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Response of Underwater Light Transmittance in the Rhode River Estuary to Changes in Water-Quality Parameters

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ABSTRACT: A year-long study of incident and underwater light transmittance (400–800 nm) in the Rhode River, Maryland, a tidal tributary to Chesapeake Bay, indicated that light transmittance responded in both intensity and spectral quality to changes in the amount and type of dissolved and suspended materials in the water. At times of relatively clear water, transmittance was similar to that previously reported in the literature for coastal waters. With high concentrations of suspended and dissolved materials in the water, attenuation of irradiance was high in the upper part of the water column and different for the various wave bands, depending on the type of material present. At such times, attenuation was higher in the upper part of the water column under sunny, clear skies than on cloudy days. We believe this to be due to higher concentrations of pigments and suspended particles in the water on sunny days, increasing the scattering and adsorption. A second factor was a lower average cosine on cloudy days, decreasing the effect of scattering on the average path length per meter of depth. High attenuation coefficients in the middle of the spectrum are attributed to accessory pigments. Regression of the diffuse attenuation coefficient on eight water-quality parameters explained up to 93% of the variance in the attenuation coefficient. Chlorophylls *a* and *c* and mineral suspensates were the three most important variables for data taken under clear skies. In contrast, under cloudy skies, the three most important variables were different for different wavelengths. Models of irradiance attenuation in turbid estuarine waters require the use of more variables than models for open ocean waters.

Introduction

Few data have been published on the penetration of solar radiation through turbid estuarine waters in contrast to that for clear open ocean water. This is surprising because many biologists consider light to be one of the limiting factors in estuarine primary productivity (Macalaster et al. 1983; National Research Council 1983). High turbidity, a normal condition in most estuaries, limits light penetration and changes the spectral character of the underwater light from that incident upon the water surface. Thus, much of the primary productivity in turbid estuaries is due to phytoplankton.

Interpretation of the causes of spectral changes occurring in turbid waters is much more difficult than for clear oceanic waters (Duntley 1963). The large number of suspended particles causes multiple scattering and reflection, while high concentrations of dissolved organics and photosynthetic pigments attenuate selected parts of the spectrum by absorption.

This paper reports on the transmittance of solar radiation into and through the water column of the Rhode River estuary, a tidal

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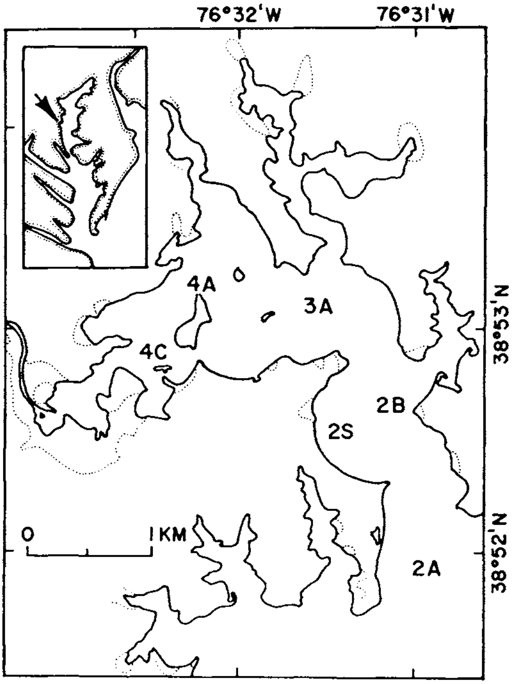

Fig. 1. Map of Rhode River showing locations of sampling stations.

tributary to Chesapeake Bay in Maryland. We attempt to explain some of the spectral changes and energy losses through the water column as a function of changes in water-quality parameters.

Sampling Area

The Rhode River estuary is a small (485 ha) tributary to Chesapeake Bay, located along the western shore in the upper part of the Bay (Fig. 1). Mean depth is 2 m, with the maximum depth approaching 5 m. Salinity at the junction with Chesapeake Bay ranges from less than 5 to over 20 ‰; at the head, from near 0 to 17‰. Water exchange is controlled by the larger Bay and, because of the shallow depth of the Rhode River, exchange is primarily with the surface waters of the Bay. Astronomic tidal ranges are small, less than 35 cm, although meteorological tides are much larger, up to 2.41 m during the period of 1970–1978 (Cory and Dresler 1980).

