Monitoring the Spring Bloom in an Ice Covered Fjord with the Land/Ocean Biogeochemical Observatory (LOBO)

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***Abstract*-The Land/Ocean Biogeochemical Observatory (LOBO) system was initially developed by MBARI under the NSF Biocomplexity program to monitor the land/ocean interface for coastal zone management. The system utilizes highly robust and accurate sensors to provide sustained monitoring of critical watershed habitats in challenging environmental conditions in real time. With the incorporation of novel anti-fouling technology developed by WET Labs, the system has an unprecedented six week maintenance cycle, greatly reducing operational costs while providing high quality data sets. LOBO measurements include nitrate, dissolved oxygen, conductivity, temperature, chlorophyll fluorescence, turbidity and CDOM.**

A LOBO was deployed in the Northwest Arm of Halifax Harbour in January of 2007 and has been monitoring the biogeochemical parameters continuously since (see http://lobo.satlantic.com). Despite heavy icing at -20° C, heavy winds, and sea ice the system reported data every hour where the detailed nature of the annual spring phytoplankton bloom was recorded at high resolution. The coincident and continuous record of nutrients, phytoplankton and other physical and chemical parameters is unique, and provides a robust means to base predictive coastal ecosystem models in sensitive marine areas.

I. Introduction

The Land/Ocean Biogeochemical Observatory (LOBO) is a complete monitoring system for routine, robust and accurate water quality measurements, particularly in sensitive and diverse ecological areas such as estuaries and inland waters [1]. Developed by Dr. Ken Johnson's team at MBARI under the NSF Biocomplexity in the Environment program, the LOBO was designed to create a real time sensor network for aquatic systems. LOBO uses a system of high quality, high temporal resolution in situ sensors to biogeochemical fluxes. Water properties such as salinity, temperature, and current velocity are combined with nutrient measurements and other parameters to monitor important processes that affect biogeochemistry.

The LOBO system has been extensively tested in a wide range of extreme water quality conditions for the past three years with a network of five systems in the Elkhorn Slough National Estuarine Research Reserve. Online real-time and archived data is available at www.mbari.org/lobo/loboviz.htm. After completing the technology transfer from MBARI, Satlantic has placed an additional 14 systems in operation at public and private sites, including demonstration systems in the Northwest Arm, Halifax, Canada (http//:lobo.satlantic.com) and Yaquina Bay, Newport, Oregon (http//:yaquina.satlantic.com).

The LOBO addresses specific concerns of coastal resource managers, such as degraded coastal water quality, loss and alteration of estuarine and watershed habitat, habitat restoration, reduction of biodiversity, and problematic effects of pollutions and invasive species. The Northwest Arm LOBO deployment has demonstrated how a real time aquatic sensor network can significantly increase our ability to address these issues and contribute to the generation of information that leads to sound resource management. The ability to study the interactions of

Fig. 1. LOBO buoy in the Old Salinas River, Moss Landing, CA.

the hydrologic cycle, nutrient chemical cycles and human alterations of these cycles at the land/ocean interface is a fundamental component of coastal zone management, and one that has traditionally been a major scientific challenge.

II. LOBO SYSTEM

The LOBO system consists of a fully integrated package with buoy platform, sensors, power system, telemetry system, data acquisition system, navigational aids and web data visualization software (LOBOviz).

The LOBO system is available in several form factors. The most commonly used is the RiverLOBO configuration shown in Fig. 2. This design is well suited for shallow protected waters of estuaries and rivers where strong currents are present. The system is designed to be highly robust and can resist heavy icing, and even ice floes with sufficient anchor weight. The entire system is completely submersible with waterproof communication systems, and no exposed solar panels. The durable hull exterior and lack of exposed cables ensures that this design is highly resistant to vandalism, a key feature for heavy recreational and commercial traffic areas. The system is also quite compact, approximately 1.4 m in length, and weighs about 70 kg in air when fully configured. The BayLOBO features a conventional discus buoy hull that is suitable for more exposed locations with sustained wave action. The DockLOBO and BenthicLOBO platforms are designed without flotation for submerged deployment on fixed structures such as docks or pilings, or mounted on the sea bottom itself and cabled back to shore. All the platform designs feature a modular instrument bay that provides superior environmental protection for all the sensors, while permitting easy access for maintenance.

