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The Marine Carbon Cycle of the Arctic Ocean: Some Thoughts About The Controls on Air-Sea CO_2 Exchanges and Responses to Ocean Acidification

by Jeremy T. Mathis[1] and Nicholas R. Bates[2]

1. University of Alaska Fairbanks, Fairbanks, AK · 2. Bermuda Institute of Ocean Sciences, Bermuda

Introduction

The Arctic Ocean and the shallow continental margins that surround it (Fig. 1) play an important and likely increasing role in the global freshwater cycle, Atlantic overturning circulation, and biogeochemical cycling of carbon, nutrients, and gases such as carbon dioxide (CO_2) and methane. The region is particularly sensitive to atmosphere-ocean-sea-ice forcing and feedbacks and ecosystem changes associated with warming temperatures and sea-ice loss. Numerous studies over the last decade have shown that warming and increased sea-ice loss is occurring in the Arctic and the IPCC Fourth Assessment reported that average Arctic temperatures have increased over the last century at nearly twice the global average and since 1978, sea-ice extent decreased on average by 2.7% per decade. However, over the last several years, the pace of decline has accelerated beyond model predictions and in summer 2007, sea-ice extent declined by 20-25% with an additional loss of ~1.5 million km². Much of this loss occurred over the deep Makarov and Canada Basins of the Arctic Ocean (Fig. 1). Although ice extent rebounded in 2008 and 2009, the duration of ice-free conditions in the Arctic continues to increase.

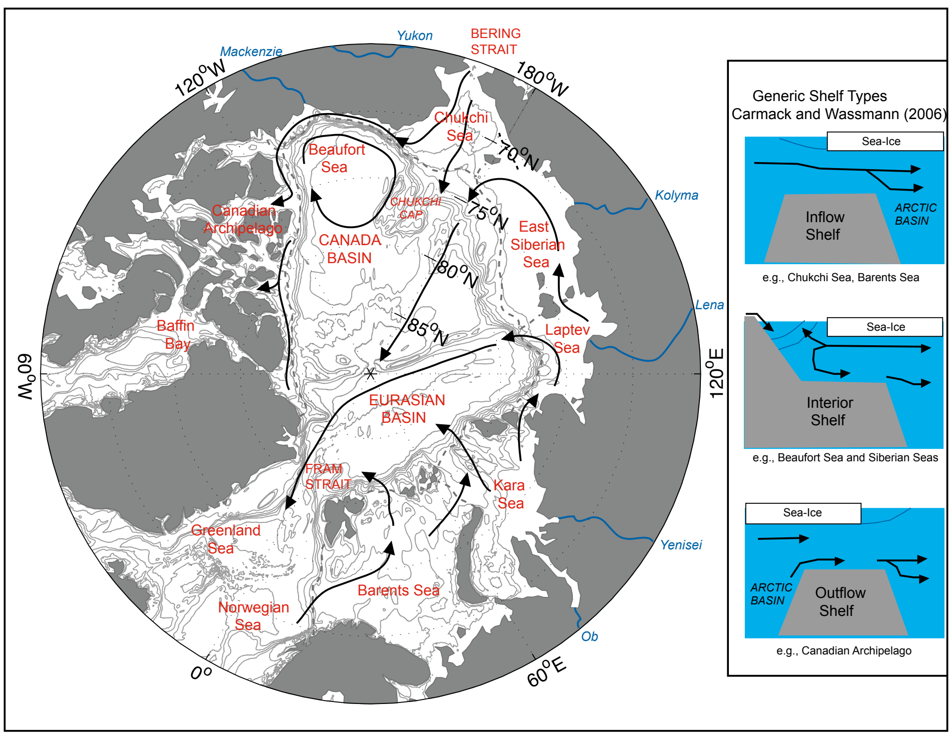

Figure 1. Schematic of the Arctic Ocean, central basin (Canada and Eurasian Basins) and Arctic continental shelves (with approximate boundaries of each Arctic shelf sea), and major rivers draining into the region. General surface circulation features are also shown. Inset: Characterization of Arctic Ocean continental shelves as “inflow,” “interior,” or “outflow” shelves, according to Carmack and Wassmann (2006). Modified from Bates and Mathis (2009).

The Arctic Marine Carbon Cycle

The Arctic has a dynamic carbon cycle that is responsive to change. There are large reservoirs of terrestrial and oceanic carbon in the region that are projected to respond rapidly to changes in climate forcing (i.e. thawing permafrost, coastal erosion, etc.). Additionally, seasonally intense riverine fluxes of freshwater contain high concentrations of dissolved organic carbon (DOC), particulate organic carbon (POC), and dissolved inorganic carbon (DIC) that are disproportionately large compared to other basins and much more susceptible to climate change. On the continental shelves and deep basins of the Arctic Ocean, there are many processes, interactions, and feedbacks that can change the biological and physical controls on the marine carbon cycle, which in turn can change the magnitude and direction of air-sea gas exchange and the regional response to ocean acidification. The supply of warmer, nutrient-rich Pacific and Atlantic Ocean waters has a large impact on the marine carbon cycle of Arctic inflow shelves such as the Chukchi and Barents Seas (Fig. 2). On interior shelves (i.e. Kara, Laptev, East Siberian, and Beaufort Sea) river runoff and sea-ice melt/production processes have a much more significant impact on the marine carbon cycle (Fig. 3).

Seasonal light and temperature changes, sea-ice dynamics, and freshwater inputs all play a role in controlling the marine carbon cycle of the Arctic shelves and the broader Arctic Ocean. Cooling of Pacific and Atlantic Ocean waters as they flow into the Arctic acts to decrease the partial pressure of CO_2 (pCO_2) of surface waters. During spring and summer, sea-ice retreat, abundance of light, and availability of nutrients facilitates a short but intense growing season for phytoplankton in surface waters on the shelves of the Arctic, further decreasing seawater pCO_2. For example, rates of water column primary production can exceed 100-300 g C m^{-2} y^{-1} for the Chukchi and Barents Sea shelves (Fig. 2), while the central Arctic Ocean remains largely oligotrophic with extremely low rates

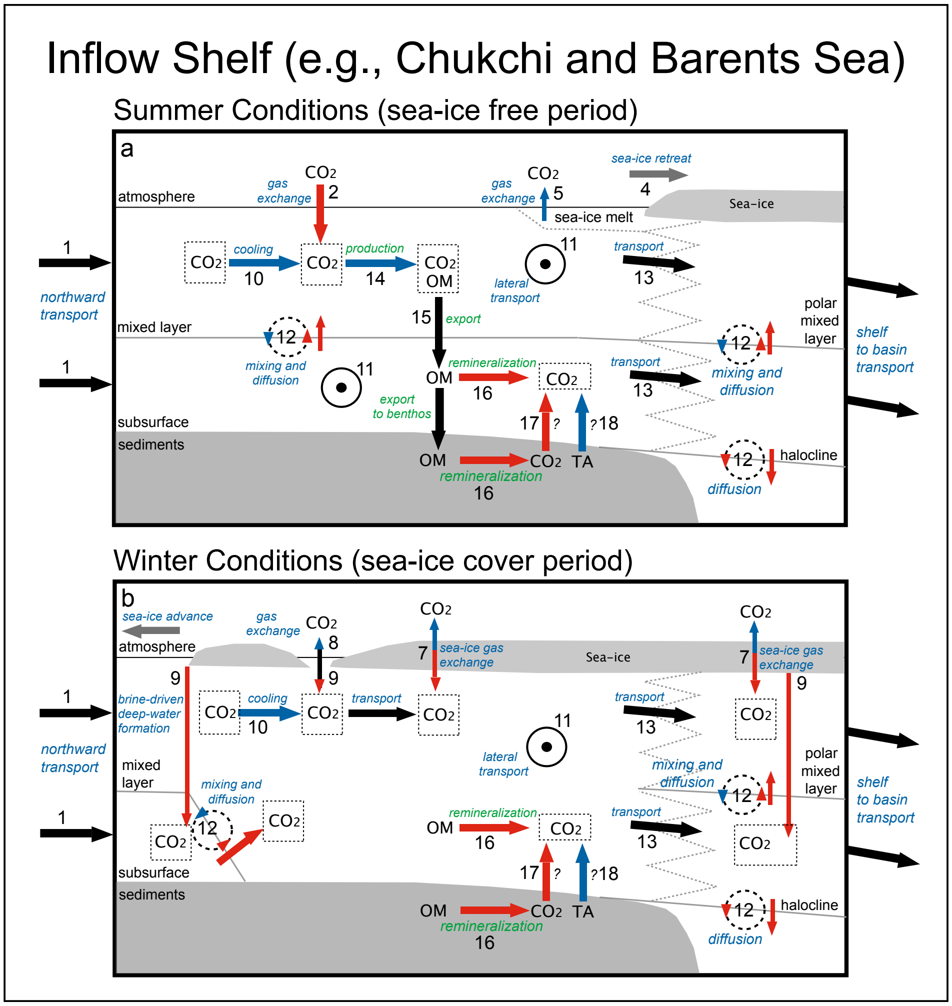

Figure 2. Schematic of processes potentially influencing the inorganic carbon cycle and air-sea CO_2 gas exchange on "inflow" shelves of the Arctic (e.g., Barents and Chukchi Seas). The two panels represent physical and biological processes likely operating during the summertime sea-ice-free period (Panel a), and during the wintertime sea-ice-covered period (Panel b). The processes are denoted by numeral with the caveat that the size of arrow does not necessarily reflect magnitude of flux, transport, or transformation of CO_2. Blue arrows denote processes that likely decrease seawater pCO_2, while red arrows denote processes that likely increase seawater pCO_2. Black arrows denote processes that do not impact pCO_2 directly or reflect uncertainty as to whether the process decreases or increases seawater pCO_2. The processes include: 1. northward transport of inorganic carbon; 2. air-sea gas exchange; 4. exposure of surface water to the atmosphere due to sea-ice retreat and melting; 5. localized air-sea gas exchange from surface water highly influenced by sea-ice melt; 7. air-sea gas exchange through sea-ice; 8. winter air-sea gas exchange in leads and polynyas; 9. inorganic carbon flux due to brine-rejection during deep-water formation in fall and winter; 10. cooling of surface waters during northward transport on Atlantic or Pacific Ocean waters into the Arctic Ocean; 11. between-shelf transport of water and carbon; 12. redistribution of inorganic carbon between mixed layer and subsurface due to vertical diffusion and vertical entrainment/detrainment due to mixing; 13. shelf-basin exchanges of inorganic carbon (i.e. DIC) and organic carbon due to generalized circulation and eddy mediated transport; 14. net uptake of CO_2 due to phytoplankton photosynthesis or new production; 15. export flux of organic matter (OM) or export production; 16. remineralization of organic matter back to CO_2 either in subsurface waters or in sediments; 17. release of CO_2 from sediments; and 18. release of alkalinity from sediments due to anaerobic processes in sediments. Modified from Bates and Mathis (2009).

