BNL of the Cariaco Basin were similar or lower than adjacent water column values, and CDOM concentrations were also low. EEMS revealed a high protein-like peak. These results imply that BNL in Cariaco are an area of high organic matter turnover.

T21. Biogeochemical, remote sensing, and modeling approaches to evaluating the sources and fluxes of dissolved organic matter and particles in the northeastern U.S. continental margin

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Our approach integrates biogeochemical measurements, optical properties, remote sensing, and a coupled physical-biogeochemical model to examine the sources and fluxes

of organic matter in the U.S. Middle Atlantic Bight (MAB) and Gulf of Maine (GoM). Algorithms developed to retrieve colored DOM (CDOM), Dissolved (DOC) and Particulate Organic Carbon (POC) from NASA's MODIS-Aqua and SeaWiFS satellite sensors are applied to study the processes that produce and remove organic matter in the coastal ocean. In order to develop empirical band-ratio algorithms for POC, CDOM and DOC, the CDOM absorption coefficient (a_{CDOM}) and POC were each correlated with *in situ* radiometry (remote sensing reflectance, Rrs, band ratios), and DOC was then derived from a_{CDOM} through the a_{CDOM} to DOC relationships (Mannino et al., 2008). Furthermore, we developed neural network-based (NN) algorithms from field measurements of a_{CDOM}, DOC, POC, chlorophyll-*a*, CDOM spectral slope (Sg) and in-water radiometry of all available visible SeaWiFS or MODIS bands. The relationships between DOC and CDOM vary seasonally and between regions requiring variable coefficients for the band-ratio algorithms for each region (southern MAB, Hudson plume and western Gulf of Maine). Satellite validation analysis demonstrates successful retrieval of POC, DOC and the CDOM absorption coefficient (a_{CDOM}) for the MAB and GoM. Our results show that CDOM is a major contributor to the bio-optical properties of the northeastern U.S. continental shelf, accounting for 35-70% of total light absorption at 443 nm, as compared to 30-45% for phytoplankton and 0-30% for non-pigmented particles (Pan et al., 2008). Remote sensing of CDOM is applied to track terrigenous DOM and quantify DOC within the coastal ocean. The neural network (NN) satellite algorithms demonstrate very good results and have the advantage of yielding a single NN algorithm per data product for all study regions and seasons. As our work progresses, we will apply SeaWiFS and MODIS data and U.S. ECoS model (Hofmann et al., 2008) results to quantify the inventories and fluxes of POC, DOC and a_{CDOM} which can be used to ascertain impacts of meteorological events and climate change on coastal marine ecosystems.

T22. Coastal carbon budgets in the Arctic Ocean and Bering Sea: Synthesis activities and data gaps

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The continental shelves of the Arctic Ocean and Bering Sea are dynamic areas where air-sea, land-ocean, and ocean-sediment interactions modify the carbon biogeochemistry of the water column as it makes its way from the North Pacific to the North Atlantic. The broad, shallow eastern Bering Sea shelf acts as a gateway into the Arctic, conditioning waters through cooling, freshwater inputs, primary production, and sea ice formation. Recent observations have shown that rates of net community production (NCP) are variable across the shelf, with the highest rates found in the area referred to as the "green zone" where a combination of high-nutrient, iron-limited Bering Sea water mixes with low-nutrient, iron-rich water from the inner shelf. This NCP, in conjunction with cooling decreases the pCO_2 of the surface waters providing a seasonal sink for atmospheric CO_2. The subsequent remineralization of the exported organic matter in the bottom waters enhances DIC concentrations, lowering the pH and suppressing the carbonate mineral saturation states (Ω).

Once through Bering Strait, the water is further conditioned over the Chukchi Shelf. During spring and summer, nutrient-rich waters fuel some of the highest rates of NCP found in the ocean. On the northeastern part of the shelf near Barrow Canyon, rates of NCP can reach 2,000 mg C m^{-2} d^{-1}. Approximately 10% of NCP is converted to DOC, 15% is converted to suspended POC, and the remaining 75% is exported from the mixed layer. The remineralization of this organic matter at depth again suppresses carbonate mineral saturation states, dropping $\Omega_{aragonite}$ to less than one. A portion of this water is carried offshore into the Canada Basin by eddies and filaments while the remainder flows eastward into the Beaufort Sea in a shelf-break current. Once in the Beaufort, the water is further modified by the influence of Mackenzie River discharge and brine formation during winter cooling and sea-ice production. Both the Chukchi and Beaufort Seas provide seasonal sinks for atmospheric CO_2 with the Chukchi likely taking up as much as 39 ± 7 Tg C yr^{-1}. Once the water leaves the Beaufort Sea, it flows through the Arctic Archipelago before being exported into the North Atlantic.

