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The Spectral Irradiance Field at the Surface and in the Interior of the Ocean: A Model for Applications in Oceanography and Remote Sensing

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A spectral model of irradiance is presented for the computation of light energy available at the surface and at various depths in the ocean for the wavelength range from 400 to 700 nm. For any latitude, irradiances are computed as a function of geographic location, date, and time. Application of the model is demonstrated through computation of the profiles of vertical attenuation coefficient and of the effective specific absorption of phytoplankton. The model results are compared with those from conventional procedures, which disregard spectral and angular distributions of the underwater light field, for calculation of the effective specific absorption. The magnitude of the errors incurred by such simplifications is estimated and is shown to be nonnegligible and variable with solar elevation, depth, and the phytoplankton pigment concentration in the water.

INTRODUCTION

For many oceanographic applications it is useful to have a simple model of the irradiance available at the sea surface, as a function of position and time, and its penetration through the water column. In most parts of the ocean, phytoplankton dominate the variable component of optical attenuation. To address related contemporary problems, such as the storage of energy in photosynthesis [*Platt et al.*, 1984; *Herman and Platt*, 1986], the rate of heating of the mixed layer by shortwave radiation [*Woods*, 1980; *Shetye*, 1986; *Lewis and Platt*, 1987], the local intensification of heating through absorption of light in the deep chlorophyll maximum [*Lewis et al.*, 1983], and the remote sensing of ocean color [*Sathyendranath*, 1986; *Platt and Lewis*, 1987], it is important that the irradiance model contain the wavelength dependence, either explicit or implicit. But simple spectral models useful for such applications are not generally available, and it is a common practice to think in terms of the mean properties of the water column averaged over some spectral range. This approach can lead to serious errors, as we show for the calculation of an important optical quantity, the effective specific absorption of phytoplankton.

Here, we adapt the clear sky, spectral irradiance model of *Bird* [1984] to give wavelength-resolved irradiance at the sea surface as a function of latitude, season, and time of day and extend it to describe the underwater light field as modified by absorption and scattering. Although our interest is primarily in the photosynthetically active part of the spectrum, the approach is easily extended to include other spectral bands.

We illustrate the application of the model through calculation of the effective specific absorption coefficient of phytoplankton and of the energy stored by phytoplankton in photosynthesis.

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THE MODEL

For a given location, date, and time, solar elevation is calculated by standard procedures [see *Paltridge and Platt*, 1976]. The direct and diffuse components of spectral irradiance at sea level are then computed using the atmospheric transmission model of *Bird* [1984], which assumes cloud-free skies. Seasonal variations in extraterrestrial solar irradiance have been accounted for, using data from *Thekaekara* [1977]. Reflection losses at the air-sea interface are computed assuming Fresnel reflectance at a flat sea surface for the direct component, and a 5.5% reflection for the diffuse sky light. This is a mean (range from 5 to 6.6%) of reported values of reflectances for sky light under uniform skies [see *Jerlov*, 1976]. Sea surface roughness is known to affect reflectance significantly only for solar elevations less than 20° [*Cox and Munk*, 1956].

The total downwelling spectral irradiance $E(z, \lambda)$ (Einsteins h^{-1} m^{-2} nm^{-1}) at depth z and wavelength λ is then computed as follows:

$$E(z, \lambda) = E_d(z, \lambda) + E_s(z, \lambda) \tag{1}$$

where $E_d(z, \lambda)$ is the direct component of the downwelling irradiance on a horizontal surface at depth z and wavelength λ and $E_s(z, \lambda)$ is the corresponding diffuse irradiance (sky light), given by

$$E_d(z, \lambda) = E_d(z - \Delta z, \lambda)e^{-K_d(\lambda)\Delta z}$$

$$E_s(z, \lambda) = E_s(z - \Delta z, \lambda)e^{-K_s(\lambda)\Delta z}$$

where K_d and K_s are the vertical attenuation coefficients for the direct and diffuse components of irradiance and Δz is a small increment in depth. For computing K_d and K_s, we have used the following approximations:

$$K_d(\lambda) = [a(\lambda) + b_b(\lambda)]/\cos\theta \tag{2a}$$

$$K_s(\lambda) = [a(\lambda) + b_b(\lambda)]/\bar{\mu} \tag{2b}$$

where $a(\lambda)$ (m^{-1}) is the total volume absorption coefficient of the water at depth z and for wavelength λ, $b_b(\lambda)$ (m^{-1}) is the corresponding backscattering coefficient, θ is the Sun zenith

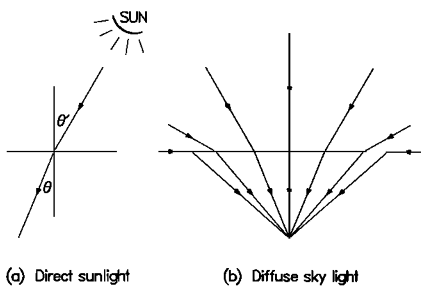

Fig. 1. Angular distribution of the underwater light field. (*a*) Direct sunlight; sin θ'/sin θ = 1.33, the refractive index of seawater. (*b*) Diffuse sky light, assumed to be uniformly distributed, with refraction at a flat sea surface.

angle in water, and $\bar{\mu}$ is the mean cosine for perfectly diffuse sky light, after refraction at a flat sea surface (see Figure 1). Note that (2*a*) and (2*b*) neglect multiple scattering effects.

The total volume absorption coefficient at wavelength λ, $a(\lambda)$, is computed using the method of *Prieur and Sathyendranath* [1981]. In this approach the absorption due to phytoplankton at wavelength λ, $a_c(\lambda)$, is expressed as the product of the pigment concentration C (milligrams per cubic meter) and the specific absorption coefficient $a_c^*(\lambda)$ ($m^{-1}(mg\ m^{-3})^{-1}\ nm^{-1}$), which is defined as the pigment absorption at unit concentration. In the computations here, we have assumed that the concentration of nonchlorophyllous particles is zero and that the concentration of yellow substances varies proportionately to total absorption at 440 nm. However, using (5*a*) and (5*b*) of *Prieur and Sathyendranath* [1981] for computing phytoplankton absorption at 440 nm leads to a sharp discontinuity at 1 mg Chl *a* + Phaeo m^{-3} (chlorophyll *a* plus phaeophytin), which is not realistic. On the other hand, their equation (5*c*) yields unacceptably high phytoplankton specific absorption for pigment concentrations less than 1 mg m^{-3} (for example, for pigment concentration equal to 0.01 mg m^{-3}, specific absorption at 440 nm is 0.375 m^{-1} (mg $m^{-3})^{-1}$, which is many times higher than the maximum values reported in the literature). We have therefore used the following, improved expression:

$$a_c(440) = 0.355C/(6.103 + C) \qquad (3)$$

where $a_c(\lambda) = Ca_c^*(\lambda)$. This equation has the advantage of having neither a sharp discontinuity at 1 mg m^{-3} of C, nor unacceptably high $a_c^*(440)$ for C less than 1 mg m^{-3}. At the same time the new equation closely follows the earlier equations in the range 0–10 mg m^{-3} of C (see Figure 2). The applicability of (3) is confined to concentrations less than 10 mg m^{-3}.

The coefficient a_c^*, which is an inherent property, is defined for monochromatic radiant flux incident normally on a small volume of the medium. Therefore it is not dependent on the nature of the underwater light field.

