WQM: A New Integrated Water Quality Monitoring Package for Long-Term *In-Situ* Observation of Physical and Biogeochemical Parameters

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ABSTRACT

We describe a collaborative effort to develop and implement a new integrated water quality monitoring package that provides continuous and simultaneous multi-parameter physical and biogeochemical measurements, including: conductivity, temperature, pressure, dissolved oxygen, chlorophyll fluorescence, and turbidity. The "Water Quality Monitor" (WQM) features autonomous operation and multiple anti-fouling approaches, and is intended for long-term deployments (months) in potentially high-fouling coastal environments. Our primary objectives for our in-field tests are 1) to collect high quality data for > 3 months without the need for instrument service, 2) to present results from field trials in coastal regimes in order to assess the WQM's longevity and efficacy of multiple antifoulant approaches, and 3) to demonstrate that the WQM as a single, multi-sensor instrument provides reliable, multi-parameter data in a single data stream, simplifying data analysis and management for ocean observing system integrators. Results from preliminary performance testing of the WQM deployed in Chesapeake Bay, MD, from April 20, 2006 to July 3, 2006 showed negative effects of biofouling within 2 months. Lessons learned from this deployment helped evolve the instrument design and highlighted the need for more aggressive measures to deter the effect of biofouling. To determine the best approach to further reduce the effect of biofouling over the deployment period in addition to copper guards, WQMs were deployed with Sea-Bird Anti-Foulant cartridges (AF) only, WET Labs BLeach Injection System (BLIS) only, or a combination of AF and BLIS. A total of 5 prototype WQMs were deployed in two separate coastal environments. Sea-Bird Electronics conducted tests at Shilshole Marina, WA continuously for 5 months straddling the end of the summer growing season, fall and winter months (August 15, 2006 to January 15, 2007). WET Labs conducted tests in Yaquina Bay, OR for just over 4 months during similar growth conditions (September 13, 2006 to January 23, 2007). Since the deployment period extended from late summer to winter, biofouling conditions were considered to be moderate. Results show temperature, salinity, dissolved oxygen, turbidity and chlorophyll fluorescence values were highly coherent among multiple instruments over 4 and 5 month deployment durations. WQMs equipped with either the AF or combination of AF + BLIS recorded high quality data for 110 – 152 days (> 3-5 months). Of particular importance was the stability of the dissolved oxygen measurements which showed less than 5% signal degradation over the deployment period. In-field validation measurements of dissolved oxygen were made with a calibrated reference SBE43 dissolved oxygen sensor and with discrete water samples for Winkler analysis. Temperature and salinity were very stable based on pre and post-deployment calibrations and drift was < 0.001 degrees C and 0.006 psu, respectively. Designed specifically to address the ocean and estuarine observing needs, the WQM provides a reliable, cost effective, research-grade water quality monitoring solution for long-term deployments without need for frequent instrument service.

I. INTRODUCTION

The development of the Water Quality Monitor (WQM) was a collaborative effort between Sea-Bird Electronics, Inc. and WET Labs, Inc. to combine proven technologies into an integrated sensor package to provide continuous and simultaneous multi-parameter physical and biogeochemical measurements, including: conductivity, temperature, pressure, dissolved oxygen, chlorophyll fluorescence, and turbidity. Designed for long-term deployments (months) in potentially high-fouling coastal environments, the WQM features autonomous operation and multiple anti-fouling technologies. The design is based on the proven technologies of Sea-Bird Electronics, Inc., combined CTD and dissolved oxygen sensor (SBE52) and WET Labs, Inc. combined chlorophyll fluorescence and turbidity sensor (ECO-FLNTUS). It is compact and ruggedly made of titanium and other low-maintenance (plastic) materials. The Sea-Bird Electronics SBE 43 dissolved oxygen (DO) sensor used on the WQM is a redesign of the Clark polarographic membrane dissolved oxygen sensor, re-engineered to provide stable, rapid response DO measurements. The ECO-FLNTUS measures chlorophyll fluorescence at 695 nm and turbidity at 700 nm within the same volume and is equipped with an integrated Bio-wiper™ for anti-fouling protection. The WQM features a central processor (Persistor® CF2) to handle data integration and seamless data output of simultaneous multi-parameter measurements at 1 Hz frequency. Data storage is provided by a compact flash card. The WQM also contains an Uninterruptible Power Supply (UPS) which provides power long enough to save any recent data, close any open files, and store required operating parameters.

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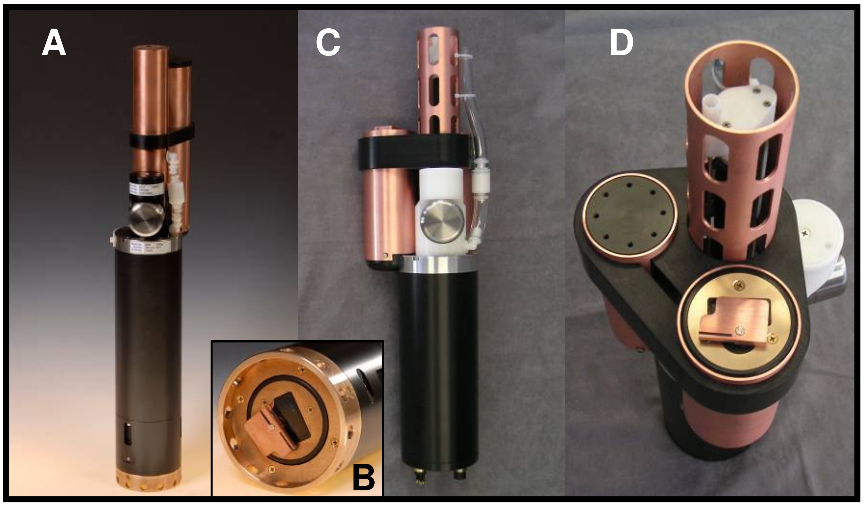