Overall, the continental shelves of the Arctic Ocean and the Bering Sea are strong seasonal sinks for atmospheric CO_2. Each shelf has its own unique characteristics, but they are all influenced by seasonally varying terrestrial inputs, sea-ice cover, and primary production. Given the difficult logistics of working in these regions, particularly when sea-ice is present there are still many areas where the paucity of data limits our understanding of the cycling and transformation of carbon that occurs over the shelves. Only through continued field observations, modeling efforts, and synthesis activities will we be able to fully understand the carbon budgets in the Arctic and sub-Arctic coastal oceans.

T23. Understanding the carbon budget of Lake Superior

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Lake Superior is the largest freshwater lake in the world and its carbon cycle is of particular interest because its fluxes can influence nearby observations of the terrestrial carbon cycle. The ongoing CyCLeS (Cycling of Carbon in Lake Superior) project is working to quantify carbon fluxes from the Lake and to place them in the context of regional carbon budgeting efforts by the North American Carbon Program (NACP).

We analyze direct pCO_2 observations and indirect estimates from the last decade with the goal of reconciling the independent observations and using them to understand temporal and spatial variability in lake carbon processes. Using direct *in situ* observations from 2001 and biannual EPA survey data from 1996-2006, we find that Lake Superior is, on

average, supersaturated (mean = 412.7 μatm) with respect to atmospheric pCO_2 (mean = 380.3 μatm) in April and approximately at equilibrium (mean = 364.8 μatm) with respect to atmospheric pCO_2 (mean = 359.3 μatm) in August. Temporal variability in surface lake pCO_2 is controlled by variations in dissolved inorganic carbon (DIC), as opposed to temperature. A well-mixed water column prevents large fluctuations in pCO_2 in spring, but through summer and early fall, short-term variability in pCO_2 (100-200 uatm) is large at the depth of the thermocline. Year to year changes in surface lake pCO_2 and temperature are of the same sign and approximate magnitude across the lake, consistent with its small size relative to the synoptic-scale meteorological systems that force it. We do not find evidence of direct forcing of the variability by the major modes of climate variability.

We have also configured a three-dimensional hydrodynamic model (MITgcm, Marshall et al., 1997) with an ecosystem-carbon module for the Lake. The model allows us to study the seasonal cycle of pCO_2 and the air-lake fluxes of CO_2 and to assess sensitivity to variable physical and biogeochemical forcings. We find that even without carbon or nutrient inputs from the land, the model is able to reproduce offshore measurements of pCO_2, net primary productivity (NPP), and other biogeochemical quantities. This suggests that the open waters of the Lake may not be respiring significant amounts of terrestrial carbon, in contrast to findings by previous authors for Lake Superior (Cole et al., 1994, Alin and Johnson, 2007). The nearshore zone, however, may be a region where substantial processing of terrestrial material is occurring, and part of our current work is to add these inputs to the model.

T24. Carbon dioxide partial pressure and air-sea CO_2 fluxes for Egyptian Mediterranean Coastal waters

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Carbon dioxide partial pressure (pCO_2) in seawater and corresponding air-sea fluxes were determined for Egyptian Mediterranean coastal waters. The coastal area was divided into 20 sectors between El-Salum to the west and El-Arish to the east. The pCO_2 distribution in the western coastal area ranged from 144.29 to 564.42 μatm, and the corresponding air-sea fluxes ranged from -7.52 to 5.64 mmol $m^{-2}day^{-1}$. The spatial average indicated that the western area is a sink for atmospheric CO_2 of -2.76 mmol $m^{-2}day^{-1}$. The pCO_2 distribution in the eastern coastal area varied from 149.5 to 1310.87 μatm, and the corresponding air-sea fluxes ranged from -7.4 to 29.11 mmol $m^{-2}day^{-1}$. The eastern area is considered to be a source of CO_2 to the atmosphere with an average daily flux of 5.3499 mmol $m^{-2}day^{-1}$, which is attributed to freshwater from Nile River discharge and other land-based sources. On average, the entire Egyptian Mediterranean coast represents a net CO_2 source of 2.58 mmol $m^{-2}day^{-1}$ to the atmosphere.

