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Inherent Optical Properties of Natural Seawater

SHUBHA SATHYENDRANATH
National Institute of Oceanography, Dona Paula, Goa-403004.

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Abstract. The inherent optical properties of pure seawater and of optically active substances generally present in seawater are briefly reviewed. Interrelationship between inherent properties and some of the important apparent properties are also presented, so that apparent properties can be calculated quite simply, if the inherent properties are known, or vice versa.

1. Introduction

Optical devices are being designed increasingly for underwater applications such as ranging, sounding and communications. Passive and active remote sensing techniques, which make use of the visible part of the electromagnetic spectrum, have been developed recently, for studying oceanic parameters such as phytoplankton concentration, suspended sediment load, and water clarity, as well as for monitoring pollution from hydrocarbons. Energy transfer from sun to sea, and primary productivity of the oceans are dependent on the behaviour of light in the sea. Underwater photography is now being increasingly used, for studying the depths of the oceans. In all such studies the parameters of common interest are the optical properties of the sea.

Studies on the optical properties of the sea are complicated because of their high variability with time and space, and difficulties in developing suitable instruments for direct measurements of these properties. This paper reviews briefly the present knowledge on the inherent optical properties of pure seawater and on optically active substances that are generally present in seawater.

2. Terminology, and Symbols

When treating a complex science, it is desirable to work with a concrete foundation of notations, units, symbols and definitions for the parameters that are to be studied. interpreted and analysed. This is especially true in a field like optical oceanography, where some of the terms are specific to this branch of optics and liable to confuse the non-initiated. The committees of experts have been working since the nineteen fifties, at formulating a complete and standardised set of definitions for the use of optical oceanographers. The latest updated version of this can be found in Morel and Smith[1].

Same important definitions of relevance to the present study are briefly presented and discussed in Appendix I.

3. Optically active substances in seawater

It is generally admitted that three categories of substances are optically active in seawater. These substances are :

(i) Phytoplankton and associated detrital matter, (ii) Dissolved organic matter and (iii) Suspended material not belonging to group (i), such as sediments in suspension (non-chlorophyllous particles).

Inherent optical properties are invariant with changes in radiance distribution. They also obey simple additive laws. That is, if there are *n* constituents in a medium, the inherent optical properties of the medium can be obtained simply by adding those of the individual *n* components. So, if subscripts *w*. p, y and x refer to pure seawater, phytoplankton, yellow substances and non-chlorophyllous particles respectively, then the absorption and scattering coefficients of seawater at wavelength λ can be expressed as :

$$a(\lambda) = a_w(\lambda) + C_p.\, a_p^*(A) + C_y.\, a_y^*(\lambda) + C_x\, a_x^*(A)$$

and

$$b(\lambda) = b_w(\lambda) + C_p.\, b_p^*(A) + C_x.\, b_x^*(A)$$

where C is the concentration, and a* and ***b**** are specific absorption and scattering coefficients respectively (m^{-1} per unit concn).

If the 'spectral signatures' (i.e. the spectral values of the specific absorption and scattering coefficients) of the different substances and those of pure seawater are known, then the total absorption and scattering coefficients a and ***b*** at any wave length can be calculated, for any given concentrations of the substances. From ***b***, the volume scattering function $\beta(\theta)$ can be calculated, if the probability distribution function with respect to angle of this parameter is known.

In the following sections, our knowledge of the spectral signatures of these substances is briefly examined.

4. Pure seawater

Optical properties of optically pure water (fresh water and seawater) and those of the clearest natural waters, have been the subject of numerous investigations. One of the latest critical appraisals of these studies can be found in Smith and Baker[2].

The scattering properties of pure fresh water and seawater are quite accurately known. Morel[3] found good agreement between theoretical and experimental values of scattering. He computed b_w and $\beta(\theta)$ for pure seawater using the following equations

$$R_{\text{iso}} = \frac{2\pi^2}{\lambda_0^4} KTn^2 \frac{1}{\beta_T} \left(\frac{\partial n}{\partial p} \right)_T^2$$

$$R_{\text{tot}} = R_{\text{iso}} \frac{6 + 6\delta}{6 - 7\delta}$$

$$\beta(\theta) = \beta(90) \left(1 + \frac{1 - \delta}{1 + \delta} \cos^2 \theta \right)$$

$$b_w = \frac{8\pi}{3} \beta(90) \frac{2 + \delta}{1 + \delta}$$

where

$R_{lol} \equiv \beta(90)$ = Rayleigh ratio
R_{tso} = isotropic part of R_{tot}
δ = depolarisation ratio
K = Beltzmann constant
T = absolute temperature
β_T = isothermal compressibility
n = refractive index
p = pressure

For $\delta = 0.09$, which was found most suitable, and T = 20°C and for salinity of sea water $S = 35 - 39‰$, Morel found b_w at 500 nm to be equal to $0.00288\ m^{-1}$. For expressing the wavelength dependence of b_w as a power law, the best exponent was found to be -4.32. Pure seawater was found to scatter 30% more than pure fresh water.

The best values of absorption coefficient of pure seawater, as recommended by Smith and Baker[2], are presented in Table 1, for the spectral region from 200 to 800 nm. These values are estimated on the basis of a critical evaluation of the many laboratory and in *situ* experiments performed by various authors. Smith and Baker estimated that these values are accurate within +25 and −5% from 300 to 480 nm, and +10 and −15% from 480 to 800 nm.

Table 1. Optical properties2 of pure seawaetr. Absorption coefficient a m^{-1}, scattering coefficient $b m^{-1}$ and irradiance attenuation coefficient $K m^{-1}$ for wavelength varying from 200 to 800nm.

