海洋生物地球化学
全国重点实验室（厦门大学）
State Key Laboratory of Marine Environmental Science

厦門大學
Optical Oceanography Laboratory

Inherent Optical Properties (IOPs)

Lecture 1: Basics & Relationships with AOPs

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Research Interest:

- Modeling of radiative transfer
- Inversion algorithms for optically deep and shallow waters
- Theory and estimation of water clarity/transparency
- Atmospheric correction algorithm and satellite data processing
- Application of satellite ocean color products
- Estimation of primary production
- Techniques related to field measurements of AOPs

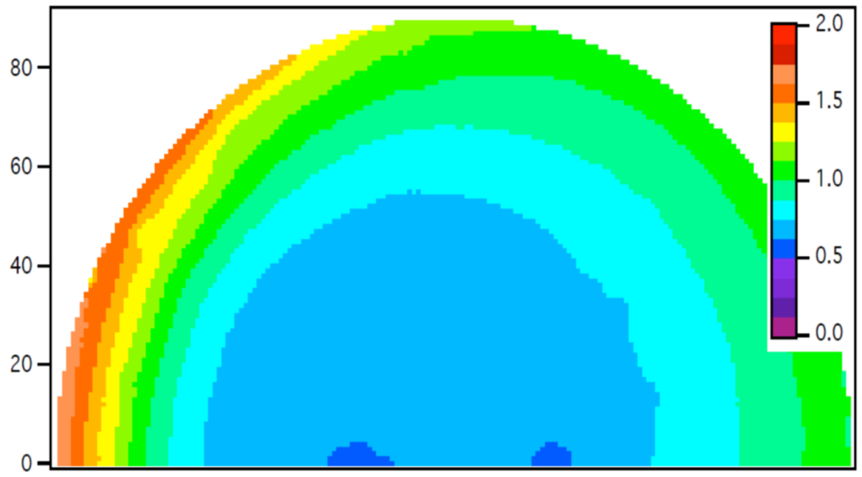
Contents:

1. Inherent Optical Properties (IOPs)

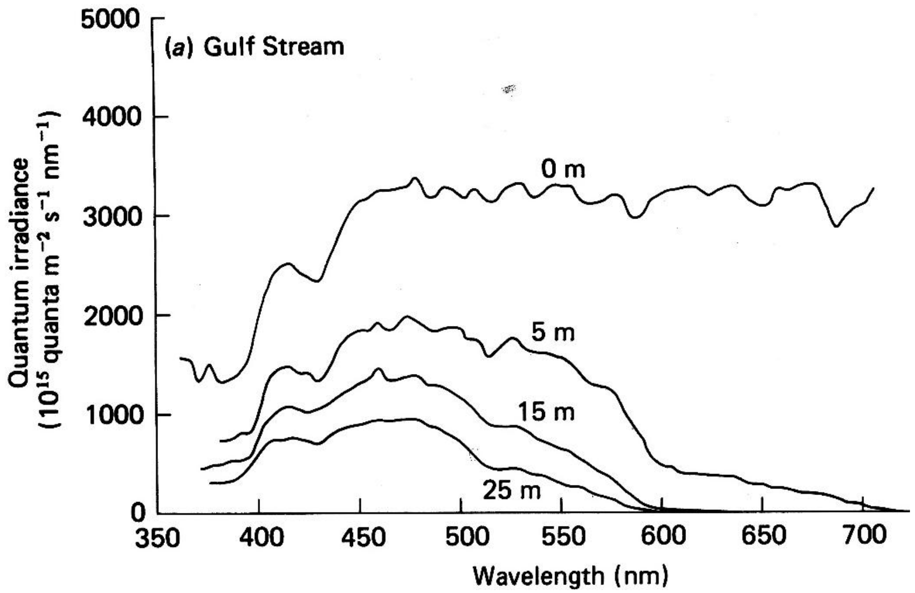
ocean (water) color

light within water medium

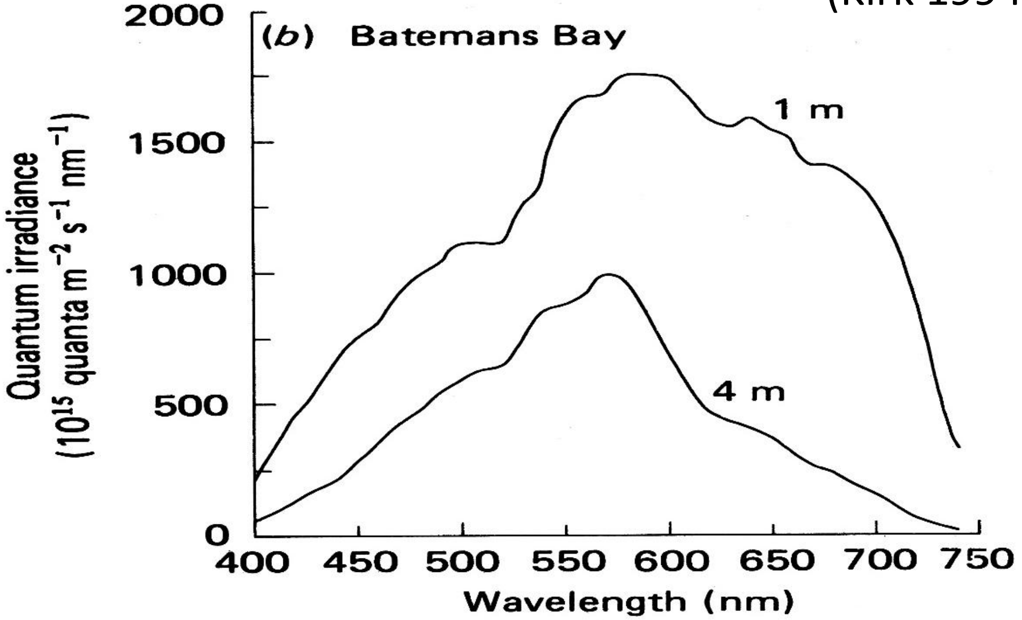
Lu(Θ,ϕ)



(Voss et al 2007)



(Kirk 1994)



They are modulated by water constituents.

Boundary conditions

↓

Water constituents → **IOPs** → **color**

IOPs (Inherent Optical Properties):

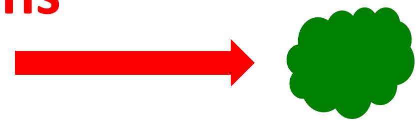
The optical capability regardless of the ambient light environment.

Absorption properties; Scattering properties

Energy transfer processes:

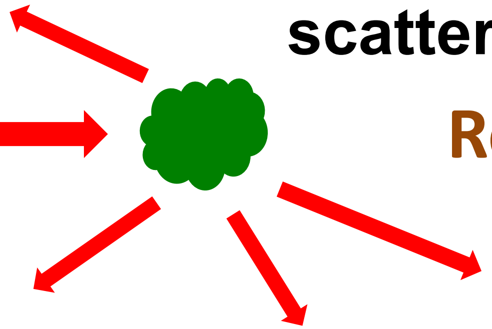
photons

absorption



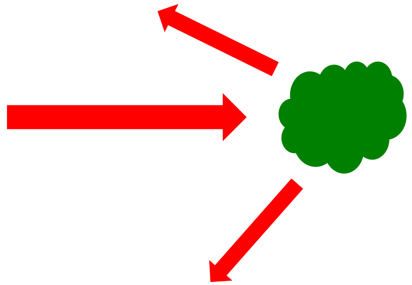
Transfer of energy

scattering



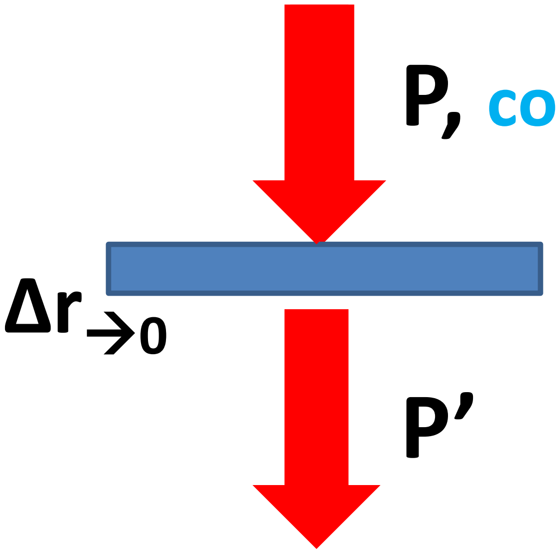
Redistribution of energy

backscattering



Scattering has angular dependence

Definition of absorption and scattering **coefficients**



$$IOP_{process} = \frac{1}{P}\frac{\Delta P_{process}(= P' - P)}{\Delta r_{\to 0}}$$

$$a = \frac{1}{P}\frac{\Delta P_{absorption}}{\Delta r_{\to 0}} \qquad b = \frac{1}{P}\frac{\Delta P_{scattering}}{\Delta r_{\to 0}}$$

Units: **Δr: infinitesimal (m)**
a&b: m^{-1}

$a = 1.2\ m^{-1}$
$b = 3.5\ m^{-1}$

IOPs are additive

$$a = a_w + \sum a_{xi} \qquad b = b_w + \sum b_{xi}$$

D. Stramski et al. / Progress in Oceanography 61 (2004) 27–56 31

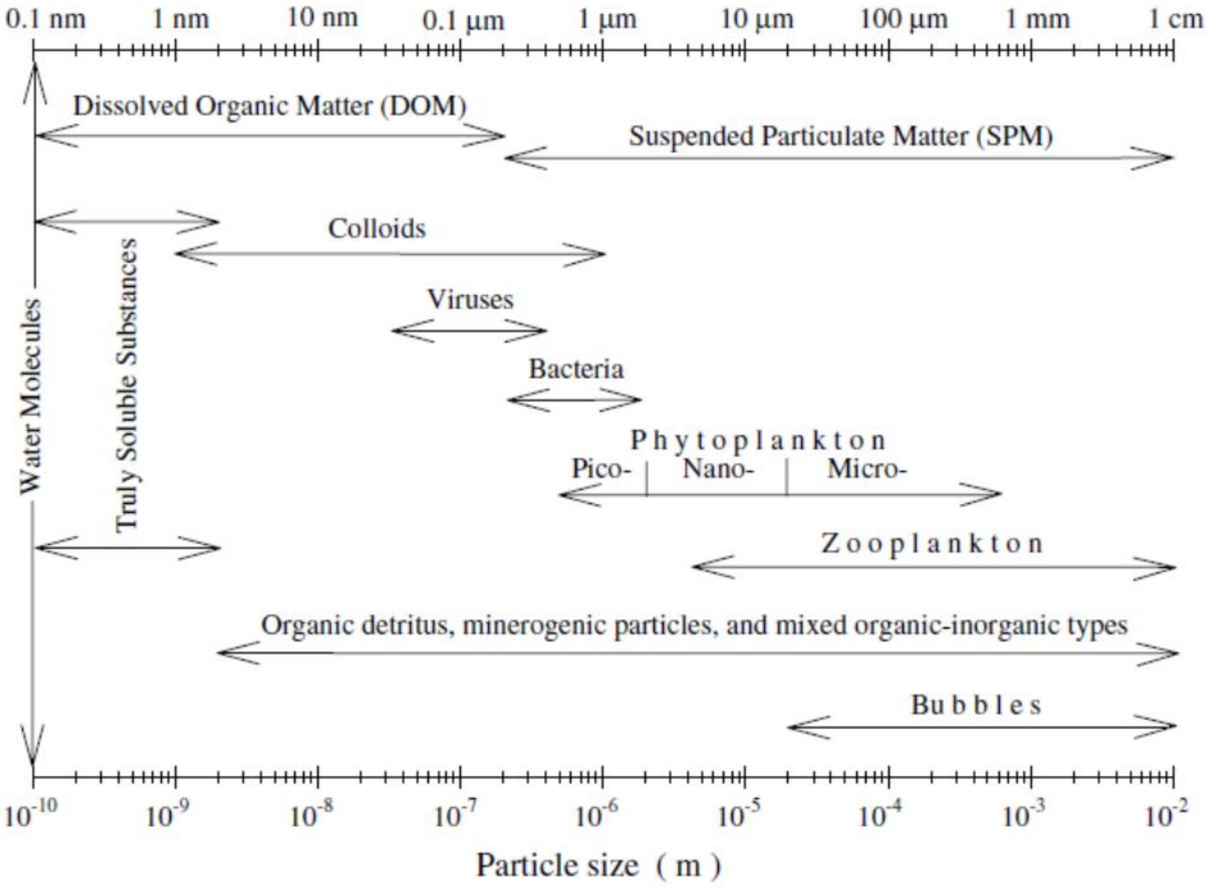


Fig. 1. Schematic diagram showing various seawater constituents in the broad size range from molecular size of the order of 10^{-10} m to large particles and bubbles of the order of 10^{-3}–10^{-2} m in size. The arrow ends generally indicate approximate rather than sharp boundaries for different constituent categories.

A. absorption properties

$$a = a_w + \sum a_{xi}$$

Very detailed:

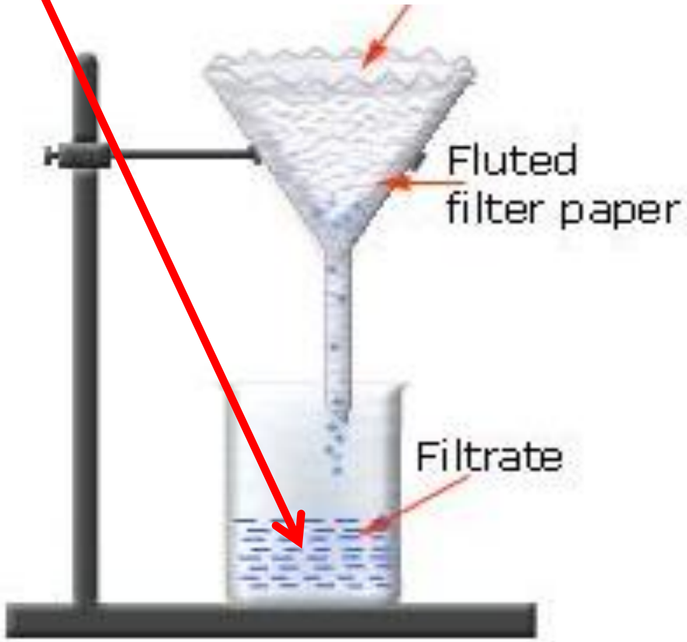
$$a(\lambda) = a_w(\lambda) + \sum_{i=1}^{18} a_{\text{pla},i}(\lambda + a_{\text{det}}(\lambda) + a_{\text{min}}(\lambda) + a_{\text{CDOM}}(\lambda)$$
$$= a_w(\lambda) + \sum_{i=1}^{18} N_{\text{pla},i}\sigma_{a,\text{pla},i}(\lambda) + N_{\text{det}}\sigma_{a,\text{det}}(\lambda)$$
$$+ N_{\text{min}}\sigma_{a,\text{min}}(\lambda) + a_{\text{CDOM}}(\lambda), \qquad (1)$$

(Stramski et al 2001)

Practical (and common) separation:

$$a = a_w + a_p + a_g$$

(google)



(google)

$$a = a_w + a_{ph} + a_d + a_g$$

$$a = a_w + a_{ph} + a_d + a_g$$

Pure water (seawater): a_w

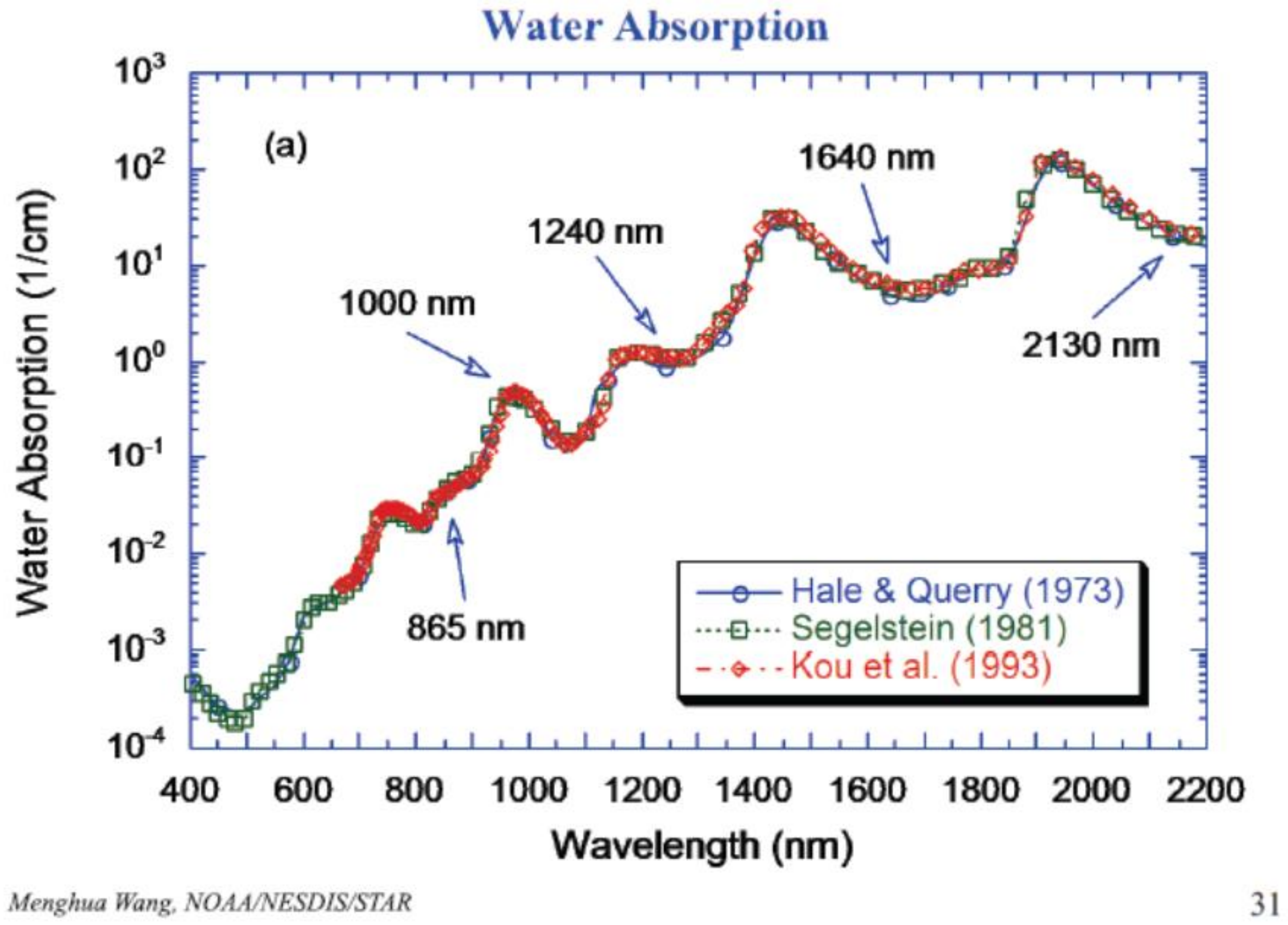
Particulate: $a_p = a_{ph} + a_d$

Pigments of living phytoplankton: a_{ph}

Detritus: a_d

Gelbstoff (yellow substance; colored dissolved organic matter): a_g

a_w spectrum



Water Absorption
(a)
Water Absorption (1/cm)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1640 nm
1240 nm
1000 nm
2130 nm
865 nm
Hale & Querry (1973)
Segelstein (1981)
Kou et al. (1993)
400 600 800 1000 1200 1400 1600 1800 2000 2200
Wavelength (nm)
Menghua Wang, NOAA/NESDIS/STAR
31

“true” values of a_w?