To compute the backscattering coefficient $b_b(\lambda)$, we have assumed that

$$b_b(\lambda) = \tilde{b}_{bw} b_w(\lambda) + \tilde{b}_{bc} b_c(\lambda)$$

where b_w and b_c are the scattering coefficients for seawater and phytoplankton, respectively, and $\tilde{b}_{bw}$ and $\tilde{b}_{bc}$ are the corresponding backscattering to total scattering ratios. The quantity $b_w(\lambda)$ has been computed using the results of *Morel* [1974]. It is well known that molecular scattering by pure seawater is symmetrical about the plane of incidence. Therefore backscattering is half the total scattering. In other words, $\tilde{b}_{bw} = 0.5$. The value of b_c at 550 nm was computed from *Morel* [1980]:

$$b_c(550) = 0.12C^{0.63}$$

The spectral values of b_c were then computed by assuming that the total volume attenuation coefficient for phytoplankton, $c_c(\lambda)(= a_c(\lambda) + b_c(\lambda))$ is independent of wavelength. This is based on the experimental and theoretical results of *Morel and Bricaud* [1981] and *Bricaud et al.* [1983] which suggest that the spectral forms of scattering and absorption are roughly complementary. Therefore

$$b_c(\lambda) = c_c(550) - a_c(\lambda)$$

The results of *Morel and Bricaud* [1981] and *Bricaud et al.* [1983] also show that $\tilde{b}_{bc}$ is generally less than 1%. We have assumed it to be a constant, equal to 0.5%.

We have used the clear sky, spectral irradiance model of *Bird* [1984] to compute the irradiance at the sea surface. The model uses a two-term Ångström formalism (based on a bimodal lognormal size distribution for the particles), with wavelength exponents $\alpha_1 = 1.0274$ between 400 and 500 nm and $\alpha_2 = 1.2060$ for the longer wavelengths. In our computations we have kept the aerosol concentration constant (aerosol turbidity τ_a at 500 nm equal to 0.27, with Ångström turbidity coefficients $\beta_1 = 0.1324$ and $\beta_2 = 0.1170$, corresponding to α_1 and α_2, respectively). The results of atmospheric transmission models are sensitive to changes in aerosol type and concentration (see, for example, *Brine and Iqbal* [1983]). Though it is common to use a single-term Ångström formalism to compute aerosol attenuation, some observations indicate that marine aerosol size distributions may require up to three lognormal curves to describe them [*Gathman*, 1983]. Therefore the results presented here cannot be said to be representative of all clear sky conditions. We have selected the Ångström coefficients to correspond to a horizontal visibility of about 25 km.

The underwater light transmission model does not account for beam spreading due either to sea surface roughness or to multiple scattering. Also, all backscattered light is considered lost to the system and therefore unavailable for absorption by phytoplankton at shallower depths (see (2*a*) and (2*b*)). Natural fluorescence by phytoplankton is also not taken into account,

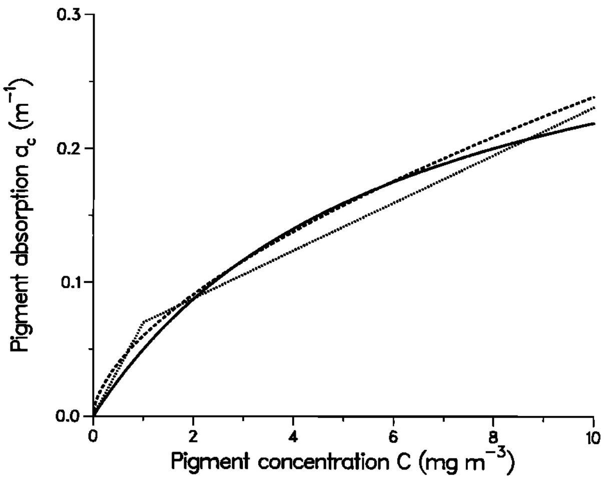

Fig. 2. The curve used for computing $a_c(440)$, the absorption at 440 nm due to phytoplankton pigments (Chl *a* + Phaeo). Continuous line, the equation used in this paper (equation (3)); dotted line, (5*a*) and (5*b*) of *Prieur and Sathyendranath* [1981]; dashed line, (5*c*) of *Prieur and Sathyendranath* [1981].

though it could make a significant contribution to red light at high concentrations of phytoplankton.

Neglecting multiple scattering effects could lead to serious underestimation of the vertical attenuation coefficient K and related parameters in turbid waters where scattering dominates over absorption [see *Kirk*, 1983]. This error would increase with depth, until the asymptotic radiance distribution were reached. To obtain an order of magnitude for the error due to this effect in the phytoplankton-dominated waters under consideration here, the ratio b/a was computed for all wavelengths, for different chlorophyll concentrations, using the model. It was found that the ratio increases with concentration. At a chlorophyll concentration of 10 mg m^{-3}, b/a was less than 2 except in the middle wavelengths (500–600 nm), where it varied from 2 to 3.5. According to *Kirk* [1986], for $b/a = 3$, disregarding multiple scattering can lead to an underestimate in K of $\sim$25% at half the euphotic depth (for normally incident radiation at the sea surface). The error would be less for lower b/a values and for smaller depths.

Computation of the Effective Specific Absorption of Phytoplankton

Phytoplankton constitute one of the principal absorbers of visible radiation in the ocean. Their capacity to trap photons is a fundamental limitation on marine primary production. Computation of energy absorbed by phytoplankton has therefore preoccupied oceanographers for many years. Central to these computations is a parameter known as the "effective specific absorption coefficient of phytoplankton." In this section we present two approaches currently in use for its computation and discuss their limitations. We then present a modified calculation that takes into account the angular distribution of the underwater light field.

The Nonspectral Approach

Evaluation of energy available for photosynthesis at various depths in the ocean should be based on a complete spectral and angular distribution of the underwater light field, and the spectral absorption and scattering properties of pure seawater and of all the optically active substances present in it. Unfortunately, such complete information is rarely, if ever, available, and it is a widespread and necessary practice to speak in terms of the "mean" properties for the entire spectral range of photosynthetically active radiation (PAR). The most commonly used of these is the attenuation coefficient for PAR $\bar{K}$ (m^{-1}), which is usually computed from the following expression:

$$\bar{K} = \bar{K}_{w1} + C\bar{k}_{c1} + \bar{K}_{x1} \tag{4}$$

where $\bar{K}_{w1}$ is the mean attenuation coefficient of PAR, due to pure seawater (m^{-1}); $\bar{k}_{c1}$ is the effective specific attenuation coefficient of phytoplankton per unit concentration of pigment, usually chlorophyll *a*, or chlorophyll *a* plus phaeophytin (m^{-1} (mg m^{-3})$^{-1}$); C is the pigment concentration (milligrams per cubic meter); $\bar{K}_{x1}$ is the mean attenuation coefficient due to other substances, such as suspended sediments or dissolved organic matter (m^{-1}); and the subscript 1 indicates that the parameters are evaluated using the nonspectral approach. This is a formalism that has been used extensively to evaluate the amount of light energy absorbed by phytoplankton. It is also a convenient approach to computations of solar heating of the oceanic mixed layer. In open ocean waters, away from terrigenous influences, it is generally possible to neglect the last term in (4) or to express it as a covarying function of the previous term. In other words, phytoplankton and substances covarying with it usually dominate changes in $\bar{K}$. This means that given C (a variable that is routinely measured at sea) and knowing $\bar{K}_{w1}$ and $\bar{k}_{c1}$, it would be possible to compute the light attenuation at sea. Considerable effort has therefore been devoted to the determination of the coefficients $\bar{K}_{w1}$ and $\bar{k}_{c1}$.

These coefficients are generally determined from measurements of PAR as a function of depth, from which $\bar{K}$ may be computed as

$$\bar{K} = -\frac{1}{E_t(z)}\frac{d}{dz}[E_t(z)].$$

where E_t is the integral of downwelling irradiance over the range from 400 to 700 nm.

If $\bar{K}$ and C are known for a number of stations, $\bar{K}_{w1}$ and $\bar{k}_{c1}$ can be estimated by least square linear curve fitting, if the last term of (4) can be neglected. In cases where it is not possible to neglect this term, some method has to be devised to correct for it. One such method is to plot a scatter diagram of $\bar{K}$ versus C and use the limit of the envelope lying closer to the abscissa to estimate $\bar{k}_{c1}$ and $\bar{K}_{w1}$ [e.g., *Seaburg et al.*, 1983]. The coefficients reported are usually mean values for the total euphotic zone.

