Optics of Marine Particles

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What is ocean optics?

In principle it sounds straightforward, but in reality it's not...

Seawater is a highly complex medium containing a “witch's brew” of dissolved substances and suspended particles which strongly alter its optical properties.

Because of this, ocean optics is a strongly interdisciplinary science combining physics, biology, chemistry, geology, and atmospheric sciences.
Seawater is a complex optical medium with a great variety of particle types and soluble species.

**Suspended Particulate Matter**
- Molecular water
- Inorganic salts
- Dissolved organic matter
- Plankton microorganisms
- Organic detrital particles
- Mineral particles
- Colloidal particles
- Air bubbles
Seawater is a complex optical medium with a great variety of biological and mineral particle types.

Mineral particles

Biological particles

Colloids / nanoparticles
Plankton microorganisms
Example long-term goals

• Understand the magnitudes and variability of oceanic optical properties

• Predict ocean optical properties given the types and concentration of suspended particles (*forward problem*)

• Obtain bio-optical properties and biogeochemical information from optical in situ and remote-sensing measurements (*inverse problem*)
OCEAN COLOR

\[ R_{rs}(\lambda) \equiv \frac{L_w(\lambda)_{z=0^+}}{E_d(\lambda)_{z=0^+}} \propto \frac{b_b(\lambda)}{a(\lambda)} \]

remote sensor

SUN

phytoplankton and other microorganisms

non-living organic and inorganic particles

H₂O

CDOM
Inherent Optical Properties

\[
\begin{align*}
    a(\lambda) + a_{ph}(\lambda) + a_d(\lambda) + a_g(\lambda) + b_{bw}(\lambda) + b_{bp}(\lambda)
\end{align*}
\]

Remote-sensing reflectance

\[\text{Remote-sensing reflectance } R_{rs}(\lambda)\]
Direct problem

Dragon

Tracks

Inverse problem

Tracks

Dragon

(Bohren and Huffman 1983)
Fundamentals of single-particle optics and the linkage between the single-particle and bulk optical properties of particle suspension
Linkage between the single-particle optical properties and bulk optical properties of particle suspension

\[ a = (N/V) \ Q_a \ G = (N/V) \ \sigma_a \]

\( a \) is the absorption coefficient of a collection of particles in aqueous suspension (units of m\(^{-1}\))

\( N/V \) is the number of particles per unit volume of water (units of m\(^{-3}\))

\( Q_a \) is the absorption efficiency factor (dimensionless)

\( G \) is the area of cross section of a particle (units of m\(^{2}\)). For spherical particles \( G = (\pi/4)D^2 \) where \( D \) is a diameter

\( \sigma_a \) (\( = Q_a \ G \)) is the absorption cross-section (units of m\(^{2}\))

Note: \( a \), \( Q_a \), and \( \sigma_a \) are the spectral quantities (i.e., functions of light wavelength)
Geometry for defining Inherent Optical Properties

(Mobley, 1994)
Measurement of particulate absorption coefficient with a spectrophotometer equipped with a center-mount integrating sphere

Very small or negligible scattering error

monochromatic incident light beam

Babin and Stramski (2002)
Particle size distribution

Microscopy

Coulter Particle Analyzer
Optical diffraction method for particle sizing
(e.g., LISST-100 Instrument)

- $0.016 < \psi < 3.2^0$
- $0.1 < \psi < 20^0$

transmissometer acceptance angle: $0.007^0$ or $0.036^0$

(Agrawal 2005)
Particle size distributions of *Prochlorococcus* and *Synechococcus*

Figure 1. Relative size distribution functions (normalized to their maximum) for the various strains of *Prochlorococcus* (panel a) and *Synechococcus* (panel b), labelled as in Table 1. For clarity only one size distribution per strain is represented; the other curves, not shown, are almost identical apart from slight shifts of the maximum.

(Morel et al. 1993)
Absorption efficiency factor for particles

\[ Q_a(\lambda) = \frac{F_a(\lambda)}{F_o(\lambda)} \]

particle in water

\[ \phi' = 4 \alpha n' = a_s D \]
\[ \alpha = \frac{\pi \cdot D \cdot n_w}{\lambda} \]
\[ n' = \frac{\lambda a_s}{4 \pi n_w} \]

Note: \( Q_a, a_s, \) and \( n' \) are functions of \( \lambda \)

(Morel and Bricaud 1981)
Example spectra of absorption efficiency factor

Figure 5. Spectral values of the efficiency factor for absorption for the various strains.
Absorption efficiency for various phytoplankton and heterotrophic microorganisms

Figure 1. The theoretical variations of $Q_a$, the efficiency factor for absorption (dashed curves), as a function of the dimensionless parameter $\rho'$. The triangles are experimental determinations of $Q_a$ (at 675 nm) for various algae (Morel and Bricaud, 1986; Ahn, 1990); other symbols are for determinations of 3 algal species studied by Sosik (1988). The values for heterotrophic organisms, as indicated, come from Morel and Ahn (1990, 1991). The inset is an enlargement of the initial part of the curve.
The package effect

\[ a^* = a / Chl = a / [(Chl_{cell}/V_{cell}) (N/V)V_{cell}] = a / [Chl_i (N/V)V_{cell}] \]

