Optical properties of the clearest natural waters (200–800 nm)

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A new UV submersible spectroradiometer has been employed to determine the diffuse attenuation coefficient for irradiance in the clearest natural waters $[K_w(\lambda)]$ with emphasis on the spectral region from 300 to 400 nm. $K_w(\lambda)$ can be related to the inherent optical properties of pure water, in particular the total absorption coefficient $a_w(\lambda)$ and the molecular scattering coefficient $b_m(\lambda)$, by means of equations derived from radiative transfer theory. We present an analysis showing that limiting values of $K_w(\lambda)$ can be estimated from $a_w(\lambda)$ and vice versa. Published $a_w(\lambda)$ data, which show discrepancies much larger than their estimated accuracies, are briefly reviewed and then compared, via our analysis, with $K_w(\lambda)$ data (our own new and previously published data as well as relevant data of others). This comparative analysis and new data allow a consistent and accurate set of optical properties for the clearest natural waters and for pure fresh water and saltwater to be estimated from 300 to 800 nm.

I. Introduction

The optical properties of both pure liquid water and the clearest natural fresh waters and saltwaters have been investigated by numerous authors. Recent critical reviews of experimental data include those by Irvine and Pollack,[1] Jerlov,[2] Hale and Querry,[3] Kopelevich,[4] Morel,[5] Smith and Tyler,[6] and Querry et al.[7] Most recently, measurements of the optical absorption coefficients of pure water (usually doubly distilled in quartz) have been made in selected regions of the visible spectrum by Morel and Prieur[8] by absorption spectrophotometry, Hass and Davisson[9] by adiabatic laser calorimetry, Querry et al.[7] (using deionized filtered water) by a split-pulse laser method, and Tam and Patel[10] by laser optoacoustic spectroscopy.

Most early absorption measurements were made by employing conventional absorption spectrophotometer techniques. These techniques require careful evaluation of the optical characteristics of the transmission cell and preparation of water free from contaminant scattering and absorbing material. The large discrepancies among the experimental data of this early work have been noted in the above reviews, and possible reasons for these discrepancies are discussed at length.[6] The

latest data, save for the careful work of Morel and Prieur, involve new techniques that avoid many of the experimental problems associated with the earlier methods. Thus there is less discrepancy among the later data, although the agreement is not as good as the published accuracies would suggest. As a consequence, there is still uncertainty in the choice of the most reliable data set.

Researchers concerned with the penetration of solar radiation into natural waters have a keen interest in the inherent optical properties of pure water, since, in principle, these inherent optical properties can be used to calculate the apparent optical properties of the clearest natural waters.[2,11,12–14] These properties can, in turn, be used to describe quantitatively the maximum penetration of solar radiation to depths in natural waters for the estimation of a variety of aquatic photoprocesses.[15,16]

Conversely, experimental values of the apparent optical properties for the clearest natural waters can be used to estimate theoretically values of the inherent optical properties of pure water. In the following we summarize both the most recent and the most reliable data of the total absorption coefficient of pure water $a_w(\lambda)$, in the 200–800-nm spectral region. By means of simple approximations derived from radiative transfer theory, these data are then compared with values of the diffuse attenuation coefficient $K_w(\lambda)$ determined for the clearest natural waters. The comparison demonstrates that some laboratory determinations of $a_w(\lambda)$ are inconsistently large. From our own experimental $K_w(\lambda)$ data, which includes the UV region from 300 to

400 nm and from the published $a_w(\lambda)$ data, we have selected a consistent set of data for the optical properties of the clearest natural waters. This selection provides upper bound estimates for the absorption coefficient of pure water.

II. Theoretical Background

The optical properties of the sea can be divided into two classes, the inherent and the apparent optical properties of the medium.[11,12] An optical property is inherent if its operational value at a given point in a medium is invariant with changes of the radiance distribution at that point. Inherent optical properties (IOP) directly specify the true scattering and absorbing characteristics of the medium and are dependent upon the dissolved and suspended material in the water and the electromagnetic properties of the medium. These properties are of particular practical importance when considering high-resolution image transmittance through ocean waters.

An optical property is apparent if its operational value at a given point in a medium is dependent upon the radiance distribution at that point. Apparent optical properties (AOP) can be related to IOP by means of radiative transfer theory and, like the IOP, are dependent on the dissolved and suspended material in the water in addition to the geometry of the lighting distribution. AOP are of particular importance when considering the penetration of radiant energy to depths in ocean waters.

The diffuse attenuation coefficient for irradiance $K(\lambda)$ is the AOP that provides the most direct measure of the penetration of radiant energy in ocean water, i.e.,

$$E(\lambda,z) = E(\lambda,0^-) \exp[-K(\lambda) \cdot z], \quad (1)$$

where $E(\lambda,z)$ is the spectral irradiance at depth z and $E(\lambda,0^-)$ is the irradiance just beneath the surface. $K(\lambda)$ is the ocean optical property necessary for the solution of a wide range of ocean scientific and engineering problems, is measurable *in situ* by appropriate instrumentation, is directly related to the inherent optical properties,[12,13] and has been shown to be quasi-inherent.[17]

A number of experimental and theoretical studies have shown or derived relationships between the diffuse attenuation coefficient and the inherent optical properties of natural waters.[2,11–14,18,19] Preisendorfer,[12] for example, derived a set of inequalities and approximations,

$$c \approx K + b_f > K = D \cdot a + b_b > a + b_b > a, \quad (2)$$

where $c = a + b$ is the total beam attenuation coefficient, a is the total absorption coefficient, $b = b_f + b_b$ is the total scattering coefficient, b_f is the forward scattering coefficient, b_b is the backscattering coefficient, and D is the distribution function. All these coefficients are a function of wavelength. (We suppress the explicit λ dependence unless it is necessary for clarity.)