The LOBO power system is typically a user serviceable 51 Ah alkaline D cell battery pack that is easily removable from the instrument bay. This allows the system to operate for six weeks with a one hour schedule, with a fully configured instrument package. The D cell pack was chosen for low operational costs, with a battery change costing less than $40.

The LOBO has various telemetry options, the most common being a GSM/GPRS modem. This is a compact communications module that is easily configured on site by a user by simply inserting a SIM card from a local service provider and configuring the LOBO with the service provider's network access information. LOBO systems can also be configured with CDMA/1xRTT, CDMA/EV-DO, point-to-point wireless and direct cable.

The data acquisition system used is a compact 5 serial port STOR-X system. This controller manages scheduled operation of the system including, powering up sensors, acquiring data, and operating the active anti-biofouling systems. In the GSM/GPRS and CDMA/1xRTT configurations the STOR-X formats the data from the sensors as an email message that is automatically parsed and ingested by the LOBOviz data system on a shore side server. The scheduling of the system can also be configured remotely by sending an email to the shore side

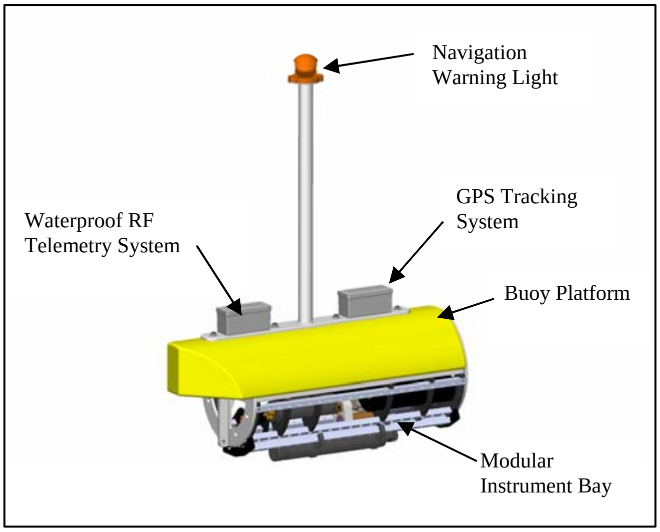

Fig. 2. Typical RiverLOBO System.

server for the STOR-X to automatically retrieve. The STOR-X buffers several days of data on board to prevent data loss in case of poor RF signal (or in extreme cases, if the system is forced under water).

For navigational aids, the RiverLOBO and BayLOBO typically have a one nautical mile amber navigation light, yellow Surlyn foam flotation, radar reflector and highly reflective tape. These LOBO platforms also use a GPS tracking system to assure the platform is on station.

III. LOBO SENSORS

The LOBO system uses robust, high accuracy, high stability sensors with integrated anti-biofouling systems to maximize deployment time, minimize operational costs and provide high quality data sets. The standard sensor suite includes the Satlantic ISUS chemical free nitrate sensor [1,2,3,4], WET Labs WQM (integrated sensors for conductivity, temperature, pressure, dissolved oxygen, chlorophyll fluorometer, and tubidity) [5], WET Labs ECO series chromophoric dissolved organic matter (CDOM) fluorometer, and a Nortek Aquadopp current profiler.

The key to maintaining consistent high quality data sets over maximum deployment times is directly related to the anti-biofouling systems. The LOBO uses a multi-tiered approach to anti-biofouling creating a highly effective barrier for biofouling organisms, even in high productivity coastal waters. The outermost layer of anti-biofouling is E-Paint, a zinc based peroxide generating ablative paint which has been shown to be highly effective against biofouling organisms, even barnacles. To aid cleaning, exposed pressure cases and submerged platform infrastructure is covered with a vinyl based tape before application of the E-Paint. Sensor systems themselves are surrounded by copper where possible (ie CTD, fluorometers). The flow path for the ISUS and WQM (including the DO sensor) are enclosed in opaque tubing with an EPA approved TBT cartridge (optional) and is injected with