For spherical particles:

\[ a = (N/V) Q_a (\pi/4)D^2 \text{ and } V_{cell} = (\pi/6)D^3 \]

\[ a^* = (3/2) Q_a / (Chl_i D) = (3/2) (a_s / Chl_i ) [Q_a / (a_s D)] = \]

\[ = (3/2) (a_s / Chl_i ) (Q_a / \rho') = (a_s / Chl_i ) Q^*_a = a^*_sol Q^*_a \]

where \( a^*_sol = a_s / Chl_i \)

\[ a^* = a^*_sol \text{ if } \rho' \rightarrow 0 \text{ and } Q^*_a = 1 \]

The package effect factor:

\[ Q^*_a = a^* / a^*_sol = (3/2) Q_a / \rho' = (3/2) Q_a / (a_s D) \]

(Morel and Bricaud 1981)
Fig. 1. Dimensionless functions $Q_a$ and $Q_a^*$ (equations 1 and 6) plotted vs $\alpha n'$. The corresponding scale in diameter $d$ (\(\mu m\)) is obtained assuming that the absorption coefficient, $a_{cm}$, for the cellular material is equal to $2 \times 10^5$ m\(^{-1}\), which is a representative mean value for many algal cells at $\lambda = 430$ nm (see text). Note that $\rho' = da_{cm} = 4\alpha n'$. 

(Morel and Bricaud 1981)
Solid lines: intact cells in cultures

Dotted lines: hypothetical aqueous solution of the material forming the cells

(Morel and Bricaud 1981)
Fig. 2. Change in spectral absorption values with variable cell size (diameter, $d$, in $\mu$m) whereas the cell material forming the cells remains unchanged. The spectral absorption values of this material, somewhat arbitrarily adopted, are shown as the dotted curve. All curves are normalized, at $\lambda = 430$ nm, to evidence the progressive deformation. The variations with size of the specific absolute value at 430 nm (m$^2$ mg$^{-1}$ Chl $a$) are shown in inset, under the same assumption of a constant absorption of the cell material ($a_{cm} = 2 \times 10^3$ m$^{-1}$ at 430 nm) and with the additional assumption of a constant intracellular pigment concentration ($c_i = 2.86 \times 10^6$ mg Chl $a$ m$^{-3}$).
Optical efficiency factors versus phase shift parameter

phase shift parameter $\rho = 2 \alpha (n-1)$

$$Q_a = \frac{F_a}{F_o} \quad Q_b = \frac{F_b}{F_o} \quad Q_c = \frac{F_c}{F_o} \quad Q_c = Q_a + Q_b$$

Fig. 3. Variations of the efficiency factors for attenuation, $Q_c$, for absorption, $Q_a$ (a), and for scattering, $Q_b$ (b) vs. the parameter $\rho = 2 \alpha (n-1)$, for increasing values of the ratio $n'/(n-1)$ where $n$ and $n'$ are the real and imaginary parts of the relative refractive index of the particles.

(Morel and Bricaud 1986)
Scattering by a single particle: Phase shift parameter

Figure 3.5. Phase fronts of a light wave traveling through a sphere of radius $r$. The wave slows down while traveling through the particle. The accumulated phase difference is proportional to the total distance traveled through the particle and is a function of the point of entry. The phase difference between the light passing through the center of the sphere and the light passing outside the sphere is $2(n - 1)r$. 

(Jonasz and Fournier 2007)
The effect of polydispersion on attenuation efficiency

Fig. 4. Mean efficiency factor for attenuation $Q_c$ of a "mean" particle representative of a polydispersed population, plotted as a function of $q_m$, the $q$ value which corresponds to the maximum of the size distribution function $F(q)$ (see Equation 17). The index of refraction is real (no absorption) and the curves 1 and 3 correspond to log-normal distributions such as $F(q_M/2) = F(2q_M)$ = respectively 0.01, 0.1, 0.3 $F(q_M)$. The dashed curve, redrawn from Fig. 3 for $n' = 0$, represents the limiting case of a population of monosized particles.

(Morel and Bricaud 1986)
Scattering and backscattering efficiencies versus particle size

(Stramski and Kiefer 1991)
Figure 2. The theoretical variations of $Q_s$, the efficiency factor for scattering by non absorbing spheres (solid curve with marked oscillations) as a function of the dimensionless parameter $\rho$. The smoothed curve is for an averaged $\bar{Q}_s$ to be applied for population with a log-normal size distribution. The crosses are the $\bar{Q}_s$ values (at $\lambda \approx 580$ nm) determined for various phytoplankters grown in culture (see Table 1 in Morel and Bricaud, 1986); additional data for algal cells come from Ahn (1990). The circles indicate the $\bar{Q}_s$ values (at $\lambda \approx 550$ nm) determined for free living marine bacteria, heterotrophic flagellates, and naked ciliates, (Morel and Ahn, 1990; 1991).
Spectra of scattering efficiency for various phototrophic and heterotrophic microorganisms

Figure 3. Spectral variations of $Q_s$ within the 400-750 nm range of various phototrophic and heterotrophic organisms as experimentally determined (Morel and Ahn, 1990, 1991).