Fig. 1. (A) WQM with solid copper ring-guard (top, center) and BLIS (right), shrouded in a copper canister. (B) A view of the ECO-FLNTU with the copper Bio-wipper^{TM}, copper faceplate and copper ring-guard. (C) Initial WQM prototype with perforated ring-guard assembly covering the temperature and conductivity sensor (top, center). WET Labs BLeach Injection System (BLIS, not shown in this view) is located behind the ring-guard assembly. (D) WQM prototype used during the San Luis Bay, CA and Chesapeake Bay, MD deployments with ECO-FLNTU oriented facing upward.

The WQM sensor is 65.4 cm in length and 18.5 cm in diameter with the ECO-FLNTUS incorporated into the instrument body oriented facing downwards and the CTD, oriented upwards (Fig. 1 A, B). The CTD is shrouded in a solid copper ring guard assembly which acts to deter biofouling near the plumbing intake and exhaust ports. Additionally, the CTD is protected from biofouling by two EPA approved anti-foulant cartridges (AF), one placed at the intake duct and one near the exhaust. The ECO-FLNTUS has a copper faceplate and a copper Bio-wiper^{TM} to sweep over the optical window when sensor is powered on and to cover the sensor window while the sensor is quiescent. The sensors are protected from biofouling by molecular diffusion of AF into the sensor plumbing and WET Labs designed BLeach Injection System (BLIS) that injects a user determined volume of bleach directly into the DO chamber.

A series of field deployments led to modifications which improved the operation and use of WQM including implementation of all of these multiple anti-biofouling methods simultaneously. The focus of this paper is to describe the evolution of the instrument performance, electronics, and anti-biofouling approaches over a series of successive field deployments. Each deployment required the WQM to meet different goals and metrics providing an opportunity to track its progress as it evolved into the commercial package design. The WQM with the anti-fouling technology described in this paper has also been integrated with the Satlantic Inc., Land/Ocean Biogeochemical Observatory (LOBO) monitoring system with integrated nutrient sensing capabilities [1].

II. INITIAL WQM PROTOTYPE DEPLOYMENTS

The primary objective of the initial deployments was to assess the in situ system operation of the WQM. A secondary objective was to determine the effects of biofouling in moderate to heavy biofouling environments. In the initial WQM prototype design both the ECO and CTD components were oriented upward (Fig 1 C & D). For biofouling protection, a perforated copper ring guard was installed around the T-C sensor components and the ECO was equipped with a copper faceplate and copper optical shutter (Bio-wiper^{TM}). In addition, Sea-Bird standard anti-foulant cartridges (AF) were inserted at the inlet and exhaust of the sensor plumbing.

On February 22, 2006 the first WQM prototype was deployed at 2 m below the water surface beneath the California Polytechnic State University pier in San Luis Bay, CA. The WQM was powered from the shore power and data were telemetered in real time using a serial to WiFi interface to a host computer via an Ethernet connection maintained at California Polytechnic State University. As the goal of the first deployment was to test the overall *in situ* operation of the integrated WQM instrument prototype, validation data for instrument measurements were not obtained. The WQM was deployed in San Luis Bay, CA for 66 days and was able to provide 100 % of expected data via the WiFi telemetry interface and from data downloaded from the on-board memory. Prior to instrument retrieval, an underwater inspection of the WQM showed biological growth on the outside of the conductivity and temperature sensors, despite the perforated copper ring guard. Inspection of the WQM after the deployment showed that the combination of the copper faceplate and Bio-wiper^{TM} was effective in mitigating biofouling on the ECO optical sensing window over the deployment period (Fig. 2 A, B).

A second WQM prototype was deployed from a mooring and powered by DC marine battery in Chesapeake Bay, MD from April 20, 2006 to July 3, 2006 with the same configuration. The ECO-FLNTU was incorporated into the WQM body and oriented facing downward (Fig. 1 C, D). Discrete water samples were collected periodically to validate the dissolved oxygen sensor and were used to determine the period of time the WQM was collecting data without the effect of biofouling. The WQM was deployed in Chesapeake Bay, MD for a period of 43 days and collected 80 % of expected data. Data loss was due to the loss of battery power from the mooring during the deployment period. The WQM DO data agreed well with *in situ* Winkler titrated water samples throughout most of the deployment. Near the end of the deployment period, the WQM DO indicated a negative difference compared to the Winkler values, which suggested fouling of the sensor. Additional methods to deter biofouling were investigated and integrated into the next edition of the WQM body design (see below).