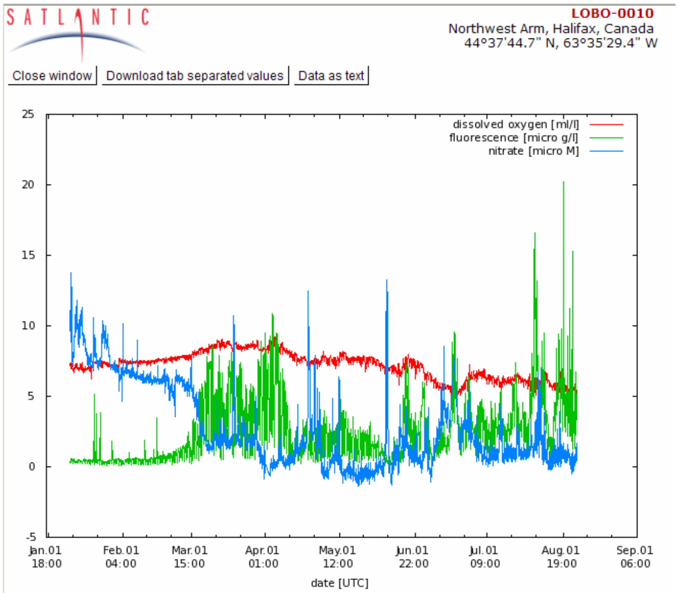

Fig. 3. Seven months of Northwest Arm LOBO Data demonstrating the effectiveness of the multi-level anti-biolfouling systems implemented.

chlorine bleach from an integrated BLIS™ system developed for the WQM by WET Labs Inc. [5]. Bleach injection protocols are modified for the LOBO to inject 120 µl of bleach each hour into the flow path which has proven to be effective at keeping the extended flow path sensors (CTD, DO, ISUS) clean for at least six weeks. Sensors outside the flow path such as the turbidity sensor and fluorometers are all cleaned and covered when not in use by the novel copper bio-wiper™ system, also developed by WET Labs. As can be seen in Fig. 3, these combined anti-biofouling techniques have been shown to be highly effective at providing reliable and high quality data set for seven months with a six week maintenance cycle. This demonstrates the efficacy of the anti-biofouling systems on the LOBO and the ability of the system to provide high quality data and operate effectively for long periods in highly productive coastal waters, greatly reducing operational costs, which is the major cost of any observing system. The data also shows the magnitude of episodic events, demonstrating the improved understanding of ecosystems provided by high temporal sampling in situ of a full biogeochemical instrument suite.

IV. LOBOviz

Another component of the LOBO system is LOBOviz, an integrated data visualization and display package that allows for an entire network of monitoring sites to be viewed through a web browser. This powerful tool allows users to access and view real time or archived data, comparing multiple sensors at a site or multiple sites simultaneously though a simple web interface. This gives system users rapid and easy access to the monitoring network to help make informed decisions.

The LOBOviz web-based data query interface allows remote users to select any number of available biogeochemical sensor measurements from one or more LOBO platforms. The resulting data covered by the specified date range is returned to the user as graphical time series or scatter plots. Query results may be additionally downloaded in tabular text format for easy importation to spreadsheet applications or custom modeling software.

The LOBOviz data ingestion module is a server-side Java application built on DACNet [6] Instrument Services technology, which has been extensively used in other observing systems [7,8,9,10]. It can fully support both LOBO and non-LOBO data sources through externally configurable XML sensor metadata descriptors. LOBOviz manages reception of data transmitted by email from any number of LOBO nodes (or other data sources) on a network. It parses binary and/or ASCII data file attachments and averages sensor sample bursts, applying calibration functions with sensor-specific coefficients in order to fit measurements to physical units as required. Averaged and fitted measurements can be further combined by the ingestion module to create higher-order derived products and water quality indices. All measurement products are inserted along with sensor metadata to a JDBC-compliant PostgreSQL relational database management system that provides industry-standard data management features.