When discussing natural waters the attenuation coefficient can be written

$$c = c_w + b_p + a_p + a_y, \quad (3)$$

where c_w is the attenuation coefficient for pure water, b_p is the scattering coefficient for particles, a_p is the absorption coefficient for particles, and a_y is the absorption coefficient for dissolved organic material (yellow substance).

Optically pure water is defined as a medium that is devoid of dissolved and suspended particulate material ($b_p = a_p = a_y = 0$). Thus

$$c_w = a_w + b_m, \quad (4)$$

where a_w is the absorption coefficient for pure water, and b_m is the molecular scattering coefficient for pure water. Morel[5] has determined (and reviewed previous values for) the total scattering coefficient for both pure freshwater b_m^{fw} and pure saltwater (35–39‰) b_m^{sw} as a function of wavelength. Compared with $a_w(\lambda)$, $b_m(\lambda)$ is accurately known.

From the above relations we can obtain the inequality,

$$K_w^{fw} \geq a_w + \tfrac{1}{2}b_m^{fw}, \quad (5)$$

where K_w^{fw} is the diffuse attenuation coefficient for the clearest natural freshwaters (e.g., Crater Lake, Ore.[20]), and $\tfrac{1}{2}b_m^{fw}$ is the backscattering coefficient for molecular (Rayleigh) scattering in freshwater. Thus, $K_{\min}^{fw} = a_w + \tfrac{1}{2}b_m^{fw}$ represents the lowest experimental value one could expect to encounter in natural freshwater based on laboratory measured values of the inherent optical properties for pure water.

An analogous argument holds for the clearest ocean waters if we assume that the absorption of freshwater and saltwater is the same so that a minimum expected diffuse attenuation coefficient for seawater (e.g., Sargasso Sea[2]) is

$$K_{\min}^{sw} = a_w + \tfrac{1}{2}b_m^{sw}. \quad (6)$$

If the salts in seawater cause a weak absorption in the UV region, slowly increasing with shorter wavelengths,[21,22] the inequality corresponding to Eq. (6) holds even more strongly.

A further refinement to Eq. (6) can be made. The total backscattering coefficient for clear ocean waters can be written

$$B \cdot b = B \cdot b_m^{sw} + B \cdot b_p(\lambda_0) \cdot \left(\frac{\lambda}{\lambda_0}\right)^n, \quad (7)$$

where $B = b_b/b$ is the backscattering function, and n is an exponent defining the wavelength dependence of particle scattering. For the Sargasso Sea $b_p (515) \approx 0.023$ (m^{-1})[23,24] and $B \approx 0.044$ (Ref. 25) so that

$$K_{\min}^{sw} = a_w + \tfrac{1}{2}b_m^{sw} + 0.0010 \left(\frac{\lambda}{515}\right)^n. \quad (8)$$

The procedure described above for estimating a value of $K_{\min}$ from the inherent optical properties can be reversed by rewriting the inequality, i.e.,

$$a_w \leq K_w - \tfrac{1}{2}b_m. \tag{9}$$

Thus given experimental values for $K_w(\lambda)$ from very clear ocean waters a maximum value for $a_w(\lambda)$ can be estimated by setting $a_{max} = K_w - \tfrac{1}{2}b_m$ (or $K_w - B \cdot b$). In other words, if reliable field data from the clearest natural waters are available, an upper bound for the absorption of pure water can be estimated.

III. Brief Review of $a_w(\lambda)$ Data

Figure 1 presents the results from a selected number of investigators[22,26–32] from a previous review[6] plus more recent results.[7–10] In anticipation of the discussion to follow, the data of Morel and Prieur[8] and Tam and Patel[10] are indicated by solid and dashed lines, respectively. The other data are indicated by symbols as noted in the figure caption. For this figure we have converted $c_w(\lambda)$ (when that is what was experimentally determined) to $a_w(\lambda)$ by means of Eq. (4) using Morel's[5] $b_m^{fw}(\lambda)$ data.

Critical observations with respect to Fig. 1 are as follows: the data agree reasonably well (roughly within ±10%) for wavelengths >600 nm; a marked disagreement (at some wavelengths nearly an order of magnitude) among the data exists at wavelengths <600 nm,

in spite of claims of higher accuracies; the recent data of Morel and Prieur[8] (MP) and Tam and Patel[10] (TP) generally agree within ±10% except between 446 and 480 nm and between 515 and 546 nm; the other recent data of Querry et al.[7] are high compared with most other data for wavelengths less than ~580 nm; the few data points of Hass and Davisson agree with TP and MP at 488 nm but fall below these workers at 515 nm and below most other data at 633 nm.