III. ANTI-BIOFOULING ENHANCED WQM PROTOTYPE DEPLOYMENTS

> ***"Biofouling and corrosion remain the major impediments to making long-term unattended measurements in the oceans [2]."***

Initial deployments of the first WQM in Chesapeake Bay, MD and San Luis Bay, CA showed that bio-fouling was encroaching within a month in these highly productive coastal environments, despite the use of copper guards around the primary sensors (Fig. 2). Such fouling can limit deployments by blocking flow through the sensors and impairing sensor output if it takes hold inside the sensor. To deter external fouling around the sensors, the perforated guards were replaced with solid copper can rings. The next stage in the development of the WQM was to implement an active device directed at inhibiting biofouling inside the sensors. WET Labs developed an automated bleach injection system (BLIS) to deliver a specified volume of 6% commercial grade bleach solution directly into the dissolved oxygen sensing chamber within the WQM after each sampling interval. The BLIS system was integrated into the WQM. A micro-volume pump and bleach reservoir is housed within a copper cylinder and located next to the T-C sensing components. A small diameter tube connects the BLIS pump and bleach reservoir with the DO plenum chamber. WQM electronics provide for direct control of the frequency and volume of bleach delivery. Replacement of the bleach reservoir is easily accommodated by removing the BLIS end cap, removing the empty bleach reservoir, and dropping in a full bleach container. Used in this manner, the bleach acts as a biological growth deterrent and cleansing agent within the T-C and DO plumbing. BLIS systems were implemented on the next round of WQM prototypes and a series of deployments were conducted to evaluate the efficacy of the BLIS in deterring biological fouling, especially of the DO sensor. It was expected that BLIS would increase instrument deployment periods as a result.

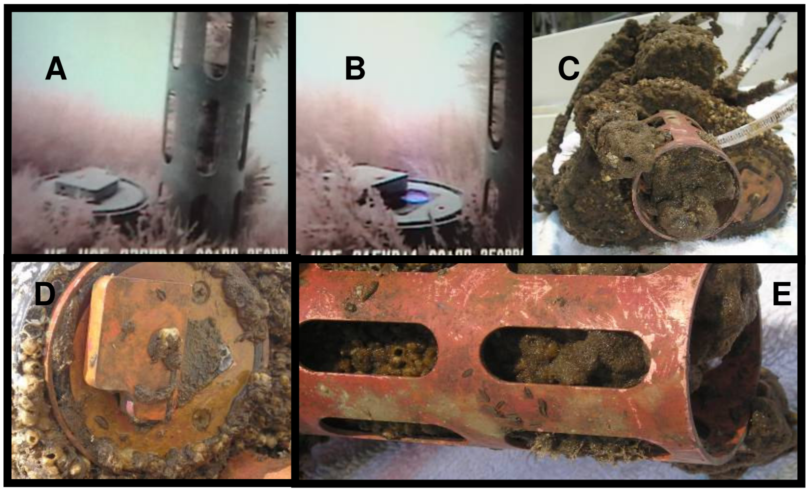

Fig. 2. WQM after 66 days deployment, in San Luis Bay, CA. (A) ECO with copper shutter covering optical window and perforated copper guard of T-C sensor with biofouling interior. (B) ECO without shutter over copper window, taking a measurement. (C) WQM after 43 days deployment, in Chesapeake Bay, MD WQM with heavy biofouling, viewed from top. (D) ECO with copper shutter open and optical window with heavy biofouling. Note that the WQM remained deployed without power for a few weeks prior to instrument retrieval, which can account for the growth on the optical window. (E) Perforated copper guard with external biofouling growth outside the conductivity and temperature sensors.

WQM Prototype Tests at Shilshole Marine, WA - 2006

Sea-Bird deployed three WQM prototypes between August 15, 2006 and January 15, 2007 at Shilshole Marina, WA at a water depth of 2 m. WQMs were programmed to collect 1 sample every 10 minutes. The instrument flushed for 30 seconds, at which point the SBE 43 recorded a sample. Bleach was injected into the plumbing after the sample point was taken and flushing stopped. The SBE 43 is continuously polarized, eliminating the power-up delay of earlier Clark designs. The 30 second flush prior to making a measurement is strictly to remove the trapped water from the plumbing and to deliver a fresh sample of water to the sensor. Sea-Bird modified the body design of an existing CTD to include the use of solid copper can guards (Fig. 1 A) to deter external fouling around the plumbing intake and T-C sensors. The three WQMs were configured to test the anti-fouling efficacy of SBE AF cartridges placed inside the plumbing only, the bleach injection (BLIS) only (without AF cartridges installed), and the combination of both AF cartridges and bleach injection. The BLIS units operated by injecting 8 μL of 6% commercial grade bleach into the dissolved oxygen chamber of the SBE43 after every sample interval. ECO-FLNTUS were not included on the SBE WQM prototypes. To determine if the anti-fouling technologies were effective in retarding biological growth on the DO sensor, DO values were validated by weekly collection triplicate water samples using a Niskin bottle lowered to 2 m depth. Samples were analyzed at Sea-Bird following the WOCE protocol for Winkler determination [3, 4].