In addition to the interactive web interface, the LOBOviz server exposes non-interactive network interfaces for programmatic retrieval of archived data by third-party applications for republication, reprocessing, modeling, etc. It also publishes hourly updates of most-recent sensor measurements to several templated formats such as WML files for mobile wireless access, KML files for contextual visualization in Google Earth™, XHTML blocks for insertion to web pages, and RSS for feed readers.

V. Northwest Arm LOBO

Satlantic deployed the first production version LOBO to a site on the Northwest Arm of Halifax Harbour, Halifax, Nova Scotia. The Northwest Arm is 18 m deep waterway approximately 4.9 km long, 300 m wide, and is a heavy traffic area. The Northwest Arm has a 2 m tidal range and flushes anthropogenic effluents into the main harbour, making it an excellent location to measure water quality of the estuary. The LOBO site is located halfway along the Northwest Arm in 15 m of water, directly adjacent to the heavily used main navigation channel. This site was selected both for its proximity to Satlantic facilities and for the extreme range of environmental conditions under which the LOBO and its sensors could be rigorously tested. Our goal was to establish continuous, long-term, in situ monitoring of Northwest Arm's spring bloom in real time and at high temporal resolution using a full suite of biogeochemical sensors. This has never before been accomplished due to the destructive effects of extreme ice conditions on conventional forms of in situ monitoring.

A RiverLOBO system was installed at the Northwest Arm site on 10 January, 2007 and has since been operating continuously and autonomously (data is freely available online

Fig. 4. Northwest Arm LOBO with heavy icing at -20 °C.

at **http://lobo.satlantic.com**). A weather station provided by Dalhousie University was integrated with the system on 30 April, 2007. Conditions in the Northwest Arm during the winter months included frequent drops in air temperature to -20 °C, heavy icing of the platform (Fig. 4) and icing of the lower reaches of the Arm which produced pan ice (Fig. 5) and heavy ice sheets at the monitoring site. The heavy ice sheets were the most challenging in that they submerged the entire platform completely beneath the water surface while the ice sheets passed overhead. The system was purposely deployed with a very heavy (180 kg) anchor and heavy duty 9 mm steel mooring line to keep the buoy on station in these conditions.

Fig. 6 shows the regular battery changes every 6 weeks, even as the water temperature dropped as low as -1 °C. The sensor systems were also cleaned at this same interval.

Fig. 5. Northwest Arm LOBO in pan ice.

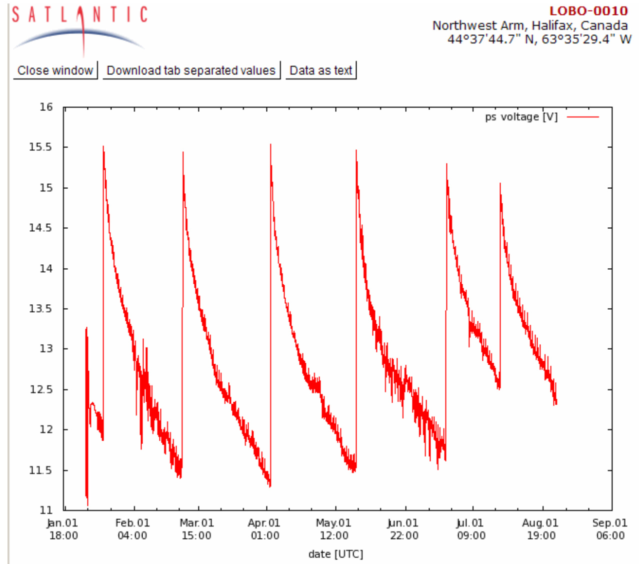

Fig. 6. NW Arm LOBO battery change and service interval showing a six week maintenance cycle.

VI. Data Analysis

The Northwest Arm LOBO data was analysed by the Department of Oceanography at Dalhousie University as the spring bloom progressed. The spring bloom represents a time of ecologically important change. Increasing solar irradiance frees phytoplankton from light limitation, allowing them to build up biomass by taking up nutrients that have accumulated in surface waters over the winter. With instrumentation to provide estimates of phytoplankton, oxygen concentrations, and nitrate in particular, the LOBO buoy provided what may be an unprecedented continuous time series of chemical and biological variables during the spring bloom.