Methods

Incident and underwater irradiance were measured with a portable spectral radiometer, which receives light from 180°, through a cosine-corrected collector, built and calibrated by the Smithsonian Environmental Research Center (Goldberg et al. 1985). The collector is constructed of teflon, an excellent diffuser. Calibration of the radiometer against a referenced standard of the National Bureau of Standards indicates an accuracy of ±3% with a stable light source. Irradiance was measured in eight spectral bands, isolated by means of interference filters, from 400–800 nm, each band approximately 50 nm in width. Measurements were made 3.5 m from the boat on the sun side.

Concurrent with the radiometer measurements, we recorded chlorophyll *a* fluorescence at ½ m depth increments through the water column and made a transmissometer profile, using a Martex transmissometer with a 500–550 nm band pass and a ½-m path length.

Water samples were taken at both the surface and near the bottom at all stations on all cruises; samples were taken also where a break, if present, occurred in the transmissometer profile. Water samples below the surface were taken with 5-l Van Dorn bottles.

These samples were analyzed for bacterial and phytoplankton populations by enumeration; for chlorophylls *a, b, c,* and carotenoids by extraction of the pigments from filterable solids retained on glass-fiber filters and determination of absorbance at selected wavelengths (Strickland and Parsons 1972; Jeffrey and Humphrey 1975; Shoaf and Lium 1976). Total suspended material (TSM) and mineral suspensates (MSM) were determined by filtration through 0.6 μm nominal-pore-size filters, gravimetric determination of the weight gain of the filter, firing to destroy the filter and organic material, and reweighing the residue. Total and dissolved organic carbon were determined by potassium dichromate-sulfuric acid oxidation of whole and filtered samples with back titration of the residual dichromate solution.

Forty-one cruises were made on the Rhode River between 13 May 1980 and 12 May 1981, a weekly sampling plan except when the estuary was frozen. Five stations were occupied on each cruise. After 31 March

