Application of an Ocean Color Algal Taxa Detection Model to Red Tides in the Southern Benguela

Collin S. Roesler[1], Stacey M. Etheridge[2], and Grant C. Pitcher[3]

[1]Bigelow Laboratory for Ocean Sciences, PO Box 475, West Boothbay Harbor, Maine, 04575 USA
[2]Dept. of Marine Science, University of Connecticut, 1084 Shennecossett Rd., Groton, Connecticut, 06340 USA
[3]Marine and Coastal Management, Private Bag X2, Rogge Bay 8012, Cape Town, South Africa

Abstract

A forward reflectance model is used to demonstrate the sensitivity of hyperspectral ocean color observations to phytoplankton biomass, species composition and cell size. An inverse ocean color model is developed which has explicit terms for 5 taxonomic groups of phytoplankton. The model expresses the contributions of each group in terms of the magnitude of the absorption coefficient, which is proportional to biomass. The model is applied to a time series of reflectance data from an expansive red tide off the west coast of South Africa. The results compare favorably with those derived from microscopic cell counts. This demonstrates the utility of in situ ocean color detection of the composition and concentration of potentially harmful algae.

Introduction

Toxic and harmful algal blooms occur globally and are often associated with discolored water, giving rise to the misnomers 'red tides' and 'brown tides' among others. Until recently, it was thought that the algae responsible for such discolorations contained causative unique pigmentation. However, the taxa responsible for toxic and harmful blooms cannot be distinguished from their non-toxic and non-harmful counterparts based upon their optical properties (Etheridge and Roesler 1998) or their pigment composition, with one minor exception (Millie et al. 1997). This does not however, negate the wealth of information that can be gleaned from the quantitative analysis of ocean color as a tool for the detection of algal species composition (Roesler and Etheridge 1998).

In this paper we demonstrate the sensitivity of the hyperspectral ocean color signal to variations in algal concentration, composition, and size distribution. We present an ocean color inversion model (Roesler and Perry 1995; Roesler and Boss, 2003) modified to quantify the relative contributions of 5 groups of phytoplankton. This model is applied to hyperspectral ocean color spectra collected in the southern Benguela Upwelling System during the onset and development of a red tide event. The derived taxa composition is compared with that obtained from microscopic counts.

Methods

Expansive red tides occur annually along the western coast of South Africa during the latter half of the upwelling season (January–April). While red water is a predictable phenomenon, significant year-to-year variations are observed in bloom dynamics, spatial extent and, in particular, species composition (Pitcher et al., 1998). We sampled the waters off Lamberts Bay, north of Cape Columbine, in March of 2001 during the initiation and development of an expansive red tide that was characterized by significant temporal variations in algal species composition.

A station located 2 nm offshore (~60 m depth) was occupied daily for nearly three weeks. Hyperspectral downward irradiance and upward radiance were measured with a Satlantic HTSRB radiometer buoy between 10h00 and 14h00. Values were corrected for the dark signal at in situ temperatures, and averages were computed over periods of >100 observations where the coefficient of variation was <1%. Upward radiance, measured at a depth of 0.63 m was corrected to the surface using spectral attenuation coefficients derived from upward radiance profiles in the top meter. Spectral reflectance was calculated from the ratio of upward radiance to downward irradiance.

Water samples were collected from the upper meter. Samples were preserved for microscopic enumeration of the phytoplankton . Spectral absorption coefficients were measured spectrophotometrically on the dissolved (<0.7μm) and particulate fractions of each sample. The particulate fraction was further separated by parallel filtration through 5 and 20 μm Supor filters and the total and each size fraction collected on glass fiber filters. Spectral absorption coefficients were determined using the methods and corrections as in Roesler (1998). Phytoplankton absorption was determined by extraction (Kishino et al. 1985).

Taxon-specific absorption spectra were statistically identified based upon co-occurence of distinct pigment absorption features and taxon dominance within a size fraction (0.7-5, 5-20 and >20 µm). The separable taxonomic groups were: diatoms, dinoflagellates, cryptophytes (which were symbiotically associated with *Mesodinium rubrum*), and chlorophytes. *Dinophysis* was further separable from the dinoflagellate group due to statistically significant deviations due to pigment packaging within its size fractionation (Fig. 1A).