λ (*nm*)	a_w (m^{-1})	b_w (m^{-1})	K (m^{-1})	λ (*nm*)	a_w (m^{-1})	b_w (m^{-1})	K (m^{-1})
200	3.07	0.151	3.14	500	0.0257	0.0029	0.0271
210	1.99	0.119	2.05	510	0.0357	0.0026	0.0370
220	1.31	0.0995	1.36	520	0.0477	0.0024	0.0489
230	0.927	0.0820	0.968	530	0.0507	0.0022	0.0519
240	0.720	0.0685	0.754	540	0.0558	0.0021	0.0568
250	0.559	0.0575	0.588	550	0.0638	0.0019	0.0648
260	0.457	0.0485	0.481	560	0.0708	0.0018	0.0717
270	0.373	0.0415	0.394	570	0.0799	0.0017	0.0807
280	0.288	0.0353	0.306	580	0.108	0.0016	0.109
290	0.215	0.0305	0.230	590	0.157	0.0015	0.158
300	0.141	0.0262	0.154	600	0.244	0.0014	0.245
310	0.105	0.0229	0.116	610	0.289	0.0013	0.290
320	0.0844	0.0200	0.0944	620	0.309	0.0012	0.310
330	0.0678	0.0175	0.0765	630	0.319	0.0011	0.320
340	0.0561	0.0153	0.0637	640	0.329	0.0010	0.330
350	0.0463	0.0134	0.0530	650	0.349	0.0010	0.350
360	0.0379	0.0120	0.0439	660	0.400	0.0008	0.400
370	0.0300	0.0106	0.0353	670	0.430	0.0008	0.430
380	0.0220	0.0094	0.0267	680	0.450	0.0007	0.450
390	0.0191	0.0084	0.0233	690	0.500	0.0007	0.500
400	0.0171	0.0076	0.0209	700	0.650	0.0007	0.650
410	0.0162	0.0068	0.0196	710	0.839	0.0007	0.834
420	0.0153	0.0061	0.0184	720	1.169	0.0006	1.170
430	0.0144	0.0055	0.0172	730	1.799	0.0006	1.800
440	0.0145	0.0049	0.0170	740	2.38	0.0006	2.380
450	0.0145	0.0045	0.0168	750	2.47	0.0005	2.47
460	0.0156	0.0041	0.0176	760	2.55	0.0005	2.55
470	0.0156	0.0037	0.0175	770	2·51	0.0005	2·51
480	0.0176	0.0034	0.0194	780	2.36	0.0004	2.36
490	0.0196	0.0031	0.0212	790	2.16	0.0004	2.16
				800	2.07	0.0004	2.07

For wavelengths below 300 nm, the suggested values represent an 'educated estimate'. There does not appear to be any appreciable difference between absorption by **pure** seawater and pure fresh water in the visible part of the electromagnetic spectrum. For wavelengths shorter than 375 nm, some authors have claimed that absorption increases with increasing concentration of dissolved salts, the increase becoming more marked for smaller wavelengths. But Smith and Baker conclude that convincing evidence is still lacking for proving this. (Fig. 1, Table 1).

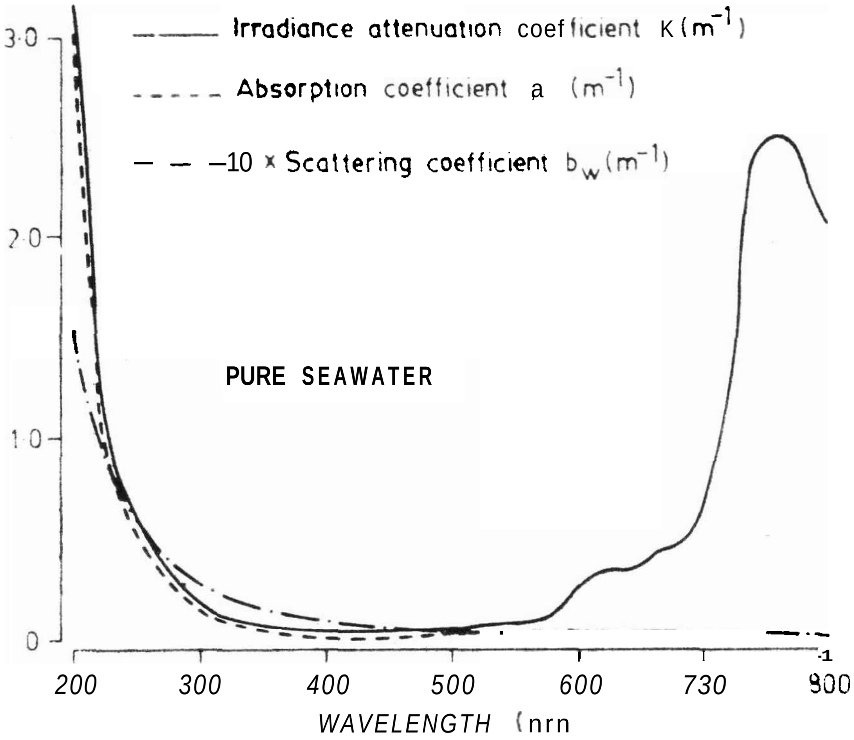

Figure 1. Absorption coefficient (a m^{-1}). scattering coefficient (b m^{-1}) for pure sea-water and irradiance attenuation coefficient (K m^{-1}) for the clearest natural waters are given[2]. (The scattering coefficient has been multiplied by 10, in order to avoid a change of scale).

It is to be mentioned that the work of Smith and Baker has fulfilled a long felt need of identifying a consistent, reliable and logical set of values for the absorption coefficient of pure seawater, from a large set of published data which show a great amount of disparity, far beyond the estimated accuracy of individual measurements.

