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Power from Benthic Microbial Fuel Cells Drives Autonomous Sensors and Acoustic Modems

By Clare E. Reimers and Michael Wolf

ABSTRACT. Autonomous platforms that support low-power sensors represent one approach to expanding ocean observing. This paper describes a unique autonomous platform designed to deliver long-term sensor measurements from the benthic boundary layer at low cost. The platform, called a Benthic Observer (BeOb), is powered by energy harvested with a benthic microbial fuel cell (BMFC), and it uses an acoustic modem to both store and transmit data organized in daily reports of hourly measurements. A BeOb equipped with sensors to measure dissolved oxygen, temperature, and conductivity ~1 m above the seabed has been active for over 14 months on the Oregon slope at a location within the core of the oxygen minimum zone. During this observation period, the system's battery reserves have been kept fully charged by the BMFC. A 90-day time series of sensor data are compared to simultaneous high-frequency measurements at a neighboring Ocean Observatories Initiative cabled Benthic Experiment Package to examine the expected quality and confidence levels for seasonal or annual means of continued measurements. An ocean observing system incorporating arrays of BMFC-powered platforms transmitting to central gateway modems is proposed for future ocean-property monitoring programs. Such arrays may be especially helpful for tracking expansions of ocean oxygen minimum zones.

INTRODUCTION

Accurate, long-term, and widespread sensor measurements of essential ocean variables are needed for documenting changes in ocean conditions and circulation on both regional and global scales. Oceanic processes that are critical to the planet such as heat transport, oxygenation, acidification, and primary production may be better understood and interconnected through sustained multiscale observations. Observations are also needed to both calibrate and validate ocean models that seek to predict the influence of anthropogenic forcing, and are crucial for the detection of potentially hazardous oceanic events such as tsunami waves and harmful algal blooms. The US Ocean Observatories Initiative (OOI), highlighted in this special issue of *Oceanography*, combines Lagrangian and Eulerian sensing platforms including gliders, autonomous underwater vehicles, surface buoys, profilers, inductive mooring cables, and seafloor junction boxes to create arrays of instruments for sensing and sampling the ocean through time and in three dimensions. Although OOI has an unprecedented variety of nearly 75 models of specialized instruments and the capability to follow transient phenomena through high-speed measurements, its coverage of large-scale phenomena measured consistently over months, years, and eventually decades, remains limited. More broadly, it is estimated that the coverage of all existing and planned international ocean observing time series stations represents only 9%–15% of the global ocean surface area (Henson et al., 2016). The greatest limiting factor for ocean observing is the high cost of installing and maintaining in situ observing assets widely distributed in the ocean.

This problem of sustaining measurements, and the larger goal of contributing to an adaptive framework for global ocean observing, encouraged us to devise a low-cost, easy-to-deploy, autonomous sensor platform well suited for expanding the spatial footprint of ocean observations. This new platform, which we call a Benthic Observer or BeOb, employs bioelectrical energy harvesting to recharge batteries and acoustics to relay data. By operating at the seafloor, it provides observations from within the benthic boundary layer apart from the sampling reach of most gliders and floats. This article briefly describes the platform's technology and illustrates sensor temperature, conductivity, and dissolved oxygen data from a trial deployment on the Oregon slope at a site within the oxygen minimum zone (OMZ) of the Northeast Pacific. A BeOb was deployed on August 12, 2016, from R/V *Sally Ride* at 44°21'39"N, 124°56'17"W, at a target water depth of 580 m, 1.6 km south of OOI's Benthic Experiment Package CE04OSBP. The deployment was executed by winch and wire using an acoustic release (ORE Offshore) that was triggered after lowering the platform to within 10 m of the seafloor. Several cruises of opportunity connected to the OOI mission have allowed a partial retrieval of BeOb data, which are evaluated here by comparing them to contemporaneous OOI observations. The variability of water column parameters at a fixed point is also assessed and used to make recommendations for future BeOb sensor configurations. An ocean observing system incorporating arrays of networked BeOb platforms is envisioned and is fully within the capabilities of these systems.