IV. Experimental Results [$K_w(\lambda)$ Data]

Before continuing a discussion of the laboratory $a_w(\lambda)$ data displayed in Fig. 1, we now introduce experimental data of the diffuse attenuation coefficient for irradiance obtained at sea in clear ocean waters. Some of these data were obtained with the original Scripps submersible spectroradiometer,[33] whereas our more recent data have been obtained with a new underwater spectroradiometer capable of measuring spectral irradiance $E(z)$ throughout the near UV and visible region of the spectrum. This instrument, designed especially to include the mid UV region from 280 to 340 nm, and our method for determining $K_w(\lambda)$ by means of Eq. (1) are described in detail elsewhere.[34,35]
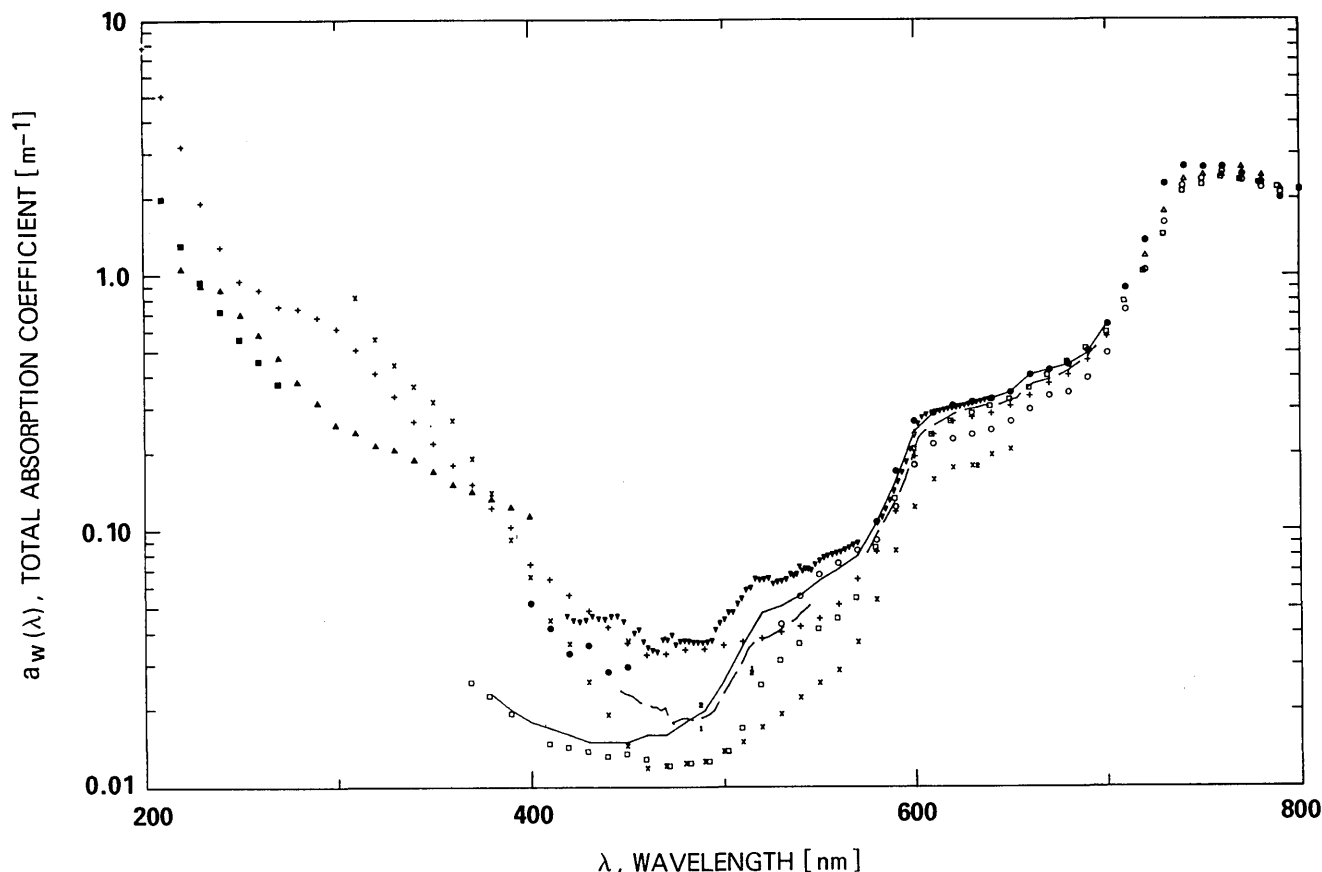

Fig. 1. Total absorption coefficient for pure freshwater $[a_w(\lambda)(m^{-1})]$ vs wavelength $[\lambda(nm)]$ as given by various authors: solid line, Morel and Prieur[8]; dashed line, Tam and Patel[10]; ▼, Querry et al.[7]; 1, 2, Hass and Davisson[9]; ×, Sawyer[26]; +, Dawson and Hulburt[27] (200–400 nm) and Hulburt[28] (400–700 nm); ▲, Lenoble and Saint-Guilly[31]; □, James and Birge[29]; ○, Clark and James[30]; △, Curcio and Petty[40]; ●, Sullivan[32]; ■, Armstrong and Boalch.[22]

Figure 2 presents $K(\lambda)$ data from various workers for clear ocean water. These data are distinguished by being from remote open ocean areas, where the absorption and scattering of dissolved and suspended particulate material are very low (e.g., chlorophyll concentrations of <0.04 mg chl m^{-3}); and the optical properties are relatively uniform to depths over which optical measurements were made. The solid circles, from 350 to 700 nm, show our determination of $K_w(\lambda)$ from earlier data obtained in the Sargasso Sea[36] as reanalyzed and augmented with data from the same region using both the new and old submersible spectroradiometers. The solid circles from 300 to 340 nm are our data from the Central Equatorial Pacific.[16] The solid boxes are our most recent data from the Sargasso Sea, and + and × indicate our recent data from other clear ocean areas. Also shown in Fig. 2 are Jerlov's $K(\lambda)$ values for his water type I solid ▼. An early determination of $K(310)$ for clear ocean water by Jerlov[37] ◊ and a more recent determination by Hojerslev[38] ◊ are indicated, and a recent value of $K(315)$ by Calkins[39] is indicated by □. Data of Lenoble[21] for clear ocean waters lie significantly above the data shown.