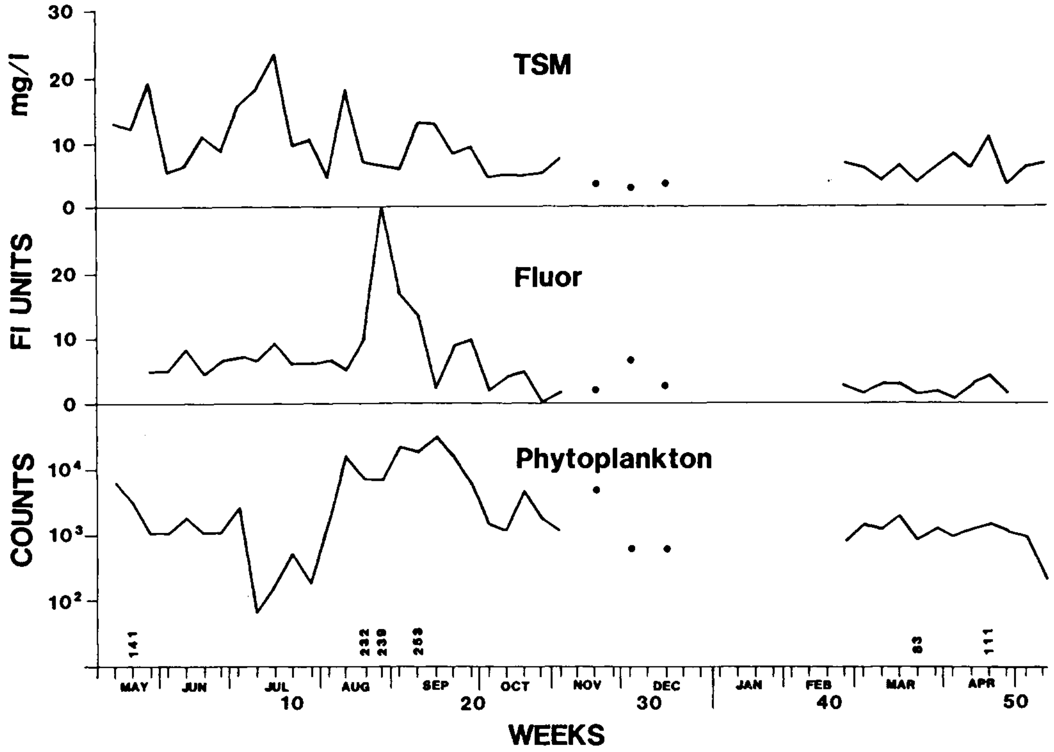

Fig. 2. Plot of total suspended material (TSM), *in vivo* fluorescence, and phytoplankton counts in surface water at station 2A for the sampling year (13 May 1980 through 12 May 1981).

1981, we occupied station 2S in addition to the other five stations (Fig. 1).

Irradiance, in μW cm^{-2}, was calculated from the portable radiometer data using calibration constants derived by comparison against a standard lamp. The instrument was calibrated seven times during the year-long project, with little change occurring in the calibration constants. From these energy values, we calculated the diffuse attenuation coefficient for downwelling spectral irradiance, $K_d(\lambda)$, from (Jerlov 1976; Smith and Baker 1981)

$$E_d(\lambda, Z_2) = E_d(\lambda, Z_1)e^{-K_d(Z_2-Z_1)}$$

where $E_d(\lambda, Z_1)$ is the irradiance for a spectral band λ at depth Z_1, and $E_d(\lambda, Z_2)$ is the irradiance remaining after passing through thickness $(Z_2 - Z_1)$.

Results

WATER-QUALITY PARAMETERS

The normal situation in the Rhode River is a decrease in weight concentrations of mineral suspensates from the head of the estuary to its junction with Chesapeake Bay. Differences between the head and mouth are most pronounced during the spring, at the time of high freshwater discharge, and less pronounced in the fall and winter. During 1980, this normal course of events occurred with decreasing amounts of mineral suspensates during the year (Fig. 2). Phytoplankton numbers increased, peaking on 9 September, then decreasing till the end of the year with a range between 30 and 87,000 counts ml^{-1} (Fig. 2). Concentrations of suspensates in 1981 did not attain the 1980 levels (Fig. 2) because of low freshwater discharge beginning in late 1980 and continuing into 1981. A much higher proportion of the suspensates was more biologic in origin in 1981 than 1980.

For consecutive weeks in 1980, concentrations of suspensates were often higher in surface waters when the skies were clear than when cloudy conditions prevailed. Average values for total suspensate concentration

TABLE 1. Average and standard deviations of concentrations of total suspended material (TSM) and *in vivo* fluoresence of data acquired under clear and cloudy skies for 1980 and 1981. Student t-tests are for significance of difference between averages with degrees of freedom as shown (n1 + n2 − 1).

	TSM	n	t	Fluor	n	t
1980						
Cloudy	9.04 ± 5.30	47	3.03[1]	5.63 ± 4.09	34	4.27[1]
Clear	13.58 ± 9.43	80		9.52 ± 4.51	72	
1981						
Cloudy	5.61 ± 1.97	17	1.83	2.15 ± 1.17	10	3.32[1]
Clear	6.86 ± 2.55	46		3.34 ± 0.93	32	

[1] Significant at the 0.05 level.

(TSM) and *in vivo* fluorescence in surface waters showed that both were significantly higher (at the 0.05 level) on sunny days than on cloudy days in 1980 (Table 1). There was also a significant difference in the average of *in vivo* fluorescence readings for 1981 relative to sky conditions.

UNDERWATER RADIOMETER MEASUREMENTS

The change in concentrations and the relative proportions of suspended particles and photosynthetic pigments caused drastic changes in the amount of radiation, as well as its spectral character, reaching the floor of the estuary. At times of high concentrations of suspensates, much of the diffuse water-column attenuation and spectral change occurred in the uppermost part of the water column.

There was little difference in the spectral character of the incident irradiance between cloudy and sunny skies. On the other hand, the magnitude of the incident irradiance, on the average, was about three times higher on clear days than on cloudy days.