T25. The effect of river freshwater discharge on U.S. Eastern continental shelf carbon cycling (USECoS)

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Rivers on the continental shelf bring freshwater and nutrients to the ocean. Recent research shows that in the past half century, one-third of the world's largest rivers have undergone significant changes in river discharge. The flow of ~71% of rivers has decreased, perhaps due to global warming and increased evaporation, while the flow of the remaining rivers, mostly in polar regions, has increased due to rapid ice melting. River discharge affects ocean circulation by changing salinity and density of water masses. Also, changes in river flow will affect the biogeochemical and carbon cycling processes on the continental shelf, which could ultimately have feedbacks on global climate. In this study, we use a Northeast North American (NENA) biological model that is based on the Regional Ocean Modeling System (ROMS), and examine how changes in river discharge along the U.S. Eastern continental shelf may affect biogeochemical processes on annual time scales. Preliminary results show that changes in river discharge affect chemical properties in the mixed layer, primarily along the mid-Atlantic Bight shelf and southern Gulf of Maine. Varying the river discharge by 50-100% yields a 15-90% change in POC and a 25-200% change in chlorophyll in coastal shallow waters, but <5% changes in the outer-shelf and continental slope regions.

SESSION 5. THE FUTURE OF OCB RESEARCH IN THE SOUTHERN OCEAN

W1. Southern Ocean end-to-end food web model

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* Presenter

As part of the GLOBEC Pan-Regional Synthesis effort, food web models are being developed to address the overarching question of whether marine ecosystems that support large fisheries are controlled from the top down, the bottom up, or a combination of the two. To address this question we will: (1) compare end-to-end energy budgets of four U.S.-GLOBEC study regions in the context of top-down vs. bottom-up forcing, (2) assess the skills of the regional models in capturing basic material fluxes, (3) extract diagnostics from the regional models that will be used to evaluate the effects of climate change and

fishing pressure across GLOBEC regions, and (4) develop quantitative methods to compare the diagnostics. The regions include: the Antarctic Peninsula, Georges Bay, northern California Current System, and the coastal Gulf of Alaska. Our inability to conduct controlled experiments is a major impediment to the scientific study of open sea ecosystems. An alternative is to compare studies of different ecosystems as a proxy for manipulations of the same system, particularly when climatic change and over-fishing provide inadvertent perturbations at the bottom and top of trophic webs. This approach is especially appropriate for end-to-end analysis of marine trophic webs with their complicated structure and complex dynamics. Such analyses depend on the comparability of the available data and the compatibility of the analytical methods. Ideally, such comparisons are based on identical methods for data collection and analysis. The four U.S. GLOBEC programs provide one of the closest approximations to this ideal situation. All four systems have been subject to large amplitude trends or perturbations, from climatic changes in the Antarctic Peninsula to over-fishing on Georges Bank. Extensive data sets are available for each region, covering most trophic components from nutrient input to top predators. Here, we present an end-to-end food web model for the Southern Ocean, our approaches, and preliminary results.

W2. Analyzing the carbon cycle: A unifying theory of the soft-tissue and carbonate pumps, whole ocean alkalinity, gas-exchange limitation, and their impacts on atmospheric CO_2

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In geochemical ocean models the processes that control CO_2 may be parsed into the solubility pump, the soft-tissue pump, the carbonate pump, and the open system carbonate cycle. The soft-tissue component of the biological pump has previously been related to the ocean average concentration of regenerated nutrients (Ito and Follows, 2005; Marinov et al., 2008). An analysis of an ocean box model reveals that the carbonate cycle may be diagnosed similarly: the strength of the carbonate pump is tied to the regenerated alkalinity from carbonate dissolution at depth (closed system dynamic), while the CO_2 effect of the open system carbonate cycle is moderated by the ocean's average concentration of alkalinity. Using these three prognostic parameters and appropriate stoichiometry, it is possible to quantitatively parse the modeled CO_2 change into its geochemical components. Not being linearly independent, the interactions of the components give rise to synergetic CO_2 effects, which can be quantified as well. Furthermore, building on this geochemical theory, kinetic (air-sea gas exchange limitation) and thermodynamic (temperature distribution and thus the solubility pump) boundary conditions that modulate ocean carbon sequestration may also be assessed. The methods developed to diagnose the carbon cycle in a box model may also be implemented into GCMs. One interesting dynamic we observe is the tendency of the abyssal ocean to sequester the regenerated alkalinity from carbonate dissolution, which weakens the capacity of the abyssal C storage to lower atmospheric CO_2 during ice ages. Furthermore, the rate at which these abyssal waters are being ventilated in the Southern

