Observing biologically induced optical variability in coastal waters

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ABSTRACT

Biological and optical measurements were compared during studies in Bedford Basin, Nova Scotia. A principal objective was to evaluate a tethered spectral radiometer buoy, which measured downwelling irradiance at 490 nm and upwelling radiance in wavebands corresponding to the SeaWiFS satellite, along with the fluorescence of chlorophyll *a*. Movements of the buoy and changes in solar spectral irradiance influenced measurements. Nonetheless, records of upwelling radiance clearly described optical variability in the water. For example, blue:green radiance ratios were well correlated with water transparency, consistent with a published relationship, but for greener and more turbid waters than previously studied. Optical profiles, including diffuse attenuation at 3 wavelengths, detected a subsurface dinoflagellate bloom in August 1993. When the bloom was entrained into surface waters by afternoon winds, the radiometer buoy easily distinguished darker, red water from the background green water. During the study, a red:green radiance ratio and a measure of chlorophyll fluorescence (683 nm:670 nm radiance ratio) were well correlated with chlorophyll concentration near the surface, whereas green:blue ratios were not. Optical detection of a bloom during its development demonstrates that simple autonomous instruments might be used for detecting some phytoplankton blooms prior to significant environmental impact.

1. INTRODUCTION

Ocean color (water-leaving radiance) is an easily observed and immensely informative optical property. The magnitude and spectral distribution of water-leaving radiance depends on the characteristics of solar irradiance at the surface and the optical properties of the upper water column. These optical properties are strongly influenced by biogenic particles (phytoplankton[1], and to a lesser extent bacterioplankton and viruses[2-4]), which vary in concentration, size-distribution and cellular optical characteristics[5]. Thus, in the open ocean, local biological processes are largely responsible for the temporal and spatial variability in optical properties such as ocean color and water transparency. The situation is more complicated in coastal waters, because large and varying quantities of absorbing and scattering materials can be introduced to surface waters from sediments and terrestrial sources[6]. Nonetheless, phytoplankton are more abundant and variable near the coast[7, 8], and their optical properties are distinct from other absorbing and scattering materials[9], so it is worthwhile to pursue optical methods for detecting biological variability in coastal waters.

Spatial and temporal variability in the concentrations and physiological properties of microscopic plankton has been studied for some time, but the optical manifestations of this variability are still being explored[5, 10-13]. A central objective of our research program is to examine the links between optics and biology in the sea. One goal is to describe variability in phytoplankton biomass, community structure, and water transparency in terms of downwelling irradiance and upwelling radiance, measured at the surface in coastal waters with instruments that are appropriate for autonomous deployment on moorings or drifters. We describe here some preliminary observations and interpretations that may help with the analysis of data from optical buoys in coastal or open-ocean waters.

2. APPROACH

Biological and optical sampling was conducted from small (ca. 8 m) boats during 1992 and 1993 in Bedford Basin, near Halifax, Nova Scotia. Observations were made regularly during each spring, but ice and strong salinity gradients near the surface made it difficult to obtain reliable data on several of the sampling days. An intensive study was conducted from 17 to 20 August, 1993, during a predominantly subsurface bloom of the non-toxic dinoflagellate, *Gonyaulax digitale* [14]. Sets of observations were made each morning, near midday, and late afternoon. About one week subsequent to the study, anoxia

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in the northern reaches of the Basin caused a fish kill that generated considerable public interest. Our optical observations from the week before made it easier to associate the anoxia with the decline of the dinoflagellate bloom.

2.1 Measurement of surface irradiance and near-surface upwelling radiance

A Tethered Spectral Radiometer Buoy (TSRB; Satlantic, Inc.) was deployed from the boat for about 1 h or less during each set of observations, drifting near the boat at the end of a 100 m conducting cable. It recorded downwelling solar irradiance at 490 nm (Ed_{490}; $\mu W\ cm^{-2}\ nm^{-1}$) and upwelling radiance (Lu; $\mu W\ cm^{-2}\ nm^{-1}\ sr^{-1}$) in seven wavebands corresponding to the six bands of the SeaWiFS ocean color satellite, and a channel for the fluorescence of chlorophyll *a* (Fig. 1). The TSRB is similar to the Expendable Spectral Radiometer[15] (ESR) which is a drifter. The ESR transmits through the ARGOS satellite a statistical summary of measurements over the previous 1 h. With a sampling frequency of 1 s^{-1}, the TSRB is suited for examining the influence of short-term variability on those 1-h averages.