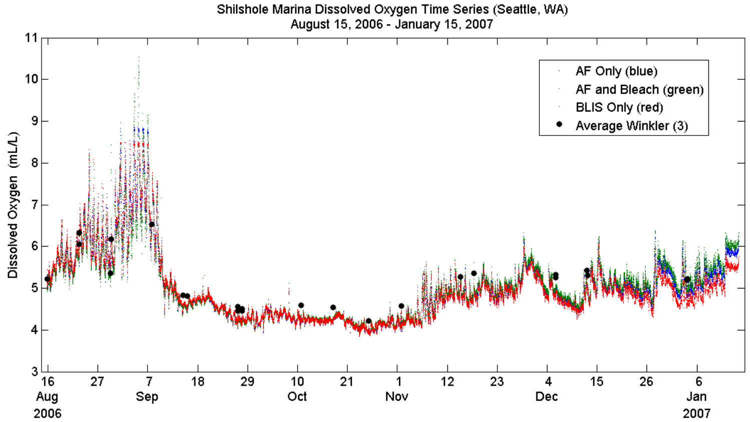

Fig. 3. Dissolved oxygen time series from Shilshole, WA for three WQMs deployed. Winkler titration points represent an average of three samples collected. AF only (blue), AF + BLIS (green), BLIS only (red), Average (3) Winkler dissolved oxygen concentration (mL/L).

Temperature, conductivity and DO data were in good agreement amongst all three instruments for most of the deployment duration. The Winkler samples used for sensor validation reported consistent though slightly higher DO values with respect to WQM DO measurements (Fig. 3). The efficacy of the anti-fouling technology to extend the length of the deployment period was determined by the number of days data were within a 5% threshold of the validation measurement. WQM dissolved oxygen concentration was within 5% of the Winkler titration values for 120 days for the BLIS only unit, and remained within 5% for 152 days in both the AF cartridge only and AF + BLIS prototypes. The fewer number of days for the BLIS only unit is attributed to fouling that occurred following the bleach pump failure about three months into the deployment.

Pre and post factory calibration data show that the stability of the DO sensors used on the WQMs were maintained over the deployment period. The WQM dissolved oxygen sensor deployed with AF + BLIS experienced a factory calibration shift of -0.3%. The WQM DO sensor deployed with AF cartridges experienced a shift of only -1.0% over five months. The BLIS only experiment experienced a calibration drift of -7.0%, larger due to the loss of anti-fouling protection during the BLIS failure. The T-C sensors on all three WQMs remained within in calibration specifications (drifts < 0.001 ^{o} C and < 0.006 psu, respectively).

WQM Prototype Tests at Yaquina Bay, OR - 2006

WET Labs conducted tests in Yaquina Bay, OR for just over 4 months during similar growth conditions as experienced at the Shilshole site (September 13, 2006 to January 23, 2007). Two WQM prototypes were configured with the ECO and CTD oriented facing upward (Fig. 1 D), however the WQMs were deployed facing downward in order to eliminate possible interference effects of direct sunlight on the optical measurements. An air-bleed hole was drilled into the elbow of the CTD exhaust to allow the escape of air after the instrument package was brought to the surface. An external data logger (WET Labs DH4) was used to collect and telemeter data and to provide a common time-stamp for both WQM measurements. Dissolved oxygen validation measurements were made bi-weekly using a separate calibrated SBE43 DO sensor lowered to the depth of the WQM cage for a 5 minute period corresponding to the WQM sample interval. Both WQMs deployed by WET Labs were equipped with SBE AF cartridges in the plumbing intake and exhaust ports. One WQM unit incorporated both the AF cartridges and a BLIS module. The BLIS unit was programmed to inject 28 µL of 6% bleach solution into the DO chamber of the WQM once per hour. The other WQM deployed for this study was outfitted with AF cartridges only. Since copper faceplate and copper Bio-wiper^{TM} of the ECO-FLNTU has already been shown to effectively deter biofouling [5, 6], the performance of the ECO-FLNTU was only considered with respect to the number of data points collected and the resolution of data collected. The reference SBE43 was flushed with fresh water after each use to keep the sensor clean. Periodically, WET Labs also collected replicate water samples by plumbing the outflow of the SBE43 to the surface. Discrete water samples were analyzed using Winkler titration methods by Oregon State University until 27 November, 2006 after which they were analyzed at WET Labs using the same method [3, 4, and 7].

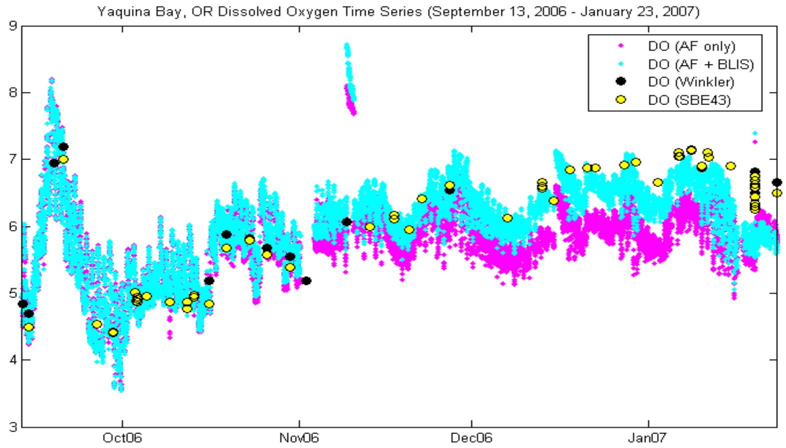

Fig. 4. Dissolved oxygen time series (September 13, 2006 - January 23, 2007) in Yaquina Bay, OR. The concentration of dissolved oxygen collected with WQM AF only (magenta) WQM AF + BLIS (cyan) was validated with both Winkler titration (black) and SBE43 (yellow) measurements.