Ocean – transforming regenerated into preformed alkalinity – is of singular importance in setting the strength of the global carbonate pump.

W3. Model circulation and Fe transport in the Antarctic Peninsula and southern Scotia Sea

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Recent observations have identified a natural iron fertilization area over the shelf of Elephant Island, Antarctica, where the southern Antarctic Circumpolar Current impinges upon the shelf and interacts with the shelf current, leading to strong off-shelf transport of Fe-rich shelf waters. Satellite and *in situ* measurements suggest that this iron input sets the stage for a massive bloom downstream in the southern Scotia Sea, one of the most productive regions in the Southern Ocean. We have developed a high-resolution (~2-km) regional model based on the Regional Ocean Modeling System (ROMS) for this area and coupled it with a simple NPZD-Fe-Radium model to simulate the circulation, mixing, and Fe transport. The goals are (1) to understand the sources of shelf Fe in the Antarctic Peninsula and to quantify the off-shelf Fe flux, and (2) to understand the impacts of the off-shelf Fe transport on the primary productivity and carbon cycle in the southern Scotia Sea. In this presentation, we will report preliminary results from a climatological simulation including the seasonal circulation pattern, mixing, and transport. The implications for Fe sources and transport over the Antarctic Peninsula will be discussed as well.

W4. Incorporating *Phaeocystis* into a Southern Ocean ecosystem simulation

Shanlin Wang and Keith Moore

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Phaeocystis antarctica is an important phytoplankton species in the Southern Ocean, often observed to bloom in coastal waters. We are incorporating *Phaeocystis* into the Biogeochemical Elemental Cycling (BEC) model as a phytoplankton functional group to study the ecosystem dynamics and biogeochemistry of the Southern Ocean. We are seeking the optimum values of ecological parameters for *Phaeocystis* through synthesizing laboratory and field observations, and evaluating the model output with observed chlorophyll, biomass, and nutrient distributions. Several factors have been proposed to control the ecosystem structure and the competition between diatoms and *Phaeocystis*. Those factors include variations in light adaptation parameters, iron requirements and uptake capability, grazing and loss processes (Schoemann et al., 2005). We are adjusting model parameters and testing different grazing mechanisms in the BEC model to investigate the relative roles of these different factors. We also propose to evaluate the impacts of *Phaeocystis* on biogeochemical cycles and primary production in

the Southern Ocean, which may allow us to better simulate carbon cycle dynamics under different climate scenarios.

SESSION 6. IMPLEMENTING RESEARCH AT THE INTERSECTION OF OCEAN CHEMISTRY AND BIOLOGY

W5. Seasonal distribution of dissolved inorganic carbon and net community production on the Bering Sea shelf

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The extensive Eastern Bering Sea Shelf is one of the most productive marine ecosystems in the world, supporting millions of migratory birds, large populations of marine mammals, and a valuable commercial fishery. While the region remains productive today, the character of ecosystem production has undergone dramatic changes in the past decade, marked by increasing dominance of temperate organisms rather than more traditional arctic species. Measuring the seasonal consumption of dissolved inorganic carbon (DIC) and subsequent production of organic matter, or Net Community Production (NCP), is one way to evaluate the ecosystem. Here, we examine the 2008 NCP and spring and summer concentrations of DIC across the inner (high iron, low nutrient) middle, and outer (low iron, high nutrient) parts of the shelf. The inner shelf, characterized by rapid nutrient depletion between spring and summer, had the lowest NCP (231.8 to 270.3 mmol C m^{-2} d^{-1}). The middle shelf, where stratification is strongest, had the highest NCP in the region (448.75 mmol C m^{-2} d^{-1}), while the NCP on the outer shelf was 409.75 mmol C m^{-2} d^{-1}. These findings are consistent with previous studies that showed the highest productivity in the "Green Belt" of the Bering Sea, which lies between the middle and outer parts of the shelf. The high rates of NCP observed are likely due to the mixing of iron-rich waters from the inner shelf, and high nutrient waters from the deep Bering Sea.