BENTHIC OBSERVER TECHNOLOGIES

Any ocean observing platform requires a reliable power source, instrument control, a means of data recovery, and sensor systems that can produce and maintain high-quality measurements. Various approaches can meet these requirements, but numerous trade-offs influence the extent of sensor measurements throughout the ocean. BeOb incorporates a small footprint (0.28 m^2) benthic microbial fuel cell (BMFC) and a power management platform (PMP) to harvest energy continuously and to keep two serial stacks of 3.7 V cylindrical lithium-ion batteries (three per stack) charged (total capacity 57 Wh) and ready to supply power to sensors and communication systems on board (Figure 1). With the present design, the BMFC can supply ~10–20 mW reliably over the long term. This provides the intended benefit that large, potentially hazardous, battery packs are not needed, nor do batteries need to be replaced. The 57 Wh capacity of the lithium ion batteries, combined with the BMFC, means that even fairly power-hungry sensors can be run if they are constrained to low duty cycles (e.g., 5 W for 0.2% of the time).

The BMFC harvests energy by taking advantage of the natural oxidation of organic matter by bacteria to supply electrons to an inert carbon fiber brush electrode (anode) enclosed in an anaerobic benthic chamber (Tender et al., 2002; Reimers, 2015; Reimers et al., 2017a,b). This chamber also creates a base structure for the BeOb (Figure 1). Extra “fuel” is pre-packaged inside the chamber in the form of paper packets of 20% by weight dried plankton flake (fish food) and 80% $CaCO_3$ (that helps buffer the pH). Electricity flows through the BMFC as electrons are passed from the anode to the cathode to reduce dissolved oxygen. Like in a battery, the voltage difference between the cathode (+) and the anode (–) depends on the chemistry surrounding the electrodes and the load placed on the cell. This voltage difference is always ≤0.9V; therefore, part of the function of the PMP is to create electricity at higher voltages by passing current through a primary charge pump to a supercapacitor, to a secondary charge pump, and then on to lithium-ion batteries that are connected in series (Figure 1c; Schrader et al., 2016). The PMP microcontroller and an RS-232 buffer also draw energy from a small “micropower” charge pump that doubles the supercapacitor voltage and regulates it to 3.3 V. Other functions of the PMP are to trigger the powering and reading of sensors, run certain failsafe operations, and time the storage of system data. The PMP electronics were uniquely designed for this application and are enclosed inside the acoustic modem housing. We have also customized the PMP software for nearly every deployment.

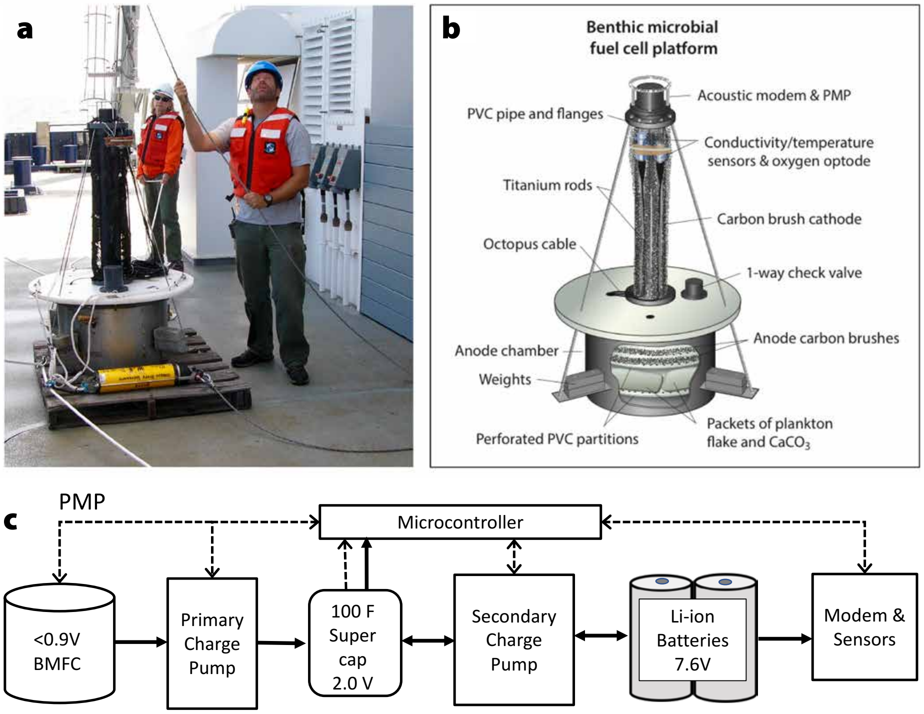

FIGURE 1. (a) The Benthic Observer platform is shown with an acoustic release before deployment in August 2016 as author C. Reimers and marine technician M. Durham (Scripps Institution of Oceanography) ready taglines and wire. (b) Components of the platform and its benthic microbial fuel cell (BMFC). (c) Schematic of the power management platform (PMP) electronics. Solid lines and arrows indicate the flow of energy. Dashed lines and arrows depict function controls and inputs from status components and sensors.

