zhongping lee

EDUCATION

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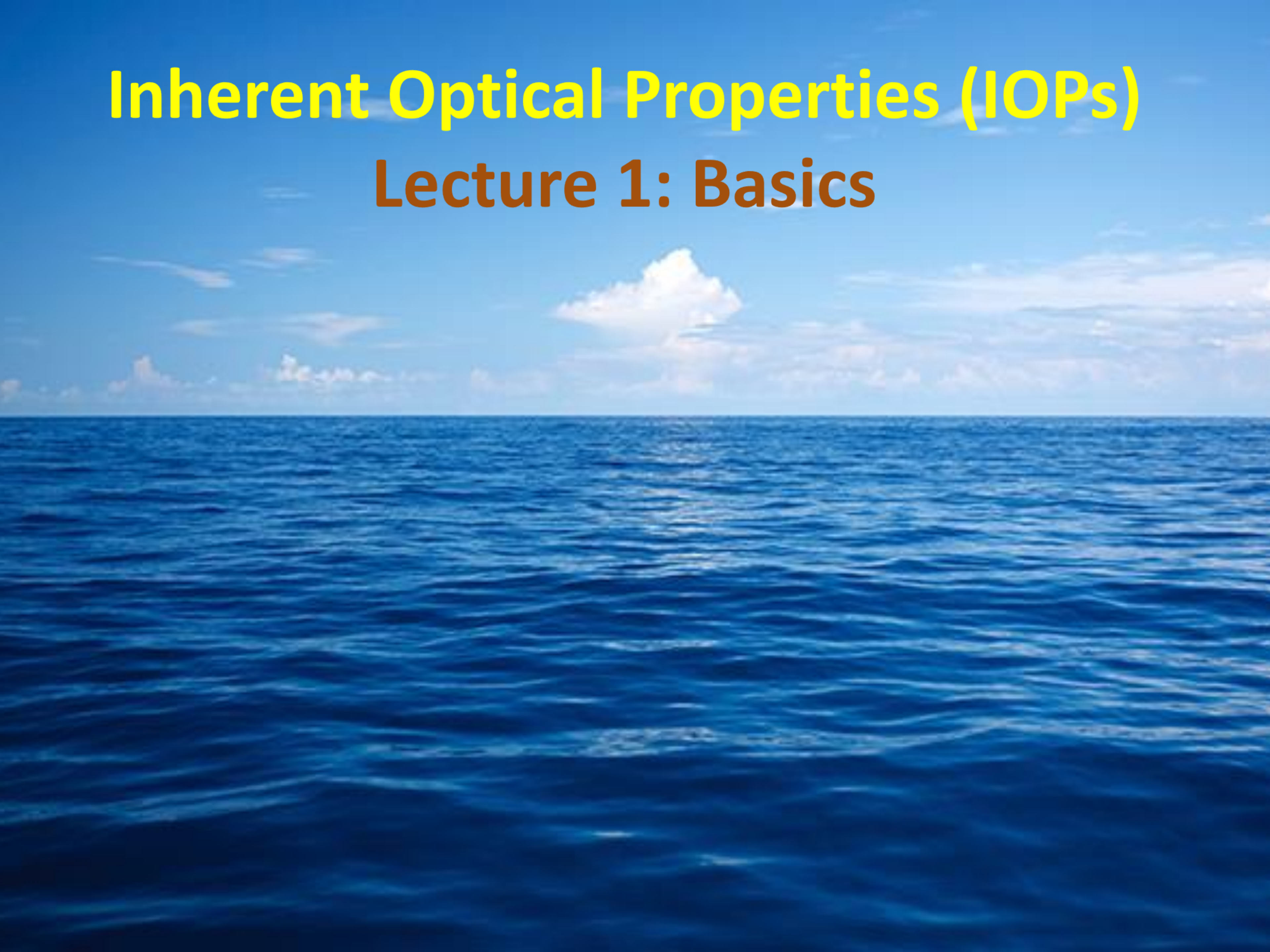
My research discipline is in ocean optics and ocean color remote sensing. It covers three aspects to:

- understand how the light field changes in a natural environment (radiative transfer);
- develop effective tools that use the light information to retrieve important environmental properties (remote sensing);
- use the remotely sensed products (either from airborne or space borne sensors) to study the ocean/Earth system.

My ongoing and past efforts have been focused on the development of remote sensing algorithms that can be applied to both oceanic and coastal environments. In addition, we have also conducted studies on field measurement techniques, estimation of primary production, and the dynamics of biogeochemical properties of waters in the South Pacific gyre.

Inherent Optical Properties (IOPs)

Lecture 1: Basics



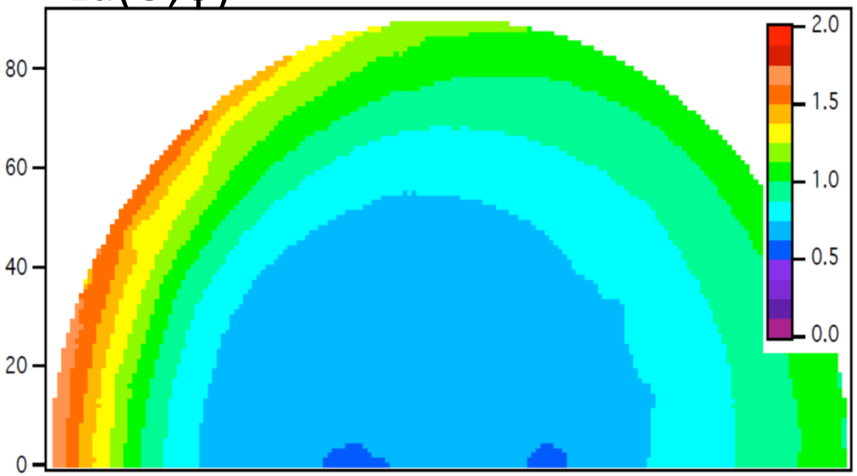
Absorption properties

Scattering properties

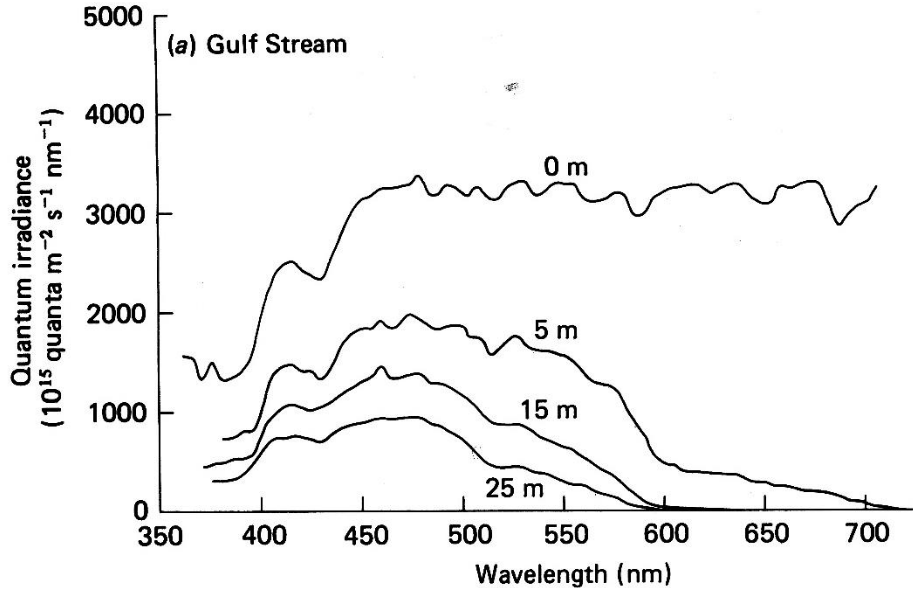
ocean (water) color

light within water medium

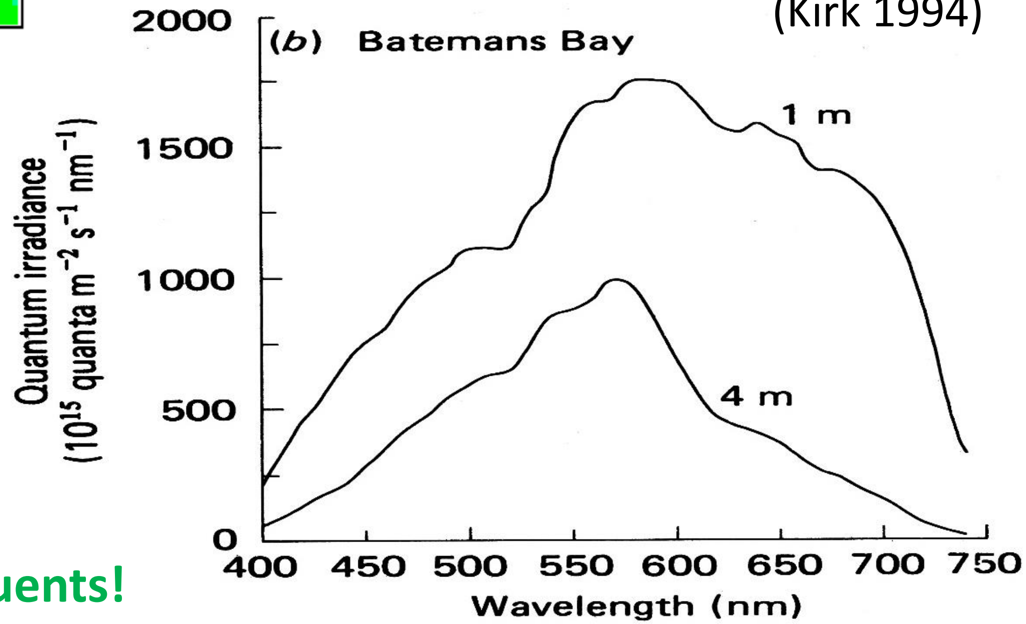
Lu(Θ,φ)



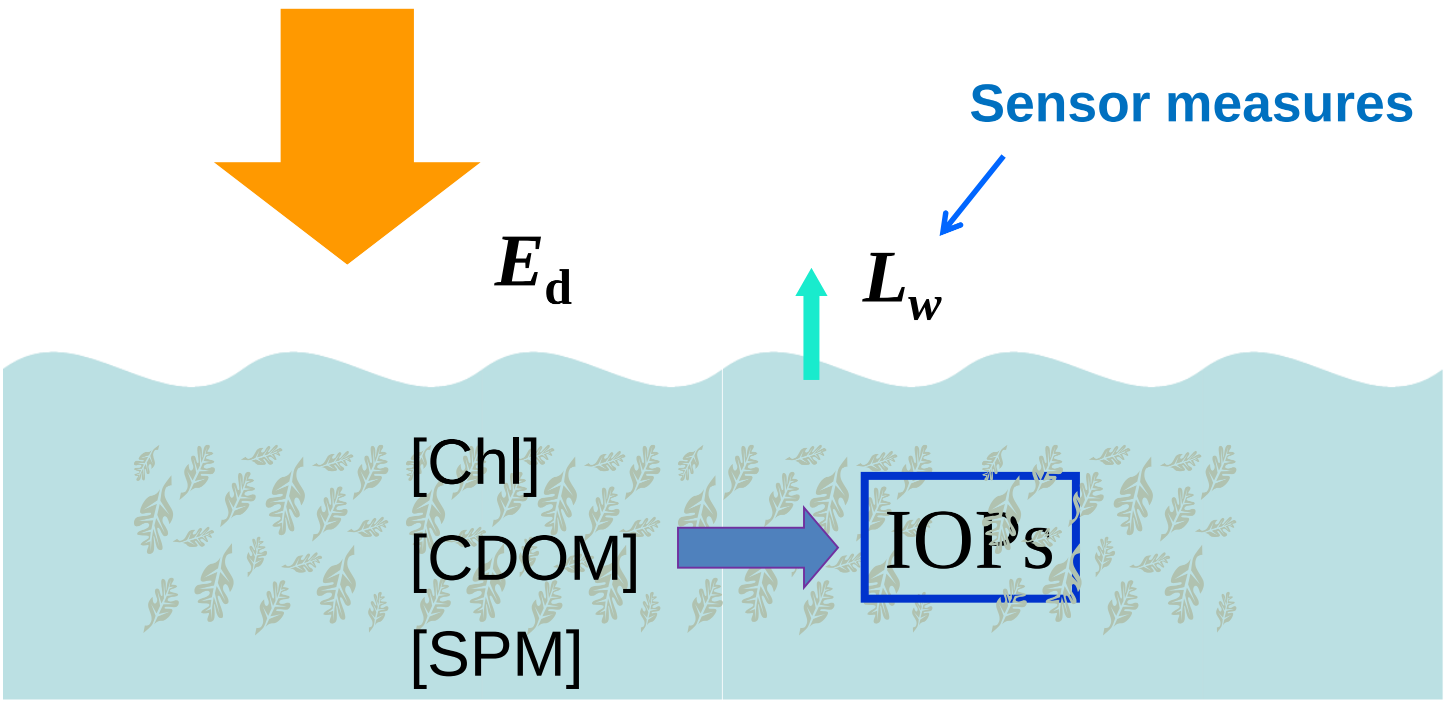
(Voss et al 2007)



(Kirk 1994)

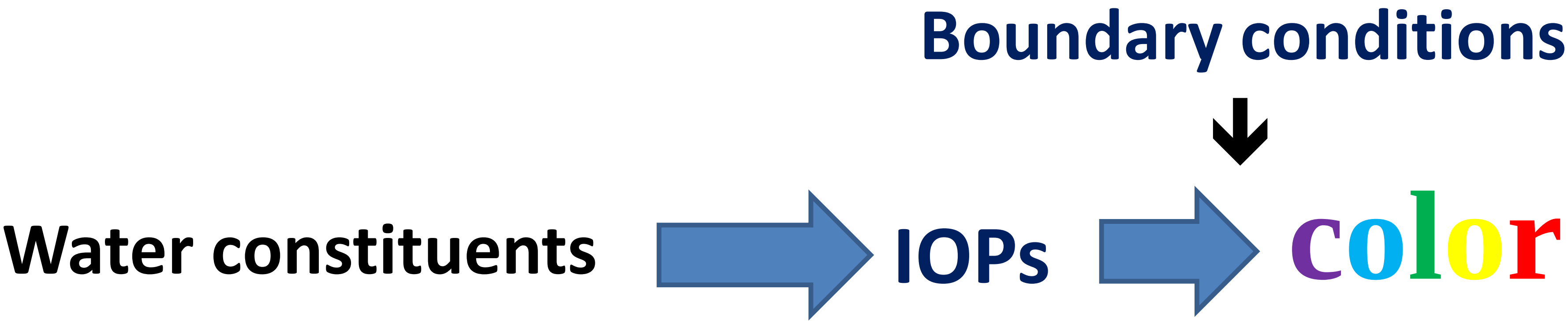


They are modulated by water constituents!



Inherent Optical Properties (IOPs)

a: absorption coefficient $= a_w + \sum a_{xi}$
b_b: backscattering coefficient $= b_{bw} + \sum b_{bxi}$
c: beam attenuation coefficient $(a+b)$

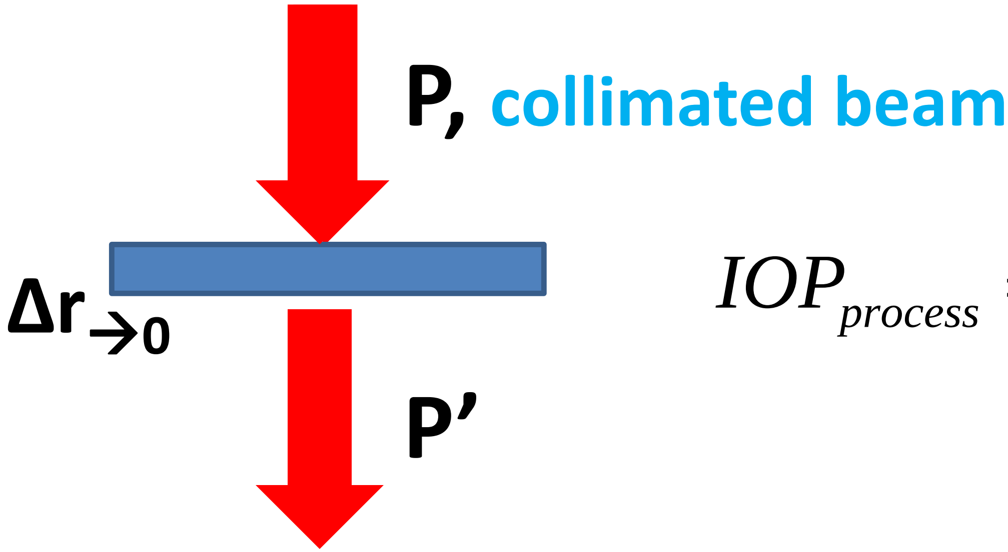


IOPs (Inherent Optical Properties):

The optical capability regardless of the ambient light environment.

Absorption properties; Scattering properties

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}

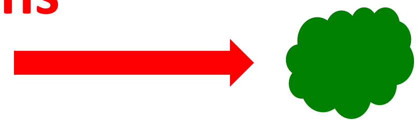
$a = 1.2\ m^{-1}$

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

Energy transfer processes:

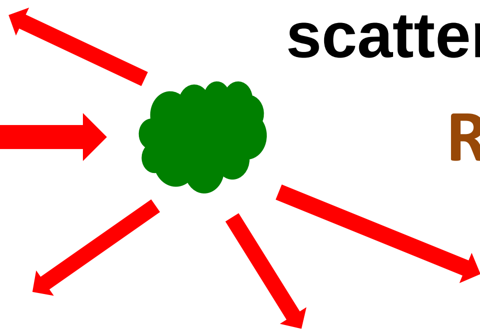
photons

absorption



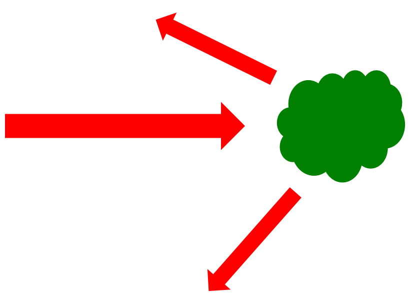
Transfer of energy

scattering



Redistribution of energy

backscattering



Scattering has angular dependence

Scattering

Rayleigh scattering

“d” << λ

Mie scattering

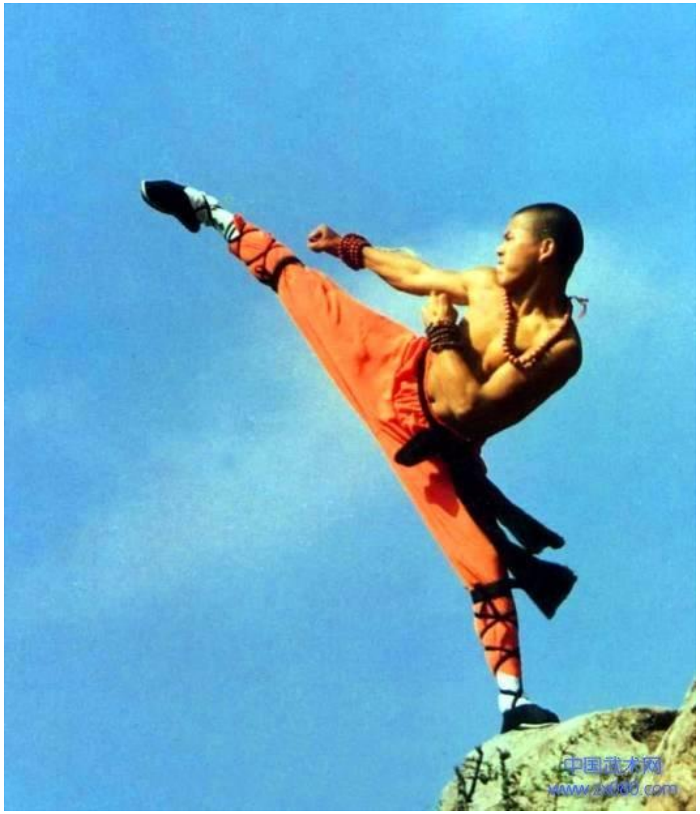
“d” >> λ

Scattering

Elastic scattering

In-elastic scattering/absorption

(e.g., Raman scattering)



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

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

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})

IOPs are additive.

