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Preliminary Carbon Budgets for the Laurentian Great Lakes

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Summary:

We offer three approaches to estimating carbon budgets and lake-air CO_2 fluxes for each of the five Great Lakes, two based on literature review and one based on simple models for each lake. Results for the net lake-to-air CO_2 flux range over two orders of magnitude from one-tenth to several 10s of Tg C yr^{-1}. To improve these predictions, whole-lake biogeochemistry and its spatio-temporal variability require substantial additional research, with particular focus needed on net primary productivity (NPP), respiration, and surface-lake pCO_2.

1. Introduction and Background

There is a growing awareness that lakes are hotspots for carbon cycling in the landscape (e.g., Buffam et al. 2011; e.g., Christensen et al. 2007; Karlsson et al. 2010), and that, worldwide, they may represent both sites of significant CO_2 release to the atmosphere as well as carbon sequestration in sediments (Cole et al. 2007; Tranvik et al. 2009). Compared to the IPCC's estimate of annual carbon storage on the continents (2.2 Pg C yr^{-1}) (IPCC 2007), the burial of organic carbon in lake sediments (0.6 Pg C yr^{-1}) (Tranvik et al. 2009) and the emission of CO_2 from world lakes and rivers (1.2 Pg C yr^{-1}) (Battin et al. 2009; Tranvik et al. 2009) are of comparable magnitude. Clearly, there is a need to understand the magnitude and controls on fluxes of carbon in lakes on a global basis.

The Laurentian Great Lakes, an enormous freshwater resource, are a major component of the U.S. coastline and have some similarities with the coastal oceans. The Great Lakes contain nearly 20% of the surface fresh water of the earth. The length of the U.S. coastline on the Great Lakes is equal to 49% of the total ocean coastline of the lower 48 states. One major distinction between the Great Lakes and the global oceans is the circulation regime. The oceans have a large reservoir of deep water that is isolated from the atmosphere and that only slowly mixes with the oceanic surface water. The timescale for mixing of surface and deep ocean waters is about 1000 years. It is this deep reservoir that provides the ongoing capacity of the oceans to sequester anthropogenic CO_2 emissions. In contrast, each of the Great Lakes mixes top to bottom at least once each year. Hence, the entire volume of the lakes equilibrates annually with atmospheric CO_2. Seasonal storage of CO_2 in the bottom waters of each lake occurs (Atilla et al. 2011), and the timing of seasonal mixing shows interannual variability as well as long-term trends (e.g., Austin and Colman 2007; Trumpickas et al. 2009). Future warming of the lakes will reduce the solubility of CO_2 in the lakes and drive a degassing tendency that will oppose the tendency for increased CO_2 uptake driven by increasing atmospheric pCO_2.

There are differences among the Great Lakes that are likely to affect

Table 1. Summary of Great Lake characteristics. Relative magnitude with respect to Lake Erie in parentheses.

Lake	Surface Area (m^2)	Hydrologic Residence Time (yr)	Mean depth (m)	Max. depth (m)
Superior	8.21×10^{10} (3.2)	174 (67)	150 (7.7)	406 (6.3)
Michigan	5.78×10^{10} (2.2)	104 (40)	85 (4.5)	282 (4.4)
Huron	5.96×10^{10} (2.3)	21 (8.2)	59 (3.1)	229 (3.6)
Erie	2.57×10^{10} (1.0)	26 (1.0)	19 (1.0)	64 (1.0)
Ontario	1.90×10^{10} (0.7)	7.3 (2.8)	86 (4.5)	244 (3.8)

carbon cycling. These differences include size, location within the chain of lakes, trophic state, and geologic and geographic setting. Depending on the dimension being considered, the lakes differ among themselves only by factors of 3 to 8 (Table 1). Lake Superior, the largest, has 3.2 times the surface area of Lake Erie, the smallest, and Lake Superior is also nearly 8 times deeper on average. The large size of Lake Superior means that even small process rates (expressed per unit area) can represent large carbon fluxes (Tg C yr^{-1}). The much shallower depth of Lake Erie implies that the average summer temperature will be much higher, that a larger fraction of primary production will be buried in the sediments, and that primary production will occur over a larger fraction of the water column; all of these factors will favour the production, and potentially also the burial, of autochthonous organic carbon. This may make the lake more likely to be a net sink for atmospheric CO_2. The small size of Lake Erie also allows the lake to cool sufficiently such that complete ice coverage occurs in most years; ice cover blocks the release of CO_2 throughout winter. The lakes lower in the chain have a much larger flow of water and carbon through them than do the upper lakes. Consequently, the lower lakes will have lower water retention times, and less time for respiration of allochthonous DOC. Small errors in the estimation of carbon concentrations in the inflows from upstream lakes as well as in the lake outflows can have major impacts on the carbon budgets; in other words, the carbon budgets are more sensitive to the accuracy of carbon concentration measurements. Historically, the Great Lakes have shown a wide range of trophic state, with variability across the lakes and through time. In general, lakes with higher algal productivity (net primary production or NPP) are more likely to be net sinks for atmospheric CO_2 than lakes with low NPP (Del Giorgio et al. 1997). Recent measurements confirm that the greater algal abundance in the lower lakes in summer is associated with lower pCO_2 in surface waters (Karim et al. 2011).

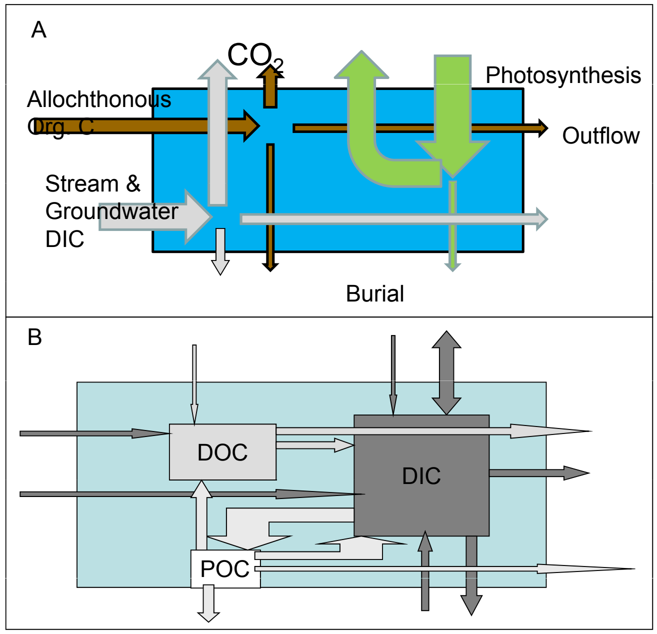

Figure 1. Alternative depictions of carbon cycling and the carbon mass balance. (a) This framework categorizes carbon according to its source and depicts the pathways taken by each category. (b) This framework categorizes carbon according to easily measurable classes, and depicts transformations among those pathways.

There are a host of other features of the geographic and geologic setting of the individual lakes that impact carbon cycling. Much of the Lake Superior basin lies in the Canadian Shield; the slow weathering of the volcanic rocks and shallow overlying soils result in low carbonate and phosphorus inputs into this lake relative to the other Great Lakes that in turn contribute to low NPP and no annual calcite precipitation (whiting events) in Lake Superior. Over the past 20 years, the intensity of whiting events has declined due to the removal of calcium and carbonate from the water by invasive *Dreissenid* mussels (Barbiero et al. 2006). Geologic and climatic setting also impact the loadings of allochthonous DOC to the lakes; loadings are higher to Lakes Superior and Huron than to the other lakes (Shih et al. 2010). The climate and geologic setting influenced the development of agriculture, now the dominant control on anthropogenic inputs of phosphorus (Dolan and McGunagle 2005) and hence on lake NPP.

2. Literature Review: Carbon budgets for each of the Great Lakes

The carbon budget for a lake or coastal ocean may be depicted in several ways. One approach is to focus on processes, and to separate allochthonous and autochthonous organic carbon in the lake (Figure 1a). The cycle of autochthonous carbon consists of only three processes that must be balanced: photosynthesis, respiration, and burial (outflow may be important in the lower lakes). Similarly, allochthonous organic carbon inputs are respired within the lake, passed through the lake to the outflow, or converted to particulate matter and buried. A lake will have a net efflux of CO_2 only if respiration of allochthonous organic carbon plus degassing of inorganic carbon inputs is greater than the burial of autochthonous organic carbon. Lakes such as Superior with large inputs of allochthonous DOC, long residence times that allow for complete respiration of that DOC, low NPP and low burial rates of organic matter are likely to be net sources of CO_2 to