The appeal of (4) lies in its simplicity. However, it should be used with caution: Diffuse attenuation coefficient is not an inherent optical property. In other words, the coefficients in (4) depend on the angular and spectral distribution of the underwater light field. Though (4) implies that $\bar{K}$ is a quasi-inherent property, the errors inherent in the assumption have not, as far as we know, been evaluated. Adoption of mean values of $\bar{K}_{w1}$ and $\bar{k}_{c1}$ over the euphotic zone automatically disregards any possible depth-dependent variation in these coefficients. If $\bar{k}_{c1}$, as estimated through (4), were used for computing phytoplankton light absorption, further errors would be incurred, because (1) the second term on the right-hand side of (4) includes attenuation of light due to backscattering by phytoplankton, which is not available for photosynthesis, and (2) it would be extremely difficult to isolate the effect on $\bar{k}_{c1}$ of any optically active substance covarying with phytoplankton through application of (4). *Bannister and Weidemann* [1984] and *Jewson et al.* [1984] have discussed some of the drawbacks of this approach.

Spectral Approach

Because of the limitations of (4) some workers have preferred to compute the effective specific absorption of phytoplankton from the following expression [*Morel*, 1978]:

$$\bar{k}_{c2}(z) = \frac{\int a_c^*(\lambda)E(z, \lambda)\, d\lambda}{\int E(z, \lambda)\, d\lambda} \tag{5}$$

where the subscript 2 indicates use of the spectral approach. Equation (5) is an improvement over (4) in that it takes due account of changes in the spectral distribution of the underwater light field and in that scattering losses are not assimilated into absorption losses. This approach has been used to demonstrate that the effective specific absorption of phytoplankton varies with depth and the type of water considered [*Morel*, 1978; *Atlas and Bannister*, 1980; *Kishino et al.*, 1986]. But the application of (5) has been limited, because it requires measurements of the spectrum of underwater light as a function of depth, and of the specific absorption spectrum of phytoplankton.

The Spectral and Angular Approach

The spectral approach does not by itself account for the facts that light has a complex angular distribution under water and that absorption per unit vertical distance increases when the optical path length deviates from the normal [see *Talling*, 1984]. We are interested in evaluating whether this simplification leads to significant errors in the estimation of the effective specific absorption. We therefore propose a modified calculation of the effective absorption coefficient, which takes the angular distribution into account. This coefficient, a_E^*, is computed from $Q(z, \lambda)$, the light absorbed by phytoplankton at depth z and at wavelength λ, which is given by

$$Q(z, \lambda) = Q_d(z, \lambda) + Q_s(z, \lambda) \tag{6a}$$

where

$$Q_d(z, \lambda) = E_d(z, \lambda)\{1 - \exp[-C(z)a_c^*(\lambda)\Delta z/\cos\theta]\} \tag{6b}$$

$$Q_s(z, \lambda) = E_s(z, \lambda)\{1 - \exp[-C(z)a_c^*(\lambda)\Delta z/\bar{\mu}]\} \tag{6c}$$

Here $Q_d(z, \lambda)$ and $Q_s(z, \lambda)$ are the portions of direct and diffuse light that are absorbed by phytoplankton in the depth interval from z to $(z + \Delta z)$, and $C(z)$ (milligrams per cubic meter) is the chlorophyll concentration in this layer. Then a_E^*, the effective specific absorption coefficient of phytoplankton for total downwelling light at depth z, is given by

$$a_E^*(z) = \frac{1}{\Delta z C(z)} \ln \left[1 - \frac{\int Q(z, \lambda)\, d\lambda}{\int E(z, \lambda)\, d\lambda} \right] \tag{7}$$

where the integrations are carried out over the photosynthetically active range, 400–700 nm.

It is easy to see from the definition of a_E^* that it is influenced by the spectral distribution of the underwater light field, as well as its angular distribution (defined here in terms of cos θ and $\bar{\mu}$). Changes in the incident light field would therefore affect the magnitude of a_E^*. Furthermore, a_E^* would change with depth, depending on the spectral inherent properties $a(\lambda)$ and $b_b(\lambda)$.

In the following section we use our spectral model to compute the rate of light absorption by phytoplankton and its variation with depth, incident light field, and the type of water considered. The results are compared with those obtained using (4) and (5), and the magnitude of the errors incurred by the conventional methods of calculating the effective specific absorption coefficient of phytoplankton is discussed.

COMPUTED a_E^* AND $\bar{K}$ VALUES

The model was used to compute light penetration and attenuation for hypothetical stations supposed to be at the equator on June 21. The computations were carried out for the period 0700–1200 local apparent time at half-hour intervals. The wavelength interval of computation is 5 nm, and the depth interval is 1 m.

Uniform Chlorophyll Distribution

In the first instance, it was assumed that the chlorophyll concentration does not vary with depth. Computations were carried out for stations with chlorophyll concentrations ranging from 0.01 to 10 mg m^{-3}. The computed a_E^* values are presented in Figure 3. The following points may be noted:

1. In addition to obvious changes in the euphotic depth with change in chlorophyll concentration, there is a change in euphotic depth with time of day, reflecting largely the change in solar elevation and, to a minor extent, the change in the spectral composition of the incident radiation (see Figure 4). The euphotic depth may increase by 20% from early morning to noon.

2. Similarly, there is a decrease in a_E^* values (by about 30%) from early morning to noon.

3. There is a considerable variation in a_E^* over the water column. In chlorophyll-poor waters the a_E^* values increase with depth, whereas in chlorophyll-rich waters they decrease with depth. This is a consequence of the fact that the wavelength of maximum transmission shifts from blue (corresponding to chlorophyll absorption maximum) to green (chlorophyll absorption minimum), when chlorophyll concentration in the water increases (see Figure 5). The variability is maximal in the near-surface waters. Similar effects have been reported by *Morel* [1978], *Atlas and Bannister* [1980] and *Kishino et al.* [1986] on the basis of measurements of underwater spectral irradiance.

The $\bar{K}$ values corresponding to the a_E^* values of Figure 3 are presented in Figure 6. The striking feature in these profiles is the rapid decrease of $\bar{K}$ in the near-surface waters due to the rapid attenuation of red light. *Smith and Baker* [1986] have also shown this effect based on their spectral diffuse attenuation model. The attenuation coefficient also decreases by about 20% from morning to noon. The data of *Baker and Smith* [1979] on the spectral values of K also show a similar dependence on the Sun zenith angle. Note that the residual attenuation of light by processes other than phytoplankton absorption ($\bar{K} - Ca_E^*$), also shown in Figure 6, increases with phytoplankton concentration, because of (1) increased absorption by yellow substances and increased backscattering by phytoplankton and (2) increased attenuation by pure seawater itself, as the wavelength of maximum penetration shifts from blue toward longer wavelengths.

In Figure 7 the depth- and time-averaged values of a_E^* and ($\bar{K} - Ca_E^*$) are presented as a function of $C\bar{a}_c^*$, where $\bar{a}_c^*$ is the wavelength-averaged specific absorption coefficient of phytoplankton. Time averaging is carried out over a day, with the incident radiation just below the sea surface as the weighting function. The coefficients are plotted against $C\bar{a}_c^*$ rather than C to suppress the nonlinearity arising from the relationship adopted in the model for computing a_c^*. It is seen that a_E^* is a decreasing function of $C\bar{a}_c^*$, as would be anticipated from the function used for computing a_c^*, which itself is a decreasing function of C. But note also that $a_E^*/\bar{a}_c^*$ is also a decreasing function of C(see Figure 7), which shows that the spectral composition of the underwater light field becomes progressively more unfavorable for phytoplankton absorption as the phytoplankton concentration increases. The quantity ($\bar{K} - Ca_E^*$) is an increasing function of $C\bar{a}_c^*$, since in our model, phytoplankton backscattering and absorption by yellow substances increase proportionately to pigment concentration. The curvature of this function, as well as that in the a_E^* curve, arises mainly from the changing spectral composition of underwater light with changing pigment concentration. Note that when C approaches zero, ($\bar{K} - Ca_E^*$) decreases but remains significantly higher than 0.027 m^{-1}, the $\bar{K}_w$ value reported for clearest oceanic waters [*Smith and Baker*, 1978]. This may be because the computations presented here are carried out in quantum units and not energy units. The result is a shift in the maximum in the incoming solar radiation toward the red wavelengths, where water has a high absorption coefficient. Another factor is nonzero absorption by yellow substances.