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

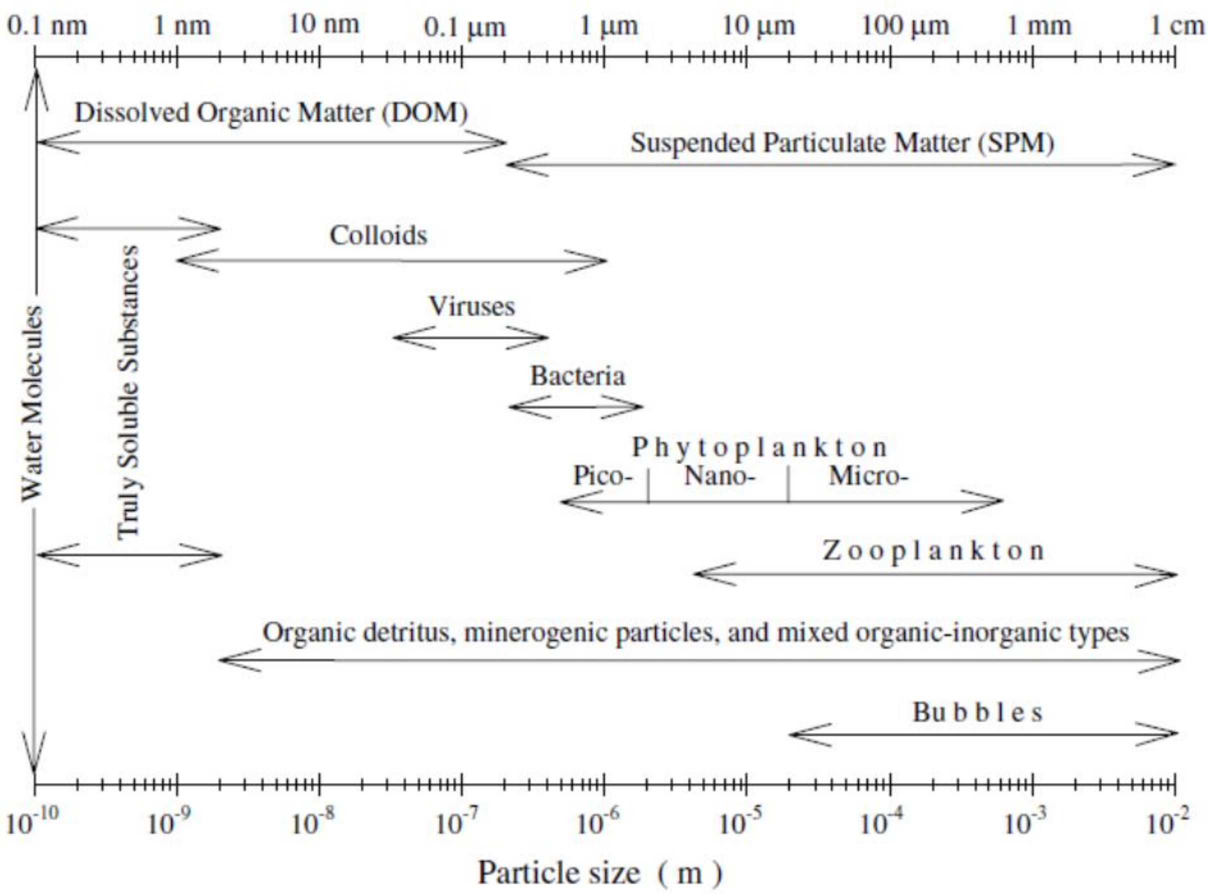


Fig. 1. Schematic diagram showing various seawater constituents in the broad size range from molecular size of the order of 10^{-10} m to large particles and bubbles of the order of 10^{-3}–10^{-2} m in size. The arrow ends generally indicate approximate rather than sharp boundaries for different constituent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

1. absorption properties

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

Very detailed:

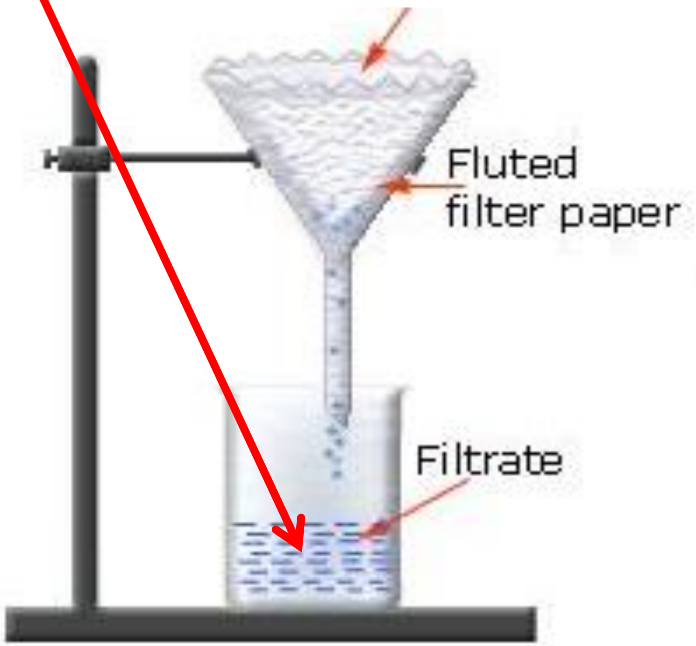
$$a(\lambda) = a_w(\lambda) + \sum_{i=1}^{18} a_{\mathrm{pla},i}(\lambda + a_{\mathrm{det}}(\lambda) + a_{\mathrm{min}}(\lambda) + a_{\mathrm{CDOM}}(\lambda)$$
$$= a_w(\lambda) + \sum_{i=1}^{18} N_{\mathrm{pla},i}\sigma_{a,\mathrm{pla},i}(\lambda) + N_{\mathrm{det}}\sigma_{a,\mathrm{det}}(\lambda)$$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

(Stramski et al 2001)

Practical (and common) division:

$$a = a_w + a_p + a_g$$

(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

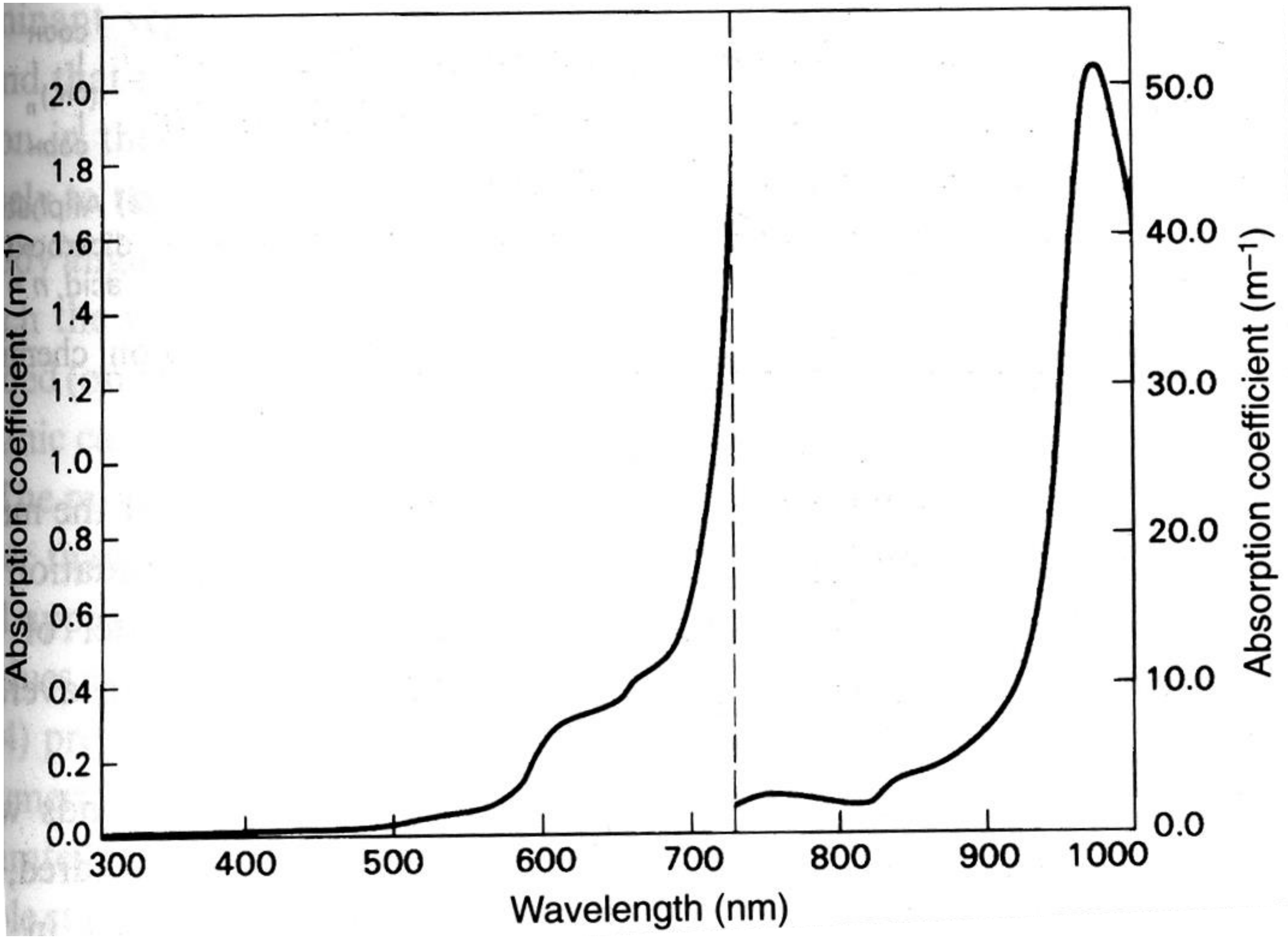
Particulate: $a_p = a_{ph} + a_d$

Pigments of living phytoplankton: a_{ph}

Detritus: a_d

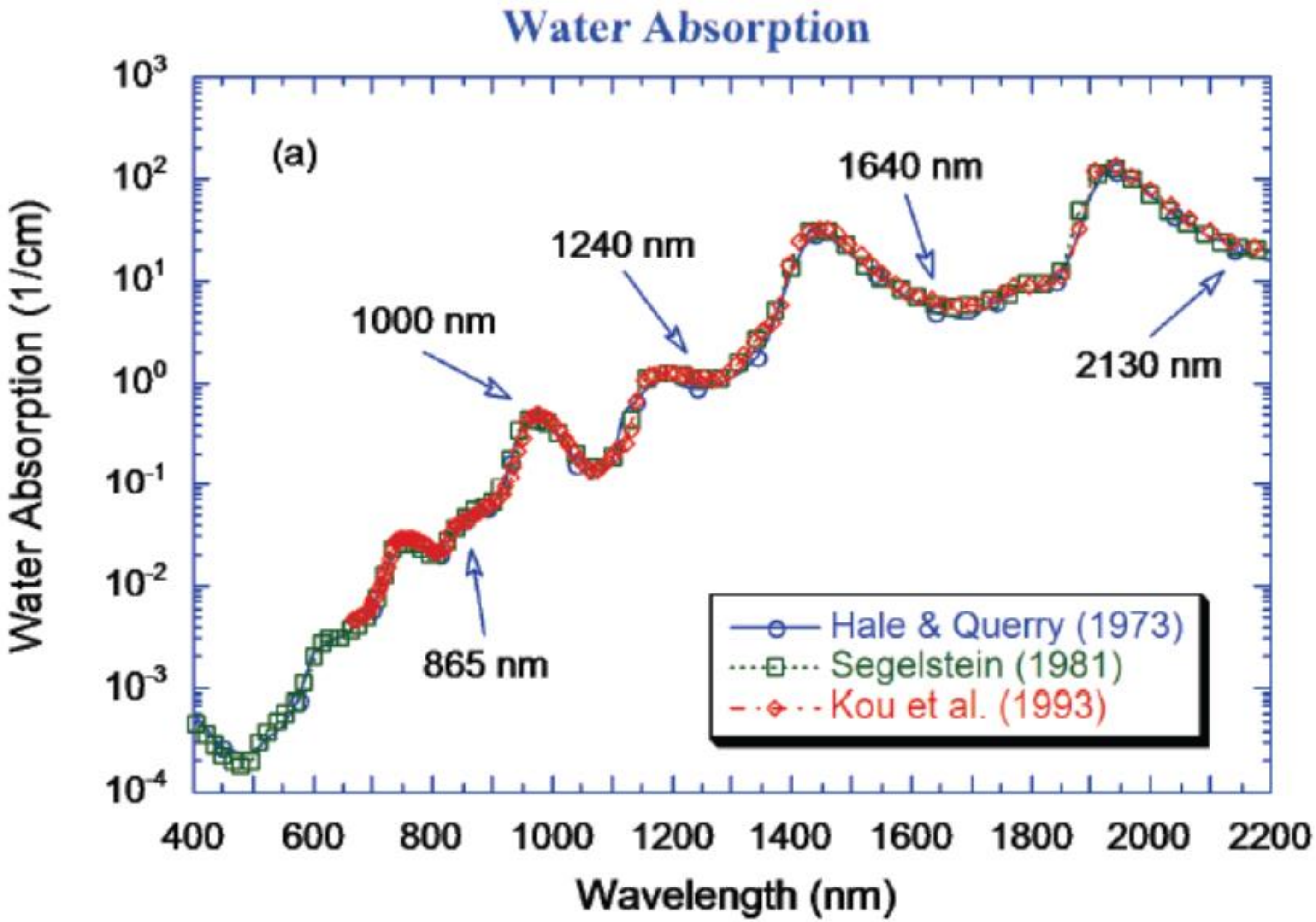
Gelbstoff (yellow substance; colored dissolved organic matter): a_g

a_w spectrum



(Mobley 1994)

a_w spectrum



Water Absorption
(a)
Water Absorption (1/cm)
Wavelength (nm)
1000 nm
1240 nm
1640 nm
2130 nm
865 nm
Hale & Querry (1973)
Segelstein (1981)
Kou et al. (1993)

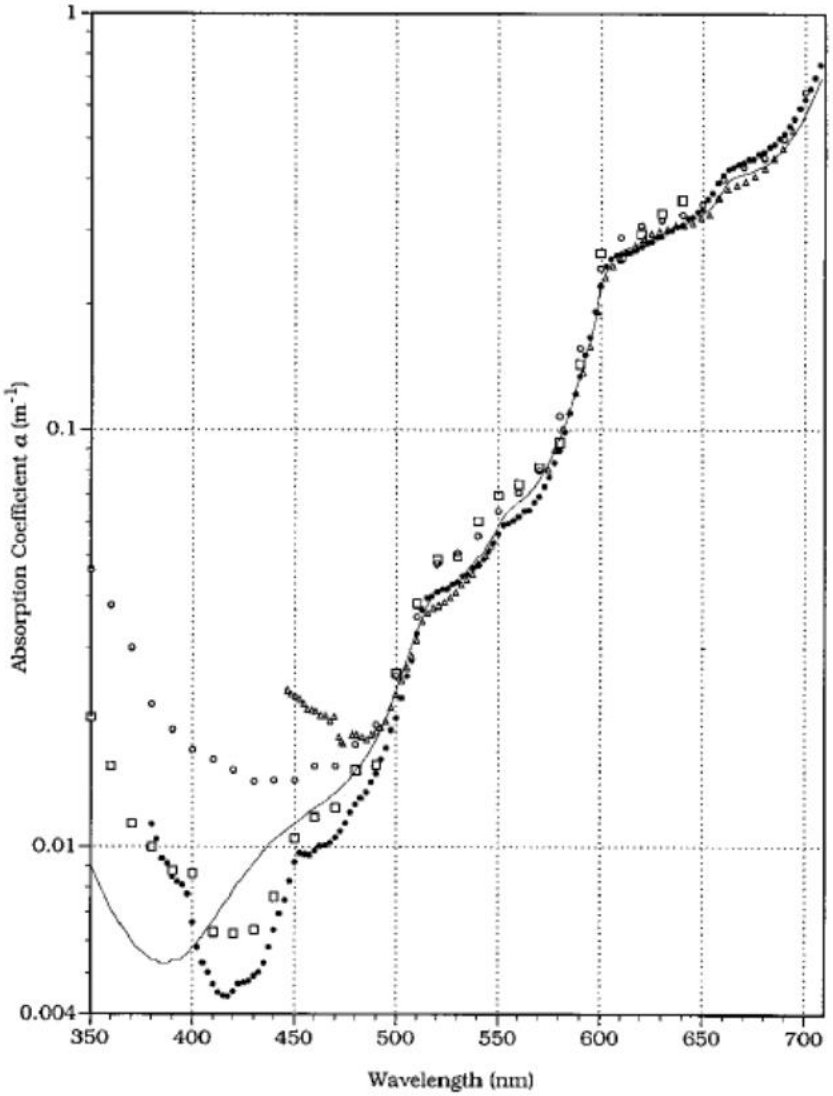
a_w

Table 3.1. *Absorption coefficients for pure water: 280–320 nm, Quickenden & Irvin (1980); 366 nm, Boivin et al. (1986); 380–700 nm, Morel & Prieur (1977); 700–800 nm, Smith & Baker (1981)*

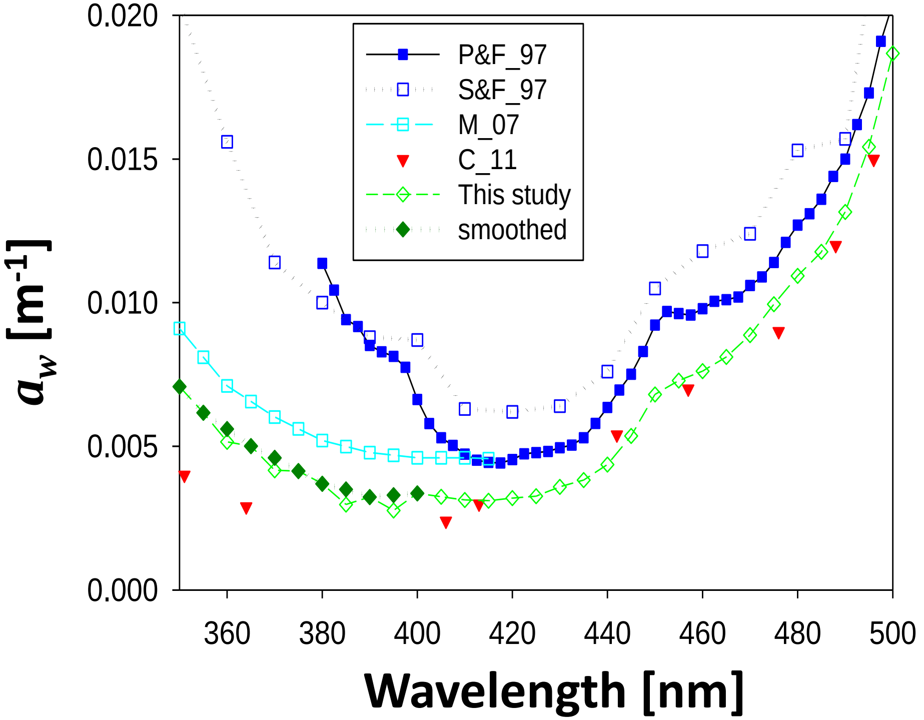
λ (nm)	*a* (m⁻¹)	λ (nm)	*a* (m⁻¹)
280	0.0239[ab]	560	0.071
290	0.0140[ab]	570	0.080
300	0.0085[ab]	580	0.108
310	0.0082[ab]	590	0.157
320	0.0077[ab]	600	0.245
366	0.0055[a]	610	0.290
380	0.023	620	0.310
390	0.020	630	0.320
400	0.018	640	0.330
410	0.017	650	0.350
420	0.016	660	0.410
430	0.015	670	0.430
440	0.015	680	0.450
450	0.015	690	0.500
460	0.016	700	0.650
470	0.016	710	0.839
480	0.018	720	1.169
490	0.020	730	1.799
500	0.026	740	2.38
510	0.036	750	2.47
520	0.048	760	2.55
530	0.051	770	2.51
540	0.056	780	2.36
550	0.064	790	2.16
		800	2.07