W6. Nutrients, phytoplankton, and climate change

Stephanie Dutkiewicz, Mick Follows and Jeff Scott

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We examine the interplay between ecology and biogeochemical cycles in the context of a global change simulation. We utilize a three-dimensional ocean model in which self-assembling phytoplankton communities emerge from a wide set of potentially viable cell types. In a climate change scenario, driven by predicted emissions of greenhouse gases (with no policy) through 2100, the simulated earth reaches a mean surface air temperature 5°C warmer than the present. The marine biogeochemical response includes a reduction

in surface macronutrient concentrations and biomass over most of the ocean. We use resource competition theory to interpret mechanisms underlying the coupled ecosystem and nutrient response in the tropical and subtropical oceans, revealing a subtle and complex relationship: Reduced biomass can be explained by reduced supply of limiting nutrients. However, reduced nutrient concentrations are explained not as a direct result of the reduced supply, but are due to changing phytoplankton community structure and growth rates.

W7. Observations of air-sea fluxes of ozone

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Over the past 3 years, researchers from the University of Colorado (Institute for Alpine and Arctic Research; INSTAAR and the Cooperative Institute for Research in Environmental Sciences; CIRES) and the NOAA Earth Sciences Research Laboratory (ESRL) developed a ship-based system for measurement of the turbulent flux of ozone from the lower atmosphere to the ocean surface. A key component of this package is a fast-response chemiluminescence instrument (FRCI) that measures the small-scale perturbations of ozone at unprecedented sensitivity. In addition, a series of corrective steps are required to compensate for platform motion, pressure broadening, humidity quenching, and sampling tube design.

Near-surface ozone is being recognized for its role as a climate-relevant compound but also for its role in marine atmospheric chemistry. The reactions of ozone with halogen compounds at the surface also play a role in air-sea biogeochemical cycling. The poster will provide some context as to the role of ozone in air-sea biogeochemical exchange and will also present some of the ozone flux results from the ship-based work of 2006-2008 (including the Southern Ocean GasEx deployment).

W8. Developing physical models of gas exchange using observations of DMS flux

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Since air-sea gas exchange (ASE) is one of the principal budget terms for many gases, realistic algorithms for these gas fluxes are critical components of oceanic and atmospheric chemistry models. Empirical power-of-wind-speed models have been widely used for at least two decades, in part because techniques for measuring fluxes on the same ~hourly time scales as changes in flux-controlling factors have been lacking. The recently demonstrated APIMS eddy covariance (EC) technique for measuring hourly

fluxes of dimethyl sulfide (DMS) has removed that restriction, enabling us to test physics-based models of gas exchange in the open ocean.

Physical models commonly divide gas fluxes into a component due to momentum-driven renewal of water at the surface and a component due to bubbles. We have shown that the CO_2 exchange velocity (k_{CO2}, flux per interfacial concentration difference) exceeds k_{DMS} when whitecaps and breaking waves are present. Due to its relatively low solubility compared to DMS, CO_2 exchange is enhanced more by bubbles.

The surface-renewal term should be similar for both gases. According to Soloviev and Schlüssel, this term changes as the physics change. At low wind speeds (< ~4 m/s) buoyancy-driven surface renewal causes gas exchange, even at zero wind speed. In the intermediate range (~4 to ~12 m/s) ASE is dominated by wind-driven momentum transport. Here the surface-renewal term should be proportional to friction velocity, u*. When white-capping begins, both surface renewal and bubble-mediated ASE are important. Physics in the highest-wind range involves long-wave breaking and very different relationships between momentum transport and surface renewal: As wind pushes on waves and flow separates from the lee of waves, less stress-driven surface renewal takes place.

We have confirmed with open-ocean flux measurements that exchange velocities in the intermediate range are indeed proportional to u*, and thus dominated by momentum transport. This was facilitated by the insensitivity of DMS fluxes to bubbles, which enabled us to focus on the surface-renewal term. Interestingly, k_{DMS} is also nearly proportional to wind speed, U.