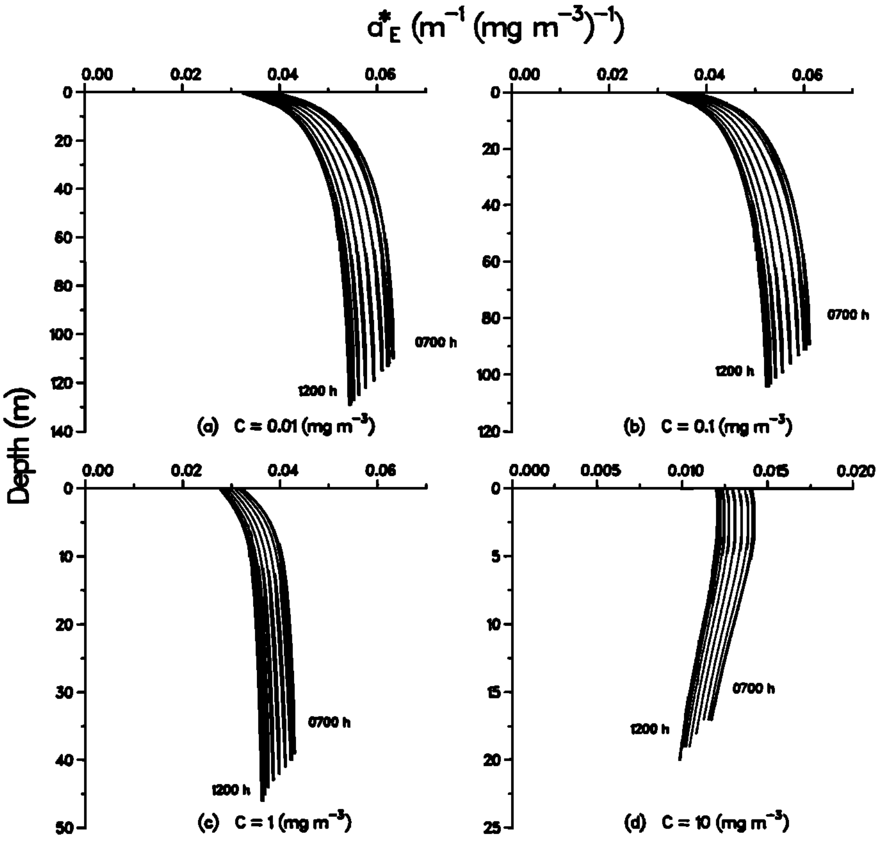

Fig. 3. Computed profiles of the effective specific absorption of phytoplankton (a_E*) for four hypothetical stations at the equator, with uniform pigment concentrations. The a_E* profiles are plotted for every half hour from 0700 to 1200 LT. Each profile is plotted to the limit of the euphotic zone. (*a*) $C = 0.01$ mg m^{-3}. (*b*) $C = 0.1$ mg m^{-3}. (*c*) $C = 1.0$ mg m^{-3}. (*d*) $C = 10$ mg m^{-3}.

Deep Chlorophyll Maximum

The $\bar{K}$ and C values for the case of a station with deep chlorophyll maximum are shown in Figure 8. It is seen that the often made assumption that the attenuation coefficient covaries with the chlorophyll profile is not true in the near-surface waters. Here, the $\bar{K}$ variations seem to be dominated by the rapidly changing spectral composition in the incoming light. In deeper waters, there is certainly a correspondence between the variations in $\bar{K}$ and C with depth, but as noted earlier, the $\bar{K}$ values show, in addition, a pronounced dependence on time of day.

COMPARISON WITH CONVENTIONAL CALCULATION METHODS

Comparison With the Nonspectral Approach

To evaluate the errors in calculating effective specific absorption coefficient of phytoplankton and in calculating the

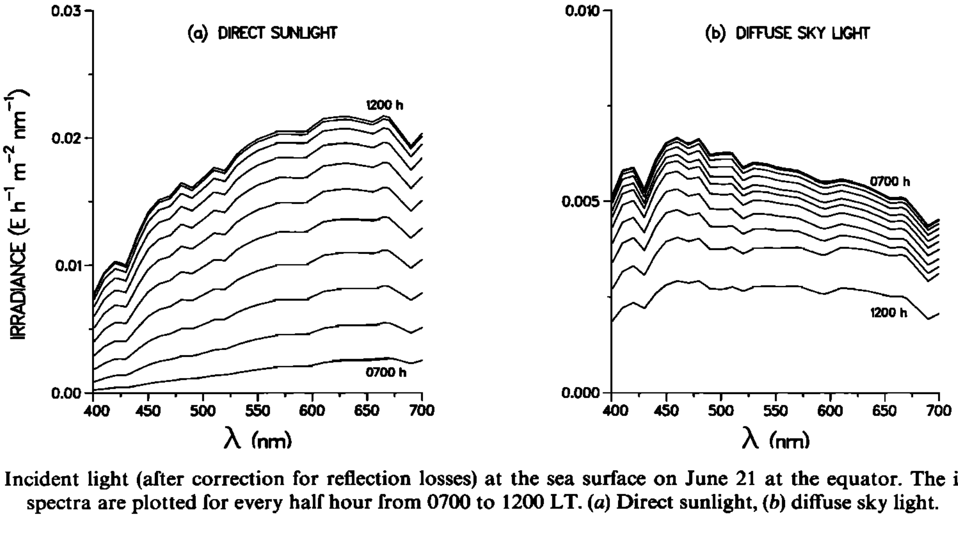

Fig. 4. Incident light (after correction for reflection losses) at the sea surface on June 21 at the equator. The irradiance spectra are plotted for every half hour from 0700 to 1200 LT. (*a*) Direct sunlight, (*b*) diffuse sky light.

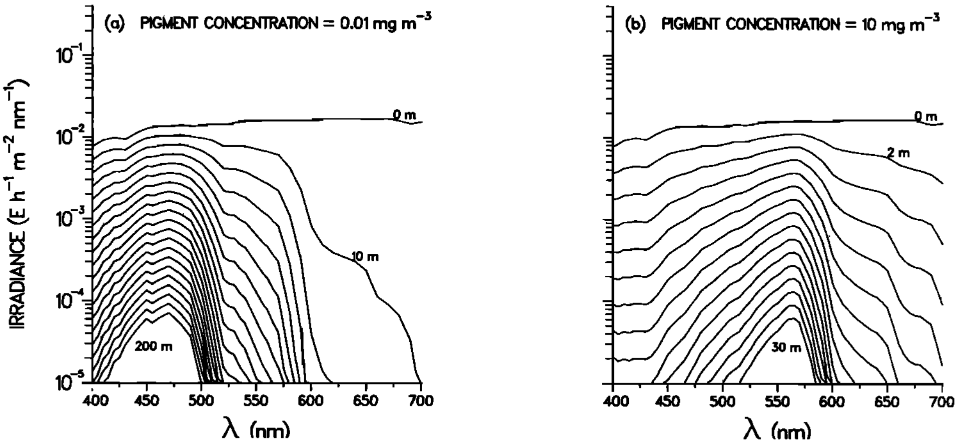

Fig. 5. The spectra of downwelling irradiance for hypothetical stations at the equator on June 21, 0900 LT. (*a*) Phytoplankton-poor waters, with $C = 0.01$ mg m^{-3}. The spectra are plotted for every 10 m. (*b*) Phytoplankton-rich waters, with $C = 10$ mg m^{-3}. The spectra are plotted every 2 m.

fraction of incident light that is absorbed by phytoplankton, using the nonspectral approach, we proceeded as follows:

1. For each hypothetical station with a given, vertically uniform chlorophyll concentration, a daily average for the euphotic depth (z_p) was computed, using the solar radiation just below the sea surface as a weighting function.