Presented below is a brief study of how the nutrients, phytoplankton, and dissolved oxygen changed throughout the initial stages of the spring bloom, including a simple model to reconcile estimates of chlorophyll *a* (chl*a*) from a factory-calibrated fluorometer with measurements of dissolved oxygen (DO) and nitrate from the Northwest Arm LOBO. The comparison is excellent, suggesting that LOBO is a useful tool for describing ecological and biogeochemical processes in coastal waters.

A. Spring Bloom Data

During the wintertime, it is generally assumed that the water column of most coastal waters becomes completely mixed due to cold temperatures and heavy winds. This mixing and the lack of light, required for phytoplankton growth, allow nutrient concentrations to rise uniformly in the water column until light levels increase and surface waters stratify in late winter or spring. When light levels become favorable for phytoplankton, they take advantage of nutrients that have accumulated over the winter and a phytoplankton bloom occurs. As seen in the highlighted section of Fig. 7, the sharp increase in chl*a* matches a sharp decline in nitrate concentration, and a

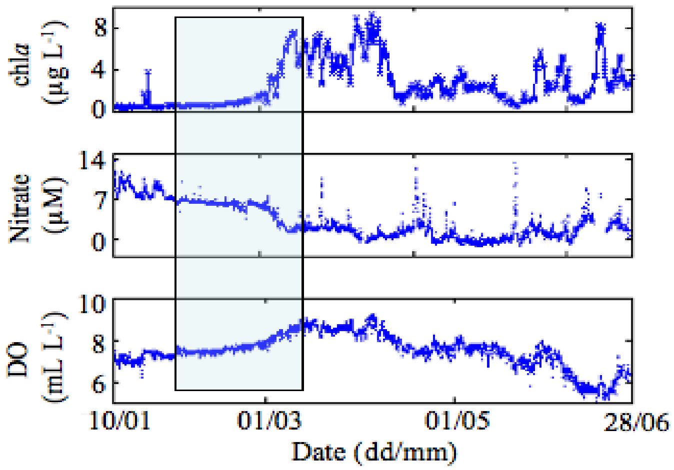

Fig. 7. The spring bloom can be seen as rise in chl*a* as estimated from fluorescence, decrease in nitrate, and an increase in DO within the water column. The blue shaded region, is the time period of the study. The chlorophyll data are measurements from 1:00 am to 5:00 am (local time) to exclude effects of nonphotochemical quenching of fluorescence by sunlight. A factory calibration was employed to the fluorometer to estimate chl*a* concentration.

raise in DO. This pattern is commonly observed during times where phytoplankton growth is the dominant process of the water column, and is analogous to batch cultures of phytoplankton.

B. *Estimates of nitrogen uptake from decline of nitrate measured from the Northwest Arm LOBO*

The decline of nitrate over the selected time range was utilized to estimate nitrogen uptake of phytoplankton based on two assumptions: the dominant nitrogen source in the water column was nitrate, and the decline of nitrogen was solely due to the uptake from phytoplankton. This study was not focused on slight deviations from the trend of nitrogen decline, such as those due to rain events or advection, so the record was smoothed by a lowess linear curve fitting technique implemented in Matlab (Fig. 8).

Daily estimates of nitrate uptake were calculated from (1),

$$-\Delta NO_3^- / \Delta t = \rho_N \tag{1}$$

where $-\Delta NO_3^- / \Delta t$ is the change of smoothed nitrate data over time measured from the Northwest Arm LOBO, and ρ_N is an estimate of absolute nitrogen uptake rate by phytoplankton. Both variables have units of µM d^{-1}.

C. *Modeled chla from* ρ_N

With an estimate of ρ_N, it is possible to obtain production estimates of different compounds, such as carbon or chl*a* by following simple stoichiometric averages. Assuming phytoplankton obtain nutrients according to the Redfield ratio, 6.6C:1N (by atom), estimates of carbon production rates (*P*) with units of µM day^{-1} can be calculated according to (2).

$$\rho_N \times 6.6 \frac{C}{N} = P \tag{2}$$

From this estimate of (*P*), chl*a* production (P_{chl}), with units of µg L^{-1} day^{-1}, can be derived with (3), with a C:chl*a* ratio of 70. This ratio is known to vary, but was taken as an average from a nearby water body [11].

$$\rho_N \times 6.6 \frac{C}{N} \times 12 \times \frac{chla}{70C} = P_{chl} \tag{3}$$

In (3), the constant 12 is the atomic weight of carbon (µg μmol^{-1}), and the carbon to chl*a* ratio by weight is unitless.

