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The Light and Motion Sensor Program: Low cost coral reef monitoring

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Abstract
Effective coral reef management requires early identifications of potential sources of contaminants before significant degradation of the reefs occur, allowing stakeholders, politicians, businesses and concerned citizens to have sufficient information with which to take appropriate, timely remedial action. The Rainbow Sensor program can provide a reliable, continuous, low-cost measurement of the organic content of seawater, needed by managers in economically important marine protected areas to monitor basic water quality information near significant human development. Increases in organic content can come from the addition of nutrients and hence algae growth or dissolved and particulate organic contaminants from land. The Rainbow Sensor uses spectral optical attenuation of light through the water column to detect the presence of shore based, human generated contamination. The first implementation of the moored Rainbow Sensor, the Light and Motion Sensor Program (LMSP) on Bonaire has, in its first year, shown that it can detect organic matter in the water column. The low cost (< US $1500) of each Rainbow Sensor mooring brings the capability of continuous, long-term measurement of the organic content of seawater to many agencies that do not have the budget for more expensive traditional monitoring systems.

Key Words: organic matter, contaminants, monitoring, light attenuation, water quality

Introduction

Coral reefs are vulnerable to a range of environmental effects, from the local to global scales. The local scale includes several types of effects. Removal of fish or shifts in population structure due to invasive species (top-down effects) can result in loss of grazing pressure on reef algae (Littler et al. 2006). Reefs can also be affected by mechanical damage. Mechanical damage can come from either human activities that include construction, boat anchors or diving activity or from natural processes such as wave damage during hurricanes. Bottom up effects come from modification of the base of the food web such as increased algal growth due to nutrient input, contaminants, or other processes that will affect the lower trophic levels (e.g., Lapointe 1997). Nutrient and contaminant inputs are usually associated with anthropogenic sources that increase with increasing population pressure that has resulted both from modernization and population migration to coastal regions. Regional processes often include fluctuations in regional circulation, eddies, coastal upwelling, storm systems, etc. Global processes include global climate change (IPCC 2001), ocean acidification (Caldeira et al. 2007; Feely et al. 2004), and global climatic oscillations. Climate variaibility has been suggested as a possible mechanism for rapidly altering the state of the ecosystem (Scheffer et al. 2008). Local processes, usually the most manageable processes, are often associated with human activities that include coastal modification, watershed and land use changes, sewage discharge, etc.

Maintaining as healthy a reef system as possible by local intervention may offset some of the effects of changing global and regional phenomena. Providing marine protected area managers with indications of increasing contamination levels that could degrade a reef enables them to seek effective solutions, ideally, before significant degradation occurs or becomes noticeable. Effective coral reef management, then, requires that contaminants are detected and identified before significant reef degradation can occur, so that the stakeholders can understand the presence and threat to a reef system and take preventive action as rapidly as possible.

The Light and Motion Sensor Program (LMSP) was developed to provide an inexpensive monitoring tool that will detect the presence and/or effects of contaminants in the water column. Anthropogenic inputs from runoff and sewage discharge into the coastal ocean (whether intentional or inadvertent) contribute inorganic nutrients contributing to algal growth, and organic matter that may alter the trophic structure of a reef (e.g., Lapointe 1997, 1999; Littler et al. 2006). Both organic matter and planktonic algae absorb light more strongly in the blue region of the spectrum than seawater (Kirk 1994; Fig. 1). Runoff and sewage discharges are characterized by increased colored dissolved organic matter (CDOM), suspended particulate matter and nutrient inputs (e.g., Petrenko et al. 1997; Twardowski and Donaghay 2001; Wu et al. 1994). Thus, it should be possible to create an index of the organic matter content of the water column, the organic index.

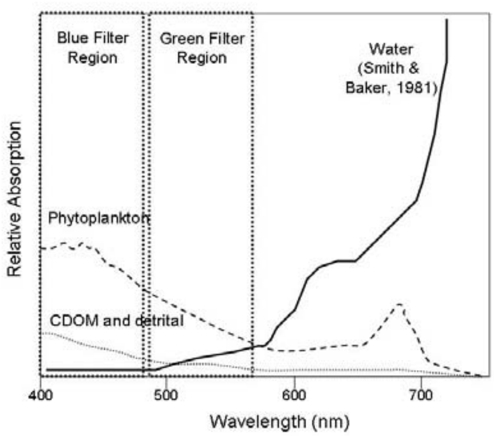

Figure 1: Sketch of Rainbow Sensor absorption spectrum. X-axis: light spectrum; Y-axis: Relative absorption of light in the water.