5. Phytoplankton and their by-products

Phytoplankton are minute free floating plants of the sea. They are capable of photosynthesis and are the principal primary producers of the sea, and as such they are the first main link in the marine food chain. Their optical properties are of particular interest, since these determine the phytoplankton efficiency for fixing light energy through photosynthesis. The presence of varying quantities and qualities of phytoplankton in the sea can significantly alter the colour of the sea and the transmission characteristics of light in the sea. Phytoplankton comprise millions of species of unicellular algae, of varying size, shape and composition. Initially, it may appear to be an impractical task to classify their optical properties. However, scientists working over the last few decades, have made some headway in this direction.

The principal light absorbing pigment in phytoplankton is the chlorophyll-a characterised by an ***in vivo*** absorption peak at around 440 nm and a secondary peak at around 675 nm. Chlorophyll-a is generally accompanied by secondary pigments like chlorophylls *b* and *c*, and carotenoids, in varying concentrations. Decaying phytoplankton contain the degradation products of these pigments, like the pheophytins. The presence of these pigments gives rise to additional absorption bands superimposed on those of chlorophyll-a. The *in vivo* absorption characteristics of these pigments are different from those of the extracted pigments. Most of the experimental studies on phytoplankton absorption *in vivo* have been carried out on monospecific cultures. These measurements, and supporting theoretical studies, have shown that, generally, these absorption spectra show some common characteristics. with a certain variability superimposed on it. This variability may be attributed to variations in pigment composition, intracellular pigment concentration, and the size and shape of the cells. Detailed discussions on the theoretical and experimental aspects of this intricate problem can be found in literature.[4,5]

Laboratory measurements under controlled conditions are very useful when we are attempting to understand the causative factors leading to the observed phenomena; but in this particular case it cannot be claimed that laboratory experiments are carried out under conditions truly representative of those *in situ*. Recently, some efforts have been made to estimate the *in situ* absorption spectra of phytoplankton. Direct measurement of this parameter is usually a difficult proposition because of the low concentrations of phytoplankton *in situ* (as compared to the high concentrations that can be achieved in laboratory cultures) and the presence of other absorbing material (particulate or dissolved) along with the phytoplankton. Since in *situ* optical properties are of greater relevance to this paper than laboratory results, they are discussed here in detail.

Prieur and Sathyendranath[6] used *in situ* total absorption coefficient, estimated from measured values of diffuse attenuation coefficient and diffuse reflectance. From the total absorption, the contributions due to phytoplankton, dissolved organic matter and non-chlorophyllous particles were evaluated by regression techniques. They used the sum of chlorophyll-a and pheophytin-a concentrations as the index of phytoplankton concentration. In other words, no effort was made to separate the spectral signatures of live phytoplankton, and those in varying stages of decay. According to their results, the form of the phytoplankton absorption curve shows apparently little variation from one region to another, though the absorption efficiency (or specific absorption) is variable. The absorption efficiency at 440 nm was found to vary from 0.018 $[m^{-1}/(Chl\text{-}a+Pheo\text{-}a)]$ in productive coastal waters, to 0.070 in oligotropic open ocean waters and 0.077 in very turbid, eutrophic near-shore waters. These results came off a large number of measurements made in Central East Pacific, Sargasso Sea, Gulf of Mexico, off the west coast of Africa, Indian Antarctic waters, and off Marseilles in the Mediterranean. Kiefer and SooHoo[7] made their measurements in the coastal waters of Baja California. Seawater samples were filtered through glass fibre filtres to concentrate the phytoplankton, and their absorption was measured directly by a specially constructed single beam spectrophotometer with a vertical light path. In the waters sampled, particulate material was predominantly

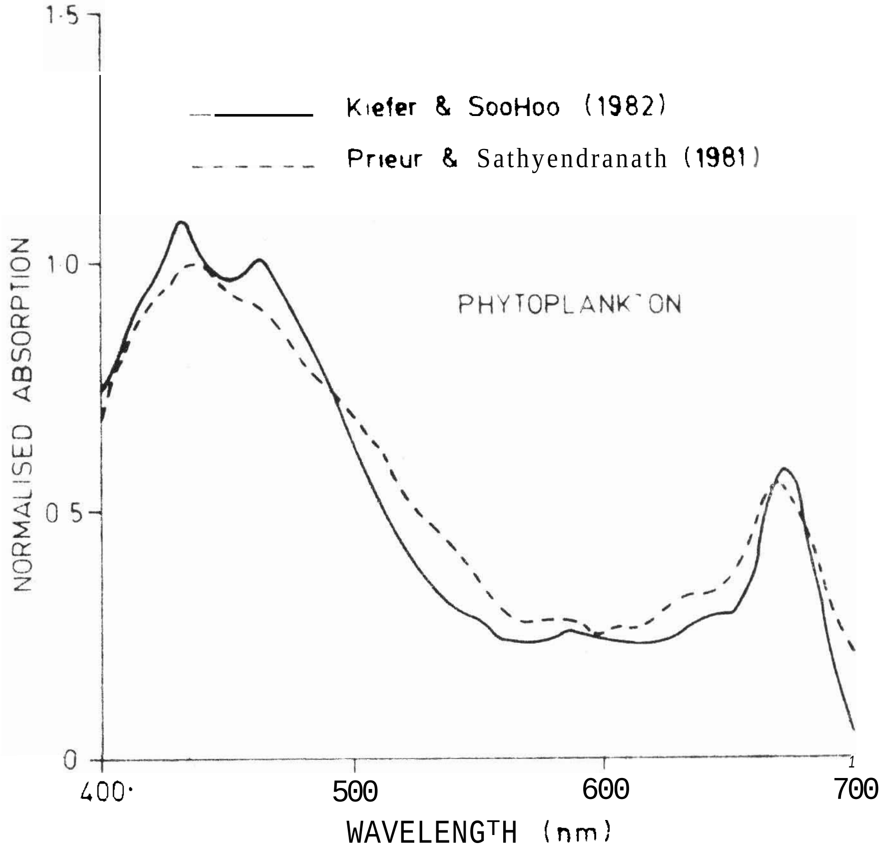

Figure 2. **Absorption spectra associated with phytoplankton in *vivo* and *in situ*. In order to compare the form of the spectra, the (P & S curve has been normalised at 440 nm, and K & S curve at 442 nm.)**