The premise of the ocean color inversion model is that the spectral reflectance, R, can be theoretically expressed as a function of the absorption, a, and backscattering, b_b, coefficients (e.g. Gordon et al. 1983):

$$R \approx \frac{b_{bw} + b_{bp}}{a_w + a_\varphi + a_{nap} + a_{CDOM} + b_{bw} + b_{bp}}$$

where the subscripts w, p, φ, CPOM, and CDOM indicate water, particles, phytoplankton, and colored particulate and dissolved matter, respectively, and particulate backscattering includes the influence of both algal and non-algal particles. This model has been recently modified to express the particle backscattering as a function of parameters that have explicit dependence on the particle size spectrum (Roesler and Boss, 2003). We use this expression to generate forward simulations of reflectance as a function of phytoplankton biomass, composition, and size distribution. Inversion of this equation is based upon the approach of assuming spectral shapes for each component and solving for the magnitude of each (Roesler and Perry 1995). In this paper the phytoplankton absorption component is further separated into the 5 algal groups represented by the 5 non-dimensional absorption spectra in Fig. 1A so that the contribution by each can be quantified upon inversion.

Results

Forward ocean color simulations. Forward simulations of ocean color reflectance demonstrate that as algal cell concentrations increase, the magnitude and the spectral shape of the reflectance changes dramatically, darkening (lower magnitude) and shifting in color from blue to red wavelengths (Fig. 1B). The resulting red color is due to selective absorption of the shorter wavelengths and enhanced scattering of the red wavelengths. Phytoplankton are weak absorbers in the red, aside from the chlorophyll a peak, but at high concentrations can effectively scatter red photons before they can be absorbed by water. Thus, as the concentration of phytoplankton increases, the ocean color signal arises from increasingly shallower depths.

Phytoplankton communities, owing to different pigment compositions, yield variable features in reflectance spectra (Fig. 1C). This is seen by eye most dramatically during high algal biomass conditions (~50 µg chl l^{-1}), but can be detected radiometrically or computationally at lower biomass conditions. Perhaps most dramatic are the features associated with cyanobacterial or cryptomonad phycobilipigments and chlorophytic chl b. Potentially the most difficult to distinguish would be diatoms and dinoflagellates due to the spectral overlap between their respective dominant carotenoids, fucoxanthin and peridinin. However, differences are detectable and therefore should be retrievable by inversion.

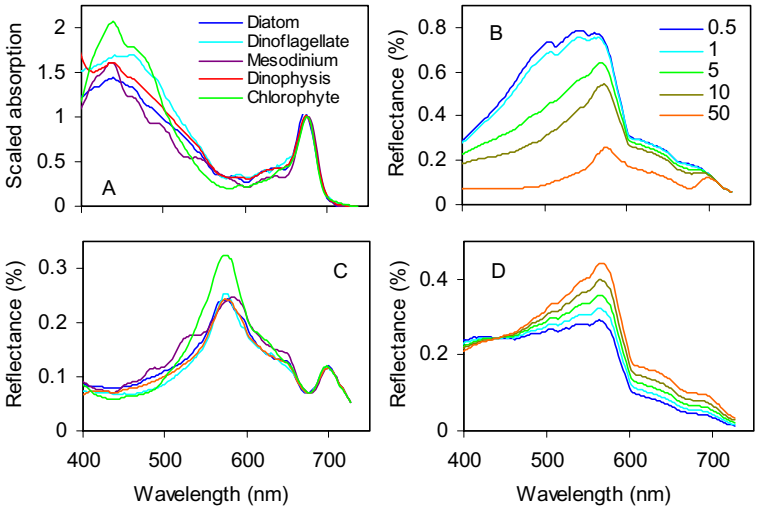

Fig. 1. (A) Scaled taxon-specific absorption spectra for 5 separable groups based upon spectrophotometric analysis of size-fractionated samples and corresponding microscopic species counts. Results of reflectance simulations as a function of (B) algal biomass (µg chl l^{-1}), (C) algal composition at 50 µg chl l^{-1} concentrations, symbols as in part A, (D) particle size distribution, where long wavelength reflectance increases as particle size increases.