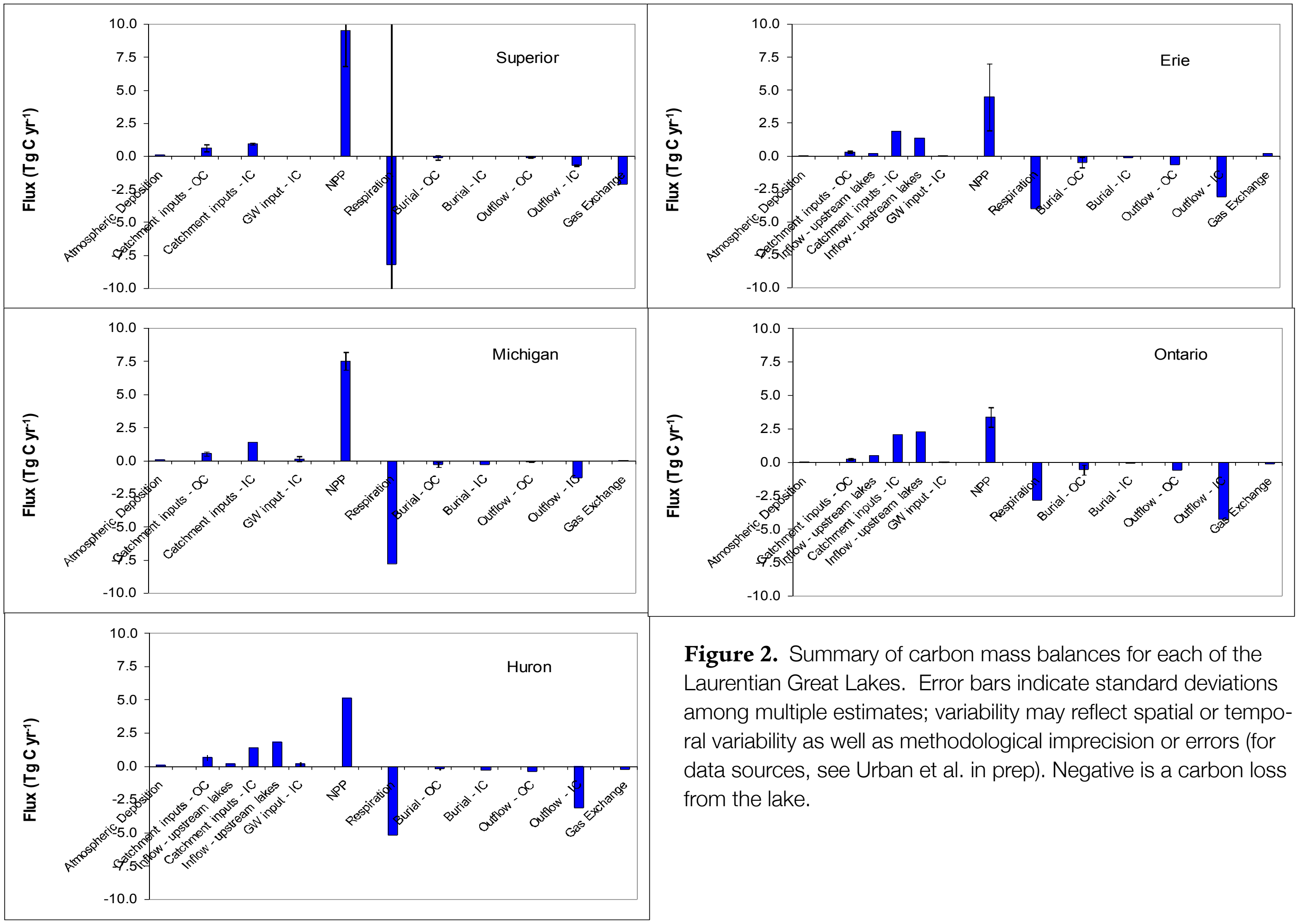

Figure 2. Summary of carbon mass balances for each of the Laurentian Great Lakes. Error bars indicate standard deviations among multiple estimates; variability may reflect spatial or temporal variability as well as methodological imprecision or errors (for data sources, see Urban et al. in prep). Negative is a carbon loss from the lake.

the atmosphere. Lakes such as Erie that have higher NPP, higher burial efficiencies on account of shallower water depths, and short water residence times (hence low efficiencies for oxidation of allochthonous organic carbon) are more likely to be net sinks for atmospheric CO_2.

Although this approach gives crude estimates at best of the magnitude of fluxes, it does suggest that lakes Superior, Michigan and Huron are sources for atmospheric CO_2, and that lakes Erie and Ontario are sinks (Table 2). The estimate of respiration of allochthonous organic carbon could be improved by accounting for seasonal temperature effects on respiration. The values in Table 2 assume that all organic carbon in the sediments is autochthonous (cf. Meyers and Ishiwatari 1993). Budgets for inorganic carbon have not been compiled for any of the lakes except Superior and Ontario. While these caveats suggest that the uncertainty about the magnitude of the net CO_2 flux is large, they reinforce the conclusion that lakes Superior, Michigan and Huron are likely sources of CO_2 to the atmosphere. Correction for the errors mentioned above would likely reduce the magnitude of the CO_2 sink estimated for lakes Erie and Ontario.

An alternative framework for the carbon budget is shown in Figure 1b. This framework separates the measurable pools of carbon and considers the transformations among these pools. In this framework, photosynthesis and respiration appear as internal processes rather than as inputs and outputs to the lake. The air-lake flux of CO_2 is dependent on the changes in magnitude of dissolved CO_2 relative to atmospheric CO_2. While the pools of carbon depicted in this framework are measurable, some individual fluxes are not. Because very few measurements of gas exchange or of dissolved pCO_2 have been reported for the Great Lakes, the tabulation of the mass balance (Figure 2) is a hybrid of the frameworks shown in Figure 1 and retains terms for photosynthesis and respiration.

While we emphasize the preliminary nature of the carbon budgets tabulated from the literature (Urban et al., in prep) in Figure 2, several important features of the carbon balance for the Great Lakes are revealed. First, the magnitudes of the fluxes

Table 2. Estimate of net CO_2 fluxes (positive for out of lake) for each lake based on three component process rates (Tg C yr^{-1}).[a]

Lake	Respiration of Alloch. OC	Degassing of DIC inputs	Burial of Autoch. OC	Net CO2 flux
Superior	0.63	0.25	0.08 ± 0.17	+0.80
Michigan	0.53	?	0.28 ± 0.18	> +0.25
Huron	0.27	?	0.20 ± 0.09	> +0.07
Erie	0.02	?	0.49 ± 0.40	> -0.47
Ontario	0.04	?	0.57 ± 0.36	> -0.53

a. Data sources summarized in Urban et al. (in prep.).

(Tg C yr^{-1}) generally decrease from Superior to Michigan to Huron to Erie and Ontario simply as a result of the lake sizes. Second, the inflows from upstream lakes constitute major components of the carbon budgets for lakes Huron, Erie and Ontario; small errors in estimation of DIC concentrations (e.g., lack of winter samples) could lead to significant errors in carbon budgets for these lakes. For each of the lakes except Ontario, photosynthesis and respiration are the largest carbon cycling processes; these two processes are poorly characterized on a whole-lake basis. Again, these processes are included in the mass balance only because of a lack of adequate measurements of pCO_2 (or direct flux measurements of CO_2) to enable estimation of lake-wide gas exchange. Finally, inputs of DIC from the catchments of all of the lakes except Superior and Ontario are poorly constrained. Here, these inputs have been estimated by balancing the inorganic carbon budget under the assumption of no degassing of DIC inflows; that assumption is almost certainly incorrect. Because of this assumption, estimates of net gas exchange (calculated by difference from all of the fluxes) are underestimated (i.e. in Figure 2 these fluxes should be more negative, indicating a smaller efflux) for all lakes except Superior.

The sum of the gas exchange estimates shown in Figure 2 for the 5 Great Lakes results in a flux to the atmosphere of 2.3 Tg C yr^{-1}. However, until watershed inputs of DIC are better constrained, the net gas fluxes calculated from these mass balances should not be viewed as realistic. The value of Figure 2 is in illustrating the relative magnitudes of fluxes for each lake individually as well as among the different lakes. Our analysis suggests that catchment inputs, photosynthesis, and respiration would be the areas most in need of improvement, both in terms of additional measurements and further compilation of existing data.

3. Mechanistic Models

Lake Superior has the best-known lake-wide carbon budget due to several recent projects using data and models in an attempt to balance the budget. Consistent with Figure 2, whole-lake budgeting efforts (Urban et al. 2005, Cotner et al. 2004, Urban et al. in prep) indicate that the dominant terms in the annual budget are NPP and respiration, with other terms being small. The U.S. EPA makes twice-annual surveys of the open lake (Figure 3), collecting pH and alkalinity data from which pCO_2 can be estimated, albeit with significant uncertainty in a freshwater system. These data indicate that Lake Superior tends to be slightly supersaturated with carbon dioxide during the spring and near equilibrium during the summer (Atilla et al., 2011), which is consistent with limited influence from the watershed. Furthermore, analysis of an eddy-resolving, coupled physical-biogeochemical-carbon model of Lake Superior (MITgcm.Superior, Figure 3, Bennington 2010, McDonald et al. 2011, Bennington et al. in prep) indicates that the annual cycles of NPP and vertical mixing are the fundamental controls on the seasonal cycle of surface lake pCO_2, and thus of the seasonal cycle of air-lake CO_2 flux.

Since we do not have spatially explicit coupled physical-biogeochemical-carbon models for the lower

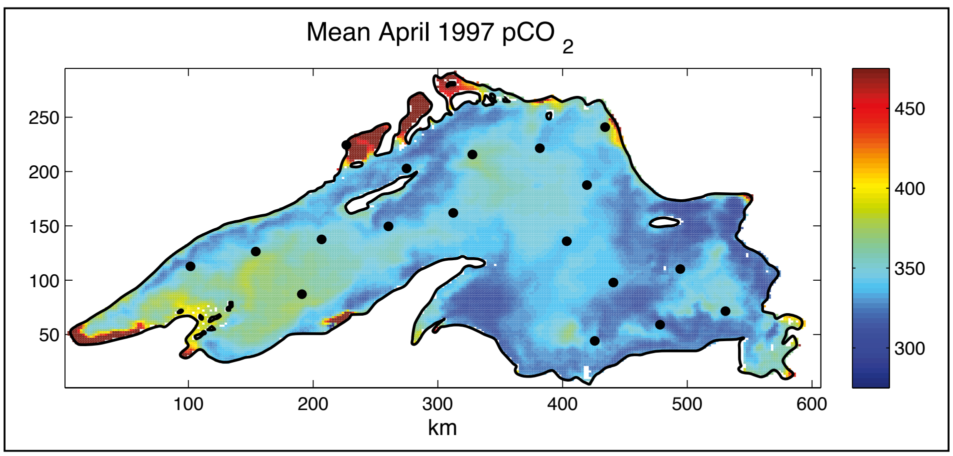

Figure 3: April 1997 pCO_2 (matm) from MITgcm.Superior. DOC, DIC and ALK inputs from nine major rivers are represented (Bennington 2010). Dots are EPA bi-annual sampling locations.

Great Lakes (Michigan, Huron, Erie, Ontario) available to us, we proceed to develop simple 2-box models that focus on the impacts of NPP, mixing

Table 3: Lake properties input to box models.

Lake Property	Superior	Michigan	Huron	Erie	Ontario
Mean depth (m)	149	85	59	19	86
Thermocline (m)	20	20	20	15	20
DIC (mmol m^{-3})	860	2165	1569	1782	1817
Alkalinity (meq m^{-3})	838	2181	1561	1817	1836
Annual NPP (gC m^{-2} yr^{-1})	116	130.5	86	174	178
Surface Area (km^2)	82,000	57,800	59,600	25,700	18,960
Net Input (Tg C yr-1)	0.8	20	10	0.7	5
Lake-air CO_2 flux (Tg C yr^{-1})	0.8	20	10	0.7	5

of the water column, and net inputs from the watershed on air-lake CO_2 fluxes. These models estimate a lake-wide seasonal cycle of pCO_2 and CO_2 exchange with the atmosphere. Our validation data are the EPA bi-annual survey in spring and summer for years 1986-2009 (1996-2009 for Lake Superior). Sampling locations are shown in Figure 3 for Superior, and for other lakes can be found at http://www.epa.gov/glnpo/monitoring/guard/sampling_stations.html.

The 2-box models have two layers, surface (epilimnion) and deep, with the sum being the observed mean lake depth. The surface layer has a constant thickness equal to the summer maximum thermocline depth (Table 3). Temperature is set at a constant value of 3.91°C in the bottom layer, and surface layer temperatures follow the 1992-2010 climatology, derived by the Great Lakes Surface Environmental Analysis using satellite observations (GLSEA2, http://coastwatch.glerl.noaa.gov/statistic/statistic.html). Tracers within the two model layers convectively mix when the epilimnion temperature is within 1.0°C of the bottom. All biological production occurs within the model surface layer, and a prescribed annual cycle of net primary production reduces surface concentrations of dissolved inorganic carbon (DIC) (Sterner, 2010 for Superior, with a similar shape assumed for other lakes due to lack of better information). Remineralization of organic matter returns carbon to its dissolved inorganic form. The lake exchanges carbon dioxide with the atmosphere, using regional atmospheric concentrations of CO_2 from Park Falls, WI. Climatology of ice cover from observations is applied to block air-sea gas fluxes in proportion to the fractional coverage.