It should be noted that the precision in determining

$K_w(\lambda)$ can be quite good (±5% with cooperative environmental conditions). This is because our optical measurements can be, and generally are made to depths of several diffuse attenuation lengths $K_w^{-1}(\lambda)$ by means of a number of independent determinations of $E(z)$. A least squares fit to these independent determinations of $\ln E(z)$ vs depth z provides a precise determination of

$$K_w(\lambda) = \frac{-1}{E(z)}\frac{dE(z)}{dz} = \frac{-1}{z_2 - z_1}\ln\frac{E(z_2)}{E(z_1)}.$$

The absolute accuracy in determining $K_w(\lambda)$ is poorer than the precision because $K_w(\lambda)$, being an apparent optical property, is dependent on the radiance distribution of solar energy and hence has a slight functional dependence with depth even for uniform waters. However, it has been shown[17,38] that $K_w(\lambda)$ displays quasi-inherent characteristics, showing a relative insensitivity with sun angle. Thus absolute uncertainties in estimating $K_w(\lambda)$, save for very near surface values, are generally less than ±25% even under moderately adverse conditions. Given relatively calm seas, a clear sky, and a small sun zenith angle the accuracy in determining $K_w(\lambda)$ improves.
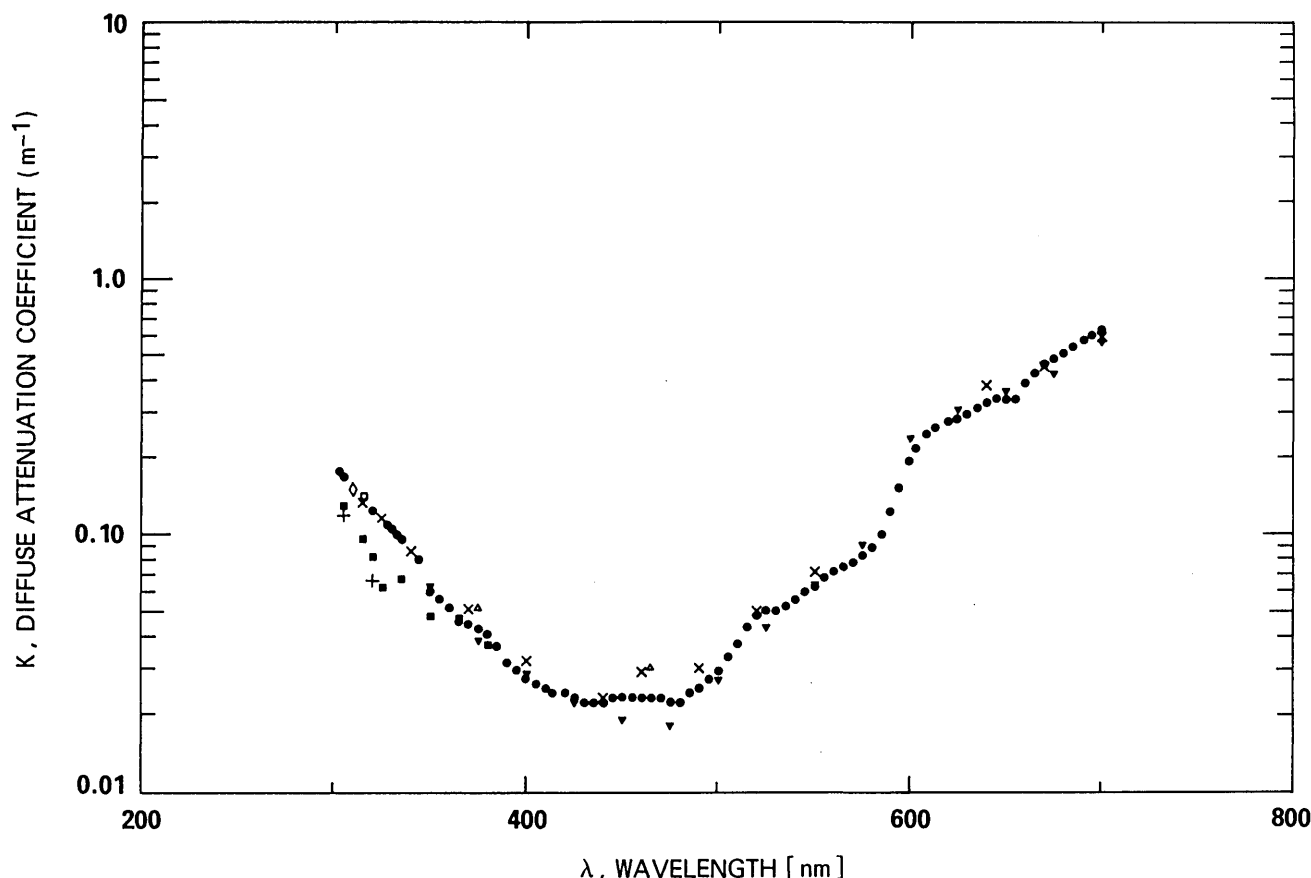

