An Autonomous Mobile Platform for Underway Surface Carbon Measurements in Open-Ocean and Coastal Waters

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I Summary

We are working to integrate a suite of existing state-of-the-art pCO_2, *p*H, CTD, CDOM, chlorophyll, and turbidity sensors onto the existing Wave Glider autonomous (sea) surface vehicle (ASV), and then exercise the resulting system in open-ocean and coastal deployments. Liquid Robotics will supply the Wave Glider and the NOAA Pacific Marine Environmental Laboratory (PMEL) will provide the sensor suite.

While the primary payload, the $MAPCO_2$ sensor, and the mobile platform, the Wave Glider, are the products of relatively recent development efforts, they have both been extensively tested and deployed for extended periods at sea. The Biogeochemical/Bio-Optical Wave Glider will be tested in the stable, oligotrophic North Pacific subtropical gyre where instrument stability and reliability can be assessed, and in the dynamic, optically complex coastal waters along the west coast of North America where the ability operate under a wide range of environmental conditions can be tested. The Wave Glider package will operate like the current network of CO_2 ships of opportunity (SOOP), but with the distinct advantage that the Wave Glider can be specifically directed to sample in areas outside of the normal shipping lanes where we are currently unable to monitor air-sea CO_2 flux. The ocean testing program will address fundamental questions in ocean carbon chemistry through a sequence of trials, also assessing the durability of the package. This research will improve our understanding of the ocean carbon cycle and constraining air-sea CO_2 fluxes in the global ocean and on the North American continental margins.

The major outcome of this project will be a robust autonomous surface vehicle capable of extended voyages measuring carbon and other physical and bio-optical properties in the ocean. The ultimate goal is to provide a useful new surface underway measurement technology to the community and a new paradigm of observations that is not reliant on expensive research ships or the standard shipping lanes of volunteer vessels.

The planned deployments will not only test the technology, but will also contribute valuable scientific data that will help improve our understanding of the spatiotemporal variability of CO_2 and insight into the process-level biological and physical factors controlling CO_2 sources and sinks in open-ocean and coastal waters of the conterminous United States. It will provide *in situ* data autonomously that will improve the development of satellite algorithms for both ocean color and CO_2. This project will also make a significant contribution to our knowledge of the extent of ocean acidification in US coastal waters.

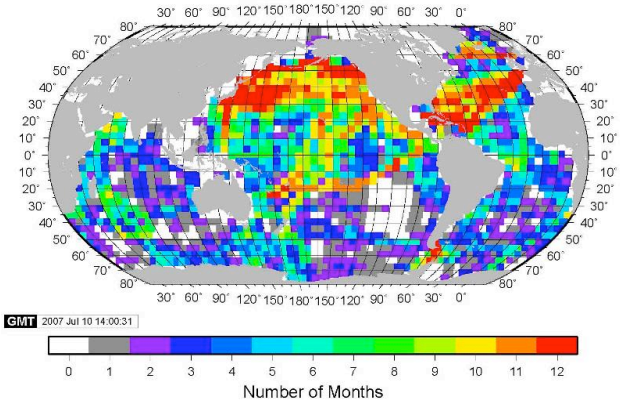

Figure 1: Number of months with observations for each 4° x 5° grid cell (Takahashi et al., 2009)

II Ocean Carbon Science Background

Understanding the role of anthropogenic carbon as a forcing factor in global climate change is an important scientific goal that has far reaching implications for government policy formulation with associated impacts upon social and economic activities and infrastructures. The presence of excess green-house gases in the atmosphere is fundamentally tied to the uptake of carbon by the world's oceans. The ocean stores carbon primarily in the form of dissolved inorganic carbon, which is increasing with time due to the absorption of CO_2 gas from the atmosphere. Greater understanding of the global ocean's ultimate capacity as a sink of anthropogenic carbon is much needed.

