A Diver-Operated Optical and Physical Profiling System

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ABSTRACT

A new instrument package for measuring physical (temperature, salinity, and depth) as well as optical (absorption and attenuation at nine wavelength) parameters using SCUBA is described. The package is attached to the SCUBA bottle and allows for sampling very close to the sediment–water and water–air interfaces. This package can also provide measurements of sediment pore water properties using a 0.2-μm prefilter. Data recently collected with the package highlight the variability in the optical properties between areas with different bottom substrate (coral, sea grass, and sand) and the importance of pore water in productive sediments as sources of colored dissolved organic matter.

1. Introduction

The scattering and absorption coefficients, the inherent optical properties (IOPs) of the ocean, determine the radiative transfer once the external light field is given (Preisendorfer 1976). In turn, the IOP depend on the nature of the dissolved and suspended materials. It is thus possible to learn much about these materials and their distributions by measuring the distribution of the IOP. The determination of the IOP on small time- and space scales is now routine (Zaneveld et al. 1992; Moore 1994). IOP profiles, together with ancillary data such as CTD, are obtained using profiling packages from ships (Pegau 1997) and moorings (Chang and Dickey 1999). Measurements are rarely performed close to the bottom from research vessels due to the dangers of losing the package. In this paper we describe a diver-operated IOP–CTD package that can be used to study the distribution of IOP on very small time- and space scales (seconds and centimeters) at distances of less than 10 cm off the bottom. Furthermore, the package allows the study of the distribution of derived properties such as colored dissolved organic matter (CDOM), particle concentration, particle size distribution, and chlorophyll concentration close to the bottom. The distributions of the latter enable the quantification of biological, geological, and chemical processes in the ocean. The IOP–CTD package was also used to sample, in situ, physical and dissolved optical properties of sediment pore waters. Such measurements are of importance in establishing the diffusive flux of CDOM into the water column from the sediment pore waters.

Radiative transfer modeling is most often done assuming horizontal homogeneity in IOP. Close to the bottom, and on small scales, one may expect this assumption to be invalid, due to heterogeneities in both the substrate and the fluid flow in its vicinity. As the IOP–CTD package is well suited to measure these small-scale horizontal gradients, data provided by this system can be used to examine this assumption.

2. Instrumentation

As part of the Office of Naval Research–sponsored Coastal Benthic Optical Properties Program (CoBOP), we developed a diver-portable instrumentation package that includes a nine-wavelength absorption and attenuation meter [Western Environmental Technology Laboratories (WET Labs) ac-9, an underwater spectrophotometer], and a CTD (SeaBird SBE 37-SI). Alternatively, a spectral fluorometer (WET Labs SAFIRE) can be used in lieu of the ac-9. The package is shown in Fig. 1.

The instruments are set up in series as a flow-through system with a pump (Sea Bird SBE-5T). In order to measure the temperature and conductivity of the inflowing water, the CTD was modified by ducting the temperature sensor into the water stream. The intake of the system is a 1/2-in. diameter tygon tube in the diver's

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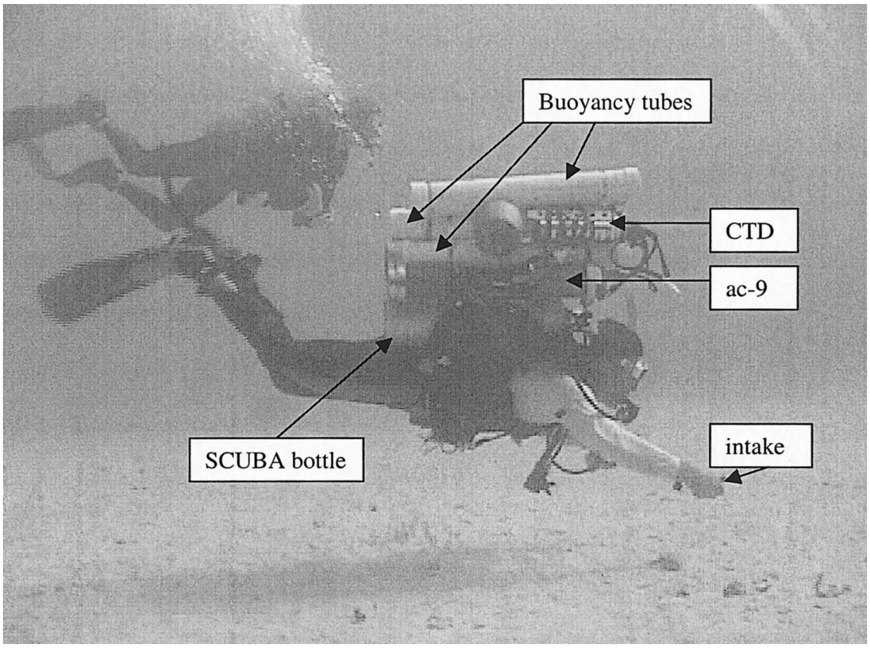