The acoustic modem, mounted at the center of the BeOb platform (Figure 1), serves as the instrument for data storage and recovery. The modem receives data from the PMP in daily reports configured by the user before deployment. Currently, the sensors onboard are read hourly, and the BMFC performance is assessed once daily by executing polarization tests (Logan et al., 2006) that indicate the power levels the BMFC can deliver as a function of load resistance. This information and the supercapacitor and battery voltages are items in each daily report. The modem must be prompted to transmit its stored data (nominally, we set the modem to transmit at 600 bits per second, and a one-day report = 1 kb) to a receiving modem located within a ~2 km radius. This range is constrained primarily by the power level of the transmitting modem, but it can be increased to ~5 km by using higher power levels and/or lower bit rates, and to ~20 km using repeater functionality.

For this study, we enlisted marine technician help and used shipboard 12 kHz systems on seven cruises of opportunity on four different research vessels to communicate with the Benthic Observer, and thus far have a partial 450-day-long record of recovered reports. The data retrieved illustrate that the BMFC is harvesting energy and keeping the supercapacitor and the batteries fully charged (Figure 2). This is in part because the energy being drawn to power the sensors and the PMP electronics is relatively small (~5 mW), and the more energy intensive acoustic communications (~2 W during data transmission) have been short and infrequent. To establish regular communications, other acoustic gateways would be needed, such as modems linked to nearby cabled observatories, moorings, or autonomous gliders that would then relay the data ashore. The latter framework is envisioned should next generation Benthic Observers become integrated components of observing networks in the future. As indicated above, many other sensor configurations could be utilized on these platforms, provided their operation meets a realistic energy supply budget from the BMFC.

THE QUALITY OF BENTHIC OBSERVER SENSOR DATA FROM THE OREGON SLOPE

One of the conceptual advantages of the Benthic Observer is its ability to operate for many years unattended because it does not run out of battery power or need to be physically recovered to transfer data. Low-power sensors that can remain accurate and fully operational over the long term represent the remaining challenge for these systems. It is known from profiling float applications that many CTD sensors and oxygen sensors can maintain required (or at least correctable) accuracies in multiyear applications if they are operated mostly below the thermocline, in the dark, away from regions of enhanced biological growth (Riser et al., 2008; Takeshita et al., 2013). Following this example, we chose to mount a conductivity/temperature sensor (Aanderaa model 4319) and a dissolved oxygen/temperature sensing optode (Aanderaa model 4330) on the BeOb and to evaluate the data quality of these sensors by comparing them to similar sensors on the OOI Oregon Slope Benthic Experiment Package (CE04OSBP) located ~1.6 km away and at the same depth (within a few meters). The BeOb optode was calibrated prior to deployment using air-saturated water and an anoxic solution of 1 M Na ascorbate and 0.5 M NaOH diluted to 10% with N_2-purged deionized water, but for the conductivity sensor we relied on the factory calibration. For comparison, the relevant OOI sensors are a Sea-Bird SBE 16plusV2 CTD and an Aanderaa model 4831 oxygen optode.

Focusing on a 90-day period where 94% of hourly measurements from the BeOb have been recovered acoustically thus far, we find that the mean, standard deviation, and range (maximum-minimum) of temperature data are nearly identical between platforms, but that conductivity measurements from the BeOb appear systematically low, with spikes of extremely low readings probably due to contamination (biofouling or suspended sediment interference) of the unpumped Aanderaa conductivity cell (Table 1, Figure 3). Much better agreement (means within 0.005 S m^{-1} equivalent to within 0.06 PSU) occurs in comparisons of conductivity records measured during the first month after BeOb deployment (data shown in Reimers et al., 2017b). No OOI oxygen data are shown in Figure 3c because of a faulty factory calibration of the CE04OSBP optode that gave erroneous concentrations that remain in the OOI database. We do note, however, that after this OOI sensor was replaced with a properly calibrated version on August 10, 2017, the dissolved oxygen at CE04OSBP