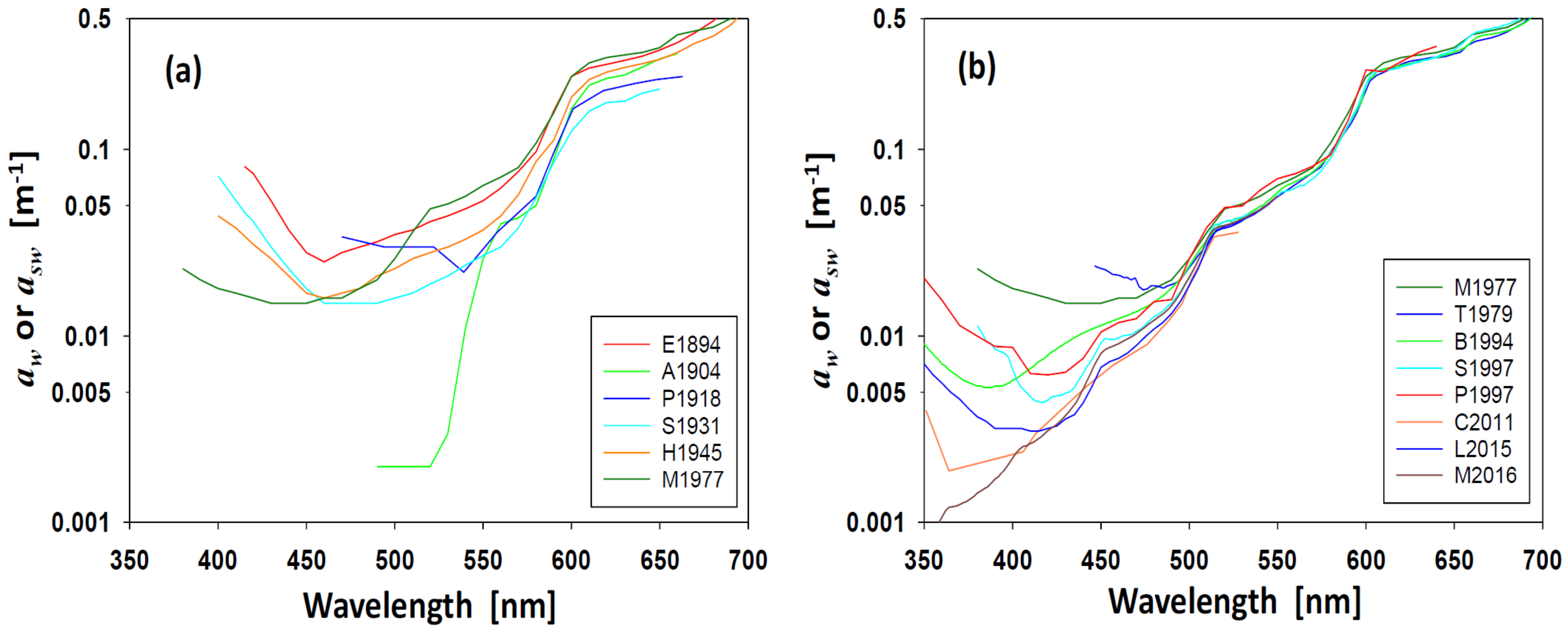
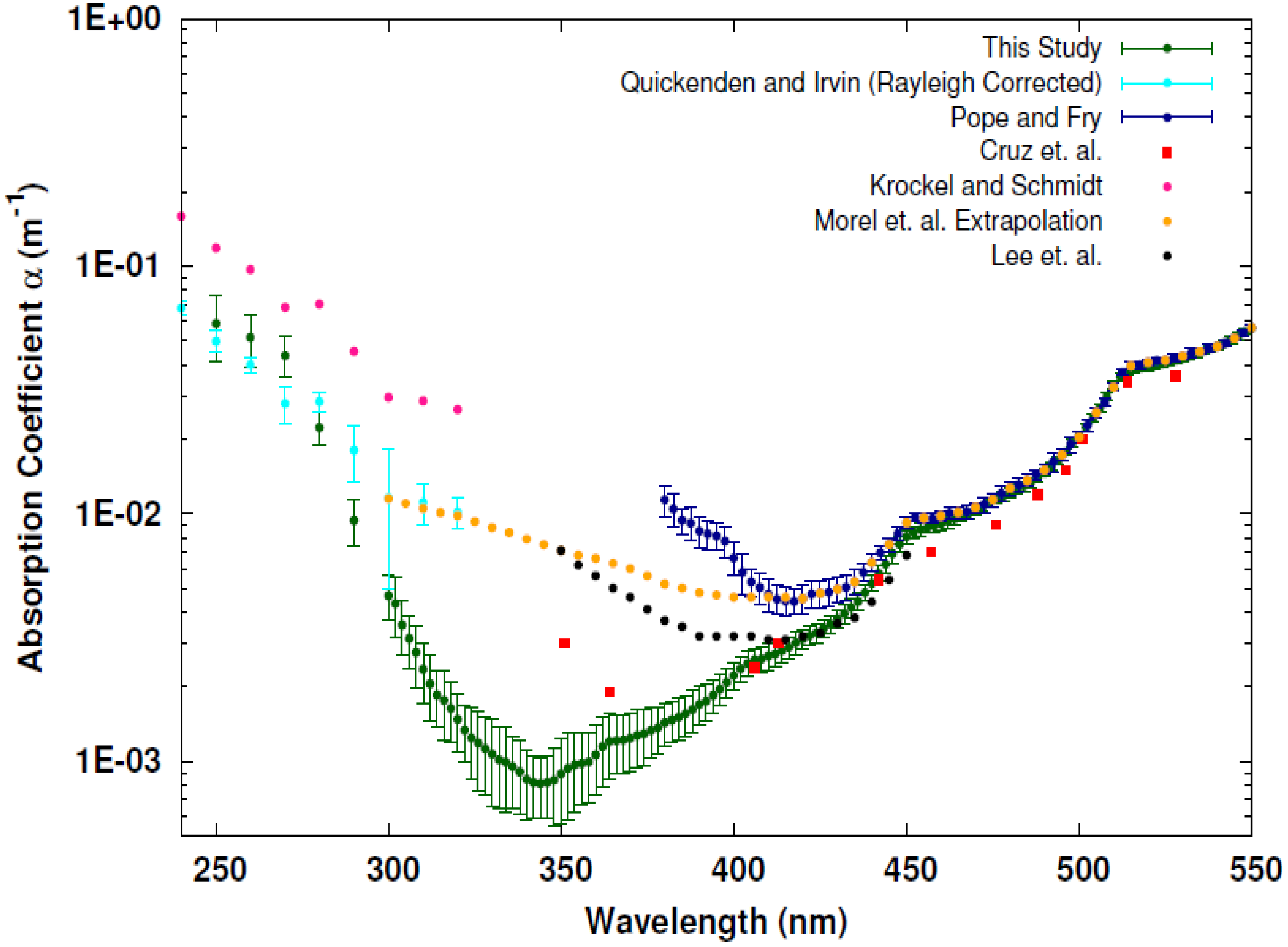


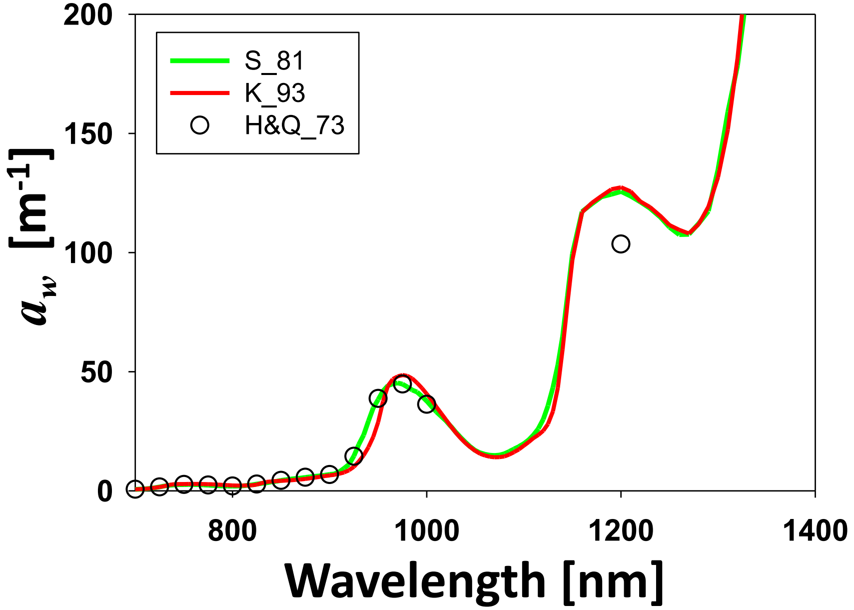
Fig. 1. Examples of historical measurements or determinations of a_w or a_{sw}. (a) Older data, (b) later data. The values of Morel and Prieur (1977) are included in both (a) and (b) for reference. E1894: Ewan (1894); A1904: Aufsess (1904); P1918: Pietenpol (1918); S1931: Sawyer (1931); H1945: Hulburt (1945); M1977: Morel and Prieur (1977); T1979: Tam and Patel (1979); B1994: Buiteveld et al. (1994); S1997: Sogandares and Fry (1997); P1997: Pope and Fry (1997); C2011: Cruz et al. (2011); L2015: Lee et al. (2015); M2016: Mason et al. (2016).

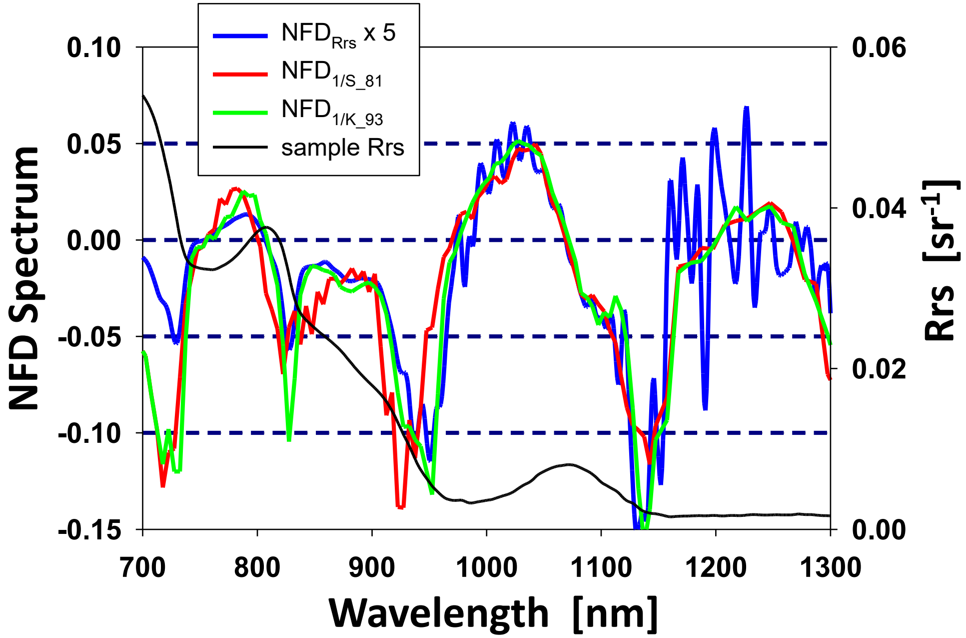
(Lee and Tang, 2022)



(Mason et al, 2016)

In the NIR-SWIR range …





(Lee et al 2016)

H&Q_73: Hale and Querry 1973

S_81: Segelstein 1981

K_93: Kou et al. 1993 √

a_w is temperature and salinity dependent

$$a_w(\lambda, T, S) = a_w(\lambda, T_r, 0) + \Psi_T(T - T_r) + \Psi_S S, \quad (1)$$

There are contrasting values regarding ψ_T.

The influence of temperature on light transmission in the spectral range from 400 to 760 nm has been determined in a two-cell instrument constructed especially for this purpose. Light transmission was measured over a 1-m path length in both a photometric and a spectral mode in double-ion-exchanged fresh water and filtered seawater with a salinity of approximately 25‰. For both groups of samples the temperature-dependence coefficient of the absorption was found to be $-0.00091 \pm 0.00006\ m^{-1}\ K^{-1}$ in the range from 400 to 550 nm, in contrast to earlier findings. Reproducible signals could be observed only when the samples were left undisturbed for long periods of time between shifts in temperature. The temperature was scanned in alternating directions between 6 and 30 °C in steps of ±2 °C. The

(Trabjerg and Hojerslev, Appl. Opt., 1996)

Table 2. Linear Slopes of the Temperature Dependence of the Absorption Coefficient Measured in the Laboratory[a]

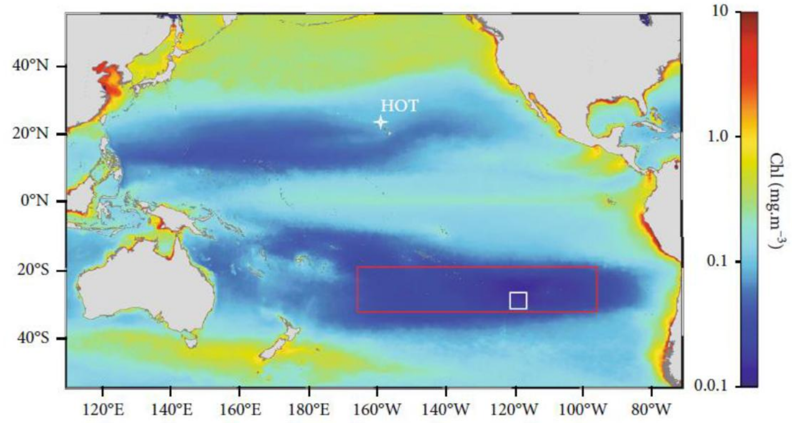
Wavelength	Ψ_T, Pure Water	Standard Deviation, Pure Water	Ψ_T, Saltwater	Standard Deviation, Saltwater
412	0.0001	0.0003	0.0003	0.0003
440	0.0000	0.0002	0.0002	0.0002
488	0.0000	0.0002	0.0001	0.0002
510	0.0002	0.0001	0.0003	0.0001
520	0.0001	0.0002	0.0002	0.0002
532	0.0001	0.0002	0.0001	0.0002
555	0.0001	0.0001	0.0002	0.0002

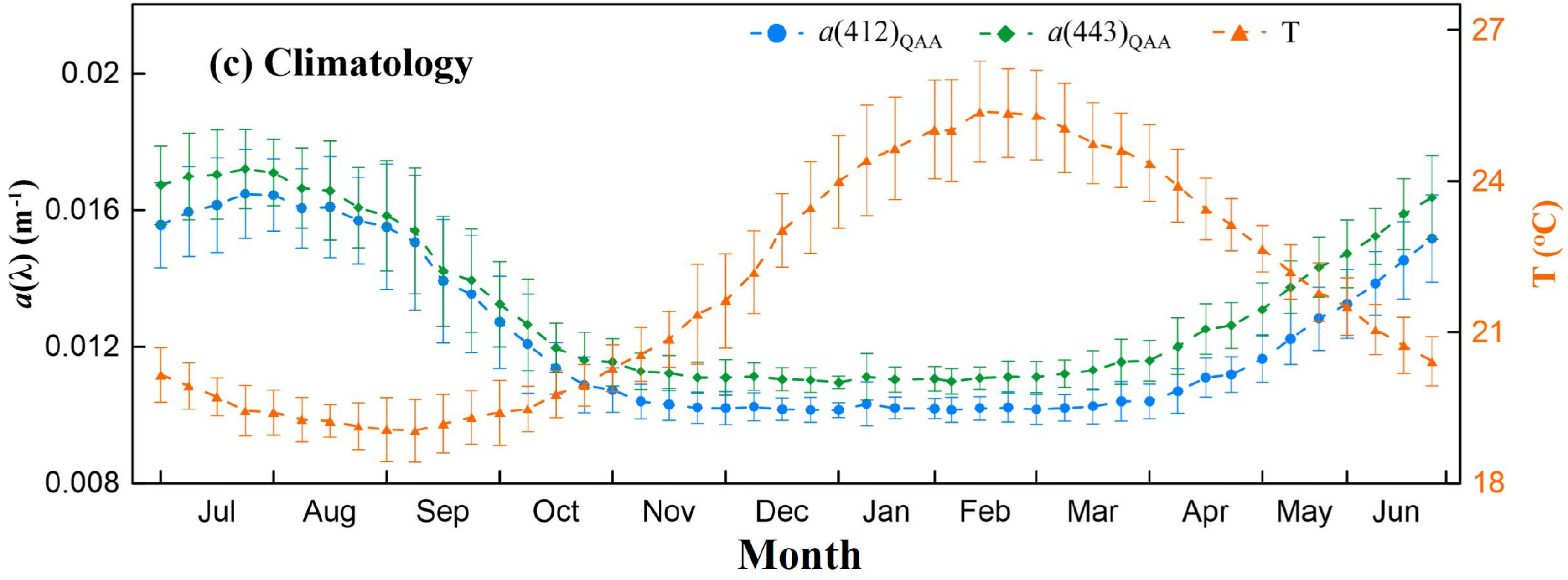
(Pegau et al 1997)

No clear dependence of a_w on T in the visible domain.

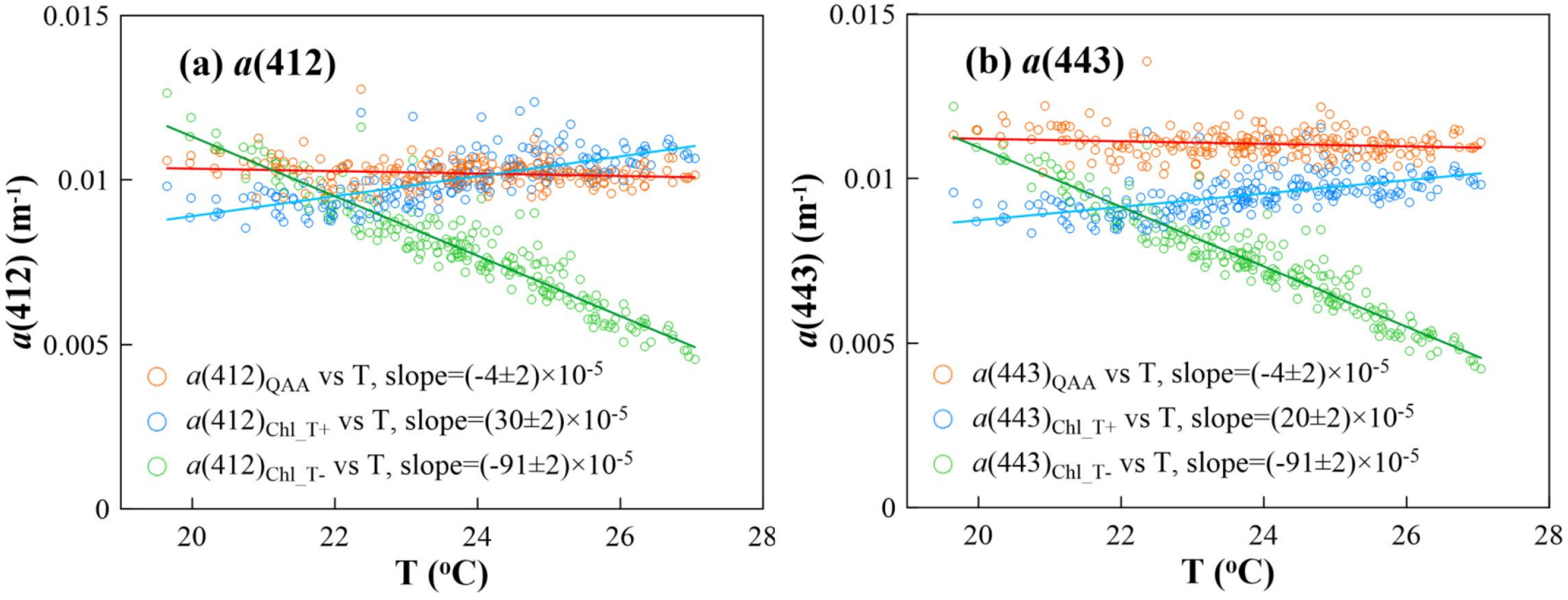
(Rottgers et al. 2014)

$a(\lambda, \mathrm{T})$ vs T





(Wei et al., 2021)

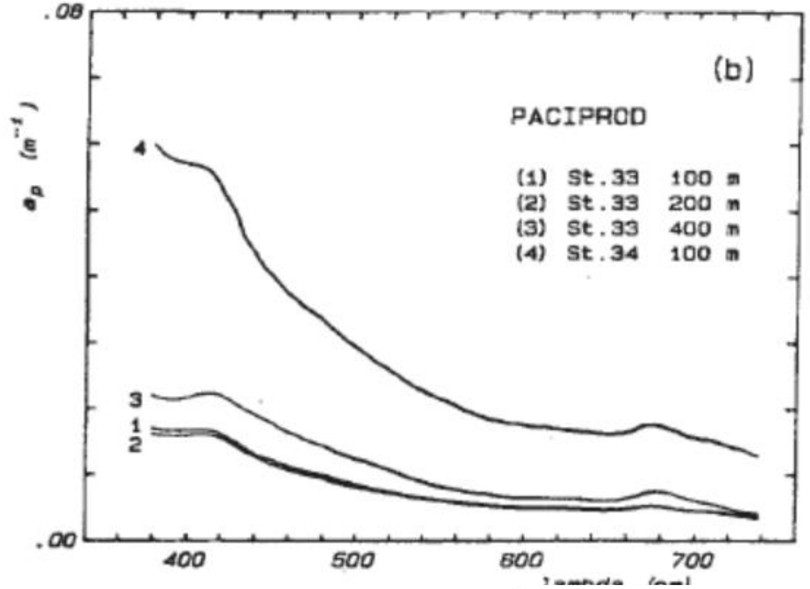


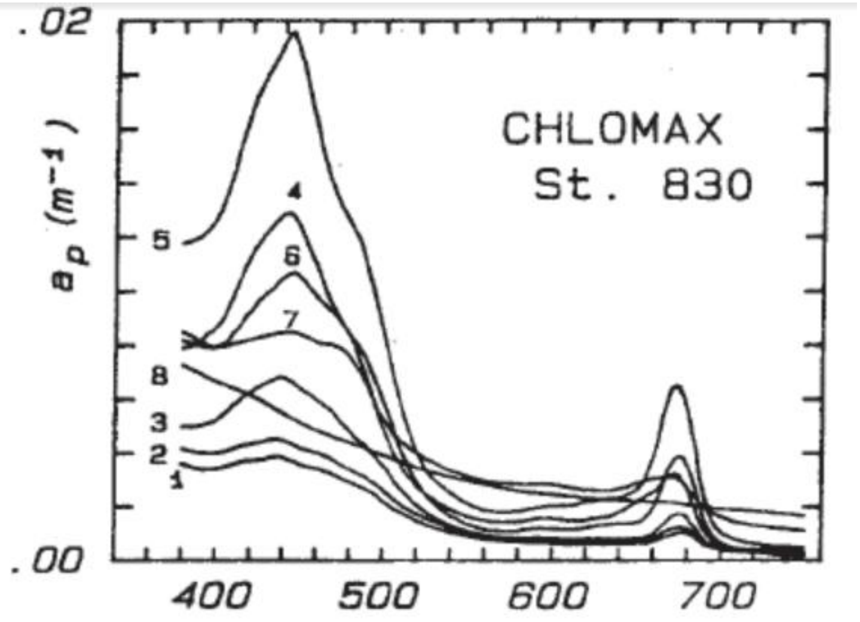
(Wei et al., 2021)

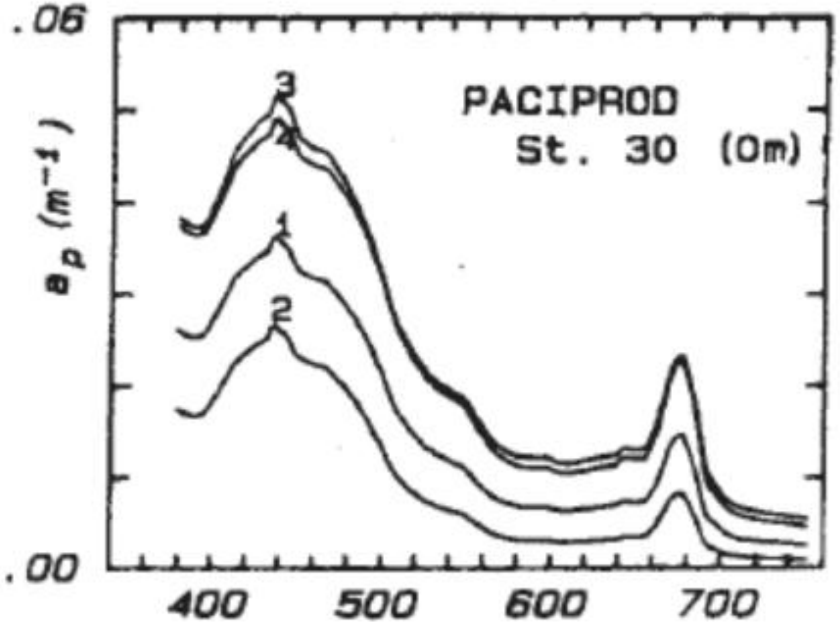
- **$a(\lambda)_{Chl\_T-}$: $a(412)$ is expected to decrease by ~56%**
- **$a(\lambda)_{Chl\_T+}$: $a(412)$ is expected to increase by ~26%.**