(Morel 1991)
Optical efficiency factors:
Examples for monospecific cultures of algal cells
(deduced from the absorption and attenuation coefficients, and size distribution measurements)

(Morel and Bricaud 1986)
Anomalous dispersion of the refractive index within the absorption band

(Morel and Bricaud 1986)
Schematic diagram of general-angle scattering meter

(Kirk 1994)
Scattering phase function: Effect of polydispersion

**Fig. 5.** Normalized volume scattering functions, $\beta(\theta)$ (Equations 5' and 18), for a particle of relative size $\alpha = 12$, when the refractive index is 1.035 and 1.035−0.01 $i$. The dotted curve represents the same $\beta(\theta)$ function for a polydispersed population of particles with $n = 1.035$, computed according to Equation 20. The size distribution function $F(\alpha)$ is a log-normal law such that the modal relative size $\alpha_{M}$ is also 12, and $F(\alpha_{M}/2) = F(2\alpha_{M}) = 0.01 F(\alpha_{M})$.

(Morel and Bricaud 1986)
Scattering phase function: Effects of particle size and refractive index

Fig. 6. (a) Normalized volume scattering function $\tilde{\beta}(\theta)$ for increasing $\alpha_M$ values (increasing size) and for $m = 1.035$. (b) Normalized volume scattering function $\tilde{\beta}(\theta)$ for increasing (real) index of refraction and for $\alpha_M = 100$. For Fig. 6a and b the log normal size distribution used is as in Fig. 5. The “bump” which occurs at about $75^\circ$ for $m = 1.075$ and at smaller angles when the refractive index decreases (see also Fig. 6a) is the first “rainbow”, at $138^\circ$ for water droplets ($n = 1.33$). It appears for sufficiently large and perfect spheres. Thus it is unlikely that it can be observed for algal cells.

(Morel and Bricaud 1986)
Normalized scattering function for various microorganisms (from Mie calculations)

Figure 6. Volume scattering function (normalized at $\theta = 0^\circ$ and for $\lambda = 550$ nm) computed for various organisms by using their refractive index and size distribution as experimentally determined (see text).

(Morel 1991)
Backscattering ratio versus relative size parameter

Fig. 8. Variations of the backscattering ratio $\bar{b}_b (= b_y/b)$ vs. the modal relative size $\alpha_M$ (same log-normal law as before in Fig. 5). The different curves correspond to various values of the refractive index given in inset. The curve for a monodispersed population (with $m = 1.02$) is also shown (dotted line). The arrow indicates the limiting value of $b_y/b (=0.5)$ when $\alpha$ tends toward 0 (Rayleigh domain).

(Morel and Bricaud 1986)
INTERSPECIES OPTICAL VARIABILITY OF PLANKTON ORGANISMS

Particle size and complex refractive index are the first-order determinants of interspecies variability in plankton optical properties.
# Plankton microorganisms

Table 1. Microbial components in the database and source of raw data. Values for the average equivalent spherical diameter (D), the real part of refractive index at 550 nm (n), and imaginary part of refractive index at 440 and 675 nm (n') are also given for each component.