(Mobley 1994)

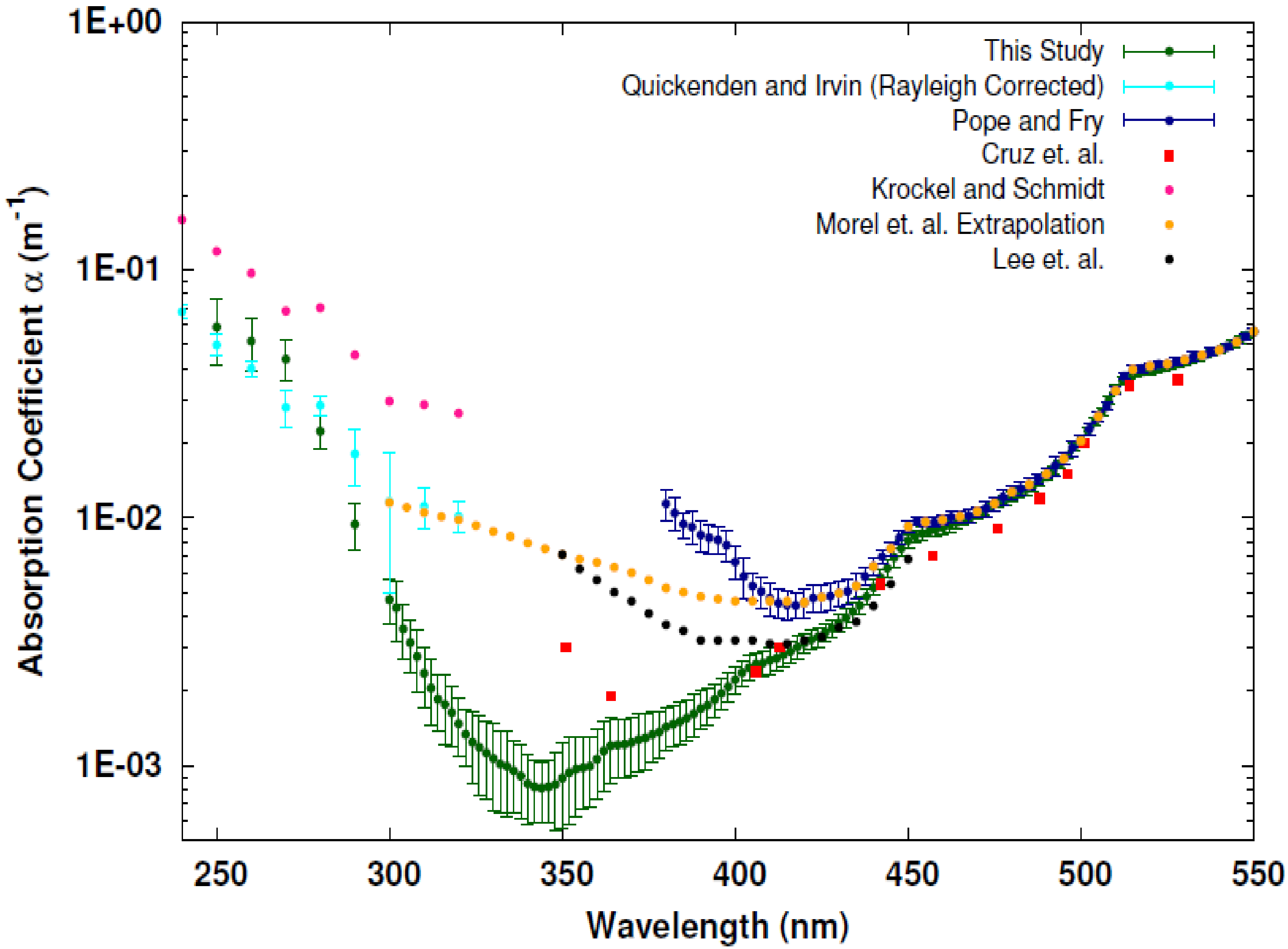
Uncertainties of a_w:



(Pope and Fry, 1997)

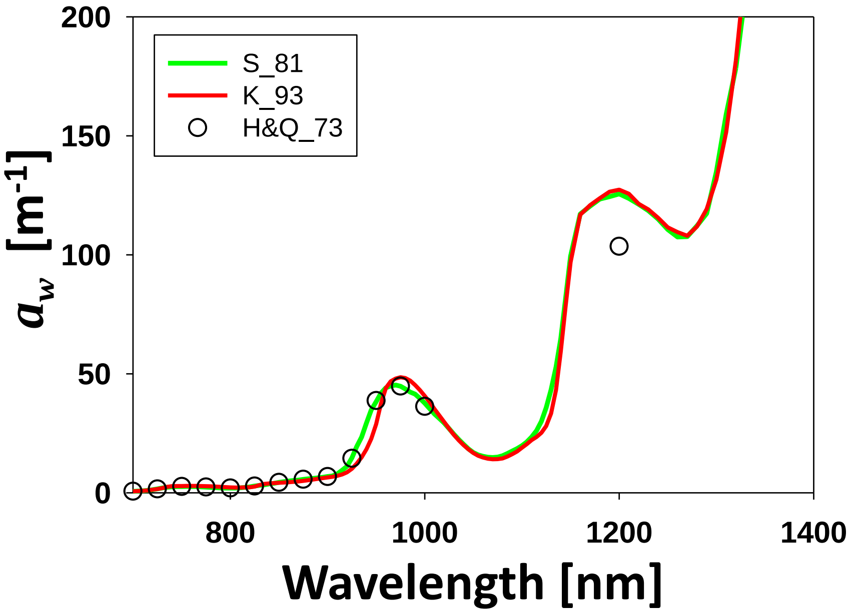


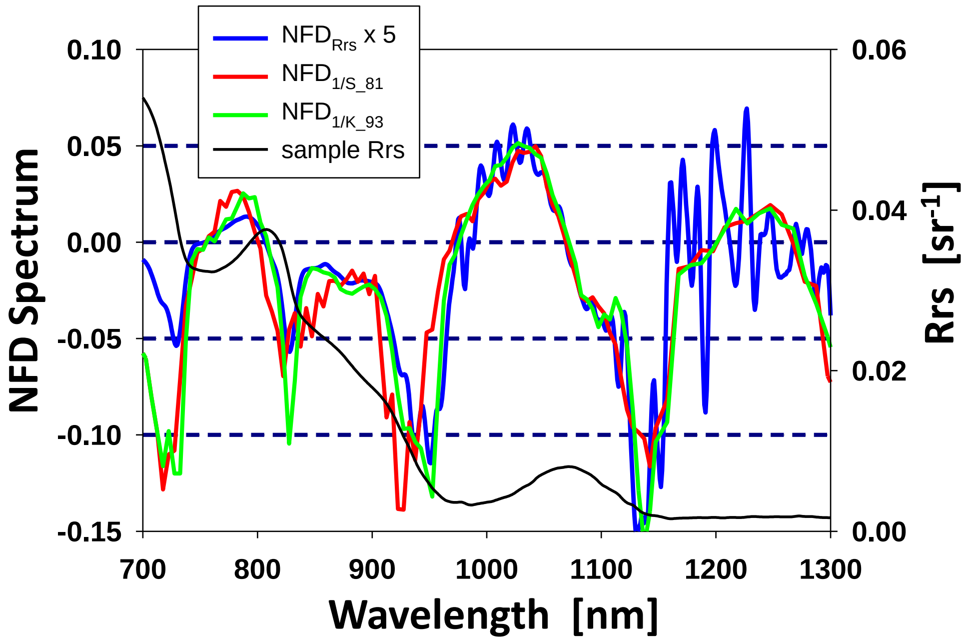
(Lee et al 2015)



(Mason et al, 2016)

In the NIR-SWIR range …





(Lee et al 2016)

S_81: Segelstein 1981

K_93: Kou et al 1993

H&Q_73: Hale and Querry 1973

a_w is temperature and salinity dependent

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

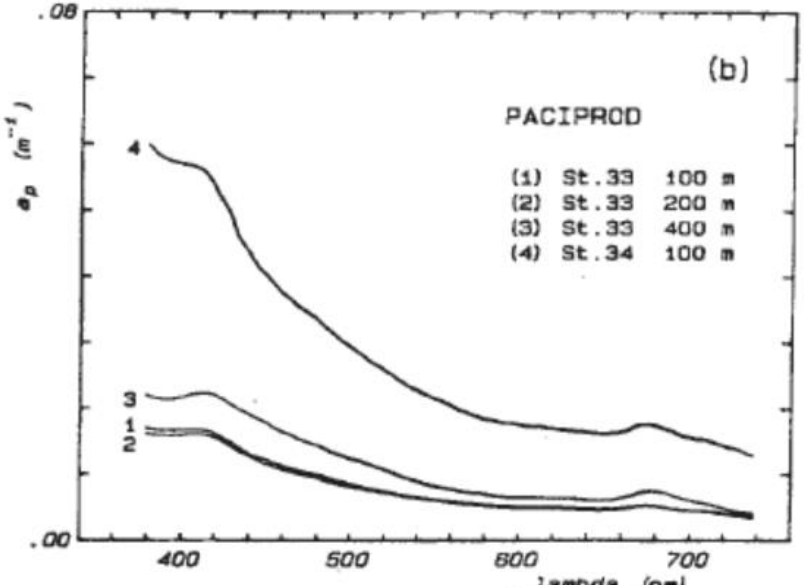
Table 2. Linear Slopes of the Temperature Dependence of the Absorption Coefficient Measured in the Laboratory[a]

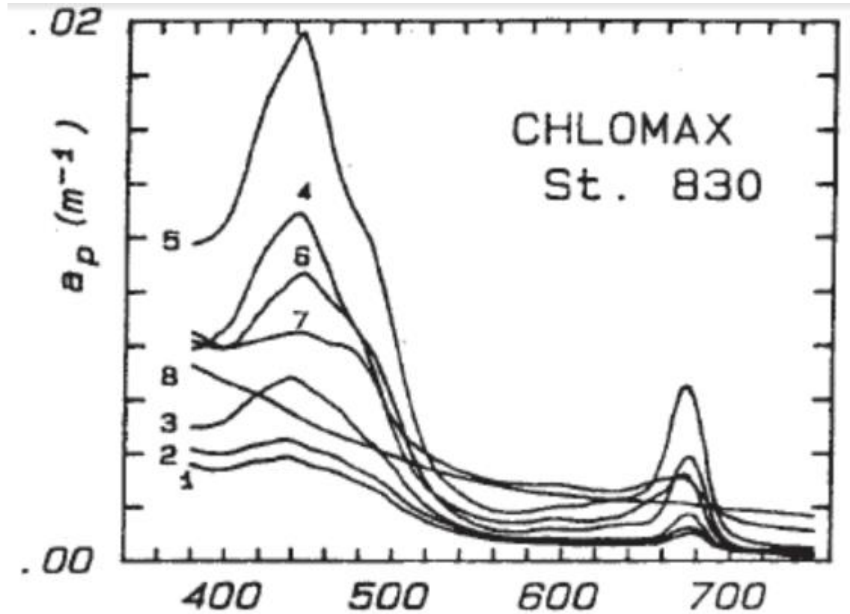
Wavelength	Ψ_T, Pure Water	Standard Deviation, Pure Water	Ψ_T, Saltwater	Standard Deviation, Saltwater
412	0.0001	0.0003	0.0003	0.0003
440	0.0000	0.0002	0.0002	0.0002
488	0.0000	0.0002	0.0001	0.0002
510	0.0002	0.0001	0.0003	0.0001
520	0.0001	0.0002	0.0002	0.0002
532	0.0001	0.0002	0.0001	0.0002
555	0.0001	0.0001	0.0002	0.0002
560	0.0000	0.0002	0.0000	0.0002
650	−0.0001	0.0001	−0.0001	0.0001
676	−0.0001	0.0001	−0.0001	0.0002
715	0.0029	0.0001	0.0027	0.0001
750	0.0107	0.0003	0.0106	0.0005
850	−0.0065	0.0001	−0.0068	0.0001
900	−0.0088	0.0001	−0.0090	0.0002
975	0.2272	0.0028	0.2273	0.0009

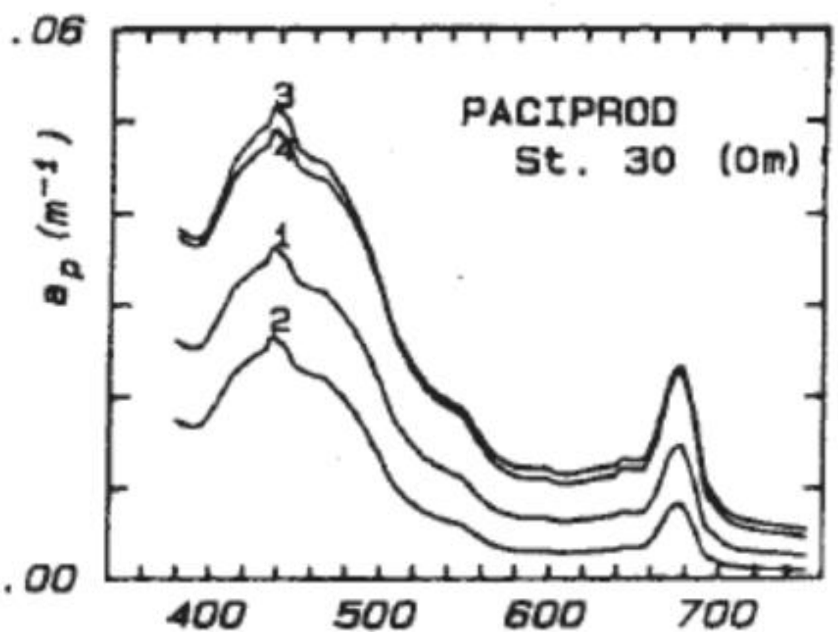
[a]For pure water the results of five tests are combined. The results of two tests were combined for the saltwater results. The absorption and attenuation meter results have been pooled together as well as pooling the common wavelengths between instruments. The standard deviations of the pooled values are provided.

(Pegau et al 1997; Sullivan et al 2006)

a_p spectrum



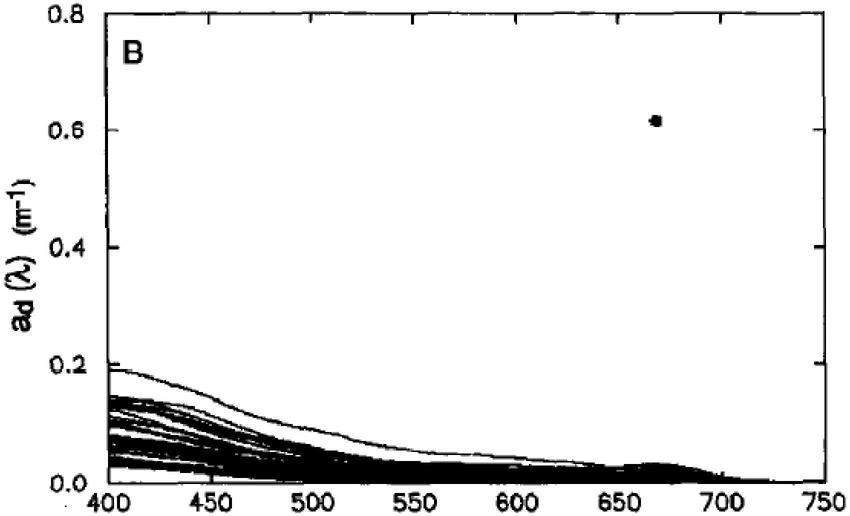


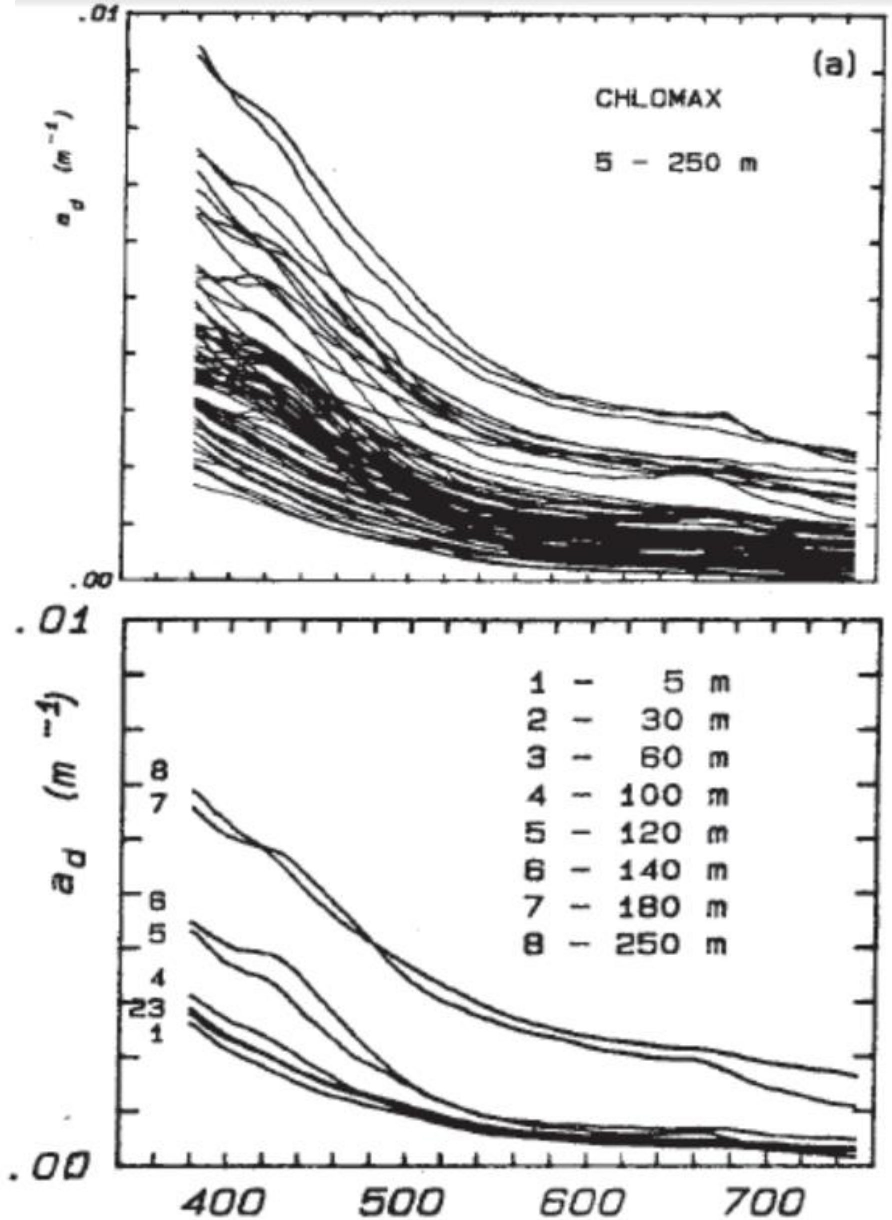


Bricaud and Stramski (1990)