2. The mean attenuation coefficient over the euphotic zone was then determined as $\langle \bar{K} \rangle = 4.6/z_p$, where the angle brackets indicate averaging over the euphotic depth.

3. The $\langle \bar{K} \rangle$ values so obtained were regressed against the chlorophyll concentrations to get $\bar{K}_{w1}$ and $\bar{k}_{c1}$ (see (4)).

Computations using 10 values of C ranging from 0.01 to 10 mg m^{-3} gave $\bar{K}_{w1} = 0.0611$ m^{-1} and $\bar{k}_{c1} = 0.0232$ m^{-1} (mg m^{-3})$^{-1}$, with an r^2 of 0.90 (see Figure 9). In view of the fact that the mean value of a_E^* over the euphotic zone, averaged over a day, is variable (range 0.01–0.05 m^{-1} (mg m^{-3})$^{-1}$), this good correlation is rather surprising. It might be attributable to the fact that a_E^* is a decreasing function of pigment con-

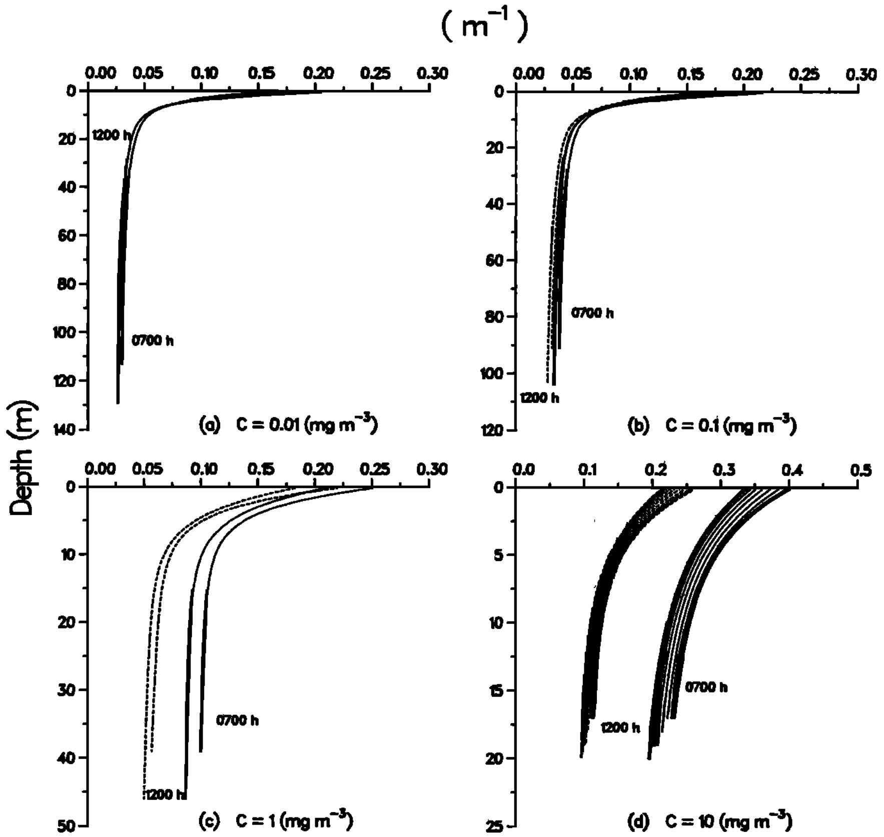

Fig. 6. Profiles of the vertical attenuation coefficient ($\bar{K}$) and the residual attenuation ($\bar{K} - Ca_E^*$) corresponding to the a_E^* curves presented in Figure 3. Continuous line denotes $\bar{K}$. Dashed line denotes ($\bar{K} - Ca_E^*$). In some instances, only the curves for 0700 and 1200 LT have been plotted in order to avoid cluttering. In part (*a*), with $C = 0.01$ mg m^{-3}, only the $\bar{K}$ curves have been plotted, since in this case the $\bar{K}$ and ($\bar{K} - Ca_E^*$) curves practically overlap.

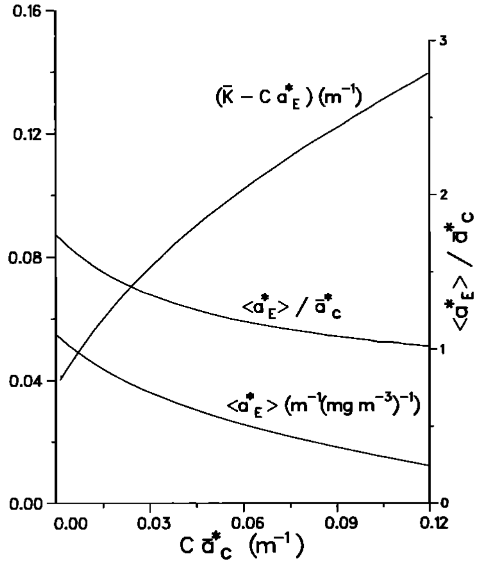

Fig. 7. Time- and depth-averaged values of the effective absorption coefficient, $\langle a_E^* \rangle$ (m^{-1} $(mg\ m^{-3})^{-1}$), the ratio $\langle a_E^* \rangle / \bar{a}_c^*$ and the residual attenuation ($\bar{K} - Ca_E^*$) (m^{-1}) (also time- and depth-averaged), plotted as functions of $C\bar{a}_c^*$ (m^{-1}). The scale on the right-hand side applies to $\langle a_E^* \rangle / \bar{a}_c^*$, whereas the scale on the left-hand side applies to the other two curves.

centration, whereas the residual attenuation ($\bar{K} - Ca_E^*$) is an increasing function (see Figure 7), such that for high concentrations of C the $\langle \bar{K} \rangle$ curve is only slightly nonlinear. In spite of the good correlation, therefore, the coefficients $\bar{K}_{w1}$ and $\bar{k}_{c1}$ might not represent realistic evaluations of, respectively, the background absorption and the effective absorption by phytoplankton. At best, they may be considered loosely as "mean values."

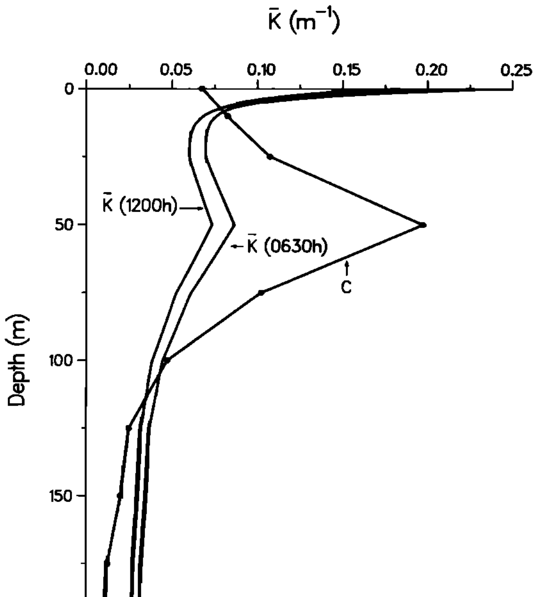

Fig. 8. The profiles of C and $\bar{K}$ for a station with deep chlorophyll maximum. As an example, we have taken station 43, located in the Indian Ocean on August 2, 1963, at 18°55.5'N, 39°08'E. Data from *Laird et al.* [1964].