Phytoplankton size distributions play an important role in determining ocean color. For example, the pelagophyte *Aureococcus* sp., responsible for brown tides, is a small cell (~2 µm) while many dinoflagellate species responsible for red tides can exceed 25 µm in diameter. The difference in color that can be accounted for solely by changes in size distribution are dramatic (Fig. 1D) and due to the fact that small particles scatter predominantly in the blue wavelengths, while large particles scatter all wavelengths equally or, under very distinct monospecific situations, more in the red wavelengths.

Inverse ocean color model results. Absorption is a biomass-dependent parameter, a function of cell size as well as concentration. Thus, the microscopic counts were converted to biomass to account for cell size differences. Once that was done, the ocean color inversion model yielded estimates of the contribution (to absorption) by each of the taxonomic groups that compared well with those derived from microscopic counts (Fig. 2) over the time series. Some differences are expected owing to differences between in situ versus discrete sampling in a highly patchy environment .

Discussion

By far the most significant impact on spectral reflectance is the concentration of absorbing constituents, particularly algae, with brightness being determined by the magnitude of scattering relative to absorption. The spectral slope of backscattering, in response to variations in particle size distributions, also impacts the shape of reflectance, albeit to a lesser degree than does biomass concentration. These processes both lead to the dramatic changes in ocean color observed during blooms. Subtle variations in the color are primarily driven by pigment composition and it is this process that allows for pigment-based taxonomic identifications via ocean color observations.

The capability to deconvolve these different sources of variation, using reflectance inversion techniques, provides us with the capability for determining not only the algal biomass but additionally the composition and size distribution of the population. While this is still a far distance from species composition, it does allow us to monitor transitions between the major algal groups and community size structure. This is a significant improvement over simply monitoring biomass. The advantage to this approach lies in the potential for remote monitoring of ocean color in sensitive areas to detect changes in the phytoplankton community that are indicative of harmful algal species and/or harmful concentrations.

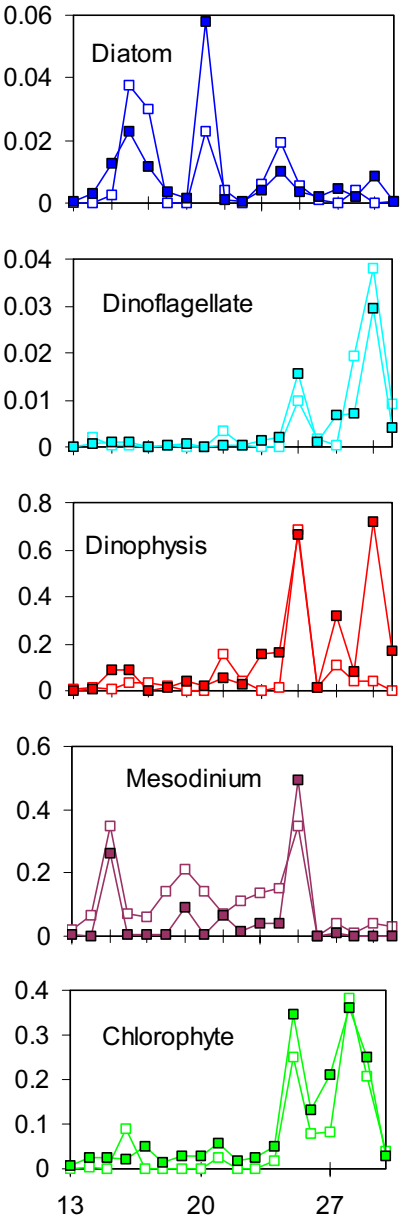

Fig. 2. Absorption at 676 nm for taxonomic groups during the time series: inverse ocean color modeled values (filled) and those based upon microscopic cell counts, cell size and cellular absorption efficiency (open). X-axis is date in March 2001.

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