FIG. 1. The diver-operated optical and physical profiling package.

hand. Data storage is provided on the package by means of a WET Labs MPK3. Alternatively, real-time readout of absorption and attenuation spectra can be provided by means of an underwater display unit. This unit also can record the data. The display unit is particularly useful when profiling sediments (see below), to ascertain the proper operation of the system. Power is provided by a 12-V rechargeable battery pack (WET Labs BPR). The instruments are arranged on a stainless steel frame that is attached to the diver's air tank by means of two pins and a quick release. The pins and quick release mate to fittings on two stainless bands attached to the diver's air tank. It is possible to measure either total IOP (particles plus dissolved materials) or the IOP due to CDOM by means of a 0.2-μm prefilter (Gelman SuporCap 100) attached to the water intake by the operator. The ac-9 was calibrated daily using optically pure water from a Barnstead Nanopure water purifier.

The package can be used in a variety of modes. Horizontal sections are carried out with the diver swimming either at a constant height above the bottom (error of estimation typically smaller than 20% of depth above bottom), or at a constant depth (error in depth depends on depth gauge, generally ± 0.6 m). The pressure reading is taken by the CTD on the diver's back, which can be offset relative to the diver's hand. Vertical profiles can be measured from the surface to the bottom or conversely. Profiles of dissolved IOP and derived properties such as CDOM concentration were also obtained in sediments. This was done by attaching a solid small-diameter tube to the water intake of the system and pushing it into the sediment to various distances. Profiles within the sediment were obtained up to 16-cm depth.

3. Results

We will provide here examples of the type of IOP and CTD distributions that can be obtained with the diver-operated instrumentation package. The package has been deployed during the Coastal Benthic Optical Properties experimental program at the Caribbean Marine Research Center at Lee Stocking Island, Bahamas. Sampling sites (Fig. 2) included a 20-m-deep reef (North Perry), a 14-m-deep reef (South Perry), a 12-m-deep reef (Horseshoe), a 3-m-deep reef (Rainbow Garden), and a 3-m-deep sea-grass bed (Channel Marker). North Perry, South Perry, and Horseshoe are fringing reefs on the seaward side of Lee Stocking Island. Their seaward edges are contiguous with sand plateaus at nearly constant depth. Rainbow Garden is a patch reef north of Lee Stocking Island on the east side of a series of barrier islands interspersed with channels. Data shown in this paper were obtained in May 1999.

a. Horizontal sections near the sediment–water interface

A number of horizontal profiles at 10-, 50-, and 200-cm height above the bottom perpendicular to the reef edge were carried out at North Perry, South Perry, and Horseshoe reefs. A typical horizontal transect obtained approximately 10 cm above the bottom is presented in Fig. 3. The pattern consists of a line of approximately 40 m in length, starting at approximately 8-m depth on the coral reef, proceeding seaward to the sand plateau at 16 m. The offshore sites (North Perry, South Perry, and Horseshoe reefs) clearly showed horizontal gradi-