Estimates of carbon or chl*a* production are useful, however in order to validate our model, its results must be compared with measured data. To directly compare chl*a* data from the Northwest Arm LOBO ($chla_{lobo}$) with model results ($chla_{modeled}$), a cumulative sum of P_{chl} was taken each day. An initial chl*a* concentration, chosen from an average of the first night's $chla_{lobo}$ data, was added to each day's cumulative sum to provide daily estimates of $chla_{modeled}$ with units of µg L^{-1}. This estimate of $chla_{modeled}$ is analogues to the total chl*a* in absence of any loss terms (such as respiration, grazing, sinking, etc.), while $chla_{lobo}$ accounts for such loss terms. A comparison of $chla_{lobo}$ and $chla_{modeled}$. is seen in Fig. 9.

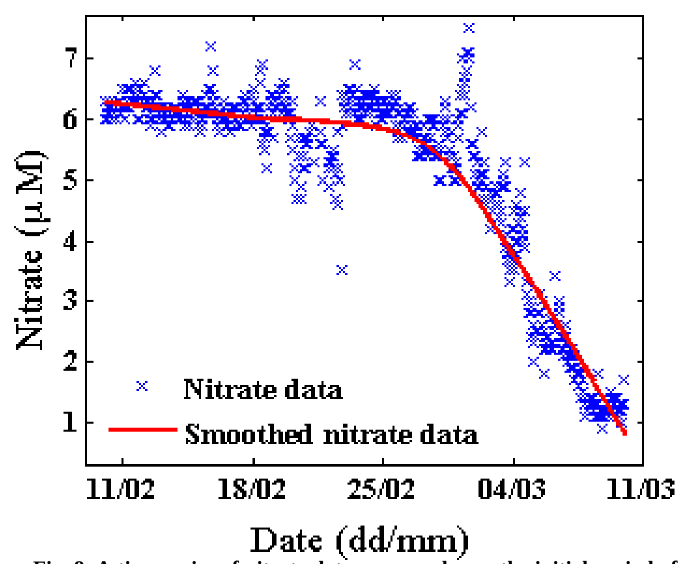

Fig. 8. A time series of nitrate data measured over the initial period of the spring bloom. The red line represents smoothed data from a lowess linear curve fitting technique implemented in Matlab.

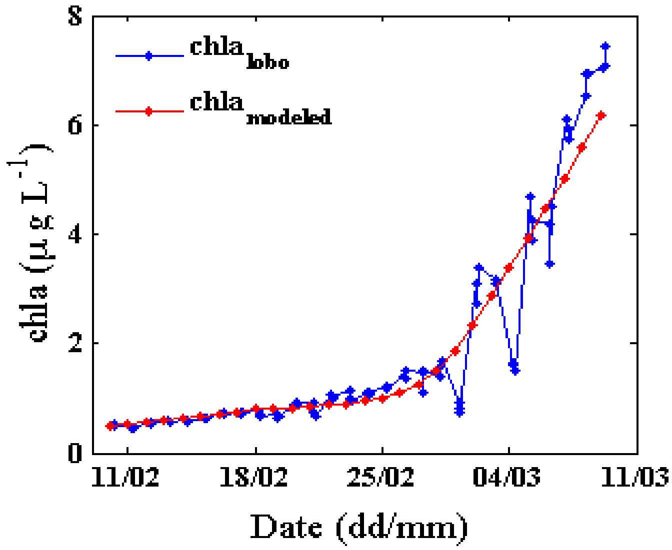

Fig. 9. A time series of chlorophyll *a* concentration estimated from night time fluorescence, as well as estimated from nutrient uptake. Night time fluorescence data is defined from 1:00 am to 5:00 am local time.