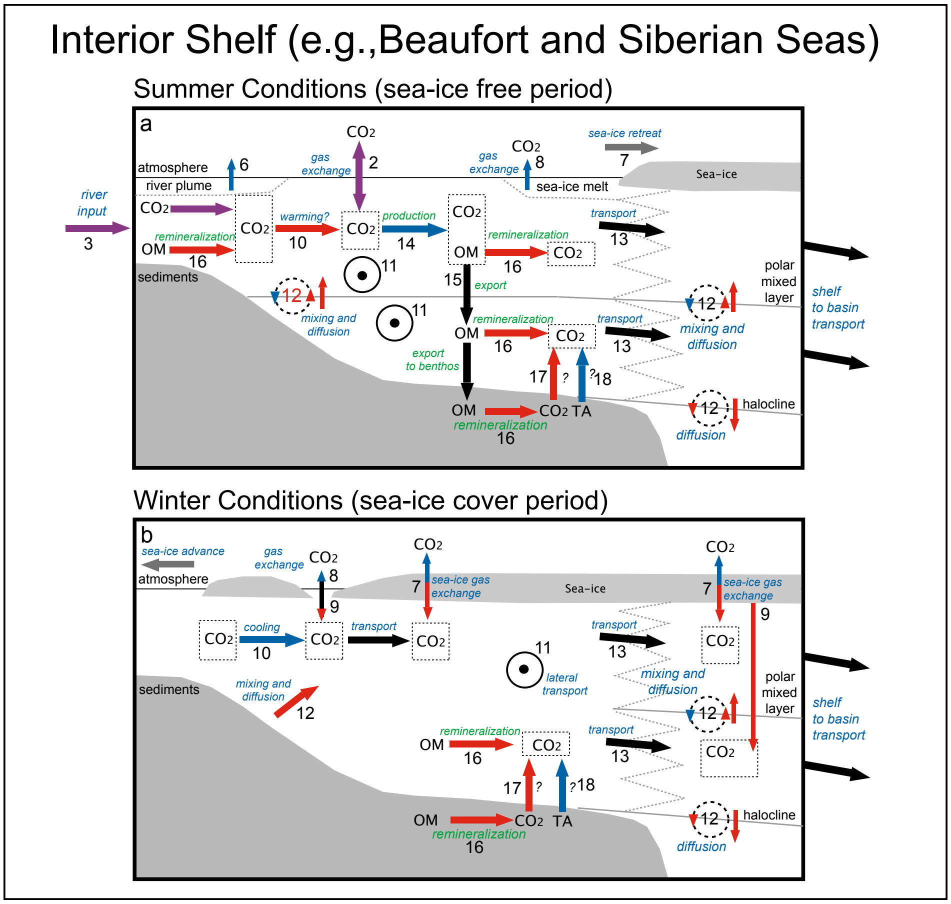

Figure 3. Schematic of processes potentially influencing the inorganic carbon cycle and air-sea CO_2 gas exchange on "interior" shelves of the Arctic (e.g., Beaufort and Siberian shelf Seas such as the Kara, Laptev and East Siberian Sea). The two panels represent processes likely operating during the summertime sea-ice-free period (Panel a), and during the wintertime sea-ice-covered period (Panel b). The processes are denoted by numeral with the caveat that the size of arrow does not necessarily reflect magnitude of flux, transport or transformation of CO_2. Blue arrows denote processes that likely decrease seawater pCO_2, while red arrows processes that likely increase seawater pCO_2. Black arrows denote processes that do not impact pCO_2 directly or reflect uncertainty as to whether the process decreases or increases seawater pCO_2. The processes include those described for Fig. 2, but also include the following: 3. river input of organic carbon and DIC. This can also include inputs of carbon from coastal erosion of sediments, for example; and 6. efflux of CO_2 from river dominated surface waters. Process 10 includes warming of surface waters during sea-ice free period from solar input or lateral transport of warmer waters from upstream "inflow shelf". Modified from Bates and Mathis (2009).

of net community production (NCP) and export production. In general, the inflow shelves (i.e. Chukchi and Barents Seas) are much more productive than the interior shelves (i.e. Siberian Seas, Beaufort Sea, Canadian Archipelago) due to greater nutrient supply and less turbidity from riverine discharge (Fig. 3). As ice retreats from the shelves in spring and summer, intense phytoplankton blooms cause DIC concentrations to be drawn down by as much as 300 µmoles kg^{-1} and seawater pCO_2 to decrease by 100-200 µatm, while nitrate is completely exhausted in the mixed layer. Subsequently, in winter, sea-ice advance and brine rejection processes, mixing and homogenization of the water-column, and continuing inflow of Pacific and Atlantic Ocean waters act to return the marine carbon cycle to its pre-summer condition.

The ultimate fate of the organic carbon produced during these summer phytoplankton blooms is still not well understood. Studies in the Chukchi Sea found that ~10% of NCP is converted to DOC, while ~15% is converted to POC suspended beneath the surface layer. The remaining 75% of NCP is exported from the mixed layer as sinking particles, thus sustaining the rich benthos occupying the sea floor, a process that sustains the benthos of most Arctic shelves.

Sea-ice melt and river runoff also have significant impacts. Sea-ice melt injects freshwater at the surface, dilutes total alkalinity and DIC, and enhances stratification, with associated impacts for phytoplankton primary production and air-sea CO_2 flux. River runoff in the interior shelves (e.g., Mackenzie River for the Beaufort Sea and the Ob and Yenisey for the Siberian shelves) delivers low alkalinity, high pCO_2 freshwater and a large terrestrially-derived organic matter load, which significantly alters the hydrography and carbon cycling of these regions (Fig. 3).

Air-Sea CO_2 fluxes in the Arctic

Very few broad studies of the spatio-temporal distributions of pCO_2 and subsequent air-sea fluxes of CO_2 have been conducted in the Arctic Ocean and adjacent shelves compared to other coastal and open-ocean environments. Seasonal sea-ice cover plays an important role in determining air-sea CO_2 exchange, acting as a barrier (or at least suppressing gas exchange significantly) between the atmosphere and surface waters of the region for much of the year. The major determinants of seawater pCO_2 undersaturation/oversaturation, and hence, air-sea CO_2 exchange in the Arctic Ocean, are the preconditioning of Pacific and Atlantic Ocean waters flowing into the Arctic, the amount of cooling during poleward transport of surface waters, and the net ecosystem metabolism (NEM) of the shelves, which is the net balance of autotrophic (photosynthesis and NCP) and heterotrophic (respiration and remineralization) processes.

The capacity of seawater to absorb CO_2 depends primarily on the buffer capacity (or Revelle Factor) of seawater. Tropical and subtropical waters tend to have low Revelle Factors (8-10), with a greater capacity to absorb atmospheric CO_2 compared to temperate and subpolar waters with high Revelle Factors (11–14). However, recent studies indicate that the surface waters of the Canada Basin have unusually low Revelle Factors (~3.5–6.5) due to the removal of DIC (while alkalinity remains unchanged) on the Chukchi Sea shelf by primary production, and by the addition of river TA that acts to decrease the DIC:alkalinity ratio (shifting waters to lower Revelle Factors). All of these factors have a strong influence due to the relatively short residence time (~10–15 years) of Arctic Ocean surface waters.

Within the Arctic, seasonally variable rates of photosynthesis and remineralization, sea-ice melt, and river runoff produce a diverse pattern of surface seawater pCO_2 across the region. The inflow shelves of the Chukchi and Barents Sea and the outer parts of the Siberian Sea and Beaufort Sea shelves tend to have lower seawater pCO_2 than the atmosphere. The limited data collected in the Arctic suggests that the large seasonal drawdown of CO_2 associated with ice retreat across the shelves cause the Arctic Ocean and adjacent continental shelves to act as sinks for atmospheric CO_2. In the deep basins of the Arctic (e.g., Canada and Eurasian Basins) perennial ice-cover has inhibited the uptake of CO_2 in the undersaturated waters of the polar mixed layer. With sea-ice loss, however, a short-lived increase in the ocean uptake is anticipated and a partial equilibration is expected to occur in ice-free waters of the deep Arctic basin (Fig. 2). Importantly, not all regions of the Arctic are potential sinks for atmospheric CO_2. Nearshore areas of the Siberian Sea shelves and parts of the Beaufort Sea that are highly influenced by river runoff and sea-ice melt can have surface water with much higher seawater pCO_2 than the atmosphere. For example, in the East Siberian Sea, there is some evidence that the surface waters are a slight source of CO_2 to the atmosphere due to high rates of terrestrial DOC inputs, marine DOC production, and remineralization to CO_2. In addition, seasonal upwelling could bring waters supersaturated with respect to atmospheric CO_2 into the mixed layer during late summer and fall.

