A Device for Protecting Moored Spectroradiometers from Biofouling

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ABSTRACT

A shutter mechanism for reducing the effects of biofouling on bio-optical instruments deployed on oceanographic moorings has been designed, built, and tested. The initial development was carried out on a spectroradiometer. The optics of the spectroradiometer are protected by copper shutters that rotate out of the field of view prior to a measurement and rotate back after the measurement is completed. The shutter system can sense an obstruction and, if one is detected, attempt to rotate in the opposite direction. The controlling software stores the home position in the memory so the shutter can return to cover the optics, irrespective of direction of rotation. The system has been tested in the equatorial Pacific, where it has provided five months of data that are unaffected by biofouling.

1. Introduction

Bio-optical oceanography could be said to have had its origins in the early 1970s, when in vivo fluorescence was first used as an indicator of chlorophyll concentration and hence phytoplankton biomass (Platt 1972; Denman 1976). In subsequent years the field developed strongly in the direction of satellite oceanography, culminating in 1978 with the launch of the Coastal Zone Color Scanner (CZCS), which successfully produced images of global ocean color from space for more than seven years. While the CZCS and the recently launched SeaWiFS satellite provide excellent large-scale spatial and temporal surface measurements of ocean color, and hence chlorophyll concentration, a need also exists for high-frequency temporal sampling at biologically relevant scales (Harris 1980).

Over the last 20 years, in parallel with an increased understanding of the bio-optical properties of seawater (Morel 1988; Kirk 1994), monochromatic and spectral radiometers have become more widely used for monitoring the variability in upper ocean optical properties. This variability is driven by changes in particulate and colored dissolved constituents. In a large portion of the ocean, phytoplankton and detrital pigments are the primary light-absorbing elements, so spectroradiometers are effective in tracking changes in the concentration of these organisms (Smith et al. 1991). Also there have been suggestions that they can be used to measure phytoplankton physiological status (Kiefer et al. 1989). Therefore, moored bio-optical instrument arrays exhibit great potential for describing fluctuations in phytoplankton biomass and productivity in coastal and open ocean environments because of the high temporal frequency measurements that are possible (Dickey 1991). Moored spectroradiometers also provide continuous measurements, making them useful as calibration devices for ocean color satellites (Smith et al. 1991). However, these instruments are susceptible to biofouling in the form of microbial and algal films that can cover optical windows and degrade data quality (McLean et al. 1996). The settlement of larvae of sessile invertebrates on the optical windows and their subsequent growth is also a common problem (Chavez et al. 1997).

Historically, antifoulant compounds, such as tributyl tin (TBT), commercial polymers, and bromine have been used to prevent the growth of such films, with limited success (Butman and Folger 1979; Davis et al. 1997; McLean et al. 1996). The toxicity of these compounds and their limited period of efficacy led us to develop alternative methods of biofouling protection. Here we describe a shutter system designed to reduce the effects of biofouling on moored spectroradiometers. We present data from the central equatorial Pacific that show that the protection offered by the shutter is at least 5 months, compared to less than 2 months for unprotected instruments, and 3–5 months for instruments fitted with TBT devices in the same location.

2. Methods

The Monterey Bay Aquarium Research Institute (MBARI) currently maintains bio-optical and chemical

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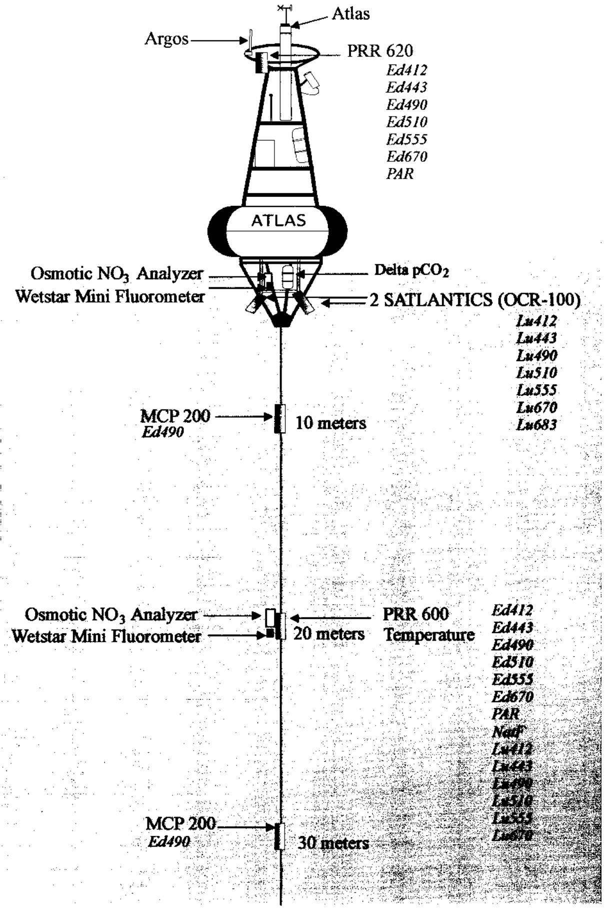