<table>
<thead>
<tr>
<th>i</th>
<th>Label</th>
<th>Microbial species</th>
<th>$D$ [μm]</th>
<th>n 550 nm</th>
<th>n' $10^3$ 440 nm</th>
<th>n' $10^3$ 675 nm</th>
<th>Source of raw data</th>
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<tr>
<td>1</td>
<td>VIRU</td>
<td>Viruses</td>
<td>0.07</td>
<td>1.050</td>
<td>0</td>
<td>0</td>
<td>Stramski and Kiefer, 1991</td>
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<td>HBAC</td>
<td>Heterotrophic bacteria</td>
<td>0.55</td>
<td>1.055</td>
<td>0.509</td>
<td>0.057</td>
<td>Stramski and Kiefer, 1990</td>
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<td>generic Prochlorophyceae: the average of:</td>
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<td>PMED - Prochlorococcus strain MED</td>
<td>0.59</td>
<td>1.055</td>
<td>23.25</td>
<td>13.77</td>
<td>Morel et al., 1993</td>
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<td>PNAS - average of Prochlorococcus strains NATL and SARG</td>
<td>0.70</td>
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<td>13.78</td>
<td>6.687</td>
<td>Morel et al., 1993</td>
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<td>SM41 - Synechococcus strain MAX41 (Cyanophyceae)</td>
<td>0.92</td>
<td>1.047</td>
<td>5.415</td>
<td>2.905</td>
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<td>SM01 - Synechococcus strain MAX01 (Cyanophyceae)</td>
<td>0.94</td>
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<td>4.505</td>
<td>2.547</td>
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<td>SROS - Synechococcus strain ROS04 (Cyanophyceae)</td>
<td>1.08</td>
<td>1.049</td>
<td>4.516</td>
<td>2.154</td>
<td>Morel et al., 1993</td>
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<td>SDC2 - Synechococcus strain DC2 (Cyanophyceae)</td>
<td>1.14</td>
<td>1.050</td>
<td>4.249</td>
<td>2.375</td>
<td>Morel et al., 1993</td>
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<td>S103 - Synechococcus strain WH8103 (Cyanophyceae)</td>
<td>1.14</td>
<td>1.062</td>
<td>9.251</td>
<td>4.668</td>
<td>Stramski et al., 1995</td>
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<td>generic phycocyanin-rich picophytoplankton; the average of:</td>
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<td>SCYS - Synechocystis (Cyanophyceae)</td>
<td>1.39</td>
<td>1.050</td>
<td>4.530</td>
<td>1.910</td>
<td>Ahn et al., 1992</td>
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<td>MARI - Anacystis marina (Cyanophyceae)</td>
<td>1.43</td>
<td>1.060</td>
<td>8.460</td>
<td>3.603</td>
<td>Ahn et al., 1992</td>
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<td>6</td>
<td>PING</td>
<td>Pavlova pinguis (Haptophyceae)</td>
<td>3.97</td>
<td>1.046</td>
<td>4.177</td>
<td>2.709</td>
<td>Bricaud et al., 1988</td>
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<td>Thalassiosira pseudonana (Bacillariophyceae)</td>
<td>3.99</td>
<td>1.045</td>
<td>9.231</td>
<td>7.397</td>
<td>Stramski and Reynolds, 1993</td>
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<td>LUTH</td>
<td>Pavlova lutheri (Haptophyceae)</td>
<td>4.26</td>
<td>1.045</td>
<td>5.767</td>
<td>2.403</td>
<td>Bricaud et al., 1988</td>
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<td>9</td>
<td>GALB</td>
<td>Isochrysis galbana (Haptophyceae)</td>
<td>4.45</td>
<td>1.056</td>
<td>7.673</td>
<td>5.101</td>
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<td>HUXL</td>
<td>Emiliania luxielyi (Haptophyceae)</td>
<td>4.93</td>
<td>1.050</td>
<td>5.012</td>
<td>2.950</td>
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<td>CRUE</td>
<td>Porphyridium cruentum (Rhodophyceae)</td>
<td>5.22</td>
<td>1.051</td>
<td>3.351</td>
<td>2.443</td>
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<td>FRAG</td>
<td>Chroomonas fragarioides (Cryptophyceae)</td>
<td>5.57</td>
<td>1.039</td>
<td>4.275</td>
<td>2.904</td>
<td>Ahn et al., 1993</td>
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<td>Prymnesium parvum (Haptophyceae)</td>
<td>6.41</td>
<td>1.045</td>
<td>2.158</td>
<td>1.329</td>
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<td>Dunaliella bioculata (Chlorophyceae)</td>
<td>6.71</td>
<td>1.038</td>
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<td>TERT</td>
<td>Dunaliella tertiolecta (Chlorophyceae)</td>
<td>7.59</td>
<td>1.063</td>
<td>6.260</td>
<td>5.076</td>
<td>Stramski et al., 1993</td>
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<td>16</td>
<td>CURV</td>
<td>Chaetoceros curvisetum (Bacillariophyceae)</td>
<td>7.73</td>
<td>1.024</td>
<td>2.877</td>
<td>1.480</td>
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<td>17</td>
<td>ELON</td>
<td>Hymenomonas elongata (Haptophyceae)</td>
<td>11.77</td>
<td>1.046</td>
<td>13.87</td>
<td>7.591</td>
<td>Ahn et al., 1992</td>
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<td>18</td>
<td>MICA</td>
<td>Prorocentrum micans (Dinophyceae)</td>
<td>27.64</td>
<td>1.045</td>
<td>2.466</td>
<td>1.710</td>
<td>Ahn et al., 1992</td>
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(Stramski et al., 2001)
Interspecies variability in absorption

(Stramski et al. 2001)
Interspecies variability in scattering

(Stramski et al. 2001)
Interspecies variability in single scattering albedo

(based on data from Stramski et al. 2001)
Mie calculations of scattering phase function for plankton microorganisms

Viruses
Heterotrophic bacteria
Prochlorococcus (2 strains)
Synechococcus (Cyanophyceae, 5 strains)
Anacystis marina (Cyanophyceae)
Pavlova pinguis (Haptophyceae)
Thalassiosira pseudonana (Bacillariophyceae)
Pavlova lutheri (Haptophyceae)
Isochrysis galbana (Haptophyceae)
Emiliania huxleyi (Haptophyceae)
Porphyridium cruentum (Rhodophyceae)
Chroomonas fragarioides (Cryptophyceae)
Prymnesium parvum (Haptophyceae)
Dunaliella bioculata (Chlorophyceae)
Dunaliella tertiolecta (Chlorophyceae)
Chaetoceros curvisetum (Bacillariophyceae)
Hymenomonas elongata (Haptophyceae)
Prorocentrum micans (Dinophyceae)

(Stramski et al. 2001)
Backscattering properties of plankton microorganisms
(subject to uncertainties associated with Mie scattering calculations for homogeneous spheres)
Plankton optical properties vary in response to varying growth conditions: light, nutrients, temperature
Intraspecies variability due to irradiance - *Synechocystis*

Absorption

Scattering

(Stramski and Morel 1990)
Intraspecies variability due to temperature, nitrogen, and light limitation – *Thalassiosira pseudonana*

Absorption vs. growth rate

Scattering vs. growth rate

(Stramski et al. 2002)
Intraspecies variability over a diel cycle

*Thalassiosira pseudonana*

(Stramski and Reynolds 1993)
Cellular carbon and chlorophyll-a from refractive index