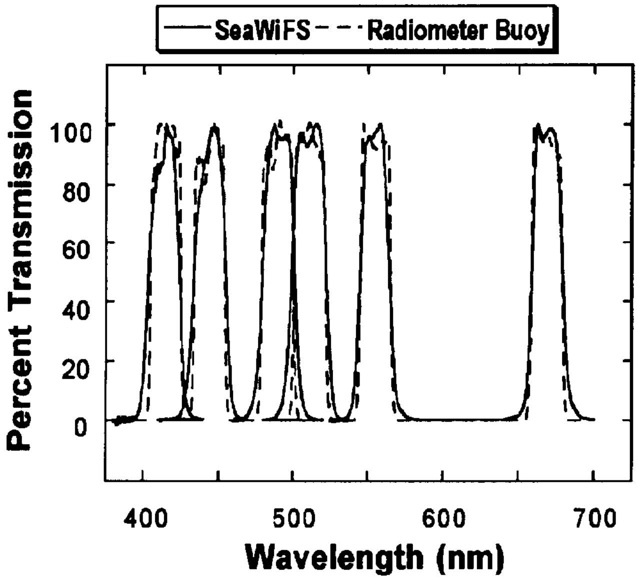

Fig. 1. Transmission characteristics of the filters on the TSRB (dashed line) compared to the SeaWiFS ocean color satellite (solid line). Nominal wavelengths are 412, 443, 490, 510, 555, and 670 nm. The TSRB has an additional band (10 nm half-band width) at 683 nm (not shown) for the estimation of fluorescence from chlorophyll [16, 17].

2.2 Vertical profiles of downwelling spectral irradiance

During 1992, an Ed_{490} sensor was lowered and raised through the water column to estimate the attenuation of downwelling irradiance. Measurements were normalized relative to solar irradiance with reference to a Biospherical Instruments QSL-100 quantum scalar irradiance meter (400 - 700 nm) on deck, against a black background. Diffuse attenuation of downwelling spectral irradiance (K_{490}; m^{-1}) was calculated for 0.5 m intervals, and averaged for up- and down-casts.

In August, 1993, a profiling K-meter was used to measure K at 3 wavelengths: 412, 510, and 555 nm (filters as in Fig. 1). Two sets of the three Ed sensors were attached to a frame, separated by 1.4 m. This distance is adjustable; for turbid coastal waters, a smaller separation would be better. The K-meter also measured pressure and temperature, and transmitted data to a logger on deck. Diffuse attenuation at each wavelength was calculated appropriately from the difference between the lower and upper sensors, and is reported for the mid-point depth.

2.3 Other measurements

A Sea-Bird Seacat 19 CTD was used for vertical profiles of temperature and salinity. It was equipped with a SeaTech transmissometer with a 25 cm pathlength and a SeaTech fluorometer. Beam attenuation (c; m^{-1}) was corrected for the contribution from water by subtracting 0.364 m^{-1}, as specified by the manufacturer. The fluorometer was saturated when it encountered the subsurface algal bloom.

Discrete samples for the measurement of chlorophyll *a* (Chl) and microscopic cell enumeration were taken from 0.5 cm I.D. Tygon hose, taped to exclude light. To achieve maximum vertical resolution and correspondence between profiles and discrete samples, the inlet was attached to the CTD very close to the fluorometer sensor. A small centrifugal pump (Little Giant, model 2E-N) provided propulsion. Samples for physiological measurements (not reported here) were taken from a Niskin bottle attached close to the CTD. The concentration of Chl was determined fluorometrically on triplicate samples, collected on Whatman GF/F filters, and extracted for at least 24 h at -10°C in the dark, using DMSO:90% acetone (1:3) as a solvent. The fluorometer (Turner Designs 10-005R with Corning filters and a blue lamp) was calibrated with Chl from Sigma.

3. EVALUATION OF THE RADIOMETER BUOY

Consistent with modern demands for radiometric accuracy, the TSRB is designed and calibrated to exacting specifications. Once the instrument is deployed, however, it encounters many insults that compromise accurate recording of Lu and Ed. Wave action is an obvious problem for a floating instrument, and all of our records show short-term variability associated with tilting and bobbing of the TSRB. Currents or wind can cause a tethered instrument to tilt in one direction: that problem will be discussed below. For long-term deployments, mechanical damage and fouling are concerns. One of our moorings was sheared by ice. An expendable drifter with inflatable flotation disappeared prematurely in the equatorial Pacific. Possibly, it attracted a shark. We address here the variability that was observed during relatively short deployments of the TSRB in a protected embayment.