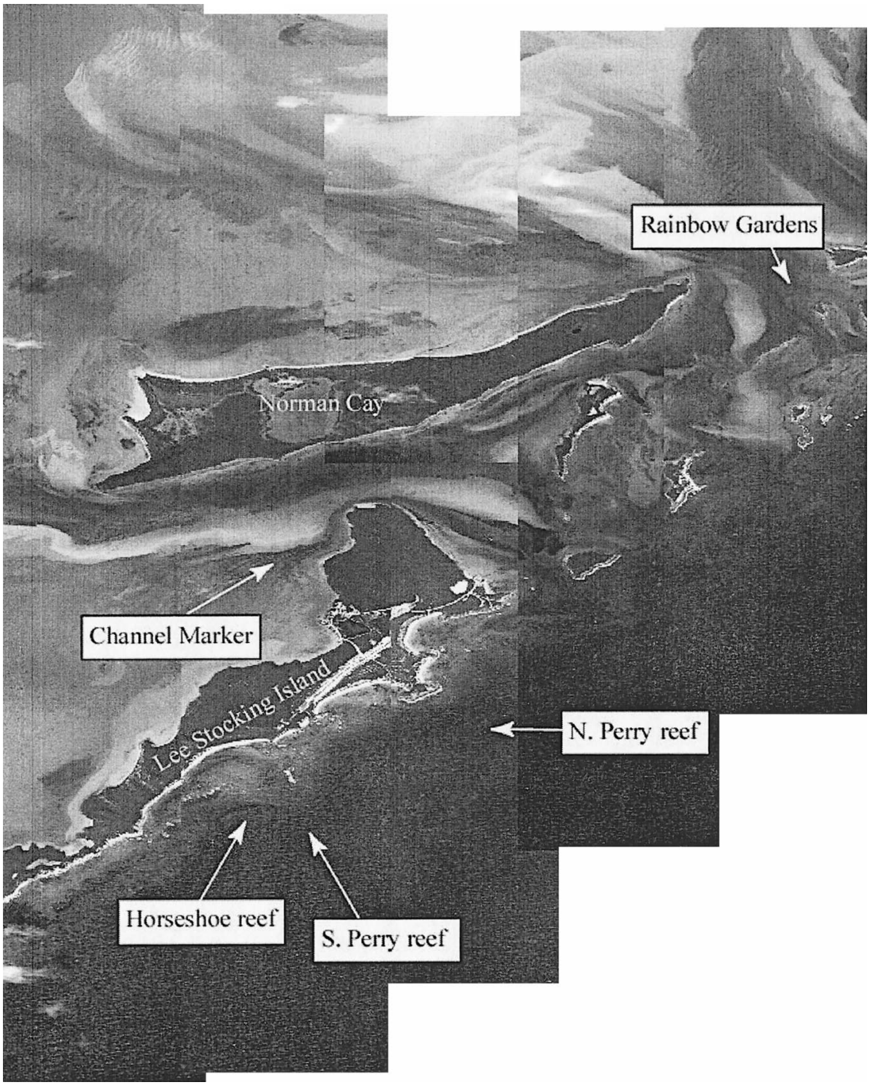

FIG. 2. The location of the sampling sites. Rainbow Garden and Channel Marker are on shallow banks, while Horseshoe and North Perry reef, face Exuma Sound to the east of Lee Stocking Island, Bahamas. (Remote sensing image courtesy of Dr. C. Davis of the Naval Research Laboratory, Washington, D.C.)

ents in light absorption and attenuation and derived properties as a function of substrate (Figs. 3 and 4). These gradients were much stronger during calm conditions (not shown). The water was stratified with respect to both physical and optical parameters.

Figure 3 shows that the beam attenuation coefficient is higher over the sand than over the reef, indicating higher particle concentration, presumably due to resuspension over the sand and/or removal of particles by the coral. The absorption by chlorophyll-containing particles (estimated from the difference in absorption at 676 and 650 nm) is higher over the reef than the sand, indicating higher concentration of phytoplankton. We hypothesize that this is due to removal of zooplankton by the coral, which reduces grazing pressure. A first-order particle size gradient can be obtained from the beam attenuation spectrum (Boss et al. 2000), whose hyperbolic slope, γ, is related to the exponent of the hyperbolic particle size distribution (PSD), ξ, when the PSD is modeled as $N(D)dD = D^{-\xi}$, and where $N(D)dD$ is the number of particles per unit volume with sizes between D and $D + dD$. The hyperbolic slope, γ, is larger when there are relatively more small particles. We found γ to be larger over the coral than over the sand (Fig. 3). There are two possible explanations for this observation. The first is that the corals and sponges are preferentially removing larger particles. The second is that, over the sand, a balance between sediment resuspension and settling, compared to settling only over coral reefs, is enriching the water over the sand with relatively larger particles. The latter explanation, however, is not consistent with the vertical gradients of at-