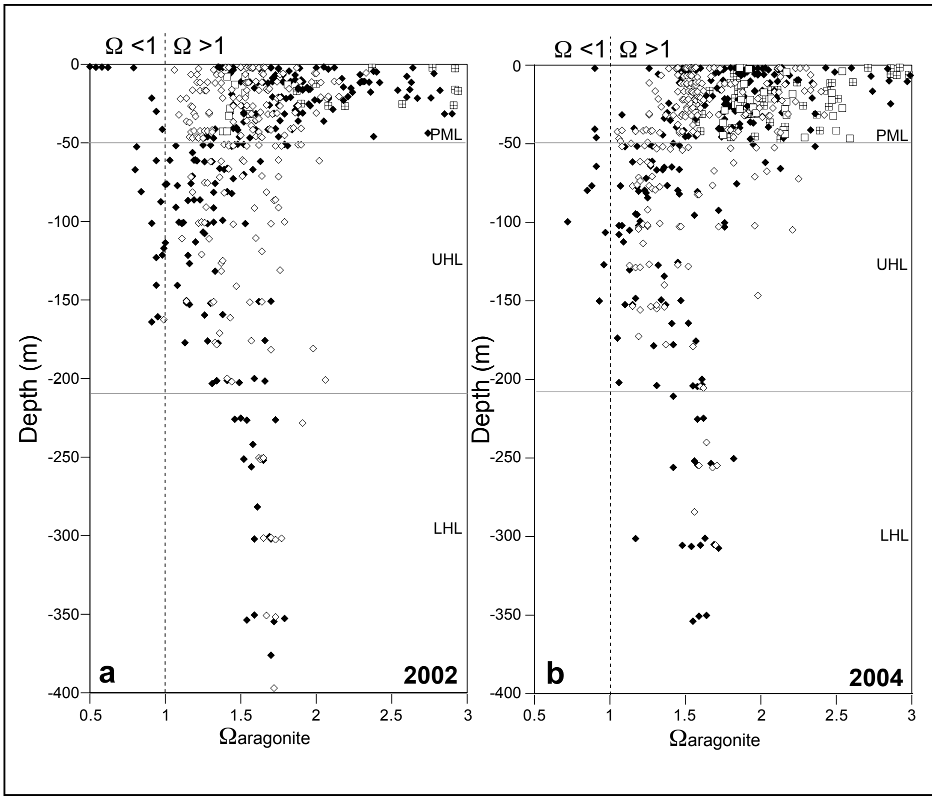

Figure 4. Aragonite mineral saturation state ($\Omega_{aragonite}$) plotted against depth observed in the Chukchi Sea of the Arctic Ocean. Most of the data represent mixed layer water (0–30 m) and underlying halocline water (30 m to bottom depth of 60–100 m) from the Chukchi Sea shelf. Also included are data from the Chukchi Sea shelf slope where water depths varied from ~60 to ~500 m. (a) The 2002 spring and summer data; and (b) the 2004 spring and summer data. The black vertical dashed lines represent the saturation depth where Ω = 1. Modified from Bates et al. (2009)

Several previous estimates using indirect mass balances to constrain the net oceanic CO_2 sink in the Arctic Ocean and adjacent shelves have ranged from 70 to 120 Tg C yr^{-1} with considerable uncertainty due to the assumptions made in the mass balance approach. Recently, a mass balance approach using data from the Shelf-Basin Interactions (SBI) II project showed that the annual net air-to-sea flux of CO_2 from the Chukchi Sea was ~27 to 39 ± 7 Tg C yr-1, making it the largest CO_2 sink in the marginal seas of the Arctic Ocean. This sink for CO_2 has likely increased over the last 3 decades due to sea-ice retreat with future sea-ice melting enhancing air-to-sea CO_2 flux by ~25% per 10 years.

In summary, surface waters of the Arctic Ocean tend to be pre-conditioned to take up large quantities of atmospheric CO_2 in response to continued sea-ice loss, likely fundamentally changing the carbonate chemistry of the region. Among several caveats to this assertion, is that winter conditions across the Arctic need to be resolved, and rapidly changing conditions in the Siberian Sea shelves could act to increase these areas as sources of CO_2 to the atmosphere.

Ocean Acidification in the Arctic

In addition to rising temperatures and sea-ice loss, the Arctic Ocean is also vulnerable to seawater chemistry changes in response to the ocean uptake of anthropogenic CO_2 released to the atmosphere through fossil fuel use and changes in land use practices. As the global ocean has absorbed anthropogenic CO_2 from the atmosphere, the average pH of the surface ocean has decreased by about 0.1 units with the most rapid changes occurring in the last half century due to accelerating anthropogenic CO_2 emission rates. If CO_2 emission rates continue as projected, the average pH of the ocean could decrease by another 0.3–0.4 units by the year 2100. This ocean acidification (OA) process is a tangible manifestation of environmental change that could impact a variety of pelagic and benthic marine organisms by reducing the saturation state of calcium carbonate ($CaCO_3$) minerals such as aragonite and calcite ($\Omega_{aragonite}$ and $\Omega_{calcite}$).

The cold waters of high latitude regions are particularly sensitive to OA because they are naturally low in carbonate ion concentration due to ocean mixing patterns and the increased solubility of CO_2 at low temperatures. Consequently, seawater $\Omega_{aragonite}$ and $\Omega_{calcite}$ are typically lower in polar and subpolar areas than in temperate and tropical regions. Limited data have shown that most surface waters of high latitude oceans are presently supersaturated with respect to aragonite, a mineral form of calcium carbonate that is about 50% more soluble than calcite. However, recent observations in the Bering Sea and Arctic Ocean have found locations where waters are undersaturated with respect to aragonite at the surface, and models project that under current rates of CO_2 emissions, even larger areas of the Arctic Ocean and parts of the subarctic Pacific Ocean could become undersaturated with respect to aragonite within two decades. In this scenario, calcifying organisms that form $CaCO_3$ shells and tests could be particularly vulnerable, especially during the larval stage. These rapid rates of change in high latitudes could have major consequences for both pelagic and benthic calcifiers, as well as cascading effects up the foodweb.

There is also a complex feedback between biological processes and seawater carbonate chemistry. High rates of CO_2 uptake in surface waters through NCP and subsequent remineralization at depth can exert strong controls over surface and subsurface levels of seawater pCO_2 and thus drive divergent trajectories for $\Omega_{aragonite}$ and $\Omega_{calcite}$, particular for inflow shelves (Fig. 4). During sea-ice retreat, NCP acts to increase $\Omega_{aragonite}$ and $\Omega_{calcite}$ in surface waters, but remineralization of organic carbon (either from marine phytoplankton production or input of river runoff derived organic matter) acts to decrease $\Omega_{aragonite}$ and $\Omega_{calcite}$ in subsurface waters. As biological processes and ecosystems respond to future environmental change in the Arctic, the mitigation of OA impacts in surface waters and amplification of OA impacts in subsurface waters will also change. In addition, compared to many other coastal environments there are large uncertainties in the duration and extent of primary production in the region. Most studies have been conducted in spring and early summer, with virtually no measurements made later in the season, particularly during times of intense upwelling, which could replenish nitrate in the surface waters while solar irradiance is still sufficient to support primary production. It is likely that along with nitrate, waters with high seawater pCO_2 and low Ω/pH are fluxed onto the shelves during these events, reinforcing and perhaps exacerbating the suppression of Ω for $CaCO_3$ minerals.

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Low Oxygen Regions in the Oceans

by Kendra Daly[1], Francis Chan[2], and Nancy Rabalais[3]

1. University of South Florida, St. Petersburg, FL · 2. Oregon State University, Corvallis, OR · 3. Louisiana Universities Marine Consortium, Chauvin, LA

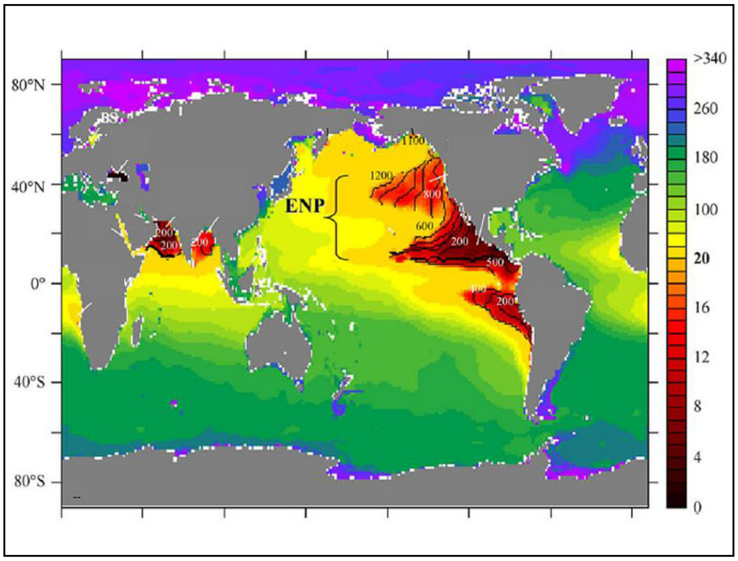

Figure 1. Locations of OMZ regions after (1)