D. Estimates of DO from nitrogen uptake

Just as chl*a* production was modeled from ρ_N, oxygen production can be estimated from P by means of the photosynthetic quotient, PQ — moles of O_2 produced divided by moles of CO_2 consumed. This ratio can vary depending on the dominant nitrogen source the phytoplankton are acclimated to (i.e., nitrate or ammonium) [12]. As an average for spring bloom conditions, a PQ of 1.58 was chosen [13]. Oxygen production (P_{O2} mL L^{-1} d^{-1}) can be modeled by (4),

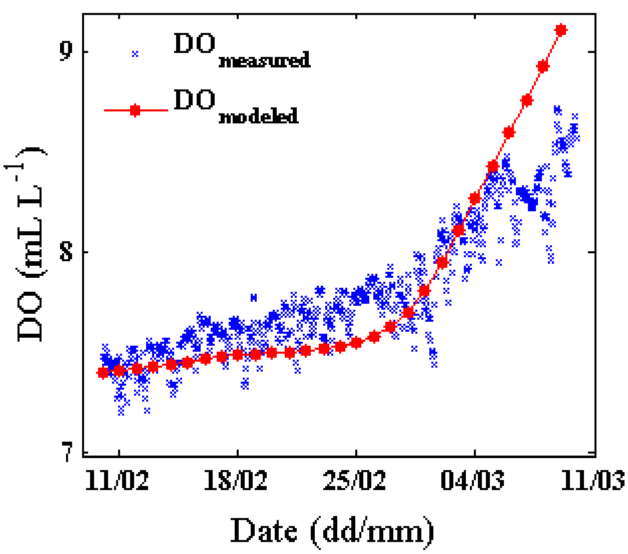

Fig. 10. A time series of measured and modeled dissolved oxygen over the spring bloom.

$$\rho_N \times 6.6\frac{C}{N} \times 1.58\frac{O_2}{C} \times G_c = P_{O2} \quad (4)$$

where G_c equals 2.27x10^4 mL mol^{-1} and is a coefficient to convert moles of oxygen to volume at standard temperature and pressure, calculated from (5).

$$R \times T \times \Pr = G_c \quad (5)$$

R is the universal gas constant (8314 [mL kPa (K mol)$^{-1}$]), T is temperature (273 K), and Pr is the pressure (100 kPa).

DO_{modeled} (mL L^{-1}) was calculated by taking a cumulative sum of P_{O2}, from the first time period to each day, and adding DO_{measured} from the first day for an initial value. The results of O_2 estimated from the nitrogen uptake ($DO_{modeled}$) and O_2 estimated from the dissolved oxygen sensor ($DO_{measured}$) are directly comparable as seen in Fig. 10.

VII. Conclusions

The Northwest Arm LOBO demonstrates the ability of the LOBO design to maintain a high quality in situ data set under extreme conditions. With maintenance cycles of up to six weeks, the LOBO system represents a significant reduction in operational cost over traditional monitoring systems and demonstrates the effectiveness of multi-tiered anti-biofouling systems. The automated data processing and database system provides easy access to a range of users from the general public to researchers. Continuous in situ monitoring of estuaries shows the importance of episodic events, the effects of which can only be well understood using high temporal resolution data.

Studies such as this one using the Northwest Arm LOBO data are extremely useful to the understanding of biogeochemical variables. As seen in Figs. 9 and 10, $DO_{modeled}$ and chla_{modeled} were remarkably similar to $DO_{measured}$ and chla_{measured} respectably, the estimates of percent O_2 saturation, and chlorophyll *a* concentration were remarkably similar to those measured by the Northwest Arm LOBO. This similarity suggests that the dominant process occurring in the Northwest Arm over this time period, is indeed the spring phytoplankton bloom.

The Northwest Arm LOBO can measure relevant biogeochemical variables on time the scales necessary to appreciate the dynamic range of the coastal environment. Such studies can open the door for more quantitative studies of nutrient dynamics of phytoplankton. This study analyzed a short time period representing early stages of the spring bloom. The study of coastal oceanography will continue to progress with the use of these types of coastal monitoring systems.

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