The 2-box models without external supplies of carbon come into equilibrium with the atmosphere after a few years of integration and there is no net influx or efflux because loss of C to the sediments is not included. A term for the net input of carbon from upstream and from the watershed (Net Input) is added, distributed in time according to the fact that the spring melt drives a significant fraction of total runoff into the lakes (Bennington 2010). The annual Net Input is tuned until results are within the 1 standard deviation uncertainty estimate for EPA-based estimates of pCO_2. Because the lakes are in equilibrium without river input, the Net Input directly determines the lake-air CO_2 flux (Table 3).

For each lake (Figure 4), the box model has elevated pCO_2 in January as respired DIC is returned to the surface box by mixing. Late winter cooling and NPP then begins to draw down pCO_2. In April and May, Net Input is maximal (if turned on) and this drives up pCO_2. In August, NPP reaches its peak at the same time temperature peaks, and these have opposite effects on pCO_2. In fall, cooling occurs as NPP falls off, again compensating, and then in December winter mixing raises pCO_2.

For Lake Superior (Figure 4a), the 2-box model is able to reasonably capture the EPA-based pCO_2 estimates as well as the lake-wide integrated results from MITgcm.Superior with either zero Net Input or Net Input of 0.8 Tg C yr^{-1} (Table 2), though the seasonal variability is muted in the 2-box model. In Lake Michigan (Figure 4b), a Net Input two orders of magnitude larger than suggested from the literature (20 TgC/yr as opposed to 0.25 Tg C yr^{-1}, Table 2) allows the 2-box model to capture observed summer pCO_2, and still does not quite capture spring pCO_2. In Lake Huron (Figure 4c), we also must increase the Net Input by approximately two orders of magnitude (10 Tg C yr^{-1} as opposed to 0.07 Tg C yr^{-1}, Table 2) in order to approach the lower bound of the observed pCO_2 in both seasons. In Lake Erie (Figure 4d), the range of observed pCO_2 in both seasons is quite large, and the 2-box model is able to capture these observations within the uncertainty with zero Net Input. This is as close as the 2-box model can get to the net sink suggested from the literature review (-0.47 Tg C yr^{-1}, Table 2). In Lake Ontario (Figure 4e), the

2-box model is able to capture the low summer observed pCO_2 with zero Net Input, similar to the literature review sink (-0.53 Tg C yr^{-1}, Table 2). However, we are only able to begin to capture the spring observed pCO_2 by including a Net Input that is ten times larger than this (5 Tg C yr^{-1}), and with this, the summer pCO_2 is no longer consistent with the observations.

Though the 2-box models include the processes that are quantitatively dominant to carbon cycling on the lake-wide, annually integrated scale (NPP, respiration, Net Inputs, Figure 2), they are unable to capture bi-annual observations of lake-wide pCO_2 with Net Input estimates that are consistent with the literature review (Table 2). The exception is Lake Superior, the lake for which the 2-box model is best parameterized. A critical uncertainty whose resolution might improve this approach is the seasonal cycle of NPP, for which we do not have a good lake-wide description for any lake except Superior. Recent coupled physical-ecosystem modeling studies of Lake Michigan (Pauer et al. 2011) and Lake Erie (Leon et al. 2011) might be sources for improved lake-wide estimates. Better characterization of the seasonal cycle of inputs from the catchment and of lake-wide pCO_2 is also needed.

The lack of success with a single-column, 2-box model approach outside of Superior also suggests that spatial heterogeneity needs better characterization. Figure 3 illustrates the significant spatial variability of surface lake pCO_2 in April 1997 in Lake Superior from MITgcm.Superior. Here, we see the localized elevation of pCO_2 due to river inputs, as well as open-lake variability driven by spatial heterogeneity in local NPP and temperature, as well as redistribution of tracers by the circulation (Bennington et al. 2010). The climatological mean lake-wide seasonal cycle of pCO_2 from MITgcm.Superior is significantly more variable than the pCO_2 cycle from the 2-box model (Figure 4a), further suggesting that spatial variability needs to be taken into account in order to understand and quantify Great Lake carbon budgets.

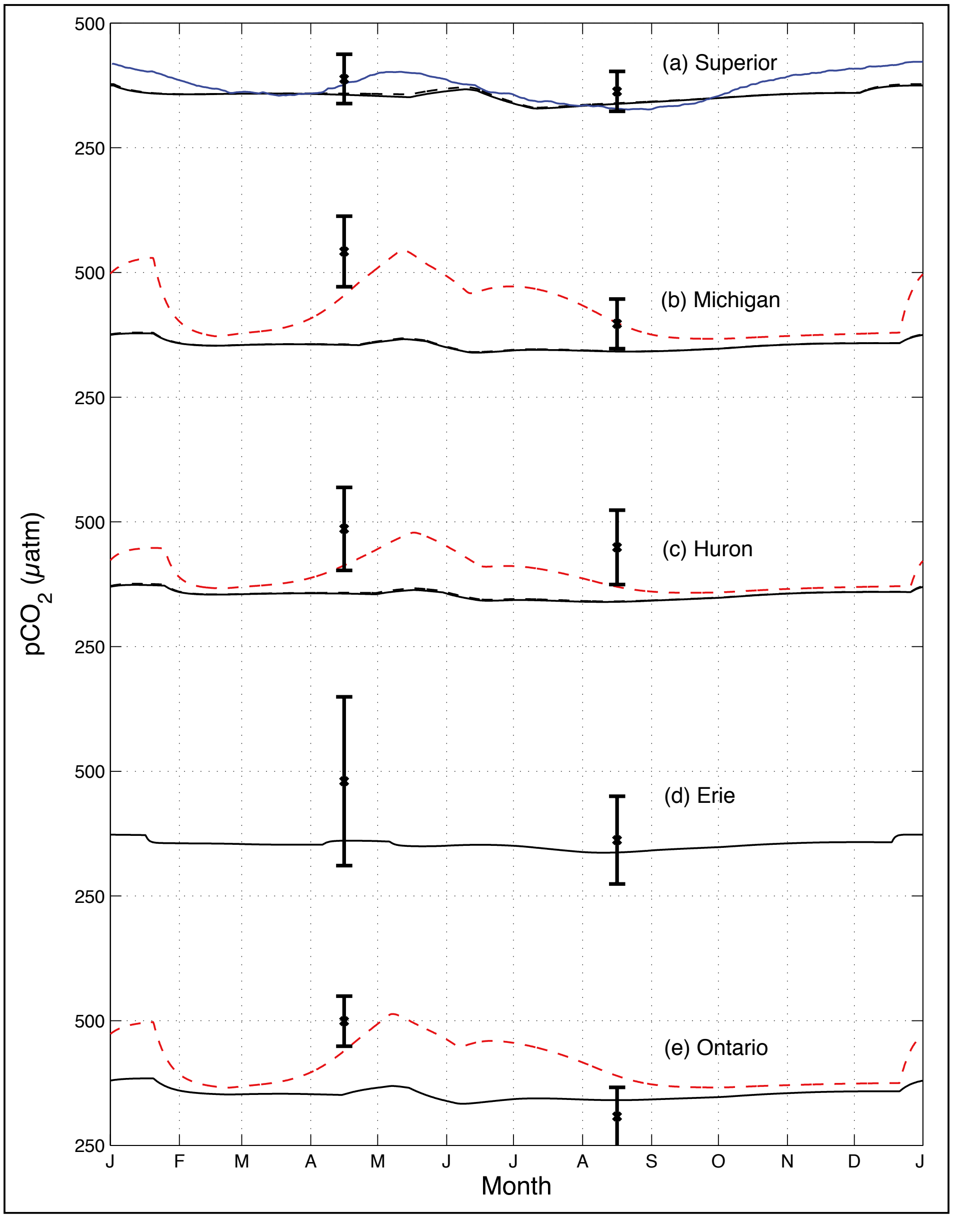

Figure 4: Climatological mean surface lake pCO_2 cycle from 2-box models for (a) Lake Superior, (b) Lake Michigan, (c) Lake Huron, (d) Lake Erie, and (e) Lake Ontario. Mean lake (with 1 standard deviation) EPA bi-annual survey data for April and August is shown with x and vertical bars. Solid black line has zero Net Input; dashed black line has Net Inputs of (a) 0.8 Tg C yr^{-1}, (b) 0.25 Tg C yr^{-1} and (c) 0.07 Tg C yr^{-1}, consistent with Table 2; and red dashed line is for enhanced inputs of (b) 20 Tg C yr^{-1}, (c) 10 Tg C yr^{-1}, and (e) 5 Tg C yr^{-1}. In (a), the blue line is lake-mean pCO_2 for 1996-2001 from MITgcm.Superior, with river inputs of 0.15 Tg C yr^{-1}.

4. Conclusions

From a literature review, a lower-bound estimate for the net carbon efflux from the Great Lakes, based only on respiration of allochthonous organic carbon, degassing of DIC inputs (Superior only), and burial of autochthonous organic carbon, is 0.12 Tg C yr^{-1} (Table 2). When literature values for internal cycling of carbon are included and an alternative budget is created, the net carbon efflux estimate is 2.3 Tg C yr^{-1} (Figure 2), which may still be an underestimate. For a series of simple 2-box models that approximately capture the climatology of bi-annual surface lake pCO_2 observations, the Great Lakes efflux needs to be at least 35.8 Tg C yr^{-1}, which is most likely an overestimate. These estimates range across two orders of magnitude and thus indicate the poor state of knowledge regarding carbon budgets of the Great Lakes. The discrepancies between the three approaches highlight the areas most in need of further work.

Critical unknowns that are ripe for future research include lake-wide spatial heterogeneity of carbon processing, in particular NPP and respiration. Direct observations with better temporal resolution of surface lake pCO_2 observations are needed. The effects of circulation on biogeochemistry and carbon cycling are beginning to be addressed in Lake Superior (Bennington 2010, McKinley et al in prep), and need to be studied in the other lakes. The impact of temporal variability in response to climate forcing is also poorly characterized. To address these issues, field studies and numerical modeling efforts will be required. In addition, the development of well-validated algorithms for space-based retrievals of biogeochemical parameters for the Great Lakes is critically needed (Mouw et al. in prep).