phytoplankton and associated detritus. By multiple regression, they estimated the components of absorption covarying with *Chl-a* and with pheopigments. They found a specific absorption of 0.022 ($m^{-1}/Chl\text{-}a$) at 440 nm. The normalised absorption curves associated with phytoplankton, a sestimated by Prieur and Sathyendranath[6] and Kiefer and SooHoo[7] are presented in Fig. 2. It is seen that, in spite of vast differences in the techniques employed, the two curves show good comparison. The specific absorption curve associated with pheopigments, as proposed by Kiefer and SooHoo, is shown in Fig. 3. It may be noted that the phytoplankton absorption curve proposed by Prieur and Sathyendranath do not show the characteristics of the curve in Fig. 3, even though they have used (*Chl-a*+*Pheo-a*) as the index of phytoplankton concentration. According to Kiefer and SooHoo, low concentrations of pheopigments in most of the samples of Prieur and Sathyendranath contained would account for this.

Regarding the scattering due to phytoplankton, various observations have shown that this parameter shows strong selectivity[8-11]. The scattering minima are associated with absorption maxima, in accordance with the theory of anomalous dispersion. For calculating scattering coefficient b_p at 550 nm from known concentrations of phytoplankton, Morel[12] has proposed the following relationship based on in *situ* observations :

$$b_p\,(550) = 0.12\,[\,(Chl\text{-}a + Pheo\text{-}a)\ mg.m^{-3}]^{0.63}$$

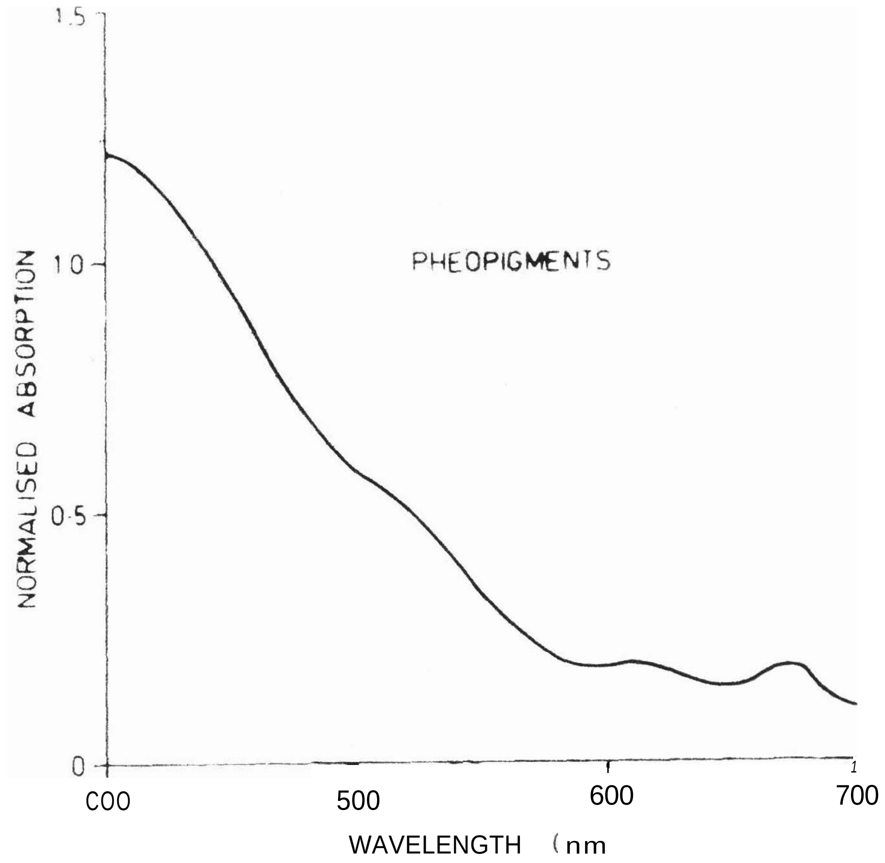

Figure 3. Absorption spectrum' associated with pheopigments normalized at 442 nm.

As a first approximation, the spectral variations in scattering due to phytoplankton may be supposed to be inversely proportional to absorption, until better models are evolved. The scattering by phytoplankton is always predominant in the forward direction. However, backscattering is still of particular interest in many investigations, and this parameter also has been the subject of some studies[11,13&14]. Some of these studies indicate that the ratio of backscattering to total scattering is generally much less than 1 per cent and shows spectral dependence. The spectral dependence of this ratio suggests that the volume scattering function does not have the same form from one wavelength to another. Efforts at modelling the inherent optical properties of phytoplankton using the Mie Theory have met with a certain amount of success[10,14 & 15].

6. Dissolved organic matter

Various organic substances (mostly melanoidines and humic acids) in dissolved or colloidal states are generally present in seawater in varying quantities. It is common practice to club this complex amalgam of substances under the name of yellow substances, 'gelbstoff' or 'gilvin'. Their concentrations are found to be much higher in coastal waters where land drainage is considerable, than in open ocean waters. The absorption spectrum of dissolved organic matter was studied[16] as far back as

1938. A number of investigations[17–26] have followed since then. These studies have indicated that the absorption increases exponentially towards shorter wavelengths. Morel and Prieur[27] expressed this by the equation :

$$a_y\,(A) = a_y\,(\lambda_o)\,\exp\,[-\mathbf{0.014}\,(A - \lambda_o)\,]$$

where

$$a_y\,(A) = C_y \,.\, a_y^*\,(\lambda)$$

The study[35] on 105 water samples from diverse regions confirmed this as a mean law, with a standard deviation of **0.003** around the exponential coefficient **0.014.**