Fig. 2. Diffuse attenuation coefficient for irradiance [$K_w(\lambda)$(m^{-1})] vs wavelength [λ(nm)] as determined by various authors for clear ocean waters: ●, (350–700 nm), present work plus Smith and Baker[34]; ●, (300–350 nm) Smith and Baker[16]; ■, +, and ×, present work; ◊, Jerlov[37] and Hojerslev[38]; □, Calkins[39]; ▼, Jerlov water type I.[2]

These comments with respect to the accuracy and precision of $K_w(\lambda)$ refer to a source free medium. It is known that underwater irradiance measurements in the neighborhood of 675 nm detect *in vivo* fluorescence of chlorophyll (even for downward irradiance measurements) in waters containing moderate amounts of chlorophyll. As a consequence the simple equations given above do not hold for this spectral region in waters with high chlorophyll concentrations. For the very clear water data considered here fluorescence due to chlorophyll is negligible, and the equations are valid.

V. Comparison of $a_w(\lambda)$ and $K_w(\lambda)$ Data

Figure 3 presents $K(\lambda)$ data derived from several sources. First, the light dashed curves give various values of $K_{min}^{sw}(\lambda)$ derived from the $a_w(\lambda)$ data shown in Fig. 1 by means of Eq. (6). No attempt has been made to identify individually these data except those of Morel and Prieur (heavy pluses) and Tam and Patel (heavy crosses). Second, clear ocean water $K_w(\lambda)$ data are given (with the same symbols) as described for Fig. 2. The solid curve is discussed below.

A number of observations with respect to Fig. 3 can be made: (1) In the 380–700-nm spectral region our $K_w(\lambda)$ values, those of Jerlov, and those values of $K_{min}^{sw}(\lambda)$ derived from Morel and Prieur are in substantial agreement (±25%). Furthermore, these data agree within this accuracy with the data of Tam and Patel except in the 446–480- and 515–546-nm regions. (2) Most of the remaining data are incompatible with these data in the wavelength region below 580 nm. Based on the analysis summarized by Eq. (9), we must suspect those laboratory data falling significantly above the ocean measured values of $K_w(\lambda)$ as being systematically in error. (3) By means of our analysis and this consistent data set (our data plus that of Jerlov, MP, and TP), we can estimate $a_w(\lambda)$ values in the 350–380-nm region where recent reliable laboratory data are lacking. (4) Values of $a_w(\lambda)$ estimated in this way (and discussed below) for the near UV and the blue region of the spectrum are as much as an order of magnitude lower than reported laboratory determinations of $a_w(\lambda)$ for both pure freshwater and pure saltwater.[22,27,31]

In Fig. 4 we present additional $K(\lambda)$ data (from 300 to 460 nm) determined for a range of ocean water types varying in chlorophyll concentration from 0.06 to 5.0 (mg chl m^{-3}). These data are superimposed on values of $K_{min}^{sw}(\lambda)$ derived from the $a_w(\lambda)$ data, shown in Fig.
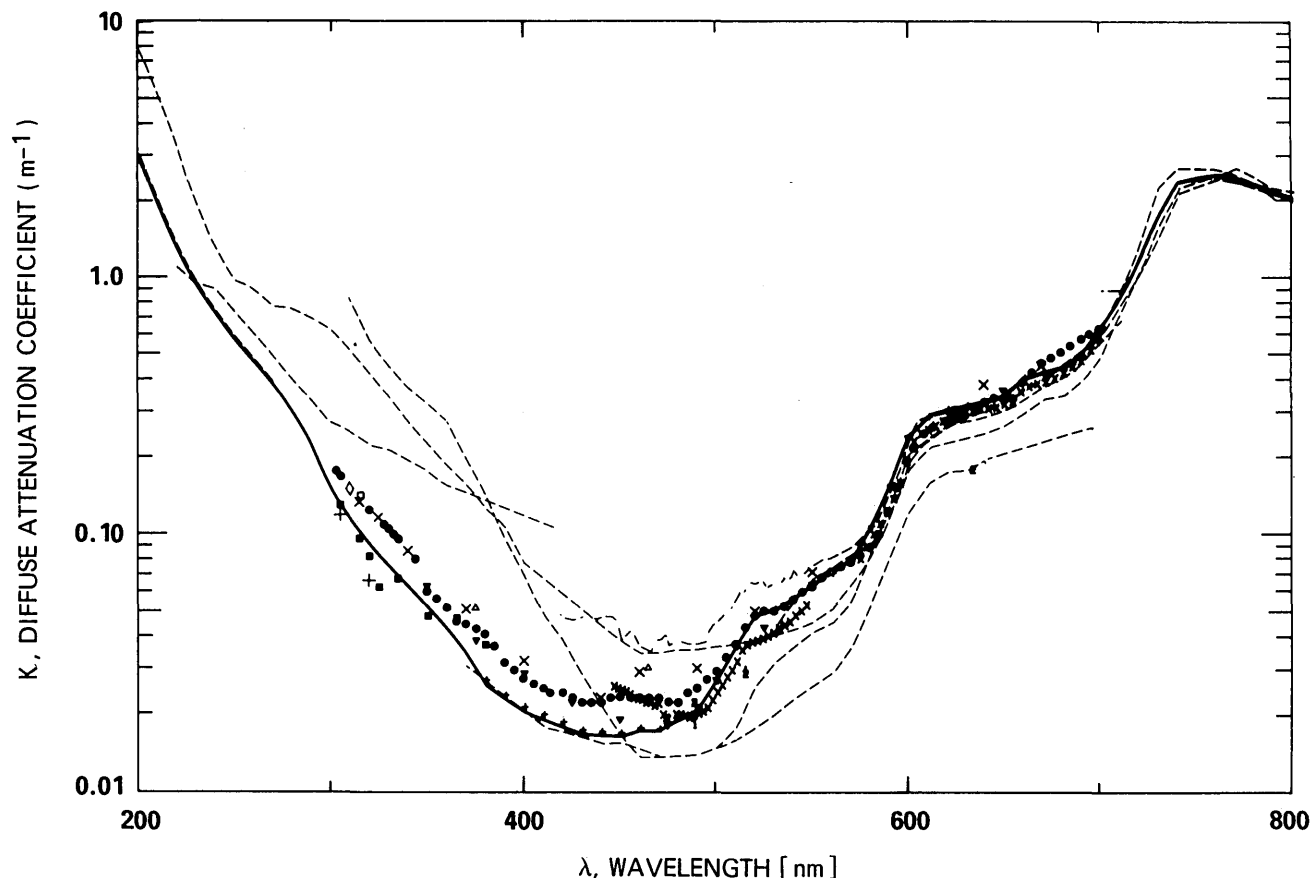