➡ **a_{sw}(412,443) slightly decreases with T.**

a_p spectrum



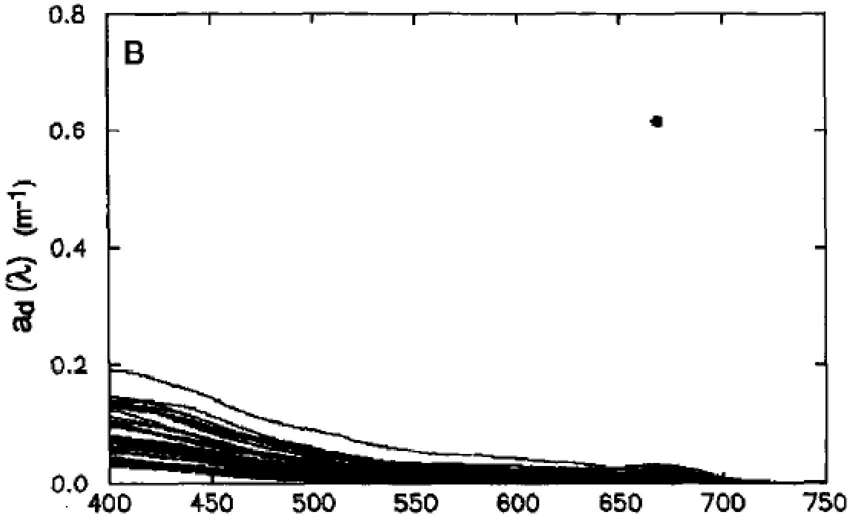




Bricaud and Stramski (1990)

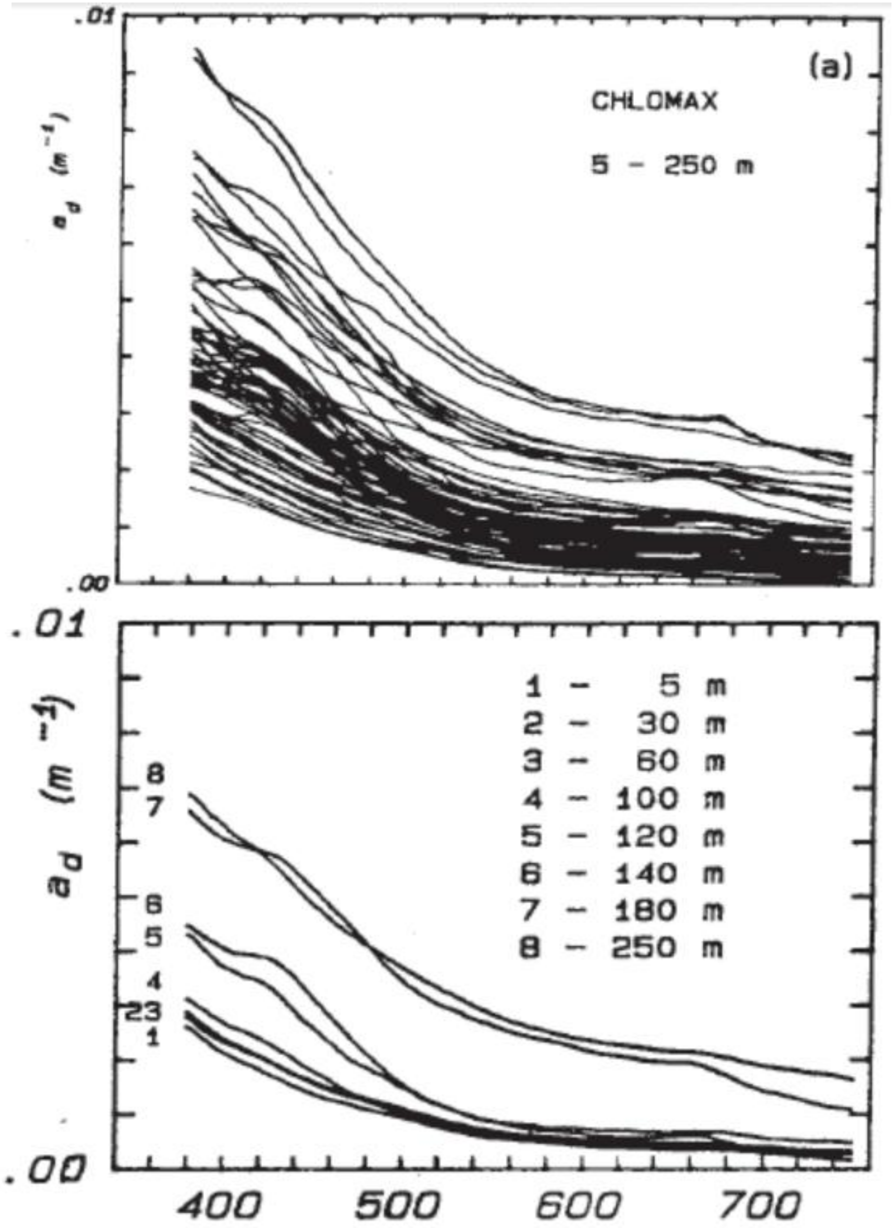
(google)

a_d spectrum



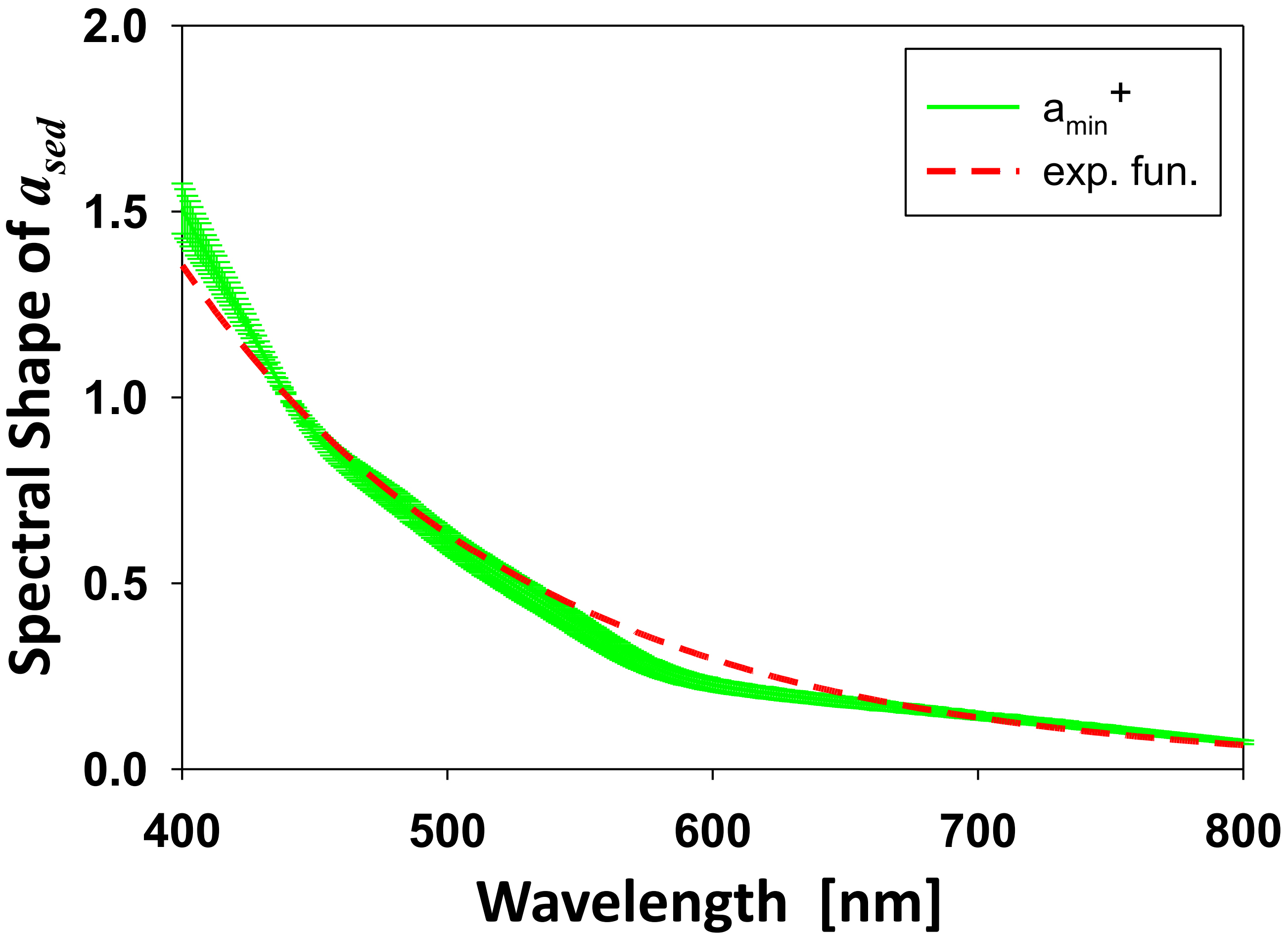
$$a_d = a_d(\lambda_0)\, e^{-S_d(\lambda - \lambda_0)}$$

S_d: ~0.005 – 0.015 nm^{-1}



Bricaud and Stramski (1990)

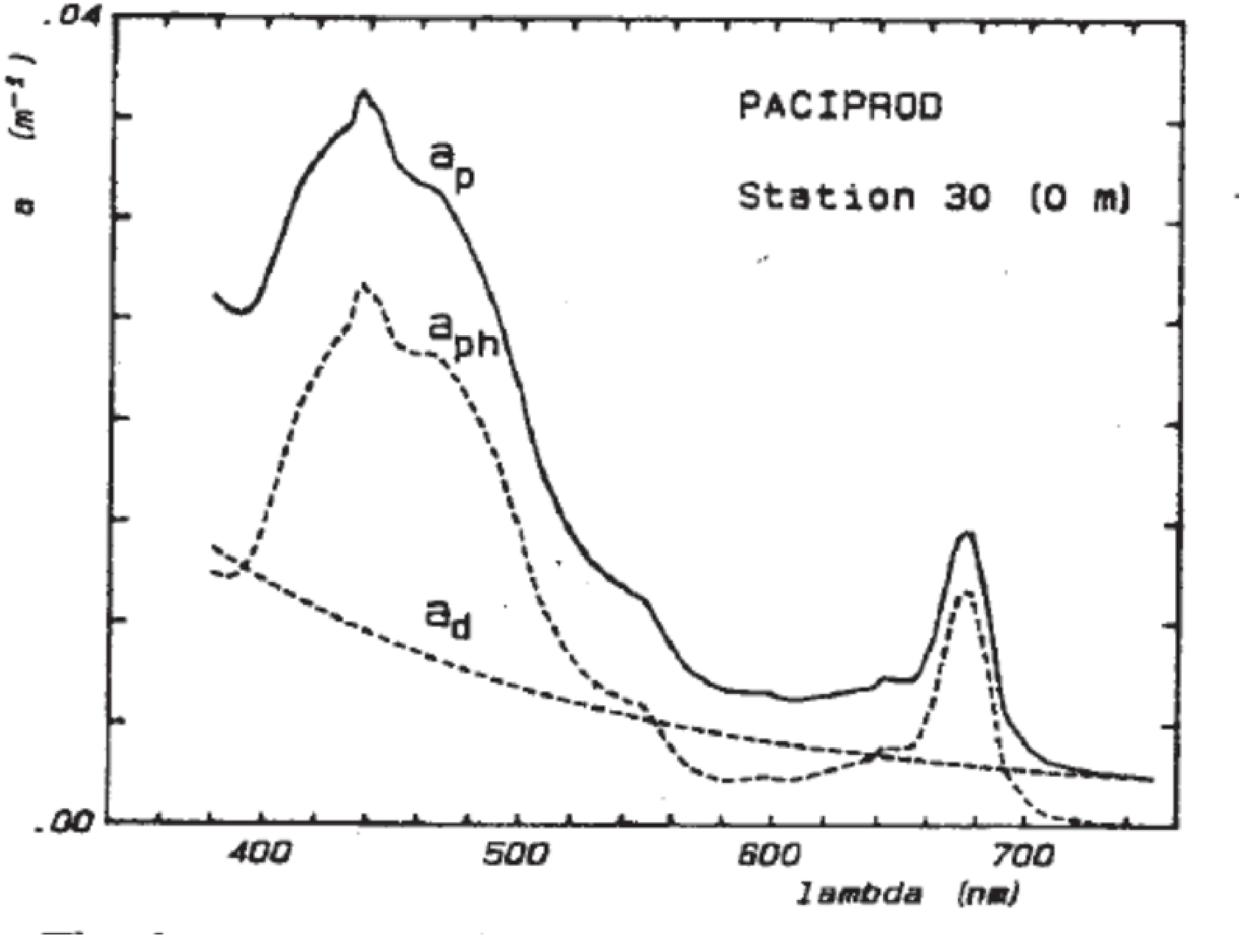
Mineral-dominated particles：



(Lee et al. 2016)

$$a_d(\lambda) = A_d(440)a_d^+(\lambda) + B_d$$

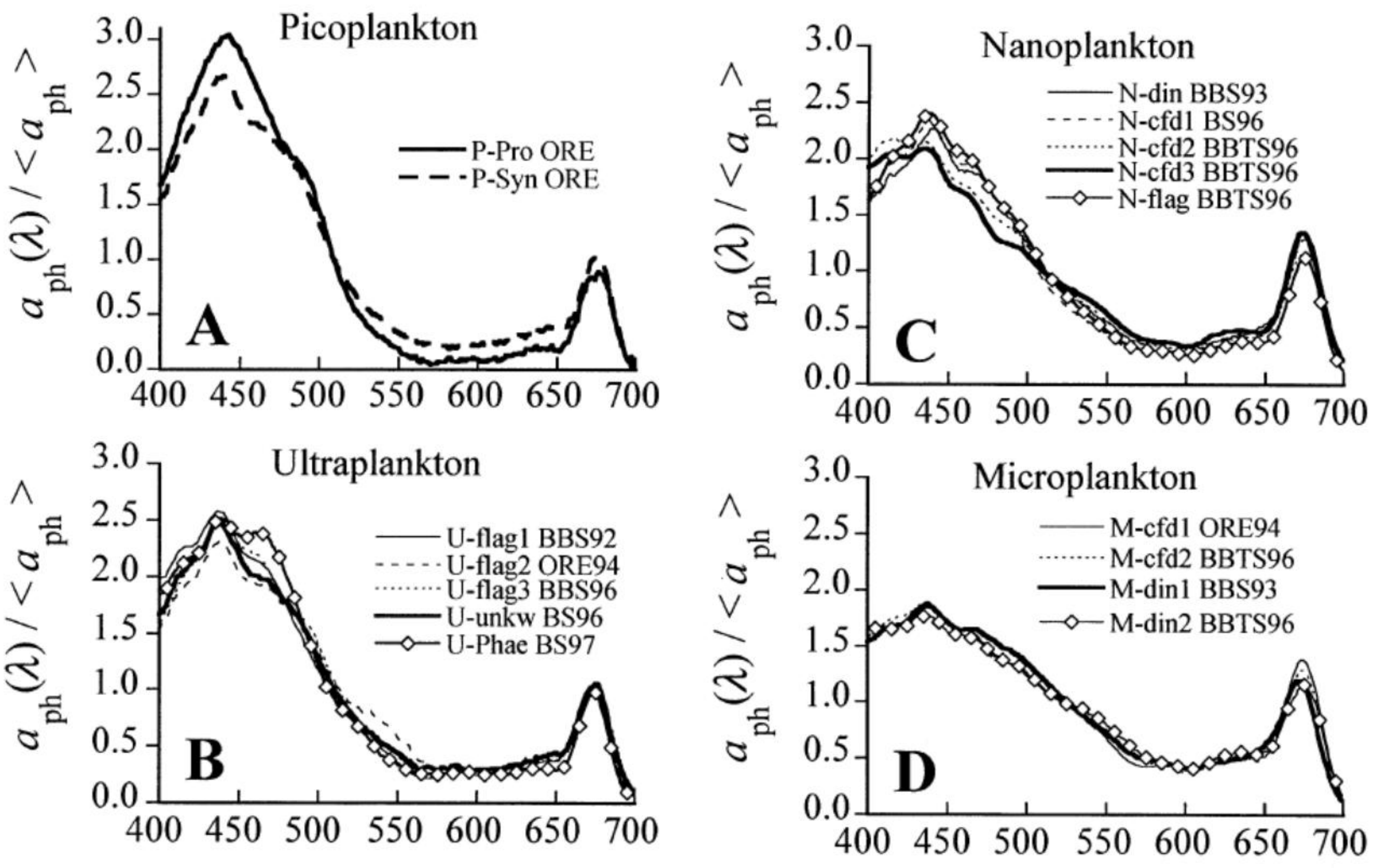
$a_{ph} = a_p - a_d$ spectrum



Bricaud and Stramski (1990)

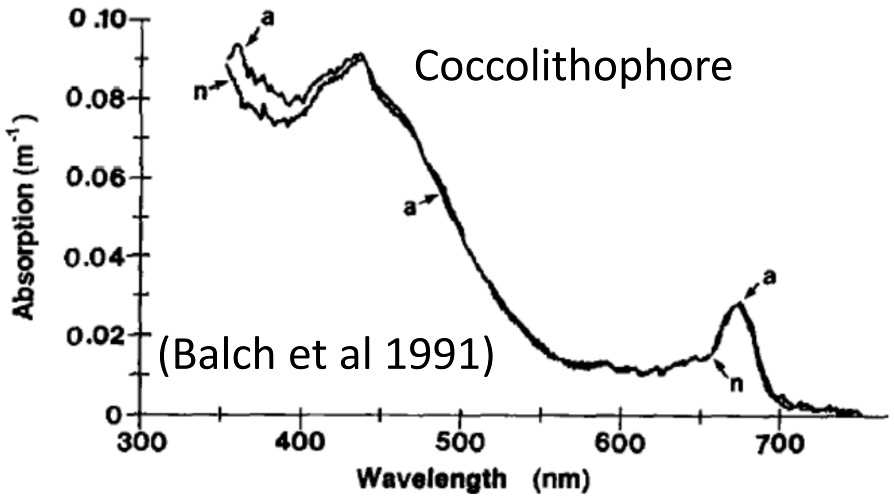
Separated by size

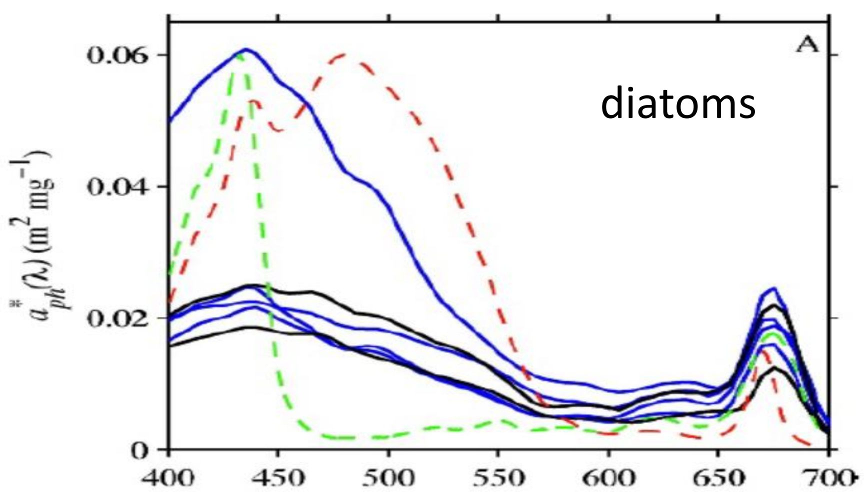
"fatness"

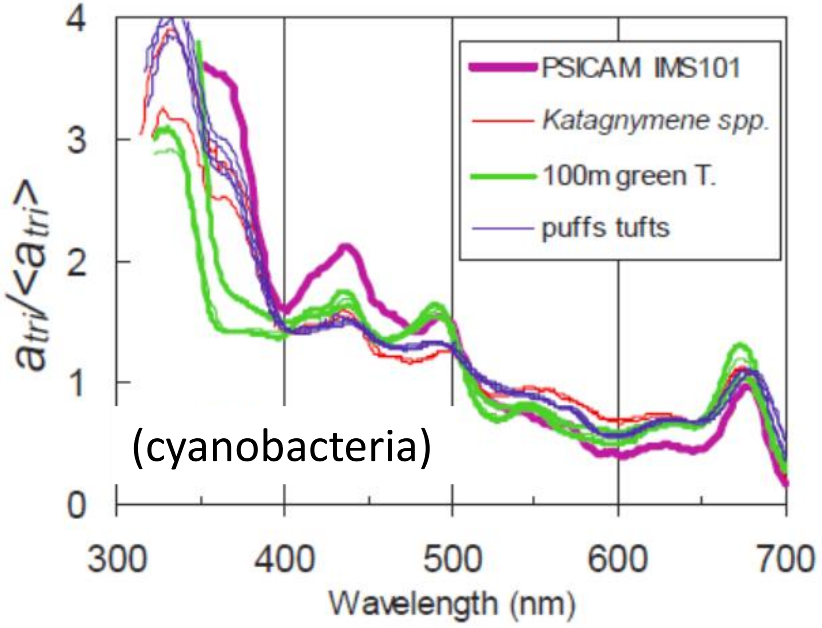


(Ciotti et al 2002)

