# A TWO-YEAR TIME SERIES OF CONTINUOUSLY MONITORED INHERENT OPTICAL PROPERTIES IN A EUTROPHIC SUB-ESTUARY OF CHESAPEAKE BAY

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## INTRODUCTION

The optical properties of natural waters are important because they determine the underwater light climate for aquatic plants, they determine the emergent light field available to remote sensing instruments, and they are diagnostic of various stressors, such as eutrophication, affecting surface waters worldwide. Case 1 waters are those in which the optical properties are determined by phytoplankton or factors that covary with phytoplankton, while case 2 waters comprise everything else. Case 1 waters are usually, though not always, associated with open ocean environments (Mobley 1994). Because of the dominance of a single factor determining the optical properties, the optics of case 1 waters are considered to be simpler than case 2 waters and have been well studied.

Interest in the optical properties of case 2 waters has been increasing in recent years (Sydor and Arnone 1997) due to growing concern about loss of water clarity in estuaries and coastal waters and its consequences for shallow water habitats. Optical properties of case 2 waters are substantially influenced by their proximity to terrestrial sources of absorbing and scattering substances which can vary on a wide array of time scales, which may be uncoupled from the seasonal wax and wane of phytoplankton. One motivation for studying the temporal variability of optical properties in Case 2 waters is identifying causes of reduced water clarity so that corrective actions can be prioritized. In addition, the effects of variation in optical properties can be better understood. What is the impact of short term increases in turbidity on light available for submersed aquatic vegetation (SAV)? How much light is available to phytoplankton at the bottom of the mixed layer or water column (Behrenfeld et al. 2001) and what is the penetration of inhibiting UV radiation (Neale 2001)?

Addressing questions such as these requires frequent, repetitive measurements for relatively long periods of time. Here we describe a 2-year time series of inherent optical properties collected in a turbid, eutrophic sub-estuary of Chesapeake Bay. Results indicate that optical properties in such systems are highly variable on a wide range of time scales. Some variability is easily attributable to known events such as phytoplankton blooms, whereas much of the short term variability remains unexplained.

## STUDY SITE

The Rhode River (Maryland, USA) is a small tributary embayment on the western shore of the mesohaline reach of Chesapeake Bay. The system is shallow (mean depth 2 m, maximum depth 4 m), turbid, and eutrophic (mean summer chlorophyll concentration = 20 to 40 mg $m^{-3}$). Salinity varies seasonally and spatially from 0 to 14 psu at the

upstream stations and from about 2 to 20 psu at the mouth, depending on flow of the Susquehanna River, the main freshwater source to the upper Chesapeake Bay. The mean tidal range is 30 cm, but wind and barometric pressure gradients frequently cause much larger changes in water level.

## MATERIALS AND METHODS

Spectral absorption [$a(\lambda)$] and attenuation [$c(\lambda)$] coefficients were measured at 9 wavelengths, 412, 440, 488, 510, 532, 555, 650, 676, and 715 nm, using a flow-through absorption-attenuance meter (ac9, Wetlabs). Three different ac9 units, of pathlengths 10 or 25 cm, have been used in this work, and they are not distinguished from one another in analysis of the data. Flow to the ac9 was by gravity feed. Water from the estuary was pumped into an open topped polyvinyl chloride (PVC) cylinder with a return arm to provide a constant head. A spigot and tubing located near the bottom of the cylinder conducted water past a bubble trap standpipe to the ac9. A Wetlabs MPak was used to control the ac9 and log the data. Once per hour the ac9 was turned on, allowed to warm up for 5 min, and sampled for 1 min at 6 hz.

The PVC cylinder, ac9, and MPak were housed in a monitoring shed at the end of the Smithsonian pier on the Rhode River. To reduce fouling within the cylinder, the pump was operated only 15 minutes per hour, extending from about 10 min before to 5 min after sampling by the ac9. At the conclusion of a sampling cycle, a solenoid valve was opened that allows about 60 ml of bromide solution to flow through the standpipe and ac9 to reduce growth of fouling organisms on the optical surfaces of the ac9. Timing of the pump and solenoid valve were controlled by a Campbell Scientific CR10 data logger and control module. The bromide solution flushed through the system without standing in the optical tubes between readings. Therefore no residual bromide absorption signal could be detected in the readings.