FIG. 1. Schematic of the TAO mooring at the equator and 155°W showing the suite of biochemical sensors.

instruments on three moorings in Monterey Bay, California, as well as two moorings that form part of the Tropical Atmosphere Ocean (TAO) Array at 0°, 155°W and 2°S, 170°W. The data presented here are from 0°, 155°W, covering the period from December 1996 to April 1997. Figure 1 shows a schematic of the mooring and a partial description of the instrument array follows.

a. Bio-optical sensors

The Biospherical PRR-620 spectroradiometer mounted approximately 3 m above the water surface measures downwelling irradiance at 412, 443, 490, 510, 555, 656 nm plus photosynthetically available radiation (PAR: 400–700 nm). The two Satlantic OCR-100 spectroradiometers, mounted at approximately 1.5 m, record upwelling radiance at 412, 443, 490, 510, 555, 670, and 683 nm. These spectroradiometers are protected from fouling by TBT rings (manufactured by Oceanographic Industries) fitted around the perimeter of the downward-looking optical window. Two Biospherical MCP-200 monochromatic cosine collector radiometers mounted at 10 and 30 m record downwelling irradiance at 490 nm. These instruments are not protected from fouling. At 20 m, a Biospherical PRR-600T2 spectroradiometer records downwelling irradiance at 412, 443, 490, 510, 555, and 656 nm plus PAR, and upwelling radiance at 412, 443, 490, 510, 555, 670, and 683 nm. This instrument is fitted with the shutter system described below. At approximately 1.5- and 20-m depth, a WETLabs miniature fluorometer records in vivo fluorescence from which chlorophyll concentration can be determined. These instruments are protected from fouling by TBT ‘‘sleeves’’ fitted to the seawater inlet/outlets. The sampling rate and sensor bandwidth for the Biospherical instruments was 2–3 Hz and 10 nm, respectively, while for the Satlantic OCR-100s, the corresponding specifications were 10 Hz and either 10 or 20 nm, depending on wavelength. The bio-optical sensors are connected to a central controlling unit called OASIS (Ocean Acquisition System for Interdisciplinary Science; Chavez et al. 1997), which logs data to a hard disk drive and transmits a subset of these data at least once daily to MBARI via ARGOS (Advanced Research and Global Observations Satellite).

b. Shutter description

Figure 2 shows a schematic of the shutter and the 20-m Biospherical PRR-600T2 to which it attaches. The shutter unit consists of a motor drive (operating at 9–15 VDC, and drawing ~200 mA) and a drive shaft that passes through the motor housing with two almost circular copper paddles at each end. These paddles attach perpendicularly to the shaft and are designed to fit over the upward-looking downwelling cosine irradiance sensor and downward-looking upwelling radiance window at each end of the PRR-600T2. Internal to the housing, the DC gear motor is coupled to the long shaft via an antibacklash gear. Also coupled to the long shaft, by way of the same antibacklash gear, is a single turn potentiometer, which is used to determine the position of the paddles relative to the optical window of the spectroradiometer. The software for the shutter, running on OASIS, is a subroutine that is called whenever the shutter needs to be opened or closed. The subroutine uses an A/D input channel and two input/output bits to communicate with a motor control circuit to control stops/starts, reverse direction, detect overcurrent, and sense position.

The system is configured such that data are collected from the PRR-600T2 every 10 min of daylight. Prior to a measurement, the motor of the shutter is activated by the OASIS controller and the paddles rotate out of the field of view, so that the sensors are unobstructed, and the instrument may sample the light field. Once the sample is taken, the shutter rotates the paddles to cover the optics, hence maintaining the instrument's sensors in a dark environment. The software controlling the shutter implements a collision recovery algorithm to deal with possible paddle obstructions in the field. This