In clear oligotrophic water, attenuation in the green portion of the spectrum is typically higher than attenuation in the blue portion of the spectrum (Smith and Baker 1981). In the blue range, K_{Ed} increases due to increased absorption by organic matter while the green K_{Ed} is largely unaffected. Therefore, the Organic Index (OI) is correlated with: chlorophyll concentration (phytoplankton biomass), CDOM, and particulate organic matter.

This paper describes this approach and provides examples from the first year of implementation that indicate the utility of this monitoring system.

Material and Methods

The Light and Motion Sensor Program on Bonaire uses the Rainbow Sensor array developed at the University of Southern California to measure K_{Ed} for blue, green and broadband white light from sensors at three depths. The program uses Hobo Pendant temperature/light sensors (Onset Computer) with transparent colored filters inserted in two of the sensors. The three sensors are placed in an array at a specific depth below the surface (Fig. 2). On the LMSP moorings sensors are placed at 5 meter, 12 meter and 20 meter depths, for a total of nine sensors per mooring. The sensors are placed face up so that they are measuring the downwelling irradiance, E_d, at each depth for each spectral range.

Figure 2: LMSP Rainbow Sensor Array on a mooring line in the Bonaire National Marine Park.

The filters currently used by the LMSP program are blue and green filters with defined optical characteristics manufactured by Lee Filters, Inc. (http://leefilters.com). Figure 3 shows the transmission characteristics of the blue light filter. It transmits about 35-55% of the light between 400 and 450 nm. This portion of the spectrum is where CDOM and chlorophyll strongly absorb. The filter also effectively transmits light at 700 nm. However, water rapidly attenuates red light (> 600nm) in the upper few meters of the water column. At 700 nm, the seawater attenuation coefficient is 0.65 m^{-1} in the clearest seawater (Smith and Baker 1981), attenuating downwelling irradiance to 4% of its surface value at 5 meters depth. While there may be slight contamination of the blue light with red light using this filter at 5m, by 12 meters depth the downwelling irradiance at 700nm is reduced to ~0.04% of surface light.

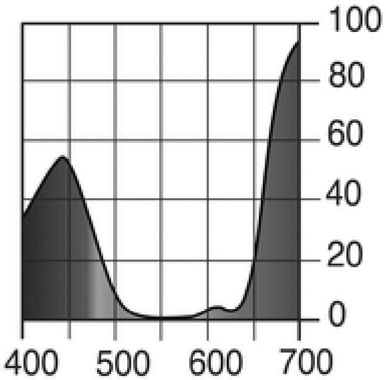

Figure 3: Blue filter transmission spectrum. The x-axis is the wavelength in nanometers and the y-axis is percent transmission. The spectrum is for the Lee Filter #798, Chrysalis Pink filter (http://www.leefilters.com/).

Figure 4 shows the green filter spectrum. The filter permits very little light in the blue range (< 470nm) but allows the entire green range (470-570nm) to pass. In this range organic matter affects light attenuation much less than at shorter wavelengths.

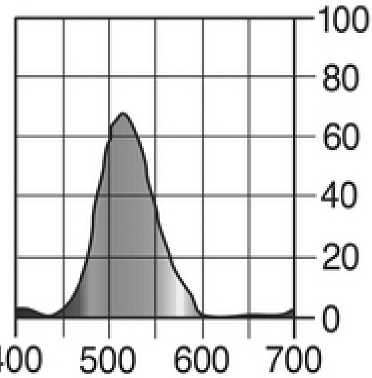

Figure 4: Filter transmission spectrum for Lee Filter #124, Dark Green (http://www.leefilters.com/). The x-axis and y-axis are the same as in Figure 3.

The sensors are programmed to measure temperature and light continuously at one minute intervals. Volunteer divers use an underwater optical reader to download data and re-launch the sensors on each mooring weekly. This data is transmitted to the University of Southern California in Los Angeles, California. Since the sensors are not self cleaning, the volunteers clean the sensors after downloading the data.

For each depth pair the diffuse downwelling attenuation coefficient [K_{Ed} (λ)] is calculated from the downwelling irradiance for each color region using equation 1.

$$K_{Ed}(\lambda) = -\frac{\ln\left(E_d(\lambda, z_2) \big/ E_d(\lambda, z_1) \right)}{z_2 - z_1} \quad (1)$$

where:

$Ed(\lambda,z)$ = downwelling (downward propagating) irradiance at wavelength λ at depth z

$K_{Ed}(\lambda)$ = diffuse downwelling light attenuation coefficient.