The system was cleaned and data downloaded three times per week. When cleaning, the water from a measurement cycle was collected before disconnecting power to the ac9, and run through the unit after cleaning to determine the increase in measured absorption and attenuation due to fouling. The measured readings were corrected for this increase by assuming it accumulated either linearly (late fall through mid-spring) or exponentially (late spring through mid-fall). Inappropriate application of a linear correction resulted in calculation of negative coefficients.

On several occasions we mounted one of the ac9's on a boat to map spatial distributions in surface optical properties (see e.g., Claustre et al. 2000). Water was pumped from a through-hull pump on a 13-m workboat into an open-topped PVC cylinder similar to that in the fixed station monitoring shed. Water flow through the ac9 and data logging was similar to that in the fixed station, except that flow and logging was continuous. A global positioning system receiver logged latitude and longitude coordinates simultaneously.

Absorption coefficients measured by the ac9 overestimate true absorption coefficients due to incomplete collection of scattered photons in the reflective tube (Kirk 1992). The loss is considered to be proportional to the scattering coefficient (Kirk 1992). Correction for the scattering loss takes the form,

$$a_{t-w}(\lambda) = a_m(\lambda) - \varepsilon[c(\lambda) - a_m(\lambda)] \quad (1)$$

where $\lambda$ is the wavelength of light, $a_{t\text{-}w}(\lambda)$ is the total ($t$) absorption coefficient less that due to water ($w$), $a_m(\lambda)$ is the measured absorption coefficient, $c(\lambda)$ is the beam attenuation coefficient, and $\varepsilon$ is a coefficient that depends on the shape of the scattering phase function and on properties of the ac9 (Kirk 1992). We estimated $\varepsilon$ by a matrix inversion procedure that simultaneously estimated the contribution of the different components of total absorption,

$$a_{t-w}(\lambda) = a_g(\lambda) + a_\phi(\lambda) + a_{p-\phi}(\lambda) \quad (2)$$

where $a_g(\lambda)$ is the absorption due to colored dissolved organic matter (CDOM), $a_\phi(\lambda)$ is the absorption due to phytoplankton, and $a_{p\text{-}\phi}(\lambda)$ is the absorption due to non-algal particulate matter.

The complete solution for the components of absorption is given by Gallegos and Neale (2002). Briefly, the procedure estimates scale factors for the normalized absorption spectra,

$$g(\lambda) = \frac{a_g(\lambda)}{a_g(440)} \quad \phi(\lambda) = \frac{a_\phi(\lambda)}{a_\phi(676)} \quad p(\lambda) = \frac{a_{p-\phi}(\lambda)}{a_{p-\phi}(440)} \quad (3)$$

where $g(\lambda)$, $\phi(\lambda)$, and $p(\lambda)$ are, respectively, the normalized absorption spectra for CDOM, phytoplankton pigment, and non-pigmented particulates. In general, $p(\lambda)$ closely resembles $g(\lambda)$, making differentiation between absorption by CDOM and that by non-algal particulates difficult (Roesler et al. 1989). We can improve the discrimination between $a_g(\lambda)$ and $a_{p\text{-}\phi}(\lambda)$ by noting that particulate matter contributes to scattering coefficient, but CDOM does not. We then represent absorption by non-algal particulate matter as

$$a_{p-\phi}(440) = \rho b(440) \quad (4)$$

where $\rho$ is the absorption-to-scattering ratio at 440 nm, and $b=c-a$ is the scattering coefficient. We developed a site-specific statistical model to estimate $\rho$ from ac9 measurements (Gallegos and Neale 2002). Substitution of (4) and (3) into (2) and (1) gives a system of linear equations which we solve for the vector of coefficients, $[a_g(440), a_\phi(676), \varepsilon]^T$, by matrix inversion.