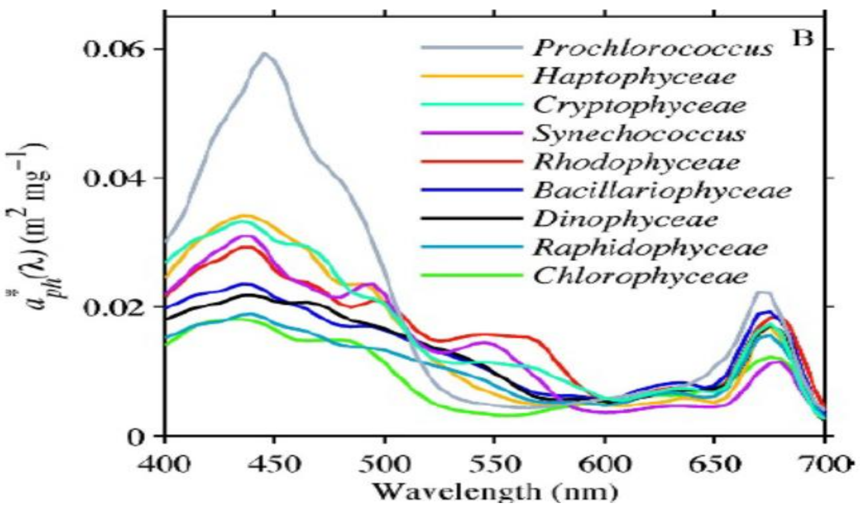
By species or groups





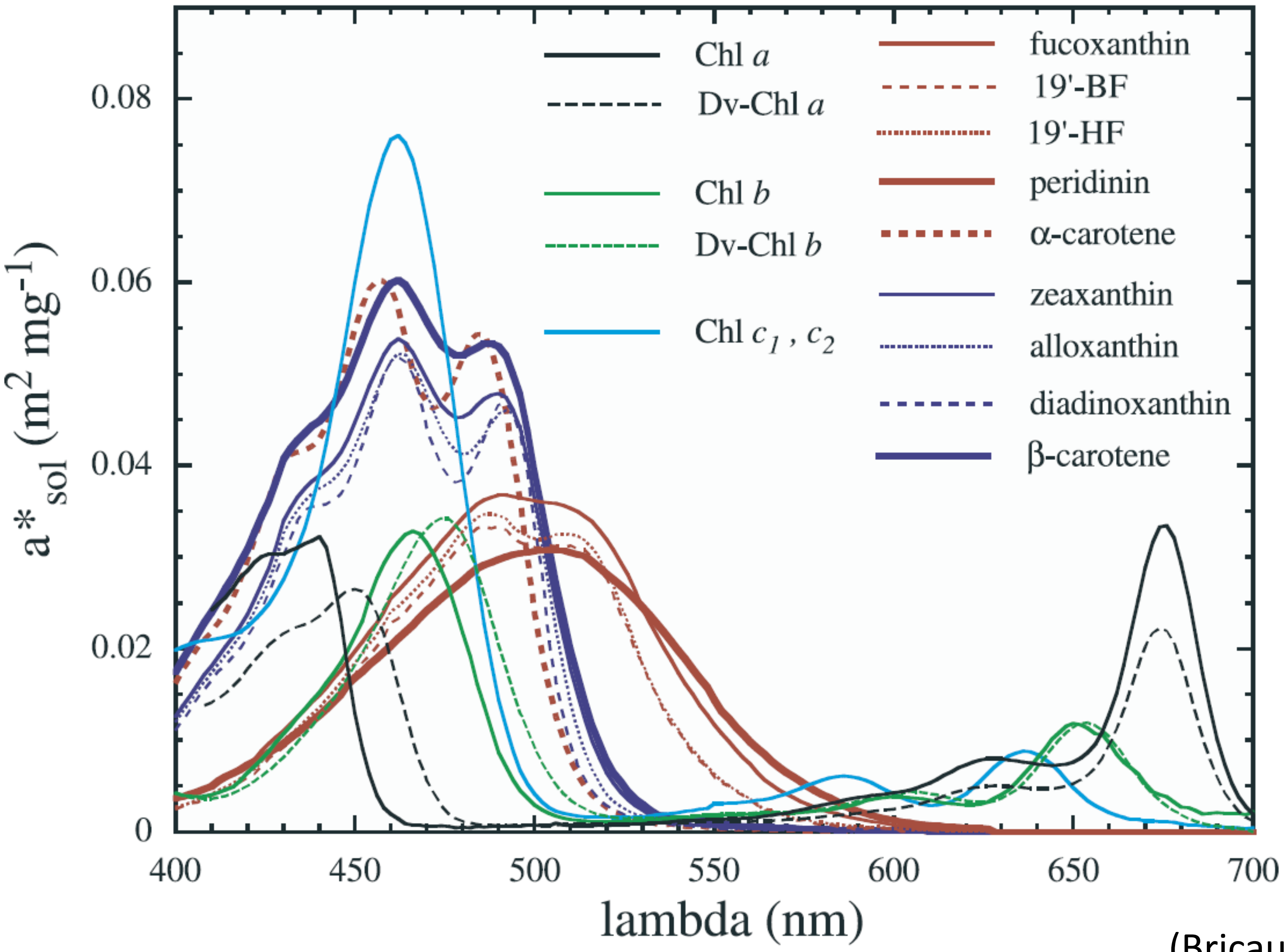


(Dupouy et al 2008)



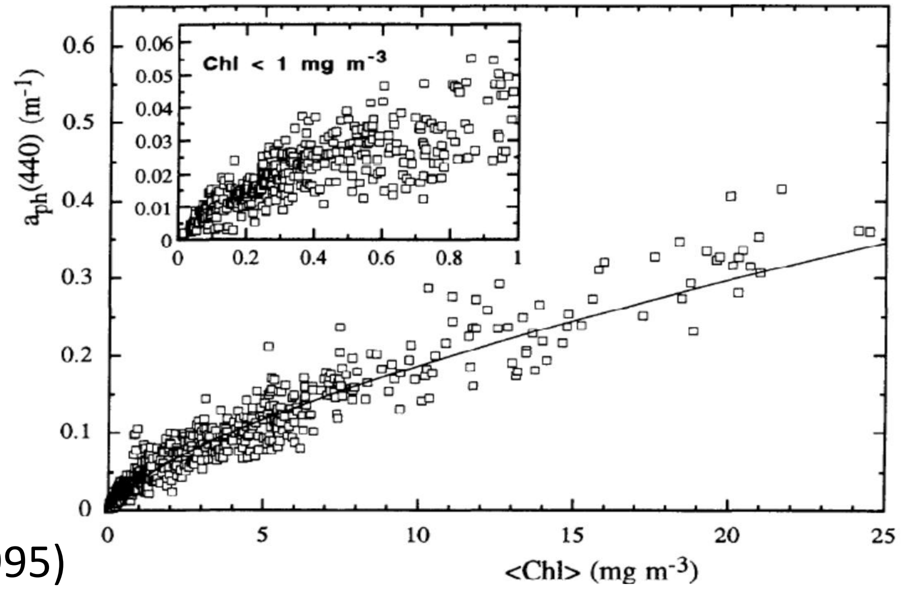
(Dierssen et al 2006)

Contribution of various pigments

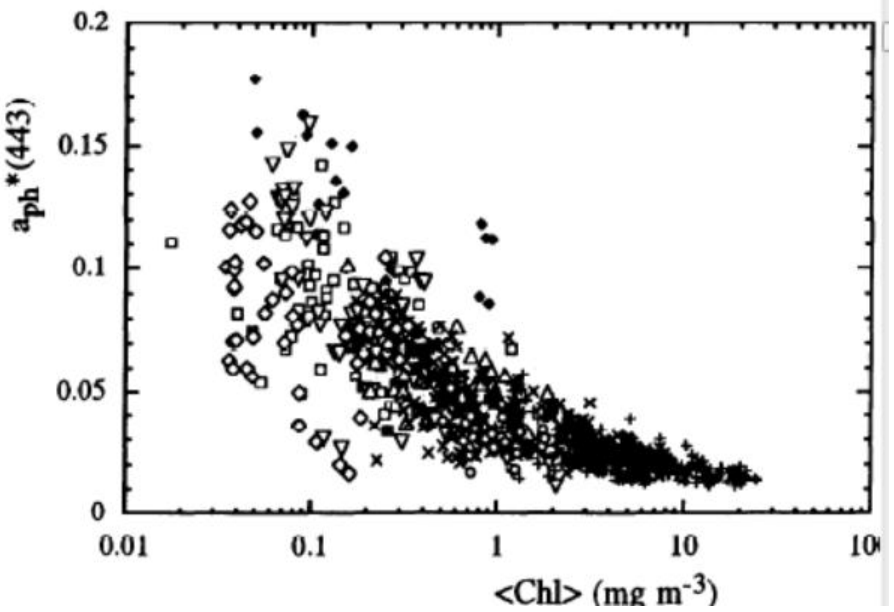


(Bricaud et al 2004)

Package effect



(Bricaud et al 1995)



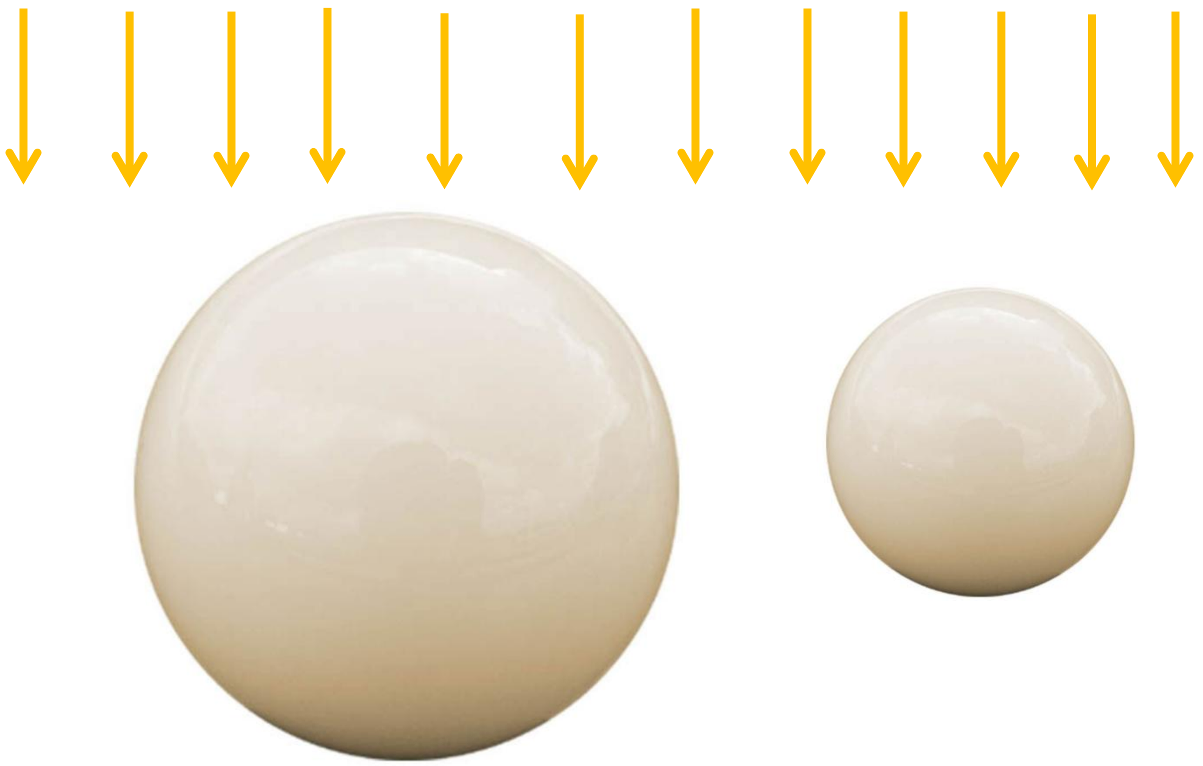
Increase of absorption is NOT linearly proportionally to Chl concentration.

$$a^*_{ph} = \frac{a_{ph}}{Chl}$$

Specific absorption/scattering coefficient =
Concentration normalized absorption/scattering coefficient

Chl↑ → specific optical property↓

Simplified case:



$$a \propto \sigma S$$

$$W \propto \rho V$$

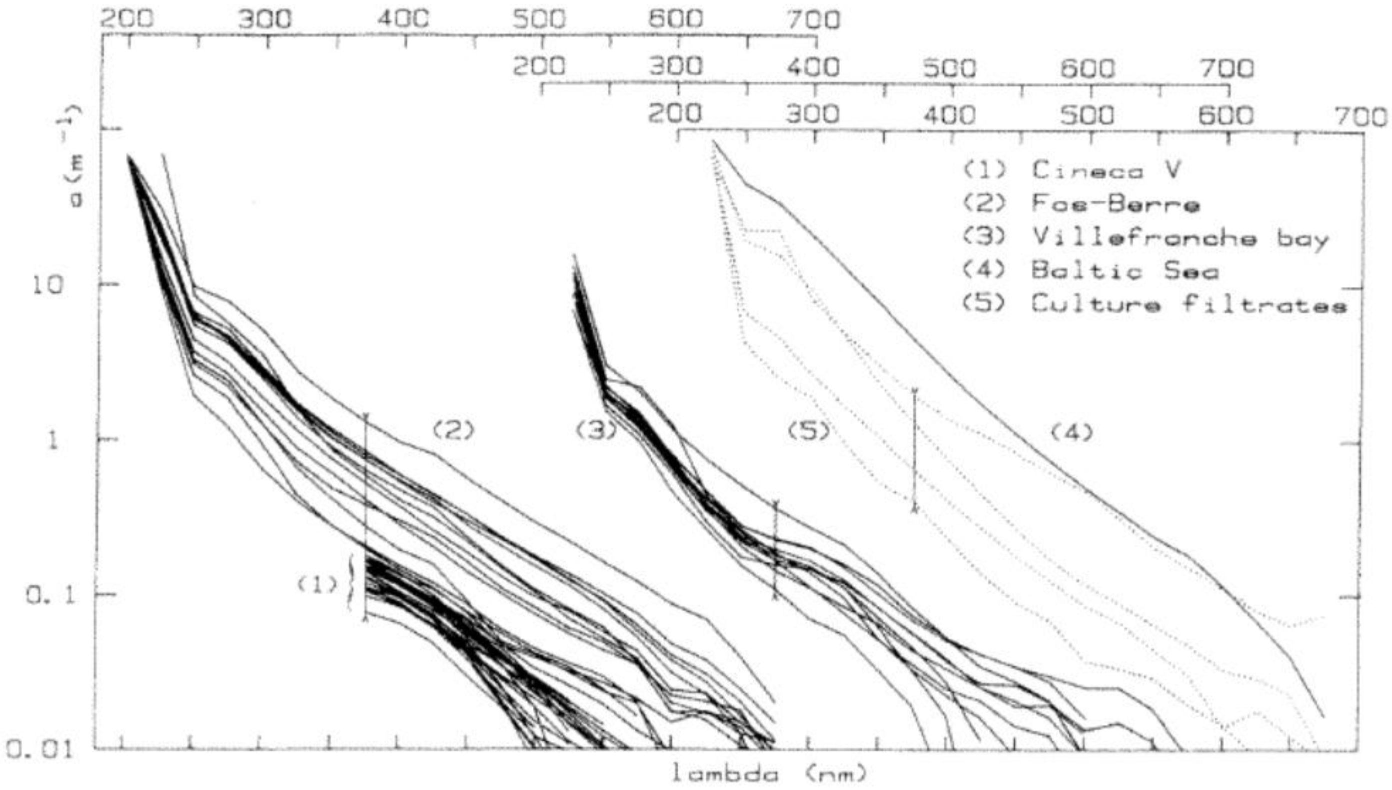
$$a^{*}_{ph} \propto \frac{a}{W} = \frac{\sigma}{\rho}\frac{S}{V} \propto \frac{1}{d}$$

S: cross section
V: volume
W: weight

Size matters on efficiency.

a_g spectrum

Absorption spectra of yellow substance (gelbstoff)

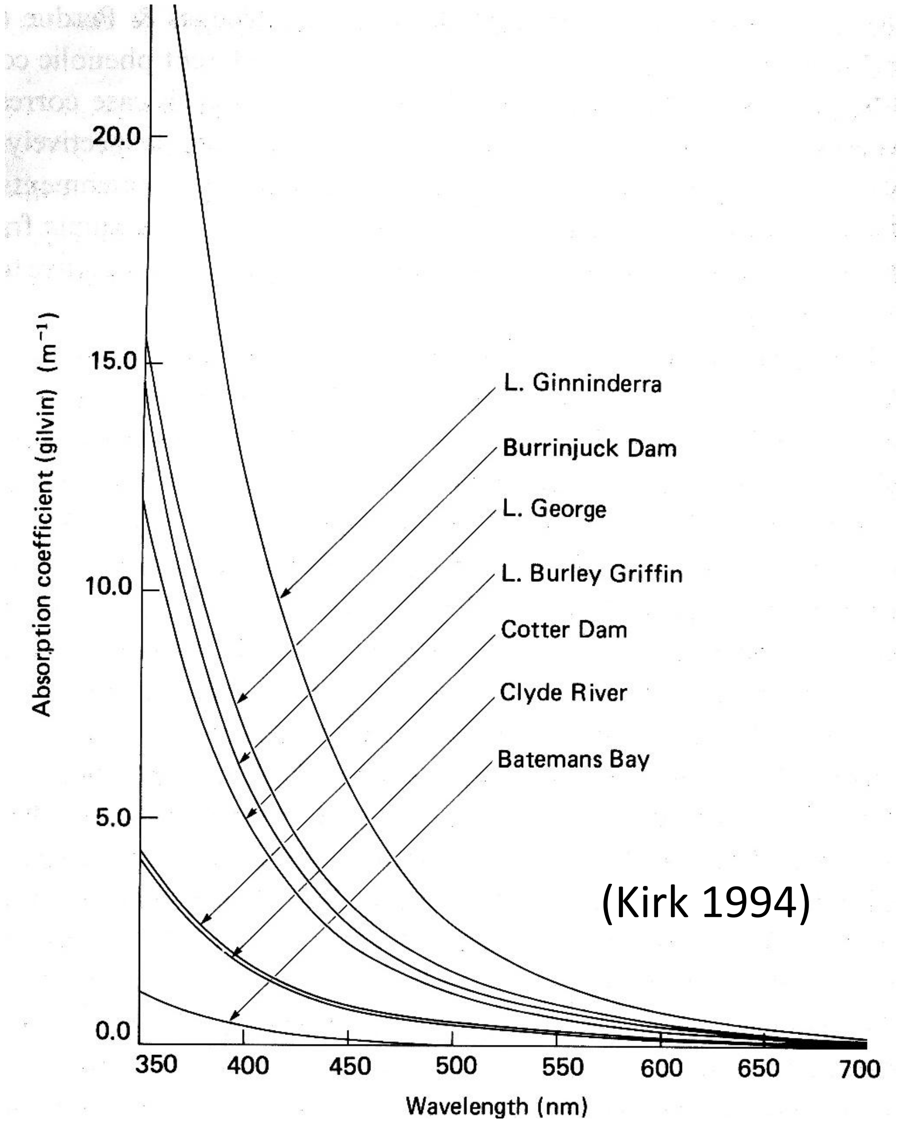


(Bricaud et al 1981)

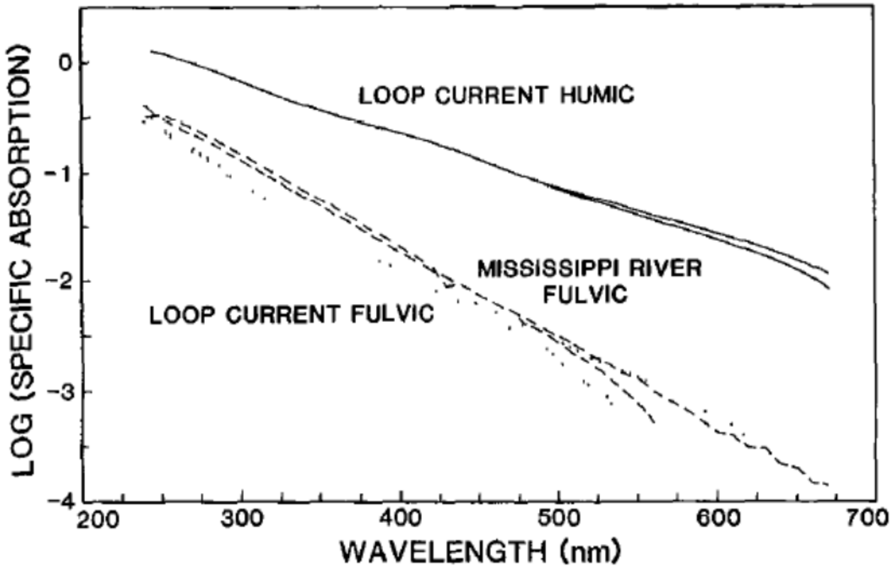
a_g spectrum

$$a_g = a_g(\lambda_0)\, e^{-S_g(\lambda-\lambda_0)}$$

S_g: ~0.01 – 0.03 nm^{-1}



(Kirk 1994)



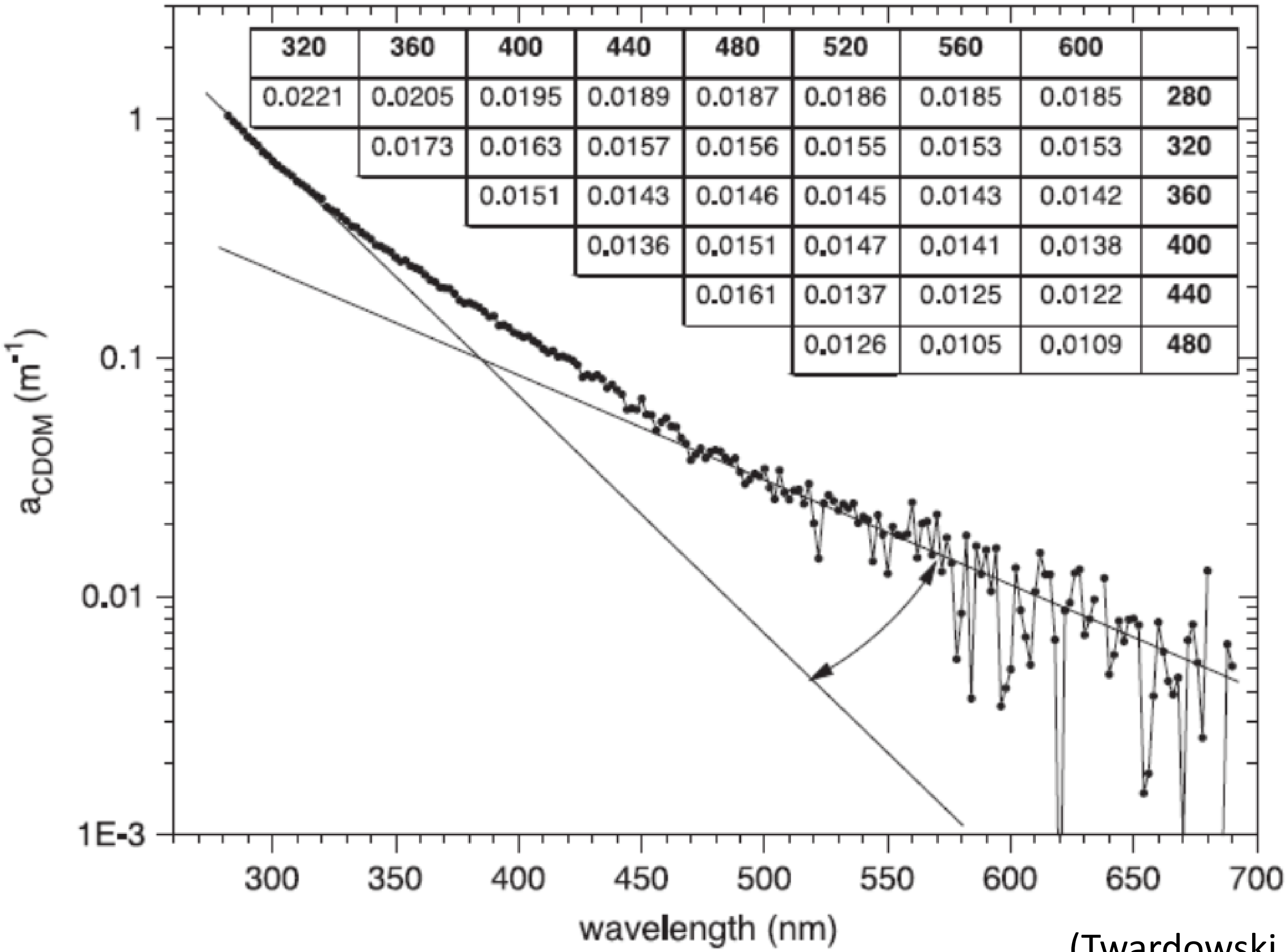
(Carder et al 1989)