In all studies of the Great Lakes, the myriad of anthropogenic influences, such as invasive species and cultural eutrophication, must be considered. An additional anthropogenic influence that has received little attention so far is the impact of acidification due to increased atmospheric pCO_2 (NOAA, 2010). Lakes that are approximately neutral with respect to atmospheric pCO_2 or a net sink should be particularly susceptible. An assessment of the likely impacts of acidification in conjunction with other anthropogenic influences is needed for all the lakes.

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The Impact of MOC Variability on Marine Productivity and Carbon Uptake and Storage in the North Atlantic

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1. The Meridional Overturning Circulation (MOC)

Our planet receives a greater flux of solar radiation at the equator than it does at the poles. Arising in response to this meridional imbalance, the large-scale fluid motions of the ocean and atmosphere act to redistribute excess heat from low to high latitudes. A significant portion of the oceanic contribution to this global poleward heat flux occurs in the North Atlantic, where observations of the bulk movement in the upper ocean reveal that warm waters are transported northward to regions where they release their heat (becoming colder and denser in the process), sink and return towards the equator as deep water masses. This overturning circulation is understood to be part of a larger, global Meridional Overturning Circulation (MOC) in which recently ventilated deep waters are exported from their source regions in the high-latitude North Atlantic into the rest of the global ocean, where they are eventually upwelled and transported back to the deep water formation sites. In addition to transporting heat, the MOC also plays an important role in the cycling of dissolved constituents such as carbon, oxygen and nutrients through the marine reservoir. Thus, changes in the strength of the MOC could be expected to impact marine ecosystems and ocean biogeochemistry.

2. Conceptualizing the MOC

2.1 The ocean conveyer belt

For much of the last half-century, the dominant mechanistic view of the global MOC has been that it operates like an oceanic 'conveyer belt' consisting of upper and deep limbs, within which the transport of water masses and their properties occurs via a system of continuous, linked currents. Bulk transports in the lower limb pass through the relatively quiescent deep ocean, while transports in the upper limb must traverse the highly energetic, wind-driven gyres. The conveyer belt model includes two basic assumptions about the overturning circulation: 1) that MOC variability is primarily driven by variability in the rate of deep water formation in the high-latitude North Atlantic, and 2) that MOC variability is coherently transmitted downstream from one point on the conveyer to another.

In keeping with this physical model, discussions of the impact of MOC variability on marine ecosystems and ocean biogeochemistry have customarily focused on the downstream effects of changes in deep water mass production. For example, from a marine ecosystems perspective, changes in overturning in the North Atlantic are expected to impact primary productivity in the surface ocean by altering the upwelling of nutrient-rich deep waters elsewhere around the globe. From a biogeochemical perspective, changes in overturning are expected to impact the transport of dissolved carbon and oxygen from the surface ocean into the deep ocean. In the case of carbon, this would alter the oceanic storage of an important greenhouse gas. In the case of oxygen, this would affect the biochemistry of organic matter respiration at depth.

2.2 Recent insights into the MOC

For decades, the ocean conveyer belt has been the dominant paradigm for describing the MOC; as such its description of the structure and mechanics of ocean overturning has shaped our ideas of how MOC variability might impact marine ecosystems and ocean biogeochemistry. Yet the ocean conveyor "model" was developed during a time when there was considerably less information about the ocean's flow field than there is today. Recent findings from observational and modeling studies have forced the ocean science community to reconsider some fundamental aspects of the MOC's structure and functioning:

Transport pathways in the upper and lower limbs — In the deep ocean, the conveyer belt model describes the continuous advection of water masses along deep western boundary currents (DWBCs) that link together across basins to create a single pathway along the deep limb of the MOC. Over the past decade, however, studies have demonstrated the presence of energetic eddy fields at depth that can not only disrupt the DWBCs, but also produce large-scale recirculations that transport water masses and their properties away from the western boundary and through the ocean interior. Similarly, transports in the upper limb of the MOC may vary strongly as a function of wind-driven gyre dynamics and as a result, not provide continuous throughput from one ocean basin to the next.

MOC coherence and temporal variability — The disruption of lower and upper limb pathways by wind and eddy activity clearly demonstrates the impact of local physical variability on MOC transports. Buoyancy changes in the high-latitude North Atlantic can thus no longer be considered to be the sole determinant of the strength of the global MOC. Indeed, studies have shown that MOC variability itself is highly spatially variable, having a strong gyre-scale structure, with transports at one location often having little correlation to those at another location. The main driver of the observed spatial patterns of MOC variability on interannual time scales appears to be basin-scale wind forcing. Further study is needed, however, to understand whether meridional coherence is recovered when the overturning is estimated in density rather than depth space.

Overturning and deep water mass properties — Recent studies have also shown that deep water mass property changes from one year to the next may not always match changes in actual overturning in the source region from which the water mass is exported. This discrepancy arises because the transfer of properties from surface to depth likely depends on other factors besides the strength of overturning. For example, the transport and properties defining the deep water mass exported from the Labrador Sea basin (Labrador Sea Water, or LSW) are believed to be a function of the property exchange between the convectively-produced interior waters and the surrounding boundary current that flows into and out of that basin (see Figure 1). With such a model, eddy activity within the basin, as well as the strength and properties of the boundary current, can impact the properties and transport of LSW to the same degree as the local buoyancy forcing that sets the interior water properties. Thus, it is possible that LSW exported from the subpolar basin may have varying properties, even over intervals where convection in the basin is unvarying.

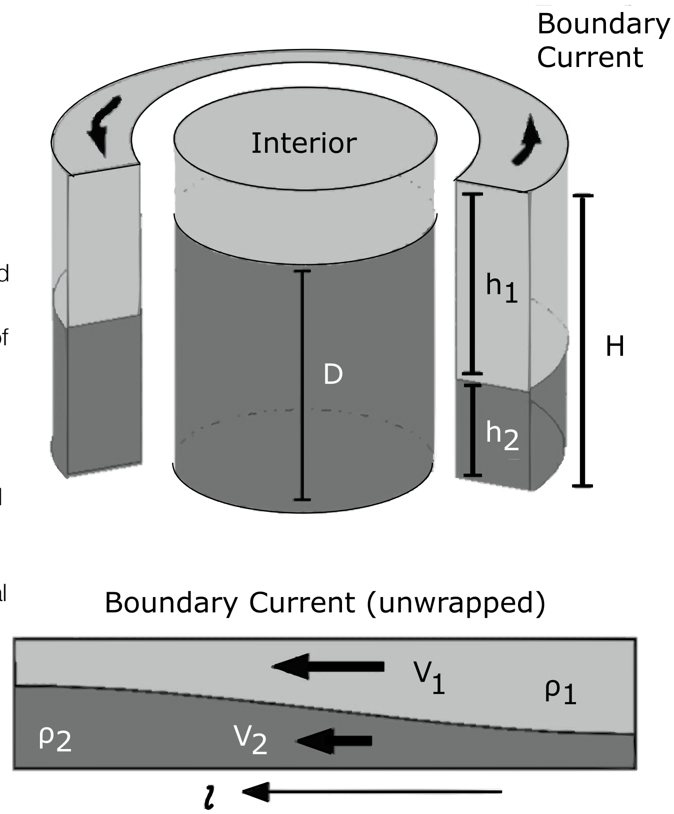

Figure 1: A schematic of the Labrador Sea shows that convection is confined to an interior region that is surrounded by a boundary current that flows into and out of the basin. The properties of Labrador Sea Water are set by the exchange of properties between the interior and the boundary current. (from Straneo, 2006) (c) American Meteorological Society. Reprinted with permission.

3. The impact of MOC variability on marine productivity and carbon uptake and storage

The dismantling of the ocean conveyer challenges us to consider interannual variability in marine ecosystems and biogeochemistry within a new physical framework. This article focuses on two processes of particular current interest: marine primary productivity and the oceanic uptake and storage of carbon. Our focus is on the North Atlantic, the basin with the most studied MOC.

3.1 MOC and marine productivity in the North Atlantic

Primary productivity in the North Atlantic is expected to be sensitive to changes in surface hydrography that result from transport variability in the MOC's upper limb. As mentioned earlier, this transport variability has a strong gyre-scale structure with little coherence between gyres. It is reasonable to suppose, therefore, that this spatial structure also imprints itself to some degree on productivity variability. Complicating matters, however, is the fact that the productivity responses to a given hydrographic change can be very different in the light-limited subpolar gyre than in the nutrient-limited subtropical gyre. Moreover, just as recent research has expanded our understanding of the mechanics of the MOC, so too have recent findings challenged accepted notions of the response of marine productivity to physical forcing in the subtropical and subpolar gyres.

Productivity response to imported nutrients — Surface MOC transports crossing the equator into the subtropical North Atlantic provide a mass balance for the export of deep water out of the basin. A recent study has demonstrated that these transports also act as a conduit for nutrients, advecting them into the subtropical gyre from source regions in the equatorial and southern Atlantic (Figure 2). The influx of nutrients by

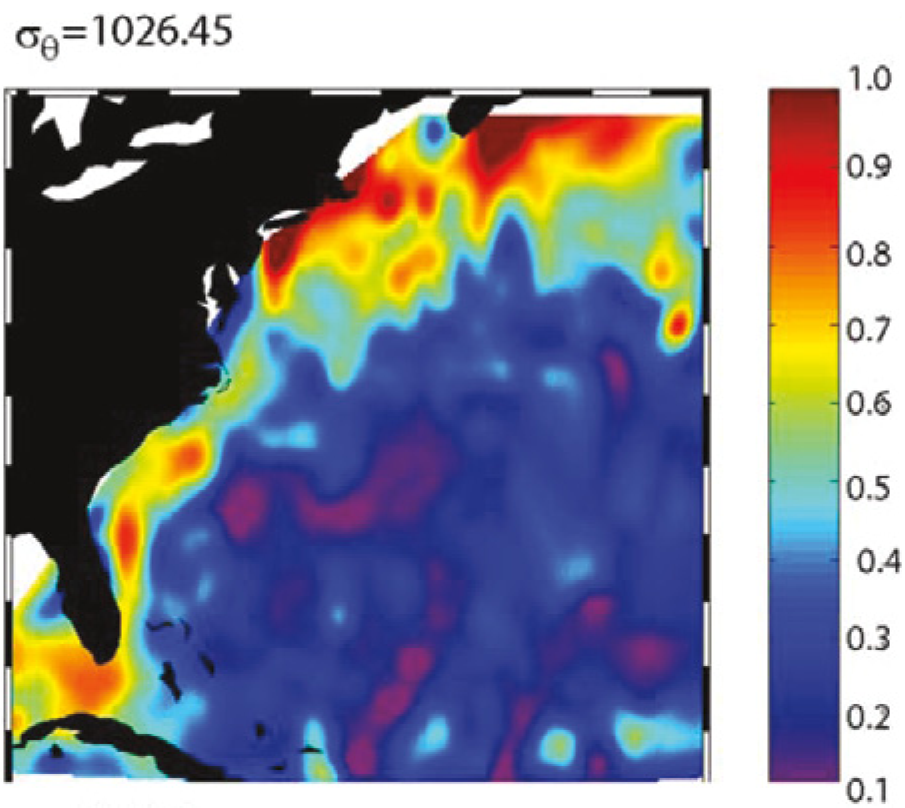

Figure 2: A map of climatological phosphate concentrations in the North Atlantic along the 1026.45 σ_θ density surface. The elevated levels observed in the Gulf Stream current reflect the advection of nutrients into the North Atlantic via the surface transports of the MOC. Thus variability in the MOC is expected to impact nutrient supply and productivity in the basin. (from Palter and Lozier, 2008)

surface transports would thus constitute a 'first-order' MOC impact on the nutrient supply into the gyre, with the expectation that increases (decreases) in the strength of the MOC transports would contribute to increases (decreases) in productivity within the gyre. Subtropical productivity variability would also likely be impacted by variability in upstream processes in the source regions for these nutrients. The impact of a variable MOC on the advection of nutrients into the subpolar gyre, however, remains unclear, primarily because the nutrient pathways between the subtropical and subpolar gyres have yet to be elucidated.