As with the Shilshole experiment, stability and accuracy of the DO data were used as metrics to determine the length of time quality measurements were collected during the deployment period. Of the 133 days the WQMs were deployed, 94% of the data expected was collected. Data loss was due to power failure at the deployment platform. DO data collected with WQMs were in good agreement with reference DO values as determined by the validation SBE43 and discrete water samples (Fig. 4). A highly correlated relationship was found between the reference SBE43 and Winkler titration values ($y = 1.02\ x + 0.0$, $r^2 = 0.97$), showing the validation methods were robust and the reference sensor was kept in calibration.

To determine the length of time reliable dissolved oxygen was collected at the Yaquina Bay site, percent deviation from the validation method (SBE43) was determined. The number of days of data collected without the need for instrument service was determined to be when WQM DO values remained within 5% of the reference SBE43 validation measurements. This criteria held for 65 days for AF cartridge only WQM, and for 99 days for the AF cartridge + BLIS WQM. Pre- and post- factory calibrations of the WQMs DO sensors deployed in Yaquina Bay showed calibration shifts of -0.5% for the AF + BLIS and -2.0 % for the AF cartridge only units.

IV. WQM COMMERCIAL EMBODIMENT DEPLOYMENT: YAQUINA BAY 2007

Improvements to the WQM that evolved over the course of one year of testing led to a commercial design that incorporates several anti-fouling techniques, and is capable of unattended long-term deployments in active biofouling environments. In the commercial WQM design the ECO-FLNTU is within the WQM body oriented facing downwards and the CTD is oriented upwards shrouded by a solid copper ring guard (Fig. 1, A). The ECO-FLNTU has a copper ring guard, copper face plate and copper Bio-wiper^{TM}. Two AF cartridges, located on the sensor plumbing intake and exhaust ports and a BLIS system are integrated with the commercial design WQM. Our goal of the next deployment was to demonstrate the efficacy of these anti-fouling techniques in maintaining accurate, high resolution, water quality measurements over long deployment (3 months) periods.

In order to clearly demonstrate the benefits of the WQM commercial design, we conducted a blind comparison experiment using two WQM systems, one configured with the commercial design as described above (WQM3) and one devoid of any anti-fouling protection (WQM1) as the control. The BLIS on WQM3 was set to inject 28 µL of 6% commercial bleach every hour. On the control WQM1, no BLIS and no AF cartridges were installed. The copper can guard was replaced with a perforated fiberglass ring guard, and the copper ring guard, copper faceplate and copper Bio-wiper^{TM} were removed from the ECO-FLNTU. The two test WQMs were deployed at a depth of approximately 2 m on May 4, 2007 at the WET Labs test facility, located in Yaquina Bay, OR. Both WQMs were set to sample for 3 minutes every 30 minutes. To track the accuracy and divergence of measurement parameters due to the effect of biofouling, bi-weekly measurements of parameters were made using a Validation Instrument Package (VIP). The VIP included a calibrated SBE43 (DO), ECO-FLNTU (chlorophyll fluorescence and turbidity) and SBE37 (pressure, conductivity and temperature). The VIP was lowered to the depth of the WQMs, and validation data collected for three minutes around a WQM sample interval. The VIP was rinsed with fresh water following each use. Triplicate discrete water samples were collected bi-weekly for Winkler analysis from the exhaust of the VIP DO sensor. Data from both WQMs and the VIP were merged and time stamped using a WET Labs DH4, powered from shore. Data were also logged on a computer installed on the test platform and cable internet allowed for data to be downloaded at WET Labs in Philomath, OR.

The two WQMs have been deployed since May 4, 2007 (Fig. 5). Although the experiment is still in progress, we present results through August 2, 2007 (90 days). To date, the WQMs have collected 92% of the data expected where data loss was due to power loss at the deployment platform and user controlled instrument shut down to download data from the data logger. At the completion of the experiment we expect 100% of the data to be recovered. Results obtained with each of the WQMs and the VIP are shown in Table 1. WQM1 deployed without the use of anti-fouling technologies exemplifies a “worst-case” effect biofouling could have measurements parameters. One of the first sensors on WQM1 that was susceptible to biofouling was the NTU sensor, showing elevated NTU values relative to the validation instrument package after 23 days of deployment (Fig. 5) and a poor relationship with the VIP ($y = -2.4064*x + 20.281$, $r^2 = 0.12$, Table 1). ECO sensors not equipped with Bio-wiper^{TM} technology have been show to foul in a similar manner in previous studies and are characteristic of a biofilm that can form on the optical window, causing an increase in scattering. Although the optical window of the NTU and CHL sensor is contiguous, biofouling effects ECO-FLNTU sensor measurements in different ways and biological growth does not seem to effect the measurement of chlorophyll as significantly. Chlorophyll values are coherent with that measured by the VIP (Fig. 5, Table 1); however over the deployment period the relationship of WQM1 chlorophyll data to that measured by the VIP decreased over time ($y = 0.98063*x + 0.1819$, $r^2 = 0.75$, Normality of Residuals = 9.92). The DO sensor on WQM1 was noticeably susceptible to the effect of biofouling. Until June 24, 2006 WQM1 DO tracked both WQM3 and the VIP. However after that period, the sensor on WQM1 failed. Temperature and salinity of both WQMs were coherent with VIP measurements over the entire deployment period (Fig. 5).