The time and space scales of variability in surface water CO_2 concentrations make it challenging to evaluate global fluxes based on *in situ* measurements alone. The latest global flux climatology, based on approximately three million measurements collected between 1970 and 2007, gives a net ocean uptake of 1.4 ± 0.7 Pg-C yr^{-1} (Takahashi et al., 2009). Gruber et al. (2009) analyzed modern oceanic uptake rates of anthropogenic CO_2 for a

wide variety of approaches including observations (sea-air CO_2 partial pressure difference (ΔpCO_2), sea-air ^{13}C disequilibrium and atmospheric O_2/N_2) and models (ocean data inversion, atmospheric data inversion and ocean general circulation/biogeochemical models). They found that these different approaches, including the Takahashi climatologies, are consistent within their uncertainties (ranging from 1.5±0.9 to 2.4±0.5 Pg-C yr^{-1}), but the uncertainties on all these approaches are still quite large. The problem is that a range of nearly 1 Pg-C yr^{-1} is not sufficient for producing a reliable global carbon budget or for predicting how the ocean carbon sink is changing over time-scales relevant to policy and management decisions (i.e. <10 years). We need improved estimates of ocean carbon uptake.

Open-Ocean Carbon Data Limitations

A full understanding of air-sea CO_2 fluxes is not currently possible due to a lack of seasonal and geographic coverage of ΔpCO_2 measurements, and an incomplete under-standing of factors controlling air-sea CO_2 exchange. The Takahashi et al. (2009) dataset shows large regions of the ocean that have no carbon measurements after 40 years (white regions in Figure 1). Most of the global ocean has been observed for <3 months of the year, making it nearly impossible to characterize the seasonal cycle. Most CO_2 measurements have been made on research ships, which have very limited coverage of the global ocean and very few seasonal repeats. In recent years, research ships have been supplemented by putting CO_2 systems on commercial ships referred to as ships of opportunity (SOOP). The yellow to red regions of good seasonal coverage in Figure 1 are from SOOP lines, but they are generally restricted to standard shipping lanes in the northern hemisphere. It is nearly impossible to collect regular measurements outside of these routes.

Coastal Ocean Data Limitations

Another limitation of the global CO_2 climatology is that it explicitly excludes continental margins, which are characterized by much higher spatial and temporal variability in the direction and magnitude of air-sea CO_2 exchange than the open ocean (e.g. Borges, 2005; Hales et al., 2005; Cai et al., 2006). The large carbon fluxes occurring within or passing through the coastal oceans are of great importance for accurately quantifying the carbon budgets of the bordering open-ocean, atmospheric, and terrestrial regions. Furthermore, coastal carbon dynamics are highly sensitive to changing wind patterns, river runoff, and upwelling dynamics. Consequently, coastal carbon fluxes can change rapidly from being a carbon source to a carbon sink. To date, air-sea carbon fluxes from North American continental margin (NACM) waters have been so poorly sampled that uncertainty remains whether these regions are net sources or sinks for CO_2 (e.g. Doney et al., 2004; Chavez et al., 2007). The most recent synthetic effort (Chavez et al., 2007) suggests that NACM waters collectively act as a weak source of 1.6 ± 36 Tg-C yr^{-1} to the atmosphere, with uncertainties over 20-fold higher than the mean. The total flux is the sum of very large CO_2 sources at low latitudes on the Pacific and Atlantic coasts and in the Gulf of Mexico (44.9 ± 14 Tg-C yr^{-1}), balanced by nearly equivalent sinks in mid-high latitude Pacific and Atlantic continental margins. However, the paucity of observations in regions contributing to the large local CO_2 fluxes (e.g. Gulf of Mexico, Gulf of Alaska) lead to ambiguity in the continent-scale integrated total annual flux.

Ocean Acidification

Ocean acidification is a global phenomenon that has received a great deal of recent attention. As CO_2 is absorbed into the ocean, it reacts with water to form carbonic acid, increasing ocean acidity. Since industrialization began, surface-ocean acidity has increased by 30%. This ongoing ocean acidification has the potential to affect calcification, reproduction, behavior, and growth of marine organisms (Doney et al., 2009). However, most of the focus thus far has been on the long term *p*H trends. Measurements of *p*H on a PMEL mooring at station PAPA in the Gulf of Alaska show a seasonal range of more than 0.1 *p*H unit (unpublished data), the same size as the estimated total change in *p*H over the last 200 years. A better understanding of ocean *p*H temporal variability is needed to fully understand ocean acidification.