During Earth's geological history, widespread anoxia (no oxygen) has occurred throughout the oceans. For example, Oceanic Anoxic Events occurred during the Cretaceous period, and elevated atmospheric CO_2 and an anoxic ocean were linked with large extinction events of marine organisms at the end of the Permian. In the modern ocean, large areas of the eastern Pacific, the northern Indian, and the southeast Atlantic oceans have persistently low oxygen concentrations (~1-20 µmoles kg^{-1}) at intermediate water depths (~100-1000 m), owing to sluggish circulation, oxygen-poor source waters, lack of exchange with oxygenated surface waters, and decomposition of sinking particles (1) (Fig. 1). Open ocean regions with permanent oxygen minimum zones (OMZs) account for ~8% of the global ocean area. These open ocean OMZs are characterized by elevated surface productivity and strong vertical O_2 gradients (oxyclines) that strongly influence biological assemblages and biogeochemical processes. Geochemical stratification supports chemolithoautotrophs (organisms that obtain energy from inorganic compounds), which can fix carbon from CO_2 and represent mid-water productivity "hotspots." Most organic matter in the ocean is remineralized aerobically, except in suboxic waters (<4.5 µmoles O_2 kg^{-1}) where denitrification (NO_3^- serves as primary electron acceptor) and anammox (anaerobic ammonia oxidation) are major sinks for global fixed nitrogen (2); however, these microbial processes appear to vary between OMZ systems. Waters overlying OMZs, in particular the eastern tropical Pacific, also emit a substantial portion of the total oceanic nitrous oxide (N_2O) flux. These emissions may further exacerbate the impacts of global warming and contribute to ozone holes. In addition, OMZs are characterized by relatively low pH levels (7.3 at 1,000 m (3)), and may therefore be sensitive to further ocean acidification associated with increasing atmospheric CO_2 levels.

OMZs intersect with continental margins in upwelling systems of eastern boundary currents and in the Indian Ocean, which impacts benthic organisms and commercially important marine resources (4, 5). The occurrence and extent of coastal hypoxia due to OMZs vary by region and latitude, and are seasonally and interannually variable due to regional and large-scale forcings such as seasonal monsoons or ENSO events. In addition, hypoxia (<63 µmoles O_2 kg^{-1}) in estuaries and near coastal regions has increased in the last 50 years due to human activities, especially nutrient loading, leading to "dead zones" (6). Hypoxia has both direct and indirect effects on the function of organisms, in that behavior and physiology may change before lethal oxygen conditions occur. Some marine organisms have adapted in response to long-term exposure to hypoxia (e.g., physiological strategies to tolerate short periods of vertical migration through suboxic OMZs and morphological features in benthic organisms inhabiting seamounts intersected by OMZs). In the case of recent anthropocene hypoxia in estuaries and continental shelves, organisms are not similarly adapted and must flee or often die if exposed to low oxygen conditions for extended periods.

The expanse and dynamics of OMZs are strongly influenced by climate change. Ocean General Circulation Models predict that increased atmospheric warming will lead to a decline in oxygen concentrations and an expansion of OMZs (7). Indeed, recent reports indicate that oxygen and pH are decreasing and OMZs are expanding (3, 8-10). The acceleration of coastal hypoxia due to human-induced stressors (increased nutrient loads, shifts in nutrient ratios, altered hydrology, and freshwater inflow) has also resulted in significant changes in coastal ecosystems. Because the interactions between low oxygen biogeochemical processes and marine food webs are not well understood, our ability to forecast the effects of climate change and human activity on elemental cycling and the efficiency of the biological pump is limited. Predicted increases in water temperature and stratification and decreases in O_2 and pH will exceed physiological tolerances of many marine organisms, thus limiting suitable habitats (habitat compression). Coupled with changes in microbial community composition, these projected changes will also impact biogeochemical cycles.

Below we describe recent results from three low oxygen regions: the eastern tropical north Pacific permanent OMZ, climate-related hypoxia on the Oregon shelf, and human-induced seasonal hypoxia in the Gulf of Mexico Mississippi River plume.

Permanent OMZs — The Eastern Tropical North Pacific

The eastern tropical north Pacific (ETNP) is approximately 41% of the area occupied globally by OMZs and is the largest of five major low-O_2 biomes (1). This region is important for its roles in climate variability (e.g., ENSO events), fisheries (e.g. yellowfin tuna, jumbo squid), and in the global carbon and nitrogen cycles. A special review volume (11) summarized results of earlier investigations. The ETNP is a complex hydrographic region of merging surface waters from the California Current and the North Equatorial Countercurrent. Unique characteristics include a strong, shallow pycnocline, overlying suboxic waters (~40 to 800 m), and the Costa Rica Dome upwelling region. Thermocline shoaling and wind stress curl-induced upwelling are the primary processes controlling macronutrient supply to surface waters. This region also appears to be iron-limited, which may limit N_2 fixation (12).

A recent NSF-funded program, the Eastern Tropical Pacific project, involved an investigation of how distinctive OMZ biogeochemical features and food webs influence carbon and nitrogen cycles using a combination of relatively new technologies and experimental approaches. For example, a camera imaging system (SIPPER) documented the fine-scale vertical distribution of particles and zooplankton in relation to environmental parameters (Fig. 2). Gelatinous zooplankton, which are not quantitatively collected by nets, were shown to have relatively high abundances. Maximum grazer densities occurred in the oxygenated surface layer, near the chlorophyll maxima, and deeper vertical ranges depended on an individual species tolerance to suboxia. Microzooplankton (ciliates, dinoflagellates, flagellates) were the major consumers of primary production. Meso- and macrozooplankton assemblages were dominated by copepods, which fed at several trophic levels. Resident mesopelagic zooplankton and vertical migrator abundances were significantly reduced compared to assemblages from more oxygenated mesopelagic regions. In addition, particle density increased relative to the total number of particles in the OMZ. Thus, sinking particles likely experience reduced biogeochemical alteration due to reduced heterotrophy, leading to enhanced carbon flux to depth. Surface warming and decreasing O_2 levels may result in further habitat compression. The combined impacts of changes in surface communities and suboxic chemolithoautrophy, denitrification, and reduced heterotrophy on carbon export need to be evaluated, especially given that these regions are increasing in extent.

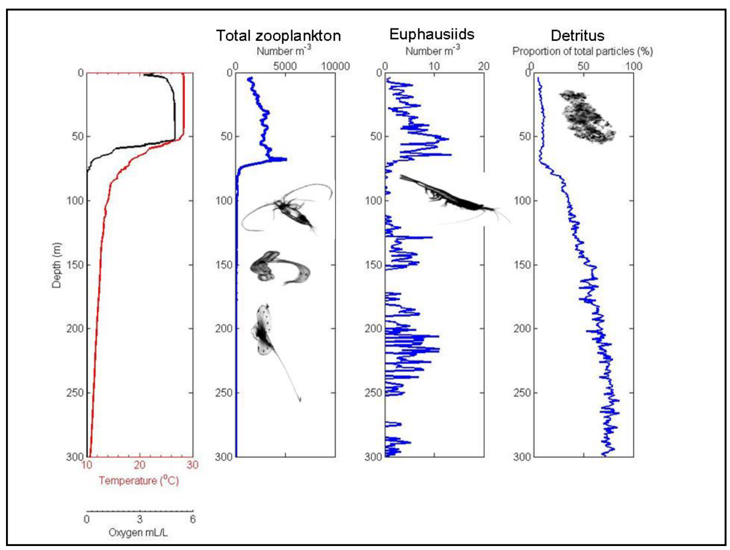

Figure 2. Fine-scale vertical profiles of detritus and zooplankton between 0-300 m (Dec. 2008) obtained by the SIPPER imaging system in the eastern tropical north Pacific (Daly and Remsen, unpubl.). The percent fraction of detrital particles increased in the OMZ relative to the total number of particles imaged.

Eastern Boundary Current Hypoxia — The California and Humboldt Current Systems

Hypoxia is a common feature of most eastern boundary current systems where wind-driven coastal upwelling transports oxygen-poor but nutrient-rich water from the ocean interior onto shallow continental shelves. While the greatest volume of hypoxic water can be found in oceanic OMZs such as the ETNP, the presence of water column hypoxia can play important roles in structuring elemental cycling, microbial communities, metazoan food webs, and fishery dynamics in some of the ocean's most productive coastal ecosystems. For example, the co-occurrence of hypoxia and enhanced flux of organic matter over upwelling shelves greatly favors the sea-air flux of N_2O, an important greenhouse gas (13). This flux reflects not only water column and sediment denitrification commensurate with the onset of suboxia, but also active rates of bacterial and archeal nitrification. Production of N_2O by the latter is elevated by oxygen-poor conditions (14). The formation of hypoxic zones can also be instrumental in determining the distribution of fish populations and their fisheries access. Catch per unit effort for demersal fish species can decline with the intensification of hypoxia stress (15), and anoxia can result in mass mortality events, including recruitment failures. Upwelling systems support some of the world's most productive fisheries, and favorable modulation of predator-prey interactions from oxygen habitat compression has been hypothesized to contribute to the exceptional productivity of the Peruvian anchoveta fishery (16).

While advective inputs of oxygen-poor water and enhancement of export production can strongly predispose eastern boundary current shelves to hypoxia, the actual expression of hypoxia and the relative contributions of physical and biogeochemical processes to oxygen deficits can vary considerably across and within systems. For example, the equatorward shoaling of the core of the oceanic OMZ along the Humboldt Current results in a direct intersection of the OMZ with the continental shelf along the Peruvian and northern Chilean coasts. There, nearshore shelf suboxia and anoxia are persistent features that reflect the direct advection of water from the OMZ. To the south, along the central Chilean coast, the OMZ deepens and anoxia occurs seasonally as hypoxic waters that overlay the core of the OMZ are advected across the shelf, where they are subject to further oxygen losses (17). Similarly, in the northern California Current, the OMZ is located at depths in excess of 600 m and thus does not intersect the continental shelf. Instead, upwelled water is drawn from below the surface oxycline but well above the core of the OMZ (18). Prior to transport onto the continental shelf, these source waters have historically had low but not hypoxic levels of oxygen. Consequently, the formation of hypoxia and anoxia is dependent on further losses of oxygen as upwelled water transits across a productive shelf.