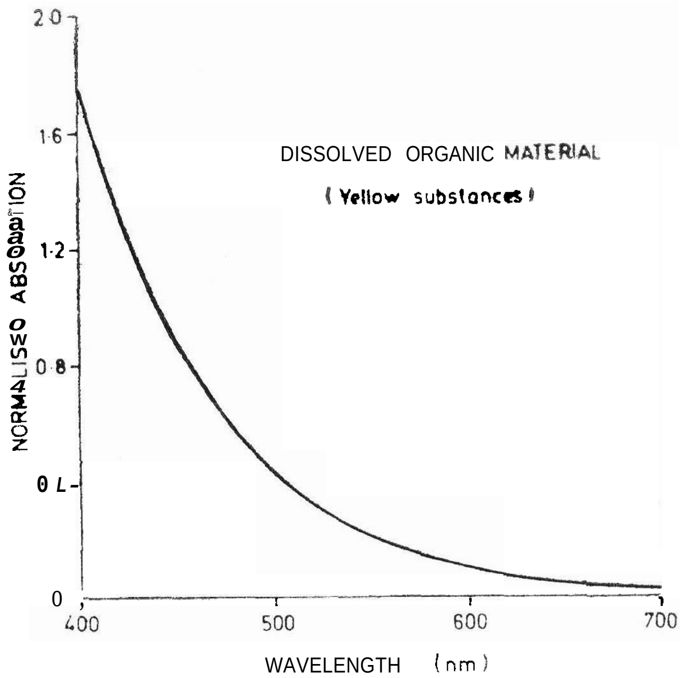

Figure 4. **Absorptiorr spectrum of dissolved organic matter, as given by the mean exponential law. Spectrum is normalised at 440 nm.**

The mean absorption curve of yellow substances is presented in Fig. 4 and the values are presented in Table 2.

7. Non-chlorophyllous particles

Only a few studies so far have thrown light on the absorption properties of such particles. Prieur and Sathyendranath[R] proposed a U-shaped curve (Fig. 5) based on measurements off the west coast of Africa. But Yentsch[28], studying the absorption spectrum of suspended particles, observed a neutral spectrum in the coastal

Table 2. The spectral values6 of the absorption coefficient associated with phytoplankton (a,), non-chlorophyllous particles (a,) and yellow substances (a . The spectral values are all normalised at **440** nm.

In order to obtain the absolute obsorption coefficient associated with each category of substance, the values given here have to be multiplied by the absorption efficiency at the wavelength of normalisation, and the concentration of the substance.

λ nm	a_c	a_x	a_y	λ nm	a_c	a_x	a_p
400	0.685	1.892	1.751	555	0.321	0.566	0.200
405	0.781	1.766	1.632	560	0.294	0.565	0.186
410	0.828	1.726	1.522	565	0.273	0.587	0.174
415	0.883	1.635	1.419	570	0.276	0.599	0.162
420	0.913	1.534	1.323	575	0.278	0.569	0.151
425	0.939	1.410	1.234	580	0.281	0.624	0.141
430	0.973	1.274	1.150	585	0.279	0.649	0.131
435	1.001	1.119	1.073	590	0.270	0.718	0.122
440	1.000	1.000	1.000	595	0.252	0.805	0.114
445	0.971	0.914	0.932	600	0.256	0.850	0.106
450	0.944	0.868	0.869	605	0.262	0.913	0.099
455	0.928	0.764	0.811	610	0.261	0.879	0.093
460	0.917	0.691	0.756	615	0.268	0.877	0.086
465	0.902	0.636	0.705	620	0.281	0.875	0.080
470	0.870	0.589	0.657	625	0.299	0.910	0.075
475	0.839	0.567	0.613	630	0.316	0.935	0.070
480	0.798	0.522	0.571	635	0.328	0.992	0.065
485	0.773	0.496	0.533	640	0.329	1.041	0.061
490	0.750	0.483	0.497	645	0.337	1.133	0.057
495	0.717	0.474	0.463	650	0.361	1.227	0.053
500	0.688	0.473	0.432	655	0.397	1.337	0.049
505	0.645	0.480	0.403	660	0.457	1.528	0.046
510	0.618	0.509	0.375	665	0.529	1.542	0.043
515	0.582	0.495	0.350	670	0.556	1.542	0.040
520	0.528	0.488	0.326	675	0.534	1.542	0.037
525	0.504	0.488	0.304	680	0.485	1.542	0.035
530	0.474	0.495	0.284	685	0.411	1.542	0.032
535	0.444	0.505	0.264	690	0.334	1.542	0.030
540	0.416	0.526	0.247	695	0.270	1.542	0.028
545	0.384	0.548	0.230	700	0.215	1.542	0.026
550	0.357	0.548	0.214				

waters off woodshole, and one similar to that of yellow substances for samples from depths greater than 100 m.

Morel[29] **has** discussed in detail the theoretical and experimental aspects of scattering in natural seawater. Assuming that scattering by mineral particles predominates over phytoplankton scattering in the cases investigated by him. some salient features may be summarised as follows :