Fig. 3. Diffuse attenuation coefficient for irradiance $[K_{min}^{sw}(\lambda)(m^{-1})]$ vs wavelength $[\lambda(nm)]$ as derived from various sources: values of $K_{min}^{sw}(\lambda)$ derived using Eq. (6) from $a_w(\lambda)$ data of Morel and Prieur,[8] +, Tam and Patel,[10] ×, and others (dashed lines) as given in Fig. 1; measured values of $K_w(\lambda)$ for clear ocean waters (with the same symbols) as given in Fig. 2; solid curve, our selected estimate of $K_w(\lambda)$ for clear ocean waters (see text for discussion).
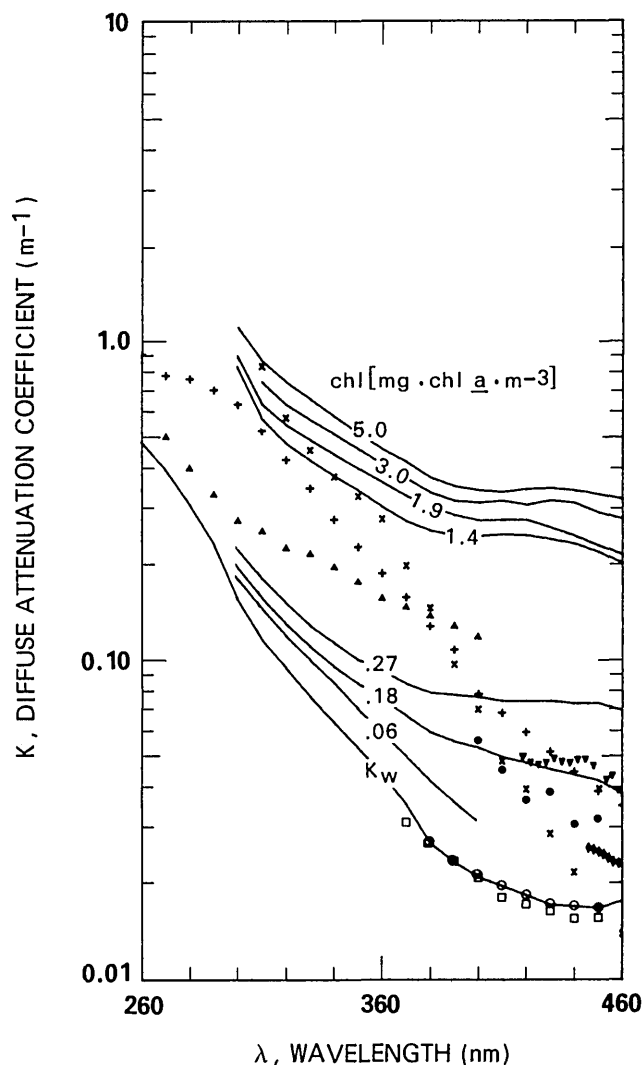
Fig. 4. Diffuse attenuation coefficient for irradiance $[K(\lambda)(\text{m}^{-1})]$ vs wavelength $[\lambda(\text{nm})]$. Solid curves, measured values of $K(\lambda)$ from ocean waters of different chlorophyll concentrations. Data points, $K_{\min}^{sw}(\lambda)$ values derived using Eq. (6) from $a_w(\lambda)$ data given (with same symbols) in Fig. 1.