A recent North American Carbon Program (NACP) coastal research cruise off the northern California coast in May–June 2007 observed upwelling of anthropogenically "acidified" waters (Feely et al., 2008). These "acidified" waters had pH values <7.75 and that dissolution of aragonite was thermodynamically favored over precipitation (or preservation). Sea surface pCO_2 values observed between British Columbia and Baja California during the cruise showed a large range (200-800 μatm). The highest pCO_2 values were strongly correlated with the lowest sea surface temperatures indicating that upwelling of CO_2-rich waters was responsible for the unusually low *p*H, corrosive waters. Recent underway pCO_2 measurements on NOAA coastal fisheries vessels have expanded the spatial and temporal range of observations along the Pacific North American margin. Measurements along the US west coast during the summer and early fall of 2007 revealed even higher pCO_2 values off the central California coast (~1020 μatm) than seen during the NACP cruise, suggesting that acidified waters may be more widespread than observed during the cruise (Feely et al., 2008). More observations are needed to understand the link between anthropogenic CO_2, upwelling and ocean acidification.

III Technology Development

MAPCO2 Development

Since December 1996, the Monterey Bay Aquarium Research Institute (MBARI) has maintained bio-optical and chemical instrumentation on two moorings in the Equatorial Pacific in collaboration with NOAA/PMEL.

As part of this project, MBARI developed an autonomous pCO_2 system based on an infra-red analyzer and bubble type equilibrator. In 2003, PMEL engineers worked with the MBARI group to take a similar MBARI designed pCO_2 system for a drifting buoy and modify it to work as a buoy based system (referred to hereafter as the $MAPCO_2$ system). One major modification was the addition of a NOAA/ESRL certified standard gas that would allow the system to recalibrate autonomously in the field. The system is designed for a nominal deployment life of 400 days with measurements every three hours and data transmissions once per day. Additional information about the moored pCO_2 program can be found at: http://www.pmel.noaa.gov/co2/moorings/ and http://www.pmel.noaa.gov/co2/coastal/.

The $MAPCO_2$ system is both reliable and accurate. In 2006 an underway pCO_2 system was added to the *R/V Atlantic Explorer*, which conducts time-series work off of Bermuda. Thus, the ship passed very close to the Bermuda Testbed Mooring with a $MAPCO_2$ system on at least a monthly basis allowing regular comparisons of the moored and shipboard CO_2 data. An analysis of the moored and shipboard data showed that the two systems agreed to within 0.5±4.7 µatm (n=15,462) when the ship was within 10km of the mooring and the time was within 3 minutes. By comparing data over a range of distances one can begin to assess the correlation length scales for the region. Preliminary analysis suggests that data are coherent within about 80 km regardless of season.

The $MAPCO_2$ technology can be adapted to work in the Wave Glider as an autonomous underway CO_2 sensor. The system will be repackaged to fit properly in the Wave Glider hull, but the basic technology is the same. Preliminary designs have been developed with the existing components, but the battery pack and calibration gas will require size reduction. This means that the system duration will have to be reduced unless we can make the operation more efficient. As part of this project we will explore ways to make the $MAPCO_2$ system more efficient such as testing alternative equilibrator designs that are smaller and faster. These alternative equilibrators can take advantage of the forward motion of the vehicle to create a water flow without the power requirements for pumping water. A shorter equilibration time means lower total power consumption.

Wave Glider Development

The Wave Glider is a new class of wave-propelled, persistent ocean vehicle. Roger Hine, the lead inventor of the vehicle and the CEO of Liquid Robotics, began work on the Wave Glider in 2005 aiming to enable ocean observations independent of costly deep-water moorings or vessels. Encouraged by immediate success with initial prototype designs, Mr. Hine and several colleagues founded Liquid Robotics, Inc. in 2007 to further develop the platform for scientific, commercial, and military applications. Since that time, engineering prototypes and the first product generation of the Wave Glider vehicles have logged a combined total of more than 41,000 nautical miles at sea, with the longest continuous mission lasting over 8 months (247 days).

The Wave Glider represents a unique and novel approach to ocean persistent presence. Wave Gliders harvest abundant ocean wave energy to provide propulsion while solar panels continuously replenish the batteries used to power the Wave Glider's control electronics and payload systems. The vehicle is propelled by the purely mechanical conversion of ocean wave energy into forward thrust, independent of wave direction. Just as an airplane's forward motion through the air allows its wings to create an upward lifting force, the submerged glider's vertical motion through the comparatively still waters at the glider's depth allows its wings to convert a portion of this upward motion into a forward propulsion force. As waves pass by on the surface, the submerged glider acts a tug pulling the surface float along a predetermined course. Separation of the glider from the float is a crucial aspect of the vehicle design.