## RESULTS AND DISCUSSION

The system produced 10,462 measurements of spectral absorption and attenuation coefficients from January 2000 through September 2001. Excluding days that the system was not operated due to threat of ice (91 days between the two winters), gross efficiency of data collection was approximately 80 percent. Data loss was due to a combination of

occasional recorder failure, loss of power, and quality-control rejection of data contaminated by entrainment of bubbles.

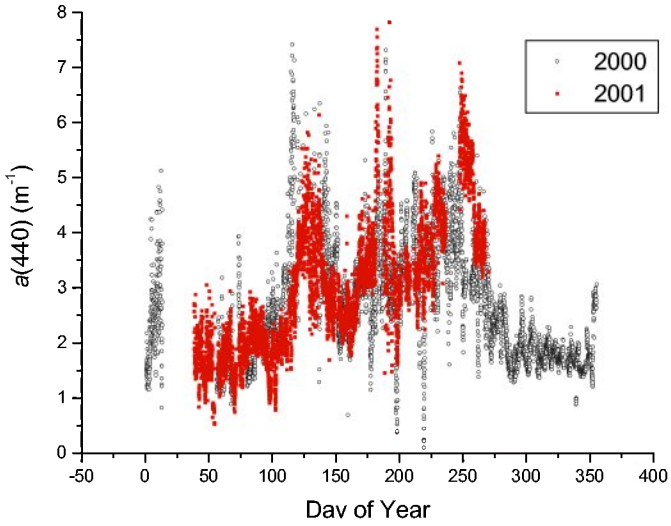


***Figure 1. Time series of absorption coefficient at 440 nm monitored by a WETLabs ac9 at the Rhode River, Maryland (USA).***

A seasonal plot of the absorption coefficient at 440 nm, $a_{t\text{-}w}(440)$, for the two years superimposed reveals both seasonal patterns and interannual differences in absorption coefficient (Fig. 1). In each year there was a period of relatively high absorption due to the spring bloom centered about day 125 (May 5). The magnitude of the spring bloom in 2000 exceeded that in 2001, as confirmed by measurements of chlorophyll and cell counts (Gallegos and Jordan 2002, Gallegos unpublished). However, the spring blooms occurred at very nearly the same time in each year. In each year there was a relative minimum in absorption in June (ca. day 150), followed by generally rising, though highly variable coefficients from June through August (ca. day 240, Fig. 1). Summertime absorption coefficients were similar between the two years (Fig. 1). The highest sustained absorption coefficients in the record occurred in September 2001. Absorption coefficients declined steadily from late September through October, and remained relatively low and less variable through November and December (Fig. 1).

The overall seasonal pattern in scattering coefficients was similar, in that *b* was high during the spring bloom, followed by a period of lower values in June, and steadily rising values during the summer and peaking in early fall (Fig. 2). However, unlike absorption coefficients, scattering coefficients were consistently higher in 2000 than in 2001. The higher scattering coefficients in 2000 are not easily attributed to the higher spring bloom in that year, since the scattering coefficients prior to the bloom were also higher in 2000 than

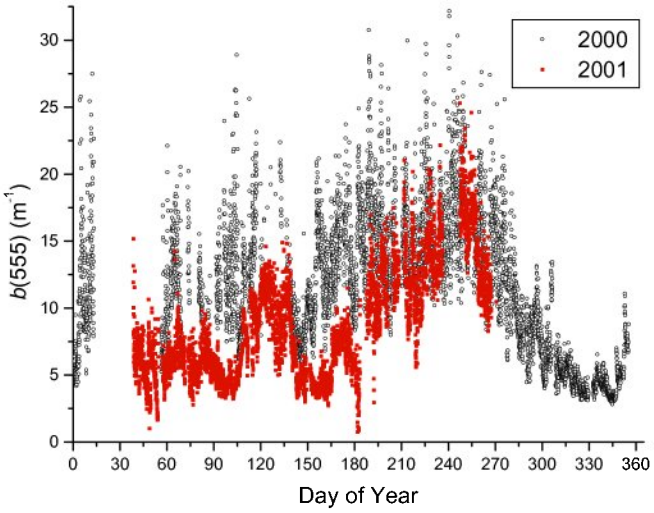


***Figure 2. As Fig. 1, for scattering coefficient at 555 nm.***

in 2001. This pattern coincides with observations of generally higher concentrations of total seston and higher in situ turbidity through the spring and summer of 2000 compared with 2001 (unpublished data).