(Stramski 1999)
Cellular carbon and chlorophyll from refractive index

DuRand et al. (2002)
Optical variability for heterotrophic bacteria

Absorption

Beam attenuation

CHB  Carotenoid-rich bacteria: grown in nutrient-enriched seawater [EX-1 (light-dark cycle), EX-2 and EX-3 (dark)], and in nutrient-poor seawater (EX-4)

NHB  Non-pigmented bacteria: fast-growing in the absorption experiment and starved in the attenuation experiment

(Stramski and Kiefer 1998)
Prey-predator interactions (cyanobacteria and ciliates)

Particle size distributions

Absorption spectra

Scattering spectra

(Stramski et al. 1992)
Viral infection of marine bacteria

Spectral particulate beam attenuation coefficient, $c_p(\lambda)$, for (a) infected and (b) control samples at different sampling times, as indicated.

Density function of particle size distribution, $F_M(D)$, for (a) infected and (b) control samples at different sampling times, as indicated.

(Uitz et al. 2010)
Mineral particles

Saharan dust

Spitsbergen fjord, Arctic

Mongolian Cyclone 7 April 2001

Cloud

Dust
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<th>Color Code</th>
<th>Description</th>
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<td>ALG1</td>
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<td>Fe(OH)$_3$</td>
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Absorption of mineral-rich particulate assemblages

Mass-specific absorption

Fe-specific absorption

(Babin and Stramski 2004)
<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Description</th>
<th>Origin</th>
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<tbody>
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<td>ILL₁</td>
<td>illite</td>
<td>Source Clay Minerals Repository, University of Missouri (ref. IMt-1)</td>
</tr>
<tr>
<td>ILL₂</td>
<td>as above but different PSD</td>
<td>as above</td>
</tr>
<tr>
<td>KAO₁</td>
<td>kaolinite (poorly crystallized)</td>
<td>as above (ref. KGa-2)</td>
</tr>
<tr>
<td>KAO₂</td>
<td>as above but different PSD</td>
<td>as above</td>
</tr>
<tr>
<td>MON₁</td>
<td>Ca-montmorillonite</td>
<td>as above (ref. SAz-1)</td>
</tr>
<tr>
<td>MON₂</td>
<td>as above but different PSD</td>
<td>as above</td>
</tr>
<tr>
<td>CAL₁</td>
<td>calcite</td>
<td>natural crystal</td>
</tr>
<tr>
<td>CAL₂</td>
<td>as above but different PSD</td>
<td>as above</td>
</tr>
<tr>
<td>QUA₁</td>
<td>quartz</td>
<td>natural crystal</td>
</tr>
<tr>
<td>QUA₂</td>
<td>as above but different PSD</td>
<td>as above</td>
</tr>
<tr>
<td>SAH₁</td>
<td>atmospheric dust from Sahara</td>
<td>red rain event, Villefranche-sur-Mer, France</td>
</tr>
<tr>
<td>SAH₂</td>
<td>as above but different PSD</td>
<td>as above</td>
</tr>
<tr>
<td>AUS₁</td>
<td>surface soil dust</td>
<td>cliff shore, Palm Beach near Sydney, Australia</td>
</tr>
<tr>
<td>AUS₂</td>
<td>as above but different PSD</td>
<td>as above</td>
</tr>
<tr>
<td>ICE₁</td>
<td>ice-rafted particles</td>
<td>glacier runoff, Kongsfjord, Spitsbergen</td>
</tr>
<tr>
<td>ICE₂</td>
<td>as above but different PSD</td>
<td>as above</td>
</tr>
<tr>
<td>OAH₁</td>
<td>surface soil dust</td>
<td>Oahu, Hawaii Islands</td>
</tr>
<tr>
<td>OAH₂</td>
<td>as above but different PSD</td>
<td>as above</td>
</tr>
<tr>
<td>KUW₁</td>
<td>surface soil dust</td>
<td>Kuwait (eastern part, close to ocean)</td>
</tr>
<tr>
<td>KUW₂</td>
<td>as above but different PSD</td>
<td>as above</td>
</tr>
<tr>
<td>NIG₁</td>
<td>surface soil dust</td>
<td>southwest Nigeria</td>
</tr>
<tr>
<td>SAN₁</td>
<td>atmospheric dust</td>
<td>San Diego, California</td>
</tr>
</tbody>
</table>

**Terrigenous mineral-rich particulate matter** (Stramski et al. 2007)
Mass-specific absorption

Mass-specific scattering

(Stramski et al. 2007)
COLLOIDS – Particle size distributions

Particle diameter $D$ ($\mu$m)

Particle concentration $N(D)dD$ (m$^{-3}$)

Wells and Goldberg (1994)

Yamasaki et al. (1998)
Results for colloidal particles

scattering

backscattering

(Stramski and Woźniak 2005)
Scattering budget in terms of particle size fractions

Low-index particles

CONTRIBUTION TO SCATTERING BY VARIOUS SIZE CLASSES

MIE SOLUTIONS FOR
\[ \lambda = 550 \text{ nm} \]
\[ n = 1.05 \text{ (living microorganisms)} \]
\[ n' = 0 \]
\[ F(D) \sim D^{-4} \]