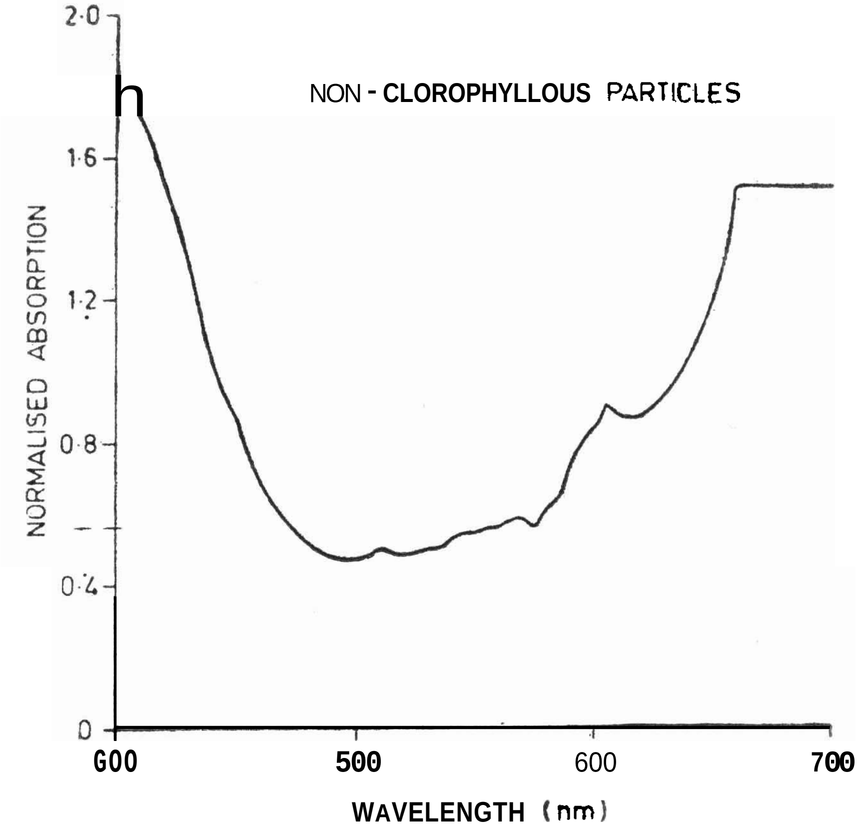

Figure 5. Absorption spectrum of non-chlorophyllous particles[6].

Table 3. A typical volume scattering function for marine particles. The β (θ) values[29] are normalised at 90°.

θ°	$\frac{\beta(\theta)}{\beta(90)}$	θ°	$\frac{\beta(\theta)}{\beta(90)}$
1	34400	20	102
1.5	26100	22	75
2	19100	24	58
3	8500	26	47
4	4750	28	38
5	2990	30	31.4
6	1920	45	8.50
7	1300	60	3.41
8	915	75	1.61
9	670	90	$\equiv 1$
10	500	105	0.74
12	314	120	0.65
14	224	135	0.65
16	168	150	0.87
18	130		

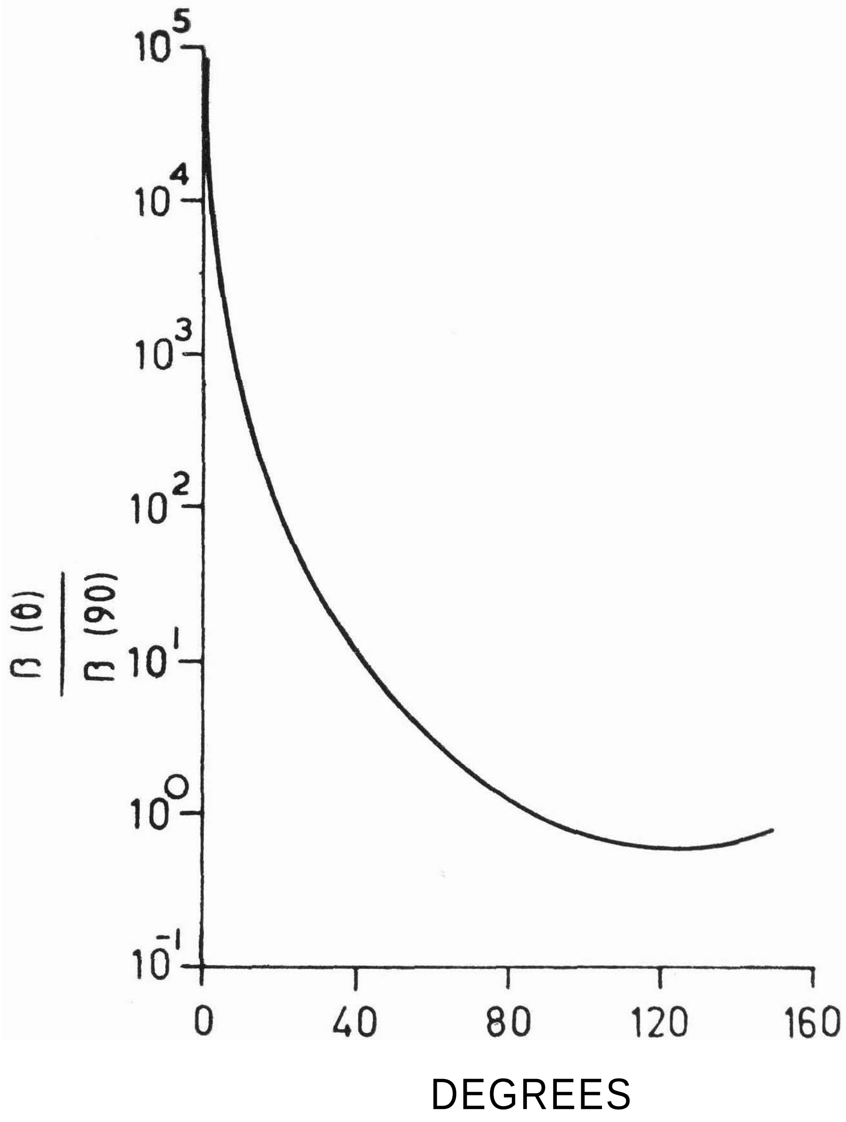

Figure 6. Curve showing a typical volume scattering function for marine particles (Morel[29]).

1. Forward scattering predominates largely over backward scattering. A typical scattering function for marine particles, as proposed by Morel is presented in Fig. 6. The typical curve is a mean curve based on a number of observations by various authors. Changes around this mean curve occur with changes in the size, shape and refractive index of the particles. The values corresponding to the curve in Fig. 6 are presented in Table 3.

