MEETINGS

Recent Advances in the Ocean Carbon System

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Ocean biogeochemistry is a critical component of the Earth's climate system, regulating on timescales of decades to millennia the atmospheric levels of carbon dioxide (CO_2), and other radiatively active gases. Since the pre-industrial era, the ocean has taken up about half of the carbon released by fossil fuel combustion, partially mitigating climate change. The future behavior of this oceanic sink, however, is not well understood and remains one of the major climate uncertainties [*Sarmiento and Gruber*, 2002].

The ocean carbon inventory depends, in part, upon the complex responses of the natural ocean ecosystems and carbon system to changes in ocean circulation, dust deposition, ocean pH, ultraviolet radiation, and other factors [*Fasham*, 2003]. Addressing this problem requires an integrated research effort on a variety of fronts, ranging from monitoring the temporal evolution of the ocean inorganic carbon inventory to innovative studies of poorly known biological and chemical dynamics.

As part of the new Ocean Carbon and Climate Change (OCCC) program [*Doney et al.*, 2004], (sponsored by the multi-agency U.S. Global Change Research Program's Carbon Cycle Science Program), a science workshop called The Ocean Carbon System: Recent Advances and Future Opportunities was held recently at the Woods Hole Oceanographic Institution, in Massachusetts. The objectives of the workshop were to highlight recent scientific findings in ocean carbon science, foster improved communication among existing ocean carbon observing programs and process studies, and discuss applications of emerging observational technologies in marine biogeochemistry.

More than 100 scientists participated in the four-day meeting, which was supported by the U.S. National Science Foundation (NSF). Electronic versions of many of the plenary talks are available through the workshop Web page (http://www.whoi.edu/sites/OCCC_workshop).

Several scientific themes emerged from workshop talks and posters, including new findings on biogeochemical cycling across the air-sea interface, in coastal margins, in the subtropical upper ocean, in the Southern Ocean, and in the mesopelagic "twilight" zone (the waters between about 100–1000 meters depth); the quantification of the oceanic uptake of anthropogenic CO_2 and the resulting geochemical and ecological impacts due to ocean acidification; and the application of new technologies and methods to ocean biogeochemistry. Material presented at the workshop on a selection of these topics is highlighted below.

Continental Margin Carbon Cycle

The coastal ocean and continental margins are highly dynamic regions with elevated biological productivity and unique biogeochemistry intimately linked to the proximity of land and bottom sediments. The time and space scales of the coastal environment are typically smaller than those of the open ocean. The time and space scales are strongly influenced by topography, tidal mixing, river inflows, and the often highly turbulent physical circulation associated with eddies, fronts, and jets.

Historically, most studies of coastal ocean carbon cycling have been local to regional in scope, and many large-scale synthesis products and models have not been designed with the coastal ocean in mind. Therefore, it has been difficult to extrapolate impact of coastal processes to the global carbon cycle.

Nick Bates (Bermuda Biological Station for Research) and Wei-Jun Cai (University of Georgia) discussed several processes whereby the coastal ocean could act as a significant sink of atmospheric carbon. Such mechanisms could involve, for example, the biological formation and offshore export of organic matter or the sinking of cold, dense water that is rich in inorganic carbon. The dominant terms affecting carbon dynamics vary considerably by region, with areas of both large net positive and negative air-sea CO_2 fluxes around North America. A global picture of the coastal carbon cycle will only emerge through a more extensive observation network (including remote sensing) across a more diverse set of environments (e.g., Arctic shelves, river-dominated systems, and upwelling regions), workshop participants agreed.

Other topical questions raised at the workshop by speakers and participants included carbon transport, deposition, and biogeochemical transformations in rivers, estuaries, and the coastal margin; episodic hypoxia events along the Oregon coast; the role of eddies in damping productivity in the California upwelling zone; the flux of the micro-nutrient iron into the coastal waters and open ocean from sediments and atmospheric dust generated on the nearby land; and high, light-driven biological production in shallow bottom sediments, in some cases equaling or exceeding that of the overlying water column.

Ocean Anthropogenic Carbon Uptake and Oceanic Acidification

The ocean acts as a major sink for the CO_2 released to the atmosphere by fossil fuel combustion and land use change. A recent synthesis, based on the World Ocean Circulation Experiment/Joint Global Ocean Flux Study (WOCE/JGOFS) global CO_2 survey, estimates that 48% of fossil fuel CO_2 now resides in the ocean, with about half of the anthropogenic carbon inventory occurring in the upper 400 meters (*Sabine et al.*, 2004).