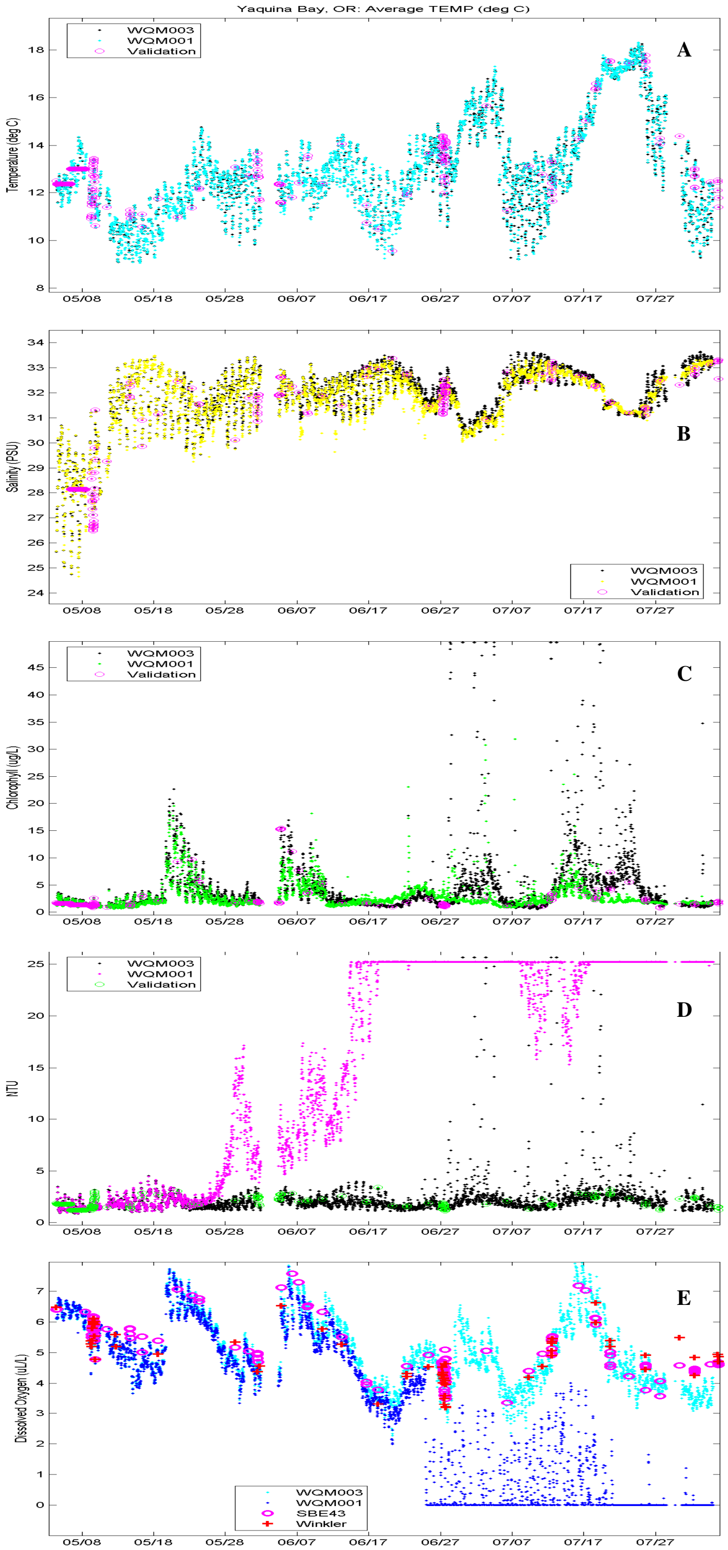

Fig. 5. Hour time series of temperature (A), salinity (B), chlorophyll (C), turbidity (D), and dissolved oxygen (E) from 4 May to 2 August 2007 in Yaquina Bay, OR as measured by a non-biofouling protected WQM (WQM001) and a fully anti-fouling equipped WQM (WQM003). Point validation data obtained using the VIP are also plotted.

To determine the number of days accurate DO was measured with WQM, percent deviation of dissolved oxygen from that measured with the VIP was calculated. WQM1 DO data was within -5 % of the VIP measurements for 36 days (Fig. 6). Implementation of a the anti-fouling methods built into the commercial design WQM3 allowed for accurate DO data collection up to 80 days (Fig. 6), significantly extending the length of time needed between instrument servicing.