Thus we do not argue that modelers should change from U to u* parameterizations. The significance of our work is rather that we have begun to validate a physical model of gas exchange. Once we have validated the functional forms of the bubble, low-wind, and high-wind terms, the resulting physics-based model can be used for generating algorithms for use in ASE models under a wide variety of conditions.

Gathering flux observations in high winds remains one of our greatest challenges. The flux-measuring systems are capable, but high-wind flux cruises are hard to come by.

W9. Transcriptional and proteomic analyses of multiple environmental stressors in marine diatoms

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Diatoms represent an abundant and widespread group of phytoplankton, responsible for significant amounts of primary production in the ocean. As such, they exert a profound influence on the global cycling of carbon. It is widely accepted that nutrient availability controls diatom production in many marine ocean systems. Although nutrient acquisition by diatoms has been investigated on the physiological level, our understanding of these pathways on the cellular and molecular levels are not well understood. Here, we present transcriptional and proteomic profiling approaches to examine how marine diatoms respond to environmental stress due to nutrient limitation. Initial experiments have focused on phosphorous limitation using the model diatom *Thalassiosira pseudonana*, for which a complete genome sequence is available. Global proteomic analysis was performed using reverse phase liquid chromatography mass spectrometry with electrospray ionization source. Protein identification was performed by SEQUEST algorithm, and relative protein abundance analysis utilized spectral counting techniques. Technical triplicates were run for each treatment and showed highly consistent results. The results to date are striking, with a number of phosphorus-related protein targets up-regulated in the phosphorus limited sample, including alkaline phosphatases and phosphate transporters. Forthcoming transcriptome data will provide us with a first glimpse of the connection between transcript regulation and protein abundance. Experiments are currently underway to examine *Thalassiosira rotula*, a species that is more naturally abundant but has not been sequenced. Evaluation of *T. rotula* allows us to develop methodologies for working with non-model organisms. The data from two species and multiple environmental conditions will allow us to examine nutrient acquisition strategies, how these strategies are regulated, how different species respond to stress, and how they respond to multiple stressors (*e.g.,* co-limitation).

W10. Response of ocean ecology to climate change over the 21st century

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Here we analyze the impact of climate change on ocean plankton ecology and the carbon cycle over the 21st century using a multi-decadal (1880-2100) experiment conducted with the latest version of the Community Climate System Model (CCSM-3.1) coupled ocean-atmosphere-land-ice model.

The oceanic ecosystem model component includes three classes of phytoplankton (diatoms, pico/nano-plankton, diazotrophs) and one class of zooplankton that grazes differentially on the phytoplankton groups. The competition between phytoplankton groups is altered by climate-induced changes in nutrients, light and zooplankton. Here we connect climate-induced changes in ecosystem structure to changes in ocean physics.

Increasing stratification in the northern hemisphere oceans decreases the nutrient supply to the ocean surface and decreases the relative and absolute diatom abundance. The northern hemisphere shift from diatoms to small phytoplankton results in decreases in total primary production, export production and export ratio, and a shift to a more efficiently recycled, lower biomass euphotic layer.

By contrast, an increase in Southern Ocean westerlies acts against increasing temperature and freshwater flux to destratify the water-column. Additionally, the wind-driven poleward shift in the Southern Ocean subpolar-subtropical front results in a southward shift and increase in the largest oceanic diatom bloom. In the Southern Ocean diatoms are favored over small phytoplankton on average, acting to increase total chlorophyll, primary production, and export production.

The impact of these ecological shifts on the global oceanic carbon sink is complex, with northern and southern hemisphere effects partially compensating each other. In the net, total chlorophyll, primary production, and export production decrease, but less than previous modeling studies have suggested, indicating a small positive feedback on atmospheric pCO_2.