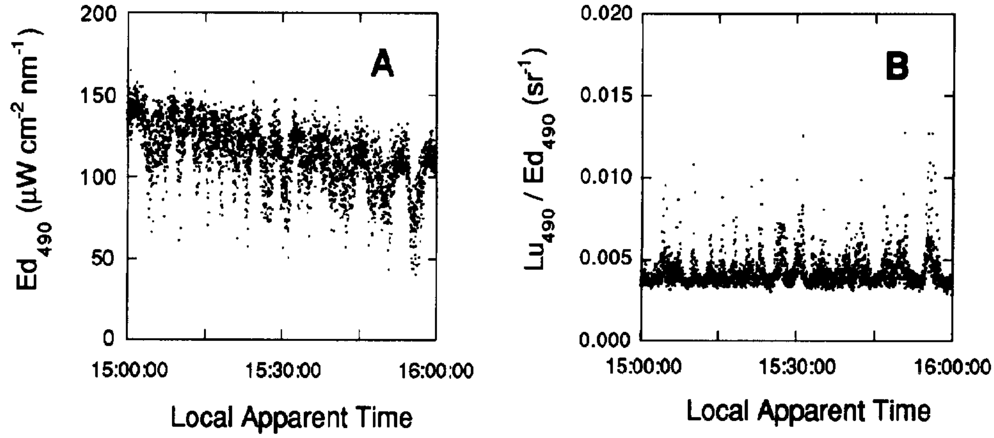

Fig. 2. Measurement from the TSRB on 9 August, 1992, in Bedford Basin, under clear skies and gentle winds, with little wave action. Atlantic Daylight time is 1 h 16 minutes later than local apparent time. A. Ed_{490}. B. TSRB reflectance at 490 nm [$R(490)_{TSRB}$, i.e., Lu_{490}/Ed_{490}].

3.1 Variability associated with orientation of the buoy

Data from a calm, clear afternoon illustrate the influence of orientation on measurements of Ed and Lu. During the deployment, the tilt of the tethered buoy, apparently caused by gentle currents and drifting of the boat, changed with a period of about 3 min, producing substantial artifactual variation in Ed_{490} (Fig 2A). A measure of reflectance (here referred to as $R(\lambda)_{TSRB} = Lu_{\lambda} / Ed_{490}$; units, sr^{-1}) was also affected severely (Fig. 2B). Longer-term changes (i.e., over 1 h), however, were consistent with expectation. The relative decline of Ed_{490}, determined by linear regression, closely matched that predicted for clear skies at that time (Bird and Riordan model[18], modified slightly). Changes in the upwelling radiance spectrum also matched model predictions: the ratio, Lu_{412}:Lu_{670} declined 8% over the hour depicted in Fig. 2; similarly, the model, not completely tuned to local atmospheric conditions, predicted a decline of 6.4%. It seems that averaging data for 5-10 min would be adequate to obtain a good representation of Ed and Lu under these conditions.

Deviations associated with motion of the buoy can be described by subtracting the linear trend from the record of Ed_{490}. Comparison of $R(490)_{TSRB}$ with the Ed_{490} residual shows that estimated reflectance was strongly influenced by the orientation of the buoy. The nature of the relationship (Fig. 3A) is consistent with large changes of Ed as the sensor points toward and away from the sun, coupled with weak variation of Lu, as expected for a diffuse upwelling radiance field near the surface[9]. For less obvious reasons, the ratio, Lu_{443}:Lu_{555} is also correlated with the Ed_{490} residual, indicating that tilting of the buoy caused about ±15% variation of that radiance ratio.

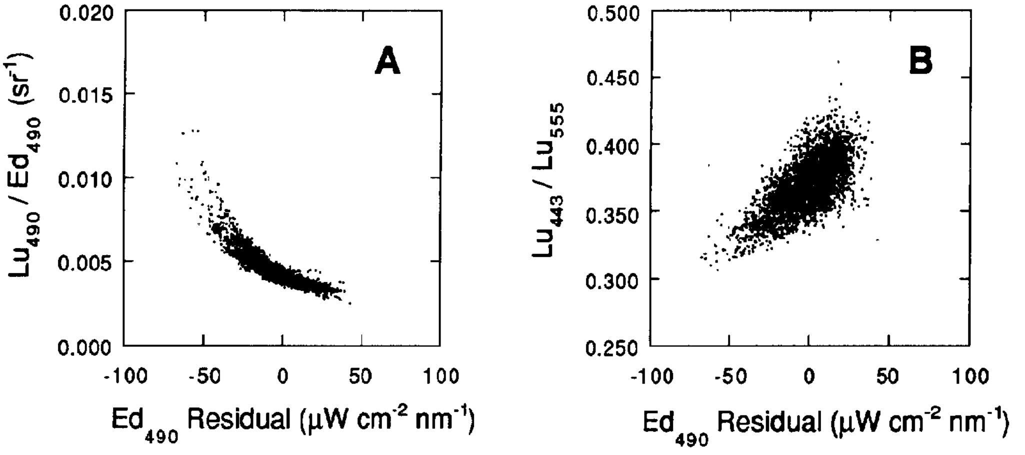

Fig. 3. Deviations of optical measurements as influenced by orientation of the buoy. Tilting of the buoy toward and away from the sun is represented by the residuals from a linear regression of Ed_{490} vs time. Same record as in Fig. 3. A. $R(490)_{TSRB}$ vs Ed_{490} residual. B. Lu_{443} / Lu_{555} vs Ed_{490} residual.