(google)

a_d spectrum

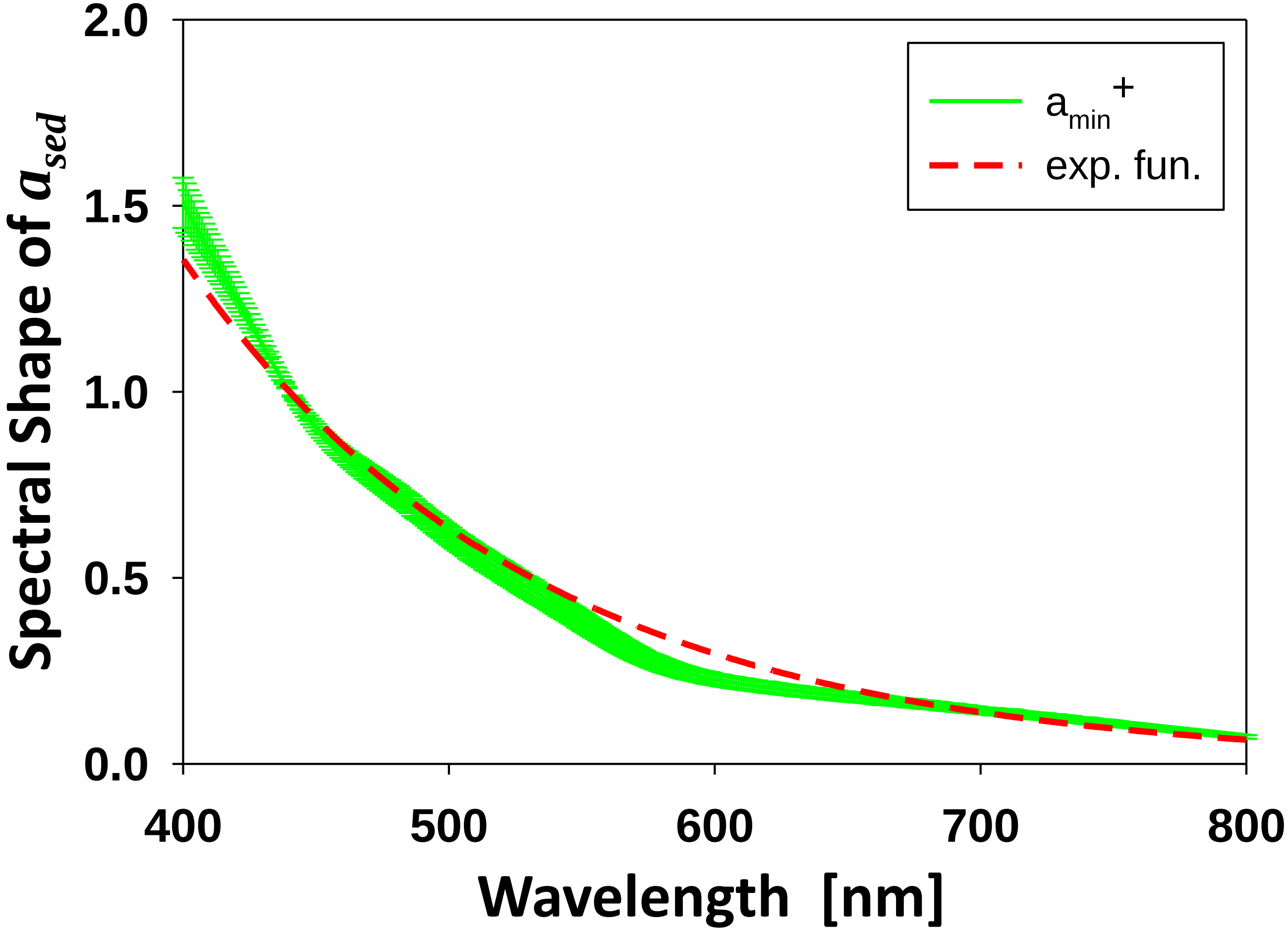




$$a_d = a_d(\lambda_0)\, e^{-S_d(\lambda-\lambda_0)}$$

S_d: ~0.005 – 0.015 nm^{-1}

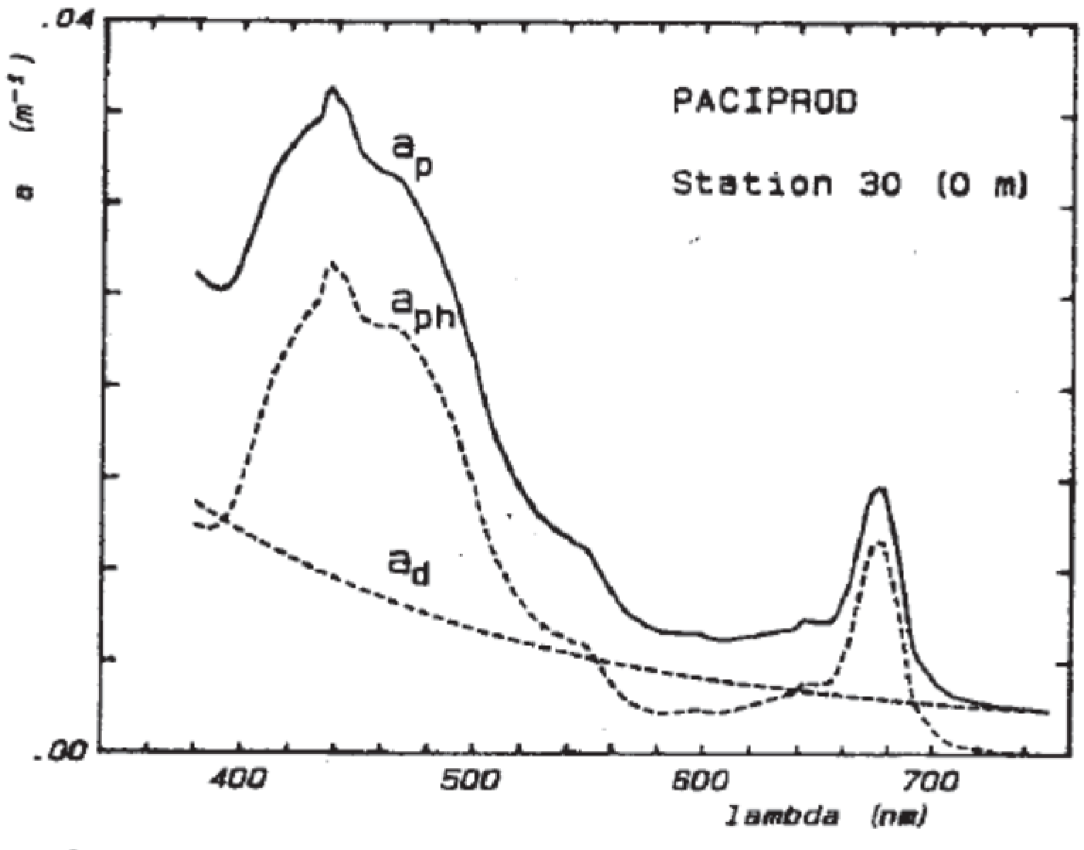
Bricaud and Stramski (1990)



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

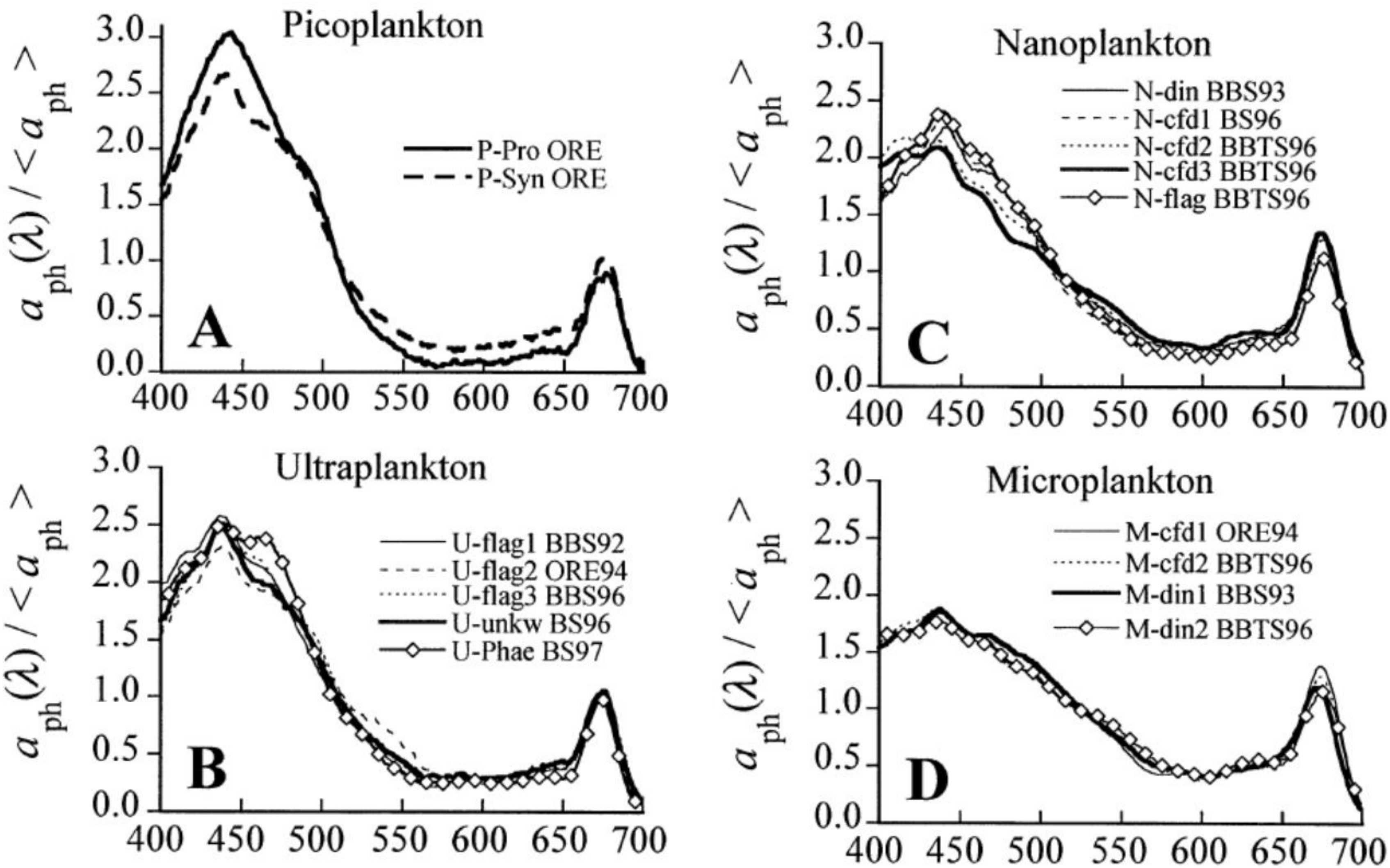
(Lee et al. 2016)

$a_{ph} = a_p - a_d$ spectrum



Bricaud and Stramski (1990)

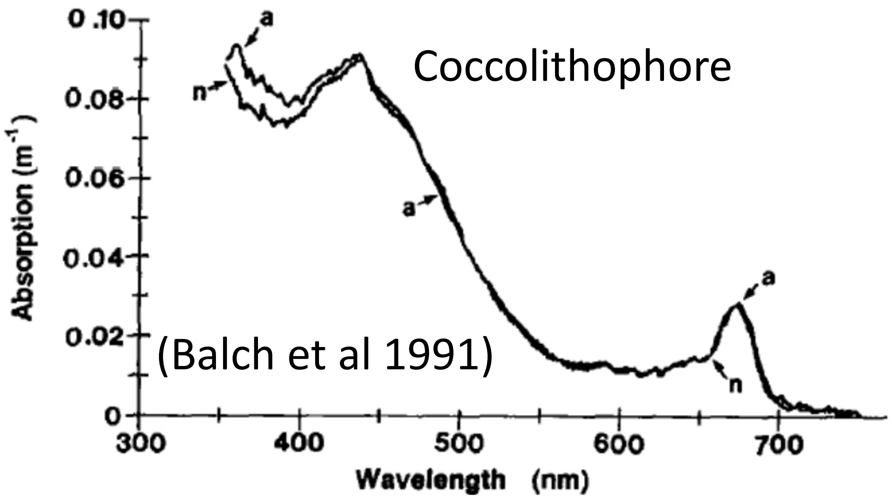
Separated by size

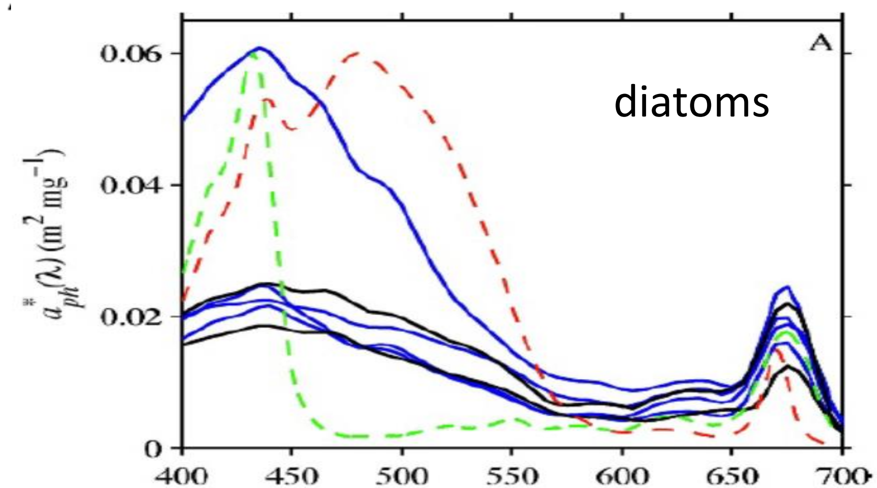


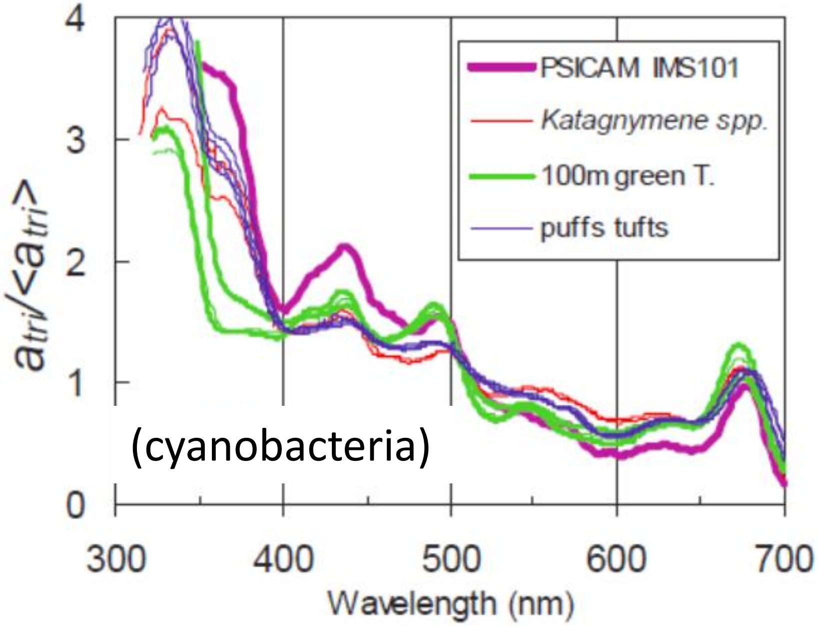
(Ciotti et al 2002)

“fatness”

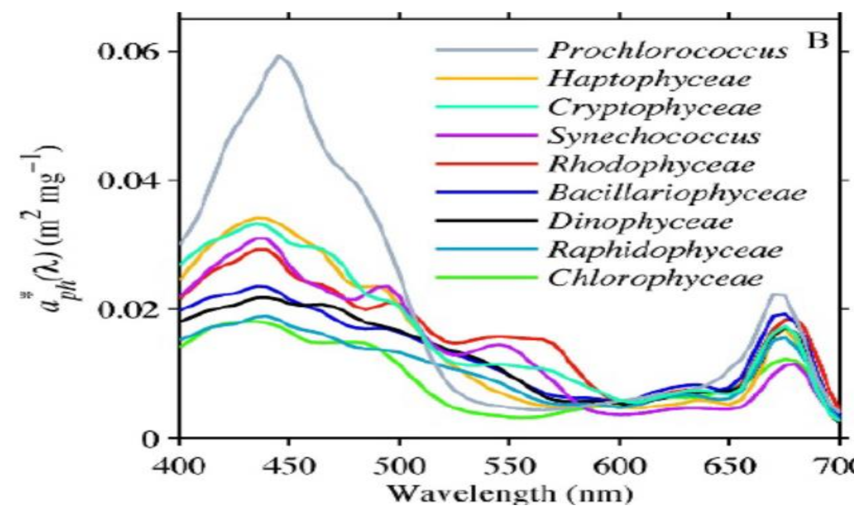
By species or groups





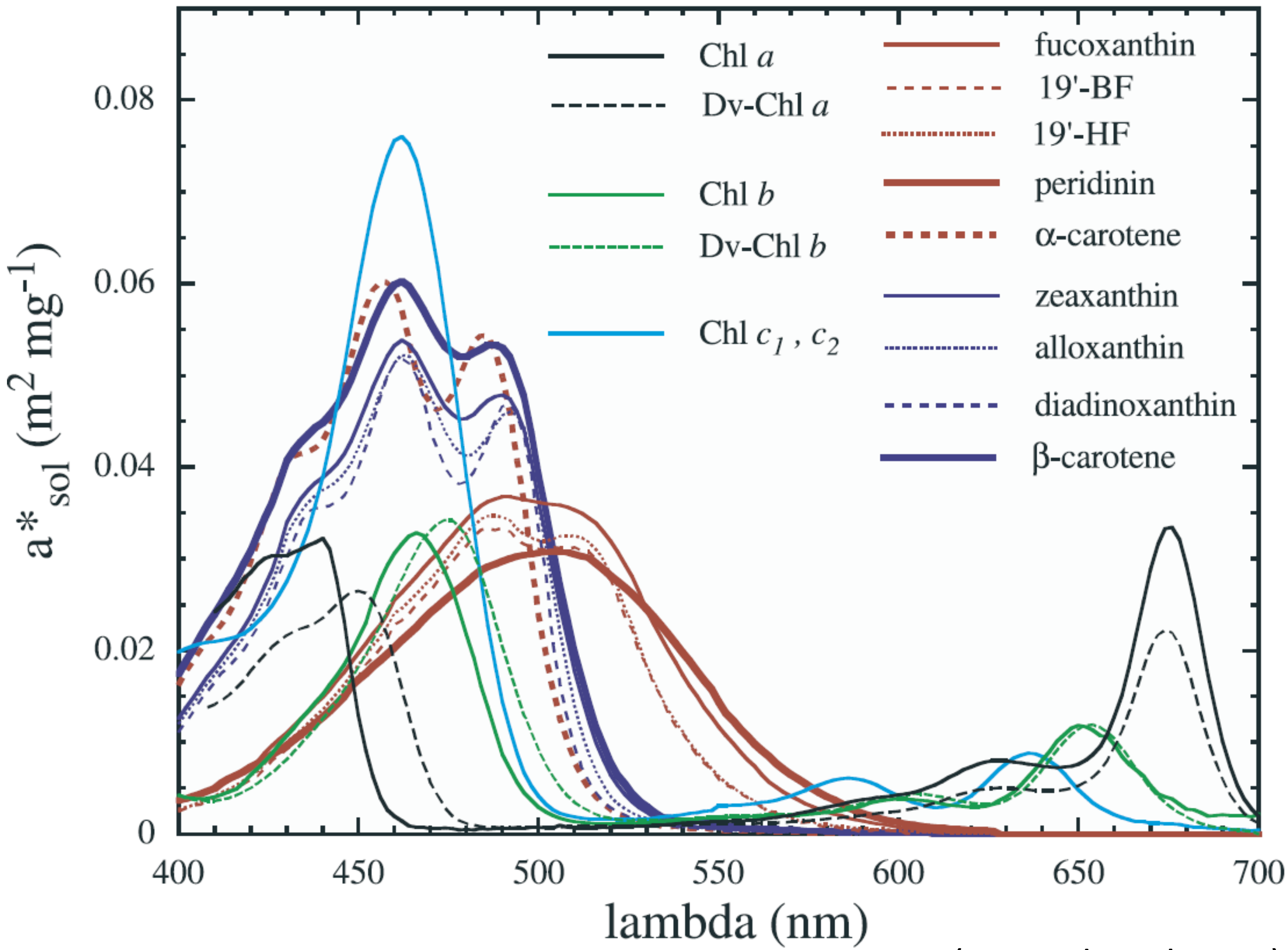


(Dupouy et al 2008)