Table 1
Spectral slope values for marine samples reported in the literature with spectral range, CDOM absorption at 412 nm, and reported precision (ordered according to starting wavelength range)

Reference	Location	n[a]	Slope (nm^{-1})[b]	Wavelength range	$a_g(412)$ (m^{-1})[c]	Prec (m^{-1})
Højerslev and Aas (2001)	Kattegat–Skagerrak	1305	0.0234 ± 0.0036, [0.0075–0.0420]	[250–450]	1.28 ± 0.70	0.002
Brown (1977)	North Sea	37	[0.0187–0.0306]	280,310	[0.022–0.327]	?
	Baltic proper	157	[0.0247–0.0305]	280,310	[0.136–0.284]	?
	Baltic riverine	1	0.0173	280,310	2.49	?
Nelson et al. (1998)	Bermuda	?	0.0235	280–350	~ 0.1–0.4	0.03
Blough et al. (1993)	Gulf of Paria (samples < 30 ppt)	47	0.0140 ± 0.0003	[290–600+][d]	[1.25–4.59]	0.092
Green and Blough (1994)	S. Florida/Gulf of Mexico	31	0.021 ± 0.005 [0.015–0.034]	[290–(330–675)][d]	[0.01–6.32]	0.092
	Amazon R. estuary	12	0.019 ± 0.005 [0.014–0.033]	[290–(370–590)][d]	[0.03–1.33]	0.092

(Twardowski et al. 2004)

Slope changes with wavelength range



320	360	400	440	480	520	560	600	
0.0221	0.0205	0.0195	0.0189	0.0187	0.0186	0.0185	0.0185	**280**
	0.0173	0.0163	0.0157	0.0156	0.0155	0.0153	0.0153	**320**
		0.0151	0.0143	0.0146	0.0145	0.0143	0.0142	**360**
			0.0136	0.0151	0.0147	0.0141	0.0138	**400**
				0.0161	0.0137	0.0125	0.0122	**440**
					0.0126	0.0105	0.0109	**480**

(Twardowski et al 2004)

Power-law model for a_g spectrum:

A generic, representative CDOM absorption model from this study which requires one absorption estimate at 412 nm as input is:

$$a_g(\lambda) = a_g(412)\left(\frac{\lambda}{412}\right)^{-6.92} \quad (4)$$

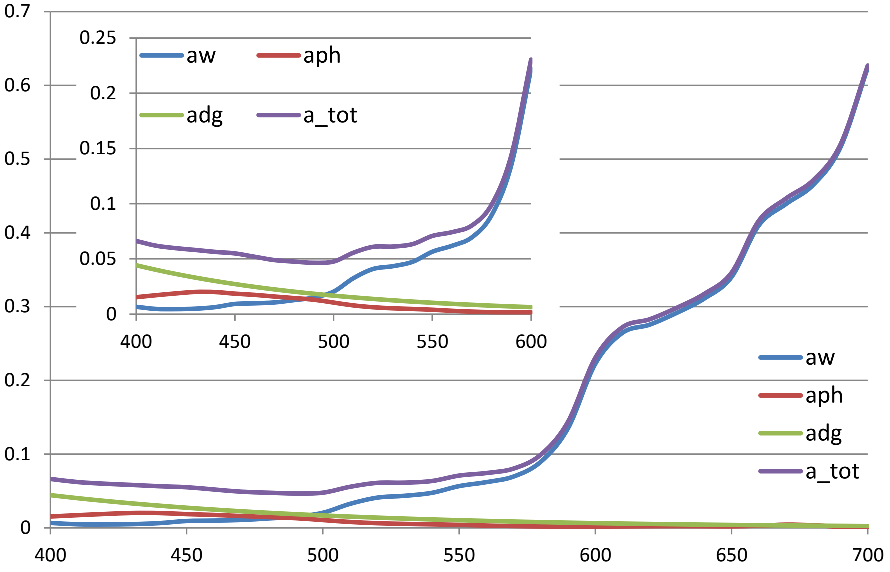
(Twardowski et al 2004)

Values of a_{ph} and a_g of natural waters

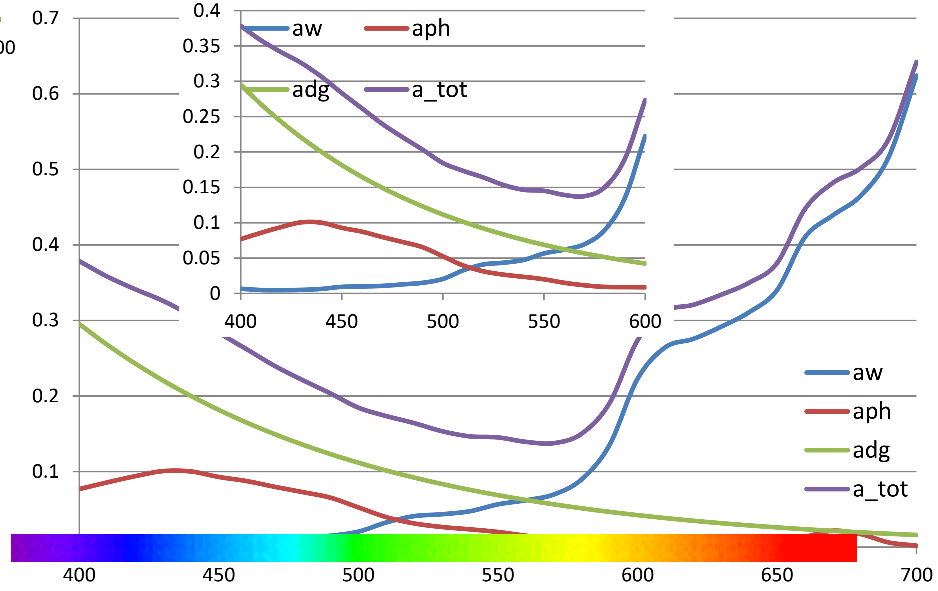
Water body	g_{440} (m^{-1})	p_{440} (m^{-1})	Reference
Adelaide L., Wisc., USA	1.85	—	408
Otisco L., N.Y., USA	0.27	0.27	981
Irondequoit Bay, L. Ontario, USA	0.90	0.65	980
Bluff L., N.S., Canada	0.94	—	328
Punch Bowl, N.S., Canada	6.22	—	328
South America			
Guri Reservoir, Venezuela	4.84	—	558
Carrao R., Venezuela	12.44	—	558
Australia			
(a) Southern tablelands			
Cotter Dam	1.28–1.46	0.77	483, 495*a*
Corin Dam	1.19–1.61	0.11	483, 495*a*
L. Ginninderra	1.54 ± 0.78	0.16–0.58	478, 479, 483, 495*a*
(3-year range)	0.67–2.81		
L. George	1.80 ± 1.06	3.73–4.21	478, 479, 483, 495*a*
(5-year range)	0.69–3.04		
Burrinjuck Dam	2.21 ± 1.13	0.63–1.44	478, 479, 483, 495*a*
(5-year range)	0.81–3.87		
L. Burley Griffin	2.95 ± 1.70	2.91–2.96	478, 479, 483, 495*a*
(5-year range)	0.99–7.00		
Googong Dam	3.42	0.83	483
Queanbeyan R.	2.42	—	495*a*
Molonglo R.	0.44	—	495*a*
Molonglo R. below confluence with Queanbeyan R.	1.84	—	495*a*
Creek draining boggy ground	11.61	—	495*a*
(b) Murray–Darling system			
Murrumbidgee R., Gogeldrie Weir (10 months)	0.4–3.2	—	677
L. Wyangan	1.13	0.38	495*a*
Griffith Reservoir	1.34	3.73	495*a*
Barren Box Swamp	1.59	2.55	495*a*
Main canal, M.I.A.	1.11	5.35	495*a*
Main drain, M.I.A.	2.12	10.34	495*a*
Murray R., upstream of Darling confluence	0.81–0.85	—	677
Darling R., above confluence with Murray	0.7–2.5	—	677
(c) Northern Territory (Magela Creek billabongs)			
Mudginberri	1.11	1.13	498
Gulungul	2.28	1.68	498
Georgetown	1.99	18.00	498

(Kirk 1994)

Contrast of absorption spectra



Wavelength [nm]



Wavelength [nm]

B. Scattering properties

D. Stramski et al. / Progress in Oceanography 61 (2004) 27–56 31

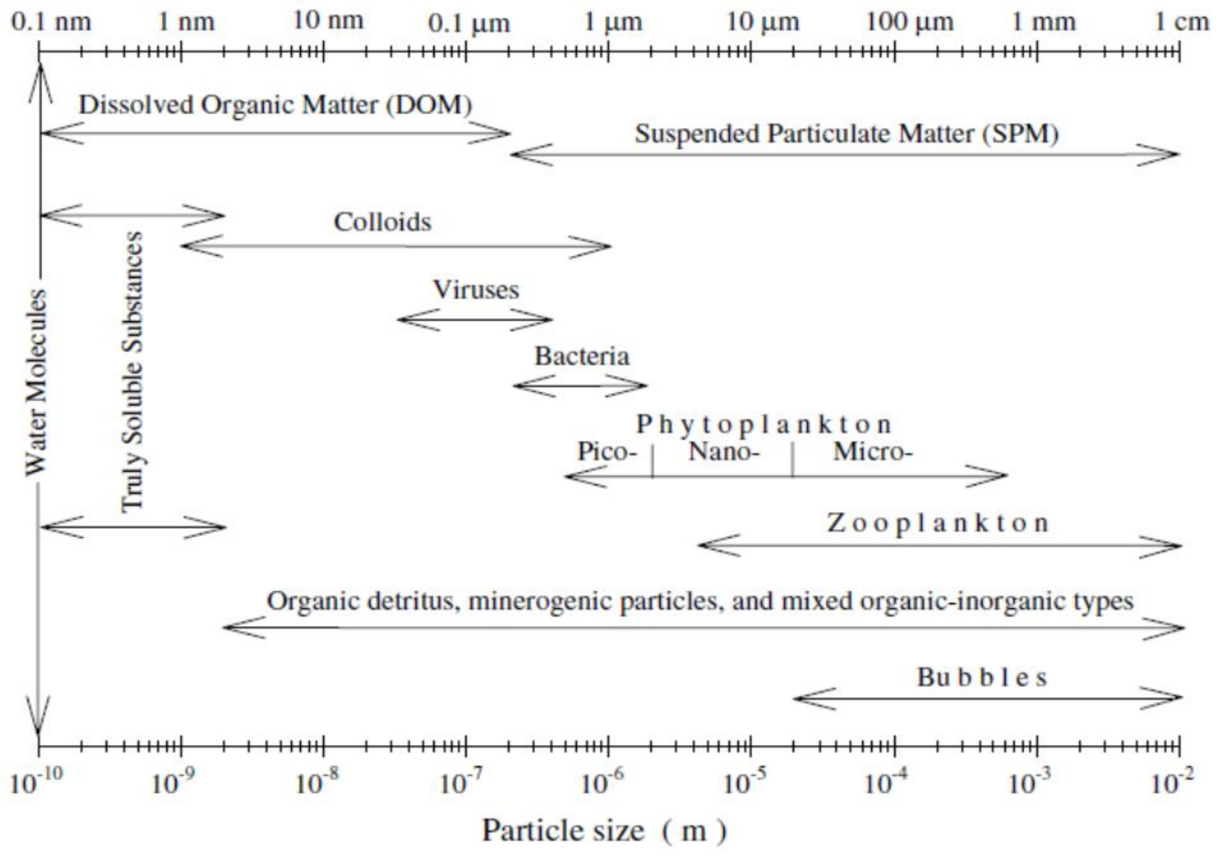
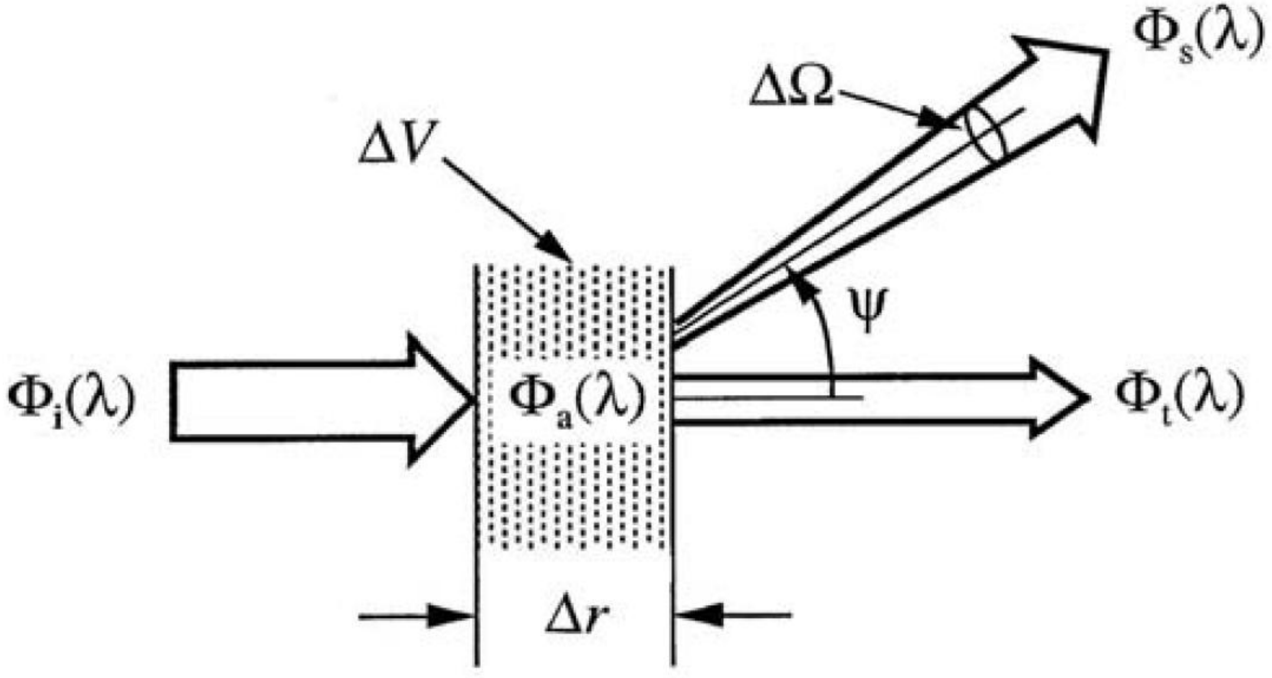


Fig. 1. Schematic diagram showing various seawater constituents in the broad size range from molecular size of the order of 10^{-10} m to large particles and bubbles of the order of 10^{-3}–10^{-2} m in size. The arrow ends generally indicate approximate rather than sharp boundaries for different constituent categories.

Volume Scattering Function (VSF): β (m^{-1} sr^{-1})



(Mobley 1994)

$$\beta = \frac{\Phi_s}{\Phi_i \; \Delta r \; \Delta\Omega}$$

(m^{-1} sr^{-1})

Volume Scattering Function (VSF): β (m^{-1} sr^{-1})

Scattering coefficient: b (m^{-1})

forward-scattering coefficient: b_f **(m^{-1}) →** $$b_f = 2\pi \int_0^{\pi/2} \beta \sin(\theta)\, d\theta$$

$$b = \int_0^{2\pi} \int_0^{\pi} \beta \sin(\theta)\, d\theta\, d\varphi = 2\pi \int_0^{\pi} \beta \sin(\theta)\, d\theta$$

backward-scattering coefficient: b_b **(m^{-1}) →** $$b_b = 2\pi \int_{\pi/2}^{\pi} \beta \sin(\theta)\, d\theta$$

Commonly separated groups for scattering:

Molecules

Suspended 'particles'

Bubbles

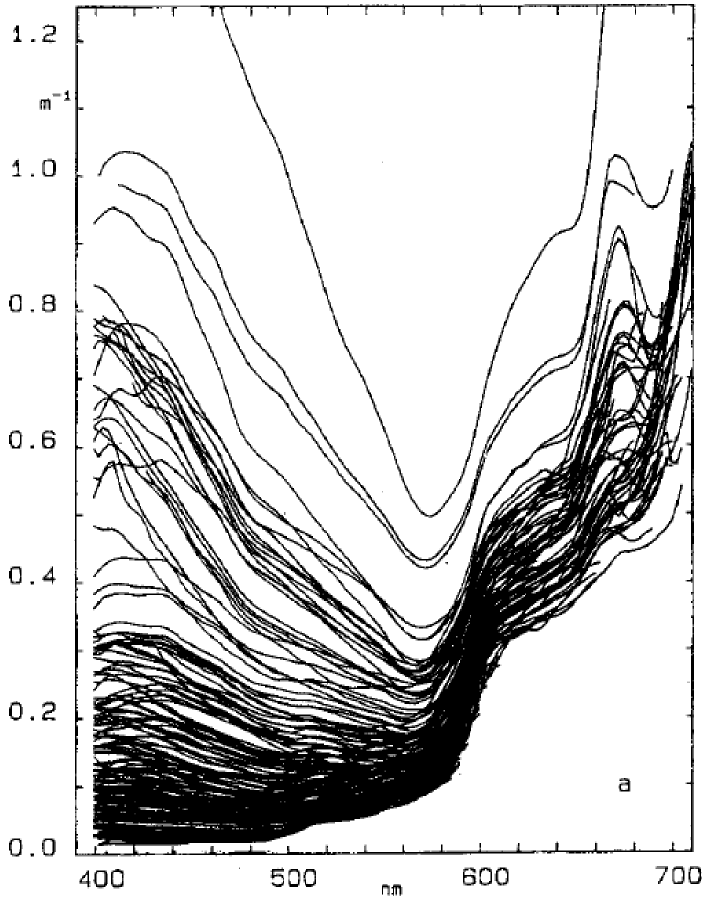
$$b = b_w + b_p$$

Or,

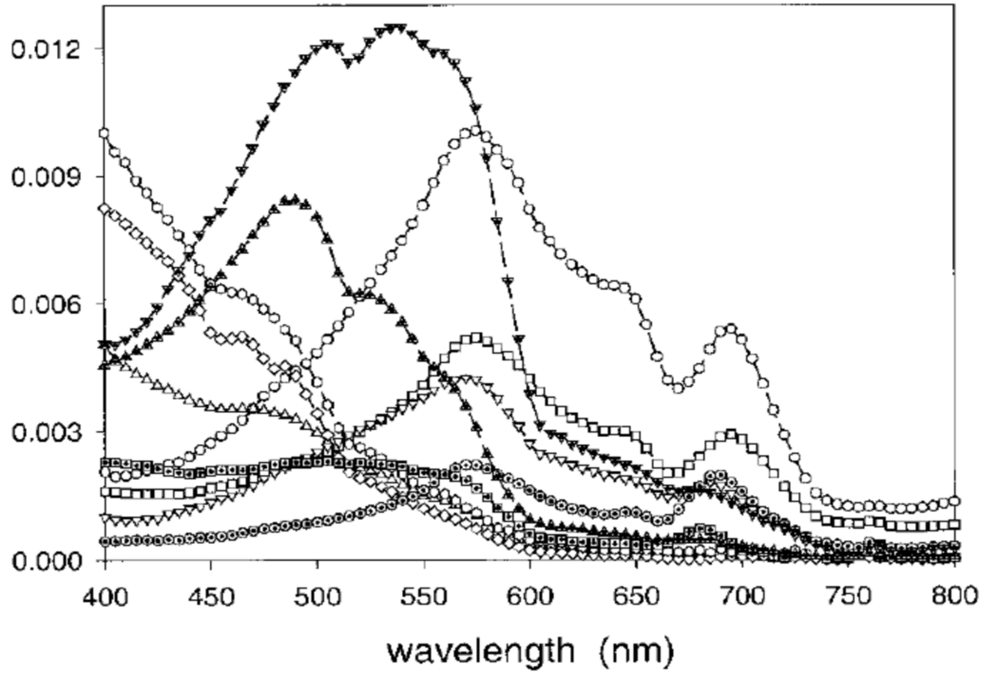
$$b = b_w + b_{PIM} + b_{POM}$$

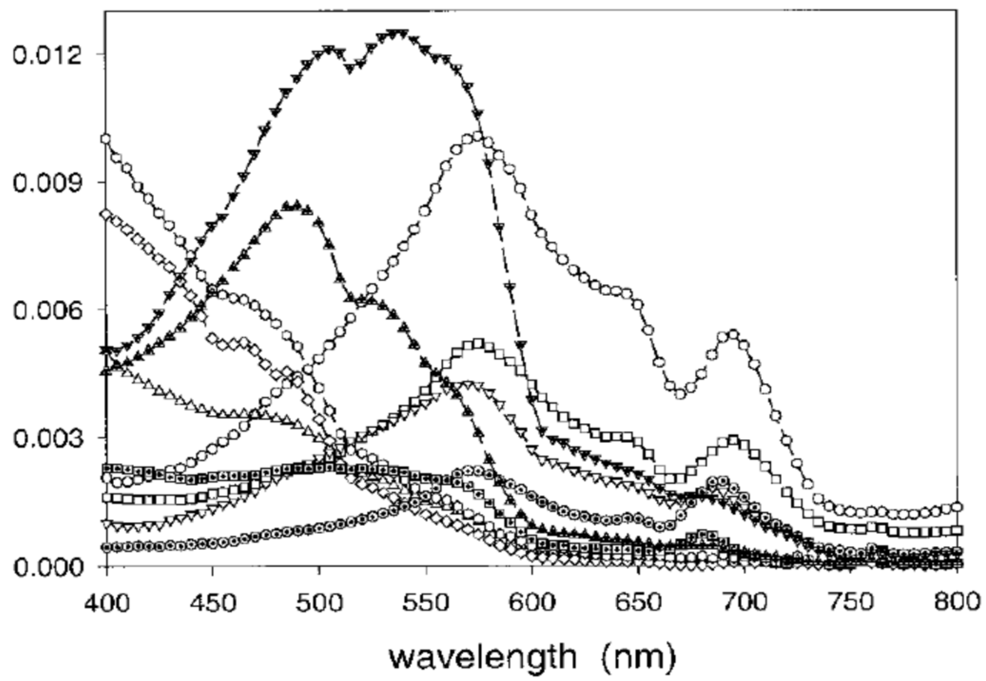
2. Relationships between IOPs and AOPs

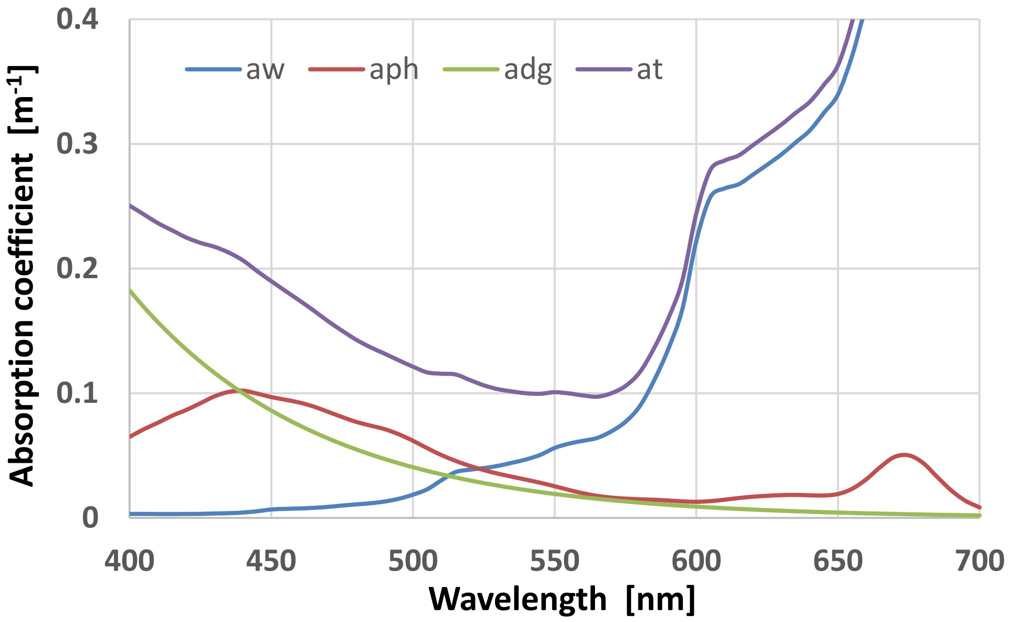
Diffuse attenuation coefficient (K_d)



Remote sensing reflectance (R_{rs})







How are they related?