3.2 Variability from changes in solar spectral irradiance

Optical variability near the sea-surface is often described with upwelling radiance ratios[19], and interpretation of these measures involves relating them to absorbing and scattering materials in the water[20, 21]. It is thus desirable to account for any changes in upwelling radiance ratios that are due to variable spectral quality of solar irradiance. The direct solution is to measure Ed_{λ} at all wavelengths corresponding to Lu_{λ}, but that is not always practical or affordable. Instead, one could resort to solar radiation models of varying complexity to predict changes in clear-sky spectral irradiance during deployments. Compared to the variability in Lu ratios that we expect in coastal waters, predicted diel changes in ratios of solar spectral irradiance are fairly small (as shown in section 3.1) and well-behaved. Also, in the context of spectral variations discussed here, uniform cloud cover is close to spectrally neutral. Thus, if estimates of spectral reflectance were desired from TSRB data, it would seem reasonable to convert Ed_{490} measurements to Ed_{λ} using modeled solar spectra.

Partial clouds present a problem. When they don't block the sun, they can be good reflectors of sunlight, causing measurements of Ed exceeding clear-sky values (S. McLean, pers. comm.). When a cloud occludes the sun while much of the sky is clear, direct sunlight is attenuated to a greater extent than diffuse sunlight, which is relatively blue[18]. As a result, the longer visible wavelengths of solar spectral irradiance are differentially attenuated when patchy clouds block the sun, and upwelling radiance ratios shift toward the blue (Fig. 4). The effect is not overwhelming, but it is rapid, and could conceivably be misinterpreted if only Lu ratios were measured.

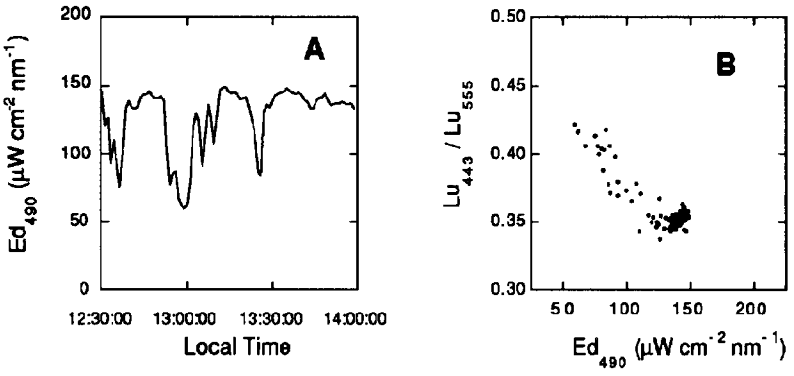

Fig. 4. The influence of patchy clouds on measurements from the TSRB. Observations from Redberry Lake, Saskatchewan, Canada, 9 June 1993. The water is green because light is absorbed principally by water and abundant dissolved organic matter. Chl was relatively low (ca. 1.5 mg m^{-3}) and biologically-induced optical variability should have been slight[22]. A. Ed_{490} vs time during the passage of patchy clouds in front of the sun; 1-min averages. B. The ratio, Lu_{443}:Lu_{555} vs Ed_{490}, showing that the blue:green ratio increased about 20% when a cloud blocked the sun.

3.3 Biologically-induced variability

Despite the potential for interference from extraneous factors, the TSRB has effectively detected biologically induced optical variability in coastal waters. For example, during a deployment in Bedford Basin, upwelling radiance ratios clearly showed the influence of a dinoflagellate bloom on near-surface optical properties (Fig. 5 and the following section). It is noteworthy that a rough measure of Chl fluorescence, the 683:670 upwelling radiance ratio, covaries strongly with the blue:green radiance ratio, a more conventional index of Chl which can be seriously compromised in coastal waters[23]. When a measure of fluorescence covaries with a reflectance ratio determined by absorption and scatter, even during minor fluctuations, the patterns look more like biology and less like noise.

The importance of upwelled radiance in red wavelengths for the description of biological variability is illustrated by a comparison of radiance ratios with Chl (Fig. 6). Log-log plots can make relationships look better than they really are. Nonetheless, it is clear that both the Lu_{683}:Lu_{670} and Lu_{670}:Lu_{555} ratios were superior to green:blue (or blue:green) ratios for describing variability of Chl during this study. The result might not be surprising, considering that a red-tide event was observed. During the spring bloom of 1992, a different wavelength pair did a better job of predicting Chl (Lu_{532}:Lu_{562} from an early filter set; data not shown, $R^2 = 0.9$, $n = 14$).

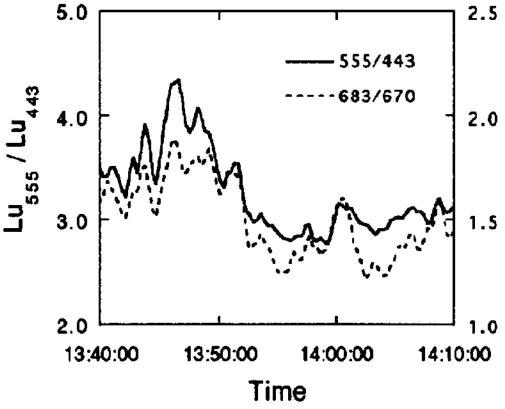

Fig. 5. Upwelling radiance ratios measured with the TSRB during a deployment on 18 August, 1993, between 13:40 and 14:10 local time. The buoy was drifting through patches of red water which appeared as a subsurface dinoflagellate bloom was entrained into the mixed layer. The ratio, Lu_{555}:Lu_{443} is positively correlated with Chl in the open ocean. The ratio, Lu683:Lu670 is a crude measure of solar stimulated Chl fluorescence. For this plot, the two parameters have been scaled proportionally so that relative changes in each line are equivalent. Data were smoothed with a locally-weighted least squared error method with the closest 3% of the data considered (Kaleidagraph, Synergy Software).