The average depth to which 1% of the measured incident irradiance, E_o (400–800 nm), penetrated was 1.79 m for the period of May through September, 1980. As the water became clearer later in 1980, this average depth increased to 3.53 m (October through December) and further to 3.87 m in 1981 (February to May, 1981). The average depths of penetration for late 1980 and 1981 are extrapolated, for the most part, by using the diffuse attenuation coefficient of the lower most 0.5 m of the water column, since the estimated depths are deeper than most of the estuary. This increase in depth of penetration for 1% of E_o during the latter part of the study period reflects the reduction of suspensates and pigments in the water (Fig. 2).

The depth to which 1% E_o penetrated and the percentage of E_o at 1 and 2 m depths were significantly greater (0.05 level) under cloudy skies than clear skies in 1980, but no significant differences in penetration under different sky conditions existed in 1981. These differences in light penetration mimic those for the water-quality parameters and, although highly suggestive, do not uniquely specify the cause of the attenuation.

During the course of the year of sampling, there was a change in the spectral character of the downwelling irradiance, E_d. Throughout the year, an average of about 24% of E_d at 1 m was in the 550–600 nm band and, although day-to-day variations occurred, the relative amount of E_d in this band remained fairly constant. The greatest changes in the spectral quality of E_d were present in the two ends of the spectrum (400–500 nm and 700–800 nm) and occurred between the times when the water was very turbid and those later periods when the water was clearer. The shorter wavelengths (400–500 nm) had a higher percentage of E_d when the water was less turbid (late 1980, 1981). When turbid conditions prevailed, more of the energy in the shorter wavelengths was attenuated and the longer wavelengths (650–800) contributed a larger percentage to the total E_d. This shift has been noted by Kirk (1980) for turbid Australian lakes and may be analogous to the "orange" shift found by Champ et al. (1980).

The averages of the spectral diffuse attenuation coefficients, $K_d(\lambda)$, for the entire water column were significantly larger under clear skies than cloudy for 1980; no significant

TABLE 2. Average values of diffuse attenuation coefficient for spectral irradiance, $K_d(\lambda)$, under clear and cloudy skies. Student *t*-tests for significance of differences in average values under different sky conditions for three periods of year.

Time Period (DAY)	Average $K_d(\lambda)$ m^{-1} for Spectral Band							
	425	475	525	575	625	675	725	775
134–274 1980								
Cloudy	2.10 ± 0.42	2.31 ± 0.43	1.98 ± 0.39	1.74 ± 0.59	1.83 ± 0.50	1.94 ± 0.47	1.91 ± 0.25	3.82 ± 1.99
Clear	2.53 ± 0.54	2.91 ± 0.52	2.43 ± 0.38	2.14 ± 0.38	2.20 ± 0.38	2.36 ± 0.37	2.41 ± 0.29	3.62 ± 0.57
t	3.52[1]	5.02[1]	4.86[1]	3.63[1]	3.63[1]	4.30[1]	7.43[1]	0.68
df	77							
281–351 1980								
Cloudy	1.45 ± 0.29	1.30 ± 0.34	0.95 ± 0.33	0.81 ± 0.30	0.91 ± 0.25	1.15 ± 0.22	1.57 ± 0.20	2.90 ± 0.17
Clear	2.00 ± 0.28	1.92 ± 0.40	1.47 ± 0.38	1.19 ± 0.32	1.24 ± 0.30	1.46 ± 0.29	1.76 ± 0.26	3.32 ± 0.38
t	5.16[1]	4.56[1]	3.98[1]	3.31[1]	3.27[1]	3.33[1]	2.62[1]	4.14[1]
df	28							
056–132 1981								
Cloudy	1.72 ± 0.34	1.39 ± 0.30	1.00 ± 0.18	0.82 ± 0.20	0.92 ± 0.19	1.19 ± 0.17	1.61 ± 0.20	2.97 ± 0.46
Clear	1.61 ± 0.31	1.42 ± 0.37	1.04 ± 0.36	0.84 ± 0.28	0.92 ± 0.26	1.15 ± 0.26	1.60 ± 0.24	3.02 ± 0.33
t	1.15	0.01	0.42	0.26	0.00	0.56	0.15	0.45
df	50							

[1] Significant at the 0.01 level.