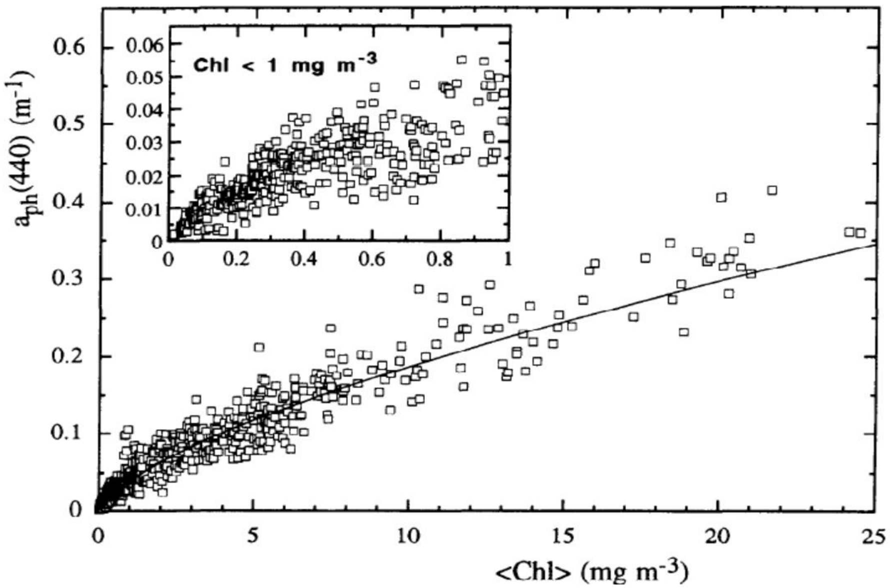
(Dierssen et al 2006)

Contribution of various pigments

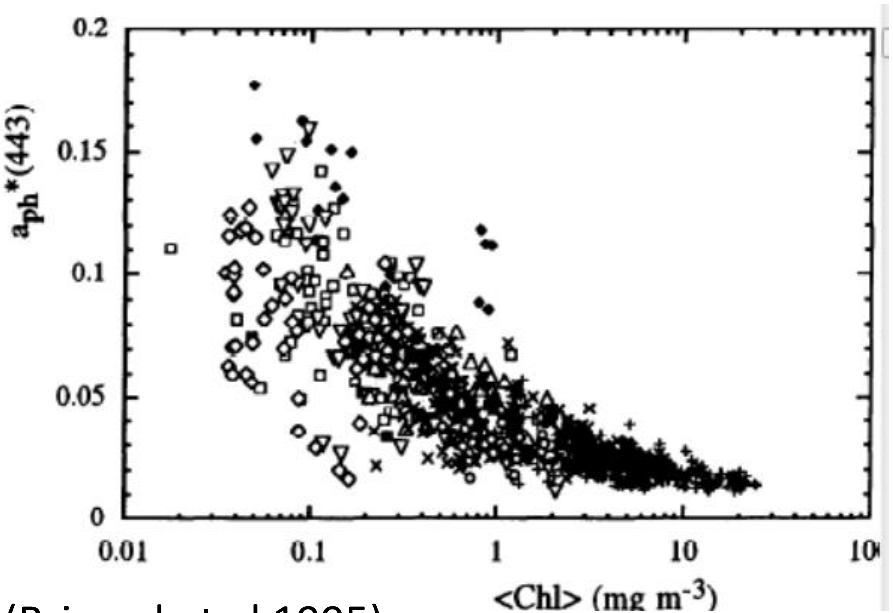


(Bricaud et al 2004)

Package effect



Increase of absorption is **NOT linearly** proportionally to Chl concentration!



(Bricaud et al 1995)

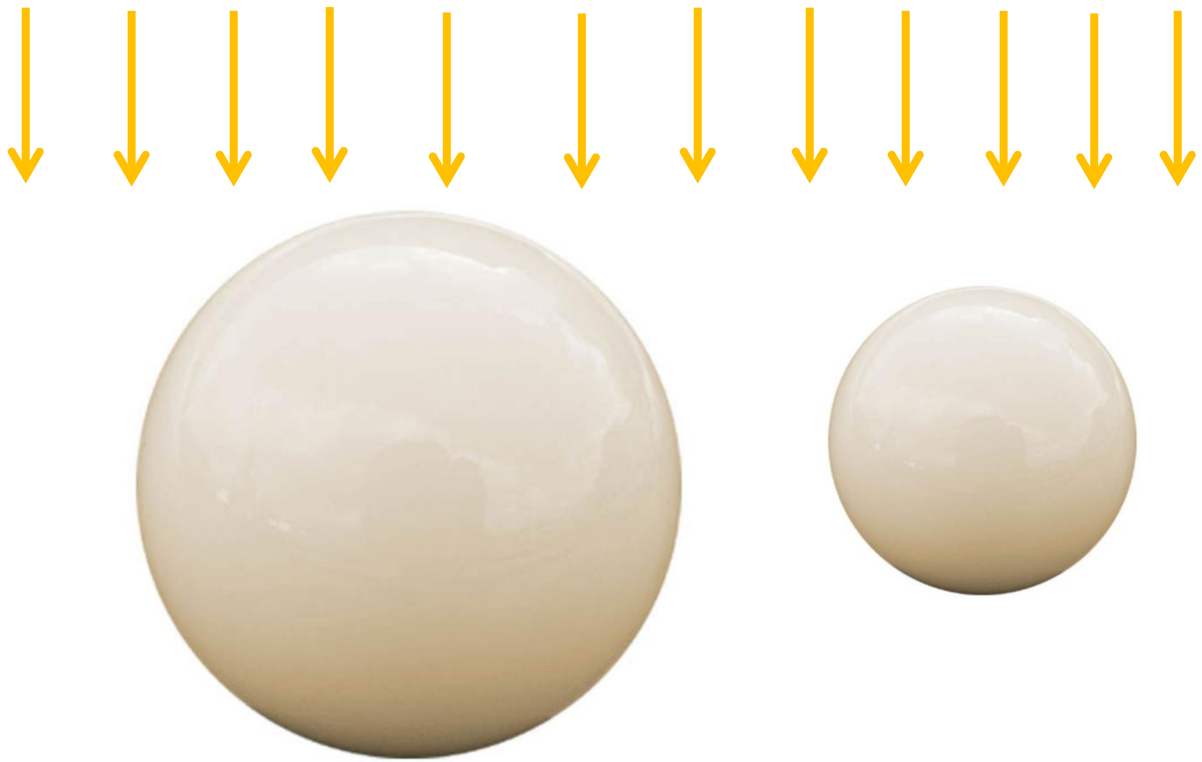
$$a^*_{ph} = \frac{a_{ph}}{Chl}$$

Specific absorption/scattering coefficient =

Concentration normalized absorption/scattering coefficient

Chl ↑ → specific optical property ↓

Simplified case:



$$a \propto \sigma S$$

$$W \propto \rho V$$

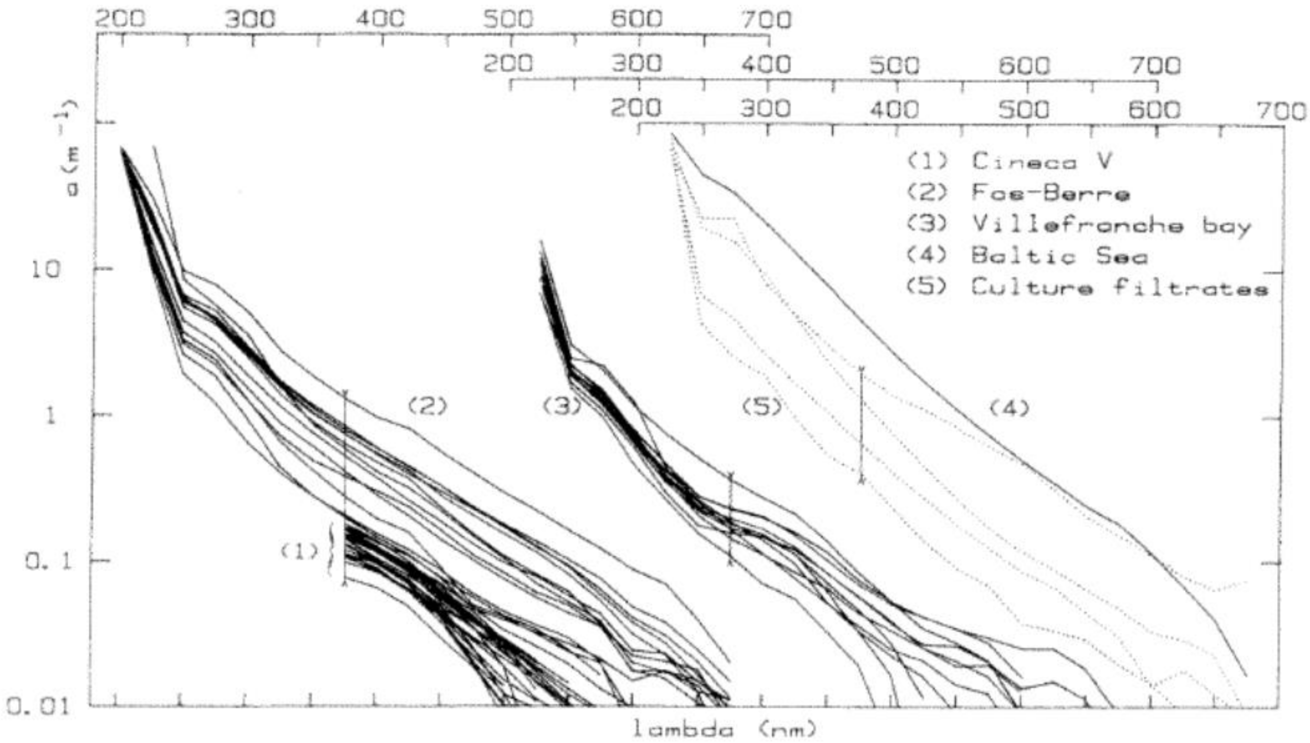
$$a^*_{ph} \propto \frac{a}{W} = \frac{\sigma}{\rho} \frac{S}{V} \propto \frac{1}{d}$$

S: cross section
V: volume
W: weight

Size matters on efficiency!

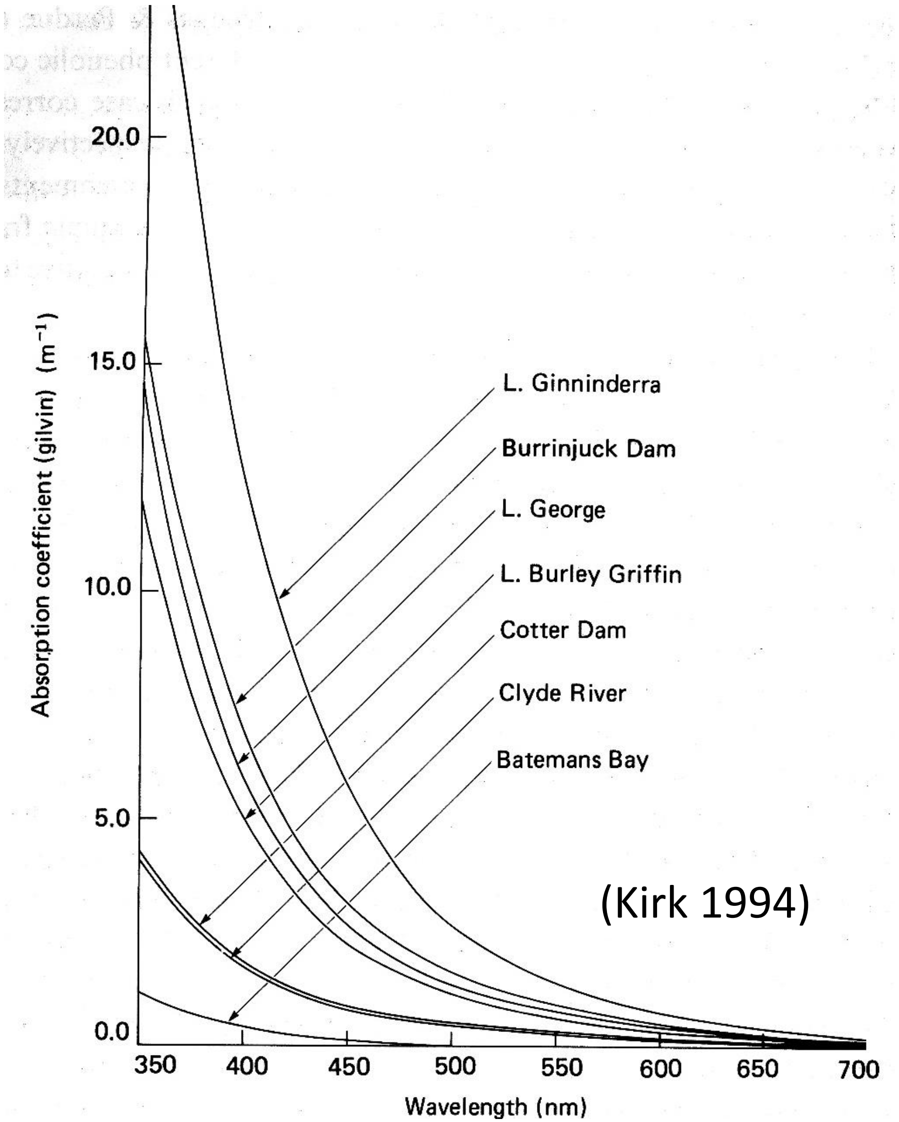
a_g spectrum

Absorption spectra of yellow substance (gelbstoff)



(Bricaud et al 1981)

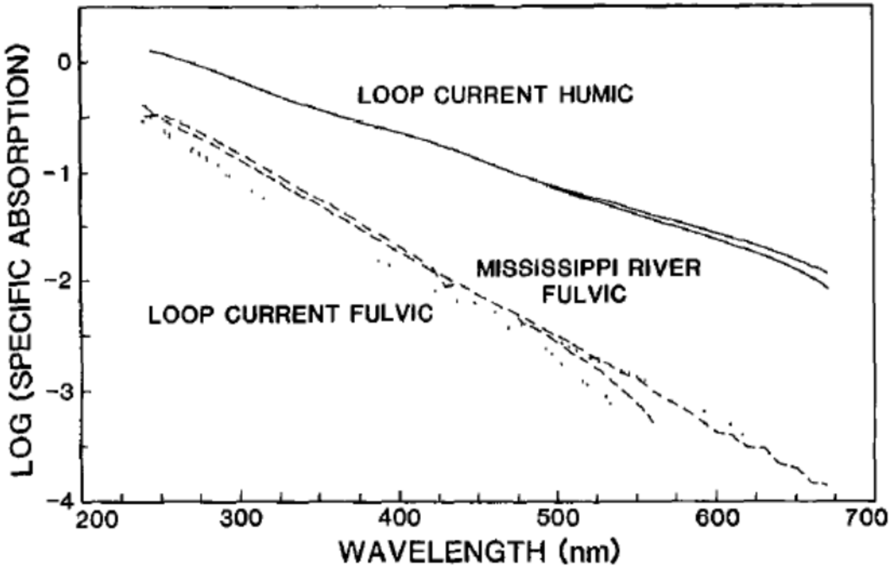
a_g spectrum



(Kirk 1994)

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

S_g: ~0.01 – 0.03 nm^{-1}



(Carder et al 1989)

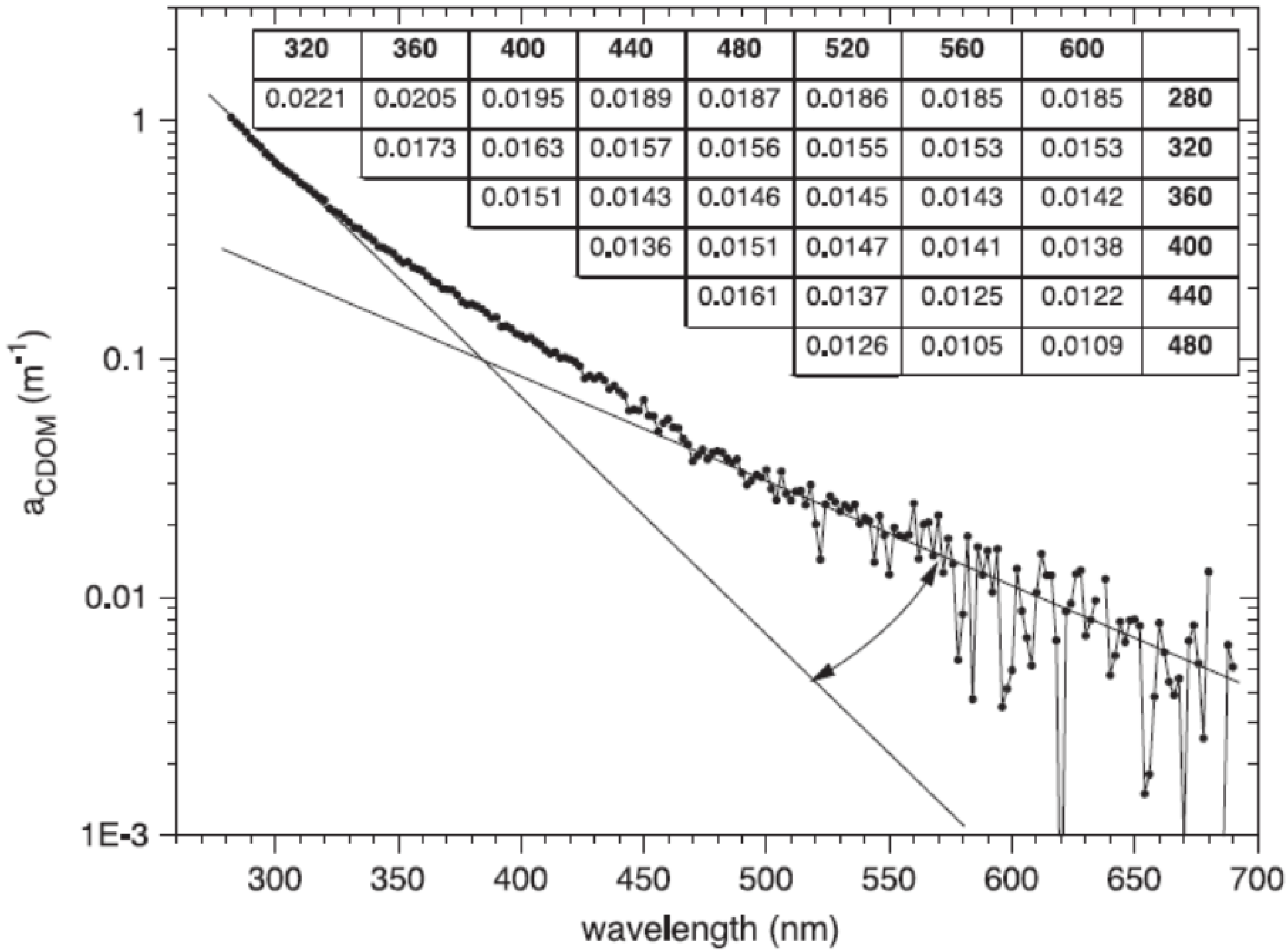
Table 1
Spectral slope values for marine samples reported in the literature with spectral range, CDOM absorption at 412 nm, and reported precision (ordered according to starting wavelength range)