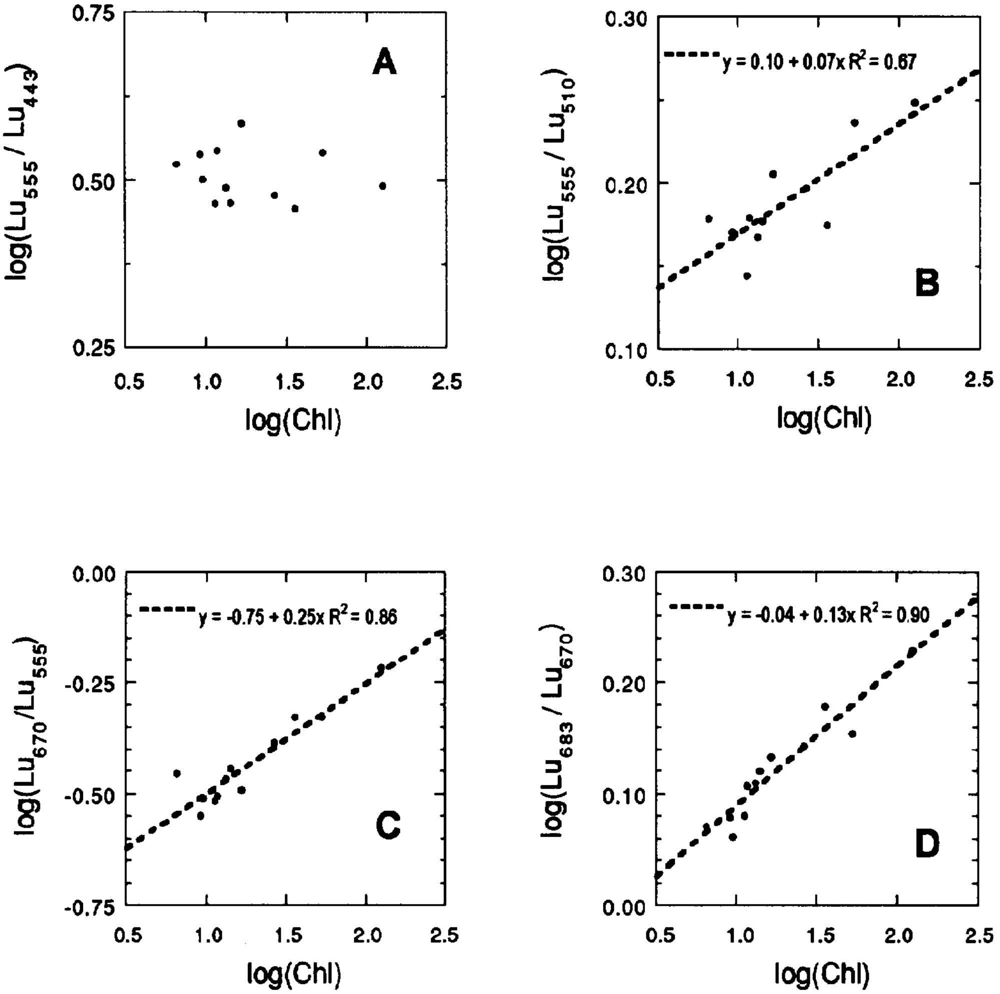

Fig. 6. Relationships between ratios of upwelling radiance and measurements of Chl (mg m^{-3}). Upwelling radiance from the TSRB was averaged for the 60 s closest to the time of sampling for Chl at 0.5 m. Regressions are for log-transformed data.

4. OPTICAL DETECTION OF A RED TIDE

The dinoflagellate bloom during August 1993 was detected in numerous ways. During equipment tests on the morning of August 6, an intense subsurface layer was observed in the thermocline at about 4 m. Beam attenuation exceeded 8 m^{-1} and the thickness of the subsurface peak was 1 m or less. Two weeks later, during the intensive study, a similar subsurface layer was observed each morning (Fig. 7A). The layer was composed of relatively large dinoflagellates, dominated by the non-toxic *Gonyaulax digitale* (30 - 45 μm). Small flagellated phytoplankton (3 - 5 μm) and other dinoflagellates (*Prorocentrum minimum,* 12 - 15 μm) populated the entire euphotic zone. Profiles of diffuse attenuation clearly distinguished the subsurface layer (Fig. 8A). During the afternoons, freshening winds eroded the thermocline, and the mixed layer intercepted the layer of dinoflagellates. When this happened, the water turned red as chlorophyll concentrations increased from roughly 10 - 30 mg m^{-3} to about 100 mg m^{-3} due to the entrained dinoflagellates. As wind-mixing continued to erode the thermocline, physical, optical and biological properties became uniform in the surface layer (Fig. 7B), and volumetric concentrations of phytoplankton declined as deeper waters diluted the mixed layer population. Spectra of Lu_λ / Ed_{490} illustrate the strong differences between green and red water during initial entrainment (Fig. 8B). The red water was redder, of course, but it was also darker and had a much larger fluorescence signal at 683 nm. Similar spectral variations were reported by Carder and Steward[9], but for their study area, brightness was greatly affected by variable detrital contributions.