Productivity response to MOC changes in the subtropical North Atlantic — In addition to altering advective fluxes of nutrients into the subtropics, variability in surface MOC transports exerts a 'second-order' influence on nutrient supply by altering the advective fluxes of heat (or freshwater) into the gyre. Thus, a weakening (strengthening) of MOC heat fluxes would be expected to reduce (increase) sea surface temperatures and weaken (strengthen) the regional stratification. Changes in stratification within the nutrient-limited subtropical gyres have traditionally been expected to be negatively correlated with productivity variability, with the expectation that weakened stratification would enhance productivity by increasing the mixing of deeper, nutrient-rich waters towards the surface. A recent observational study, however, suggests that productivity and stratification variability in the subtropics are not strongly correlated. A growing body of evidence instead supports the notion that other dynamics besides vertical mixing are controlling the supply of nutrients to the surface. Among the possibilities are: 1) wind-forced changes in the size and intensity of the downwelling subtropical regime, 2) wind-forced changes in horizontal Ekman nutrient fluxes into the gyre, and 3) wind- and buoyancy-forced changes in the formation and spread of mode waters, which would impact the sub-surface nutrient reservoir in the subtropics.

Productivity response to MOC changes in the subpolar North Atlantic — In the light-limited regime of the subpolar gyre, the relationship between stratification, vertical mixing, and productivity has traditionally been treated as the reverse of that in the subtropical gyre, with the expectation that increases in vertical mixing would suppress photosynthesis by decreasing the exposure of phytoplankton to light. However, recent research has suggested that increases in mixing might also ultimately increase net phytoplankton community growth rates by decreasing encounter rates between phytoplankton and grazers. Thus, the response of subpolar productivity to interannual stratification variability created by changes in MOC heat fluxes remains unclear.

3.2 MOC variability and carbon uptake and storage

Carbon uptake response to MOC variability — The drawdown of atmospheric carbon into the upper ocean is largely controlled by the disequilibrium between the partial pressure of carbon dioxide (pCO_2) in the atmosphere and that below the sea surface. Within the water, the pCO_2 is a function of temperature, salinity, alkalinity, and dissolved inorganic carbon (T, S, ALK, DIC). Thus, the uptake of CO_2 would be expected to be sensitive to all of the types of MOC variability discussed in the previous section, insofar as this variability is able to produce appreciable changes in surface T, S, ALK and DIC. A recent study presents evidence that this has indeed happened in the North Atlantic: CO_2 uptake has increased in both the subpolar and subtropical gyres, driven by changes in vertical mixing in the subpolar gyre and surface temperature in the subtropical gyre.

Carbon transfer to the deep ocean— As explained earlier, recent research has demonstrated that deep waters formed through the transfer of properties, rather than by direct convection, are influenced by other factors besides just the strength of overturning. For example, the CO_2 content of a deep water mass such as Labrador Sea Water will also reflect changes in the property gradients and eddy fields within the Labrador Sea basin (Figure 1). Thus, the linkage between variability in convective activity of a basin and the transfer of CO_2 from the surface to depth can no longer be safely assumed.

Carbon storage in the deep ocean — The presence of interior pathways in the deep ocean greatly expands the range of time scales associated with transport through the deep limb of the MOC; the available volume of space that can be inhabited is also greatly increased. As a consequence, the capacity of the deep ocean to store carbon may be greater than what has been estimated previously from transport calculations. Additionally, the deep eddies that generate these interior pathways are themselves fueled by instabilities in wind-driven boundary currents at the surface. Thus, transport and storage of carbon in the deep ocean reservoir could be expected to be sensitive to surface forcing at a great meridional distance from the regions of overturning.

4. Summary

The shift away from the conveyer belt paradigm reflects a new understanding of the role that the ocean's wind and eddy fields play in driving meridional transports of water masses and their properties, both at the surface and at depth. This understanding is due in large part to recent improvements in the spatial and temporal resolution and geographic coverage of our ocean observations, a development that has also produced a concurrent expansion of our understanding of marine ecosystems and biogeochemistry. Consideration of linkages between the MOC and marine ecosystems and biogeochemistry must therefore take into account developments on all sides.

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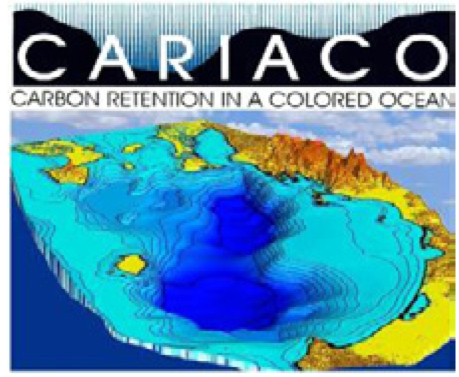
CARIACO Releases Spanish-English Handbook of Methods for Oceanographic Time-Series

by Laura Lorenzoni, Cyndy Chandler, Frank Muller-Karger, and Yrene Astor

Ship-based oceanographic time-series stations are unique platforms that allow detailed measurements of multiple components of biogeochemical cycles at relatively high temporal frequency over long time periods. The CARIACO (CArbon Retention In A Colored Ocean) Ocean Time-series Program is one such station, located on the tropical continental shelf off the coast of Venezuela. The CARIACO team has been using research vessels and moored instruments to study and monitor the ocean carbon and biogeochemical state of the Caribbean Sea since 1995. Following in the tradition of the U.S. Joint Global Ocean Flux Study (JGOFS) long-term time-series, which led to the establishment of the two longest time-series stations (BATS and HOT), CARIACO has published a methods manual that is uniquely tailored to the study area. The Cariaco Basin is influenced by the annual migration of the Atlantic Intertropical Convergence Zone (ITCZ), which induces strong coastal wind-driven upwelling during the first half of the year and rainfall during the second half. The Cariaco Basin is also the largest anoxic basin of truly oceanic character, completely devoid of oxygen from ~250 m to the bottom (1,400 m). Traditional protocols for measuring open ocean primary production, chlorophyll, and various other measurements, including pH and alkalinity, have been optimized for work in this highly productive area. Biogeochemical measurements in anoxic waters, such as hydrogen sulfide, are also included. The manual features protocols for measurements of interest to remote sensing, ocean carbon and biogeochemistry, including colored dissolved organic matter (CDOM), light absorption by particulate matter, and dissolved and particulate organic carbon concentration.



This is the first comprehensive compilation of oceanographic methods in Spanish, which promises to be useful to other countries developing their own ocean observatories around the world. The handbook of methods for the analysis of oceanographic parameters at the CARIACO Time-Series station is available on the CARIACO and OCB websites. All of the data compiled from the CARIACO Time-Series Study are available from the Biological and Chemical Oceanography Data Management Office (BCO-DMO) and the CARIACO website.

Virtual Biogeochemistry in the Whyville Plankton Lab: A Red Tide Whodunnit

by Abby Heithoff (Department of Biology, Woods Hole Oceanographic Institution)

The chatter really started to fly when the dead fish started washing up on the beach. Scientists mustered in their labs, discussing possible causes and outfitting their research vessels with sensors and sampling gear. A harmful red tide had broken out, and it was up to the scientists in the Plankton Lab at Whyville Oceanographic Institution (WhOI) to figure out why. The Plankton Lab is a state of the art facility tackling serious issues in microbial oceanography, including harmful algal blooms and microbial diversity. In that way it's very similar to its parent lab – Sonya Dyhrman's microbial biogeochemistry lab at Woods Hole Oceanographic Institution (WHOI). However, WhOI exists solely in a virtual world and the scientists that populate it and work in the plankton lab are boys and girls ages 8-14. It's all part of a novel outreach avenue pursued by C-MORE Scientist Sonya Dyhrman to create microbial oceanography content for Whyville, including activities focused on evidence-based inquiry.

Fig. 1: A graphic showing the typical population of South Beach, one of the most popular gathering places in Whyville, and the location of a red tide outbreak (top). The Microbe War game (middle) illustrating the biodiversity of marine microbes. The Plankton Laboratory in Whyville (bottom) where Sonya introduces Whyvillians to her research.

Whyville is the foremost educational virtual world for children between the ages of 8-14, with over 5 million registered users. The site consistently hosts 2 million unique visitors per month – the majority in their middle school years (ComScore Media Metrics, 2008). It is during this critical period that many students may begin to lose interest in Science, Technology, Engineering, and Mathematics (STEM) subjects. However, research suggests that exposure to scientific inquiry and engaging science content during the middle school years strongly influences future academic and career choices. Informal education via virtual worlds, like the experience provided through Whyville, provides students with an informal learning environment without the restrictions of geography, past performance, or opportunity. "When I first learned about Whyville, there was no ocean science content. Not every child lives on the coast, or down the street from an institution like WHOI. Now, millions of children are exposed to key concepts in ocean science literacy, and, more importantly, to the process of scientific inquiry," says Sonya Dyhrman. The inquiry-based approach utilized in Whyville comes at a critical period in students' lives, and offers them a unique learning experience that may positively influence future learning. This is what first interested Sonya in getting involved. "I am intrigued by the thought of education in the context of virtual worlds, and

Virtual Biogeochemistry in the Whyville Plankton Lab: A Red Tide Whodunnit (cont.)

developing Whyville content has allowed my lab's outreach activities to reach many more students than we would normally be able to – literally millions."