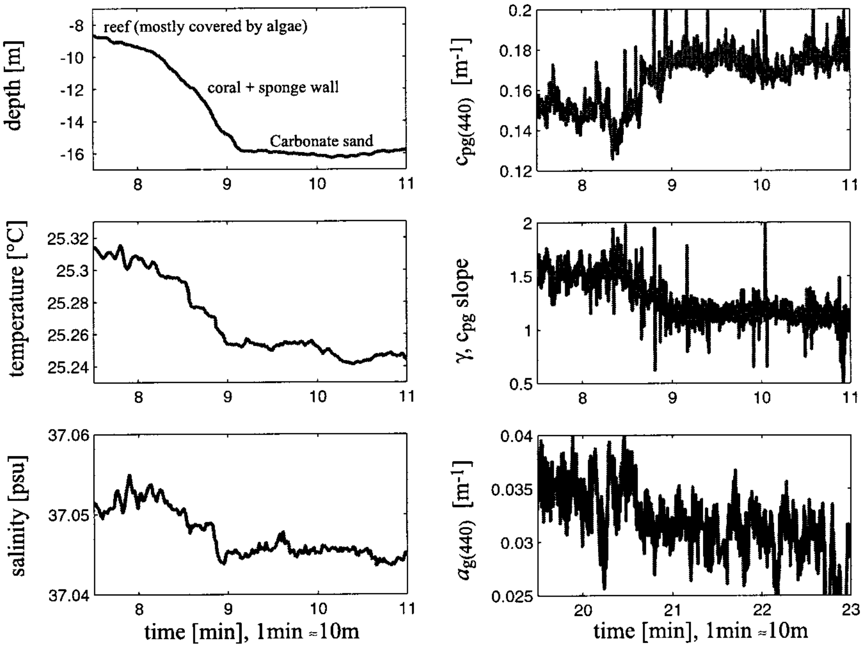

FIG. 3. Depth, temperature, salinity, nonwater beam attenuation coefficient (c_{pg}) at 440 nm, beam attenuation spectral slope (γ), and CDOM absorption (a_g) at 440 nm for a horizontal transect 10 cm above the bottom at South Perry reef, Lee Stocking Island, Bahamas. Optical, temperature, and salinity measurements were lagged to match the pressure measurement (which is measured on the diver's back). Absorption by CDOM (a_g) at 440 nm was measured on the return transect.

tenuation, which show little vertical structure above the sand (not shown). The former explanation is thus the more likely one. CDOM absorption at 440 nm was found to be higher over the reef than the sand (Fig. 3). This observation may indicate release of organic matter by the coral and sponges following particle ingestion.

The variability of the beam attenuation coefficient along a horizontal transect is an indicator of the frequency of episodic small-scale resuspension events and patchiness of processes, such as release of fecal material and sloppy feeding of fish. Figure 4a shows beam attenuation transects at North Perry reef taken at 10, 50, and 200 cm above the bottom. This transect contained a series of small coral reefs separated by sandy bottoms. The reef patches were shallower than the sand, so that the reefs are indicated by smaller depths in the transects of Fig. 4a. The highest variability is observed over the coral reef (Fig. 4a). There is less variability over sea grass (Fig. 4b), and the least variability is observed over sandy bottoms (Fig. 4c). Variability in the beam attenuation coefficient is important, because it affects the difference between the mean and median values (right-hand panels of Figs. 4a–c). The vertical attenuation from the surface to the bottom depends on the mean value of the attenuation, not the median.