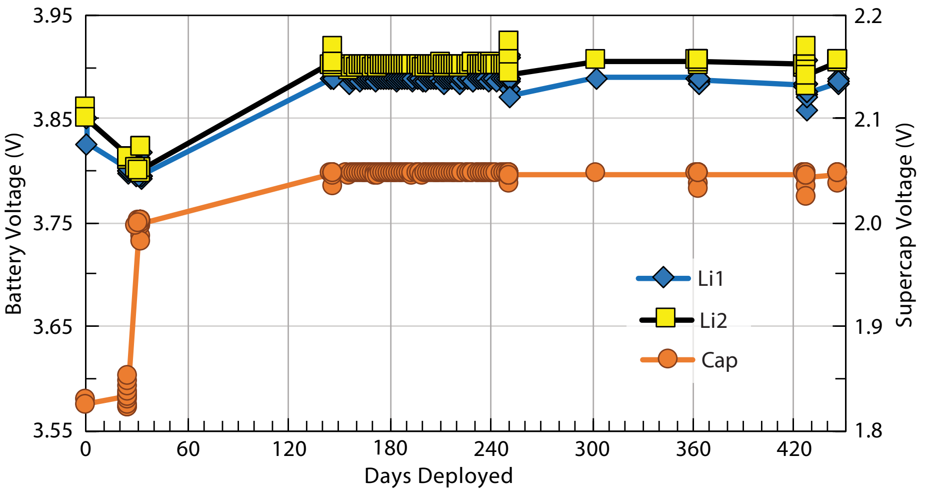

FIGURE 2. Benthic Observer battery and supercapacitor voltages measured in situ through time.

TABLE 1. Comparison of sensor data between the Benthic Observer (BeOb) and the Ocean Observatories Initiative (OOI) over a 90-day period. The mean pressure at the OOI measurement location during this period was 586 dbar.

Sensor	Number of Measurements	Mean	Standard Deviation	Variance	Autocorrelation Coefficient*	Range of Observations
BeOb temperature 1 (optode sensor)	2,031	4.9719°C	0.173	0.0299	0.9503	1.05
BeOb temperature 2 (cond. sensor)	2,031	4.9674°C	0.173	0.0298	0.9471	1.07
OOI temperature	7,626,513	5.0295°C	0.167	0.0280	1.0000	1.0299
BeOb conductivity	2,033	3.2661 S m^{-1}	0.0226	0.00051	0.9194	0.203
OOI conductivity	7,626,513	3.2963 S m^{-1}	0.0136	0.00018	0.9999	0.3909
BeOb oxygen[1]	2,033	11.16 (10.96) μmol L^{-1}	2.75 (2.70)	7.54 (7.26)	0.9100	19.35 (19)

[1] With (and without) pressure correction

[2] This parameter is derived from the correlation of a time series against a lagged (one sample) version of itself and is influenced by sample frequency and the amount of random noise in the measurements (Box et al., 2015).