The Whyville Plankton Lab is the product of collaboration between the Dyhrman lab and Numedon Inc., which began in 2006 with the formation of WhOI and the Plankton Lab with funding from NSF, NOAA, and WHOI. The initial goal of the collaboration was to promote ocean and science literacy through investigating the links between nutrients and phytoplankton growth. The activities have expanded to include multiple dependent and independent layers. In the Plankton Lab, students are invited to investigate the causes of a recent red tide event, and participate in a plant restoration project to alleviate the bloom. A general workflow might include learning about phytoplankton blooms in the lab, followed by pulling a phytoplankton sample from the beach on Whyville Bay. Students then investigate the phytoplankton community using a microscope back in the lab. Information on the culture collection, available in the lab, gives students clues to what nutrient might be favoring one species over another in the bay. Nutrient sensors, available in the lab, are then used to identify point sources along the Whyville coastline. After the nutrient sources are identified, students implement a remediation program that utilizes seedlings to absorb excess nutrients in Whyville's wetlands. Once students have implemented their remediation strategy, their next stop may be the Microbe War game. Here, students learn about the diversity of marine microbes through a competitive card game. Students collect cards, each one printed with a marine microbe and a summary of its strengths and weaknesses, and then challenge each other to battles that pit marine microbe against marine microbe. This series of activities focuses on several hot topics in biological oceanography, including harmful algal bloom dynamics and microbial biodiversity, and a possible expansion of the project has been proposed.

Possible future collaborations between the Dyhrman lab and Numedon Inc. include developing inquiry-based projects focused on the effect of climate change on microbial oceanography. This development would build on current Whyville activities, which offer users the opportunity to calculate their Whyville carbon footprint. In the future, the Plankton Lab may expand its suite of sensors to include CO_2 and temperature sensors and pH meters, which will allow students to understand phytoplankton bloom dynamics in the context of increased pCO_2, lowered pH and increased temperature. The potential extension of existing Plankton Lab projects and collaboration with current Whyville institutions would link ocean and climate data to inquiry-based activities. Through the opportunities offered at the WhOI Plankton Lab, C-MORE scientists are able to reach millions of students in a demographic that is traditionally difficult to entrain and they are able to engage them in inquiry-based science learning to increase ocean science literacy and understanding. It is possible that this project will be extended in the future, increasing the breadth of activities and bringing the C-MORE science message to millions more students.

To learn more about C-MORE's science and education initiatives, please visit:
http://cmore.soest.hawaii.edu.

OCB hosts three C-MORE Science Kits in Woods Hole

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

Ocean acidification kit (grades 6–12)

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

Ocean conveyor belt kit (grades 8–12)

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

Marine mystery kit (grades 3–8)

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

To Request a Kit

http://cmore.soest.hawaii.edu/education/teachers/science_kits/requestform.htm

Important OCB Dates

- **May 23-25, 2011:** OCB Scoping Workshop: A Biogeochemical Flux program aligned with the Ocean Observatories Initiative (OOI) (Woods Hole Oceanographic Institution, Woods Hole, MA)
- **July 18-21, 2011:** OCB Summer Workshop (Woods Hole Oceanographic Institution, Woods Hole, MA) - **note joint science session with U.S. CLIVAR on July 19**

OCB Informational Resources

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

Ocean Fertilization News

- Modeling and Synthesis Southern Ocean Natural Iron Fertilization (June 27-29, 2011, Woods Hole, MA)
- Researchers from around the world come together to form the ISIS (in situ iron studies) Consortium. View ISIS Consortium website.
- IOC of UNESCO releases A Scientific Summary for Policymakers on Ocean Fertilization
- OCB ocean fertilization website cited as a primary informational resource by the USG delegation to the London Convention

Community Resources

Research Tools

- Microbiological Targets for Ocean Observing Laboratories (MicroTOOLs) workshop reports now available
- "Simulation and assimilation of global ocean pCO_2 and air–sea CO_2 fluxes using ship observations of surface ocean pCO_2 in a simplified biogeochemical offline model" contributed by Vinu Valsala and Shamil Maksyutov (NIES/Japan) now available from CDIAC
- Archived ocean surface water radiocarbon data from surface dwelling, reef-building hermatypic corals now available at CDIAC
- CO2calc: A User-Friendly Seawater Carbon Calculator for Windows, Mac OS X, and iOS (iPhone)
- DMS fluxes and exchange velocities (Univ. of Hawaii)
- Updated DMS database (Kettle et al., 1999)
- Global monthly DMS climatology (Lana et al., 2011)

Education and Outreach

- Information portal on Ocean Science Summer Schools Contact: Ed Urban (SCOR)

Launch of new EU Program CARBOCHANGE (Changes in carbon uptake and emissions by oceans in a changing climate)

This 4-year (2011-2015) research program is a consortium of 28 research institutions (Europe, USA, Canada, Morocco, South Africa). The program will focus on combining observational data and model simulations to quantify net ocean carbon uptake under changing climate conditions. A kickoff meeting was held March 8-10, 2011 in Bergen, Norway. For more information, contact Christoph Heinze (University of Bergen).

Formation of the Blue Carbon International Scientific Working Group

The objectives of this working group are to develop effective strategies to quantify the role of coastal vegetated ecosystems in carbon storage and sequestration; identify key threats to these ecosystems and pinpoint areas of highest immediate risk (with regard to carbon sequestration potential); and develop conservation, planning, and management guidelines for these ecosystems. The first working group meeting was held at UNESCO Headquarters (Paris, France) February 15-17, 2011. Visit the working group website for more information.

Project News

IMBER

- New IMBER human dimensions working group
- New IMBER-affiliated projects
    - Amazon iNfluence on the Atlantic: CarbOn export from Nitrogen fixation by DiAtom Symbioses (ANACONDAS) (Contact: Patricia Yager)
    - The River Ocean Continuum of the Amazon (ROCA) (Contact: Patricia Yager)
    - Marine Ecosystem Evolution in a Changing Environment (MEECE) (Contact: Jessica Heard)
    - Biogeochemistry from the Oligotrophic to the Ultraoligotrophic Mediterranean (BOUM) (Contact: Thierry Moutin)
    - Marine Ecosystems Response in the Mediterranean Experiment (MerMex)
- IMBER data management cookbook

SOLAS

- UK SOLAS Final Report
- SOLAS Metadata portal

GLOBAL CARBON PROJECT

- Final RECCAP (REgional Carbon Cycle Assessment and Processes) meeting to be held in May 2011
- Canadell, J. G. (Ed.) (2010). Special issue: Carbon and nitrogen cycles. *Current Opinion in Environmental Sustainability* 2(4), 209-312.
- Dhakal, S., Shrestha, R. M. (Eds.) (2010). Special section: Carbon Emissions and Carbon Management in Cities. *Energy Policy* 38(9), 4753-5296.
- Ciais, P., Dolman, A.J., Dargaville, R., Barrie, L., Bombelli, A., Butler, J., Canadell, P., Moriyama, T. (2010). Geo Carbon Strategy Geo Secretariat Geneva/FAO, Rome, 48 pp.

U.S. CLIVAR

- U.S. CLIVAR Summit (July 19-21, 2011, **invitation only**) to be held in conjunction with the annual OCB summer workshop in Woods Hole, MA (joint science session with OCB **on July 19**)

Ocean Acidification

Studying ocean acidification's effects on marine ecosystems and biogeochemistry

OCB Hosts First Meeting for Ocean Acidification Researchers

by Sarah Cooley (OCB Project Office)

Ocean acidification research is growing by leaps and bounds, both in the United States and abroad. One of the greatest challenges facing this fast-growing community of researchers is simply to know– Who's who? What's happening? Where? Who's looking for collaborators? What obstacles should the community tackle first?

To begin answering these questions and coordinating the ocean acidification (OA) research community in the United States, the OCB-OA subcommittee and the OCB Project Office held a three-day meeting for OA researchers in March (www.whoi.edu/workshops/OAPI2011). With significant help from NSF, NOAA, NASA, USGS, EPA, and Navy program managers, OCB identified representatives from almost all OA research projects supported by these U.S. agencies to invite to this meeting. Attendees included ecologists, paleoceanographers, instrumentation specialists, chemists, biologists of all types, socioeconomists, modelers, and communications specialists.

OA research is growing so quickly across the United States and worldwide that without some care, duplication of efforts or research overlaps could occur. Until a national program is in place to help coordinate the activities of so many agencies and researchers, the community itself must strive to avoid duplication of efforts and foster collaborative opportunities. The OCB-OA Subcommittee and the OCB Project Office designed this particular meeting to offer networking opportunities for researchers presently working on OA-relevant projects, to allow them to strengthen or develop collaborations, and to minimize duplication of efforts. The meeting was also designed to build capacity for improving research in the future by entraining younger investigators and researchers from a broader range of disciplines, and by identifying short- and long-term research goals. Additional meeting goals included promoting effective data management, improving communication with the public about OA, and seeking guidance from the community about how OCB could help facilitate OA science.

The workshop was organized around five main scientific themes that reflected the dominant groupings of present OA research projects:

- paleoceanography, proxies and modeling;
- observations and monitoring;
- physiological responses to OA;
- ecology and systems responses to OA; and
- biogeochemistry and modeling

The workshop agenda and presentations are available at the meeting website. Videos of each talk will be available in the next few weeks. Each of these five scientific sessions began with a plenary talk reviewing state-of-the-art knowledge on the theme, followed by a short synthesis presentation that highlighted present research efforts related to the theme. These synthesis presentations were put together by session chairs, who drew from the abstracts and project overview slides that meeting participants sent in beforehand as well as agency-provided information on research funding for OA. After each synthesis presentation, the session chairs then led a short panel discussion including researchers whose work was affiliated with the theme to discuss possible synergies between present activities, obvious gaps between research efforts, and other allied issues. These panel discussions set the stage for more fruitful discussions in afternoon breakout sessions that focused on overarching themes.

The meeting also included stand-alone plenary talks and discussions on topics of universal interest. Lisa Dropkin of Edge Research gave a short update on the Consultative Group on Biodiversity's recent public opinion research on OA. This work highlighted communications opportunities and misunderstandings regarding OA, paving the way for future synergistic opportunities between academic researchers and communications specialists. Joanie Kleypas and Gretchen Hofmann led a meeting-wide plenary discussion of how best to integrate biological research, which set the scene for that afternoon's physiological/ecological research breakout session. Cyndy Chandler reviewed best data management practices and new funding agency requirements to help researchers make the most of their work using best practices and existing data management infrastructure. Jean-Pierre Gattuso then discussed ongoing efforts to put together an international coordinating body for OA research. Ned Cyr, Phil Taylor, Libby Jewett, and Julie Reichert (on behalf of Christine Ruf) gave updates on developments regarding OA research plans and activities for the U.S.

OCB Hosts First Meeting for Ocean Acidification Researchers (cont.)

Interagency Working Group on Ocean Acidification, NSF, NOAA, and EPA, respectively. The IWG-OA has representatives from each of the federal agencies interested in ocean acidification and is tasked with generating a strategic plan for federal research as well as facilitating the coordination of federal and international entities' OA efforts. At the same time, NSF, NOAA, EPA, and NASA (a representative was not able to attend) are supporting OA-relevant research and/or incorporating OA into their science plans.