b. Vertical profiles and observations near the sea surface

Due to the control of the operator, the package can be used to study the distribution of optical properties close to the air–sea interface. Optical variability close to the interface is very important in determining the optical remote sensing reflectance. The remote sensing reflectance is directly proportional to the optical backscattering, which is strongly influenced by bubbles. It is very difficult to measure the optical properties of the upper meter or so from ships, due to their motion. A diver approaching the surface from below can do so with relative ease, though he or she should be careful not to sample the bubble stream of the diver. At different times and locations we have observed both increases and decreases in the total beam attenuation near the surface. Figure 5 is an example of a profile from the bottom to the sea surface. Since the beam attenuation coefficient is the sum of the scattering and absorption coefficients, changes can be due to either of the components. Near-surface increases in the beam attenuation coefficient are often due to increases in the volume scattering coefficient. Increases near the surface thus may indicate the presence of bubbles. Decreases in the upper meter are often related to decreases in the absorption of CDOM. Photo-oxidation of CDOM takes place near the surface and results in a decrease in CDOM absorption.

c. Vertical structure of optical and physical parameters in sediments

The diver-operated package was used to determine the vertical structure of optical and physical parameters

(a)

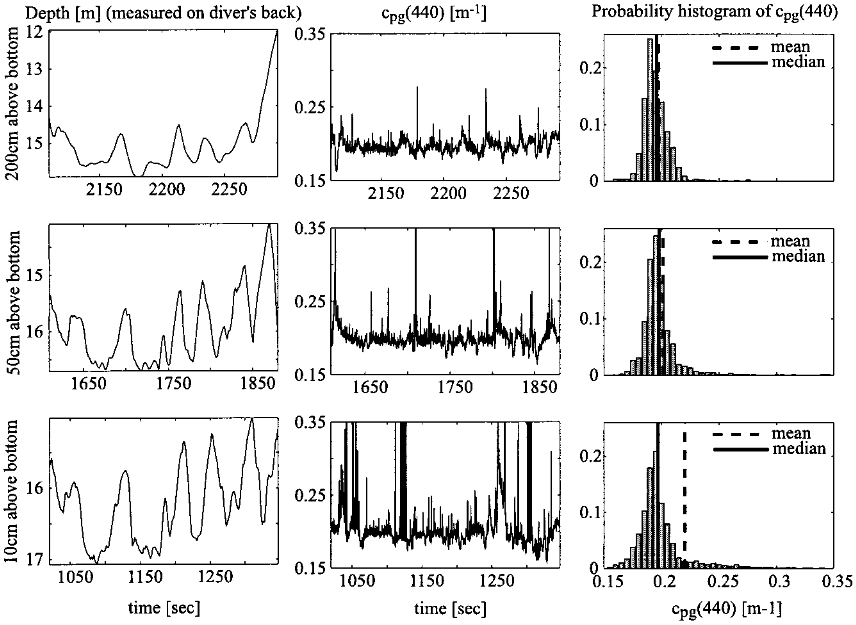

FIG. 4. (a) Depth (left-hand column) measured on the diver's back (the water intake was approximately 50 cm lower), nonwater attenuation (c_{pg}) at 440 nm, and its probability distribution for 50-m-long horizontal transects at North Perry reef. The transect consists of small coral patch reefs surrounded by a sandy bottom. Coral patches are indicated by smaller depths in the panels on the left. Notice the higher variability of nonwater attenuation closer to the bottom. Analysis of the absorption spectra showed that in 94% of the cases when the nonwater attenuation has a high value spike, the particulate absorption spectrum showed a peak at the chlorophyll-absorption wavelength of 670 nm, i.e., the attenuation maxima were associated with particles containing chlorophyll-like pigments. The panels on the right-hand side show that the spikes in c_{pg} affect the difference between the mean and median values.