TABLE 1

LINEAR RELATIONSHIP OF WQM TO VALIDATION INSTRUMENT PACKAGE

	Linear Fit		Correlation Coefficient		Normality of Residuals	
Parameter	**WQM1**	**WQM3**	**WQM1**	**WQM3**	**WQM1**	**WQM3**
Temperature	y = 0.98219*x + 0.20794	y = 0.98141*x + 0.21714	0.99	0.99	2.00	1.78
Salinity	y = 0.99767*x + 0.027551	y = 1.012*x - 0.3966	0.99	0.99	3.36	1.67
Chlorophyll	y = 0.57831*x + 1.1431	y = 0.98063*x + 0.1819	0.75	0.92[a]	12.01	9.92
Turbidity	y = -2.4064*x + 20.281	y = 0.79507*x + 0.48548	0.12	0.55[a]	115.6	7.11
	[a] The presence of the Chlorophyte Enteromorpha may be responsible for a lower than expected agreement of WQM3 chlorophyll values and a poor agreement of WQM3 turbidity values with the VIP.					

V. WATER QUALITY MONITORING CAPABILITIES

Real time monitoring of water quality in estuarine and coastal environments is crucial to managing the resources of these regions. Water quality measurements of temperature, salinity, chlorophyll concentration, dissolved oxygen and turbidity are important indicators of ecosystem status and health of the biological populations residing in these regions. Coastal and estuarine management programs, such as those associated with the National Estuarine Research Reserves, utilize water quality data to understand, predict and react to natural and anthropogenic induced ecosystem changes. As such, reliable, high quality, accurate, real time water quality measurements are vital to these monitoring efforts. However, due to the active biogeochemcial nature of these systems, maintaining high quality data from sensors deployed in these environments typically requires frequent instrument servicing and calibration, generally on the order of every two weeks. This can lead to significant costs associated with instrument servicing, maintenance, calibration, personnel, training, and data processing to insure the quality of the measurements. As described in this paper, the primary goal in developing the WQM was to produce an instrument for extended deployments (3 months) in these active biofouling regions, while maintaining water quality measurement stability, accuracy and resolution. Results presented in this paper show that the WQM can provide high quality measurements of all water quality parameters over deployment intervals up to 5 months in heavy biofouling environments. This is significant not only in reducing potential operational costs associated with a water quality monitoring program, but also in terms of utilizing the data in long term ecosystem studies.

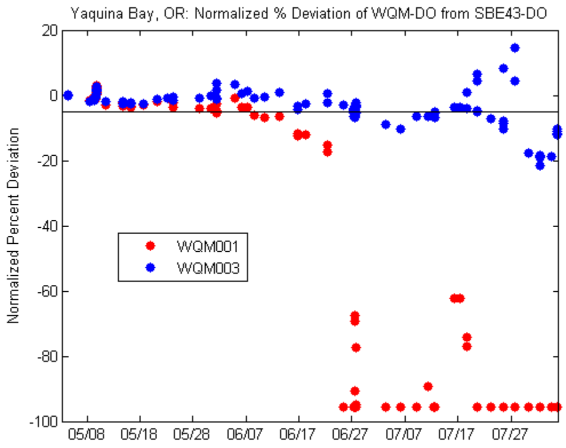

Fig. 6. Percent deviation of dissolved oxygen measurements obtained from WQMs deployed in Yaquina Bay, OR (2007) relative to dissolved oxygen obtained with the VIP. The line represents -5% deviation.

The importance of simultaneous, multi-parameter data is highlighted from data collected at the Yaquina Bay, OR site (Fig. 7). The WQMs deployed over two seasonal periods (fall/winter 2006 and spring/summer 2007) show fine-scale and event driven variability in the measured parameters, especially with respect to changes in the dissolved oxygen concentration. At the beginning of the fall/winter period, salinity was steady and conditions were still favorable for periods of biological growth. At the onset of the winter storm period during which strong winds and rainfall are common, a significant decrease in salinity was observed along with an increase in turbidity (Fig. 7, November 2-8, 2006). The increase in turbidity as the storm approached can be attributed to an increase in mixing due to wind (meteorological data not shown) or sediment laden runoff. A sudden drop in salinity was measured as the fresh water runoff from the storm dominated the Yaquina Bay region, during which dissolved oxygen and chlorophyll remained relatively stable. Short time-scale variability, such as the influence of tides on the measurement parameters was reduced during this period. The spring/summer period is known for calm conditions where the ambient salinity remained invariable. During this period, changes in several of the measurement parameters are no longer driven by storm pulses, but are largely controlled by biological production within the system. Event-scale biological variability can be seen during the beginning of the deployment (May 18-28, 2007) where the maximum levels of chlorophyll reached over 20 mg/L. The increases in dissolved DO and chlorophyll concentration, while salinity and NTU remained stable, are likely due to a phytoplankton bloom. Additional blooms were observed during the deployment period; however toward the end of the deployment period, a shift in the population contributed to high variability observed in the chlorophyll fluorescence data. A Chlorophyte, Enteromorpha was observed from mid-June to the end of the deployment period. Shorter time-scale variability in measurement parameters is seen superimposed and can be attributed to the influence of tides or phytoplankton physiology. Diurnal maximums of dissolved oxygen and chlorophyll-a fluorescence measured can be in part attributed to diurnal variations in temperature as well as physiological changes in the phytoplankton population.