Hypoxia across eastern boundary current shelf systems can be viewed as a product of remote oceanic forcing and biogeochemical modulation of oxygen budgets at the ecosystem scale. The relative contributions of these physical and biogeochemical forcings are variable, thus giving rise to marked cross-system differences in the intensity and persistence of hypoxia. The degree of coupling between shelf oxygen budgets and upwelling circulation determines the climate sensitivity of hypoxia in these eastern boundary systems. Model projections of oceanic OMZ expansion and intensification of upwelling-favorable wind stress with climate change indicate the potential for increased hypoxia/anoxia across shelf systems (7). Already, our emerging understanding indicates that shelf hypoxia is a dynamic feature of eastern boundary current systems. Over decadal time-scales, shelf anoxia (5) and marked shoaling of the hypoxia horizon (19) have been observed in the California Current System. Over centennial time-scales, paleo-records point to a modern strengthening of oxygen deficits in the northern Humboldt Current System (20). Across eastern boundary current systems, observed declines in source water oxygen content and increases in wind-forced upwelling point to the likelihood of continued biogeochemical and fishery changes in some of the ocean's most productive large marine ecosystems.

Eutrophication-Generated Seasonal Hypoxia and the Gulf of Mexico

In contrast with OMZs and Eastern Boundary Current hypoxia, much of the hypoxia and anoxia in shallow coastal marine areas has developed within the last 50 years, is closely associated with anthropogenic activities, and occurs in water depths less than 100 m (21). In their most recent compilation of human-caused coastal hypoxia, Diaz and Rosenberg (22) documented just over 400 such areas in the world's coastal ocean that accounted for an area of sea bottom greater than 245,000 km^2 (Fig. 3). Many systems that are currently hypoxic were not when first studied (6). For systems with historical data from the first half of the 20th century, declines in oxygen concentrations started in the 1950s and 1960s for the northern Adriatic Sea, between the 1940s and 1960s for the northwest continental shelf of the Black Sea, and in the 1970s for the Kattegat. Declining dissolved oxygen levels were noted in the Baltic Sea as early as the 1930s, but it was in the 1950s that hypoxia became widespread (23). Other systems have experienced hypoxia since the beginning of oxygen data collection in the 1930s for the Chesapeake Bay (24) and the 1970s for the northern Gulf of Mexico (25). There are clear linkages between increased nutrient loads (nitrogen and phosphorus) and expanding and worsening coastal and estuarine hypoxia in the last half of the 20th century that continues into the new millennium (6).

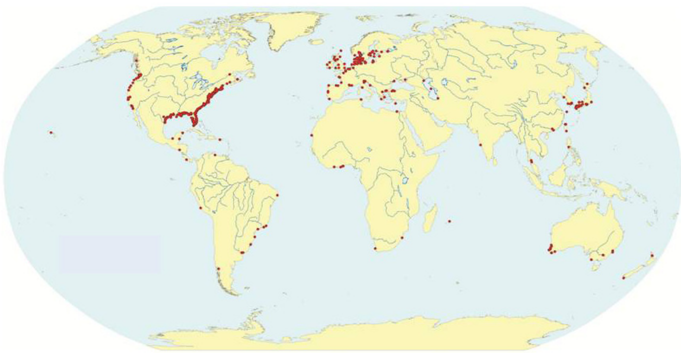

Figure 3. Locations of human-caused coastal hypoxic zones [data of (22) most recently illustrated in (6)]

The hypoxic zone on the continental shelf of the northern Gulf of Mexico is the second largest human-caused hypoxic zone in the coastal ocean (26). The Mississippi River watershed at 3.27×10^6 km² delivers 580 km³ of fresh water, 1.6×10^6 tons of nitrogen, and 0.1×10^6 tons of phosphorus annually through its two deltas. Given the open nature of the continental shelf, it is surprising that eutrophication and hypoxia would develop along the northern Gulf of Mexico. However, the water residence time is prolonged enough for the freshwater-driven stratification and nutrient-enhanced production to result in hypoxia below the pycnocline from spring through early fall. The hypoxia is most widespread and severe in summer. The area of bottom covered by hypoxic water can reach 22,000 km² and averaged 13,500 km² between 1985 and 2009 (updated from 26). Tropical storms and hurricanes will temporarily disrupt the stratification in summer and result in re-aeration of the lower water column. Once winter storms increase in frequency, development of hypoxia remains mostly limited until late winter when the process begins anew.

Evidence from paleo-indicators (27) and models that relate the size and frequency of the hypoxic zone to nitrate-N load of the Mississippi River converge on the period of the early 1970s as to when hypoxia as a large scale phenomenon began in the northern Gulf of Mexico. Community changes in hypoxia-intolerant benthic foraminifera began early in the 1900s with landscape alterations, but most shifts in eutrophication/hypoxia foraminiferal indicators began in the mid-1950s, consistent with increases in sediment total organic carbon, nitrate-N loads from the Mississippi River, and fertilizer use in the Mississippi River watershed (28, 29).

Hypoxia development in areas of the world's coastal ocean is accelerated by human activities, primarily increased nutrient loads, that have set in motion a cascading chain of events related to eutrophication. With an ever-increasing population, the inputs of nutrients to coastal systems will continue to escalate, especially in developing countries, as the application of nutrients for growth of crops to sustain human needs and the burning of fossil fuels in response to industrialization will continue, and coastal hypoxia will be more widespread and frequent than is presently the situation.

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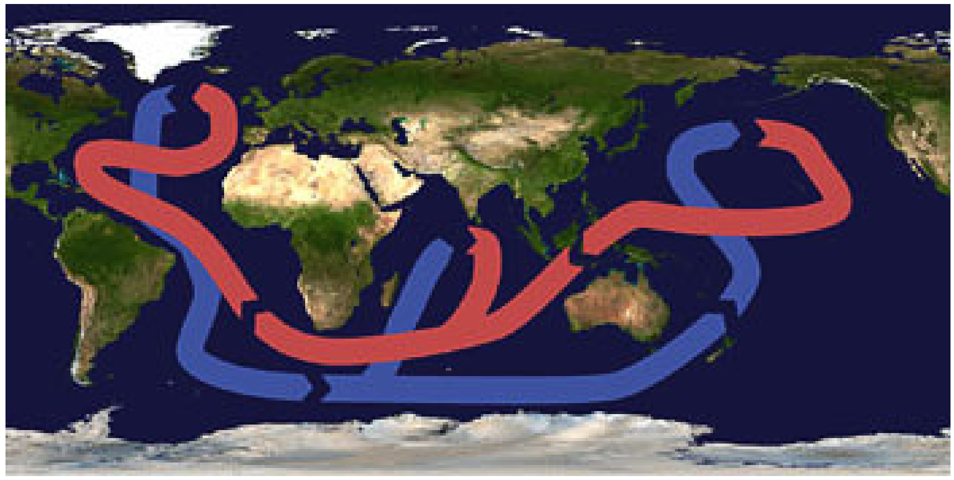
center for microbial oceanography: research and education

C-MORE *linking genomes to biomes*

New free resource for Hawaii's marine science educators

by Jim Foley and Sara Thomas



The Center for Microbial Oceanography: Research and Education (C-MORE) will release our latest Science Kit entitled *Ocean Conveyor Belt* in June 2010. C-MORE Science Kits offer standards-based lesson plans and materials for hands-on science activities in a self-contained format. All C-MORE Science Kits are easy-to-use, provide a great resource for any science classroom, and are free to borrow.

The Ocean Conveyor Belt Kit is designed for 8th–12th grade students and provides all the information and supplies necessary for educators to teach their students about this topic in oceanography. Specifically, students will be introduced to some fundamental oceanographic concepts including ocean circulation, nutrient cycling, and variation in the chemical, biological, and physical properties of seawater. This Science Kit consists of four 50-75 minute lessons, which challenge students to create a stratified water column, understand density-driven ocean circulation, explore long-term oceanographic time-series, and generate graphs.

To borrow the Ocean Conveyor Belt Kit
or for more information about any of the
C-MORE Science Kits, check out our website:

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

Important OCB Dates

- **July 1, 2010:** OCB scoping workshop proposals due (view scoping workshop solicitation)
- **July 19-22, 2010:** OCB Summer Workshop (Scripps Institution of Oceanography, La Jolla, CA) (Registration deadline: June 15, 2010)
- **September 21-23, 2010:** OCB Scoping Workshop Sea Change: Charting the course for ecological and biogeochemical ocean time-series research (Honolulu, HI) – Organizers: Matt Church, Frank Muller-Karger, Mike Lomas
- **November 8-10, 2010:** OCB Scoping Workshop The molecular biology of biogeochemistry: Using molecular methods to link ocean chemistry with biological activity (Los Angeles, CA) – Organizers: Jim Moffett, Eric Webb (Application deadline: July 1, 2010)

2010 OCB Summer Workshop Themes

This year's OCB summer workshop, to be held July 19-22, 2010 at the Scripps Institution of Oceanography in La Jolla, CA, will highlight three interdisciplinary science themes: Arctic, low oxygen regions, and benthic-pelagic coupling. Within these themes, we are especially keen to address nitrogen cycling, ecological tipping points, and strengthened connections between experimentalists and modelers.