(b)

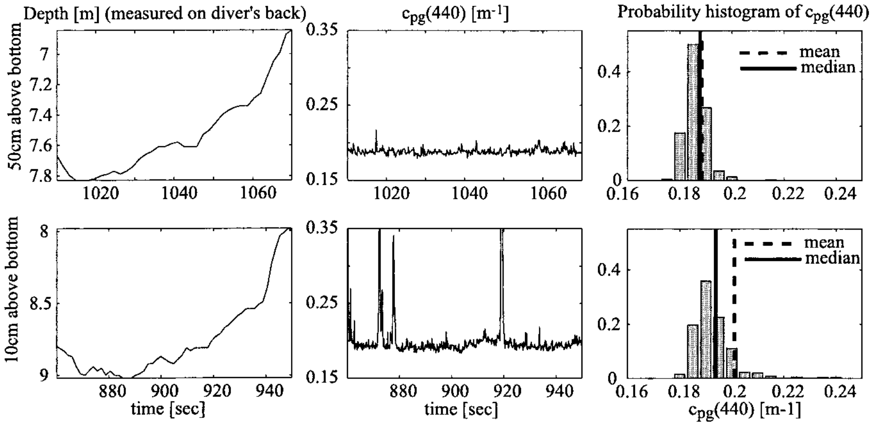

FIG. 4. (b) Depth (left-hand column), nonwater attenuation, c_{pg}, and probability of attenuation values for sections above sea grass at Rainbow Garden. Notice the higher variability closer to the bottom. In 50% of the cases the absorption spectrum associated with peaks had chlorophyll-absorption peaks at 670 nm.

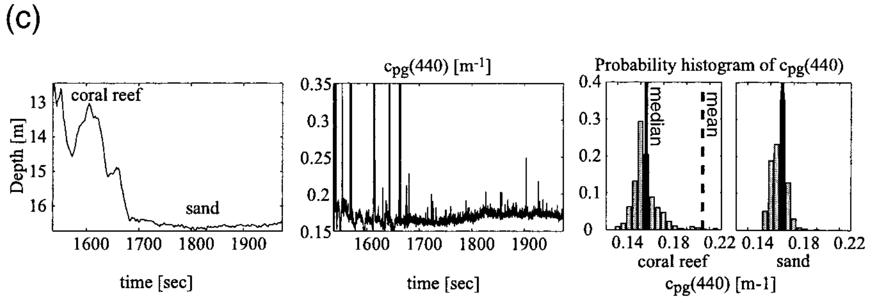

FIG. 4 (*Continued*) (c) Depth (left-hand column), nonwater attenuation, c_{pg}, and probability of attenuation values for a section above sand and corals at North Perry reef. Notice the front in variability crossing from corals to sand.

in marine sediments. Of particular interest are the temperature and CDOM structures as these parameters indicate the degree to which sediments serve as reservoirs for heat and organic materials. Figure 6 shows profiles of these parameters taken in sediment at the Channel Marker site. This profile shows an increase in temperature and CDOM with depth in the sediments. Use of the spectral fluorometer also showed an increase in CDOM fluorescence in the sediment at that time. During incoming tidewater from Exuma Sound with relatively lower temperature and CDOM concentration enters the Channel Marker site. Exchange of pore water with the Exuma Sound water would explain the observed gradient. The sediment pore water thus forms a reservoir with different properties from the overlying water. Within the sediment, water flow into the package was significantly reduced, requiring sampling of at least 1.5 min at each depth to reach a stable value (Fig. 6).

d. Release of fluorescent materials by corals

Corals fluoresce with a number of excitation–emission wavelength combinations (Mazel 1997). We used the diver-operated package with the WET Labs Safire spectral fluorometer to examine whether these fluorescent compounds are exuded by the corals. Sampling very close to the corals showed no discernable fluorescence. When the corals were scraped, the Safire measured fluorescence at coral wavelengths. It thus appears that corals do not release fluorescent compounds into the water column in discernable quantities during quiescent periods. Our study shows that fluorescent materials might be released during periods of heavy abrasion by sediments.