A number of questions remain, however, about the empirical methods currently used to separate anthropogenic from pre-industrial carbon. Efforts are under way through the Climate Variability and Predictability (CLIVAR)/CO_2 Repeat Hydrography Program to directly constrain ocean CO_2 uptake rates by reoccupying targeted ocean sections on a decadal timescale.

The acid-base chemistry of seawater is buffered by the ocean carbonate system. The dissolution of anthropogenic CO_2 into water and the formation of carbonic acid leads to a reduction in seawater pH and carbonate ion (CO_3^{2-}) concentration. Over this century, pH will drop by several tenths of a pH unit, CO_3^{2-} concentrations will fall by more than half, and high-latitude surface waters will become undersaturated for aragonite, a form of calcium carbonate used by many organisms to form shells. Such rapid changes in ocean pH are unprecedented over the last several million years, if not longer back in the geological record.

According to several speakers at the workshop (Dick Feely, U.S. National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory; Chris Langdon, University of Miami; and Vicky Fabry, California State University, San Marcos) the ecological impacts of ocean acidification include reduced calcification rates for corals, pteropods (open-ocean planktonic mollusks), and coccolithophores (phytoplankton), and the negative feedback of reduced calcification on atmospheric CO_2.

Ocean acidification has the potential to shift surface community structure from calcifiers to more siliceous diatoms in many parts of the ocean. This would have important biogeochemical ramifications because there is growing evidence that sinking particulate organic matter fluxes from the surface ocean and in the deep sea are controlled, at least in part, by the flux and composition of so-called ballast materials such as dust, silica, and calcium carbonate that are considerably heavier than organic matter and may increase gravitational sinking velocities.

New Ways of Sampling the Ocean

A number of speakers at the workshop, including Mary Jane Perry (University of Maine), Ken Johnson (Monterey Bay Aquarium Research Institute), and Mike DeGrandpre (University of Montana) offered to revolutionize the field of ocean biogeochemistry over the next decade, by providing data at much higher temporal and spatial densities than have been available in the past from ship-based studies. New in situ chemical and bio-optical sensors are being developed and tested for a wide range of biogeochemical properties including nitrate, carbonate system variables (pH, dissolved inorganic carbon, CO_2 partial pressure), oxygen, and particulate organic and inorganic carbon.

Innovative methodologies include measurements of particle composition as a function of sinking velocity and geochemical techniques for constraining gross primary production, diapycnal mixing (the mixing across density surfaces that is a key factor in water mass transformations and the supply of nutrients to the surface ocean, and respiration using the isotopic composition of dissolved oxygen.

Of equal importance is the integration of such sensors onto autonomous platforms. Two different, complementary paths are being followed involving either low-power drifters, floats, and gliders or high-power moorings, autonomous underwater vehicles, and cable-based observatories.

Pilot studies are under way to add biogeochemical instrumentation to profiling floats similar to those used in the global Argo array, and to cabled systems that may be deployed as part of the NSF-sponsored Ocean Research Interactive Observatory Networks (ORION). Michael Bender (Princeton University) made compelling arguments for instrumenting Volunteer Observing Ships (e.g., commercial vessels, research ships, and Antarctic re-supply vessels), which provide excellent platforms for rapid and routine spatial surveys of the upper ocean biological and geochemical state.

An important message arising from the workshop is the crucial need to integrate information from different approaches and across multiple time and space scales. An example of this need is the controversy surrounding whether the upper water column in the open ocean is net autotrophic or heterotrophic. Results from some diurnal bottle incubation experiments showing net oxygen consumption are in conflict with geochemically derived, positive net community production estimates based on in situ surface oxygen supersaturation and atmospheric seasonal oxygen/nitrogen (O_2/N_2) cycles. Although methodological concerns of bottle incubations are always present, some of these differences may be real, reflecting the episodic character of production and respiration and its interaction with traditional shipboard sampling strategies.

The workshop on The Ocean Carbon System: Recent Advances and Future Opportunities was held 1-4 August 2005 at the Woods Hole Oceanographic Institution, Woods Hole, Mass.