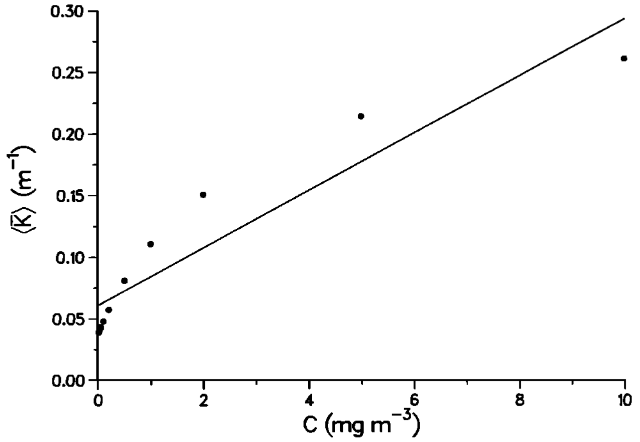

Fig. 9. Time- and depth-averaged $\langle \bar{K} \rangle$ (m^{-1}) as a function of C (milligrams per cubic meter) for 10 values of C ranging from 0.01 to 10 mg m^{-3}. The straight line is the linear fit to the data, given by $\langle \bar{K} \rangle = 0.0611 + 0.0233C$. Note that the distribution of residuals is not random.

The error in computing the fraction of incident light absorbed by phytoplankton using the parameters $\bar{K}_{w1}$ and $\bar{k}_{c1}$ was evaluated. The spectral light penetration model was used to compute the amount of light absorbed by phytoplankton at each depth. The daily integrals of light absorption by phytoplankton, normalized to incident light, S ($= \iint Q\ dz\ dt / \iint E(0)\ dz\ dt$), are presented in Table 1. The fractional light absorption by phytoplankton was also calculated using the nonspectral approach, as $S_1 = C\bar{k}_{c1}/\langle \bar{K} \rangle$. The nonspectral estimate, S_1, is seen to underestimate fractional absorption by phytoplankton for low C values (error of 48% for $C = 0.01$ mg m^{-3}) and overestimate it for high C values (error of 79% for $C = 10$ mg m^{-3}).

It is also important to note that light absorption by phytoplankton would be overestimated if it were computed as $\langle a_E^* \rangle C/\bar{K}$, where $\langle a_E^* \rangle$ is the effective absorption coefficient averaged over the euphotic zone (values presented in the fourth column from the left of Table 1). Maximum overestimation occurs at minimum concentrations (95% for $C = 0.01$ mg m^{-3}) and minimum at high concentrations (5.6% for $C = 10$ mg m^{-3}). The overestimation occurs be-

TABLE 1. Computed Optical Parameters for Different Pigment Concentrations in the Water

C	S	z_p	$\langle a_E^* \rangle$	$\langle \bar{K} \rangle$	S_1
0.01	0.72	118	0.055	0.039	0.38
0.02	1.40	115	0.055	0.040	0.72
0.05	3.27	107	0.054	0.043	1.70
0.1	5.91	95.8	0.052	0.048	4.82
0.2	9.99	80.2	0.050	0.057	8.08
0.5	17.5	56.8	0.044	0.081	14.3
1	24.3	41.6	0.037	0.111	21.0
2	31.2	30.6	0.030	0.151	30.8
5	39.5	21.5	0.019	0.214	54.2
10	44.2	17.7	0.012	0.261	79.2

Units and definitions: C, pigment concentration (milligrams per cubic meter); S, percent incident light absorbed by phytoplankton, integral over a day, calculated as $\int\int Q\ dz\ dt / \int\int E_t\ dz\ dt$; z_p, photic depth, daily average (meters); $\langle a_E^* \rangle$, effective specific absorption, daily photic zone average ($m^{-1}(mg\ m^{-3})^{-1}$); $\langle \bar{K} \rangle$, average vertical attenuation coefficient (m^{-1}); S_1, percent incident light absorbed by phytoplankton, integral over a day, calculated as $\bar{k}_{c1}C/\langle \bar{K} \rangle$.

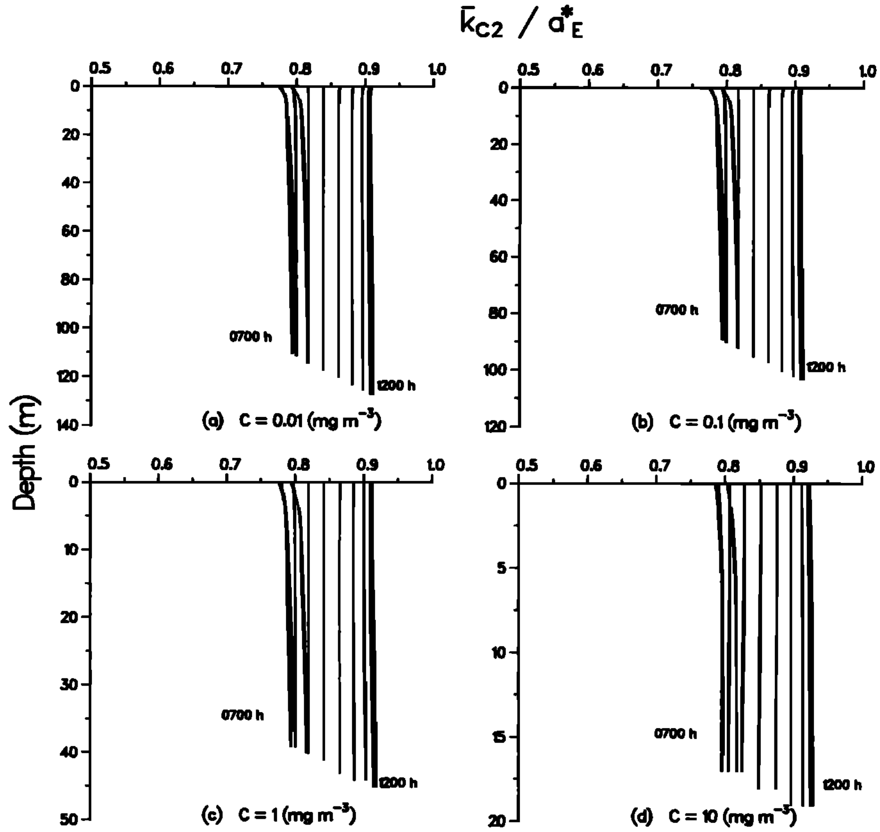

Fig. 10. The ratio of $\bar{k}_{c2}$ to a_E^*, corresponding to the a_E^* curves presented in Figure 3.

cause, generally, a_E^* increases with depth, whereas $(\bar{K} - Ca_E^*)$ decreases with depth. In other words, at the surface, where there is maximum light, a_E^* is less than $\langle a_E^* \rangle$. Therefore if a_E^* is to be averaged over depth, it should be a weighted average with the irradiance at each depth as the weighting function.

Comparison With the Spectral Approach

It is easy to show that (5) is a good approximation of a_E^* as defined in our model, for small values of a_E^* and for a normally incident light beam. Differences between the values of a_E^* and $\bar{k}_{c2}$ (estimate of the parameter value obtained through (5)) will therefore arise only from changes in the angular distribution of the underwater light field. In Figure 10 is presented the ratio of $\bar{k}_{c2}$ to a_E^*. It is seen that (5) may underestimate a_E^* by as much as 25% when the solar elevation is low. There is a very slight change in the ratio with depth, which may be due to the differences in the attenuation coefficients of diffuse sky light and of direct sunlight. No other depth dependence is evident in our results, since in the model the angular distributions of diffuse and direct light do not change with depth. But in highly scattering waters the ratio $\bar{k}_{c2}/a_E^*$ may be expected to decrease with depth, as the downwelling light becomes more and more diffuse owing to scattering.

Dubinsky et al. [1986] have introduced a new method for estimating the effective specific absorption coefficient of phytoplankton. Different quantities of water from the sampling site are filtered onto Whatman GF/F filters. The filters are attached one by one in front of a quanta meter, which is then lowered to various depths z to measure irradiance $E(z, C_f)$, where C_f is the chlorophyll concentration on the filter. The coefficient $\bar{k}_c$ at each depth is then evaluated by exponential regression on $E(z, C_f) = E(z, 0) \exp(-\bar{k}_c C_f)$. This approach may be considered a variation of the spectral approach, in which spectrally weighted coefficients are obtained at each depth, while at the same time avoiding the need for complete spectral measurements. The drawback of the method is that the presence of the filter in front of the light sensor would change the angular distribution of the light field and therefore the $\bar{k}_c$ values. It would be difficult to quantify this effect, since the increased scatter would be a function of the concentration of particulate material on the filter. But generally, if the effect of increased scattering were not corrected for, the method would tend to yield overestimates of $\bar{k}_c$. It is also to be borne in mind that the increased attenuation associated with the filters would be due to all the particulate material present on the filter, not just phytoplankton.