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
Vodacek et al. (1997)	coastal Mid-Atlantic					
	Bight: non-Nov.	~ 40	0.018 average	[290–(440–550)][d]	[0.14–0.71]	0.092
	Nov.	~ 25	0.014 average	[290–(400–550)][d]	[0.14–0.63]	0.092
	offshore Mid-Atlantic Bight	~ 150	[0.010–0.034]	[290–(340–440)][d]	[0.009–0.14]	0.092
Del Castillo et al. (1999)	Gulf of Paria and	8	0.018 ± 0.002	[290–var][e]	[0.09–1.34]	0.046
	surrounding waters	8	0.017 ± 0.002	[290–var][d]	[0.09–1.34]	0.046
Zepp and Schlotzhauer (1981)	Gulf of Mexico, St. Marks, FL	1	0.0151	[300–500]	?	?
	'Marine aquatic humus'	3	0.0147	[300–500]	?	?
Davies-Colley (1992)	coastal N. Zealand	28	0.015 ± 0.002	[300–460]	[0.023–0.165]	0.017
	Doubtful Sound	6	0.014 ± 0.0004	[300–460]	[0.678–2.60]	0.017
Stedmon et al. (2000)	Danish fjords and nearby coastal waters	586	0.0194 ± 0.0032[f]	[300–650]	[0.14–3.46]	?
Stedmon and Markager (2001)	Greenland Sea, Nov 98	20	0.02016 ± 0.00252	[300–650]	[0.04–0.08]	0.05
	Greenland Sea, Jun 99	107	0.01651 ± 0.00352	[300–650]	[0.04–0.70]	0.05
	Greenland Sea, Aug 99	67	0.01622 ± 0.00297	[300–650]	[0.04–0.31]	0.05
Bricaud et al. (1981)	Mauritanian upwelling	24	0.015 ± 0.0023	350:10:500[g]	[0.03–0.12]	0.01
	Gulf of Guinea	35	0.014 ± 0.0041	350:25:500[g]	[0.04–0.17]	0.01
	Villefrance Bay	11	0.014 ± 0.0024	350:25:500[g]	[0.09–0.24]	0.01
	Var River	1	0.015	350:25:500[g]	0.21	0.01
	Baltic Sea	1	0.018	350:25:500[g]	2.18	0.01
	Gulf of Fos-sur-Mer	14	0.013 ± 0.0012	350:25:500[g]	[0.12–0.82]	0.01
Kowalczuk et al. (in press)	Baltic, open sea	754	0.019 ± 0.004	[350–var]	[0.18–1.46]	0.023/0.046
	Baltic, coastal	221	0.020 ± 0.003	[350–var]	[0.20–1.88]	0.023/0.046
	Pomeranian Bight	312	0.020 ± 0.004	[350–var]	[0.21–1.71]	0.023/0.046
	Bay of Gdansk	1292	0.019 ± 0.004	[350–var]	[0.20–3.52]	0.023/0.046
Schwarz et al. (2002)	Globally representative	877	0.01725 ± 0.0034	[350–var]	[~ 0.003–10.0]	0.046[h]
Carder et al. (1989)	Gulf of Mexico	11	[0.0115–0.0172]	[370–440]	[0.002–0.074]	~ 0.01
Kopelevich and Burenkov (1977)	Deep Indian and Pacific	2	0.017	390:20:490[g]	~ 0.06	?
Roesler et al. (1989)	San Juan Islands	21	0.017 ± 0.003	[400–750?]	0.32 average	?
Del Castillo et al. (1999)	Gulf of Paria and surrounding waters	8	0.015 ± 0.001	[400–500]	[0.09–1.34]	0.046
Maske et al. (1998)	Gulf of California	?	0.014	412,440,512	~ 0.095	0.002

(continued on next page)

(Twardowski et al 2004)

Slope changes with wavelength range



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

(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:

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

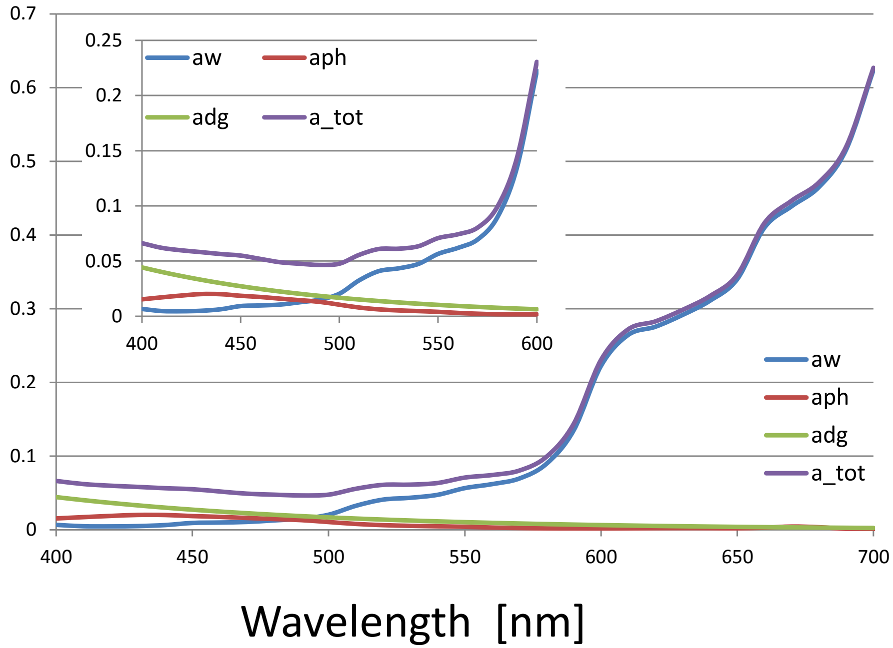
(Twardowski et al 2004)

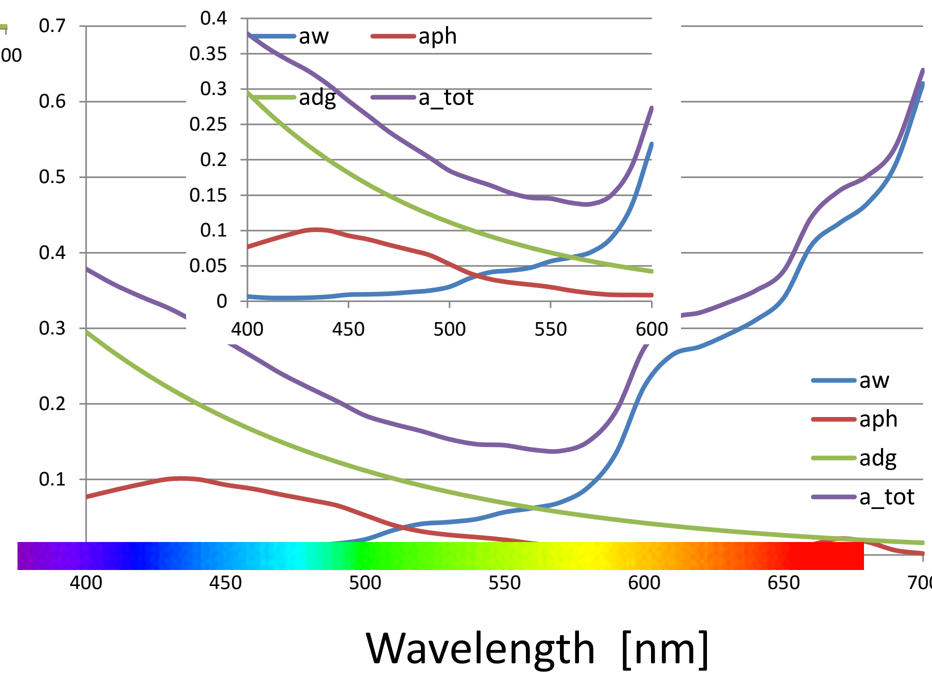
Values of a_{ph} and a_g of natural waters

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





2. Scattering properties

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

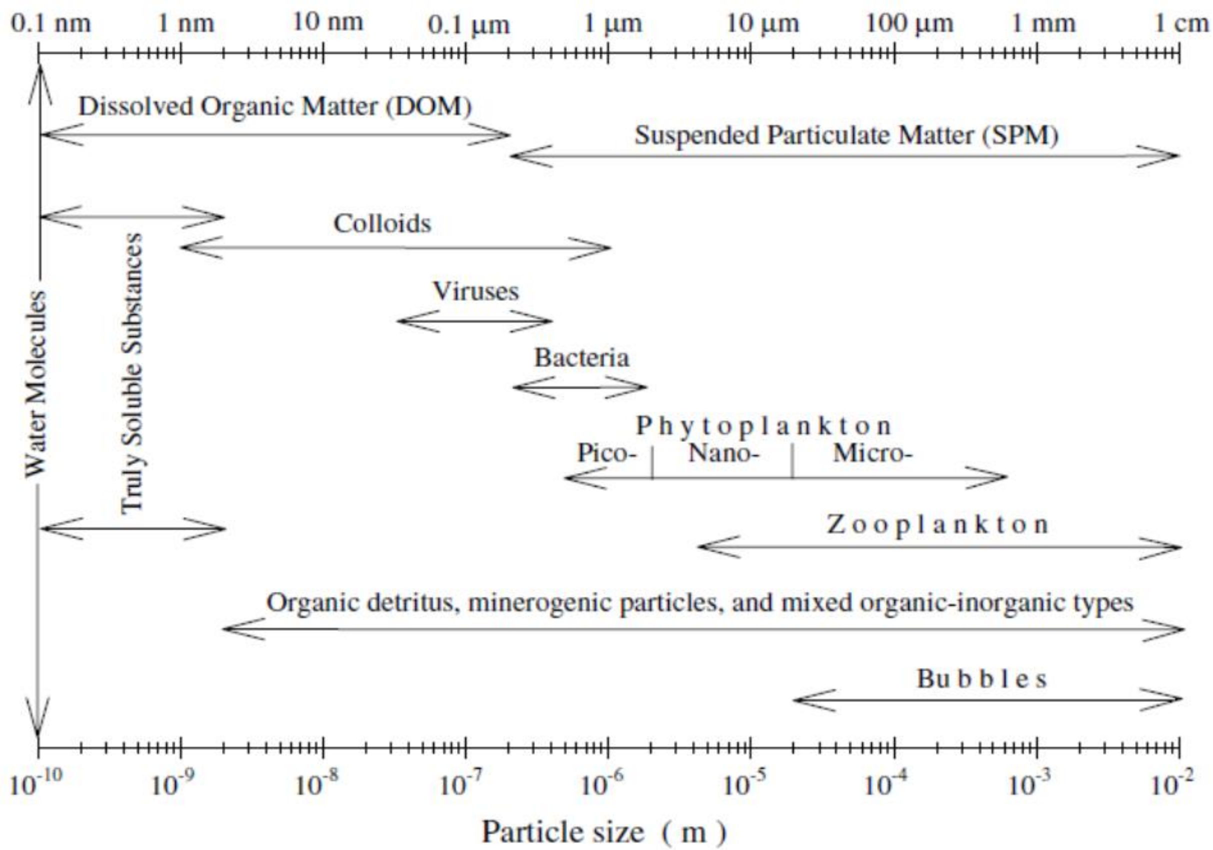
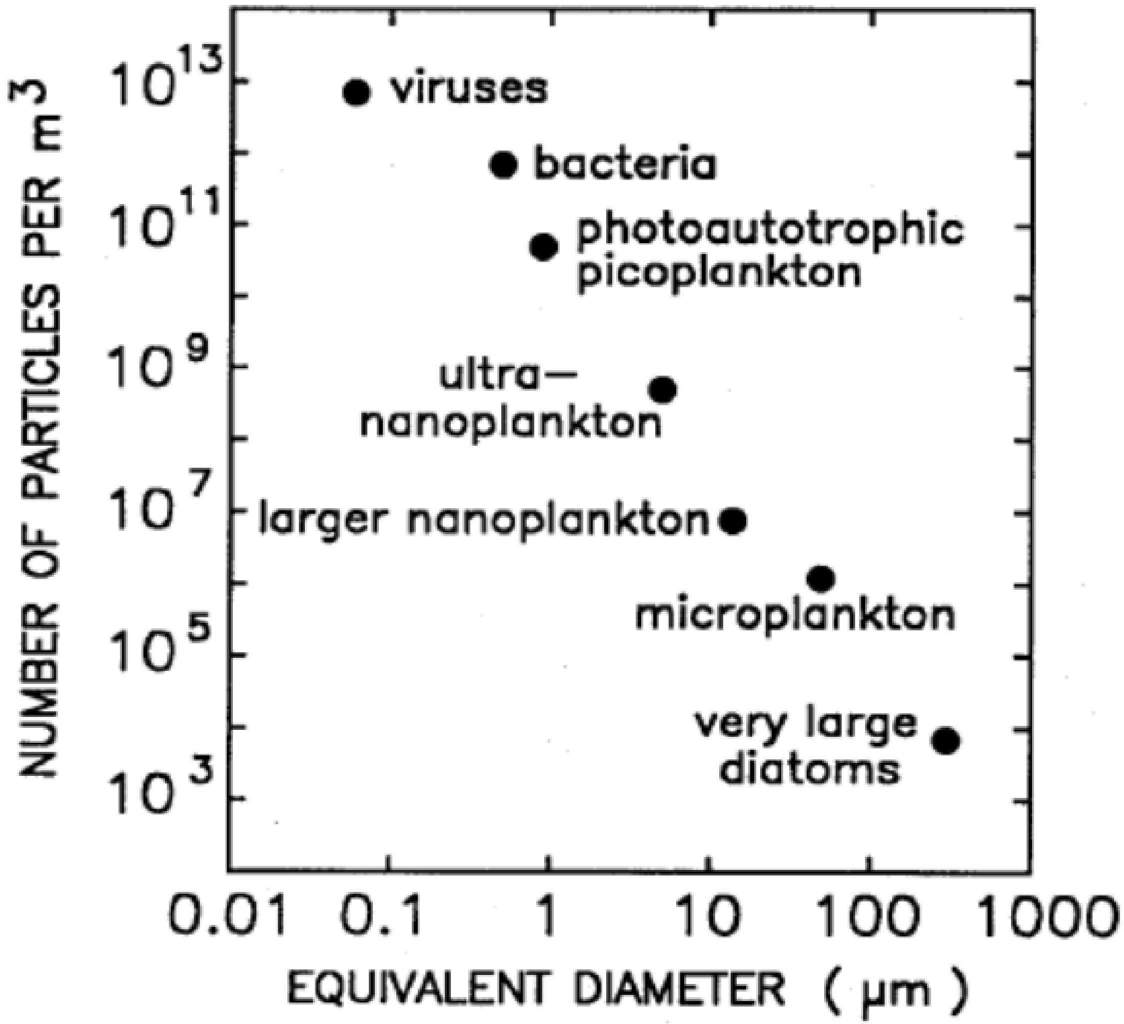


Fig. 1. Schematic diagram showing various seawater constituents in the broad size range from molecular size of the order of 10^{-10} m to large particles and bubbles of the order of 10^{-3}–10^{-2} m in size. The arrow ends generally indicate approximate rather than sharp boundaries for different constituent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

Size distribution



(Stramski and Kiefer 1991)

$$\boldsymbol{b} = \boldsymbol{b}_{\mathbf{w}} + \sum \boldsymbol{b}_{\mathbf{xi}} \qquad \boldsymbol{b}_{\boldsymbol{b}} = \boldsymbol{b}_{\mathbf{w}} + \sum \boldsymbol{b}_{\boldsymbol{b}\mathbf{xi}}$$

Very detailed:

$$\begin{aligned} b(\lambda) &= b_w(\lambda) + \sum_{i=1}^{18} b_{\mathrm{pla},i}(\lambda) + b_{\mathrm{det}}(\lambda) + b_{\mathrm{min}}(\lambda) + b_{\mathrm{bub}}(\lambda) \\ &= b_w(\lambda) + \sum_{i=1}^{18} N_{\mathrm{pla},i}\sigma_{b,\mathrm{pla},i}(\lambda) + N_{\mathrm{det}}\sigma_{b,\mathrm{det}}(\lambda) \\ &\quad + N_{\mathrm{min}}\sigma_{b,\mathrm{min}}(\lambda) + N_{\mathrm{bub}}\sigma_{b,\mathrm{bub}}(\lambda), \qquad (2) \end{aligned}$$

(Stramski et al 2001)

Commonly separated groups for scattering:

Molecules

Suspended ‘particles’

Bubbles

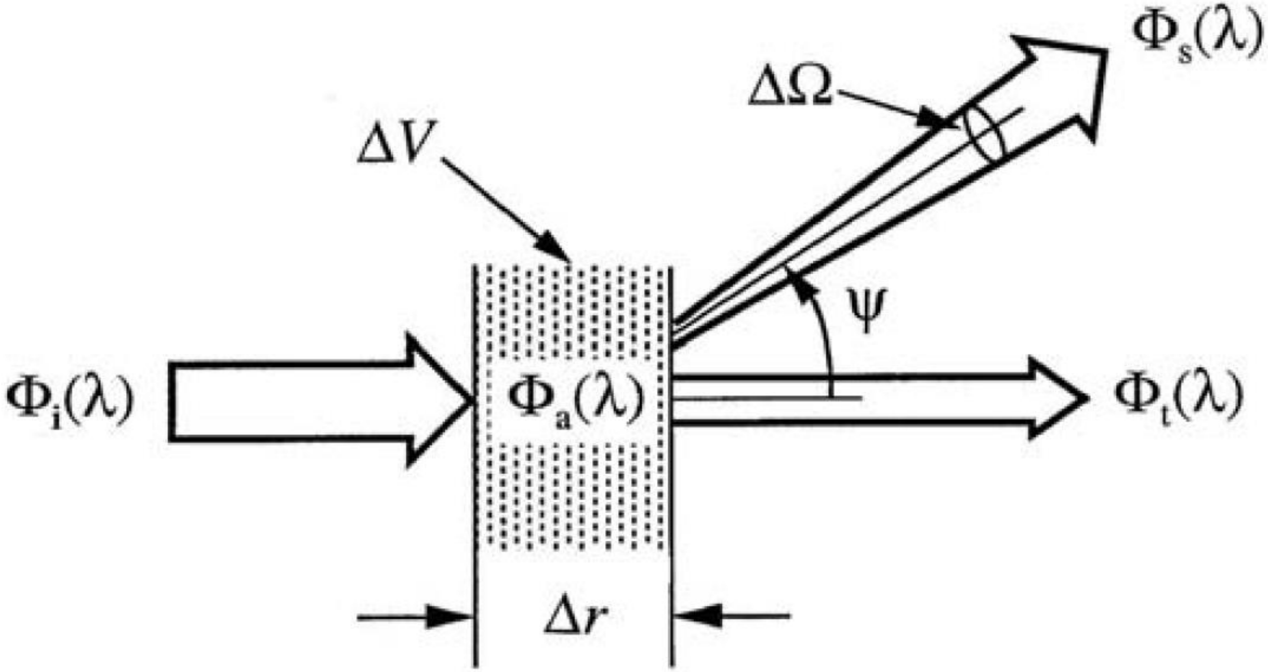
Turbulence

$$b = b_w + b_p$$

Or,

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

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



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

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

(Mobley 1994)