TOTAL SCATTERING

<table>
<thead>
<tr>
<th>Size classes in micrometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 1</td>
</tr>
<tr>
<td>1 – 2</td>
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<tr>
<td>2 – 3</td>
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<tr>
<td>3 – 4</td>
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<tr>
<td>4 – 5</td>
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<td>5 – 6</td>
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<tr>
<td>6 – 7</td>
</tr>
<tr>
<td>7 – 8</td>
</tr>
<tr>
<td>8 – 20</td>
</tr>
<tr>
<td>20 – 100</td>
</tr>
</tbody>
</table>

BACKSCATTERING

High-index particles

CONTRIBUTION TO SCATTERING BY VARIOUS SIZE CLASSES

MIE SOLUTIONS FOR
\[ \lambda = 550 \text{ nm} \]
\[ n = 1.20 \text{ (inorganic particles)} \]
\[ n' = 0 \]
\[ F(D) \sim D^{-4} \]

TOTAL SCATTERING

<table>
<thead>
<tr>
<th>Size classes in micrometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 1</td>
</tr>
<tr>
<td>1 – 2</td>
</tr>
<tr>
<td>2 – 3</td>
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<tr>
<td>3 – 4</td>
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<td>4 – 5</td>
</tr>
<tr>
<td>5 – 6</td>
</tr>
<tr>
<td>6 – 7</td>
</tr>
<tr>
<td>7 – 8</td>
</tr>
<tr>
<td>8 – 20</td>
</tr>
<tr>
<td>20 – 100</td>
</tr>
</tbody>
</table>

BACKSCATTERING

(Stramski and Kiefer 1991)

In dieser Arbeit soll gezeigt werden, daß nach der molekularkinetischen Theorie der Wärme in Flüssigkeiten suspendierte Körper von mikroskopisch sichtbarer Größe infolge der Molekularbewegung der Wärme Bewegungen von solcher Größe ausführen müssen, daß diese Bewegungen leicht mit dem Mikroskop nachgewiesen werden können. Es ist möglich, daß die hier zu behandelnden Bewegungen mit der sogenannten „Brownschen Molekularbewegung“ identisch sind; die mir erreichbaren Angaben über letztere sind jedoch so ungenau, daß ich mir hierüber kein Urteil bilden konnte.

Wenn sich die hier zu behandelnde Bewegung samt den für sie zu erwartenden Gesetzmäßigkeiten wirklich beobachten läßt, so ist die klassische Thermodynamik schon für mikroskopisch unterscheidbare Räume nicht mehr als genau gültig anzusehen und es ist dann eine exakte Bestimmung der wahren Atomgröße möglich. Erwiese sich umgekehrt die Voraussage dieser Bewegung als unzutreffend, so wäre damit ein schwerwiegenderes Argument gegen die molekularkinetische Auffassung der Wärme gegeben.

§ 1. Über den suspendierten Teilchen zuzuschreibenden osmotischen Druck.

Im Teilvolumen \( V^* \) einer Flüssigkeit vom Gesamtvolumen \( V \) seien \( x \)-Gramm-Moleküle eines Nichtelektrolyten gelöst. Ist das Volumen \( V^* \) durch eine für das Lösungsmittel, nicht aber für die gelöste Substanz durchlässige Wand vom reinen Lösungs-

\[
D = \frac{k_B T}{3 \pi \eta D_{\text{diff}}}
\]

\( D \) – diameter of particle
\( D_{\text{diff}} \) – diffusion coefficient of particle
\( T \) – temperature of the liquid medium (seawater)
\( \eta \) – dynamic viscosity of the medium (seawater)
\( k_B \) – Boltzmann constant
Measurement of a wide range of nanoparticle sizes simultaneously.
A superposition of 300 video frames acquired during 10 seconds illustrating trajectories of individual nanoparticles through time.

A mix of polystyrene nanosphere size standards of 50, 240, and 800 nm in diameter suspended in water.
Light scattering by bubbles entrained by wave breaking

(Stramski and Tęgowski 2001)
Scattering and backscattering by bubbles as a function of void fraction

(Terrill et al. 2001)
Traditional approach

Inherent Optical Properties (IOPs) described in terms of a few broadly-defined categories of seawater constituents

\[ IOP(\lambda) = IOP_w(\lambda) + IOP_p(\lambda) + IOP_{CDOM}(\lambda) \]

\[ IOP_p(\lambda) = IOP_{ph}(\lambda) + IOP_{NAP}(\lambda) \]

Example IOPs:
absorption coefficient, scattering coefficient, beam attenuation coefficient, volume scattering function
A four-component model of absorption

\[ \alpha = \alpha_w + \alpha_{\text{phy}} + \alpha_{\text{dom}} + \alpha_{\text{det}} \]

\[ \alpha_{\text{bio}} = \alpha - \alpha_w \]

Absorption coefficient (m\(^{-1}\))

Optical wavelength, \(\lambda\) (nm)
Examples of particulate absorption coefficients $a_p$, $a_d$ or NAP, $a_{ph}$ (data from the Sargasso Sea)

$$a_{ph} = a_p - a_d \text{ or NAP}$$

(Bricaud and Stramski 1990)
Example non-algal particle (NAP) absorption spectra and the corresponding exponential fits for different regions.