2. Experimental results show that weavelength dependence of the scattering coefficient due to particles can be expressed approximately by a λ^{-n} law, with n varying from 1 to 2. Theoretical calculations on Mie scattering, assuming a Junge law for particle size distribution (which appears to be realistic for marine particles), yield values of n varying between 0 and 2, which is in accordance with the experimental results.

Direct relationships between particle concentration and the total particle scattering coefficient have also been investigated. Ivanoff[30] has pointed out that linear relationships often exist between these two parameters. He, however, warns against the indiscriminate use of any single relationship, as this is subject to changes depending on the nature of the particles.

8. Relationships between inherent and apparent optical properties

The apparent properties are the attenuation coefficient for any of the radiometric quantities (such as irradiance and radiance) and the irradiance reflectance ratio (also known as diffuse reflectance). Of these, the most studied parameters are the irradiance attenuation coefficient for downwelling and upwelling light, K_d and K_u respectively, and the diffuse reflectance R. They are easily accessible to direct measurements and they have direct applications in fields such as aquatic photosynthesis and remote sensing. Besides, these are quasi-inherent properties in the sense that often, the variations in the radiance field do not introduce considerable variations in these parameters, and so they can be expressed as functions of inherent properties with a good degree of accuracy.

Many workers have proposed relationships between inherent and apparent properties based on experimental results or theoretical considerations.

For example,

$$R = 0.33\ b_b/a$$

according to Prieur and Morel[27] and Prieur[31]. Slightly different relationships have been proposed by others[32-34]. Here b_b is the backscattering coefficient.

Morel and Prieur[27] have put forward the following relationship between a, K_d and R:

$$a = \frac{K_d\,(1 - \mathrm{R}) \cos j}{0.6 + (0.47 + 2.5\,\mathrm{R}) \cos j}$$

where j is the sun zenith angle in water.

9. Discussion and conclusion

In the previous sections, we have examined the optical properties of pure seawater and particulate and dissolved substances present in it. Inherent properties have been discussed in detail, since they are invariant with changes in radiance distribution, and as such, they are very suitable for model studies. Inter-relationships between inherent properties and some of the important apparent properties are also presented, so that apparent properties can be calculated quite simply, if the inherent properties are known, or vice versa.

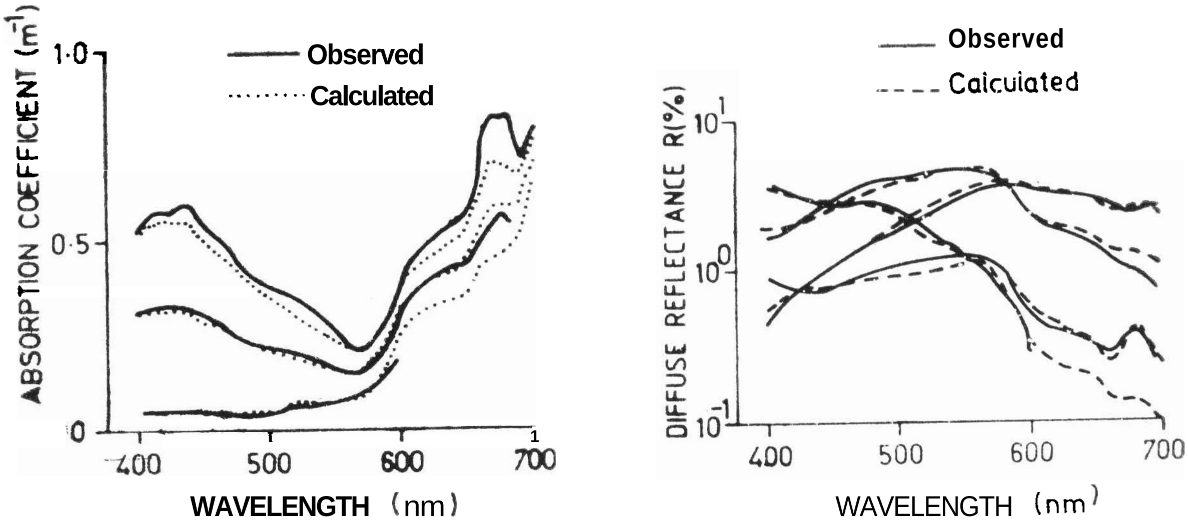

Figure 7. Some examples of the reconstruction of observed optical properties, using the concentrations of the optically active substances (phytoplankton, non-chlorophyllous particles and yellow substances) and their spectral signatures. The curves correspond to different types of seawater.

Left—Absorption coefficient'' Right—Diffuse reflectance R[4,35].

The optically active substances considered here are phytoplankton, other particulate material and dissolved organic matter. Some recent works[4,6& 35] have demonstrated that, using the spectral signatures discussed in this paper, it is possible to reconstruct some observed optical properties with a good precision, if the concentrations of the optically active substances are known (Fig.7). These results are based on a large number of observations in diverse regions of the world oceans. Similar work has been done by Smith and Baker[26,36&37] for waters where biogenous materials predominate. (They however, preferred to work directly on the attenuation coefficient for irradiance K, relying on the quasi-inherent nature of this parameter.) But it is to be stressed that, each of the three categories of substances considered here in turn represent groupings of highly heterogenous material, and so a certain amount of variability can be anticipated in their optical characteristics. As our understanding of the optical properties grows, it would be possible to sub-divide the groups and refine the models so as to account better for this variability. Some progress in this direction has already been made by Kiefer and SooHoo[7], who have separated the absorption properties of live phytoplankton from those in the process of decaying.