IV Project Plan

The NOAA Pacific Marine Environmental Laboratory and Liquid Robotics, Inc., are collaborating to address the need for long-term observation of carbon parameters over broad swathes of the global coastal and open ocean by integrating a suite of state-of-the-art sensors (Table 1) onto a Wave Glider. The resulting Bio-geochemical/Bio-Optical Wave Glider platform will be capable both of acting as a long-duration (up to 1 year) "virtual mooring" to augment the existing sparse collection of moored carbon science sensors and of conducting autonomous, basin-scale ocean transits to provide new insight into the spatial variability or carbon uptake (or release) and associated parameters. The system's primary payload sensor is the $MAPCO_2$ sensor being adapted by PMEL. Figure 1 shows a preliminary design for the integration of $MAPCO_2$, pH, and optical water properties sensors into the float portion of a Wave Glider. The autonomy, mobility, and endurance capabilities of the platform, married with its relative low-cost in comparison to ship-based sampling programs, has generated significant interest in the platform from within the National Oceanic and Atmospheric Administration (NOAA) and the greater academic community.

This poster discussed the development of the Biogeochemical/Bio-Optical Wave Glider and payload suite and the planned use of the platform for ocean carbon science observation.

Table 1: Wave Glider Biogeochemical/Bio-Optical Sensor Suite. CTD uncalibrated ranges and accuracies in parentheses. Optical sensor sensitivities and excitation/emissions frequencies in parentheses.

Supplier	Sensor	Measurement	Calibrated Range & Accuracy
NOAA PMEL	$MAPCO_2$	pCO_2 SW & Air (ppm)	200 to 600 ± 3 (stable over ~year)
Scripps (Martz)	custom pH	SW Acidity (*p*H)	0 to 14 ± 0.01 (±0.005 stability ~wks)
Seabird Electronics	Glider Payload CTD	Conductivity (S/m)	0 to 6 ± 0.0003 (0 to 9 ± 0.0010)
		Temperature (°C)	1 to 32 ± 0.002 (-5 to +45 ± 0.010)
		Pressure (dbar)	0 to 100 ± 0.1% FS (same)
		Salinity (PSS 78)	0 to 35 ± 0.005 (0 to 45 ± 0.015)
WETLabs	ECO Triplet	Chlorophyll (μg/l)	0.01 to 50 (0.01) (470/695 nm)
		CDOM (ppb)	0.18 to 375 (0.18) (370/460 nm)
		Turbidity (NTU)	0 to 125 (0.02)

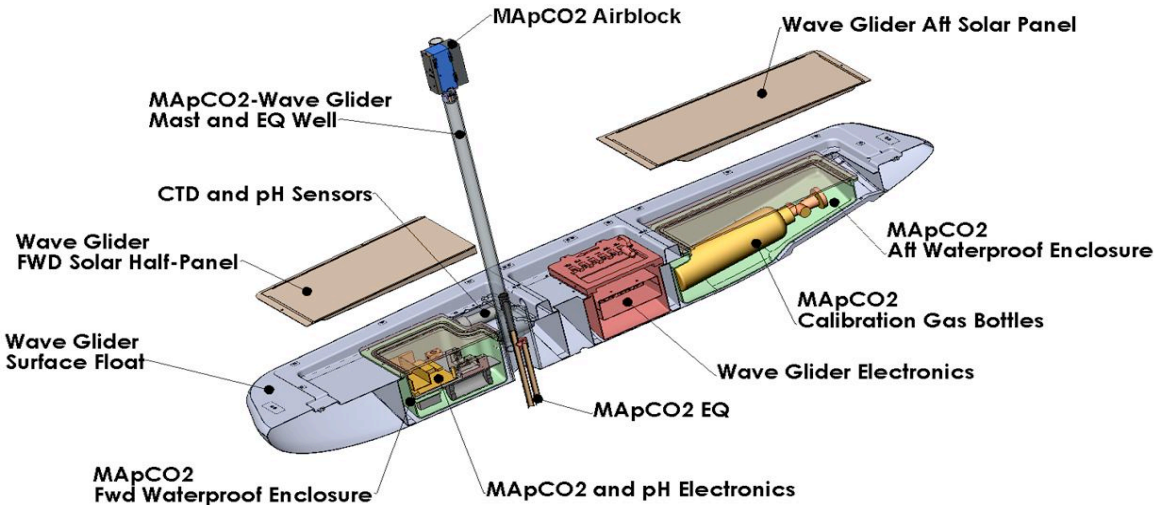

Figure 1: Integration of the bio-geo-chemical payload sensor suite onto the Wave Glider vehicle.

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