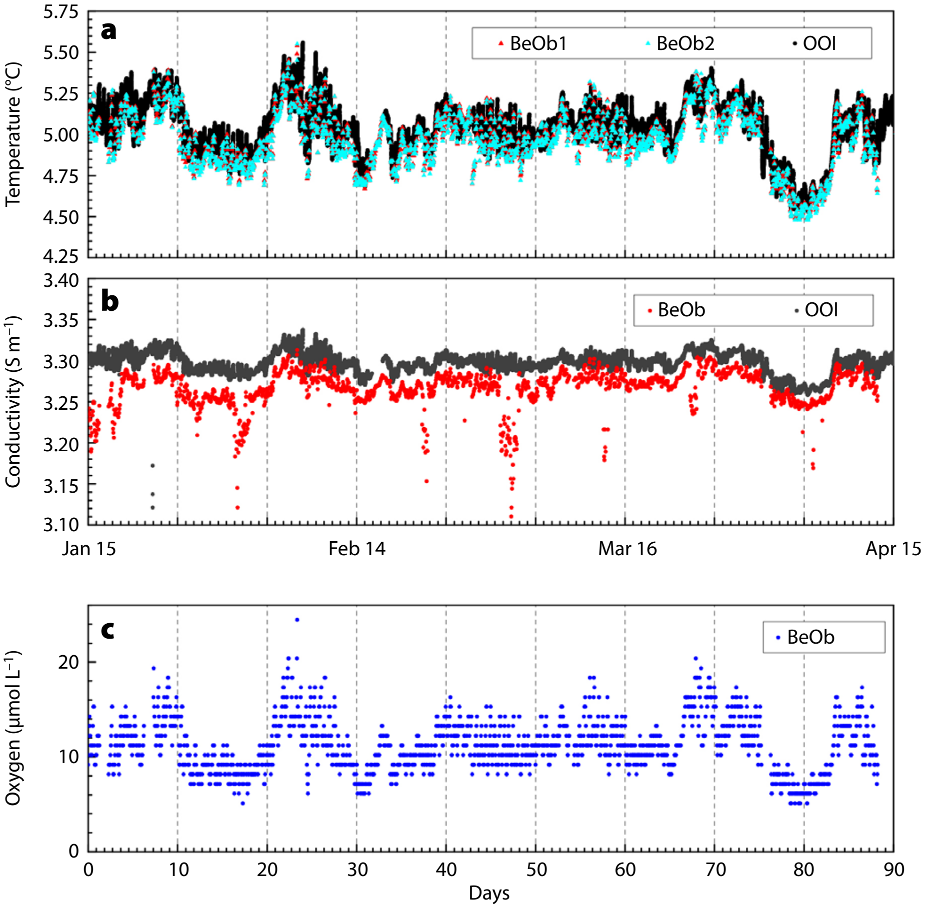

FIGURE 3. Comparative sensor data from the Benthic Observer and the OOI Oregon Slope Benthic Experiment Package (CE04OSBP). These time series were measured from January 15, 2017, to April 15, 2017, which was 154–244 days after the Benthic Observer deployment on the seafloor. OOI temperature and conductivity data are reduced to from 1 Hz to 1-minute averages in plots (a) and (b). No properly calibrated oxygen data were available from the OOI database to include in (c).

has been reported between 12 µmol L^{-1} and 38 µmol L^{-1}, with similar periodicity to Figure 3c (data spanning August 10 to November 20, 2017). These OOI sensor values are generally 5–10 µmol L^{-1} higher than BeOb sensor records from both before and after August 10. Thus, there appears to be a calibration offset between the two sensors.

The oscillations in the time series of temperature, conductivity, and oxygen are interesting because they reveal semidiurnal (M2) frequencies of variation as well as two- to seven-day weatherband variations of considerable range that are highly correlated. Some of the oscillation in the BeOb oxygen record is obscured by a ±1 µmol L^{-1} resolution of the optode output, but this can be improved in future experiments by simply enabling a higher-resolution readout.

If a researcher's goal is to detect trends in ocean time series data that could signal an oceanic response to climate change, one might ask: are the Benthic Observer data reliable and frequent enough to support statistically robust analyses? This question takes on added significance in light of several studies that suggest declines in dissolved oxygen in midwater OMZs may be signaling reduced water column ventilation coupled to enhanced stratification and ocean warming over decadal timescales (Keeling et al., 2010; Helm et al., 2011; Falkowski et al., 2011; Pierce et al., 2012). To detect such trends, researchers will commonly apply generalized least squares regressions to a time series spanning several decades, or they will apply rank-based non-parametric statistical tests to the available environmental data that may be first reduced to seasonal or annual means (Weatherhead et al., 1998; Yue et al., 2002). Without diving too deeply into the details of these tests or their pitfalls, we note that data sets without gaps or sudden shifts created by changes in instrumentation are the most useful, and the number of years of data necessary to detect trends with confidence will decrease in records with less-random noise (Weatherhead et al., 1998; Henson et al., 2016).

Table 1 suggests that the much smaller sample size of the BeOb time series compared to OOI data does not greatly alter the temporal realism of observed temperature, but that we do need to improve the quality of the direct measurement of conductivity, perhaps by switching to sensors in a pulsed-duty pumped cell and/or applying biocides to prohibit contamination, as is done routinely on Argo floats (Riser et al., 2008). A low duty cycle pump run, for example, for two seconds every hour does not add up to a significant amount of added power consumption and may help improve the long-term accuracy of inline oxygen measurements as well. With this field-based insight, we envision that the next-generation version of the Benthic Observer will be equipped with a complete pulse-pumped CTD unit and an oxygen optode to allow tracking of more highly resolved changes in oxygen at fixed points in the benthic boundary layer. Accurate CTD-O_2 time series would also allow the identification of dissolved oxygen changes on discrete potential density surfaces.

The acoustic modems of these systems are designed to support communications between platforms deployed as a network, and thus in another few years BeOb systems could be distributed throughout the full expanse of OMZs where these midwater column zones intersect the continental slope. As functioning members of ocean observing projects, future BeOb platforms would provide more spatial coverage, and could transmit data to a variety of gateways including gliders and cable nodes. These BeOb platforms might also be modified to expedite regular recoveries, every two to three years, presumably by remotely operated vehicles. Although the BMFC technology can keep the power on, eventually biofouling and corrosion are expected to win the day, necessitating recovery, sensor recalibration, and servicing. The relative cost of these autonomous systems would still be low (the principal expense is ~$25,000, stemming from the sensors and the acoustic modem), and they are adaptable to support nearly any form of low-power sensor with a serial output.

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