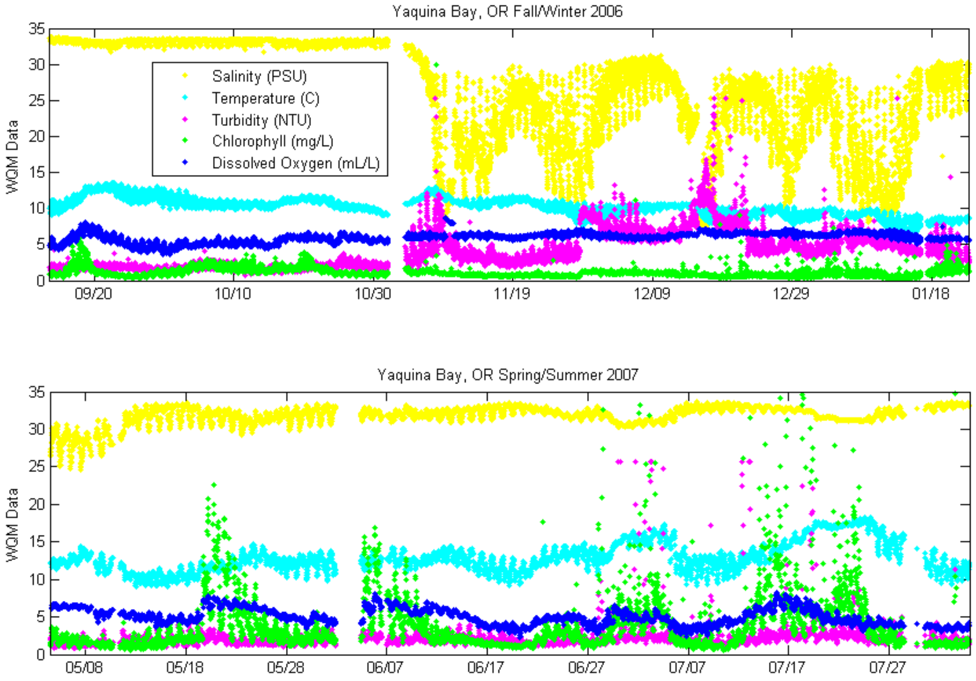

Figure 7. WQM time series collected in Yaquina Bay, OR in the fall and winter of 2006 and spring and summer of 2007.

IV. SUMMARY

> **"The accurate development of a creative means to avoid fouling or renew the sensor surfaces is essential for long-term deployments in the open ocean as well as for short-term deployments (~several weeks) in biologically rich coastal waters" [8].**

In this paper, we show how the combination of copper covers (ECO-FLNTUS faceplate and CTD solid copper ring guard), copper Bio-wiper^{TM}, AF and BLIS offer a creative means to deter the effect of biofouling, maintain accurate data collection and extend the time needed between instrument servicing over long-term deployment periods. Pre and post factory calibration of the sensors integrated on the WQM illustrate how the various anti-fouling approaches help maintain calibration stability in the T-C and DO sensors, even after exposure to fouling. Simultaneous multi-parameter measurements made in high fouling environments with WQM demonstrated 3 - 5 months of robust high-quality, multi-parameter data collection without degradation of sensor signals. This is made possible by using the combination of anti-fouling methods now available on the WQM. Designed specifically to address the ocean and estuarine observing needs, the WQM provides a reliable, cost effective, research-grade water quality monitoring solution for long-term deployments without need for frequent instrument service.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

[1] Comeau, A.J., M.R. Lewis, J.J. Cullen, R.S. Adams, J. Andrea, S. Feener, S.D. McLean, K.S. Johnson, L.J. Coletti, H.W. Jannasch, S.E. Fitzwater, C. Moore, A.H. Barnard. Monitoring the spring bloom in an ice covered fjord with the Land/Ocean Biogeochemical Observatory (LOBO). *Proceedings of Oceans 2007,* in press.

[2] Enabling Ocean Research in the 21st Century. 2003. National Research Counsel of the National Academes. The National Academy Press, WA CD, 95 pp.

[3] Culberson, C.H. (1991). Dissolved Oxygen. WOCE Operations Manual. Vol.3, Section 3.1, Part 3.1.3: WHP Operations and methods. WHP Office Report WHPO 91-1, WOCE Report No. 68/91, Woods Hole, Mass, U.S.A.

[4] Dickson, A.G. 1995. Determination of dissolved oxygen in sea water by Winkler titration. WOCE Operations Manual. Part 3.1.3 Operations & Methods, WHP Office Report WHPO 91-1.

[5] Manov, D.V, G.C. Chang, T.D. Dickey. 2003. Methods for Reducing Biofouling of Moored Optical Sensors. Journal of Atmospheric and Oceanic Technology. vol 21, pp. 958-968.

[6] Alliance for Coastal Technologies Performance Verification Statement for WET Labs *ECO* FLNTUSB fluorometer (ACT-TV0607) UMCES Technical Report Series. 2006. Reference No. [UMCES] CBL 06-053 (http://www.act-us.info/evaluation_reports.php).

[7] Sherwood, J.E., F. Stagnitti, M.J. Kokkinn, and W.D. Williams. 1991. Dissolved oxygen concentrations in hypersaline waters. *Limnol. and Oceanogr*., 36 (2): 235-250.

[8] Rudnick 2003. ALPS Autonomous Lagrangian Platforms and Sensors Workshop Report. 64 pp. www.geo-prose.com/ALSP.