The fundamental relationship: radiative transfer equation （no internal source）

$$\frac{dL(\lambda,\Omega)}{dr} = -c(\lambda)L(\lambda,\Omega) + \int L(\lambda,\Omega')\beta(\lambda,\Omega',\Omega)d\omega$$

loss

gain

$$dr = dz/cos(\theta)$$

$$\cos(\theta)\frac{dL}{dz} = -cL + \int_{4\pi} L(\theta',\varphi')\,\beta(\theta'->\theta,\varphi'->\varphi)\,dw'$$

How to solve this equation?

The two-stream approach (Aas 1987):

$$\cos(\theta)\frac{dL}{dz} = -cL + \int_{4\pi} L(\theta',\varphi')\,\beta(\theta'->\theta,\varphi'->\varphi)\,dw'$$

Integrate both sides for 4π solid angle:

$$\int_{4\pi}\cos(\theta)\frac{dL}{dz}dw = \int_{4\pi}\left(-cL + \int_{4\pi} L(\theta',\varphi')\,\beta(\theta'->\theta,\varphi'->\varphi)\,dw'\right)dw$$

Left side:

$$\int_{4\pi}\cos(\theta)\frac{dL}{dz}dw = \frac{d}{dz}(E_d - E_u)$$

Right side:

$$\int_{4\pi} cLdw = cE_o$$

$$\int_{4\pi}\left(\int_{4\pi}(\ldots)dw\right)dw' = (b)E_o$$

$$\frac{d}{dz}\left(E_d - E_u\right) = -cE_o + bE_o$$

$$\frac{d}{dz}\left(E_d - E_u\right) = -aE_o$$

Gershun Equation.

Integrate over the downwelling hemisphere:

$$\int_{2\pi_d} \cos(\theta) \frac{dL}{dz} dw = \int_{2\pi_d} \left(-cL + \int_{4\pi} L(\theta', \varphi')\, \beta(\theta' -> \theta, \varphi' -> \varphi)\, dw' \right) dw$$

Left side:

$$\int_{2\pi_d} \cos(\theta) \frac{dL}{dz} dw = \frac{d}{dz} E_d$$

1st term on the right side:

$$\int_{2\pi_d} cL dw = cE_{od}$$

2nd term on the right side:

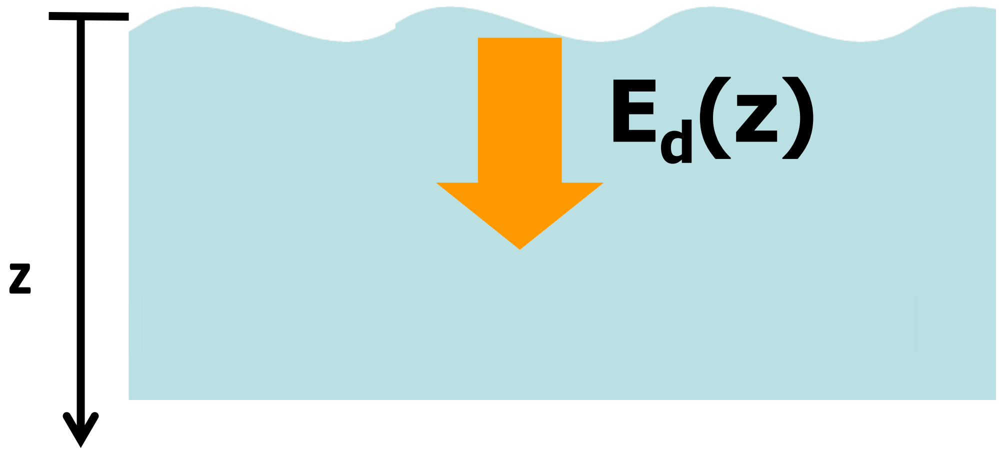
$$\int_{2\pi_d} \left(\int_{4\pi} (\ldots) dw \right) dw' = (b - r_d b_b) E_{od} + r_u b_b E_{ou}$$

Two-Stream equation:

$$\begin{cases} \dfrac{dE_d(z)}{dz} = -\dfrac{a}{\mu_d(z)} E_d(z) - \dfrac{r_d(z) b_b}{\mu_d(z)} E_d(z) + \dfrac{r_u(z) b_b}{\mu_u(z)} E_u(z) \\[2ex] \dfrac{dE_u(z)}{dz} = -\dfrac{a}{\mu_u(z)} E_u(z) - \dfrac{r_u(z) b_b}{\mu_u(z)} E_u(z) + \dfrac{r_d(z) b_b}{\mu_d(z)} E_d(z) \end{cases}$$

$$\begin{cases} \dfrac{d}{dz} E_d = -\dfrac{(a + r_d b_b)}{\mu_d} E_d + \dfrac{r_u b_b}{\mu_u} E_u \\[2ex] \dfrac{d}{dz} E_u = -\dfrac{a + r_u b_b}{\mu_u} E_u + \dfrac{r_d b_b}{\mu_d} E_d \end{cases}$$

a) Relationship for the diffuse attenuation coefficient (K_d)



$$E_d(z) = E_d(0)\, e^{-K_d z}$$

$$\frac{dE_d(z)}{dz} = -\frac{a}{\mu_d(z)} E_d(z) - \frac{r_d(z)\, b_b}{\mu_d(z)} E_d(z) + \frac{r_u(z)\, b_b}{\mu_u(z)} E_u(z)$$

$$-\frac{dE_d(z)}{E_d(z)\, dz} = \frac{a}{\mu_d(z)} + \frac{r_d(z)\, b_b}{\mu_d(z)} - \frac{r_u(z)\, b_b}{\mu_u(z)} R$$

$$R = \frac{E_u}{E_d}$$

$$K_d = \frac{a}{\mu_d} + \left(\frac{r_d}{\mu_d} - \frac{r_u R}{\mu_u} \right) b_b$$

$$K_d(z) = \mathrm{m}_0(z)\, a + \mathrm{v}(z)\, b_b$$

Both $\mathbf{m_0}$ and v > 1.

(Lee et al. 2005)

$$K_d > a; \quad K_d > b_b$$

From numerical simulations:

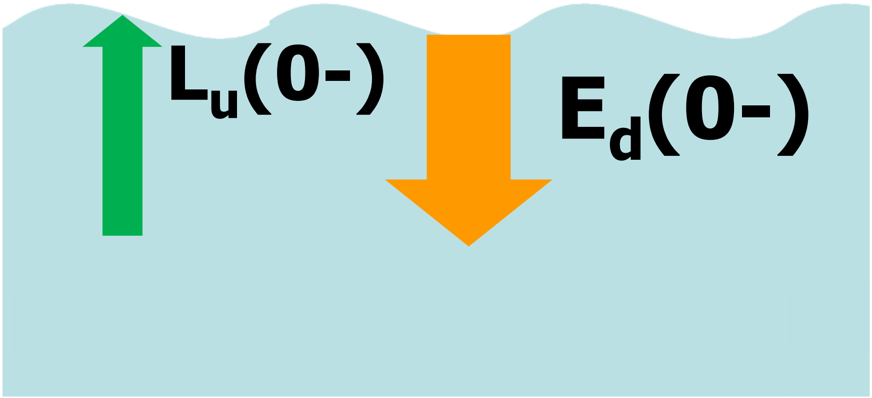
$$K_d = \frac{a}{\cos(\theta_0)} \sqrt{1 + (0.425\cos(\theta_0) - 0.19)\frac{b}{a}}$$

(Kirk 1984)

$$K_d(0) = \frac{1.04(a + b_b)}{\cos(\theta_0)}$$

(Gordon 1989)

b) Relationship for the sub-surface radiance reflectance (or remote-sensing reflectance):



$$r_{rs}(\lambda) = \frac{L_u(\lambda, 0^-)}{E_d(\lambda, 0^-)}$$

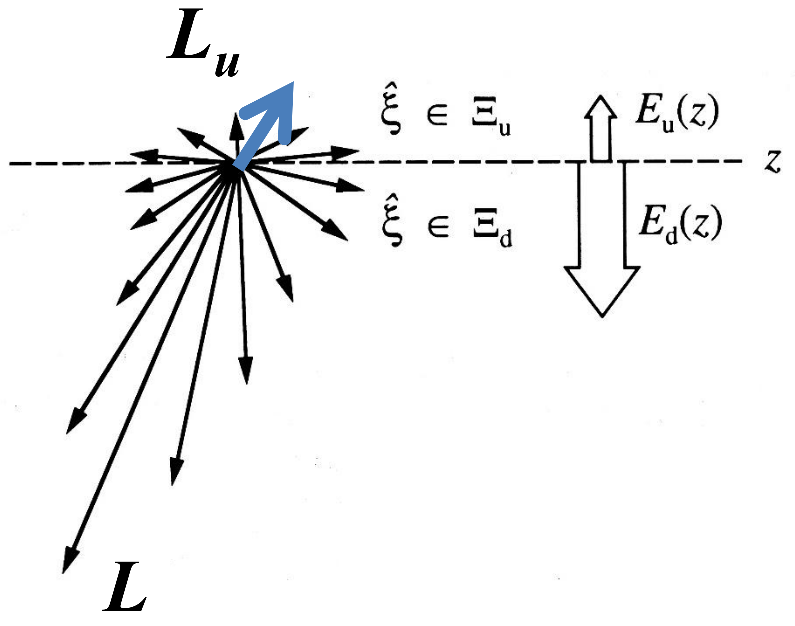
Zaneveld (1995) solution:

$$-\frac{dL_u}{dz} = -cL_u + \int_{4\pi} L(\theta',\phi')\beta(\theta' -> \theta, \phi' -> \phi)\, dw'$$

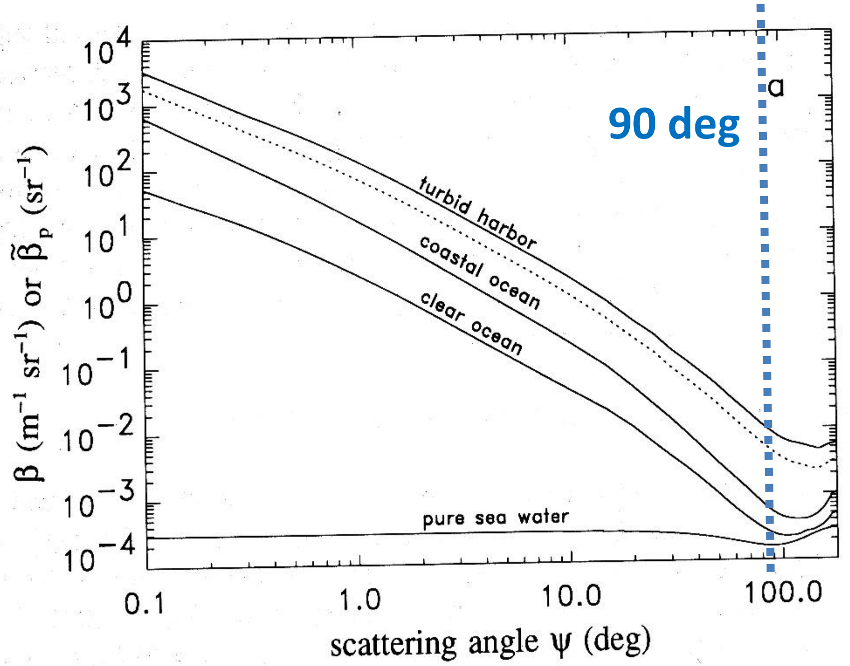
L_u: upwelling radiance at 0^o

$$\int_{4\pi} L(\theta',\phi')\beta(\theta' \to 0, \phi' \to 0)\, dw' =$$

$$\int_{2\pi_d} L(\theta',\phi')\beta(\theta' \to 0, \phi' \to 0)\, dw' + \int_{2\pi_u} L(\theta',\phi')\beta(\theta' \to 0, \phi' \to 0)\, dw'$$



L_u changes in a narrow range over angles



β changes in a narrow range in the backward domain

$$\int_{2\pi_d} L(\theta', \phi')\beta(\theta' \to 0, \phi' \to 0)\, dw' = f_b b_b \int_{2\pi_d} L(\theta', \phi')\, dw' = f_b b_b E_{0d}$$

$$\int_{2\pi_u} L(\theta', \phi')\beta(\theta' \to 0, \phi' \to 0)\, dw' = f_L L_u \int_{2\pi_u} \beta(\theta' \to 0, \phi' \to 0)\, dw' = f_L b_f L_u$$

$$\int_{4\pi} L(\theta', \phi')\beta(\theta' \to 0, \phi' \to 0)\, dw' = f_b b_b E_{0d} + f_L b_f L_u$$

$$-\frac{d}{dz} L_u = -cL_u + f_b b_b E_{0d} + f_L b_f L_u$$

$$K_{Lu} = -\frac{d\, L_u}{L_u\, dz}$$

$$K_{Lu} = -c + f_b b_b \frac{E_{0d}}{L_u} + f_L b_f$$

$$r_{rs} = \frac{L_u}{E_d} = \frac{L_u}{\mu_d E_{od}}$$

$$r_{rs} = \frac{f_b b_b / \mu_d}{c - f_L b_f + K_{Lu}}$$

(Zaneveld 1995)

$$r_{rs} = g \frac{b_b}{a + b_b}$$

Approximations:

Gordon et al (1988):

$$r_{rs}(\lambda,\pi) = \sum_{i=1}^{2} g_i \left(\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)} \right)^i ;$$

$$g_1 = 0.0949,\ g_2 = 0.0794$$

Morel et al (1993, 1996, 2002):

$$r_{rs}(\lambda,\Omega') = g(\lambda, Chl, \Omega') \frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)}$$

$$r_{rs}(\lambda,\Omega) = q(\Omega,w)\sum_{i=1}^{4} p_i \left(\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)} \right)^i$$

Albert and Mobley (2003)

$$r_{rs}(\lambda,\Omega) = g_w(\Omega)\frac{b_{bw}(\lambda)}{a(\lambda)+b_b(\lambda)} + g_p(\lambda,\Omega)\frac{b_{bp}(\lambda)}{a(\lambda)+b_b(\lambda)}$$

Lee et al (2004)

$$g_w = 0.113;\ g_p = 0.197\left(1-0.636\,Exp\left(-2.552\frac{b_{bp}}{a+b_b}\right)\right)$$

$$r_{rs}(\lambda,\Omega) = \sum_{i=1}^{4} g_i(\Omega,\nu_b)\left(\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)} \right)^i$$

Park and Ruddick (2005)

$$\ln[r_{rs}(\lambda,\Omega)] = \sum_{i=1}^{4}\ \sum_{j=1}^{4} P_{ij}(\Omega)[\ln(a(\lambda))]^i[\ln(b(\lambda))]^j$$

Van Der Woerd and Pasterkamp (2008)

$$r_{rs} \cong \frac{1}{\overline{\mu}_d}\frac{\beta(\psi)}{b_b} / \left[\frac{a}{b_b}\left(1-\cos(\theta_v)\Psi_{K_{Lu}}\overline{\mu}_{\infty}{}^{-1}\right) + f_L\left(1-\widetilde{b}_b{}^{-1}\right) + \widetilde{b}_b{}^{-1}\right]$$

(Twardowski and Tonizzo, 2018)

Contrast between IOPs and AOPs

1. IOPs has no relation/dependence on light distribution; but AOPs do.

2. IOPs are additive; NOT AOPs.

$$a = a_w + a_p + a_g$$

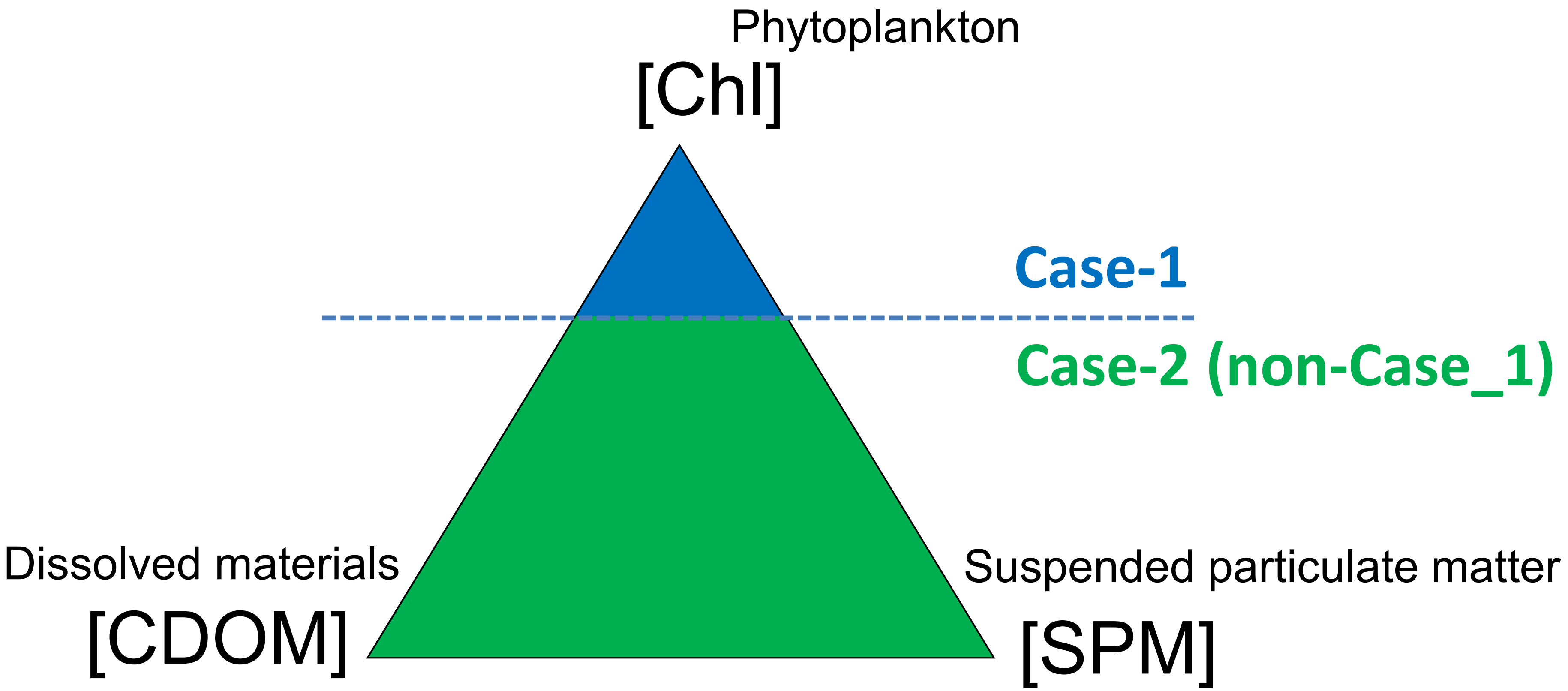
$$R_{rs} \neq R_{rs\text{-}w} + R_{rs\text{-}p} + R_{rs\text{-}g}$$

$$K_d \neq K_{d\text{-}w} + K_{d\text{-}p} + K_{d\text{-}g}$$

$$K_{par} \neq K_{par\text{-}w} + K_{par\text{-}p} + K_{par\text{-}g}$$

Case-1 / Case-2 concept

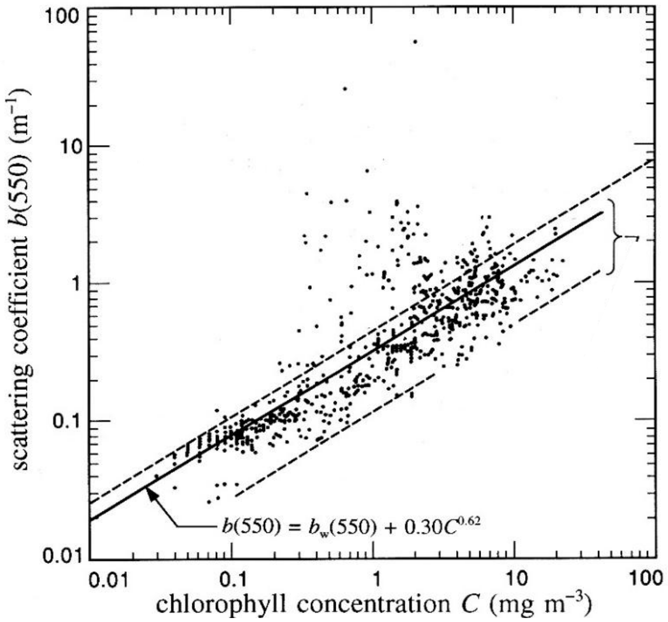
Major constituents affect optical properties

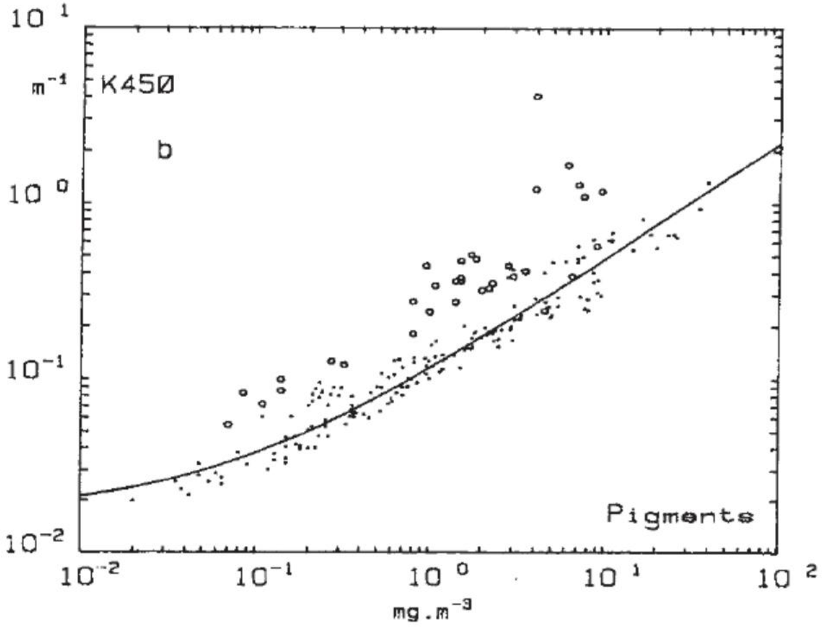


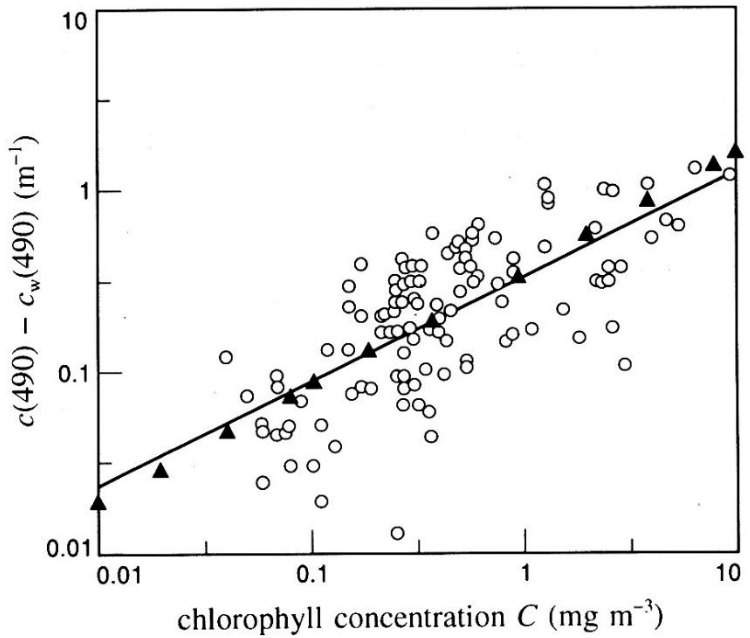
Case 1: Those waters in which phytoplankton (with their accompanying and covarying retinue material of biological origin) are the ***principal*** agents responsible for the variations in optical properties of the water.