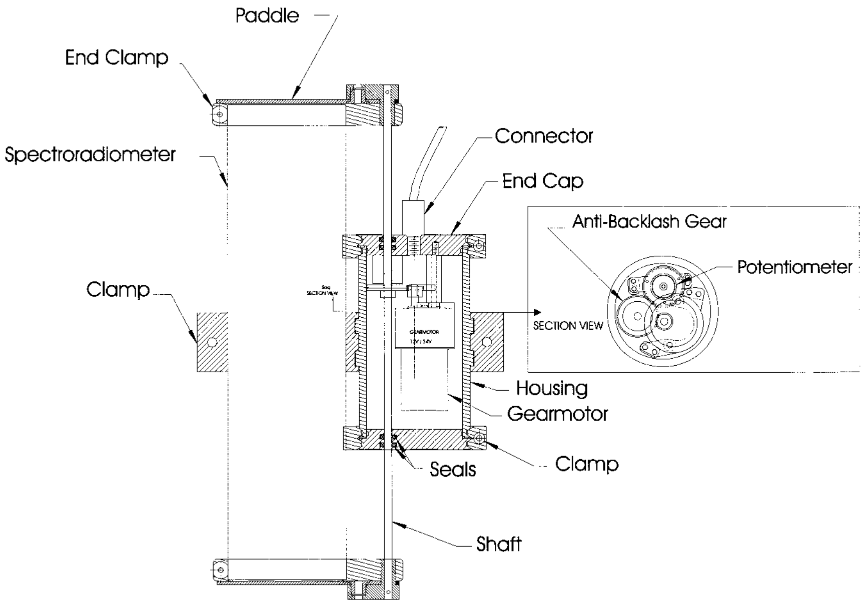

FIG. 2. Schematic of the shutter system. A detailed description can be found online at http://www.mbari.org/bog/Projects/MOOS/shutter.

is made possible by motor drive hardware that is capable of sensing the motor torque and disabling the power if a preset limit is exceeded. The software is then aware that a collision has occurred and reverses the direction of rotation in an attempt to clear the obstruction. The ‘‘home’’ position (i.e., covering the optical sensors) and the current position of the shutter are recorded by the software, thus enabling the shutter to return to the home position even after several direction reversals in an attempt to overcome an obstruction. The maximum allowable attempts to clear an obstruction are set in the software's parameters. A detailed description of the mechanical, electrical, and software components of the shutter is available online at http://www.mbari.org/bog/Projects/MOOS/shutter.

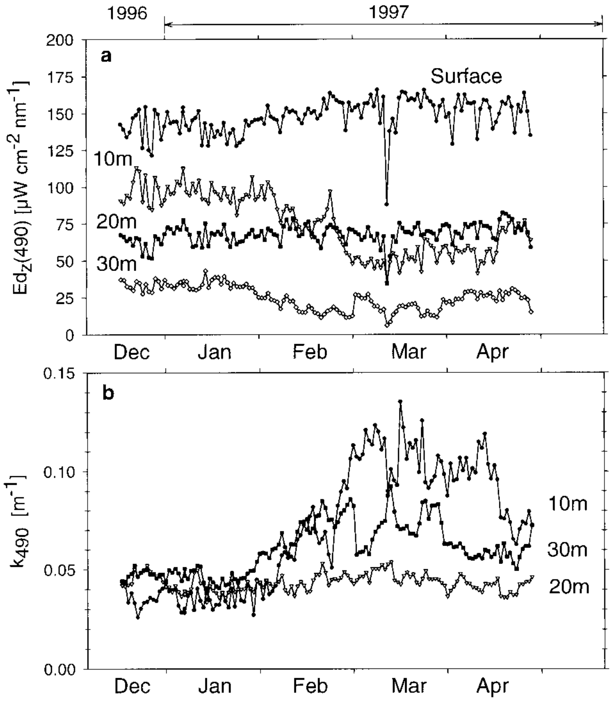

FIG. 3. (a) Above water, 10-, 20-, and 30-m downwelling irradiance data at 490 nm collected at the equator and 155°W between Dec 1997 and Apr 1998. The 20-m sensor was protected by the shutter system. Note that the 10-m data in Feb is lower than that at 20 m, indicating the presence of biofouling. (b) Diffuse attenuation coefficient at 490 nm calculated using the above-surface data and the three subsurface sensors. The series diverge in late Jan as the 10- and 30-m sensors show the effects of biofouling.

3. Results

Visual inspections by divers at the Monterey Bay sites have confirmed the efficacy of the shutter system. After several months of deployment the copper plates are completely free of biofouling, as are the optical windows that they protect. To quantitatively illustrate the efficacy of the shutter in preventing biofouling at the equatorial Pacific sites, we have compared data from the 20-m PRR-600T2 with the unprotected 10- and 30-m MCP-200s. Figure 3a shows the time series of downwelling irradiance at 490 nm [$E_{d_z}(490)$] from the above-surface, 10-, 20-, and 30-m, radiometers. Data recorded every 10 min from 1000 to 1400 local time ($\sim$2000 to 2400 UTC, $n = 24$) have been averaged to produce one data point per day. Fluctuations in cloud cover within the 4-h averaging period are a major source of variability about the mean, and the standard deviations induced by this averaging procedure were generally between 10% and 30% of the mean The time period covered is from 13 December 1996 to 20 April 1997. A substantial decrease with time is evident in the 10-m data, and to a lesser extent in the 30-m data—the disparity in the effect on these two instruments is attributable to light levels at 10 m that are more favorable for biofouling, compared to 30 m. By early 1997, the 10-m sensor has been affected by biofouling to such extent that it is measuring lower irradiance than the 20-m sensor.