(Babin et al. 2003)
Frequency distribution of spectral slope of NAP absorption

NAP absorption spectra calculated with $a_{NAP}(443) = 1 \text{ m}^{-1}$ and $S_{NAP} = 0.0123 \text{ nm}^{-1}$ ($\pm 1.96$ standard deviation, where SD=0.0013 nm$^{-1}$)

(Babin et al. 2003)
Chlorophyll-based approach

\[ IOP(\lambda) = IOP_w(\lambda) + f[Chla] \]

for example
\[ a_{ph}(\lambda) = f[Chla] \]
\[ a_p(\lambda) = f[Chla] \]

\[ AOP(\lambda) \ (e.g., \ ocean \ reflectance) = f[Chla] \]
Case 1 and Case 2 Waters

**CASE 1 WATERS**

- **LIVING ALGAL CELLS**
  - variable concentration

- **ASSOCIATED DEBRIS**
  - Originating from grazing by zooplankton and natural decay

- **DISSOLVED ORGANIC MATTER**
  - liberated by algae and their debris (yellow substance)

**CASE 2 WATERS**

- **RESUSPENDED SEDIMENTS**
  - from bottom along the coastline and in shallow areas

- **TERRIGENOUS PARTICLES**
  - river and glacial runoff

- **DISSOLVED ORGANIC MATTER**
  - land drainage (terrigenous yellow substance)

- **ANTHROPOGENIC INFLUX**
  - particulate and dissolved materials

Morel and Prieur (1977); Gordon and Morel (1983)
Absorption vs. chlorophyll-a

~ 4-fold variation
Beam attenuation vs. chlorophyll

> 10-fold variation

(Loisel and Morel 1998)
Chlorophyll-a algorithm

(Clarke, Ewing & Lorenzen 1970)

OC4 Algorithm

(R)\(^{443}\) > (R)\(^{490}\) > (R)\(^{510}\)

(O'Reilly et al. 2000)
Coastal Zone Color Scanner (CZCS)  1978 - 1985
First satellite image of global distribution of phytoplankton chlorophyll in the world’s oceans from Coastal Zone Color Scanner.
Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

1997 - 2010

SeaStar spacecraft
SeaStar orbits for remote sensing of ocean color
Global distribution of phytoplankton chlorophyll in the world’s oceans from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) based on Sep 1997 - Feb 2007 data
Coccolithophores are strong drivers of ocean biogeochemistry and optics

Ocean color remote sensing of particulate inorganic carbon (PIC)

MODIS AQUA - 2014

Emiliania huxleyi

Ophiaster sp.

Papposphaera sp.

Calcidiscus leptoporous

Balch et al., Bigelow Laboratory
Chlorophyll-based approach: Summary

- Parameterization in terms of chlorophyll-a concentration alone
- Empirical regressions (statistically-derived models)
- Provide average trends but no information about variability
- Not valid for Case 2 waters
- Not necessarily satisfactory for Case 1 waters
Reductionist approach

To develop an understanding and assemble a model of the whole, from the reductionist study of its parts

\[ IOP_p(\lambda) = \sum_k IOP_{k,pla}(\lambda) \quad \text{plankton} \]

\[ + \sum_m IOP_{m,min}(\lambda) \quad \text{minerals} \]

\[ + \sum_n IOP_{n,det}(\lambda) \quad \text{detritus} \]
Example IOP model with detailed description of plankton community

<table>
<thead>
<tr>
<th>i</th>
<th>Component</th>
<th>Concentration [ particles/m³ ]</th>
<th>Chl [ mg m⁻³ ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VIRU</td>
<td>$1.0 \times 10^{13}$</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>HBAC</td>
<td>$4.0 \times 10^{11}$</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>PROC</td>
<td>$7.0 \times 10^{10}$</td>
<td>0.1026</td>
</tr>
<tr>
<td>4</td>
<td>SYNE</td>
<td>$2.0 \times 10^{10}$</td>
<td>0.0403</td>
</tr>
<tr>
<td>5</td>
<td>SYMA</td>
<td>$8.0 \times 10^{9}$</td>
<td>0.0360</td>
</tr>
<tr>
<td>Σ</td>
<td>Picoplankton</td>
<td>$4.98 \times 10^{11}$</td>
<td>0.1789</td>
</tr>
<tr>
<td>6</td>
<td>PING</td>
<td>$4.5056 \times 10^{8}$</td>
<td>0.0540</td>
</tr>
<tr>
<td>7</td>
<td>PSEU</td>
<td>$0.9808 \times 10^{8}$</td>
<td>0.0303</td>
</tr>
<tr>
<td>8</td>
<td>LUTH</td>
<td>$0.9924 \times 10^{8}$</td>
<td>0.0107</td>
</tr>
<tr>
<td>9</td>
<td>GALB</td>
<td>$0.4839 \times 10^{8}$</td>
<td>0.0155</td>
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<td>10</td>
<td>HUXL</td>
<td>$0.4339 \times 10^{8}$</td>
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<tr>
<td>11</td>
<td>CRUE</td>
<td>$0.4496 \times 10^{8}$</td>
<td>0.0129</td>
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<tr>
<td>12</td>
<td>FRAG</td>
<td>$0.4768 \times 10^{8}$</td>
<td>0.0157</td>
</tr>
<tr>
<td>13</td>
<td>PARV</td>
<td>$0.6247 \times 10^{8}$</td>
<td>0.0181</td>
</tr>
<tr>
<td>14</td>
<td>BIOC</td>
<td>$0.3966 \times 10^{8}$</td>
<td>0.0900</td>
</tr>
<tr>
<td>15</td>
<td>TERT</td>
<td>$0.3570 \times 10^{8}$</td>
<td>0.0609</td>
</tr>
<tr>
<td>16</td>
<td>CURV</td>
<td>$0.2987 \times 10^{8}$</td>
<td>0.0099</td>
</tr>
<tr>
<td>Σ</td>
<td>Small Nanoplankton</td>
<td>$1.0 \times 10^{9}$</td>
<td>0.3284</td>
</tr>
<tr>
<td>17</td>
<td>ELON</td>
<td>$1.7 \times 10^{7}$</td>
<td>0.1595</td>
</tr>
<tr>
<td>18</td>
<td>MICA</td>
<td>$2.0 \times 10^{6}$</td>
<td>0.0508</td>
</tr>
<tr>
<td>Σ</td>
<td>Total Plankton</td>
<td>$1.0499019 \times 10^{13}$</td>
<td>0.7176</td>
</tr>
<tr>
<td>19</td>
<td>DET</td>
<td>$3.3 \times 10^{14}$</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>MIN</td>
<td>$1.1 \times 10^{14}$</td>
<td>0</td>
</tr>
<tr>
<td>Σ</td>
<td>Total Non-living Particles</td>
<td>$4.4 \times 10^{14}$</td>
<td>0</td>
</tr>
<tr>
<td>21</td>
<td>BUB</td>
<td>$7.1 \times 10^{6}$</td>
<td>0</td>
</tr>
</tbody>
</table>