Arctic

The Arctic is undergoing rapid changes in response to warming, accelerated melting of large ice sheets, and reductions in seasonal sea ice cover. This session will explore implications of these changes for marine ecosystems (e.g., primary production, food webs) and associated physical (e.g., salinity, stratification, deep ocean circulation, etc.) and biogeochemical (nutrient cycling, carbon fluxes, carbonate saturation state, etc.) processes.

Low Oxygen Regions

Many models are predicting a significant expansion of oxygen minimum zones under the IPCC "business-as-usual" scenario for anthropogenic CO_2 emissions, which will affect marine productivity, carbon and nutrient cycling, and food webs. This session will highlight new observations and applications of biogeochemical and ecological tools and approaches to study processes within different low oxygen systems.

Benthic-Pelagic Coupling

Benthic and pelagic ecosystems are intimately linked by way of biogeochemical cycling and transformation. Benthic-pelagic coupling along continental shelves represents a significant unknown in coastal carbon budgets, and the physical, chemical, and biological processes driving organic carbon export and burial in the open ocean remain poorly characterized. This session will focus on new observations and tools to explore benthic-pelagic processes.

For more information or to register, please visit the workshop website. **The registration deadline is June 15, 2010.**

New OCB Ocean Fertilization website available

The OCB Ocean Fertilization subcommittee was established to serve as an informational resource on ocean fertilization for the OCB community, educators, and the media, and to provide input on behalf of OCB to scientific planning activities related to ocean fertilization. Under the guidance of this subcommittee, the OCB Project Office recently developed an OCB Ocean Fertilization website to serve as a clearinghouse of information for scientists, educators, and the media. Please send feedback and content (e.g., paper citations, reports, white papers, outreach materials, information about research programs, etc.) for the website to the OCB Project Office.

New Community Resources

- Hofmann, E., Sarmiento, J., Smith, W. (2010). A U.S. Southern Ocean Carbon, Ecosystems and Biogeochemistry Science Plan, a report of the Southern Ocean Scoping Workshop sponsored by the Ocean Carbon and Biogeochemistry Program and the NSF Office of Polar Programs—final revisions of the report are currently underway, but the draft plan is available on the OCB website
- ICED Report of the Southern Ocean Food Web Modeling Workshop
- Special issue in *Progress in Oceanography:* Eastern Boundary Upwelling Ecosystems: Integrative and Comparative Approaches
- Special issue in *Progress in Oceanography:* Parameterisation of Trophic Interactions in Ecosystem Modelling (IMBER-sponsored)
- Carbon and Nutrient Fluxes in Continental Margins: A Global Synthesis. Liu, K-K., Atkinson, L., Quiñones, R., Talaue-McManus, L. (Eds.), Springer-Verlag, Berlin Heidelberg (2010)
- New research and education website on biogeochemistry of continental margins
- CLIVAR Ocean Synthesis Directory
- IGBP Climate-Change Index
- World list of oceanographic data bases
- EUR-OCEANS Southern Oceans Data Portal (ESODAP)
- co2forum.org: Web forum for open discussion of the global carbon cycle and its relationship to climate variability and change, human, and ecological impacts

Related Project News

Surface Ocean CO_2 Atlas (SOCAT) Southern Ocean regional meeting

SOLAS, IMBER and IOCCP are co-sponsoring this meeting June 16-18, 2010 (Hobart, Australia). The objectives of the meeting are to complete the quality control of the Southern Ocean data and develop synthesis plans for the use of these data.

U.S. GEOTRACES Arctic planning workshop (September 29-October 2, 2010, Washington, DC): The objective of this workshop is to generate an action plan for future GEOTRACES activities in the Arctic between U.S. investigators and international collaborators. There will be limited travel support available for attendees.

IMBER IMBIZO II - Integrating biogeochemistry and ecosystems in a changing ocean: Regional comparisons (October 10-14, 2010, Crete, Greece):

Dry Cruise: An interactive training workshop (Co chairs: Alberto Piola and Cyndy Chandler) (October 10, 2010)

Workshop 1. The effect of varying element ratios on community structure at low trophic levels and food quality at mid and high trophic levels (Co-chairs: Dan Repeta and Rory Wilson)

Workshop 2. Large-scale regional comparisons of marine biogeochemistry and ecosystem processes – research approaches and results (Co-chairs: Ken Drinkwater and Raleigh Hood)

Workshop 3. Sensitivity of marine food webs and biogeochemical cycles to enhanced stratification (Co chairs: Michio Kishi and Michael Landry)

NACP Announces Next All-Investigators Meeting

The scientific and federal agency leadership of the Ameriflux Program and North American Carbon Program (NACP) have agreed to take advantage of common thematic, scientific, and programmatic interests and will combine their meetings in 2011. The joint Ameriflux and NACP All Investigators Meeting will be held January 31 - February 4, 2011 in New Orleans, Louisiana. Details will soon be available on the NACP website.

SOLAS Mid-Term Strategy

SOLAS identifies future key research areas in its Mid-Term Strategy

Upcoming SOLAS Meetings

Sea ice biogeochemistry and interactions with the atmosphere (at the International Polar Year Open Science Conference June 8-10, 2010, Oslo, Norway)

Air-Sea Gas Fluxes in Eastern Boundary Upwelling Systems and Oxygen Minimum Zones (OMZs) (November 8-10, 2010, Lima, Peru)

National Science Foundation Solicitation for Ocean Acidification Proposals Generates Enthusiastic Response

The NSF electrified the United States ocean acidification (OA) research community in January when it called for proposals to understand OA's chemistry, its effects on biogeochemistry, organisms, and ecosystems, and how Earth's history informs these studies. By the April 26 deadline, program managers had received over 100 proposals, demonstrating a strong community response to the long-anticipated announcement. The participating directorates are excited to see the research move forward and expect to make award decisions by September. The program managers expect to fund about 14-20 proposals, including full research projects (up to four years), exploratory efforts, and community/capacity building projects. The total funding anticipated for this program is expected to be between $12 and $15 million.

International Effort to Answer Questions about Ocean Acidification

"How do we know what ocean pH was in the past even though the pH scale was not introduced until 1909?"

"An increase of CO_2 in seawater increases growth of photosynthetic algae — isn't that a good thing?"

As news of OA research circulates through media worldwide, the public has posed many insightful questions on the topic. This spring, an international group of OA researchers teamed up to answer 39 frequently asked questions (FAQs) about OA, including the two listed here, using plain language and facts from the peer-reviewed literature.

Participants submitted questions they had encountered, and the question list was divided into major categories. Researchers then answered questions singly or collaboratively with up to three experts. Participants then reviewed each other's answers for completeness and clarity.

Organized by the U.S. Ocean Carbon and Biogeochemistry (OCB) program, the European Project on Ocean Acidification (EPOCA), and the UK Ocean Acidification Research Programme, 27 specialists from 19 institutions and 5 countries collaborated via email to generate the document in just over 6 weeks.

The document is available on the OCB-OA site at www.whoi.edu/OCB-OA/FAQs and on the EPOCA site at http://www.epoca-project.eu/index.php/FAQ.html. It is now available in English, French, and Chinese.

OCB Community provides second round of input to EPA on Ocean Acidification

In 2009, the EPA published a notice of data availability (NODA) regarding its "aquatic life criteria for pH of marine waters" under the Clean Water Act. The OCB Ocean Acidification Subcommittee and the OCB Project Office compiled a comprehensive response to this notice that included input from numerous members of the OCB community. In 2009, the Center for Biological Diversity filed a lawsuit against the EPA on the grounds that increasingly acidic waters off the Washington state coast were in violation of EPA standards. The settlement, reached in the U.S. District Court of Seattle, has prompted a second round of information gathering. The EPA just recently solicited public comments on the effects of ocean acidification as it relates to the 303(d) (Clean Water Act) program. Specifically, the EPA sought answers about how states and the EPA can aid OA monitoring, how to address TMDLs (total maximum daily loads) development for OA-threatened or impaired waters, and how to incorporate these efforts into other programs. The OCB Ocean Acidification Subcommittee, together with the OCB Project Office, compiled another detailed response to this notice. Download the final OCB response about OA and the 303(d) program.

OCB Ocean Acidification Website News

Visit the updated OCB Ocean Acidification website, where you can check the calendar for upcoming events and link them to your own electronic calendar; learn about other OA research projects and scientists; visit the Info & Media category for new paper listings and links to gray literature, video clips, testimonies, and news stories; and locate resources for educators about Ocean Acidification.

Please send your contributions, including new papers (citations only), reports, outreach materials, and presentations to Sarah Cooley in the OCB Project Office.

Ocean Acidification on Capitol Hill

U.S. Senate Committee Hearing:
"The Environmental and Economic Impacts of Ocean Acidification"

On April 22, the 40th anniversary of Earth Day, the U.S. Senate Committee on Commerce, Science, and Transportation heard testimony about possible impacts of OA from five American citizens. Witnesses included Jim Barry (Monterey Bay Aquarium Research Institute), John Everett (Ocean Associates, Inc.), Tom Ingram (Diving Equipment and Marketing Association), Donny Waters (Commercial fisherman, past president of the Gulf of Mexico Reef Fish Shareholders Alliance), and Sigourney Weaver (actress). The hearing, testimony, and related files are available through the Senate Commerce Committee.