W11. Carbon cycling in the North Atlantic from regional to basin scales: Eddy-driven changes in phytoplankton species composition

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Recent field observations in the Sargasso Sea have shown relationships between different phytoplankton communities and different types of eddies, namely enhanced diatom biomass in mode-water eddies (McGillicuddy et al., 2007, *Science* 361:1021) and enhanced nitrogen-fixing *Trichodesmium* spp. in anticyclones (Davis and McGillicuddy, 2006, *Science* 312:1517). Field data indicated that the high abundance of diatoms in mode-water eddy A4 was the result of upwelling caused by eddy-wind interactions (Ledwell et al., 2008, *Deep-Sea Res. II* 55:1139). Regarding the correlation between *Trichodesmium* and anticyclones, at least three mechanisms may be responsible: 1. Covariance could reflect eddy-driven transport of populations from source regions or across large-scale gradients; 2. there could be a physically driven aggregative mechanism at work, or nutrient; or 3. light field perturbations may enhance *in situ* growth. We are currently using an eddy-resolving physical simulation of the North Atlantic coupled with a 24-box biological model that includes 3 phytoplankton groups to shed light on these eddy-driven changes in phytoplankton community structure, the mechanisms behind them, and their impact on carbon export to the deep ocean. Our initial results are consistent with the observed enhanced abundance of diazotrophs in anticyclones, small phytoplankton in cyclones, and diatoms in mode-water eddies. However, in contrast with the observations, the simulation also suggests enhanced diatoms in cyclones and

diazotrophs in mode-water eddies. We are currently investigating the reason for these discrepancies.

W12. The descent of diatoms: Resting cysts and ephemeral carbon flux during the North Atlantic Bloom Experiment, 2008

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Mass sinking of cells following diatom spring blooms is known to be a major source of carbon flux to the ocean's interior. The timing of flux events is thought to correlate with nutrient depletion of surface waters, inducing physiological stress and robbing silicified diatoms of their ability to maintain buoyancy. Here, we examined sediment trap material collected during the 2008 North Atlantic Bloom Experiment to determine the physiological status of a sinking spring diatom bloom and evaluate its potential to "seed" future blooms. Sediment trap material was collected from 24-hr deployments of floating sediment traps set at 300, 600 and 750 m. Diatom cells were examined immediately after trap recovery and the assemblage was dominated by resting cysts of the diatom genus *Chaetoceros*. Resting cysts were strongly fluorescent under excitation at 470-490 nm, indicating that accessory pigments were intact and that cells were photosynthetically competent. Variable fluorescence measurements of bulk sediment trap material were high, indicating the presence of live and potentially active cells. To test the hypothesis that cysts were viable and could re-seed a future bloom, sediment trap material from each depth was inoculated into nutrient-amended seawater and incubated at 9°C and 50 µmol photons m^{-2} s^{-1} on a 12:12 light:dark cycle. Within 38 hrs, the heavily silicified valves of *Chaetoceros sp.* cysts were cast off and replaced by vegetative valves, indicating that excystment had occurred. Initial excystment was followed by rapid cell division, with growth rates of *Chaetoceros sp*. reaching 1 doubling day^{-1}. This phenomenon was observed in samples collected May 15. Sediment trap materials collected from deployments on May 11 and 19 were not dominated by resting cysts. Diatom resting stages, such as cysts, are known to form within 6 hrs and can sink up to 35 times faster than vegetative cells, potentially explaining the brief pulse of cysts we observed and highlighting the ephemeral nature of important C flux events in the open ocean.

W13. Gross primary production and net community production in the equatorial Pacific

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The triple isotopic signature of oxygen is a tracer used to investigate gross production in the world's oceans. Mass independent fractionation in the stratosphere results in dissolved oxygen in seawater stemming from atmospheric oxygen having a different triple oxygen isotopic signature than dissolved oxygen resulting from photosynthesis. This signature is quantified through $^{17}\Delta$ where $^{17}\Delta = [\ln(\delta^{17}O/1000 + 1) - 0.516 \cdot \ln(\delta^{18}O/1000 + 1)] \times 10^6$. In the mixed layer, $^{17}\Delta$ is a tracer of gross production. Below the mixed layer, $^{17}\Delta$ is reflective of the interplay of various processes, including local biological production, vertical mixing, and lateral transport.

We have measured $^{17}\Delta$ in profiles in the upper 200 m of the water column at eight stations in the equatorial Pacific along 125ºW and at two stations along 140ºW. In these profiles, we find intriguing maxima of $^{17}\Delta$ below the euphotic zone. The $^{17}\Delta$ of surface waters ranges from ~45 to 75 per meg at the various stations, whereas the $^{17}\Delta$ of the deep maxima range from 105 to 125 per meg and typically occur at 100 to 140 m depth. Interestingly, on the equator at 125ºW there is no maximum in $^{17}\Delta$ below the euphotic zone. We explore possible mechanisms for creating these maxima, including the possibility of local production below the 1% light level.