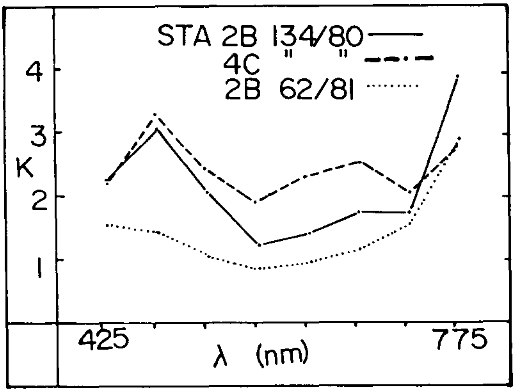

Fig. 3. Plot of $K_d(\lambda)$ m^{-1} vs. λ for entire water column at stations 2B and 4C on 13 May 1980 (Day 134) and at station 2B on 2 March 1981 (Day 62).

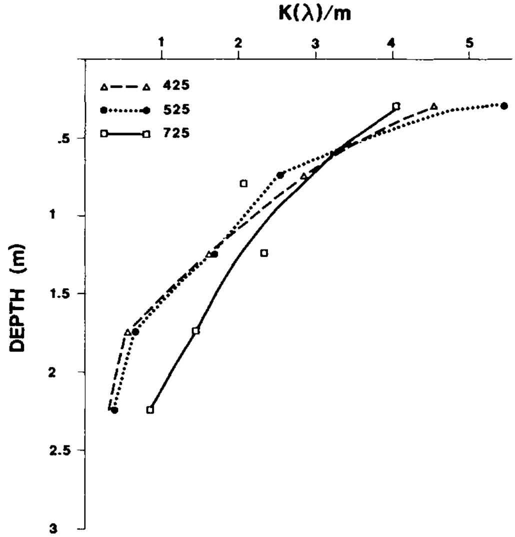

Fig. 4. Changes in $K_d(\lambda)$ m^{-1} with depth at station 2A for three wave bands on 26 August 1980.

differences in the average $K_d(\lambda)$ were present for the data taken in 1981 (Table 2). The largest single values for $K_d(\lambda)$ coincided with high concentrations of phytoplankton, but not necessarily with the highest gravimetric concentrations of suspended particles.

The spectral diffuse attenuation coefficients through the entire water column in 1980 were much higher than many values for coastal oceanic waters reported in the literature, although reasonable for turbid estuarine and fluvial systems. Our values are within the ranges reported by Kirk (1979) for turbid lakes of southeastern Australia and those reported by Champ et al. (1980) for Chesapeake Bay.

Through the spring and summer of 1980, considerably more variation in $K_d(\lambda)$ was found among stations on a given day, among days at a given station, and through the water column at a given station on a given day. Several departures occurred during 1980 from the normally expected relationships among the spectral diffuse attentuation coefficients. During much of 1980, K_d (475 nm) was often greater than K_d (425 nm) (Fig. 3). This was most pronounced when carotenoid levels were high compared to Chl *a*. With normal or high levels of Chl *a*, attenuation in the 425 nm band was higher than in the 475 nm band. K_d (675 nm) was often larger than K_d (725 nm) at selected depth intervals in the water column, indicating absorption by Chl *a*. On the days when high chlorophyll concentrations were present, this relationship held for the entire water column. In contrast, the relationships among the spectral diffuse attentuation coefficients were nearly as expected during 1981.

Concentrations of photosynthetic pigments were very high in late summer 1980, resulting in very low light transmission through the water column. Diffuse attenuation coefficients were high in the surface waters (>2.5 m^{-1} for the least-attenuated 600–650 nm spectral band). Below the surface waters, diffuse attenuation was highest in the middle bands (with the exception of the 750–800 nm band). This situation held for at least 5 wk in the late summer when chlorophyll concentrations averaged 77 μg Chl *a* l^{-1}, culminating on 26 August with values of 216 μg Chl *a* l^{-1}. Gravimetric concentrations of suspended solids at this time were slightly less than the average for 1980 (Fig. 2); phytoplankton populations consisted of dinoflagellate and cryptomonad species.