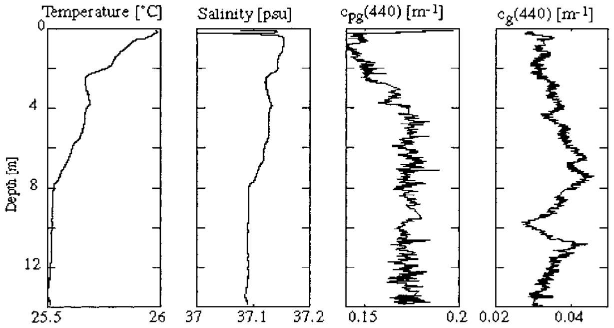

FIG. 5. An example of a vertical profile taken at South Perry reef. The nonwater attenuation (c_{pg}) was obtained during the ascent and the CDOM absorption profile (c_g) was obtained during the descent by adding a 0.2-μm filter to the water intake.

4. Discussion and conclusions

It is clear that the package was successful in describing small-scale structures of optical and physical parameters in a number of environments. The examples of horizontal and vertical variability discussed here show the wide range of potential applications. The presence of higher concentrations of CDOM and lower concentrations of particulate matter over reefs compared to other substrates had previously been obtained (Erez 1990) through painstaking collection of water samples and subsequent analysis. We show here that the CDOM released by corals and sponges affects the optical environment of reefs and, conversely, can be determined by sampling the optical properties. The corals remove particulate matter by filtration. This was demonstrated by the variability in particle concentration and size distribution as evidenced by the beam attenuation coefficient values and spectra. The variability in beam attenuation may be due to either the patchiness of coral reefs with respect to resuspension, feeding, and exudation by fish, or patchiness in resuspension by the fluid flow due to a complex bathymetry.

The reduction of the variability of optical properties in time and places where fish were scarce suggest that the first hypothesis is the more likely in the reef sampled. Similar results and conclusions were reached by R. Yahel (2000, personal communication) using cameras and sediment traps at a reef in the Red Sea.

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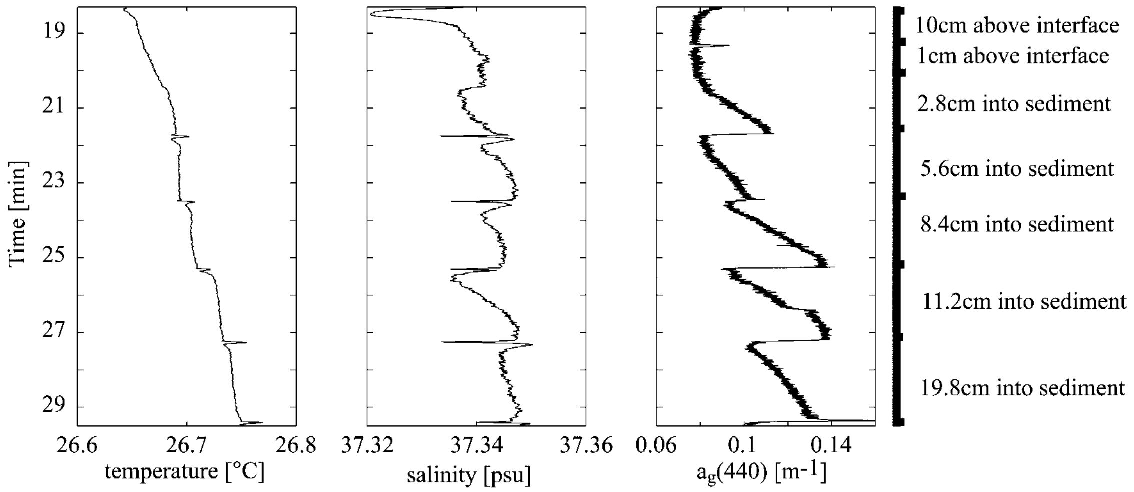

FIG. 6. An example of physical and optical data collected across the sediment–water interface obtained at Channel Marker in a dense seagrass area as a function of time. The suction tube was taken out of the sediment and inserted to a different depth in another nearby location for each sampling interval; the warmer and fresher spike between samples denotes the properties of the water column. Notice that it took approximately 1.5 min for the measurement to reach a nearly constant value. All samples were taken within a 0.5-m^2 area. Other samples showed that the horizontal variability within sediments was much smaller than the vertical variability shown here for the small area sampled.

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