(Stramski et al. 2001)
Size distribution

18 planktonic components
composite plankton
mineral particles
organic detritus
air bubbles

(Dstrmski et al. 2001)
Absorption

Scattering

(Stramski et al. 2001)
Input to radiative transfer model

\[ IOP(\lambda) = \sum_{i=1}^{j} IOP_i(\lambda) = \sum_{i=1}^{j} N_i \sigma_i(\lambda) \]

Output, e.g. ocean reflectance

\[ R(\lambda) = f \left[ \sum_{i=1}^{j} N_i \sigma_{i,a}(\lambda), \sum_{i=1}^{j} N_i \sigma_{i,b}(\psi, \lambda) \right] \]

- In what ways does variability in detailed seawater composition determine variability in ocean reflectance?
- What information about water constituents and optical properties can we hope to extract from remotely sensed reflectance?
Example combination of reductionist IOP model and radiative transfer model for simulating ocean color

Viruses (~0.07 µm in size)
Heterotrophic bacteria (~0.5 µm)
Cyanobacteria (~1 µm)
Small diatoms (~4 µm)
Chlorophytes (~8 µm)
Detritus
CDOM

Stramski and Mobley (1997)
Mobley and Stramski (1997)
### Particle Functional Types

<table>
<thead>
<tr>
<th>Particle Class</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Organic Colloids</td>
<td>SCOL</td>
</tr>
<tr>
<td>Coarse Organic Colloids</td>
<td>LCOL</td>
</tr>
<tr>
<td>Small Minerals</td>
<td>SMIN</td>
</tr>
<tr>
<td>Heterotrophic Bacteria</td>
<td>HBAC</td>
</tr>
<tr>
<td>Prochlorophytes</td>
<td>PROC</td>
</tr>
<tr>
<td>Synechococcus</td>
<td>SYNE</td>
</tr>
<tr>
<td>Picoeukaryotes</td>
<td>PEUK</td>
</tr>
<tr>
<td>Small Nanophytoplankton</td>
<td>SNANO</td>
</tr>
<tr>
<td>Large Nanophytoplankton</td>
<td>LNANO</td>
</tr>
<tr>
<td>Microphytoplankton</td>
<td>MICRO</td>
</tr>
<tr>
<td>Organic Detritus</td>
<td>DET</td>
</tr>
<tr>
<td>Large Minerals</td>
<td>LMIN</td>
</tr>
</tbody>
</table>

#### Particle Class Size Range and Average Particle Diameter

![Particle Class Size Range and Average Particle Diameter Graph](chart.png)
EXAMPLE MODELS

Base model
+ single class phytoplankton bloom
+ multiple class phytoplankton bloom
+ addition of organic colloids
+ addition of heterotrophic bacteria
+ addition of organic detritus
+ addition of minerals
+ phytoplankton bloom with the addition of detritus
+ phytoplankton bloom with the addition of detritus and minerals
Base model:
Chl a = 0.3 mg m\(^{-3}\)
POC = 60 mg m\(^{-3}\)
Multiple class phytoplankton bloom:
Chla = 1.77 mg m\(^{-3}\)
POC = 125 mg m\(^{-3}\)
Comparison of model results to field data
The complexity of seawater as an optical medium should not deter us from pursuing the proper course in future research

“The reductionist worldview has to be accepted as it is, not because we like it, but because that is the way the world works”

Steven Weinberg
1979 Nobel Prize in Physics