It is evident from Figs. 1-2 that there was a substantial degree of variability in both absorption and scattering coefficients on relatively short time scales. Closer examination of brief periods during the summer of 2000 when trends were not pronounced indicates that much of the short term variability was at a 4-7 day time scale (Fig. 3). Temporal variability in inherent optical properties occurred on similar time scales as variations in atmospheric pressure; but the phase relationship between the series changed during the period, so causality cannot be inferred. The passage of weather systems that drive changes in atmospheric pressure simultaneously affects winds, currents, and water level, so that any relationship with in situ optical properties is expected to be complex and variable.

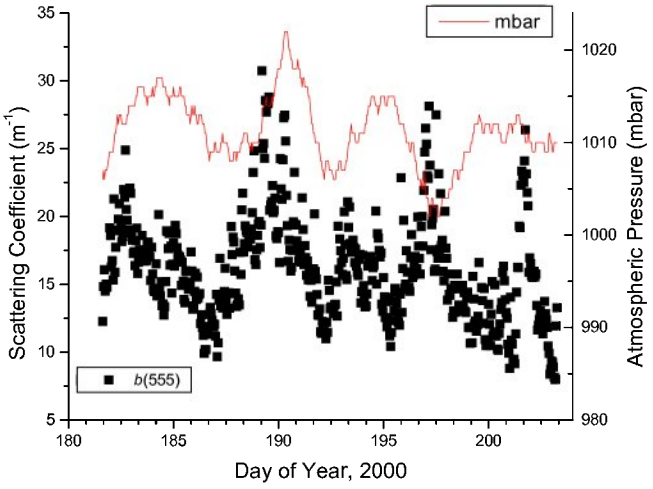


***Figure 3. Twenty-three day time series of scattering coefficient at 555 nm and atmospheric pressure during summer 2000.***

Substantial variability in absorption and scattering coefficients also occurred on semi-diurnal time scales (Fig. 4). The short term variability, however, was not coherent with measurements of water level (Fig. 4). We believe this is due to the nature of the spatial gradients in optical properties. Spatial distributions of optical properties in the Rhode River mapped with the ac9 (Fig. 5) showed steep tidal convergence fronts with high surface concentrations of particulate matter. Fronts such as this can advect past the fixed monitor on either rising or falling tides, so that variations in continuously monitored optical properties bear no fixed relationship with water level (Fig. 4).

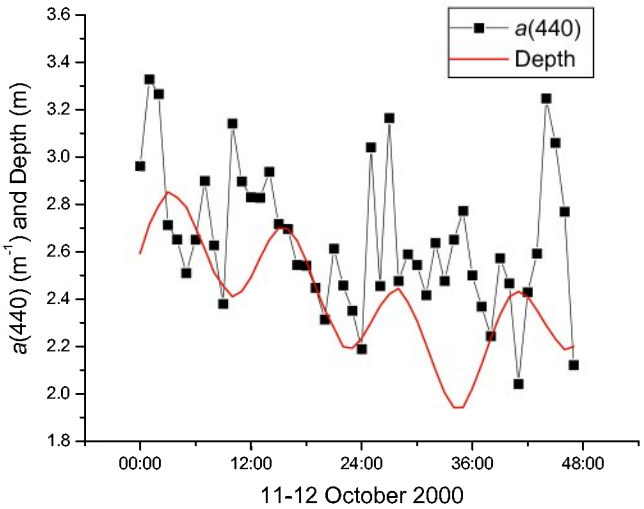


***Figure 4. Short term variation of absorption coefficient and water level, showing substantial variability on semi-diurnal time scales.***

The estimated components of absorption are shown in Fig. 6. In 2000 the absorption by CDOM estimated by the inversion