Additionally, surface measurements of $^{17}\Delta$ and of another gas tracer, O_2/Ar, measured along 125ºW and 140ºW in the Equatorial Pacific in September and October 2007 are used to constrain gross production and net community production in this climatically important area. In particular, an underway mass spectrometer was used to measure O_2/Ar, providing a dataset of continuous measurements of net community production along these two longitudes. An overview of gross production rates measured throughout the equatorial Pacific on this cruise and another cruise identify about a factor of two variation in GPP throughout the region, with the highest levels in the upwelling region and the lowest values in the oligotrophic waters to the north and south of the central Pacific and in the western warm pool.

W14. Basinwide modification of dynamical and biogeochemical processes by the positive phase of the Indian Ocean Dipole during the SeaWiFS era

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Characterizing how the Indian Ocean Dipole (IOD) modifies typical basinwide dynamical variability has been vigorously pursued over the past decade. Along with this dynamic response, a clear biological impact has been revealed in the ocean color data acquired by remote sensing platforms such as SeaWiFS. The signature feature illustrating IOD alteration of typical spatio-temporal chlorophyll variability is the phytoplankton bloom that first appears in September along the eastern boundary of the Indian Ocean in tropical waters that are normally highly oligotrophic. Positive chlorophyll anomalies are also apparent in the southeastern Bay of Bengal, while negative anomalies are observed

over much of the Arabian Sea. Moreover, *in situ* measurements obtained by the *R/V Suroit* as part of the Cirene cruise during the 2006/2007 IOD reveal anomalous subsurface biochemical distributions in the southern tropical Indian Ocean that are not reflected in SeaWiFS data. Despite the clear basinwide influence of IOD events on biological variability, the accompanying influence on biogeochemical cycling that must occur has received little attention. Here, the dynamical signatures apparent in remote sensing fields for the two positive-phase IODs of the SeaWiFS-era are used to illuminate how these events are similar or distinct. A corresponding comparison of IOD-engendered surface chlorophyll anomalies is performed, with the dynamical fields providing the framework for interpreting the mechanisms underlying the biological response. Then results from a newly developed net primary production algorithm are presented that provide the first characterization of how biogeochemical fluxes throughout the Indian Ocean are altered by IOD occurrence.

W15. SIBER: Sustained Indian Ocean Biogeochemical and Ecological Research

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There are many outstanding research questions in the Indian Ocean because it is a dynamically complex and highly variable system, yet it is substantially under-sampled compared to the Atlantic and Pacific. The unique physical dynamics of the Indian Ocean arise largely as a result of the Eurasian land boundary to the north, which, among other things, gives rise to the strong seasonally reversing monsoon winds. These winds drive intense upwelling and downwelling circulations and seasonally reversing surface current patterns. These, in turn, give rise to substantial variations in marine biogeochemical and ecosystem response.

Due to this complexity we still do not have a complete characterization and understanding of the primary production variability and dynamics in the Indian Ocean. Nor have the impacts of major physical perturbations associated with phenomena like the Madden-Julian Oscillation and the Indian Ocean Dipole been characterized. This is in marked contrast to the Atlantic and Pacific, where the seasonal blooms dynamics are relatively well described and understood, and also the impacts of interannual influences such as NAO and ENSO. Questions also persist about the role of the Indian Ocean in the global carbon and nitrogen cycles, and about the role of grazing versus nutrient limitation in mediating primary production and bloom dynamics in the Arabian Sea. Furthermore, there is exciting emerging evidence suggesting that Fe limitation may be important in the Indian Ocean and even in the Arabian Sea during the southwest monsoon. However, direct measurements and experiments are limited. Global warming impacts are also becoming apparent in the Indian Ocean, such as the emerging evidence that climate change is influencing the strength of the monsoon winds, and also the rapid warming of

the Indian Ocean surface waters, both of which could have profound impacts on biogeochemical and ecosystem dynamics.

The goal of this poster presentation is to raise awareness of the pressing research questions that still need to be addressed in the Indian Ocean and promote research there in general.