The diffuse attenuation coefficient at 490 nm (k_{490}) can be used to calculate the mean chlorophyll concentration in the upper water column (Morel 1988; Chavez et al. 1998). In order to determine the effect of the signal degradation on data quality we calculated k_{490} for each of the instruments as follows:

$$k_{490}\ [\mathrm{m}^{-1}] = \frac{\ln\{E_{d_0}(490)/Ed_z(490)\}}{z}, \qquad (1)$$

where $E_{d_0}(490)$ and $E_{d_z}(490)$ are, respectively, the incident irradiance (490 nm) immediately below the surface and at depth z (10, 20, and 30 m in this case; see Fig. 3b). For the equator, near local noon, the percentage transmission of irradiance across the air–water interface is 98% ± 1% (Kirk 1994), hence we have calculated $E_{d_0}(490)$ as $0.98 \times E^{+}_{d_0}(490)$, where $E^{+}_{d_0}(490)$ is the downwelling irradiance (490 nm) recorded at the top of the buoy tower.

Soon after deployment, k_{490} derived from the 10- and 30-m MCP-200s is very similar to the corresponding data from the 20 m PRR-600T2, which is indicative of the lack of fouling at that time. The chlorophyll concentration of $\sim 0.2\ \mu\mathrm{g\ L}^{-1}$, estimated from the initial levels of k_{490}, is typical for the equatorial Pacific and corresponds closely with in situ measurements made during the mooring maintenance cruises (Chavez et al. 1998). Toward the end of January 1997, k_{490} from the unprotected 10- and 30-m instruments begins to steadily increase, indicative of biofouling. However, the fluctuations in k_{490} from the 20-m PRR-600T2 were minimal, and, we contend, caused by real fluctuations in the mean chlorophyll concentration in the upper 20 m of the water column (Chavez et al. 1998). To determine when the level of biofouling became significant, the 10- and 30-m MCP-200 data were compared with the 20-m PRR-600T2 data by means of a paired t test. The results indicated that the 30-m data became significantly degraded (i.e., significantly different from the 20-m data at the 95% confidence level) approximately 45 days after deployment (~22 January 1997), while the corresponding timescale for the 10-m data was approximately 52 days. The time series of k_{412} (data not shown) was almost identical to that of k_{490}, but for wavelengths greater than 490 nm, the magnitude of k_λ increased, and the variability of the corresponding time series decreased, due to increased attenuation in the green and red sections of the spectrum.

4. Discussion and conclusions

The data presented here convincingly illustrate the ability of the shutter to prevent biofouling of the spectroradiometer's optical sensors for periods of up to five months and perhaps beyond. In comparison, unprotected sensors provided data that were unaffected by biofouling for less than two months. In regions of the world's oceans that are more productive than the equatorial Pacific, one might expect this time to be reduced even further. However, Abbott and Letelier (1996) report a mean and maximum period for acceptable data from drifters off the coast of California of 73 and more than 90 days, respectively. Their subsurface bio-optical instrument consisted of a downward-looking Satlantic OCR-100, which may have been less susceptible to biofouling due to shading of the optical window and changes in the physical and biological environment that occurred as the drifters moved from coastal to oceanic waters.

The use of copper is key in the design of the shutter. Copper is a biological micronutrient that becomes toxic at higher concentrations. It interferes with enzymes on cell membranes and prevents cell division. When copper corrodes in seawater the oxidized molecules release into the seawater environment rather than remaining on the metal. The reduction in light, together with the slow release of copper into the water trapped between the optical windows and the copper plates, essentially eliminates the accumulation of biofilms. While the toxicity levels may be significant for bacteria, phytoplankton, and invertebrates, the risk posed to humans is essentially nonexistent, which represents a significant improvement over antifoulant chemicals such as TBT and copper-based paints. The design of the shutter can be adapted for use on other sprectroradiometers, such as Satlantic OCR-100s or TSRB systems, with minimal modification. Future developments could focus on applying a similar concept to instruments such as fluorometers and absorption/attenuation meters.

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