U.S. Senate Committee on Environment and Public Works Joint Hearing of Subcommittee on Oversight and Subcommittee on Water and Wildlife: "EPA's Role in Protecting Ocean Health"

On May 11, the U.S. Senate Subcommittee on Oversight and Subcommittee on Water and Wildlife held a joint hearing on EPA's role in protecting the health of the oceans, which focused on ocean acidification and persistent bioaccumulative toxic (PBT) chemicals in the oceans, with added and timely discussions of the Deepwater Horizon oil spill in the Gulf of Mexico. Witnesses included Nancy Stoner and Jim Jones (EPA), Roger Payne (Ocean Alliance), Carys Mitchelmore (University Maryland, Chesapeake Biological Lab), Sam Waterston (actor and Oceana Board of Directors), and John Everett (Ocean Associates, Inc.). Statements by EPA officials indicated that EPA's pH water quality criteria for OA will likely remain the same due to the lack of data on pH variability in coastal regions. The hearing, testimony, and related files are available through the Senate Committee on Environment and Public Works.

Send us your photos!

Advertise your work, share your apparatus ideas, show off cool results, or make your colleagues envy your field site! We are always seeking photos to add to the OA slideshow.

Developing a National Plan for Ocean Acidification Research

Passage of the Federal Ocean Acidification Research And Monitoring (FOARAM) Act in 2009 has prompted the formation of an interagency committee to develop a plan for ocean acidification research and monitoring. With scientific input from the Ocean Research and Resources Advisory Panel (ORRAP) Task Force on Ocean Acidification, the Interagency Working Group on Ocean Acidification is working on a national plan for ocean acidification research, which is due to Congress in March 2011. The national plan will address important aspects of chemical and biological monitoring and research, as well as socioeconomic implications and potential education/outreach and marine conservation strategies.

The next meeting of the Ocean Acidification Interagency Working Group and ORRAP Task Force will be held June 22-23, 2010 in Washington, DC.

National Research Council Report to be Released

The National Research Council (NRC) Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment, comprising twelve OA researchers and drawing on the expertise of dozens more, is about to release their full report

"Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean."

International Ocean Acidification Headlines

- The Guide to Best Practices in Ocean Acidification Research and Data Reporting is now available as a pdf from the EPOCA website and in print from the EPOCA Project Office.
- The host and venue selection process is underway for the 3rd Symposium on the Ocean in a High-CO_2 world. The symposium will take place in 2012 and is co-sponsored by SCOR, IOC, and IGBP.
- The NOAA Cooperative Institute for Ocean Exploration, Research, and Technology (CIOERT) hosted the "Ocean Acidification Instrumentation and Research Needs Workshop" from March 8-11, 2010, in St. Petersburg, FL. A workshop report is planned to provide a roadmap for development of OA instruments for coral ecosystems, and to provide input for the CIOERT science plan.
- The BIOACID (Biological Impacts of Ocean Acidification) program has launched a new project website. This program coordinates the efforts of German institutes and universities that conduct marine research and is closely allied with EPOCA.

OCB supports U.S. student participation in European ocean acidification training course

EPOCA (European Project on Ocean Acidification), CalMarO (CALcification by MARine Organisms), BIOACID (Biological Impacts of Ocean ACIDification), and OCB co-organized an ocean acidification training workshop at IFM-GEOMAR in Kiel from March 8-12, 2010. The workshop, which included 18 lectures and 16 hands-on practicals, educated 35 students and post-docs on a range of chemical, biological, and data handling methods involved in ocean acidification research. For more details, please visit the training workshop website.

OCB provided support for five U.S. students to attend the training workshop. Following is a brief biographical sketch and a few reflections on the workshop from each student.

Joy Leilei Shih
(University of Hawaii)

Joy Leilei Shih
University of Hawaii

I am a first-year Ph.D. student at SOEST at the University of Hawaii in the Marine Geochemistry division of the Oceanography department. I completed my Bachelor's degree in Astrophysics at UC Berkeley, and then attained a Masters of Advanced Studies in Marine Biodiversity and Conservation at Scripps Institution of Oceanography. I have also had a long-time interest in coastal environmentalism and policy, and have served on the Executive Committee of the Surfrider Foundation in San Diego, and have been actively involved with other chapters throughout California, and currently in Hawaii. Surfrider Foundation's mission is to preserve the coastal environment for future generations, and is instrumental in litigation and legislation at both the national and regional levels. It is at SIO in San Diego where I discovered how much I enjoy research and field work, and decided to pursue a Ph.D. in Oceanography. My research interests include the effects of changing pCO_2 on the coastal sub-tropical habitat. On Oahu, research is currently being conducted in Kaneohe Bay and the South Shore of the island. Storm events and runoff create measurable fluctuations that change both the chemistry of the shallow body of water in the Bay and its biological activity considerably. As the bay includes fringing, patch, and barrier reefs, these changes in the direction of CO_2 flux and the rates of dissolution/calcification within the bay are very interesting in the context of climate change. I am interested in determining how projected rises in CO_2 would affect the bay and similar environments, and its calcifying organisms. Also, air-sea CO_2 flux in the bay is affected by shifts in the signature Trade Winds (winds can be very strong), the abrupt encounter with the steep Pali (high cliffs), and shallow topography of the bay. Along with wave action pushing water over the reefs and phytoplankton blooms because of the presence of rivers, nearly all aspects of carbonate chemistry play a significant role in the bay.

The Ocean Acidification training workshop in Kiel, Germany in March was an outstanding experience and an excellent opportunity to learn more about all facets of ocean acidification research. As a first-year student and someone who is relatively new to the field, I was able to learn a tremendous amount to complement the topics in ocean acidification with which I was more familiar. Although the workshop began with a comprehensive review of basic carbonate chemistry, it quickly evolved into more specific topics and research, with real examples of some of the fantastic research going on at the university itself. Opportunities to socialize with fellow attendees enabled us to learn the wide variety of research and research interests represented at the workshop. This definitely helped with thinking about future experimental design and possible future collaborations. It was truly a treat to meet many of the top researchers in the field and to have the opportunity to speak with them in person. While the presence of some of these individuals at the workshop was already an honor, several other individuals joined us to give lectures over Skype. The most valuable parts of the workshop for me were the portions on experimental design. As I am in the process of designing my research project, it helped immensely to learn what tools I had, and which pitfalls to avoid. The workshop has definitely influenced the direction in which I would like to take my research, and I will definitely incorporate several of the tools that I encountered for the first time while at the workshop.

For someone who is interested in ocean acidification, I could not have asked for a better opportunity or experience!

Nancy Muehllehner
(University of Miami)

I graduated with a BA from the University of Delaware and a MA from UC Berkeley before shifting my focus from education to scientific research. I began with an internship in Andrew Baker's lab at Columbia University and fell in love with the mental challenge of reading primary literature and dreaming up experiments to isolate the factors of interest. Thus, I pursued first a MS with a physiological ecologist, Pete Edmunds, at CSU Northridge, and am now in my 2nd year of a Ph.D. program with Chris Langdon at the University of Miami, Rosenstiel School of Marine and Atmospheric Science. While at CSU Northridge, I was very lucky to be part of the Long Term Ecological Research (LTER) in Moorea, French Polynesia. Our frequent and extended research trips provided multiple opportunities to set up experimental systems and observe the reef ecosystem over time during our monitoring efforts. While there, my MS research focused on comparing two parameters of coral growth, the mass of calcium carbonate laid down on coral branches and the extension of the rapidly growing apical tip of the coral branch under future CO_2 conditions (~2100). The results of this experiment showed that linear extension rates are approximately twice as sensitive to ocean acidification as rates of mass deposition. While the prior study was performed on two species of *Acropora* (*hyacinthus* and *pulchra*), subsequent studies on the interactive effects of temperature and CO_2 performed on *Porites rus* and *Pocillopora meandrina* showed that slight increases in temperature can offset the effects of ocean acidification. In a continuation of the focus I developed in my MS, my Ph.D. research has delved both deeper into the effects of ocean acidification on tropical stony corals and is also expanding to consider the effects at the scale of the coastal ecosystem. Baseline calcification data on the Florida Reef Tract are combined with community respiration and net community production data in order to get a measure of the overall reef metabolism. Our initial data suggest that primary productivity on the Florida Reef Tract may be a key determinant in the variable aragonite saturation states we are observing in this coastal region. I look forward to completing this project and developing some other experimental ideas during the remainder of my Ph.D., which is due to be completed by 2013.

Nancy Muehllehner
University of Miami

Kristy J. Kroeker
(Stanford)

My research is focused on the emergent effects of climate change on marine ecosystems. I am interested in how multiple climatic stressors will combine to affect marine organisms, and how the individual physiological responses of these organisms scale up to impact marine ecosystems. In my research, I use naturally occurring shallow volcanic CO_2 vents as a model system for studying ocean acidification's impact on marine communities. The vents I work on are found among diverse Mediterranean rocky reef communities and release CO_2 into the water column. This causes gradients in seawater pH, which correlate with decreases in diversity of the surrounding benthic community. I focus on how the structure and function of these communities change, by examining the contributions of individual species to community composition, alterations in species interactions, and changes in ecological processes such as succession and resilience. In addition, I am examining how species interactions change under conditions of ocean acidification using laboratory experiments that quantify changes in the feeding rates of invertebrate herbivores on their algal hosts.

Research on ocean acidification is, by nature, interdisciplinary. My background is primarily in ecology, and I was interested in participating in the Best Practices in Ocean Acidification Research (sponsored in part by OCB) in order to hone my skills in manipulating seawater carbonate chemistry. The workshop was incredibly informative and professional. The syllabus was thorough, and the instruction was impeccable. Thanks to all of those involved in putting on this workshop, I am much better prepared to measure

Kristy J. Kroeker
Stanford

and manipulate seawater carbonate chemistry, and to plan ecologically relevant experiments. Additionally, this workshop allowed me to work with numerous other scientists addressing similar questions, and will be the basis for ongoing relationships and future collaborations.