The first and second afternoons were devoted to breakout sessions that focused on four overarching topics:

- improving science through stronger collaborations, facilities, and infrastructure;
- ocean acidification and society: making OA human-relevant via science, communication, capacity building;
- scaling and modeling across time and space; and
- improving research on the physiological and ecological responses to OA

In all of these breakouts, participants considered similar questions: What pressing issues need to be tackled soonest? Are there obstacles preventing this? Can existing facilities be used differently to increase their impact? Can capacity be built in key areas to accomplish the community-wide to-do list? And, what can OCB do to facilitate answering these questions?

Breakout discussion groups identified a range of common activities that the community could undertake right away to help answer these questions. Many of these activities would support outstanding issues that came up in multiple breakout sessions. For example, promoting strong collaborations between natural and social scientists would advance societally relevant OA research and communications, and it would also enhance our ability to develop holistic OA models including all influences on nearshore marine communities. Also, maximizing better use of physical facilities/infrastructure such as flowing seawater labs, ships of opportunity, the LTER network, and satellite resources would help maintain the collaborations and collect the data needed to understand OA. These data would directly improve models spanning multiple time and space scales targeting OA. Similarly, incorporating autonomous sampling technologies (e.g., gliders, floats, buoys), as well as pursuing research that borrows from non-oceanographic biological studies (e.g., "-omics" research, behavioral or evolutionary adaptation research, mechanistic ecosystem studies, and model systems) could help both improve OA research and provide scalable information that could be incorporated into predictive models. Such models could ultimately be used to provide decision-relevant information that would help link OA's effects on ocean ecosystems from the smallest micro-scale to the largest human community scale.

In many breakout sessions, participants identified common overarching obstacles as well. Lack of customary interaction between natural scientists and social scientists hinders the development of shared language or common priorities to examine problems such as OA. This is even true for different types of natural scientists, for example, for evolutionary biologists and seagoing biological oceanographers. Ongoing efforts to bridge these gaps by a program like OCB or a national/international organizing group are needed. This will help put different types of scientists in touch with each other and facilitate overcoming the natural barriers that presently exist. In modeling efforts, the community needs to come up with better ways to handle and convey uncertainty, as well as different types of data; generating integrated multiscale smart models that can predict OA's likely effects requires incorporating different kinds of data (qualitative and quantitative) that has widely ranging uncertainties (from as small as ±0.1% to as large as the direction of change). Similarly, participants discussed the need for more funding, perhaps from centralized sources, to support larger-scale collaborative initiatives, or from foundations and agency initiatives, to support interdisciplinary research objectives less typically related to traditional oceanography goals.

During the final afternoon of the workshop, attendees began to make a list of the most pressing OA science that the research community should tackle in the next five years. In general, this list summarized the most important needs identified during the breakout sessions. Highlights include:

- Host an interdisciplinary FOCE-like experiment at a mutually interesting site
- Develop an order-of-magnitude assessment of OA's effects vs. other influences
- Compare sensitivity across systems using biological approaches like comparative phylogeography and biodiversity surveys
- Quantify fluxes and variability in particulate pools
- Assemble a comprehensive global monitoring system
- Bring in "others," such as social scientists and humanists
- Develop cheap, user-friendly biological sensors
- Determine the consequences of large pH change on the carbonate system

OCB Hosts First Meeting for Ocean Acidification Researchers (cont.)

Although one of the major goals of the three-day workshop for OA principal investigators was simply to bring together researchers to develop the OA research community via networking, updates on current research, and some science presentations, this workshop also spawned fertile discussions exploring future possibilities, given current science and organizational directions. The OCB OA subcommittee is exploring ways to facilitate many of these multi-investigator activities, such as intercomparison exercises or planning/data synthesis activities. We hope that this will be the first of many meetings for OA investigators in the United States as the research continues to gather momentum.

Ocean Acidification Resources and News Headlines

The final version of the Ocean Research and Resources Advisory Panel (ORRAP) Ocean Acidification Task Force report "Summary of Work Completed and Recommendations for ORRAP to convey to the IWGOA" is now publicly available from the NOPP Publications & Reports webpage (or via direct download)

2-part blog series on the challenges of communicating about ocean acidification and its impacts: Part I: Should Ocean Acidification Be Communicated as Closely Linked to Climate Change? and Part II: Restarting the Conversation about Ocean Acidification: How To Frame What Is At Stake?

Graduate Course "Experimental Approaches to Understanding Ocean Acidification" to be held June 20 - July 22 at the Friday Harbor Laboratories, University of Washington

The United States Environmental Protection Agency has issued a memorandum concerning its Integrated Reporting and Listing Decisions Related to Ocean Acidification.

Workshop on Acidification in Aquatic Environments to be held 27-29 September 2011 in Tromsø, Norway.

Alexander von Humboldt International Conference on Ocean Acidification to be held 20-24 June in Penang, Malaysia.

Special feature article on ocean acidification by Elizabeth Kolbert in the April 2011 issue of National Geographic

National Research Council's public outreach booklet on ocean acidification

Conclusions from international workshop Economics of ocean acidification: Bridging the gap between ocean acidification impacts and economic valuation (November 16-18, 2010, Monaco)

IMBER-HD Group Formed

The Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) has launched a new working group on Human Dimensions (http://www.imber.info/HD_WG.html), to address Theme 4 of the IMBER Science Plan: "Responses of Society." Co-chaired by Alida Bundy (IMBER SSC, Fisheries and Oceans Canada), Marie-Caroline Badjeck (WorldFish Center), and Moenieba Isaacs (University of Western Cape), the group is tasked with promoting an understanding of the multiple feedbacks between human and ocean systems, and to clarify what human institutions can do to mitigate anthropogenic perturbations of the ocean system or to adapt to such changes. The group includes social and natural scientists with many specialties.

By setting a precedent for bringing together the international natural and social science communities, the IMBER Human Dimensions Working Group's activities could help promote this activity on national scales as well. Working group member Sarah Cooley (OCB, WHOI) hopes to create strong crosslinks between the OCB and IMBER communities to help encourage collaborations between natural and social scientists in the United States, while also promoting inclusion of social science datasets into natural science studies of anthropogenic change.

OCB OA Subcommittee Welcomes New Members

Six new members have joined the OCB OA subcommittee, and they bring a range of scientific expertise and organizational talents to the OA subcommittee:

Andreas Andersson (BIOS/SIO) —
A geochemist who studies global environmental change owing to both natural and anthropogenic processes, with emphases on marine CO_2 and carbonate geochemistry and on ocean acidification's effects on marine calcifiers and coral reefs, calcium carbonate mineral dissolution, and sediment composition.

Rusty Brainard (NOAA PIFSC) — Originally a physical oceanographer, Rusty now performs interdisciplinary and integrated ecosystem observations of coral reef ecosystems across the Pacific Islands and has a particular interest in spatial and temporal changes of reef ecosystems and biodiversity in response to climate change and ocean acidification.

Gretchen Hofmann (UCSB) — A metazoan-focused ecophysiologist who broadly focuses on understanding the role of temperature and oceanographic features on marine species' distributions, and who also employs genomic and traditional biological methods to assess species responses.

Jeremy Mathis (UAF)— A carbon and nitrogen biogeochemist using classical biogeochemical methods to examine ecosystem function in various regions, particularly the Arctic Ocean, the Bering Sea, and the Gulf of Alaska, with special emphasis on human/ocean and land/ocean interactions.

Taro Takahashi (LDEO) — A geochemist who seeks to understand the fate of industrial CO_2 emissions by examining CO_2 cycling through the oceans and atmosphere and by examining the behavior of the oceanic CO_2 sink over time.

Carol Turley (PML) — Originally a microbial biogeochemist, Carol focuses on communicating the possible holistic impacts of ocean acidification, including OA's economic and policy consequences; Carol is also deeply involved in international OA organizations including EPOCA, the SOLAS-IMBER Ocean Acidification Working Group, and the UK Ocean Acidification Research Program.

The OCB-OA subcommittee and Project Office extend our deep gratitude to the six departing OCB-OA subcommittee members: **Barney Balch** (BLOS), **Jean-Pierre Gattuso** (CNRS-UPMC), **Dave Hutchins** (USC), co-chair **Joanie Kleypas** (NCAR), **Chris Langdon** (RSMAS), and **Richard Zeebe** (UH). These scientists have been key players in getting OA research off the ground in both OCB and the scientific community. In the inaugural years of the OCB-OA subcommittee, these scientists have contributed greatly to the OCB-OA subcommittee's accomplishments, some of which include: development of a white paper, "Ocean Acidification: Recommended Strategy for a U.S. National Research Program" (2009), hosting the two-week OCB short course on OA (2009), publication of a special issue on ocean acidification in Oceanography (2009), coauthorship of the National Academies report "Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean" (2010), participation in the Ocean Research and Resources Advisory Panel (ORRAP) and coauthorship of its report "Ocean Acidification Task Force: Summary of Work Completed and Recommendations for ORRAP to Convey to the IWG-OA", (2011), and hosting the first meeting for OA PIs in the US (2011).

OCB to Provide Student Travel Support for the Friday Harbor Ocean Acidification Course

by Michael O'Donnell and Heather Benway

A graduate course at the University of Washington's Friday Harbor Laboratories will immerse students in Experimental Approaches to Understanding Ocean Acidification this summer. Starting on June 20, and running for five weeks, the course will expose students to the nuts and bolts of conducting experiments on the biological effects of acidification. In the first week's module, Andrew Dickson will provide a survey of carbonate chemistry. Moving directly from lecture to the newly constructed analytical laboratory, students will gain hands-on experience actually measuring total alkalinity, pH, and total inorganic carbon. They will quickly put these skills to work documenting the effectiveness of various pH manipulation strategies and quantifying levels of environmental variability. The final module of the course will allow students to pursue independent projects, using their new knowledge and available lab equipment to pursue their own research ideas.

The course received a large number of applications, and the class will be a fascinating group. Many of the students are early in their careers, and the course will equip them with essential skills as they design their graduate research. Following the course, the laboratory handouts and student research presentations will be available on the web.

In an effort to expand the growing U.S. ocean acidification research community and facilitate the training of young scientists, OCB will provide travel support for several U.S. students to participate in the Friday Harbor course. Below is a brief bio from each student. In the Fall 2011 issue of OCB News, we look forward to hearing more from these students on their impressions of the course.