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

↓

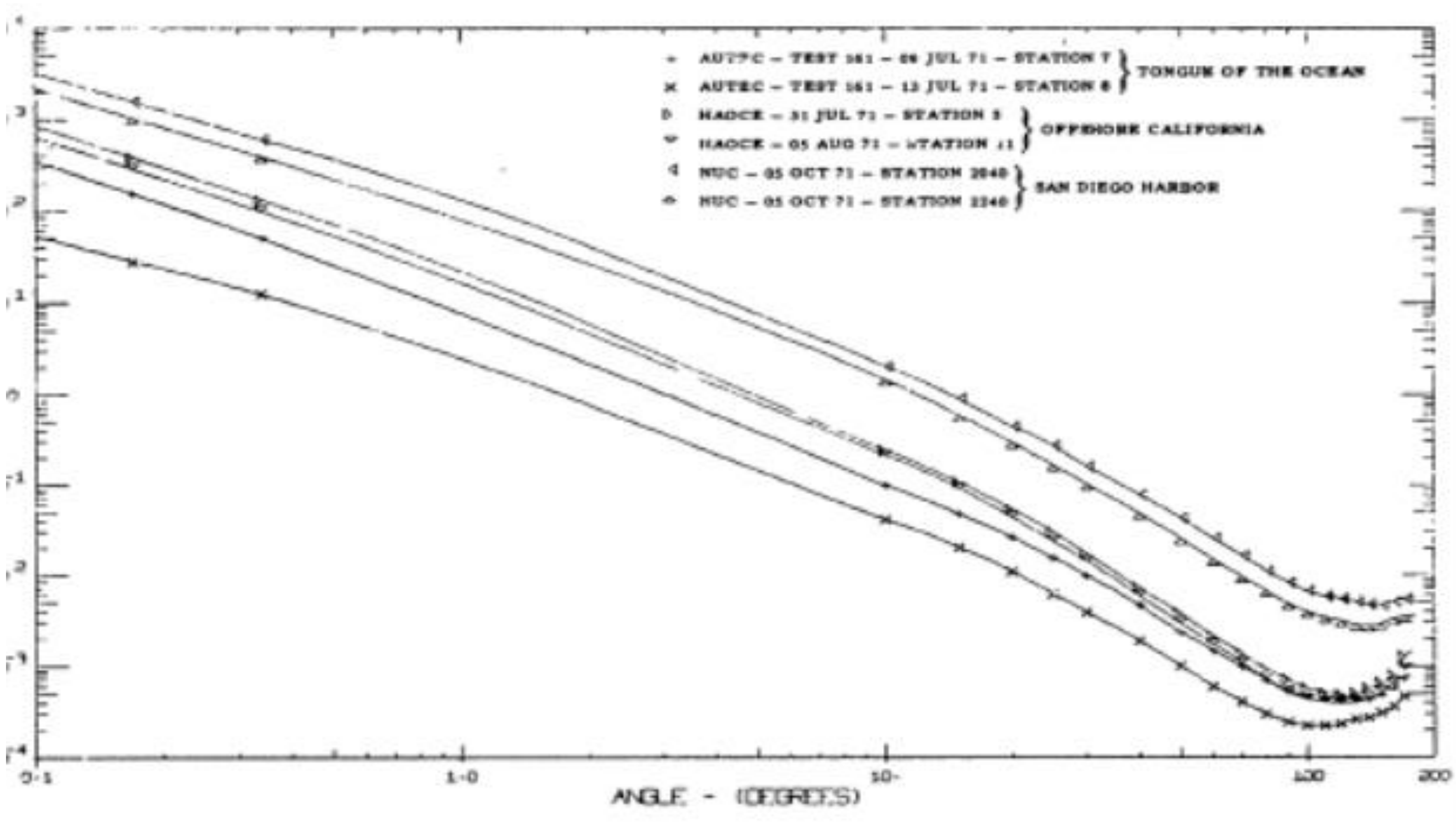
Scattering coefficient: b (m^{-1})

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

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

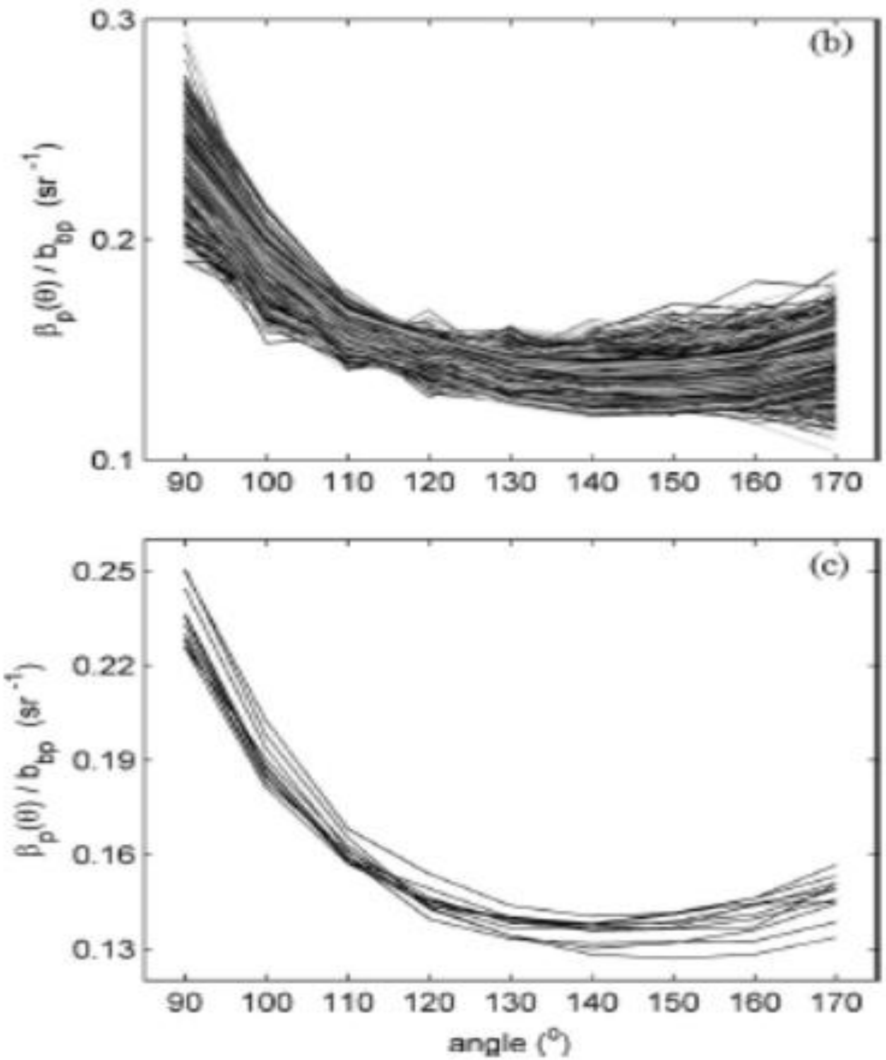
backward-scattering coefficient: b_b (m^{-1}) → $b_b = 2\pi \int_{\pi/2}^{\pi} \beta \sin(\theta)\, d\theta$

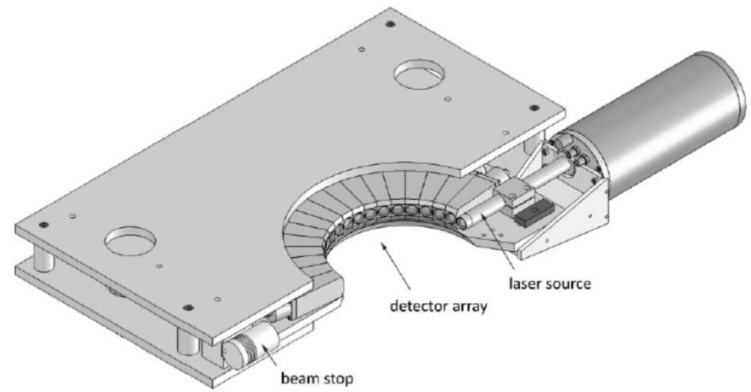
Volume Scattering Function with particles



(Petzold 1972)

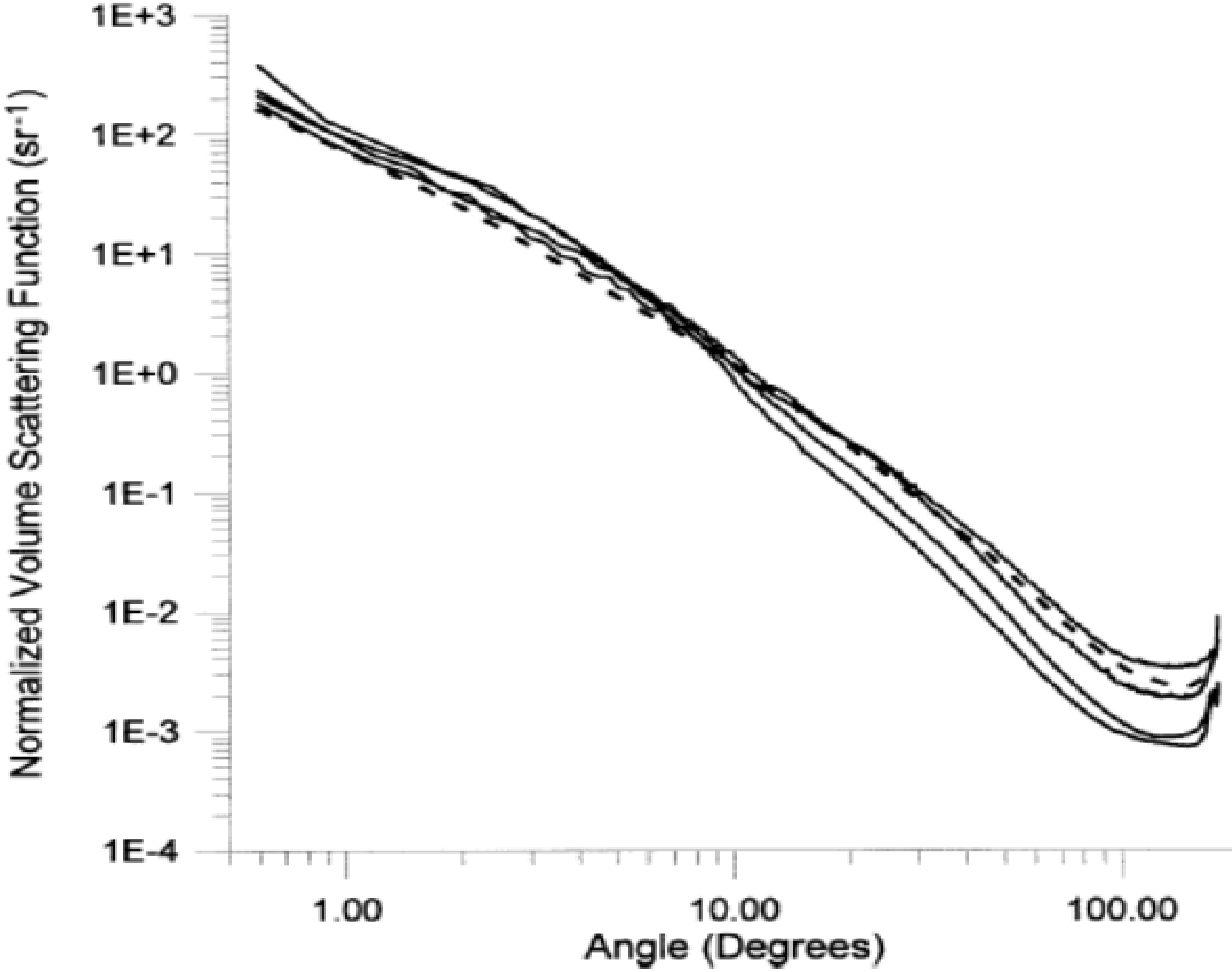
MASCOT measurements



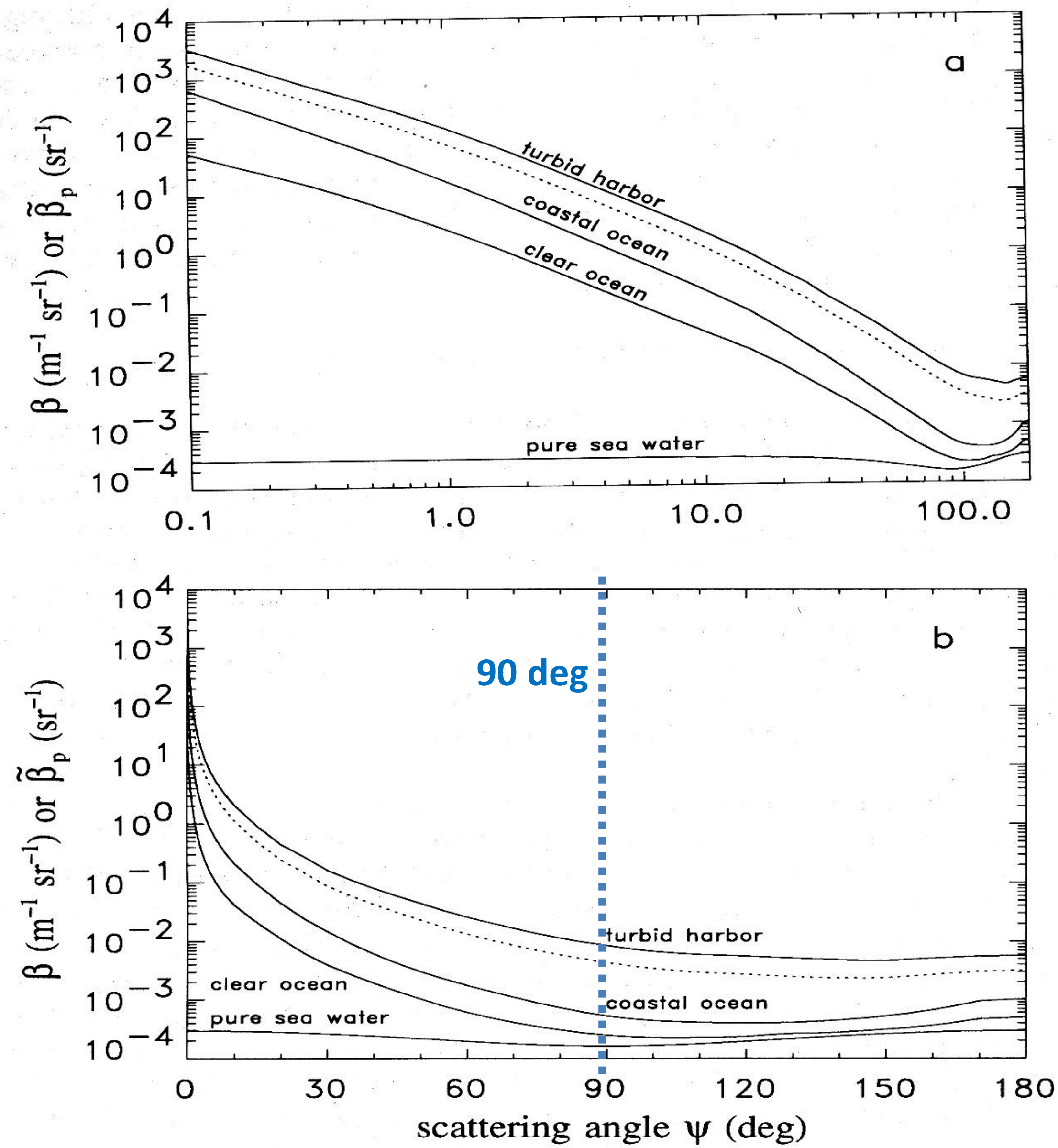


(Sullivan and Twardowski, 2009)

MVSM measurements



(Lee and Lewis, 2003)



(Mobley 1994)

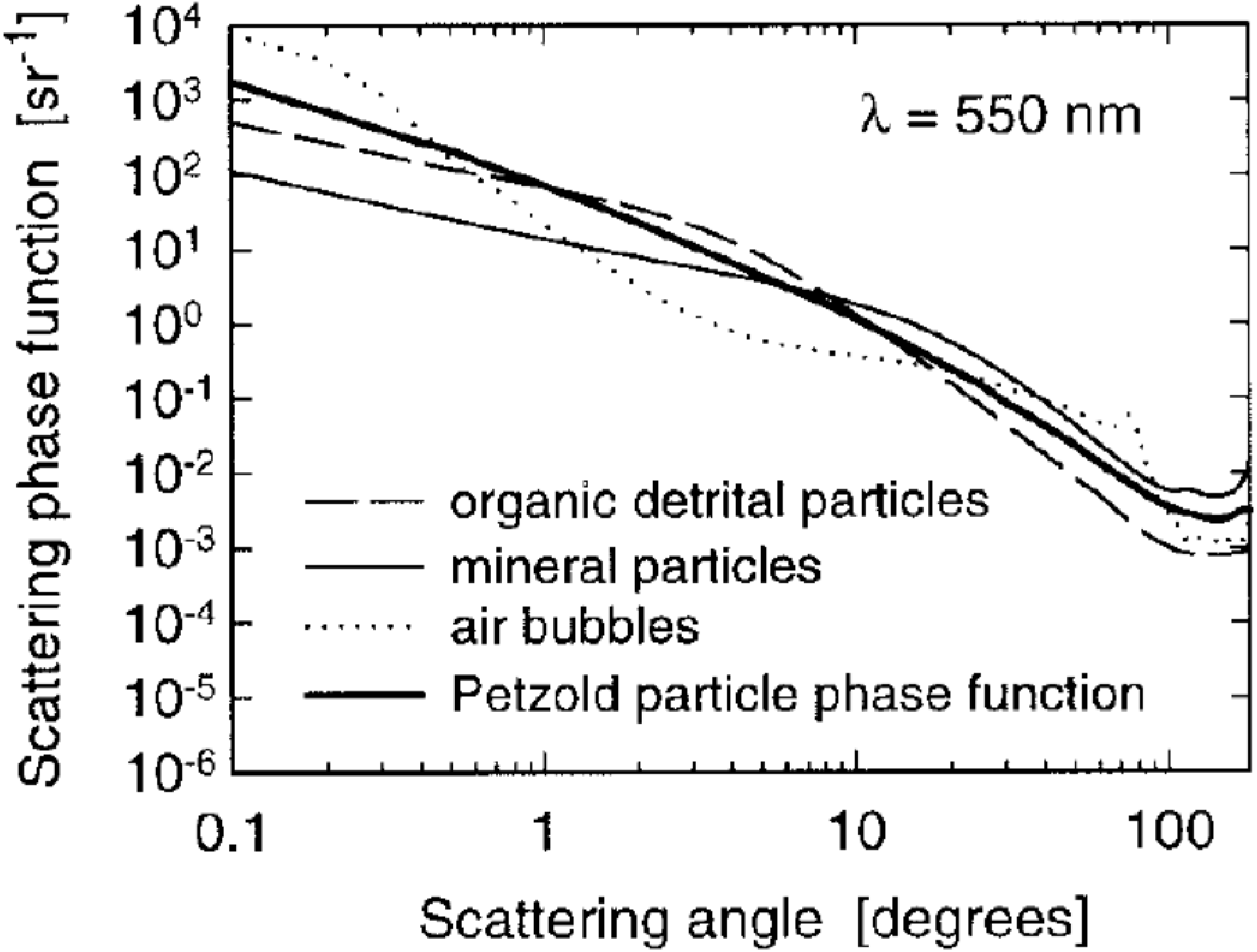
β shape changes in a narrow range in the backward domain

Particles are strongly forward scatters!