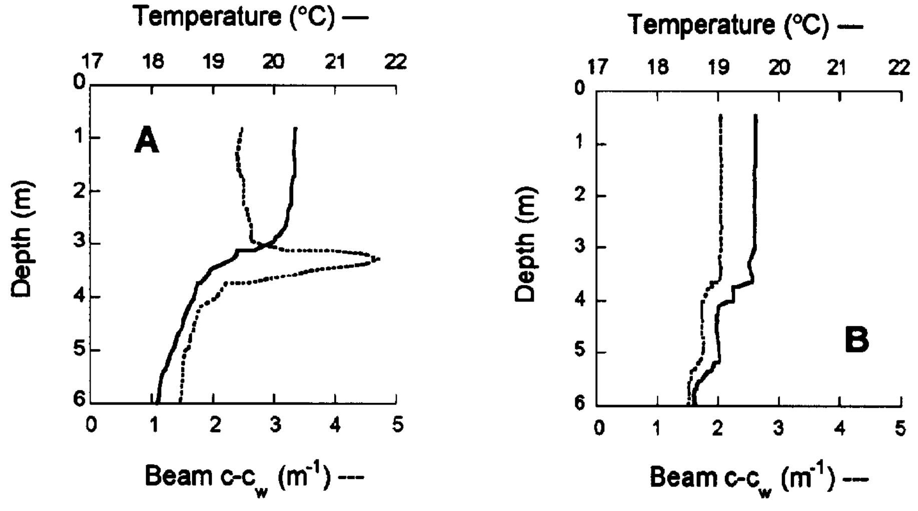

Fig. 7. Changes in the vertical distribution of the dinoflagellate bloom in Bedford Basin during August, 1993. Profiles of temperature (solid line) and beam attenuation, corrected for water (c - c_w, m^{-1}; dashed line). A. Distribution typical of the morning and early afternoon, with the dinoflagellates predominantly confined to a subsurface layer: Aug. 18, 1350 h. B. Effects of wind-mixing: Aug. 18, 1720 h. The subsurface population and deeper water has been entrained into the mixed layer and the thermocline has been eroded.

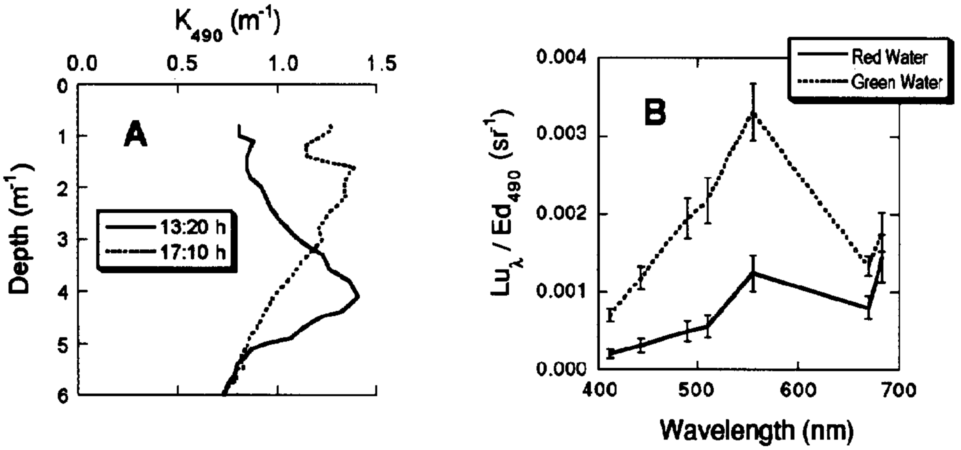

Fig. 8. Detection of the dinoflagellate bloom with passive optical measurements, Aug. 18, 1993. A. Diffuse attenuation of downwelling irradiance at 490 nm at 1320 h (subsurface peak) and 1710 h (after wind mixing). B. Spectra of $R(\lambda)_{TSRB}$ during a period of patchy entrainment of the dinoflagellates into the mixed layer (see Fig. 5): the red water spectrum is the average for 1345 - 1350 h, and the green water spectrum is for 1354 - 1359 h. Error bars are standard deviations.