Table I. Diffuse Attenuation Coefficient for Irradiance for Clearest Ocean Waters $[K_w^{sw}(\lambda)]$ and Absorption $[a_w(\lambda)]$ and Scattering $[b_m^{sw}(\lambda), b_m^{fw}(\lambda)]$ Coefficients for Pure Water

λ(nm)	K_w^{sw}(m^{-1})	a_w(m^{-1})	b_m^{sw}(m^{-1})	b_m^{fw}(m^{-1})
200	3.14	3.07	0.151	0.116
210	2.05	1.99	0.119	0.0935
220	1.36	1.31	0.0995	0.0770
230	0.968	0.927	0.0820	0.0635
240	0.754	0.720	0.0685	0.0525
250	0.588	0.559	0.0575	0.0443
260	0.481	0.457	0.0485	0.0375
270	0.394	0.373	0.0415	0.0320
280	0.306	0.288	0.0353	0.0272
290	0.230	0.215	0.0305	0.0235
300	0.154	0.141	0.0262	0.0201
310	0.116	0.105	0.0229	0.0176
320	0.0944	0.0844	0.0200	0.0153
330	0.0765	0.0678	0.0175	0.0134
340	0.0637	0.0561	0.0153	0.0118
350	0.0530	0.0463	0.0134	0.0103
360	0.0439	0.0379	0.0120	0.0091
370	0.0353	0.0300	0.0106	0.0081
380	0.0267	0.0220	0.0094	0.0072
390	0.0233	0.0191	0.0084	0.0065
400	0.0209	0.0171	0.0076	0.0058
410	0.0196	0.0162	0.0068	0.0052
420	0.0184	0.0153	0.0061	0.0047
430	0.0172	0.0144	0.0055	0.0042
440	0.0170	0.0145	0.0049	0.0038
450	0.0168	0.0145	0.0045	0.0035
460	0.0176	0.0156	0.0041	0.0031
470	0.0175	0.0156	0.0037	0.0029
480	0.0194	0.0176	0.0034	0.0026
490	0.0212	0.0196	0.0031	0.0024
500	0.0271	0.0257	0.0029	0.0022
510	0.0370	0.0357	0.0026	0.0020
520	0.0489	0.0477	0.0024	0.0019
530	0.0519	0.0507	0.0022	0.0017
540	0.0568	0.0558	0.0021	0.0016
550	0.0648	0.0638	0.0019	0.0015
560	0.0717	0.0708	0.0018	0.0014
570	0.0807	0.0799	0.0017	0.0013
580	0.109	0.108	0.0016	0.0012
590	0.158	0.157	0.0015	0.0011
600	0.245	0.244	0.0014	0.0011
610	0.290	0.289	0.0013	0.0010
620	0.310	0.309	0.0012	0.0009
630	0.320	0.319	0.0011	0.0009
640	0.330	0.329	0.0010	0.0008
650	0.350	0.349	0.0010	0.0007
660	0.400	0.400	0.0008	0.0007
670	0.430	0.430	0.0008	0.0007
680	0.450	0.450	0.0007	0.0006
690	0.500	0.500	0.0007	0.0006
700	0.650	0.650	0.0007	0.0005
710	0.834	0.839	0.0007	0.0005
720	1.170	1.169	0.0006	0.0005
730	1.800	1.799	0.0006	0.0005
740	2.380	2.38	0.0006	0.0004
750	2.47	2.47	0.0005	0.0004
760	2.55	2.55	0.0005	0.0004
770	2.51	2.51	0.0005	0.0004
780	2.36	2.36	0.0004	0.0003
790	2.16	2.16	0.0004	0.0003
800	2.07	2.07	0.0004	0.0003

1 (and similarly labeled), by means of Eq. (6). The primary observation, with respect to this figure, is that much of the laboratory determined $a_w(\lambda)$ data are systematically high, with respect to $K_w(\lambda)$ values for the clearest ocean waters and ocean waters containing significant concentrations of chlorophyll. Based on the results shown in Figs. 3 and 4 and the analysis presented above, it is our hypothesis that laboratory $a_w(\lambda)$ data, which lie appreciably above $K_w(\lambda)$ data, are probably in error.

VI. Discussion and Summary

There is need for an accurate and consistent set of data for the optical properties of the clearest natural waters and for optically pure water. Such a set of data would help to resolve the present large discrepancies in published data and would be useful for a range of practical applications. We believe our results plus those of Jerlov, MP, and TP form an accurate and

λ(nm)	K_w^{sw}(m⁻¹)	a_w(m⁻¹)	$\frac{1}{2}b_m^{sw}$	$b_b^{sw} \times 10^3$ (m⁻¹) $B \cdot b_{(n=0)}^{sw}$	$B \cdot b_{(n=-1)}^{sw}$	$\frac{1}{2}b_m^{sw}$	b_b^{sw}/K_w^{sw} (%) $B \cdot b_{(n=0)}^{sw}$	$B \cdot b_{(n=-1)}^{sw}$
200	3.14	3.07	75.4	76.4	78.0	2.40	2.43	2.48
250	0.588	0.559	28.8	29.8	30.8	4.90	5.23	5.23
300	0.154	0.141	13.1	14.1	14.8	8.51	9.15	9.6
350	0.0530	0.0463	6.73	7.74	8.21	7.03	14.6	15.5
400	0.0209	0.0171	3.78	4.79	5.08	18.1	22.9	24.3
450	0.0168	0.0145	2.27	3.28	3.43	13.5	19.5	20.4
500	0.0271	0.0257	1.46	2.45	2.48	5.31	9.04	9.15
550	0.0648	0.0638	0.97	1.98	1.91	1.09	3.05	2.95
600	0.245	0.244	0.71	1.72	1.57	0.29	0.70	0.64
650	0.350	0.349	0.48	1.49	1.29	0.14	0.43	0.37
700	0.650	0.650	0.355	1.36	1.09	0.05	0.21	0.17
750	2.47	2.47	0.26	1.27	0.95	0.01	0.05	0.04
800	2.07	2.07	0.20	1.21	0.845	>0.01	0.06	0.04

consistent set of data. Table I presents a summary of our best estimate for this consistent data set, which gives $K_w^{sw}(\lambda)$ (also shown as the solid curve in Fig. 3) values for the clearest ocean waters and $a_w(\lambda)$, $b_w^{fw}(\lambda)$, $c^w(\lambda)$ for pure water.