Transmission of irradiance through the water column during this period of high pigment concentrations was not as expected, with considerable change through the water column. High attenuation was present in all eight spectral bands in the near-surface waters. Below the surface layers, the least change occurred in the 750–800 nm band, for which detectable energy did not pene-

TABLE 3. Simple (Rs) and multiple linear regression (Rm) correlation coefficients of $K_d(\lambda)$ regressed vs. eight independent variables for subset of data taken under clear skies. Abbreviations for Tables 3 and 4: Chl *a* = chlorophyll *a*; Carot = carotenoid pigments; OSP = organic suspensates; POC = particulate organic carbon; Chl *b* = chlorophyll *b*; DOC = dissolved organic carbon.

Wavelength											
425			475			525			575		
	Rs	Rm		Rs	Rm		Rs	Rm		Rs	Rm
MSP	.70	.70	MSP	.68	.68	Chl *a*	.65	.65	Chl *a*	.71	.71
Chl *a*	.41	.78	Chl *a*	.55	.84	MSP	.63	.87	MSP	.58	.88
Chl *c*	.16	.82	Chl *c*	.28	.88	Chl *c*	.38	.91	Chl *c*	.46	.91
OSP	.68	.83	Carot	.52	.90	Carot	.62	.92	Carot	.68	.92
Carot	.37	.83	POC	.35	.90	POC	.32	.92	POC	.34	.93
DOC	.20	.84	DOC	.22	.90	OSP	.61	.92	DOC	.11	.93
POC	.34	.84	OSP	.66	.90	Chl *b*	.15	.92	OSP	.58	.93
Chl *b*	.22	.84	Chl *b*	.20	.91	DOC	.17	.92	Chl *b*	.16	.93
625			675			725			775		
	Rs	Rm		Rs	Rm		Rs	Rm		Rs	Rm
Chl *a*	.73	.73	Chl *a*	.75	.75	MSP	.66	.66	MSP	.57	.57
MSP	.55	.88	MSP	.55	.89	Chl *a*	.59	.85	Chl *a*	.44	.69
Chl *c*	.49	.91	Chl *c*	.51	.92	Chl *c*	.32	.89	Chl *c*	.22	.72
Carot	.70	.92	Carot	.72	.93	Carot	.56	.90	Carot	.42	.74
POC	.35	.92	OSP	.56	.93	POC	.34	.91	DOC	.05	.74
OSP	.58	.92	POC	.31	.93	Chl *b*	.24	.91	OSP	.47	.74
DOC	.14	.92	Chl *b*	.10	.93	DOC	.19	.91	Chl *b*	.16	.74
Chl *b*	.16	.92	DOC	.17	.93	OSP	.63	.91	POC	.22	.74
n = 116											

trate to more than 1.5 m. The diffuse attenuation coefficients for three of the spectral bands (400–450, 500–550, and 700–750 nm) consistently decreased down through the water column, with high $K_d(\lambda)$ values at the surface (Fig. 4). Between 2 and 2.5 m, the $K_d(\lambda)$ of the 400–450 and 500–550 nm bands appear to be asymptotic to about 0.35 m^{-1} and the 700–750 nm band to about 0.85 m^{-1}. This is a diffuse transmittance of 70% and 43%, respectively, over a 1-m path length. The diffuse attenuation coefficients for the three middle bands (550–600, 600–650, and 650–700 nm) changed little through the water column. These changes in attenuation of irradiance through the water column were very pronounced under clear-sky conditions and, although present, were subdued under cloudy skies.

DATA ANALYSIS

Step-wise multiple linear regressions were performed to relate changes in the diffuse spectral attenuation coefficient, $K_d(\lambda)$, to eight water-quality parameters. The attenuation coefficients for each band were used as dependent parameters and regressed on eight independent water-quality variables. Previously published studies have investigated the relationship of the optical properties of the water to chlorophyll (Wilson and Kiefer 1979; Kiefer and Soo Hoo 1982; and many others) or up to five water-quality variables (Bukata et al. 1981). We used eight water-quality parameters because of the prominence of pigments other than chlorophyll *a* (carotenoids were measured) and the high concentrations of suspensates, both mineral and organic. The independent variables were chlorophyll *a, b,* and *c,* total carotenoids, mineral suspensates, organic suspensates, dissolved organic carbon, and particulate organic carbon. These variables are not completely independent of each other. We also separated the data into one subset collected under clear-sky conditions and another subset collected under cloudy skies because of the significant differences observed in $K_d(\lambda)$, suspensates, and *in vivo* fluorescence with respect to sky conditions.