5. DIEL OPTICAL VARIABILITY

Analysis of data from the open ocean demonstrate substantial diel variation in the optical properties of planktonic assemblages[11, 24-26], and recent laboratory studies have quantified changes in cellular scatter and absorption properties that contribute to these patterns[12, 13]. Optical properties of the water are also influenced by the accumulation of growing cells during the day, and consumption by grazers at night[11]. Because coastal waters are often rich in nutrients that can support rapid growth of phytoplankton, we expected to observe dynamic microbial populations with substantial diel changes in optical properties, detectable in reflectance, diffuse attenuation and beam attenuation. However, during our 1993 study, horizontal variability and vertical shifts of the dinoflagellate population strongly interfered with our quest, and diel patterns were difficult to discriminate.

Observations from other radiometer buoys reveal an interesting pattern that merits further examination. An expendable radiometer buoy moored in Monterey Bay, California showed a consistent and statistically significant diel pattern in radiance ratios, suggesting a 40% increase of Chl during the daytime (Fig. 9A). In contrast, records from the equatorial Pacific Ocean (Fig. 9B) show no significant difference between morning and evening radiance ratios. Such diel patterns (or lack thereof) should be studied further and considered in the design and analysis of remote-sensing studies.

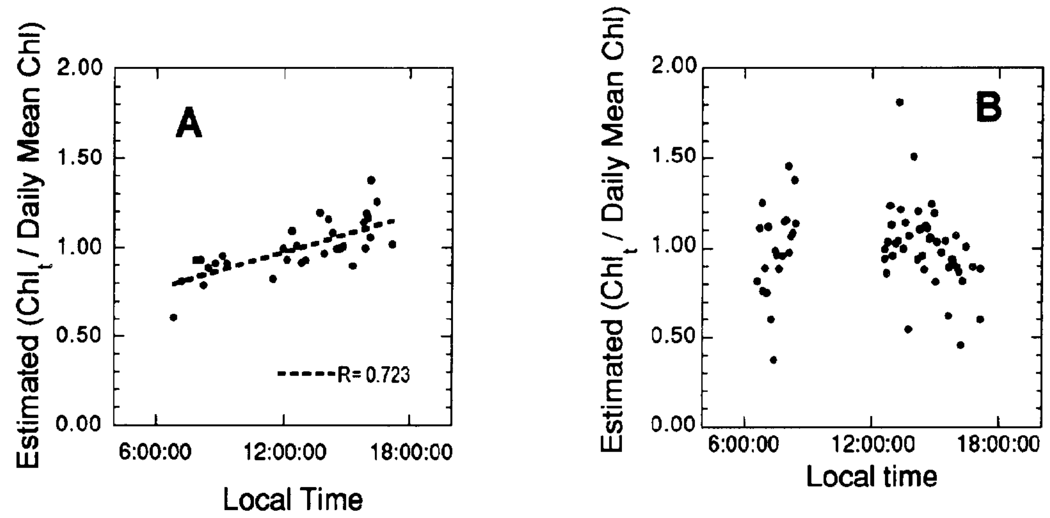

Fig. 9. Daily variation of Chl, as estimated from the ratio of Lu_{443}:Lu_{555}, measured by expendable spectral radiometers and transmitted as hourly averages. Chl algorithm according to Gordon[27]. Data for each day were normalized to the average for the day. Data corresponding to low solar angles (criterion: $Ed_{490} < 20\ \mu W\ cm^{-2}\ nm^{-1}$) were discarded. The gaps in data records correspond to periods when satellite communication was unavailable. A. Monterey Bay, California, September, 1992. B. Equatorial Pacific Ocean, between 1° and 5° S, September 1992.

6. RELATIONSHIPS BETWEEN OPTICAL PROPERTIES

It is hoped that measurements of upwelling radiance from the TSRB can be useful in extending the range of observations on which empirical and theoretical bio-optical models are based. Accordingly, one of our objectives was to relate measurements of upwelling radiance to profiles of diffuse attenuation. Results from August 1992 were very encouraging (Fig. 10A). Diffuse attenuation at 490 nm was strongly correlated with the ratio, Lu_{443}:Lu_{555}, and the relationship was almost exactly consistent with that presented by Austin and Petzold[19], extending validation of the relationship to more turbid waters.

Some of the data from August 1993 were similar to the general relationship, but deviations can be seen, particularly in the two observations most representative of red tide at the surface. Since taxonomic groups of phytoplankton can differ substantially in size and pigmentation, hence in scattering and absorption properties, there is good reason to expect that pronounced changes in phytoplankton community structure would alter the type of relation presented in Fig. 10. Analysis of these deviations is underway.