For each mooring nine K_{Ed}'s are calculated, blue, green and white sensor pairs for the depth intervals of 5-12m, 12-20m, and 5-20m.

The LMSP on Bonaire currently (September 2008) employs twelve moorings, each with nine sensors, distributed along the western leeward coast (Fig. 5). Two more moorings are expected before November 2008.

Figure 5: Locations of LMSP moorings on Bonaire along the central leeward coast.

Results

The Light and Motion Sensor Program on Bonaire has, in its first year, yielded results that show several processes that affect both the temperature and water quality on the reef. One of the moorings was located at a dive site called "Front Porch", indicated by #1 in Figure 5. During January 2008, the water column cooled by nearly 1.5°C accompanied by a doubling of the optical index (OI), calculated as the difference between K_{Ed} (blue) and K_{Ed} (green) (Fig. 6).

The temperature cooling suggested that this was likely an oceanographic process that was causing the change in the optical attenuation. MODIS-Aqua remotely sensed sea surface temperature (SST) and chlorophyll imagery (University of South Florida, Center for Remote Sensing) showed cool, chlorophyll-containing surface water extending northward from the Venezuelan coast, apparently due to coastal upwelling. Thus the cooling and increasing

OI on Bonaire advected from the Venezuelan coast to Bonaire, increasing the organic index resulted due to increased chlorophyll associated with the upwelled water.

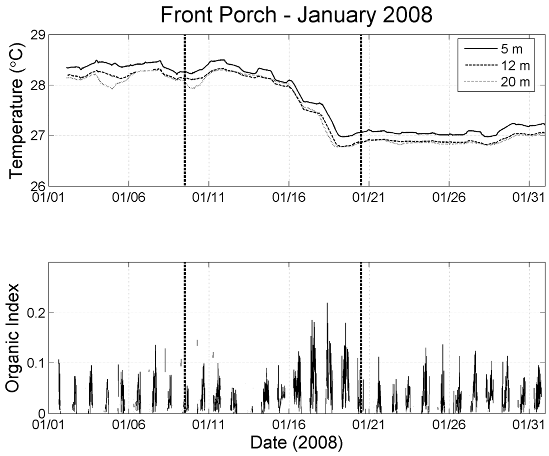

Figure 6: Time-series of temperature (top graph) and organic index (bottom graph) (K_{Ed} (blue, 12-20) –K_{Ed} (green,12-20)) for Site #1 (see Figure 2) in January 2008.

In the second example from the LMSP data set the seasonal variation from October 2007 through June 2008 is examined. During this period, K_{Ed}(blue) was often less than K_{Ed}(green), giving a negative organic index.. We therefore show only K_{Ed}(blue), which by itself is as an index of organic matter because of the strong blue absorption by phytoplankton and dissolved organic matter in the blue portion of the spectrum (Fig. 1). The time series showed a general increase in the K_{Ed}(blue) along the entire developed coast of Bonaire between November 2007 and April 2008 (Fig. 7).

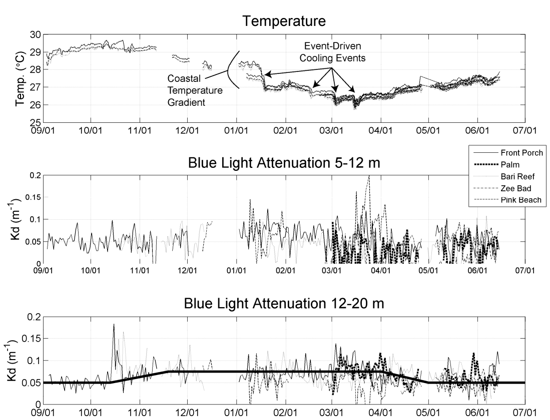

Figure 7: Example of possible local processes along the Bonaire coast. This includes data from 5 moorings.

This period coincides with seasonal cooling and is also concurrent with the highest tourist activity. The general pattern is consistent across several sites, suggesting that the increase in K_{Ed}(blue) is not due to localized contamination at any single site, and may likely result from increased mixing and primary productivity during the winter months. The K_{Ed}(blue) values in this time series are consistent with observations off the northwest coast of South America away from the influence of the Amazon River plume (Del Vecchio and Subramaniam 2004).