Under clear-sky conditions (n = 116), Rm (Table 3) ranged from 0.74 (750–800 nm) to 0.95 (650–700 nm), with mineral suspensates and chlorophylls *a* and *c* account-

TABLE 4. Simple (Rs) and multiple linear regression (Rm) correlation coefficients of $K_d(\lambda)$ regressed on eight independent variables for subset of data taken under cloudy skies. xx = Did not enter into regression equation. Chl *a* = chlorophyll *a*; Carot = carotenoid pigments; OSP = organic suspensates; POC = particulate organic carbon; Chl *b* = chlorophyll *b*; DOC = dissolved organic carbon.

Wavelength											
	425			475			525			575	
	Rs	Rm		Rs	Rm		Rs	Rm		Rs	Rm
Chl *a*	.56	.567	Carot	.70	.70	Chl *a*	.76	.76	Chl *a*	.80	.80
OSP	.47	.60	MSP	.52	.73	DOC	.03	.78	DOC	−.06	.85
Chl *b*	−.21	.62	OSP	.53	.75	MSP	.49	.81	MSP	.44	.86
MSP	.41	.63	DOC	.11	.76	Chl *c*	.69	.81	Carot	.77	.86
DOC	.04	.65	Chl *b*	−.20	.77	OSP	.50	.82	Chl *b*	−.11	.86
Chl *c*	.49	.65	Chl *c*	.64	.77	Chl *b*	−.02	.82	POC	.28	.86
Carot	.55	.65	POC	.28	.77	POC	.28	.82	Chl *c*	.68	.86
POC	.21	.65	Chl *a*	.69	.77	Carot	.75	.82	OSP	xx	.86
	625			675			725			775	
	Rs	Rm		Rs	Rm		Rs	Rm		Rs	Rm
Chl *a*	.82	.82	Chl *a*	.83	.83	Chl *a*	.62	.62	Chl *a*	.55	.55
DOC	−.01	.86	DOC	.03	.85	DOC	−.03	.65	Chl *b*	−.23	.58
MSP	.46	.87	MSP	.46	.86	MSP	.42	.68	DOC	.004	.60
Carot	.80	.87	Carot	.81	.86	Chl *b*	−.24	.70	POC	.10	.61
Chl *b*	−.12	.87	Chl *b*	−.15	.86	OSP	.41	.71	Chl *c*	.51	.62
POC	.31	.87	Chl *c*	.74	.86	Chl *c*	.55	.71	MSP	.28	.62
OSP	.47	.87	POC	.31	.86	Carot	.62	.71	OSP	.29	.62
Chl *c*	xx	.87	OSP	.46	.87	POC	.23	.71	Carot	.54	.63

n = 80

ing for 53 to 84% of the variation in $K_d(\lambda)$. For data acquired on cloudy days (n = 80), less of the variance was explained by the regressions (Table 4). The rankings of the eight variables in explaining the variance of $K_d(\lambda)$ changed with the wavelength. Carotenoid pigments, with very high simple correlations with $K_d(\lambda)$, did not figure prominently in any of the multiple regressions, appearing only once as one of the three most important variables.

For all data, the multiple correlation coefficient, Rm, for $K_d(\lambda)$ on all eight variables ranged from a low of 0.63 for the infrared band (750–800 nm) to a high of 0.93 for the red band (650–700 nm). The three most important variables, mineral suspensates, and chlorophyll *a* and *c*, accounted for 40 to 75% of the variation in $K_d(\lambda)$.