COMPARISON OF MODEL RESULTS WITH OCEAN DATA

During the cruise of CSS *Hudson* to the New England Seamounts in the northern Atlantic in June–July 1987, downwelling irradiance was measured at various stations using a 12-channel spectro-irradiance meter (model MER 1000 of Biospherical Instruments, Incorporated). The chlorophyll profile was also measured at these stations. The data set could be used for a preliminary validation of the model presented here. With the chlorophyll profile, station location, and observation time as inputs, the light penetration at the various stations was computed using the model. Initial results show good comparison between model results and observed light penetration in the waters. An example is shown in Figure 11.

The model was combined with a spectral model of photosynthesis-light relationship to compute primary production at various stations in the north Atlantic (S. Sathyen-

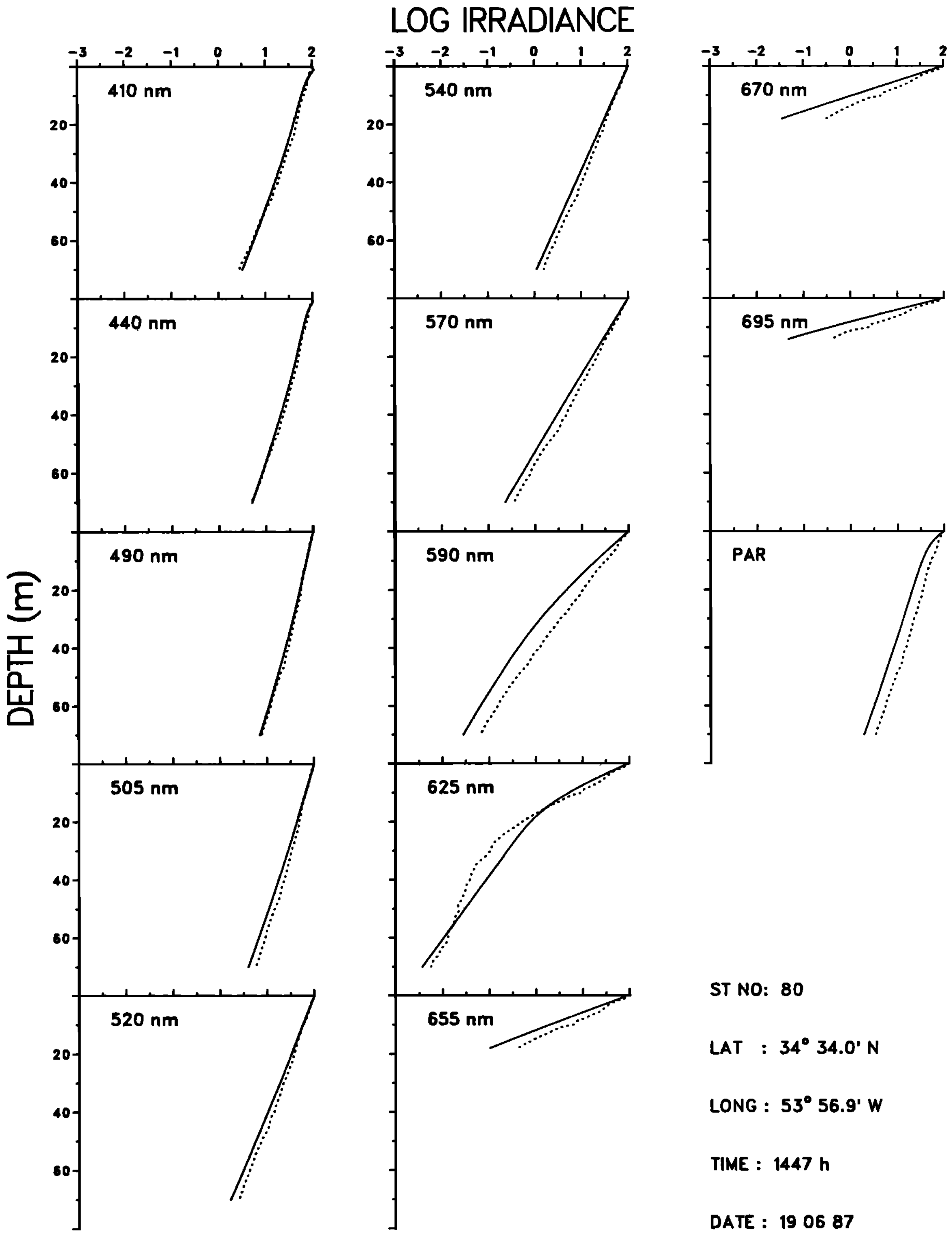

Fig. 11. Comparison of computed (continuous line) and observed (dotted line) values of spectral irradiance underwater for a station in the north Atlantic. For the three wavelengths in the red (655–695 nm), reliable measurements could only be obtained up to about 16 m.

dranath and T. Platt, Computation of aquatic primary production: Extended formalism to include effect of angular and spectral distribution of light, submitted to *Limnology and Oceanography*, 1988). Comparison with observed primary production was very encouraging ($r^2 = 95\%$, $n = 31$, with slope not significantly different from one, and intercept not different from zero). This excellent agreement could be considered indirect evidence that the model provides reasonable estimates of the light available for, and absorbed by, phytoplankton.

DISCUSSION AND CONCLUSION

We have presented here a spectral model that computes light penetration in seawater as a function of depth, for any given location, date, and time. Clear sky conditions are assumed, and the single independent variable in seawater is taken to be the phytoplankton pigment concentration. The ocean-atmosphere coupled models that have been in use so far [e.g., *Plass and Kattawar*, 1972; *Gordon*, 1978; *Plass et al.*, 1981; *Fischer and Grassl*, 1984], although more complete than the one presented here, demand complex solutions to the complete radiation transfer equations or time-consuming Monte Carlo simulations, which have hindered their oceanographic application in many cases. Our model, on the other hand, has been made as simple as possible, without loss of spectral detail. The minimum necessary information on the zenith angular distribution of underwater light is also retained. The price for simplicity has been the loss of azimuthal distribution (which is not necessary for any of the applications envisaged) and of multiple-scattering effects. For the case of open ocean waters considered here, neglecting multiple scattering is not expected to lead to serious errors in computations pertaining to the euphotic zone.

Though the model at present uses generalized optical characteristics for phytoplankton and covarying substances, it would be a fairly simple matter to adjust the model for any particular locality by adjusting these optical properties to suit local conditions. The model is easily extended to coastal waters by the addition of extra terms to account for absorption and scattering by sediments in suspension (nonchlorophyllous particles) and dissolved organic matter [see *Prieur and Sathyendranath*, 1981]. Their concentrations would also have to be specified, in addition to the concentration of phytoplankton pigments. With increasing concentration of particles the multiple-scattering effects also would increase and would have to be accounted for. The simplest way to achieve this may be through the use of depth-dependent angular distribution functions, along the lines suggested by *Dirks and Spitzer* [1987].

The model has been used here to study phytoplankton absorption at sea. We have been able to demonstrate some effects that are generally ignored or even overlooked when spectral and angular details are suppressed. Notable among these is the considerable variability in the effective specific absorption of phytoplankton with depth, time of day, and phytoplankton concentration. These results show clearly that wavelength-integrated optical properties of the water (diffuse attenuation coefficient and effective specific absorption of phytoplankton) are not invariant with depth or time, even when the water is assumed to be homogeneous. This has important consequences for computing both the light absorption by phytoplankton and solar heating of the oceans. Some of these features have been noted earlier, based on complete spectral measurements of irradiance at sea. It would now be possible to simulate them using the model presented here, even in the absence of spectral measurements. Another interesting and unexpected result is the variability (of about 20%) in euphotic depth with time of day due to changes in the angular distribution of light under water.