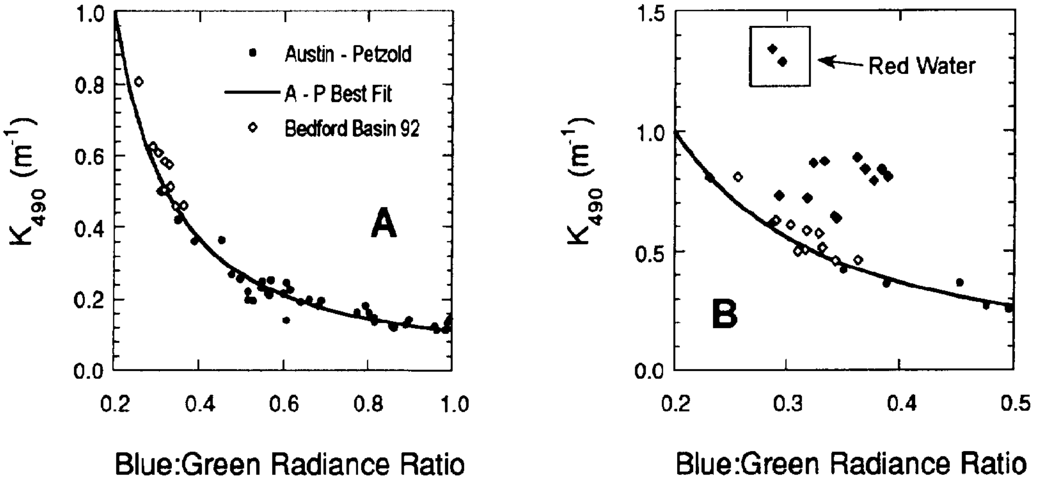

Fig. 10. Relationships between blue:green upwelling radiance ratios and diffuse attenuation at 490 nm: comparisons of data from Bedford Basin (Lu_{443}:Lu_{555}, collected with the TSRB, K_{490} estimated for the upper 2 m) and data presented by Austin and Petzold[19] (filled circles, Lu_{443}:Lu_{550} for radiance ratios <= 1.0), including the fit to their data, plotted on linear axes. A. Bedford Basin, August 1992 (open diamonds). B. An expanded view, with the same symbols as A, plus data from Bedford Basin, August 1993 (closed diamonds). The two points enclosed by a box represent red water at the surface.

7. DISCUSSION AND CONCLUSIONS

A principal objective of this research was to evaluate a radiometer buoy as a tool for observing biologically induced optical variability in surface waters. It was recognized that radiometric accuracy is not enough to ensure useful measurements; the instrument floats on the surface and records radiance and irradiance during chaotic movements in a highly variable photic environment. As expected, we found considerable "noise" associated with these movements, and as hoped, we found that suitable averaging yielded interpretable results. Further, the short-term deviations produced by movements of the buoy could be interpreted. The strong influence of tilting on estimated reflectance (inferred from Figs. 2B and 3A) indicates that any consistent effects on orientation (from tidal currents, for example) should be considered when designing long deployments and when interpreting records from those deployments. Expendable radiometers[15], similar to the tethered version used here, must transmit averaged data. It appears that this is a fortunate constraint.

The determination of spectral radiance reflectance is important for describing optical variability in surface waters, and it is directly relevant to remote sensing. The TSRB measures Ed in only one narrow waveband, however, and upwelling radiance spectra will reflect (literally) variations in the spectral quality of solar irradiance as well as variability in the optical properties of the water. We suggest that models can be used to correct for predictable aspects of solar spectral variation, but under patchy clouds (Fig. 4), spectral shifts might cause problems.

Data from Bedford Basin demonstrated clearly that optical variability in the water could be observed despite interference from extraneous factors. The agreement of our measurements of radiance ratios and diffuse attenuation with the compilation of Austin and Petzold[19] is encouraging (Fig. 10A), as is the deviation associated with large dinoflagellates (Fig. 10B). It seems that the sensing systems used during this study provide data that are comparable to historical observations. The relationship between radiance ratios and Chl is unusual, though, with most of the useful information in the red wavebands (Fig. 6). This might be a special case, because red-water dinoflagellates caused much of the variability. It is nonetheless noteworthy that a signal from Chl fluorescence (Lu683/Lu670) was a good measure of pigment.

We have presented here some striking examples of biologically induced optical variability that would overwhelm subtler changes associated with particle dynamics in coastal waters that were unaffected by an algal bloom. Examples from expendable radiometer buoys (Fig. 9) indicate that other types of variation indeed exist. The presence of a strong diurnal increase in apparent pigment in coastal water, and no diurnal increase in the open ocean, is provocative and worthy of investigation.

Other instrument systems can observe biological dynamics more sensitively, or optical properties more accurately and thoroughly. We are interested in a radiometer buoy and a K-meter because they are suited for long-term deployments, either in moorings or as drifters (the K-meter would be replaced by a string of Ed sensors). As passive sensors measuring radiometric quantities, they are readily calibrated and are suitable for long-term studies of optical variability, and measurements in support of remote sensing. Similar sensor systems might be used for autonomous, long-term environmental monitoring and impact assessment. The detection of a red tide, both below the surface and in the mixed layer, demonstrates that radiometer/K-meter systems could be useful in early warning systems, for example at aquaculture sites. It seems clear that relatively simple optical instruments can be used to observe biologically induced optical variability in surface waters. However, it remains to be shown how sensitive and accurate the biological interpretations of optical variability can be.

8. ACKNOWLEDGMENTS

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