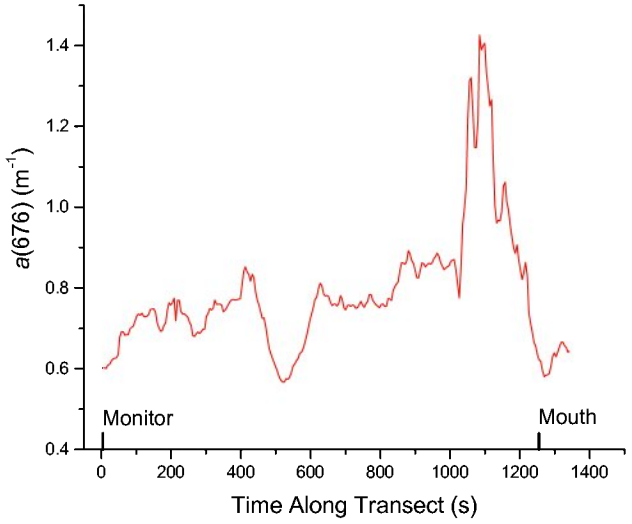


***Figure 5. Absorption coefficient at 676 nm along a transect from the location of the monitoring station to the mouth of the Rhode River, June 29, 2001. Total distance of transect is about 4 km.***

algorithm agreed with measurements, but in 2001 the algorithm consistently overestimated absorption by CDOM (Fig. 6a). We suspect that the site-specific statistical model for ρ, developed primarily using samples from 1999 and 2000, may have systematically underestimated ρ [and hence overestimated $a_g(440)$] in 2001 (Fig. 6b).

In both years the increase and decrease in chlorophyll absorption due to the spring dinoflagellate bloom was apparent (see e.g. Gallegos and Jordan 2002), though it was better resolved in 2001 than in 2000 (Fig. 6c). Occasional short lived blooms were detected at other times as well.

Absorption by non-algal particulate matter was also high and variable, constituting the main absorption component during most of the summer months (Fig. 6d). The late summer peak in absorption by non-algal particulate matter (Fig. 6d) coincided with the seasonal maximum in scattering coefficient (Fig. 2). This seasonal pattern in particulate absorption and scattering is similar to the seasonal pattern in measured concentrations of total suspended particulates in this segment of the Rhode River (Jordan et al. 1991). The peaks in inherent optical properties and in concentrations of particulate matter occurred well after the cessation of sediment inputs from the local watershed, and indeed, most storm derived sediments are trapped in the subtidal mudflats up-estuary of the monitoring location (Jordan et al. 1986). The timing of the peak in particulate absorption and scattering together with the rapid decline in the fall suggest autochthonous biological processes as the source of this particulate matter. In situ growth of heterotrophic plankton and biologically mediated increased susceptibility to resuspension of bottom sediments (i.e. bioturbation or formation of a flocculent benthic boundary) could contribute to this pattern.

## CONCLUSIONS

As with others who have deployed ac9's for long term monitoring in oceanic settings (e.g. Chang and Dickey 1999), we found that inherent optical properties in a turbid, eutrophic sub-estuary are highly variable on event time scales. Some features were readily attributable to known events, such as the spring bloom (Fig. 6), whereas short term changes appeared to be driven by movement of steep spatial gradients that are not well correlated with ancillary measurements (Fig. 3).