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Tsunami Geology and its Role in Hazard Mitigation

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The timely topic of tsunami geology was addressed during a recent international workshop sponsored by the U.S. National Science Foundation (NSF). Participants from 15 nations compared criteria for identifying tsunamis by their geologic signatures; explored applications to plate tectonics, hazard assessment, and public education; and discussed recommendations for research priorities. A post-workshop trip occasioned heartfelt exchanges with Washington state coastal residents two days after a local tsunami scare.

Motives and Objectives

The workshop was prompted by the Indian Ocean tsunami of 26 December 2004, and began with several presentations about that tsunami and about the lessons being learned from it. Lacking documented precedent in its source region, the 2004 catastrophe provided a horrific reminder of a practical problem: Written and instrumental records rarely span enough time to warn of the full range of a region's tsunami hazards.

Geology has already begun to address this problem by extending tsunami history thousands of years into the past. Examples presented at the meeting included tsunami deposits from the North Sea (S. Bondevik), New England (M. Tuttle), Chile (M. Cisternas), Mexico (M. T. Ramirez), Cascadia (northern California to British Columbia) (H. Kelsey, A. Nelson, A. Moore, and I. Hutchinson), Alaska (J. Beget), Kamchatka (J. Bourgeois), and Japan (K. Hirakawa and F. Nanayama). Much of the workshop was accordingly focused on the opportunities and challenges of identifying and quantifying past tsunamis from their geologic signatures.

Identifying Ancient Tsunamis

Modern analogs provide geologic criteria for identifying ancient tsunamis. Several case histories of modern examples were presented at the meeting, including recent surveys from the Indian Ocean region. Compiling and synthesizing these observations into accessible data repositories were deemed important by discussants at the workshop.

Tsunami geology, which began with surveys of the 1946 Aleutian tsunami in Hawaii [*Shepard et al.,* 1950] and the 1960 Chile tsunami in Japan [*Kitamura et al.*, 1961], now encompasses a broad range of stratigraphic and geomorphic evidence, and it includes several published comparisons between tsunami and storm deposits.

Although no one criterion suffices as geologic proof of a tsunami, some participants at the workshop stated that several criteria together, in the right setting, can leave little room for doubt. For example, the 1700 Cascadia tsunami can be identified with confidence from a sheet of sand that tapers landward, contains marine fossils, extends kilometers inland from the limit of sand deposition by storm surges, and coincides stratigraphically with evidence for abrupt tectonic subsidence and seismic shaking [see bibliography in *Atwater et al.,* 2005].

Much debate at the workshop, therefore, focused on settings where tsunamis and storms may have similar geologic effects, for example, on the east coast of North America. Patricia Wiberg, Bruce Jaffe, Harry Yeh, and others presented evidence that tsunamis produce flows faster than those of storm surges. Workshop attendees agreed that quantifying such differences and linking them to the physics of sediment erosion, transport, and deposition are ultimate goals of tsunami sedimentology.

Applying Tsunami Geology

Several presenters described tsunami deposits as ground truth for numerical simulations on which tsunami evacuation maps are based. In Hokkaido, Japan; Washington state; and Oregon state, tsunami deposits have already contributed to such maps [e.g., *Priest et al.*, 1995]. The next step is to interpret the deposits in terms of flow depth and velocity, parameters of interest in the engineering design of tsunami-resistant buildings. This interpretation, a frontier of tsunami research spotlighted in presentations by Vasily Titov, Pat Lynett, and Costas Synolakis and in workshop discussions, requires collaboration with wave-tank experimentalists and hydrodynamic modelers.

Tsunami deposits provide tangible evidence of a community's tsunami risk. Though best appreciated in the field, these deposits can also be taken to classrooms and public meetings. At the workshop, deposits were displayed as peeled cross sections through tsunami deposits from Sumatra, Peru, Hawaii, Japan, the Philippines, and Cascadia.

Although many people may see tsunami geology as pertaining mainly to public safety, it also offers fundamental insights into Earth science. For instance, presenters showed cases where tsunami deposits help define active plate boundaries in northeastern Russia, help determine subduction-zone behavior in Chile, and help attest to asteroid impacts through geologic time.

Reaching Out to the Public

On the evening of 14 June 2005, in the middle of the workshop, the U.S. West Coast and Alaska Tsunami Warning Center issued a warning for much of the Pacific coast of North America (http://earthquake.usgs.gov/eqinthenews/2005/usziae/). The incident brought television cameras into the workshop and public attention to a post-workshop field trip.

On this trip, workshop participants from India, Indonesia, the Philippines, Sri Lanka, and Thailand visited the southern coast of Wash-