Discussion

Diffuse transmittance of radiant energy through turbid waters is much more complex than for clear oceanic water. High concentrations of suspensates, whether mineral or organic, give rise to multiple scattering, which increases the average path length of the light rays per meter of depth and increases the probability that any single photon will be intercepted by an absorber (Kirk 1979, 1981).

Scattering, for which we have no reliable measure, probably is responsible for a large part of the changes in the spectral attenuation, especially so in the near-infrared wave bands. Other than water, few substances selectively absorb in the two bands (700–750 nm, 750–800 nm). Hence, in a turbid medium, multiple scattering increases the average path length per meter of depth and gives a spectral diffuse attenuation coefficient larger than expected. The importance of mineral suspensates in explaining the variation in $K_d(\lambda)$ for the two IR wave bands for data taken under clear conditions suggests that scattering, and hence an increased path length, is the important factor, since mineral particles are not strongly wavelength selective in absorption (Egan and Hilgeman 1979).

The relationship between scattering and attenuation for these two bands is not as clear for data collected under cloudy conditions. Phytoplankton, as evidenced by chlorophyll *a*, correlated with $K_d(\lambda)$ for these two bands for data taken under cloudy skies. However, phytoplankton are not as efficient scatterers as are mineral particles, which do not correlate as well with $K_d(\lambda)$ as on clear days. Under cloudy conditions, the incident irradiance is sky light, already diffuse, with an average angle of incidence larger than for the direct beam of the sun. The downwelling irradiance below the water surface thus will have a smaller average cosine, and $K_d(\lambda)$ is less likely to be increased by increased scattering. The limiting condition for this situation is an isotrophic radiance distribution (Kirk 1984).

During the highly turbid conditions of late summer in 1980, the attenuation coefficient, $K_d(\lambda)$, in the 425-, 525-, and 725-nm bands became asymptotic, at some depth below the water surface, due to selective attenuation of certain wavelengths within the bands. For the 400–450 and 500–550 bands, selective attenuation is attributed to absorption by pigments. For the near-IR band, based on the observations of Smith and Baker (1981), K_d (700–750 nm) would tend to be asymptotic to 0.65 m^{-1} as the longer wavelengths in this band are absorbed by the water. This would support our observed decrease in K_d (700–750 nm) with depth, where we calculated a K_d of 0.85 m^{-1} at a depth of between 2 and 2.5 m.

Wavelength selective attenuation by absorption also varied throughout the year as the proportions of photosynthetic pigments changed. During much of 1980, the high attenuation in the 450–550 nm bands could be due to the presence of accessory pigments in the phytoplankton (Yentsch 1980). As the year progressed, more of the energy in the middle wavelengths was absorbed. Dinoflagellates, with the accessory pigment peridinin, are generally an important part of the phytoplankton populations in the Rhode River (Faust et al. 1982).

Selected wavelengths can be attenuated by reflectance back out of the water due to colored particulate materials suspended in the water. Reflectance would account for no more than a small percentage of the downwelling irradiance.

The results of stepwise linear regression indicate that chlorophylls *a* and *c* and mineral suspensates are the three most important variables affecting the attenuation of radiant energy through the water column under clear conditions during the period of study. Prieur and Sathyendranath (1981) found the same variables to be the most important in their study. Carotenoids, with high simple regression coefficients, also correlate with changes in $K_d(\lambda)$, although they do not enter into the regression equations at a very high level. Chlorophyll does not selectively absorb energy in the wavelengths between 450 and 600 nm; mineral particles generally are not selective absorbers in the visible region, although they are efficient scatterers. We attribute attenuation in the middle of the spectrum to multiple scattering by particles, which not only increases the mean path length down to the sensor, resulting in more absorption by pigments and water, but also increases reflectance from the water.

This work demonstrates that light transmittance in turbid waters is considerably more complex than through oceanic water, even coastal water, with respect to depth of penetration and the spectral character. The changing spectral character of the underwater irradiance with the seasons, or in our case within the year of study, may place an added stress on rooted aquatic plants and periphyton. High attenuation of selected wavelengths in the upper part of the water column may reduce the photosynthetically available irradiance below that necessary for healthy growth of benthic plants, or modify the community structure to favor those species capable of harvesting light efficiently at wavelengths greater than 525 nm.

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