The selected $K_w^{sw}(\lambda)$ values are derived from the following: (1) The data of Morel and Prieur from 380 to 700 nm. These data are consistent with our own, with those of Jerlov,[2] and with those of Tam and Patel and have the merit that they comprise a continuous and consistent data set within this spectral range. (2) An average of the data of Curcio and Petty,[40] James and Birge,[29] Clark and James,[30] and Sullivan,[32] paying particular attention to curve shapes in the 650–800-nm region. (3) A low limit fit to our own data from 300 to 400 nm. (4) An extrapolation of our own data (and the data points near 310 nm of Jerlov,[37] Hojerslev,[38] and Calkins[39]), which follows the shape of Armstrong and Boalch's[22] data, below 300 nm.

Our estimation of the uncertainties of the selected $K_w(\lambda)$ curve is as follows: (1) The wavelength region below 300 nm is merely an educated estimate. Because of the sharp drop in solar radiation (due to stratospheric ozone) near 300 nm, $K_w(\lambda)$ measurements using natural sunlight become increasingly difficult in this wavelength region and below. (2) In the 300–380-nm region there is a spread of ±15% between the high and low $K_w(\lambda)$ data. We have chosen the lower limit of these data but recognize that we could have selected a curve ~30% higher. (3) In the 380–480-nm region our data, and to some extent those of Tam, Patel, and Jerlov, are ~30% higher than those of Morel and Prieur. Again a higher valued curve could have been selected. (4) There is a marked change of slope of the data curves in the 515-nm region. By selecting Morel's data here we are agreeing with our own work and choosing values ~10% above Tam and Patel. (5) In the region above 580 nm the selected curve is probably on the higher side of a ±15% spread in the data.

The $a_w(\lambda)$ values are derived so as to be consistent with these selected $K_w^{sw}(\lambda)$ values using the $b_m^{sw}(\lambda)$ data of Morel,[5] as extrapolated by a power law fit to his data to longer and shorter wavelengths. That is, we have

derived $a_w(\lambda)$ by means of Eq. (6) with the assumption that particle backscattering for clear natural waters is negligible.

Table II presents these $K_w^{sw}(\lambda)$, $a_w(\lambda)$ and the backscattering coefficient derived in three ways to display the consequences of this assumption. In column 4 the backscattering coefficient is calculated as one-half the molecular scattering for seawater (i.e., assuming $b_p = 0$ as for Table I). In the next two columns the total backscattering coefficient is calculated according to Eqs. (7) and (8) with $n = 0$ (column 5) and $(n) = -1$ (column 6). Thus, these columns display the relative magnitudes of pure water molecular backscattering without and with the inclusion of particle backscattering for clear ocean waters. The next three columns in Table II give the ratio (expressed as percent) of these backscattering coefficients to $K_w(\lambda)$.

From Table II we can conclude that (1) inclusion of the particle backscattering coefficient, $B \cdot b_p^{sw}$, to our calculations would increase $K_w^{sw}(\lambda)$ values by ~6% in the 440–500-nm regions, ~4% in the 350–440- and 460–500-nm regions, and only a few percent elsewhere; (2) inclusion of a wavelength dependence (difference between $n = 0$ or $n = -1$) for particle scattering would make a negligible difference to our selected $K_w(\lambda)$; (3) inclusion of particle backscattering of our results can be accomplished by the addition of 0.001 m⁻¹ [i.e., Eq. (8) with $n = 0$] at all wavelengths.

While we have distinguished between freshwater and saltwater when discussing the scattering coefficient we have not done so when dealing with the absorption coefficient. There is strong evidence that there is no significant (<10%) difference between $a_w(\lambda)$ for freshwater and saltwater[30,32] for wavelengths longer than ~375 nm. The evidence for a possible difference at shorter wavelengths is inconclusive: the work of Lenoble[21,31] and Armstrong and Boalch[22] suggests that sea salts cause a slowly increasing absorption with decreasing wavelengths in the near UV region and below; our own $K_w(\lambda)$ measurements as well as those by Calkins[39] and Hojerslev[38] plus the $a_w(\lambda)$ data of Morel and Prieur[8] at wavelengths of <400 nm are inconsistent with these laboratory results. Because of this uncer-

tainty we have chosen to rely on our own data in the 300–400-nm region. We do not have clear freshwater data with which to make a judgment regarding a possible distinction between $a_w^{fw}(\lambda)$ and $a_w^{sw}(\lambda)$ in this spectral region. Also it should be noted that if there is a difference in the near UV absorption of freshwaters and saltwaters it would indicate an even greater discrepancy between $a_w(\lambda)$ values estimated from ocean data and the reported laboratory measurements.

In summary, selected data are presented with an accuracy estimated to be within +25 and −5% between 300 and 480 nm and +10 and −15% from 480 to 800 nm. We stress the continued need for an accurate and consistent set of optical data for pure water as well as the clearest natural waters. Table I represents our present best estimate for such a data set, and we emphasize the need for more reliable laboratory measurements at wavelengths below 500 nm.

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