Ferry-Based Measurement of Spatial and Temporal *p*CO_2 Dynamics in Lake Michigan

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The Objective

While there have been numerous measurements of both photosynthetic carbon fixation and respiration in large lakes, these measurements are generally poorly resolved in space and time. As a result, several fundamental questions related to metabolism in these systems remain largely unanswered. Three particular questions related to carbon dynamics in these systems that we are interested in are:

1.How does physical forcing (storm events, internal waves, seasonal mixing dynamics) regulate the temporal and spatial dynamics of carbon metabolism?

2.What is net annual carbon fixation?

3.What is the role of these large lakes in regional carbon budgets? Are they net sources or sinks of CO_2?

We are attempting to answer these questions by making measurements of CO_2 and O_2 in the surface waters of Lake Michigan that are extensive in space and time while also being highly resolved.

The Instrument

The general approach to measuring dissolved gases is to equilibrate lake surface water with a re-circulating air stream in which gaseous CO_2 is measured with an infrared gas analyzer and O_2 is measured with a diffusion-based O_2 sensor. The system consists of two linked boxes, one of which houses plumbing components and wet sensors (the "wet box"), and one (the "dry box") which contains the gas sensors and a controller / data logger (Fig. 1). Water drawn into the "wet box" passes across a temperature sensor, followed by an air-water equilibrator, a flow meter, and a fluorometer. The flow meter is used primarily as a diagnostic tool to determine if / when clogging or pump problems occur.

The air stream that is equilibrated with the water circulates between the wet and dry boxes. Gas concentrations are measures as parts per million (CO_2) and parts per thousand (O_2), corrected to a pressure of 1 atmosphere. Both water and air pathway volumes are kept to a minimum to optimize equilibration time. Lab tests indicate that the 95% equilibration time is approximately 2.5 minutes.

A logger / controller regulates power supply to all system components and records the signals from all sensors. The controller is also linked to a GPS on the ship's upper deck, which provides position coordinates that are matched with all measurements, and provides ship speed measurements that are used to turn the sampling pump on and off (sampling is turned off at low speeds, to prevent fouling by dirty water in port).

A second system mounted on the bow of the ship collects measurements of CO_2 and O_2 concentrations in the air above the lake. Concentrations of gases in air and water are converted to partial pressures using barometric pressure measurements from land-based meteorological stations that are interpolated over the lake. These will be used along with wind speed measurements to model lake-atmosphere gas fluxes.

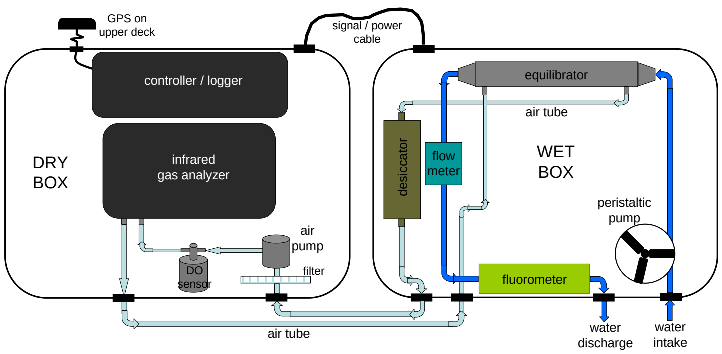

Fig. 1. Schematic diagram and photograph of ship-based CO_2 / O_2 monitoring system.

The Ferry

The Lake Express is a high speed ferry that travels the 130 km distance between the western and eastern shores of Lake Michigan six times daily, between 6:00 a.m. and 11:30 p.m. (Fig. 2). The engine room is equipped with two sea chests. Water is pumped from one sea chest through the CO_2 / O_2 monitoring system and returned to the second sea chest. Because the sea chests are small-volume and high-flow, there is little lag time (~15 s) between sampling and measuring, and water temperature change is small (<0.3°C). A serial cable extension allows for data download and system programming from the main deck. The installation of a wireless serial device server (scheduled for mid-October 2008) will allow for remote operation of the system.

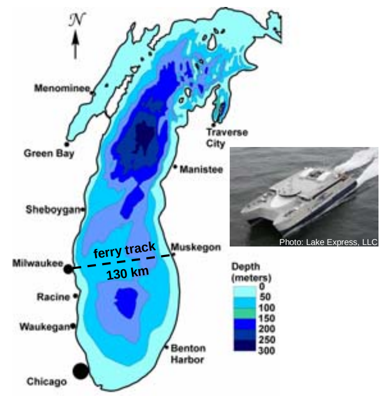

Fig. 2. Track of the high speed ferry on Lake Michigan. The ferry makes three round trips per day at speed up to 34 knots.

The Data

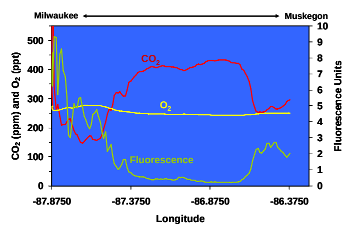

Fig. 3. Distribution of surface dissolved CO_2, O_2, and chlorophyll a fluorescence on June 25, 2008, ten days after a high rainfall event on both sides of the lake. Fluorescence units are roughly equivalent to μg L^{-1} chlorophyll *a*.

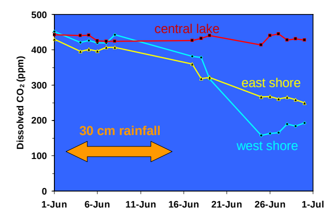

Fig. 4. Plot showing the temporal development of the spatial CO_2 pattern shown in Fig. 3. Following the rain event, the CO_2 concentration remained relatively constant at mid-lake, but decreased dramatically near the shores.

Data collected in the summer of 2008 provided novel insights into metabolic dynamics in Lake Michigan. Following heavy rainfall in early June, dissolved O_2 was elevated and dissolved CO_2 was depressed in the lake's nearshore zones (Figs. 3 and 4). Internal mixing has previously been considered the dominant mechanism controlling photosynthesis in the lake, but our results suggest that nutrient inputs from rivers may play a critical role in the stratified period, when river-borne nutrients are retained within the epilimnion.

Later in the summer, there was evidence for the influence of upwelling on phytoplankton photosynthesis. Upwelling on the lake's eastern shore, as revealed by low surface temperatures, resulted in high dissolved O_2 and low dissolved CO_2 concentrations on this side of the lake (Fig. 5).

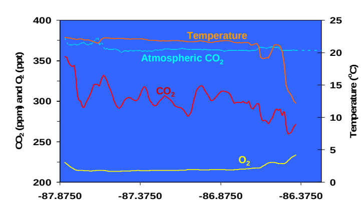

Fig. 5. Upwelling on the eastern shore in mid-August appears to promote elevated photosynthesis, reflected in low CO_2 and high O_2 concentrations.

Previously, the role of upwelling was uncertain, because there is rarely a detectable difference between concentrations of soluble reactive phosphorus in epilimnetic and hypolimnetic waters. The results shown here suggest that the lake's deep waters are sufficiently enriched in dissolved phosphorus (or another limiting nutrient) by August to result in enhanced photosynthesis when these waters are brought to the surface. This photosynthesis appears sufficient to offset any increase flux of CO_2 to the epilimnion that might results from the upwelling of CO_2-enriched hypolimnetic water.

Our future efforts will focus on combining CO_2 and O_2 measurements with meteorological data to estimate lake-atmosphere gas flux rates, and to integrate a full annual cycle of data to determine whether Lake Michigan is a net source or sink of CO_2.

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