Has nothing to do with location or Chl value.

Case-1 / Case-2 Concept

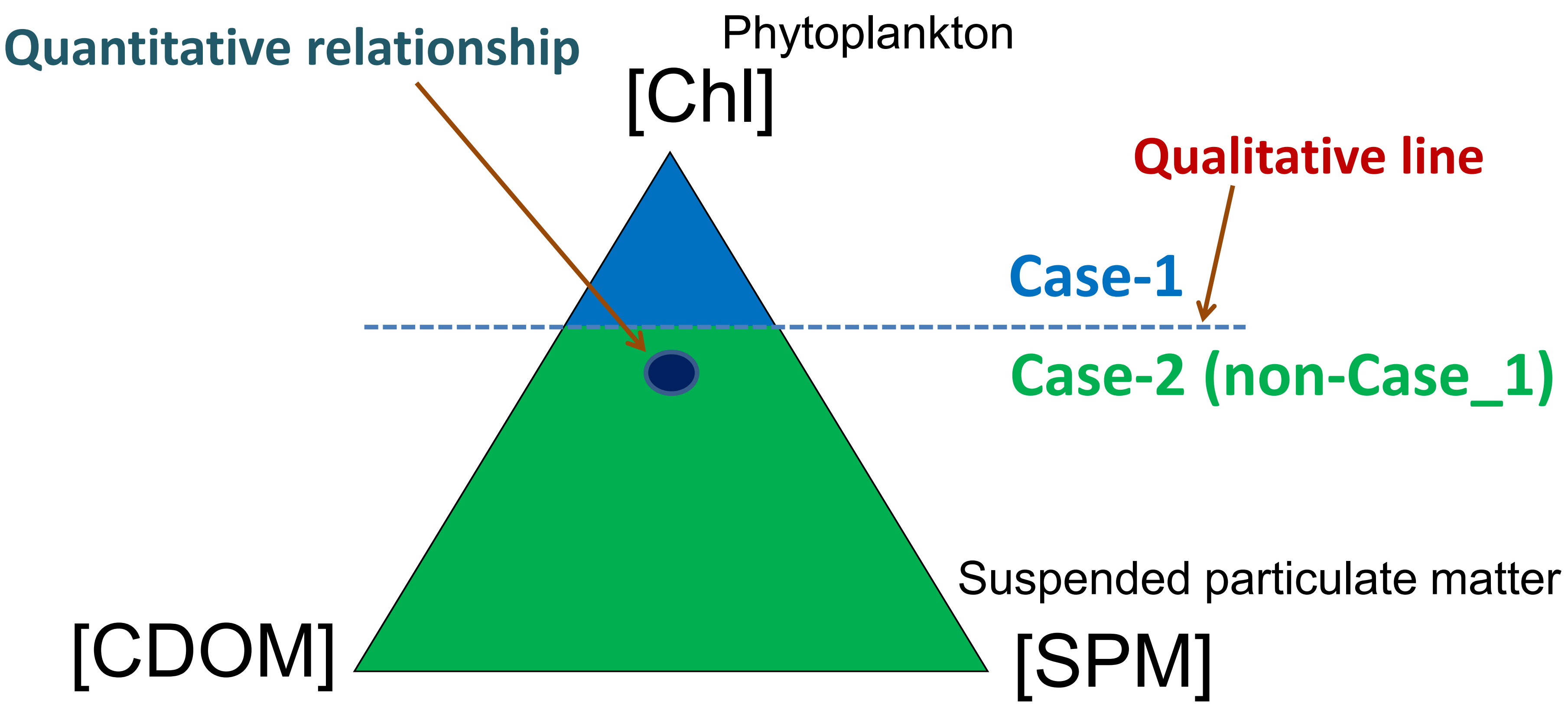






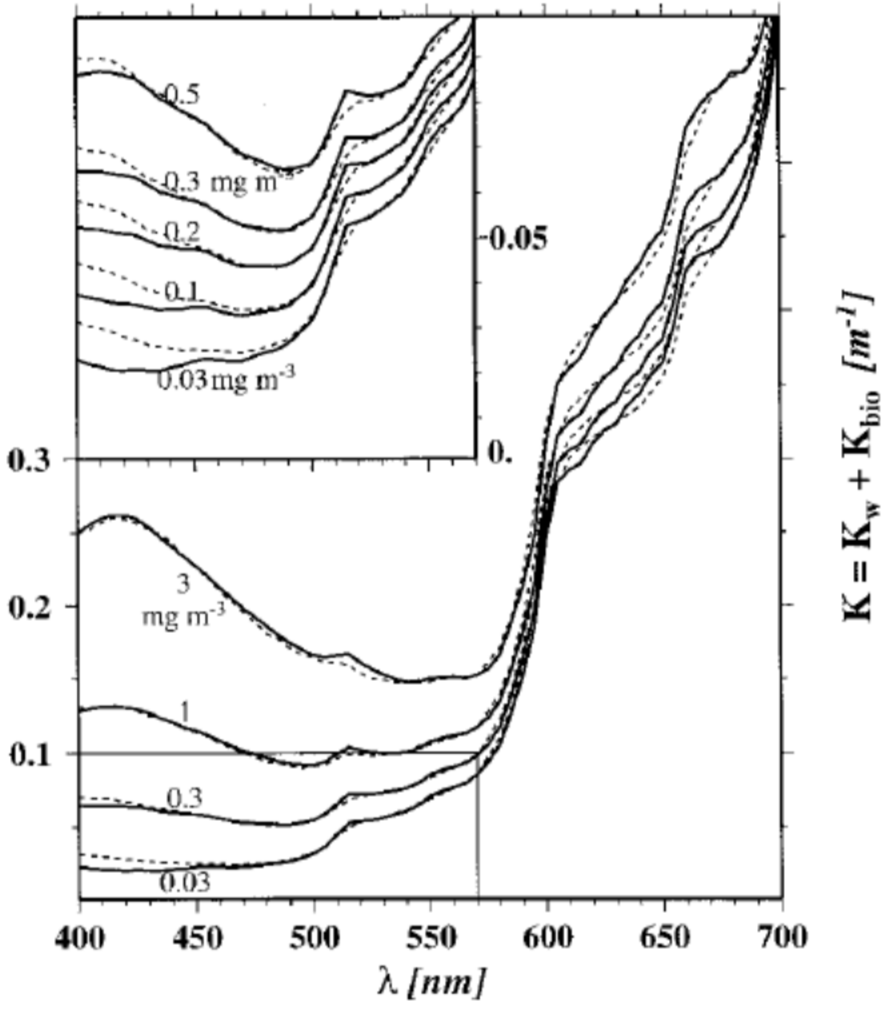
(Mobley 1994; Loisel and Morel 1998; Antoine et al. 2011)

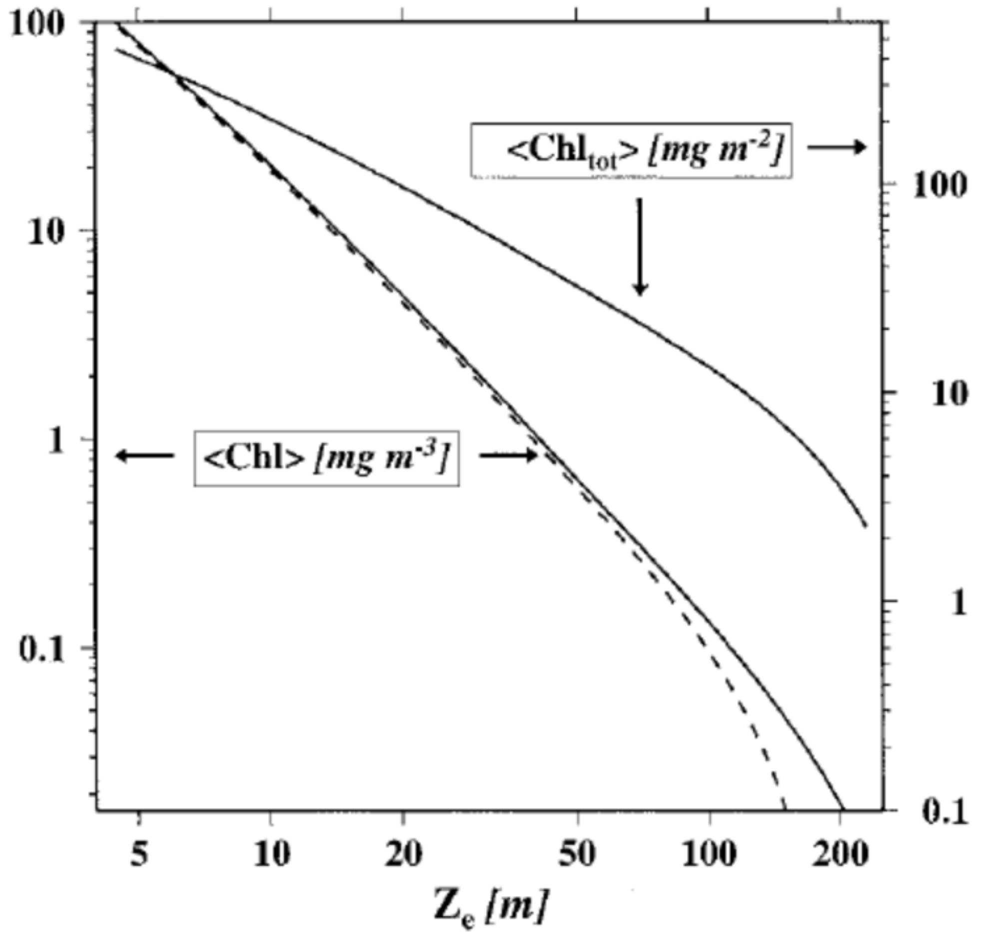
Case-1 / Case-2 concept



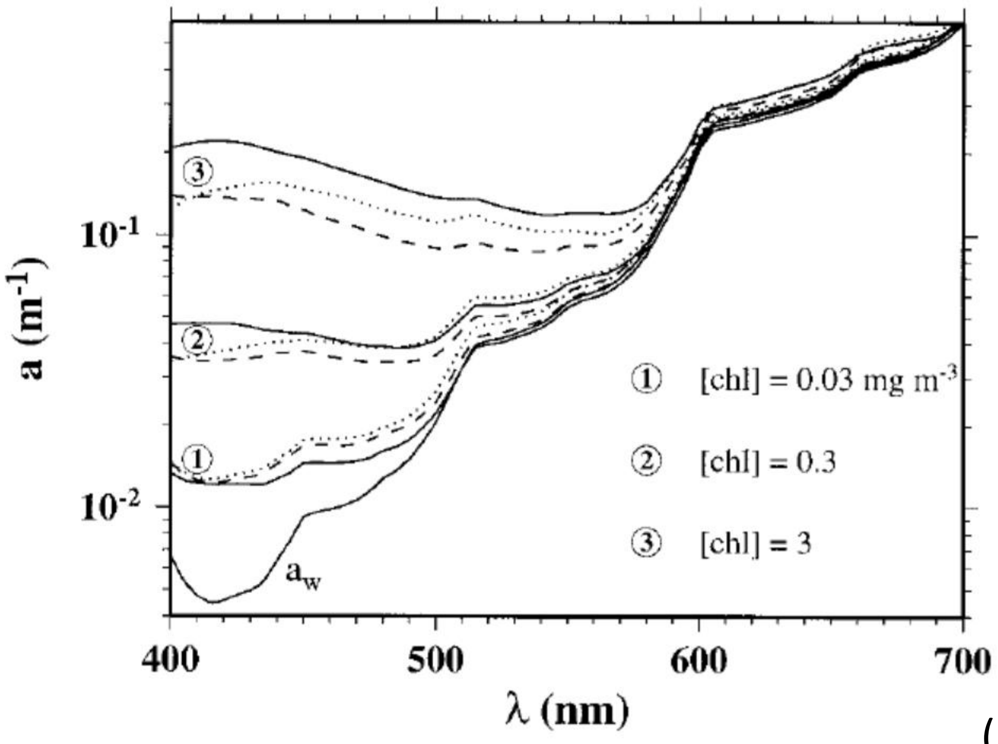
Quantitative Case 1:

IOPs, AOPs = empirical function([Chl])

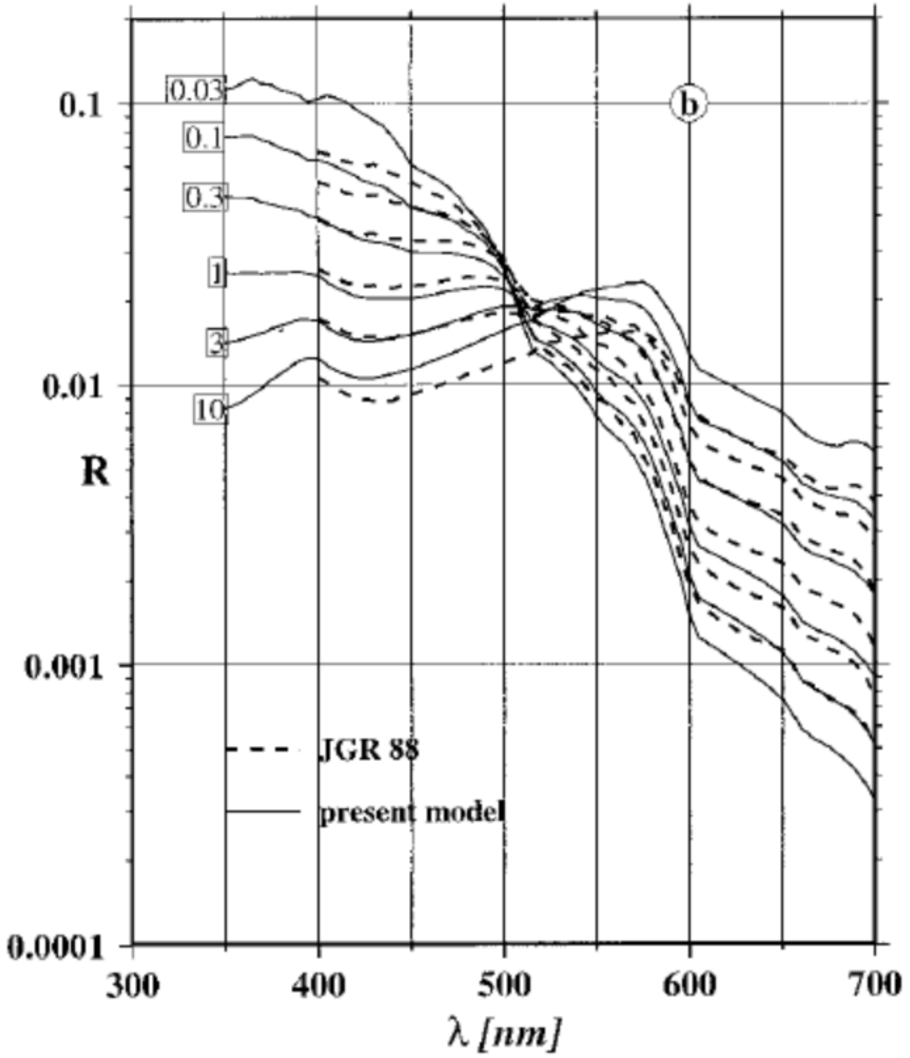




(Morel 1988,2001)



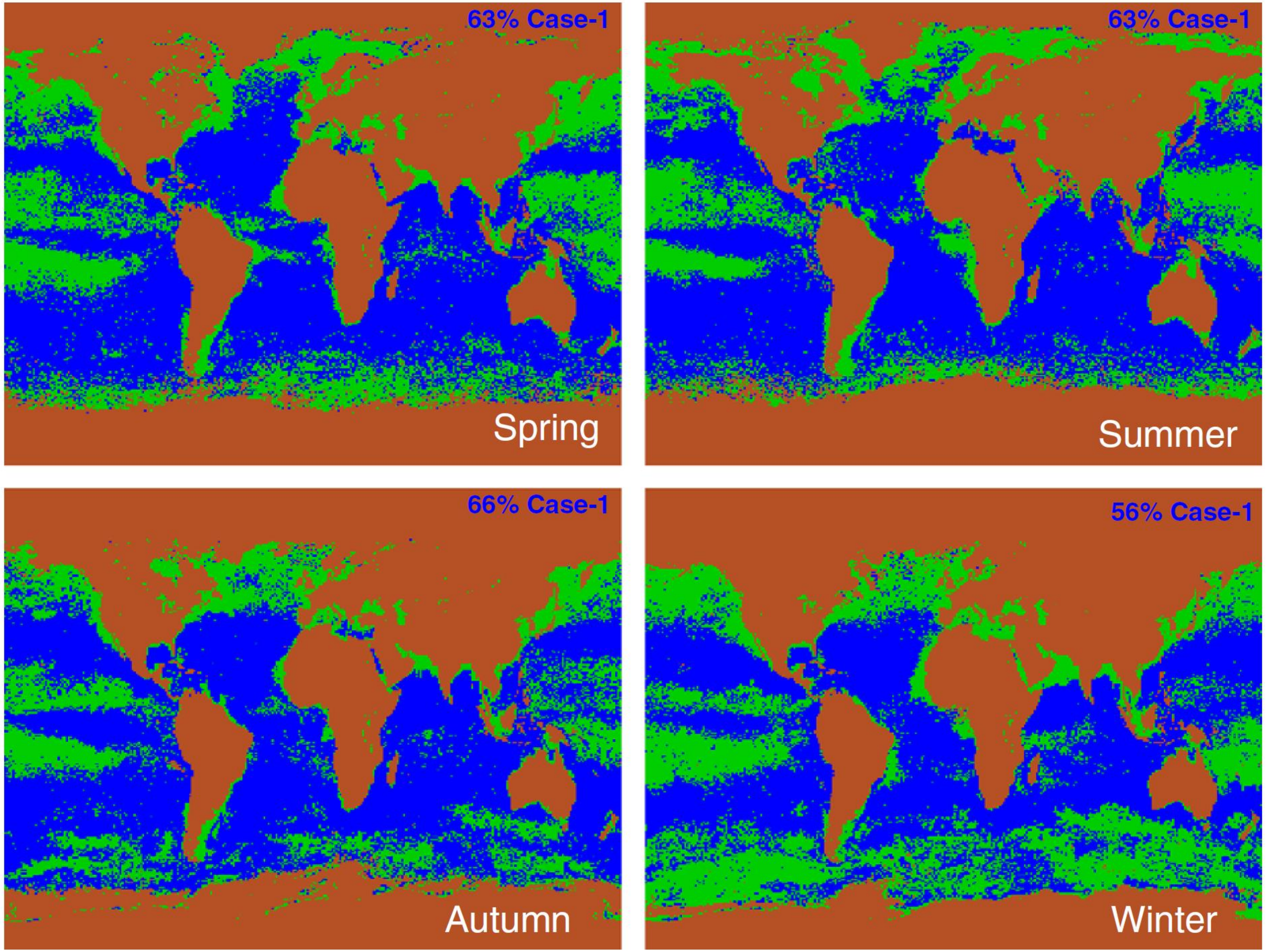
(Morel 1988,2001)



For case-1 waters, given [Chl], all other optical properties can be estimated, at least to the first order.

One-variable water.

Global distribution of "Case-1" waters



(Lee and Hu, 2006)

Key points:

1. In addition to boundary conditions, IOPs play the key role in forming ocean/water color.

2. Primary IOPs include absorption and scattering coefficients; the latter is direction dependent.

3. Bulk IOPs are lump sum contributions of the many individual, dissolved and suspended, molecules and particles.

4. Absorption and scattering coefficients of pure (sea)water are considered constant (change with temperature/salinity), but uncertainties still exist, especially for absorption in the UV range.