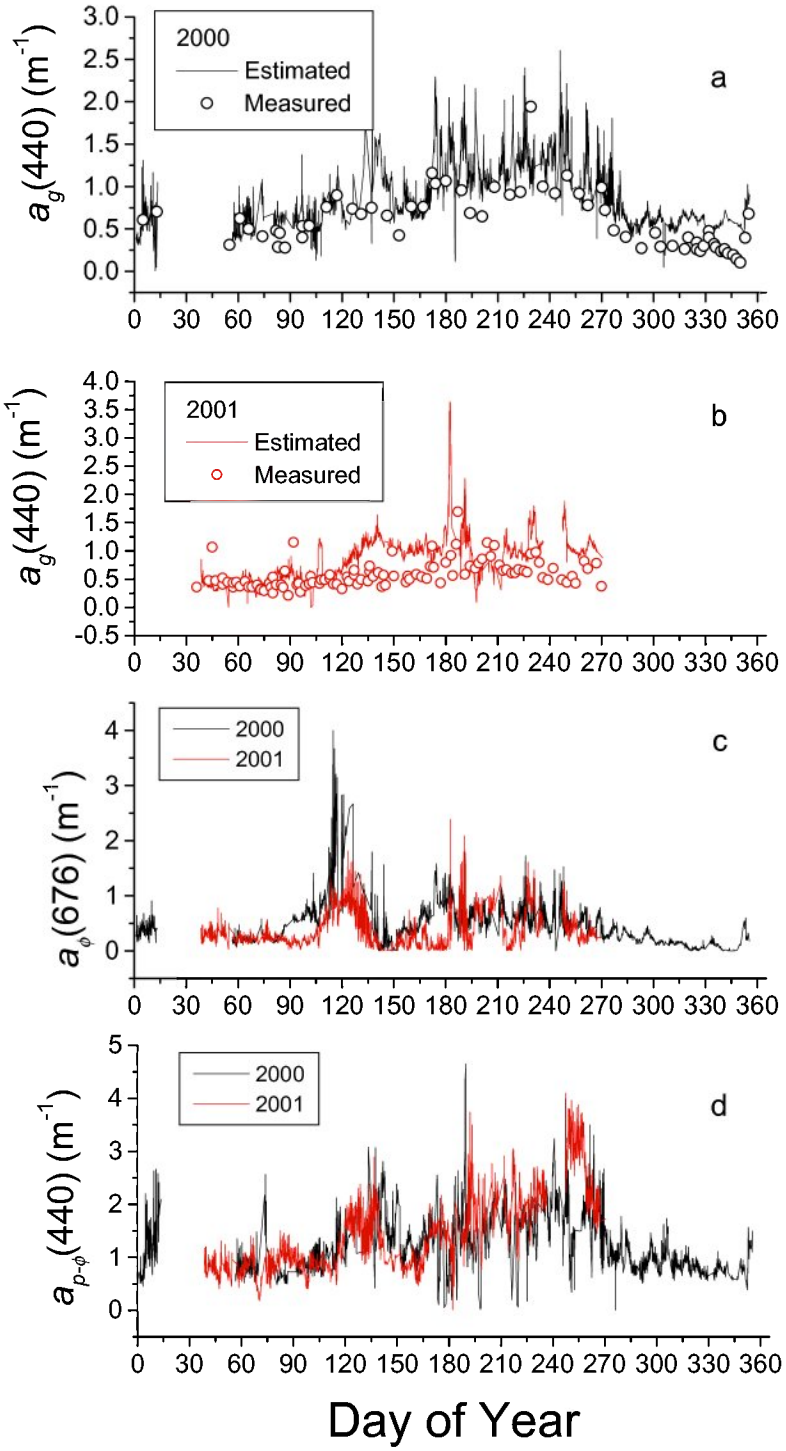


***Figure 6. Estimated components of absorption from continuously monitored ac9 data. Measurements of absorption by CDOM are compared with estimates in (a) 2000, and (b) 2001. Absorption by phytoplankton (c) is dominated by the spring bloom, and absorption by non-algal particulate matter (d) by a gradual build-up in the summer.***

Absorption and scattering coefficients had similar seasonal variations. The main features of the seasonal variation in inherent optical properties in the Rhode River were the spring bloom, a local minimum in early summer, a maximum in particulate absorption and scattering in late summer, and a steady decline in late fall. Spring blooms

vary in magnitude from year to year depending on timing and magnitude of nutrient inputs from the spring freshet of the Susquehanna River (Gallegos et al. 1997, Gallegos and Jordan 2002), the main freshwater source to upper Chesapeake Bay. The summertime increase in non-algal particulate absorption and scattering, however, appeared fairly consistent between the two years. The processes governing this increase, however, remain to be determined.

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