Ann Mooney
(University of North Carolina, Chapel Hill)

I am a Ph.D. student at the University of North Carolina—Chapel Hill. I study the effects of elevated atmospheric carbon dioxide on coral reef calcification, biomechanics and boundary layer fluid dynamics in Dr. Justin Ries's lab. In 2003, I began my career in the ocean, working first as a dive master in the Puget Sound of Washington, then with NOAA National Marine Fisheries Coral Reef Ecosystem Division in Honolulu, Hawai'i as a marine debris diver in the Northwestern Hawaiian Islands (NWHI). I spent months at sea removing derelict fishing gear and surveying and characterizing the benthic habitat for coral coverage and invertebrates. After this exposure to marine sciences, I pursued my studies at the University of Queensland. In 2008 I completed my Masters in Science at the University of Queensland working with Ove Hoegh-Guldberg in the Coral Ecology and Climate Change Lab. My studies focused on the impacts of ocean acidification on the skeletal strength of corals on the Great Barrier Reef. I then joined the field and research team of NOAA's Papahanaumokuakea Marine National Monument coordinating field operations and developing climate change research projects in the NWHI. I led a team to characterize the nearshore carbonate chemistry of carbonate atolls by utilizing shipboard CTD (conductivity, temperature and depth) casts and seawater analysis of dissolved inorganic carbon, alkalinity and dissolved oxygen. The results of this study will help to bridge the gap between open ocean models and coastal zone processes to better characterize the Monument's susceptibility to the global threat of ocean acidification.

Ann Mooney
University of North Carolina, Chapel Hill

My current work incorporates seawater chemistry with photobiology to provide a holistic view of ocean acidification's impacts on coastal ecosystems and organismal biology. The EPOCA workshop provided the opportunity to meet the pioneers in the field and build a solid knowledge base of carbonate chemistry and seawater manipulation experiments as well as sharing invaluable first-hand experiences of the complexities of working with seawater systems.

Rachel Fabian
(University of California, Santa Cruz)

I am a Ph.D. student in the Ocean Sciences department at the University of California in Santa Cruz. My research addresses the effects of ocean acidification (OA) on upwelling areas, particularly the Monterey Bay. The rich ecosystem in Monterey Bay is supported by nutrients delivered by waters upwelling along the coast during the spring and summer. These waters are naturally low-pH due to the buildup of CO_2 from respiration below the photic zone; OA could exacerbate this natural phenomenon by pushing upwelled water to lower pH levels that could be harmful to marine organisms. My research examines the susceptibility of some marine invertebrates to exposure to low-pH seawater, focusing on larval and juvenile life stages that are generally more susceptible to stress than are adults. I will also focus on bottom-up controls on ecosystem structure that may be altered by OA, primarily the change in nutrients delivered from sediments by upwelling waters due to changes in infaunal community structure and changing forms of nutrients at different pH levels.

Participating in the OA training workshop in Kiel was a great experience. I learned a lot about the carbonate system and the various ways to manipulate it, as well as about experimental design. It was also a wonderful opportunity to meet leaders in the field and meet with others in the scientific community who are also working on OA research.

Rachel Fabian
University of California, Santa Cruz

OCB Calendar

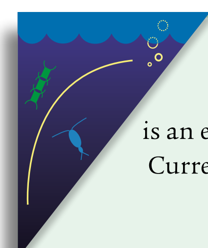
2010	
May 31-July 10:	2010 Summer Course on Microbial Oceanography (Honolulu, HI)
May 31-June 2:	EUR-OCEANS / Europole Mer 2010 Conference: Influence of meso- and submesoscale ocean dynamics on the global carbon cycle and marine ecosystems (Aber Wrac'h, France)
June 6-11:	ASLO Summer Meeting (Santa Fe, NM)
June 8-12:	2010 International Polar Year meeting (Oslo, Norway)
June 13-18:	Goldschmidt 2010: Earth, Energy, and the Environment (Knoxville, TN) Environmental Bioinorganic Chemistry Gordon Research Conference: Elements in the Environment, from Prokaryotes to People to Planets (Newport, RI)
June 16-18:	Surface Ocean CO_2 Atlas (SOCAT) Southern Ocean regional meeting (Hobart, Australia)
June 20-July 10:	BIOS Summer Course on Microbial Oceanography: The Biogeochemistry, Ecology and Genomics of Oceanic Microbial Ecosystems (BIOS, Bermuda)
June 21-23:	Deep Ocean Workshop: Observed and model-simulated property changes in the deep ocean of the Southern Hemisphere (Hobart, Australia), Contact: Bernadette Sloyan
July 1-15:	Summer Course: Mediterranean Marine Ecosystems: Functioning and Evolution (Athens, Greece)
July 4-9:	Marine Microbes Gordon Research Conference (Tilton, NH)
July 19-22:	OCB Summer Workshop (La Jolla, CA)
Aug. 3-6:	Scientific Committee on Antarctic Research Open Science Conference (Buenos Aires, Argentina)
Aug. 8-13:	2010 AGU Meeting of the Americas (Foz do Iguassu, Brazil)
Aug. 23-27:	ClimECO2: Oceans, Marine Ecosystems, and Society Facing Climate Change — A Multidisciplinary Approach (Brest, France)
Aug 26-28:	Workshop on Paleo-ocean Acidification and Carbon Cycle Perturbation Events (Wrigley Institute for Environmental Studies, Catalina Island)
Aug. 30-Sept. 1:	Ecosystem Studies of Sub-Arctic Seas (ESSAS) 2010 Annual Science Meeting (Reykjavik, Iceland)
Sept. 5-10:	FORAMS 2010 International Symposium on Foraminifera (Bonn, Germany)
Sept. 6-8:	2nd Workshop on CARBON FROM SPACE (Oxford, UK)
Sept. 6-9:	14th Biennial Challenger Conference for Marine Science (Southampton, UK)
Sept. 13-16:	2010 SCOR General Meeting (Toulouse, France)
Sept. 13-16:	Future Ocean Symposium (Kiel, Germany)
Sept. 20-24:	Annual Science Conference of the International Council for the Exploration of the Sea (Nantes, France)
Sept. 21-23:	OCB Scoping Workshop Sea Change: Charting the course for ecological and biogeochemical ocean time-series research (Honolulu, HI)
Sept. 27-Oct. 1:	17th Air-Sea Interaction Conference (Annapolis, MD)
Sept. 29-Oct. 2:	US GEOTRACES Arctic Ocean planning workshop (Washington, DC), Contact: David Kadko
Oct. 10:	IMBER Dry Cruise Workshop (Crete, Greece)
Oct. 10-14:	IMBER IMBIZO ll — Integrating biogeochemistry and ecosystems in a changing ocean: Regional comparisons (Crete, Greece)

OCB Calendar (continued)

2010 (continued)	
Oct. 18-27:	Advanced school on complexity, adaptation, and emergence in marine ecosystems (Trieste, France)
Oct. 22-31:	North Pacific Ecosystems and Challenges in Understanding and Forecasting Change (Portland, OR)
Nov. 3-5:	Upper Ocean Nutrient Limitation: Processes, Patterns and Potential for Change (Southampton, UK)
Nov. 8-10:	OCB Scoping Workshop The molecular biology of biogeochemistry: Using molecular methods to link ocean chemistry with biological activity (Los Angeles, CA) Air-Sea Gas Fluxes in Eastern Boundary Upwelling Systems and Oxygen Minimum Zones (OMZs) (Lima, Peru)
2011	
Jan. 31-Feb. 4:	Ameriflux and NACP All Investigators Meeting (New Orleans, LA)
Feb. 13-18:	ASLO 2011 Winter Meeting: Limnology and Oceanography in a Changing World (San Juan, Puerto Rico)

Funding Opportunities

- **May 24:** NSF Decadal and Regional Climate Prediction using Earth System Models (EaSM) LOI deadline
- **May 26:** NOAA Climate Program LOI deadline, download Earth System Science LOI solicitation (including global carbon cycle)
- **June 1:** NASA ROSES 2009 - A2. Land-Cover/Land-Use Change Proposal deadline
- **June 4:** NASA ROSES 2010 - A5. Carbon Cycle Science proposal deadline
- **June 8:** NSF Dimensions of Biodiversity Full Proposal Deadline
- **June 11:** NASA ROSES 2010 - A3. Ocean Biology & Biogeochemistry NOI deadline
- **June 11:** NASA ROSES 2010 - A30. Climate and Biological Response: Research and Applications NOI deadline
- **June 25:** NSF Decadal and Regional Climate Prediction using Earth System Models (EaSM) full proposal deadline
- **July 1:** OCB scoping workshop proposals due
- **July 20:** NASA ROSES 2010 - A30. Climate and Biological Response: Research and Applications Proposal Deadline
- **August 13:** NASA ROSES 2010 - A3. Ocean Biology & Biogeochemistry proposal deadline
- **August 15:** NSF Chemical and Biological Oceanography Full Proposal Target Dates
- **September 16:** NSF Macrosystems Biology: Research on Biological Systems at Regional to Continental Scales Full proposal deadline
- **November 16:** NSF Dynamics of Coupled Natural and Human Systems (CNH)
- **December 1:** NASA ROSES 2010 - A4. Land Cover/Land Use Change NOI deadline



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Editor: Heather M. Benway

OCB Project Office, Woods Hole Oceanographic Institution
Dept. of Marine Chemistry and Geochemistry
266 Woods Hole Road, Mail Stop #25
Woods Hole, MA 02543

v 508-289-2838 · f 508-457-2193

We welcome your comments and contributions for publication.
hbenway@whoi.edu