5. In addition to water molecules, practically and generally,
for absorption: there are three major optically active components: phytoplankton pigments, detritus and gelbstoff (CDOM);
for scattering: there are organic and inorganic particulates, bubbles, and many times lumped into one term.

6. Spectrally,
water molecules are strong absorber in the longer wavelengths;
phytoplankton absorption generally has two distinct peaks with a stronger peak centered around 440 nm and weaker peak centered around 675 nm; have varying spectral shapes
detritus and gelbstoff are strong absorbers in the shorter wavelengths, and gelbstoff has steeper spectral slope;

Water molecules are strong scatter in the shorter wavelengths;
'**particle**' scattering is weakly wavelength dependent. It is strongly dependent on size, composition, and abundance.

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Biogeosciences

Detailed validation of the bidirectional effect in various Case 1 waters for application to ocean color imagery

K. J. Voss[1], A. Morel[2], and D. Antoine[2]

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Progress in Oceanography 61 (2004) 27–56

Progress in Oceanography

www.elsevier.com/locate/pocean

Review

The role of seawater constituents in light backscattering in the ocean

Dariusz Stramski [a,*], Emmanuel Boss [b], Darek Bogucki [c], Kenneth J. Voss [d]

Modeling the inherent optical properties of the ocean based on the detailed composition of the planktonic community

Dariusz Stramski, Annick Bricaud, and André Morel

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Absorption spectrum (380–700 nm) of pure water. II. Integrating cavity measurements

Robin M. Pope and Edward S. Fry

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Hyperspectral absorption coefficient of "pure" seawater in the range of 350–550 nm inverted from remote sensing reflectance

Zhongping Lee,[1,*] Jianwei Wei,[1] Ken Voss,[2] Marlon Lewis,[3]
Annick Bricaud,[4,5] and Yannick Huot[6]

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applied optics

Ultraviolet (250–550 nm) absorption spectrum of pure water

John D. Mason,[1] Michael T. Cone,[2] and Edward S. Fry[1,*]

Temperature and salinity correction coefficients for light absorption by water in the visible to infrared spectral region

Rüdiger Röttgers,[1,*] David McKee,[2] and Christian Utschig[1]

20 October 2014 | Vol. 22, No. 21 | DOI:10.1364/OE.22.025093 | OPTICS EXPRESS 25093

The absorption coefficient of pure (sea)water in the UV-visible: Are we there yet?

Zhongping Lee [1] and Junwu Tang [2]

1738 Vol. 55, No. 7 / March 1 2016 / *Applied Optics* Research Article

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On the modeling of hyperspectral remote-sensing reflectance of high-sediment-load waters in the visible to shortwave-infrared domain

ZHONGPING LEE,[1,6] SHAOLING SHANG,[2,5] GONG LIN,[2] JUN CHEN,[3] AND DAVID DOXARAN[4]

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AAAS
Journal of Remote Sensing
Volume 2021, Article ID 9842702, 13 pages
https://doi.org/10.34133/2021/9842702

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Research Article

Impact of Temperature on Absorption Coefficient of Pure Seawater in the Blue Wavelengths Inferred from Satellite and *In Situ* Measurements

Guomei Wei,[1,2] Zhongping Lee,[3] Xiuling Wu,[1] Xiaolong Yu,[1] Shaoling Shang,[1] and Ricardo Letelier[4]

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Bio-optical properties of the marine cyanobacteria *Trichodesmium* spp.

C. Dupouy[a,c], J. Neveux[b], G. Dirberg[c], R. Röttgers[d], M. M. B. Tenório[e], and S. Ouillon[c]

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Michael S. Twardowski[a,*], Emmanuel Boss[b], James M. Sullivan[c], Percy L. Donaghay[c]

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DARIUSZ STRAMSKI and DALE A. KIEFER

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A model for the diffuse attenuation coefficient of downwelling irradiance

Zhong-Ping Lee[1]
Naval Research Laboratory, Stennis Space Center, Mississippi, USA

Ke-Ping Du
State Key Laboratory of Remote Sensing Science, Research Center for Remote Sensing and GIS, School of Geography, Beijing Normal University, Beijing, China

Robert Arnone
Naval Research Laboratory, Stennis Space Center, Mississippi, USA

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A theoretical derivation of the dependence of the remotely sensed reflectance of the ocean on the inherent optical properties

J. Ronald V. Zaneveld
College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis

Article

Ocean Color Analytical Model Explicitly Dependent on the Volume Scattering Function

Michael Twardowski [1,2,*] and Alberto Tonizzo [2,*]

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An analytical model for subsurface irradiance and remote sensing reflectance in deep and shallow case-2 waters

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3 November 2003 / Vol. 11, No. 22 / OPTICS EXPRESS 2873

Model of remote-sensing reflectance including bidirectional effects for case 1 and case 2 waters

Young-Je Park and Kevin Ruddick

1236 APPLIED OPTICS / Vol. 44, No. 7 / 1 March 2005

HYDROPT: A fast and flexible method to retrieve chlorophyll-a from multispectral satellite observations of optically complex coastal waters

Hendrik Jan Van Der Woerd *, Reinold Pasterkamp

Remote Sensing of Environment 112 (2008) 1795 – 1807

Diffuse reflectance of oceanic waters. II. Bidirectional aspects

André Morel and Bernard Gentili

6864 APPLIED OPTICS / Vol. 32, No. 33 / 20 November 1993

Diffuse reflectance of oceanic waters. III. Implication of bidirectionality for the remote-sensing problem

André Morel and Bernard Gentili 4850 APPLIED OPTICS / Vol. 35, No. 24 / 20 August 1996

A Semianalytic Radiance Model of Ocean Color

Howard R. Gordon,[1] Otis B. Brown,[2] Robert H. Evans,[2] James W. Brown,[1]
Raymond C. Smith,[3] Karen S. Baker,[4] and Dennis K. Clark[5]

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 93, NO. D9, PAGES 10,909–10,924, SEPTEMBER 20, 1988

Effects of molecular and particle scatterings on the model parameter for remote-sensing reflectance

ZhongPing Lee, Kendall L. Carder, and KePing Du

1 September 2004 / Vol. 43, No. 25 / APPLIED OPTICS 4957

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 93, NO. C9, PAGES 10,749–10,768, SEPTEMBER 15, 1988

Optical Modeling of the Upper Ocean in Relation to Its Biogenous Matter Content (Case I Waters)

ANDRÉ MOREL

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. C4, PAGES 7163–7180, APRIL 15, 2001

Bio-optical properties of oceanic waters: A reappraisal

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Limnol. Oceanogr., 43(5), 1998, 847–858

Light scattering and chlorophyll concentration in case 1 waters: A reexamination

Hubert Loisel and André Morel

Limnol. Oceanogr., 56(3), 2011, 955–973

doi:10.4319/lo.2011.56.3.0955

Variability in optical particle backscattering in contrasting bio-optical oceanic regimes

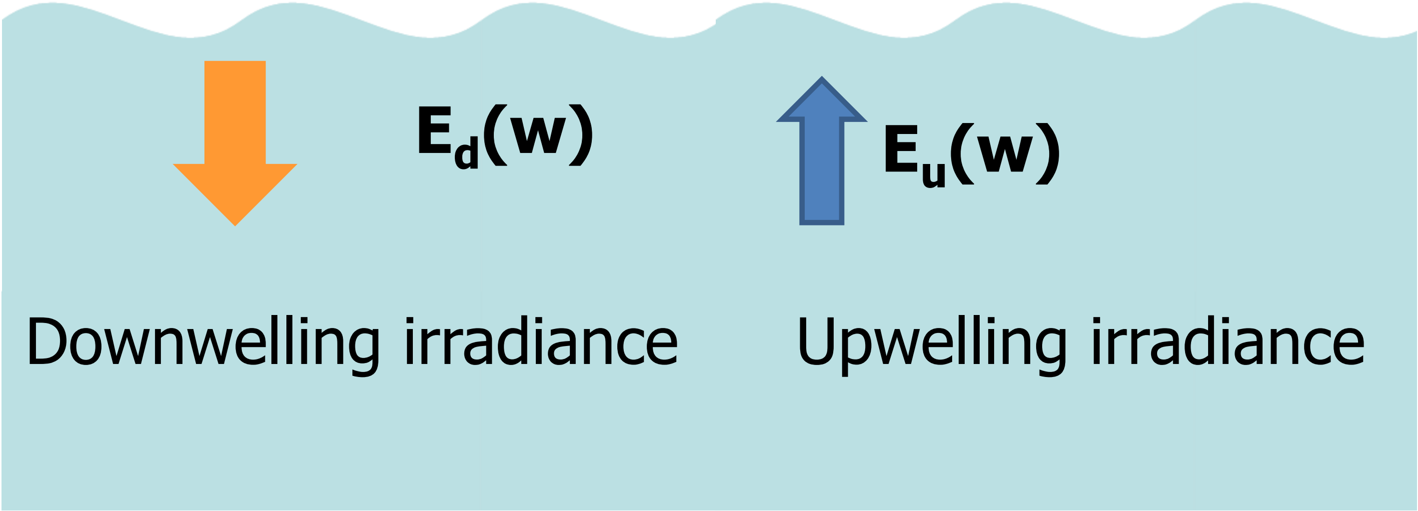
David Antoine,[a,*] David A. Siegel,[b,c] Tihomir Kostadinov,[b] Stéphane Maritorena,[b] Norm B. Nelson,[b] Bernard Gentili,[a] Vincenzo Vellucci,[a] and Nathalie Guillocheau[b]

Global distribution of Case-1 waters: An analysis from SeaWiFS measurements

ZhongPing Lee [a,*], Chuanmin Hu [b]

Remote Sensing of Environment 101 (2006) 270 – 276

b) Relationship for the irradiance reflectance (*R*)



$$R(\lambda, z) = \frac{E_u(\lambda, z)}{E_d(\lambda, z)}$$

$$\frac{d}{dz}\left(E_d - E_u\right) = -aE_o$$

$$R = \frac{E_u}{E_d}$$

$$E_o = E_{od} + E_{ou}$$

$$= \frac{E_d}{\mu_d} + \frac{E_u}{\mu_u}$$

$$\frac{d}{dz}\left(E_d - RE_d\right) = -a\left(\frac{E_d}{\mu_d} + R\frac{E_d}{\mu_u}\right)$$

Assume R does not change with z,

$$(1-R)\frac{dE_d}{E_d\,dz} = -\frac{a\mu_u + aR\mu_d}{\mu_d\mu_u} \quad \Rightarrow \quad -(1-R)K_d = -\frac{a\mu_u + aR\mu_d}{\mu_d\mu_u}$$

$$R = \frac{\mu_u}{\mu_d}\left(\frac{K_d\mu_d - a}{a + \mu_u K_d}\right)$$

$$R = \frac{\mu_u}{\mu_d} \frac{x\,b_b}{y\,a + z\,b_b}$$

$$= f \frac{b_b}{a + b_b}$$

Simplified relationships:

$$R = \sum_i f_i \left(\frac{b_b}{a + b_b} \right)^i$$

(Gordon et al 1974)

$$R = f\,\frac{b_b}{a}, \quad f = \text{fun}(b, \theta_0)$$

$$\boldsymbol{f \sim 0.33}$$

(Morel and Prieur, 1977; Kirk 1984; Morel and Gentili 1991)

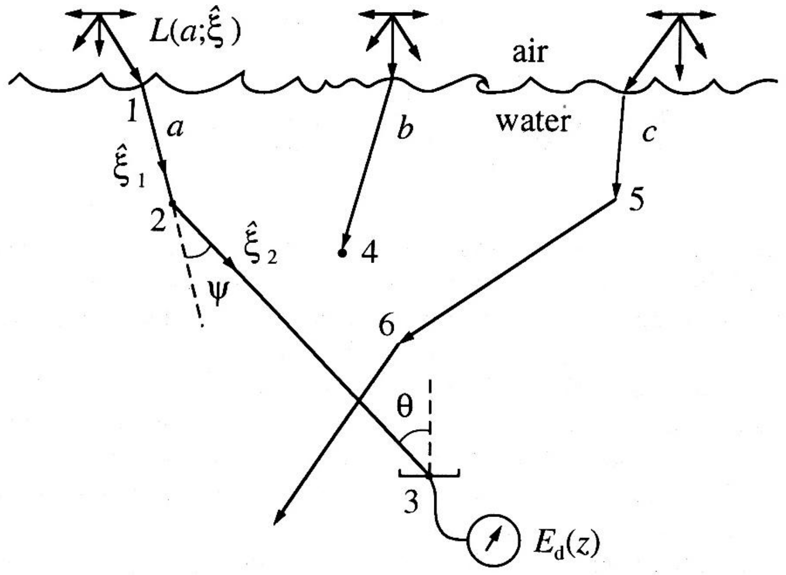
$$R = \frac{\mu_u s}{\mu_u + \mu_d} \frac{b_b}{a + b_b}$$

(Sathyendranath and Platt 1997)

($s = b_u/b_b$)

Numerical solutions:

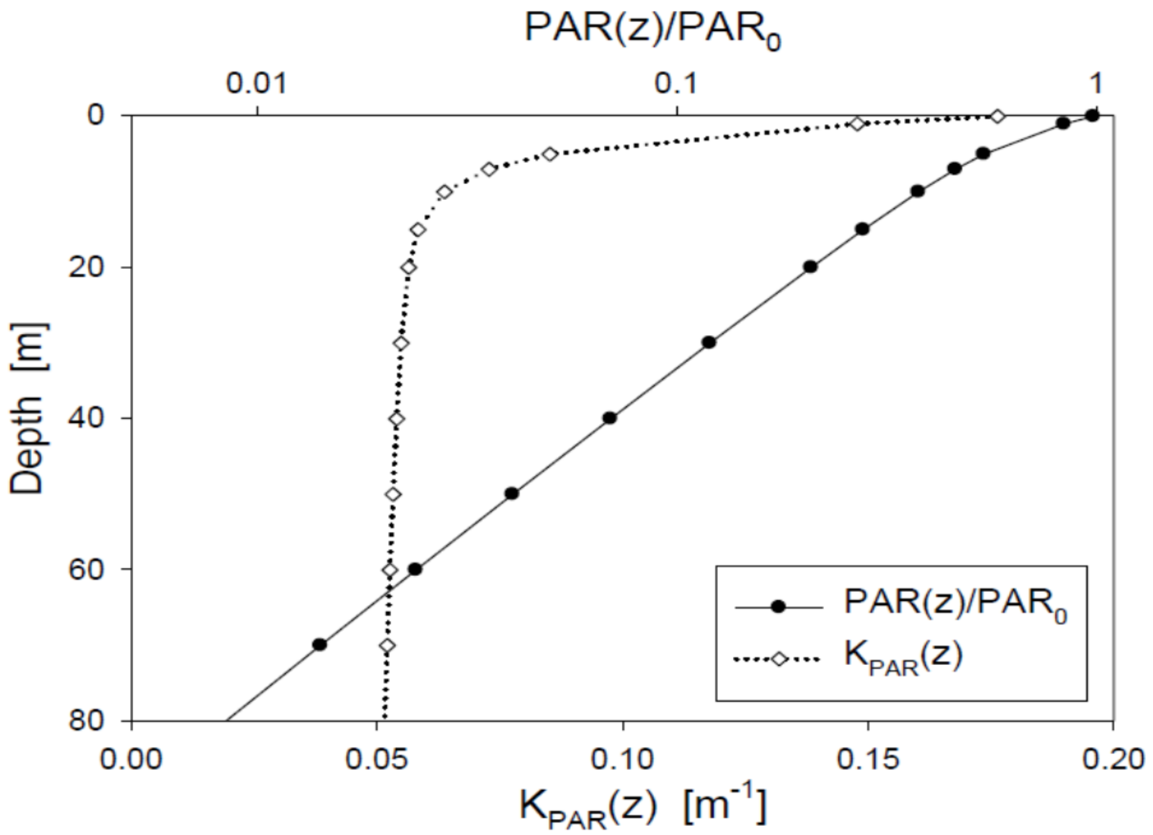
Monte Carlo Method



Invariant Imbedding Method
(Hydrolight®)

d) Relationship for the diffuse attenuation coefficient of PAR (K_{PAR}):

$$PAR(z) = PAR(0)\, e^{-K_{PAR}\, z}$$



K_{PAR} vary with depth significantly!

$$K_{PAR}(z) = K_1(IOP, \theta_0) + \frac{K_2(IOP, \theta_0)}{\sqrt{1+z}}$$

$$\{K_1, K_2\} = \mathrm{Fun}(a(490), b_b(490), \theta_0)$$

(Lee et al 2005)

Key points:

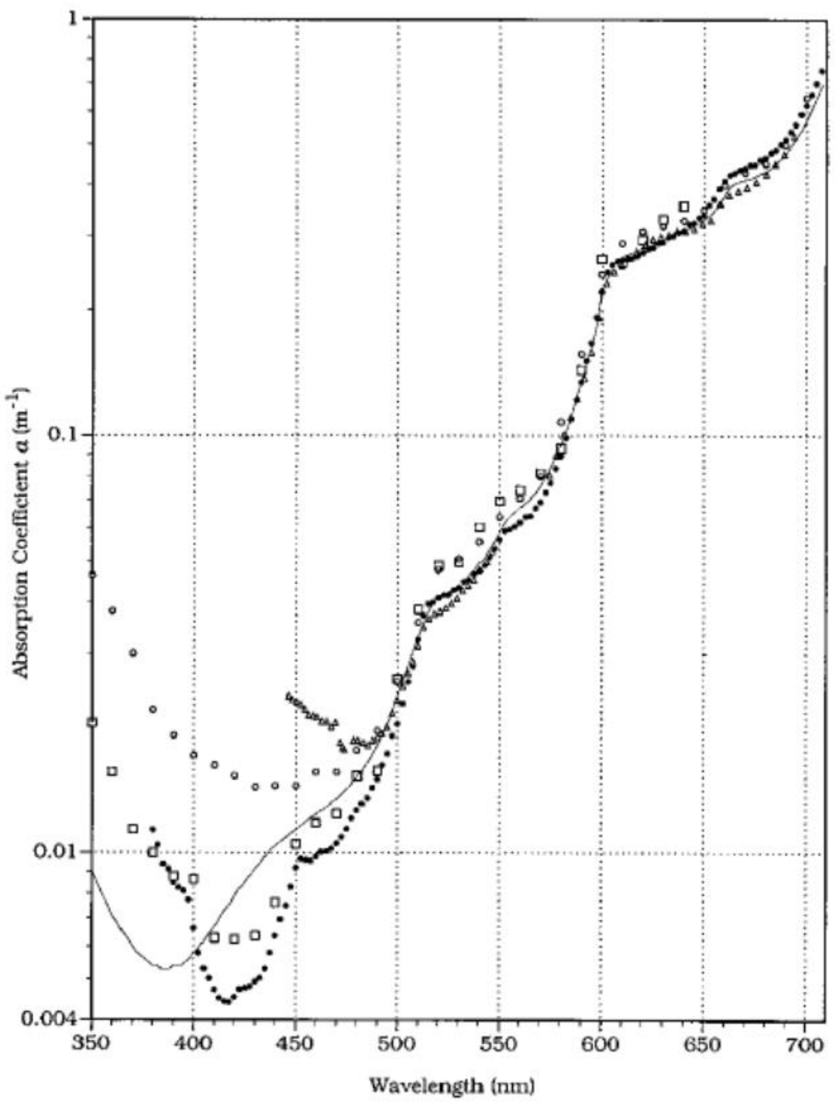
1. Primary AOPs include diffuse attenuation coefficient, irradiance reflectance, and remote sensing reflectance. All are wavelength dependent. Even for vertically homogeneous ocean, AOPs are not constant vertically.

2. All AOPs are functions of IOPs. Various models have been developed to describe AOPs as a function of IOPs.

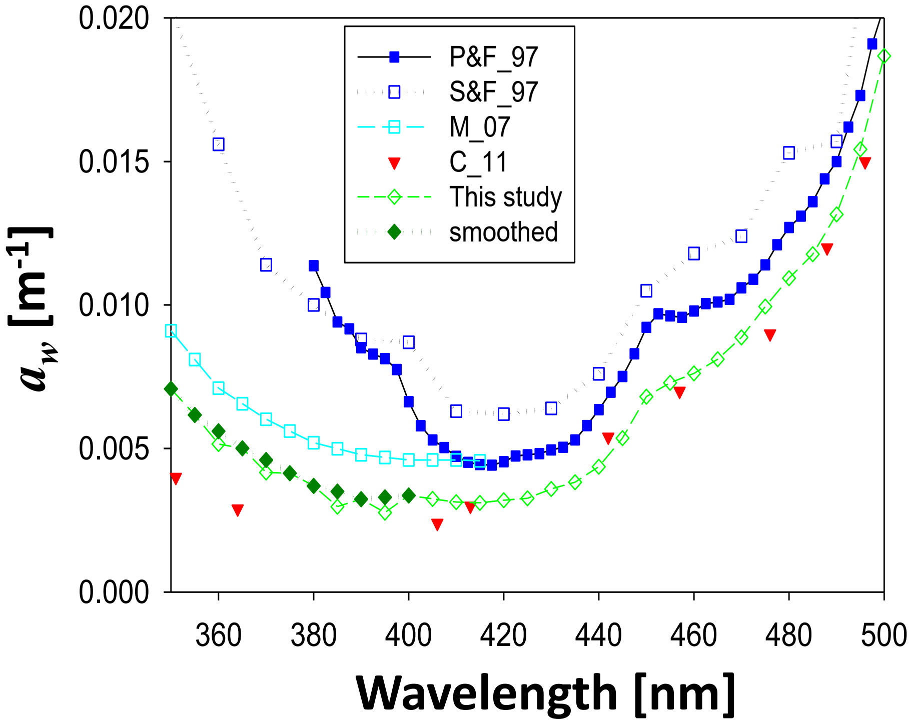
3. Diffuse attenuation coefficient is proportional to both absorption and backscattering coefficients.

4. Reflectance is proportional to backscattering coefficient, but inversely proportional to absorption and backscattering coefficients.

Uncertainties of a_w:



(Pope and Fry, 1997)



(Lee et al 2015)

absorption coefficient: a (m^{-1})

Volume Scattering Function (VSF): β ($m^{-1}\ sr^{-1}$)

(elastic)

↓

Scattering coefficient: b (m^{-1})

$$b = \int_0^{2\pi} \int_0^{\pi} \beta \sin(\theta)\, d\theta d\varphi$$

beam attenuation coefficient: $c = a + b$ (m^{-1})