The observed seasonal cooling is not a continuous process, but is characterized by several step-wise cooling events of varying magnitude. The temperature data has been particularly useful in understanding the local and regional mechanisms that affect the reef.

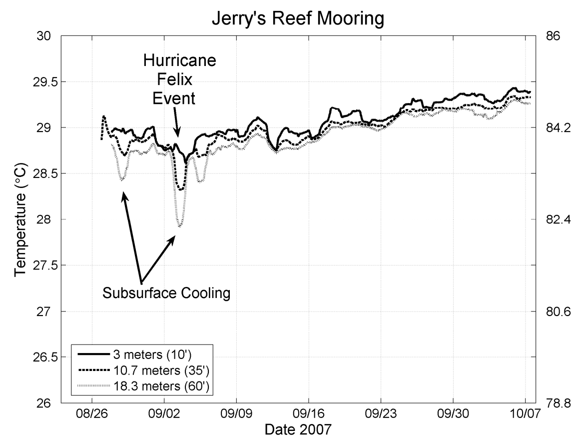

Figure 8: Vertical temperature structure during a near pass by hurricane Felix on September 2, 2007. The mooring site is Jerry's Reef near island of Klein Bonaire.

Figure 8 shows the effects of the passage of a hurricane event on the subsurface temperature. The temperature time series indicates that the cooling occurred from below rather than mixing downward from the surface. Cooling at 20 m preceded slightly the cooling at shallower depths. This contrasts with the cooling shown in Figure 7 where temperatures at all depths converged and the cooling event in Figure 6 where temperatures fell proportionally. By September 9, the effects of the event had passed and seasonal warming continued.

Discussion

After its first year of implementation, the Rainbow Sensor array has demonstrated that it can detect events in both temperature and in the diffuse attenuation coefficient in the blue portion of the spectrum. Two patterns in blue absorption were observed. One was a response to regional coastal upwelling off of Venezuela that could be seen in the remote sensing imagery to advect cool, chlorophyll enriched water toward Bonaire. The second pattern was a seasonal pattern where higher values of

K_{Ed}(blue) were observed during winter months than during spring/early summer. We are uncertain of the cause of the winter increase of attenuation, but nevertheless, the moorings were able to detect the pattern.

Improvements to the Rainbow Sensor array continue. The filter that is being used for the blue measurements also transmits light in the red region of the spectrum (Fig. 4). Although the downwelling irradiance at 700 nm is reduced to 4% of surface light at 5 meters, it may still cause a small amount of contamination in the total light and bias the K_{Ed}(blue) values higher because of the high values of red attenuation by water itself. We are looking for a suitable filter that has adequate transmission in the blue portion of the spectrum and minimal transmission in the green and red parts of the visible spectrum.

The low cost of the moorings (< US $1500) provides the possibility of continuous, long-tern measurement of the organic content of seawater to agencies that do not have the budget for more expensive traditional instrument systems. Manufacturers such as WETLabs and Satlantic produce *in situ* nutrient sensors that cost US $15-20,000 each. Similarly, CDOM and chlorophyll fluorometers cost about US $3500 each and require additional battery packs and loggers for moored applications. Although these more expensive instruments provide specific, accurate measurements, the costs of implementing a mooring with these sensors may rapidly become prohibitive.

This approach is applicable to coastal reef systems near human development where the effect of human generated pollutants could affect the health and economic viability of the reef. The approach is best suited for coral reefs at greater than 5-10 meters depth and where volunteers and/or low cost individuals that are only recreational SCUBA qualified are available and allowed to service the sensors.

We are continuously improving the procedure for the Rainbow Sensor and for analysis of the time series of temperature and K_{Ed}. We welcome the opportunity to collaborate with other groups interested in implementing this approach.

We conclude that the “Rainbow Sensor” concept appears to provide a reasonable measure of K_{Ed} in the blue portion of the spectrum. Because most of the variability between 400 and 490 nm is associated with organic matter in various forms including CDOM, chlorophyll and particulate organic material, variability of K_{ed} in this region of the spectrum should represent changes in the organic content of the water column. We believe that the Rainbow Sensor array is an effective, inexpensive approach to monitoring changes from contamination that might affect the reef ecosystem. Because it records its data at a reasonably high frequency, it provides the ability to resolve processes over a range of time scales range from minutes to years, depending on the lifetime of the moorings.

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