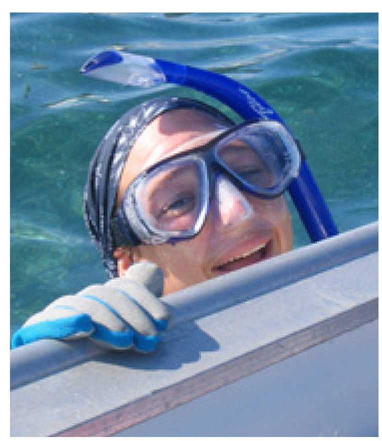
Emily Bockmon
(Scripps Institution of Oceanography)

Emily Bockmon
Scripps Insitiution
of Oceanography

Emily Bockmon received a B.A. in Chemistry from Pomona College in 2008, and came to Scripps Institution of Oceanography the following fall with an interest in chemical oceanography and ocean acidification. With guidance from her advisor, Dr. Andrew Dickson, she is building replicate aquaria, where the effects of ocean acidification on organisms can be studied in highly controlled chemical environments. Additionally she has participated in two CLIVAR Carbon and Hydrography research cruises, and last summer attended the ClimECO2 summer school in Brest, France. This course was of particular interest because of its focus on biological experimental design in ocean acidification research.

Laura Enzor
(University of South Carolina)

When Laura Enzor started her Master's degree at the University of West Florida in 2005, she quickly realized that she didn't want to become a biologist who only works with one type of organism, or only focuses on one specific process. By the time she graduated in 2008, she had been involved in several projects, all of which used different organisms and techniques. These projects included her thesis research, which examined the toxicity of Atlantic stingray venom, and two projects focused on fish behavior in Dry Tortugas National Park. She continued to expand her research experiences when she was given the opportunity to work at Scripps Institution of Oceanography examining the bioluminescence of a marine polychaete. When she started a Ph.D. program at the University of South Carolina in 2010, she wanted to continue to learn how to work with different organisms and new techniques. She decided to focus her research efforts on global climate change, and how the anthropogenic changes ecosystems are currently experiencing could be influenced even further by exotic species invasion.



Laura Enzor
University of
South Carolina

One of the environmental stressors that she will be studying is ocean acidification. The course at Friday Harbor Laboratories will not only help her learn more about this process, but about new experimental approaches as well.

Lydia Kapsenberg
(University of California, Santa Barbara)

Lydia Kapsenberg
University of California,
Santa Barbara

Lydia Kapsenberg joined Dr. Gretchen Hofmann's lab at the University of California, Santa Barbara in Fall 2010, after becoming interested in ocean acidification during an internship in Australia with Dr. Symon Dworjanyn. Her research interests revolve around the effects of ocean acidification on cellular mechanisms from gene expression to the resultant phenotype in order to identify where changes occur along a cellular pathway. She is also interested in understanding the physiological plasticity of sea urchins across their biogeographic range to identify the impact of environmental histories on the organisms' ability to deal with ocean warming and acidification and shed light on their potential for adaptation. By taking the Ocean Acidification course at Friday Harbor Laboratories in Washington, she plans to build her capacity to design and conduct ocean acidification experiments by learning new experimental approaches, developing technical skills, and expanding her knowledge of ocean climate change.

Carlie Pietsch
(University of Southern California, Los Angeles)

Carlie Pietsch is a paleontologist in her second year of a Ph.D. program at the University of Southern California in Los Angeles under the instruction of Dr. David Bottjer. She graduated from Cornell University in 2009 with a bachelor's degree in Ecology and Evolutionary Biology. The focus of her research is on the recovery of marine benthic invertebrates from the end-Permian mass extinction 251 million years ago. Hypotheses for the cause of this extinction include ocean anoxia and perhaps localized acidification events. Her goal during the FHL ocean acidification course is to learn as much as possible about modern acidification, especially the biological responses to these events, in order to apply that knowledge to hypothesized acidification intervals in the geologic record. The environmental changes and biological responses associated with acidification of the modern oceans are key to understanding the mechanisms of past mass extinctions on Earth.

Carlie Pietsch
University of Southern
California, Los Angeles

Chelsea Vaughn
(Smith College '09)

Chelsea is thrilled to have been selected to participate in the ocean acidification course at Friday Harbor Labs. Her interest in ocean acidification research is relatively recent, but her passion for coral reef conservation goes back several years. After being funded by Smith College to conduct fieldwork on the effects of sedimentation on coral reefs in Indonesia and Madagascar, she discovered not only a love for scuba diving but a desire to keep our reefs as beautiful as possible. She would like to further her understanding of ocean acidification as it applies to changes in reef health, as well as the relevant techniques used in the lab and field. The upcoming ocean acidification course at FHL will be a fantastic way to prepare for graduate school at California State University, Northridge in January 2012. Under the direction of Dr. Peter Edmunds, she will examine the influence of ocean acidification on reef health in Moorea, French Polynesia and continue working towards her goal of protecting coral reefs.

Chelsea Vaughn
Smith College

Pausing for a glamour shot while monitoring benthic percent cover at Hoga Island in the Wakatobi Marine National Park, Indonesia (July 2008)

OCB Calendar

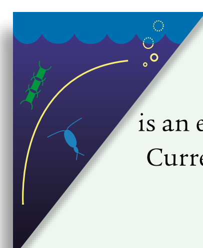
2011	
May 22–26:	Ecosystem Studies of Sub-Arctic Seas (ESSAS) open science meeting (Seattle, WA)
May 23–25:	OCB Scoping Workshop A Biogeochemical Flux program aligned with the Ocean Observatories Initiative (Woods Hole, MA)
May 31–July 8:	C-MORE summer course in microbial oceanography (Honolulu, HI)
June 13–15:	The aquatic ecosystem puzzle: Threats, opportunities, and adaptation (Siena, Italy)
June 15–July 1:	Cooperative Institute for Climate and Satellites—North Carolina (CICS-NC) Summer Institute on Climate Change: Turning Adaptation into Action - Define Your Strategic Advantage (Asheville, NC)
June 19–July 9:	Microbial Oceanography: The Biogeochemistry, Ecology and Genomics of Oceanic Microbial Ecosystems (Bermuda Institute of Ocean Sciences)
June 20–July 22:	Graduate Course "Experimental approaches to understanding ocean acidification" (Friday Harbor Laboratories, University of Washington)
June 20–24:	7th EGU Alexander von Humboldt Conference on "Ocean Acidification: Consequences for marine ecosystems and society" (Penang, Malaysia)
June 27–29:	Modeling and synthesis of Southern Ocean natural iron fertilization (Woods Hole, MA)
June 27–30:	3rd Advances in marine ecosystem modeling symposium (Plymouth, UK)
June 28–July 1:	The future of the 21st century ocean: Marine sciences and European research infrastructures, an international symposium (Brest, Le Quartz, France)
July 3–7:	11th International Conference on the Biogeochemistry of Trace Elements (Florence, Italy)
July 4–15:	Darwin Summer School on Biogeosciences: Perturbation of the global carbon cycle (Utrecht and Texel, Netherlands)
July 10–16:	11th International Symposium on Antarctic Earth Sciences (ISAES XI) (Edinburgh, Scotland)
July 11–16:	Short Course: Radiocarbon in Ecology and Earth System Science (Irvine, CA)
July 18–21:	2011 OCB Summer Workshop (Woods Hole, MA) – **note joint science session with US CLIVAR on July 19**
July 19–21:	2011 US CLIVAR Summit (Woods Hole, MA) - **note joint science session with OCB on July 19**
August 14–19:	2011 Chemical oceanography Gordon research conference (Andover, NH)
August 14–19:	Goldschmidt conference 2011 (Prague, Czech Republic)
Aug 29–Sept 10:	SOLAS Summer School 2011 (Corsica, France)
Aug 30–Sept 1:	SCOR/POGO Open Science Meeting for an International Quiet Ocean Experiment (Paris, France)
September 7–14:	Marine Ecosystem Evaluation in a Changing Environment (MEECE) Summer School 2011 (Ankara, Turkey)
September 8–15:	Young LOICZ Forum (YLF 2011) (Yantai, China)
September 11–16:	DPG Physics School Physics of the Ocean (Physikzentrum Bad Honnef, Germany)
September 12–16:	Joint IMBER/SOLAS/IOCCP meeting - The ocean carbon cycle at a time of change: Synthesis and vulnerabilities (Paris, France)
September 12:	Prospectus for UK Marine Science for the next 20 years (London, UK)
September 12–15:	LOICZ Open Science Conference 2011: "Coastal Systems, Global Change and Sustainability" (Yantai, China)
September 19–23:	ICES Annual science conference (Gdansk, Poland)

2011 (continued)	
September 22–23:	Plankton 2011: Plankton biodiversity and global change (Plymouth Guildhall, England, UK)
September 26–30:	World Conference on Marine Biodiversity (Aberdeen, Scotland)
September 27–29:	Workshop on acidification in aquatic environments (Tromsø, Norway)
October 14–23:	PICES 2011 Annual Meeting: Mechanisms of Marine Ecosystem Reorganization in the North Pacific Ocean (Khabarovsk, Russia)
October 22–29:	DISCCRS VI Interdisciplinary climate change research symposium (Colorado Springs, CO)
October 24–29:	Seventh WIOMSA scientific symposium entitled "Coping with global change" (Kenya)
October 24–28:	WCRP Open Science Conference: Climate research in service to society (Denver, CO)
October 24–26:	EUR-OCEANS conference ocean deoxygenation and implications for marine biogeochemical cycles and ecosystems (Toulouse, France)
November 14–17:	3rd GEOTRACES Data-Model Synergy Workshop (Barcelona, Spain)
Nov 29–Dec 2:	Earth observation for ocean-atmosphere interactions science - A joint ESA-SOLAS-EGU conference (Frascati, Italy)
December 5–9:	2011 American Geophysical Union Fall Meeting (San Francisco, CA)
2012	
February 19–24:	2012 Ocean Sciences Meeting (Salt Lake City, UT)
March 26–29:	Planet Under Pressure: new knowledge towards solutions (London, UK)
May 7–10:	SOLAS Open Science Conference (Cle Elum, WA)
May 15–19:	2nd International Symposium: Effect of climate change on the world's oceans (Yeosu, Korea)
September 3–6:	Bjerknes Centre open science conference: Climate change in high latitudes (Bergen, Norway)
September 24–27:	Third Symposium on the Ocean in a High-CO_2 World (Monterey, CA, contact: Ed.Urban@scor-int.org)

OCB RELEVANT FUNDING OPPORTUNITIES

For a complete listing, including NSF interdisciplinary and cross-directorate funding opportunities, please visit http://www.us-ocb.org/data/funding.html. For Gulf oil spill funding opportunities, please visit http://www.us-ocb.org/data/gulf.html.

- **June 1, 2011:** NASA ROSES 2010 - A4. Land Cover/Land Use Change proposal deadline
- **August 15, 2011:** NSF Biological and Chemical Oceanography proposal targets
- **September 1, 2011:** NSF Catalyzing New International Collaborations proposal target
- **November 15, 2011:** NSF Dynamics of Coupled Natural and Human Systems (CNH) proposal deadline



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