No effort has been made, at this stage, to separate live phytoplankton from pigment-bearing detritus. Therefore the phytoplankton absorption that is computed in this paper should be considered an absolute upper limit to that available for photosynthesis. As a first approximation a correction may be made for detrital absorption on the basis of the ratio of phaeopigment to chlorophyll *a*. Preferably, the correction would be weighted for the differences in the absorption efficiencies of these substances. But if the spectral differences in their absorption were also to be accounted for, it would become necessary to express the two concentrations as independent variables in the model.

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REFERENCES

Atlas, T., and T. T. Bannister, Dependence of mean spectral extinction coefficient of phytoplankton on depth, water colour, and species, *Limnol. Oceanogr.*, *19*, 157–159, 1980.

Baker, K. S., and R. C. Smith, Quasi-inherent characteristics of the diffuse attenuation coefficient for irradiance, *Proc. SPIE Int. Soc. Opt. Eng.*, *208*, 60–63, 1979.

Bannister, T. T., and A. D. Weidermann, The maximum quantum yield of phytoplankton photosynthesis in situ, *J. Plankton Res.*, *6*, 275–294, 1984.

Bird, R. E., A simple, solar spectral model for direct-normal and diffuse horizontal irradiance, *Sol. Energy*, *32*, 461–471, 1984.

Bricaud, A., A. Morel, and L. Prieur, Optical efficiency factors of some phytoplankters, *Limnol. Oceanogr.*, *28*, 816–832, 1983.

Brine, D. T., and M. Iqbal, Diffuse and global solar spectral irradiance under cloudless skies, *Sol. Energy*, *30*, 447–453, 1983.

Cox, C., and W. Munk, Slopes of the sea surface deduced from photographs of Sun glitter, *Bull. Scripps Inst. Oceanogr.*, *6*, 401–488, 1956.

Dirks, R. W. J., and D. Spitzer, Solar radiance distribution in deep natural waters including fluorescence effects, *Appl. Opt.*, *75*, 2427–2430, 1987.

Dubinsky, Z., P. G. Falkowski, and K. Wyman, Light harvesting and utilisation by phytoplankton, *Plant Cell Physiol.*, *27*, 1335–1349, 1986.

Fischer, J., and H. Grassl, Radiative transfer in an atmosphere-ocean system: An azimuthally dependent matrix-operator approach, *Appl. Opt.*, *23*, 1032–1039, 1984.

Gathman, S. G., Optical properties of the marine aerosol as predicted by the Navy aerosol model, *Opt. Eng.*, *22*, 57–62, 1983.

Gordon, H. R., Removal of atmospheric effects from satellite imagery of the oceans, *Appl. Opt.*, *17*, 1631–1636, 1978.

Herman, A. W., and T. Platt, Primary production profiles in the ocean: Estimation from a chlorophyll/light model, *Oceanol. Acta*, *9*, 31–40, 1986.

Jerlov, N. G., *Marine Optics*, p. 231, Elsevier, New York, 1976.

Jewson, D. H., J. R. Talling, M. J. Dring, M. M. Tilzer, S. I. Heaney, and C. Cunningham, Measurement of photosynthetically available radiation in fresh-water: Comparative tests of some current instruments used in studies of primary production, *J. Plankton Res.*, *6*, 259–273, 1984.

Kirk, J. T. O., *Light and Photosynthesis in Aquatic Ecosystems*, p. 401, Cambridge University Press, New York, 1983.

Kirk, J. T. O., Optical properties of picoplankton suspensions, *Can. Bull. Fish. Aquat. Sci.*, *214*, 501–520, 1986.

Kishino, M., N. Okami, M. Takahashi, and S. Ichimura, Light utilisation efficiency and quantum yield of phytoplankton in a thermally stratified sea, *Limnol. Oceanogr.*, *31*, 557–566, 1986.

Laird, J., B. B. Breivogel, and C. S. Yentsch, The distribution of chlorophyll in the western Indian Ocean during the southwest monsoon period, *Rep. 64-33*, p. 52, Woods Hole Oceanogr. Inst., Woods Hole, Mass., 1964.

Lewis, M. R., and T. Platt, Remote observation of ocean colour for prediction of upper ocean heating rates, *Adv. Space Res.*, *7*, 127–130, 1987.

Lewis, M. R., J. J. Cullen, and T. Platt, Phytoplankton and thermal structure in the upper ocean: Consequences of nonuniformity in chlorophyll profile, *J. Geophys. Res.*, *88*, 2565–2570, 1983.

Morel, A., Optical properties of pure seawater, in *Optical Aspects of Oceanography*, edited by N. G. Jerlov and E. Steemann Nielsen, Academic, San Diego, Calif., 1974.

Morel, A., Available, usable, and stored radiant energy in relation to marine photosynthesis, *Deep Sea Res.*, *25*, 673–688, 1978.

Morel, A., In-water and remote measurements of ocean color, *Boundary Layer Meteorol.*, *18*, 177–201, 1980.

Morel, A., and A. Bricaud, Theoretical results concerning optics of phytoplankton with a special reference to remote sensing applications, in *Oceanography From Space*, edited by J. F. R. Gower, pp. 313–327, Plenum, New York, 1981.

Paltridge, G. W., and C. M. R. Platt, *Radiative Processes in Meteorology and Climatology*, pp. 60–63, Elsevier, New York, 1976.

Plass, G. N., and G. W. Kattawar, Monte Carlo calculations of radiative transfer in the Earth's atmosphere-ocean system, I, Flux in the atmosphere and ocean, *J. Phys. Oceanogr.*, *2*, 139–145, 1972.

Plass, G. N., T. J. Humphreys, and G. W. Kattawar, Ocean-atmosphere interface: Its influence on radiation, *Appl. Opt.*, *20*, 917–931, 1981.

Platt, T., and M. R. Lewis, Estimation of phytoplankton production by remote sensing, *Adv. Space Res.*, *7*, (2)131–(2)135, 1987.

Platt, T., M. Lewis, and R. Geider, Thermodynamics of the pelagic ecosystem: Elementary closure conditions for biological production in the open ocean, in *Flows of Energy and Materials in Marine Ecosystems*, edited by M. J. R. Fasham, pp. 49–84, Plenum, New York, 1984.

Prieur, L., and S. Sathyendranath, An optical classification of coastal and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials, *Limnol. Oceanogr.*, *26*, 671–689, 1981.

Sathyendranath, S., Remote sensing of phytoplankton: A review with special reference to picoplankton, *Can. Bull. Fish. Aquat. Sci.*, *214*, 561–583, 1986.

Seaburg, K. G., M. Kaspar, and B. C. Parker, Photosynthetic quantum efficiencies of phytoplankton from perennially ice covered Antarctic lakes, *J. Phycol.*, *19*, 446–452, 1983.

Shetye, S. R., A model of the seasonal cycle of the Arabian Sea surface temperature, *J. Mar. Res.*, *44*, 521–542, 1986.

Smith, R. C., and K. S. Baker, The bio-optical state of ocean waters and remote sensing, *Limnol. Oceanogr.*, *23*, 247–259, 1978.

Smith, R. C., and K. S. Baker, Analysis of ocean optical data II, *Proc. SPIE Int. Soc. Opt. Eng.*, *637*, 95–107, 1986.

Talling, J. F., Past and contemporary trends and attitudes in work on primary productivity, *J. Plankton Res.*, *6*, 203–217, 1984.

Thekaekara, M. P., Solar irradiance, total and spectral, in *Solar Energy Engineering*, edited by A. A. M. Sayigh, pp. 37–59, Academic, San Diego, Calif., 1977.

Woods, J. D., Diurnal and seasonal variation of convection in the wind-mixed layer of the ocean, *Q. J. R. Meteorol. Soc.*, *106*, 379–394, 1980.

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