While creating an optical model for any application, it would be necessary to use not only realistic spectral signatures for the optically active substances present in the water, but also realistic concentrations of these substances. This would imply some apriori knowlege of the hydrography of the area for which the model is intended. For example, it would be realistic to included high concentrations of non-chlorophyllous particles in a model for turbid coastal waters, but this component would generally be negligible for open ocean waters. Again, for the open ocean waters, it may be reasonable to simplify the model by supposing the yellow substance concentration to covary with the phytoplankton concentration.

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Appendix-I

The parameters of optical oceanography may be categorised into three main groups.

i. Parameters needed to define the properties of light emanating from a surface or a point source.

ii. Parameters needed to define the properties of light impinging on a surface or a point in space.

iii. The inherent optical properties of the medium which determine the mode of propagation of light within the medium.

Given parameters (i), the parameters (ii) anywhere within the medium can be calculated using suitable models of radiation transfer, provided parameters (iii) are known.

The radiometric concepts leading to the definitions of parameters of category (i) and (ii) are illustrated in Fig. 8. It is easy to see that the given set of six parameters completely define all the properties of radiation reaching or leaving a given point in space.

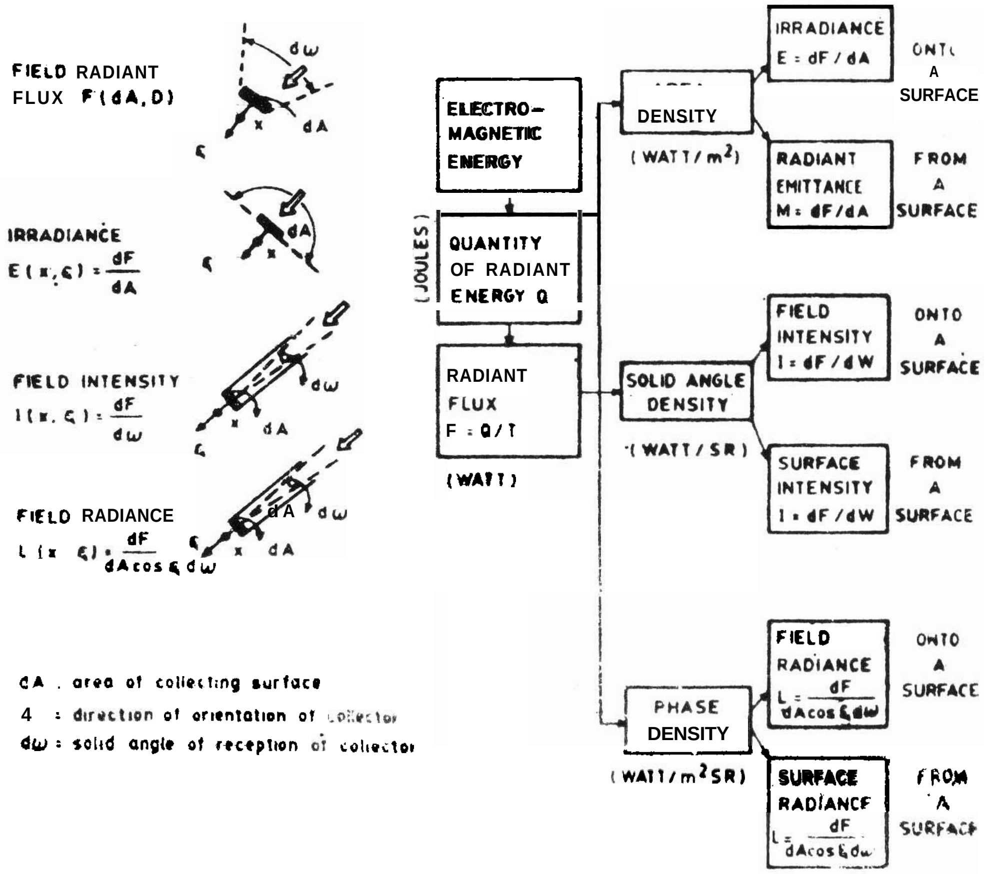

Figure 8. Radiometric concepts and units. (Adapted from Preisendorfer[38])

The absorption coefficient a and the volume scattering function $\beta(\theta)$ completely define the inherent optical properties (iii) of a medium. The total volume scattering coefficient b and the attenuation coefficient c are also inherent properties of the medium, and can be calculated, knowing a and $\beta(\theta)$, These properties are defined for a parallel, monochromatic light beam incident normally on an infinitesimally thin layer of the medium. Fig (9) illustrates the concepts of absorption and scattering coefficients. It is easy to note that absorption represents a loss of energy at that wavelength, whereas scattering entails only a change of direction of the incident photons.

Attenuation coefficients are also defined for the parameters of radiation field. For example, the irradiance attenuation coefficient expresses the rate of decrease of irradiance with distance. Such properties, however, cannot be considered as an inherent property of the medium, since they are also dependent on the angular distribution of radiation in the field. This type of properties are therefore referred to as 'apparent'. But it is often easier to devise instruments for measurement of apparent properties than inherent properties, and it is common practice to measure apparent properties, and then derive the inherent properties from them using equations established through radiation transfer models.

$$dF = a\ F\ dr$$

$$F = F_0\, e^{-ar}$$

ABSORPTION COEFFICIENT a

$$dI_\theta = \beta(\theta)F\ dr \ \underline{\text{or}}\ dI_\theta = \beta(\theta)E\ dr$$

$$dF = b \cdot F\ dr \ \text{and}\ b = \iint \beta(\theta)\, d\omega$$

SCATTERING COEFFICIENT b **and** SCATTERING FUNCTION $\beta(\theta)$

TOTAL ATTENUATION COEFFICIENT $c = a + b$

Figure 9. Schematic representation of inherent optical properties. (Adapted from Ivanoff[30])

It may be noted that terms like 'turbidity' and 'transparency' have no place in this scheme. They have no strict definition, but are often used as descriptive terms. All these parameters are wavelength dependent.