$$\tilde{b}_{bw} = 0.5;$$

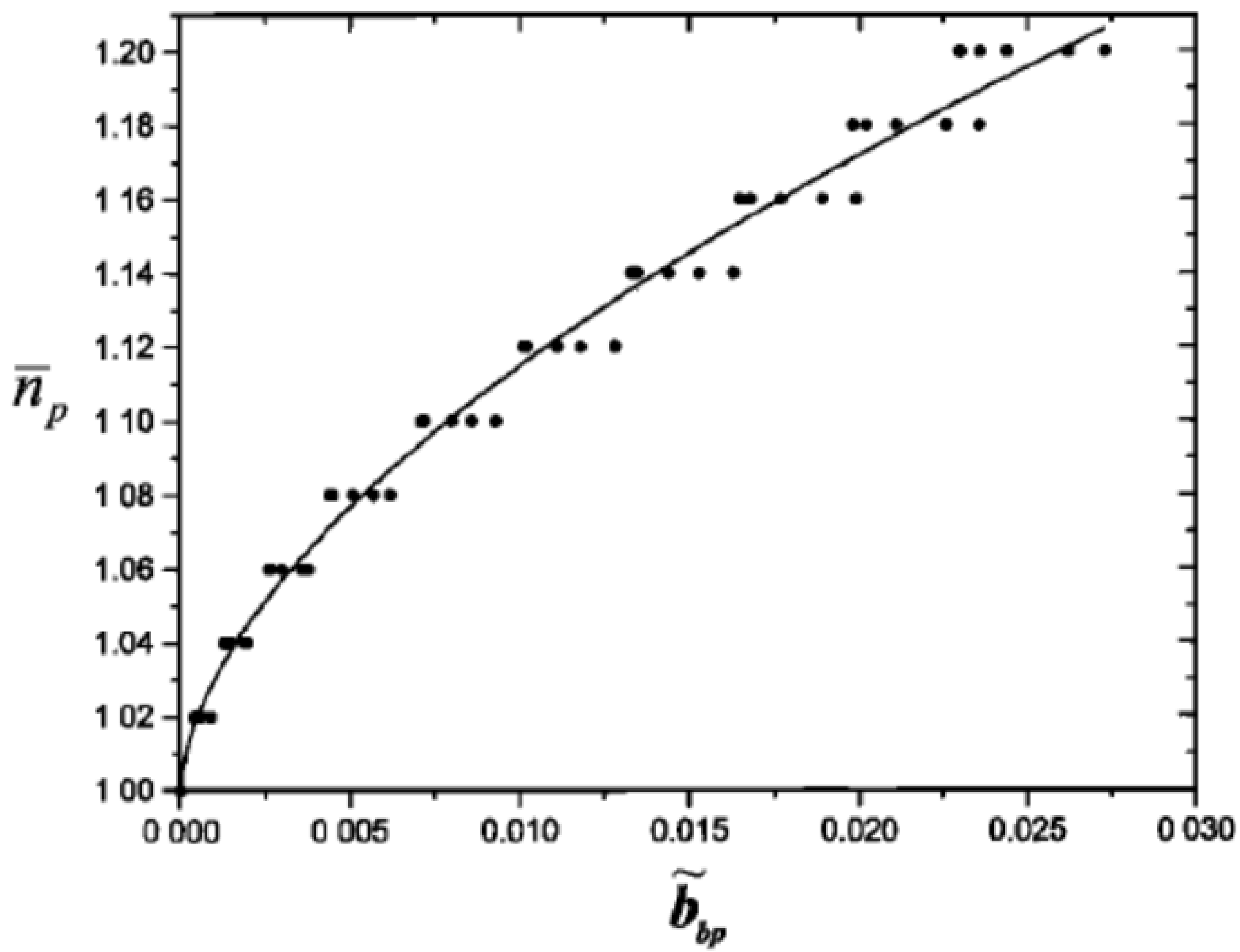
$$\tilde{b}_{bp} \sim 0.005 - 0.05$$

Backscattering ratio: $\tilde{b}_b = \dfrac{b_b}{b}$



(Stramski et al 2001)

$\tilde{b}_{bp}$ and refractive index

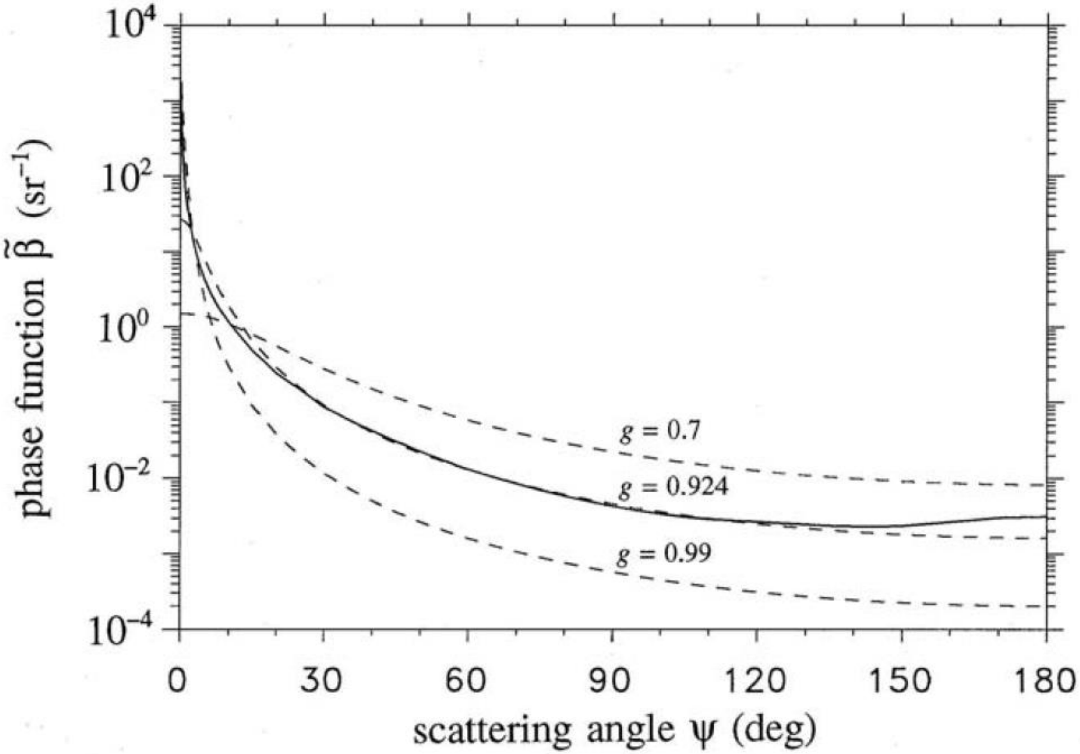


Twardowski et al (2001)

Mathematical models of VSF

Henyey-Greenstein (1941)

$$\beta = \frac{1}{4\pi}\frac{1-g^2}{(1+g^2-2g\cos\psi)^{1.5}}$$



(Mobley 1994)

Mathematical models of VSF

Beardsley and Zaneveld (1969)

$$\beta \sim \frac{1}{(1-\varepsilon_f \cos\psi)^4 (1+\varepsilon_b \cos\psi)^4}$$

Very good for large angles

Wells (1973)

$$\beta \sim \left[1+\left(\frac{\psi}{\psi_0}\right)^2\right]^{-3/2}$$

Very good for small angles

Fournier and Forand (1994)

$$\tilde{\beta}_{\mathrm{FF}}(\psi) = \frac{1}{4\pi(1-\delta)^2\delta^\nu}\left[\nu(1-\delta)-(1-\delta^\nu)+[\delta(1-\delta^\nu)-\nu(1-\delta)]\sin^{-2}\left(\frac{\psi}{2}\right)\right] + \frac{1-\delta_{180}^\nu}{16\pi(\delta_{180}-1)\delta_{180}^\nu}(3\cos^2\psi-1),$$

$$\nu = \frac{3-\mu}{2} \quad \text{and} \quad \delta = \frac{4}{3(n-1)^2}\sin^2\left(\frac{\psi}{2}\right).$$

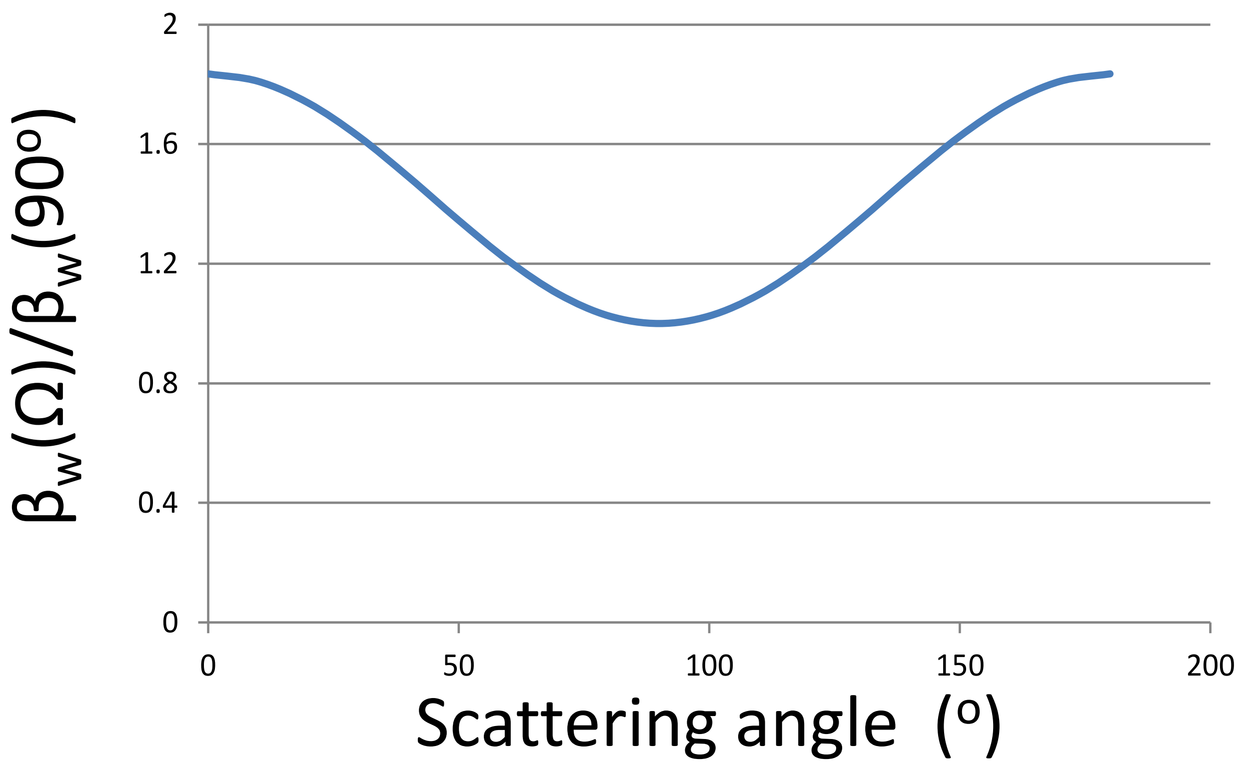
Mathematical models of VSF

Kopelevich (1983): combination of large and small particles

$$\beta_p(\psi,\lambda) = v_s \beta_s^*(\psi)\left(\frac{550}{\lambda}\right)^{1.7} + v_l \beta_l^*(\psi)\left(\frac{550}{\lambda}\right)^{0.3}$$

Scattering of water molecules

VSF of pure water (β_w)



$$b_w = 2\, b_{bw}$$

Spectral dependence

Morel 1974:

$$\beta_w = \beta_0 \left(\frac{450}{\lambda} \right)^{4.32}$$

Shifrin: 1988

$$\beta_w = \beta_0 \left(\frac{450}{\lambda} \right)^{4.17}$$

βw is also found salinity dependent; its value could be ~30% higher for marine waters.

Value and spectrum of seawater b_{bw}:

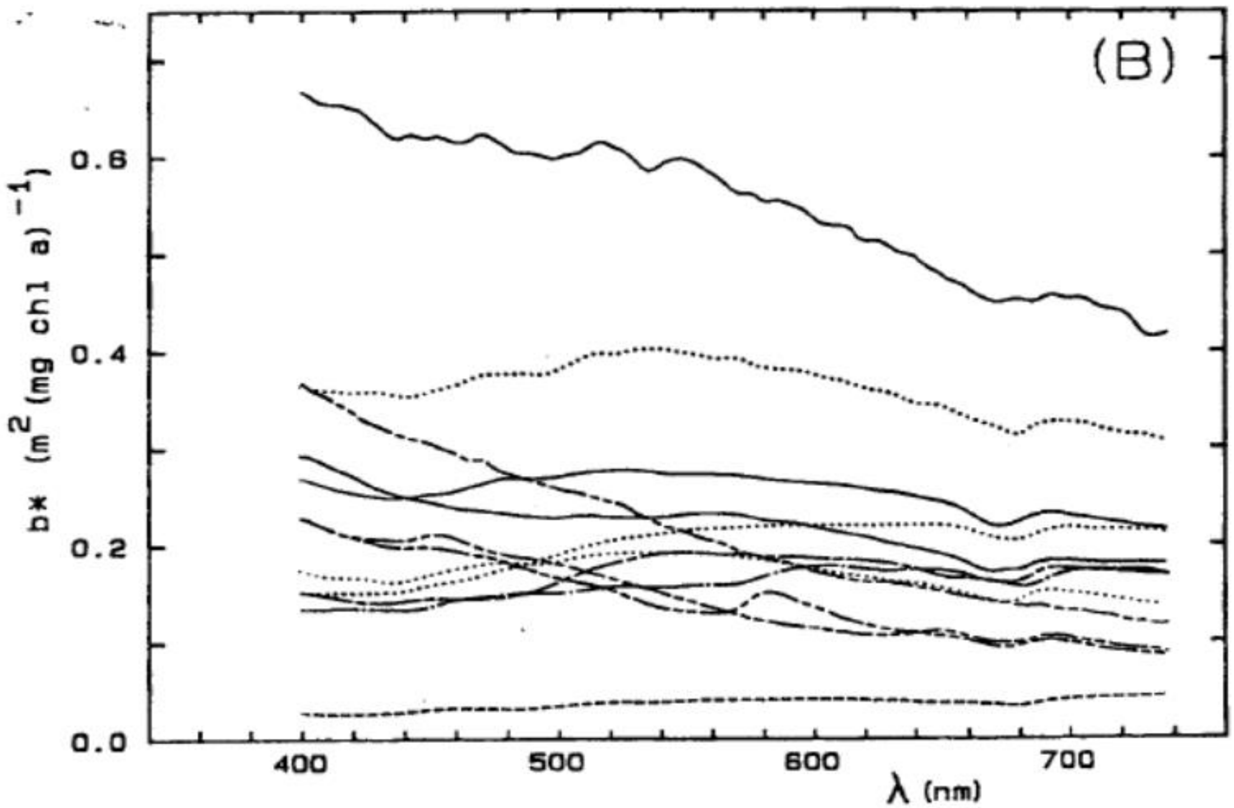
$$b_{bw}(\lambda) = 0.0023\left(\frac{450}{\lambda}\right)^{4.32}$$

(Morel 1974)

$$b_{bw}(\lambda) = 0.0020\left(\frac{450}{\lambda}\right)^{4.3}$$

(Zhang et al 2009)

Spectrum of scattering coefficient



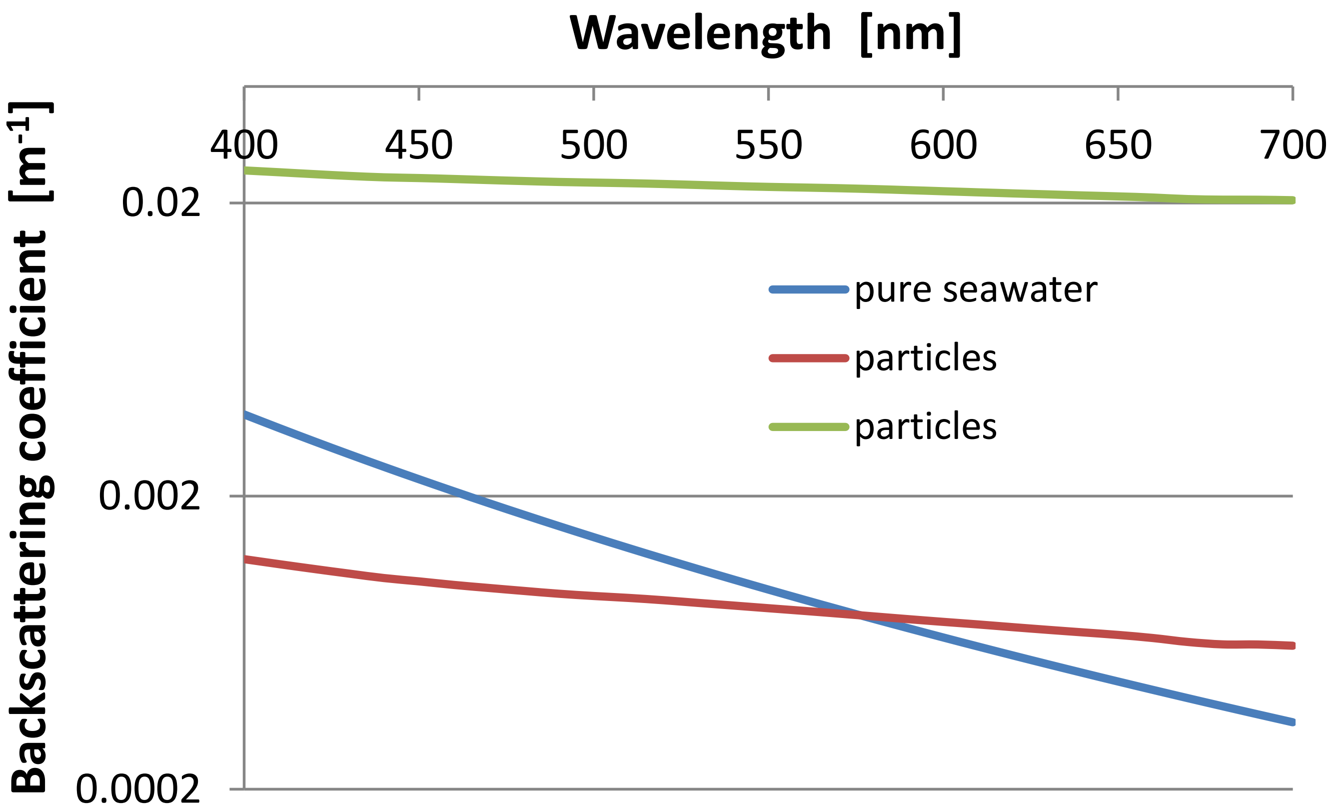
(Bricaud et al 1988)

weakly wavelength dependent

$$b(\lambda) = b(\lambda_r)\,\frac{-0.00113\lambda + 1.625}{-0.00113\lambda_r + 1.625}$$

(Gould et al 1999)

b_b spectrum contrast

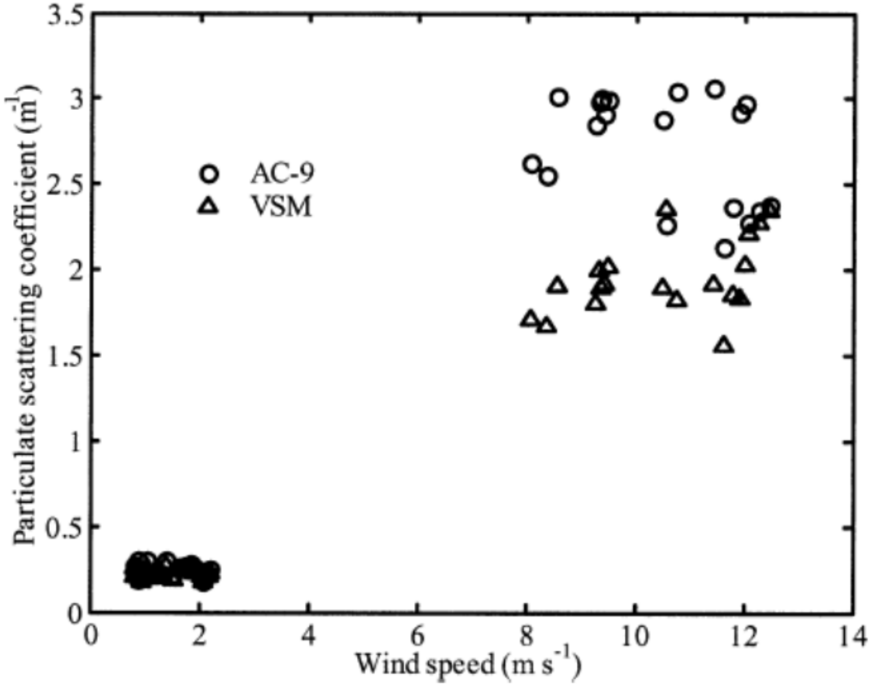


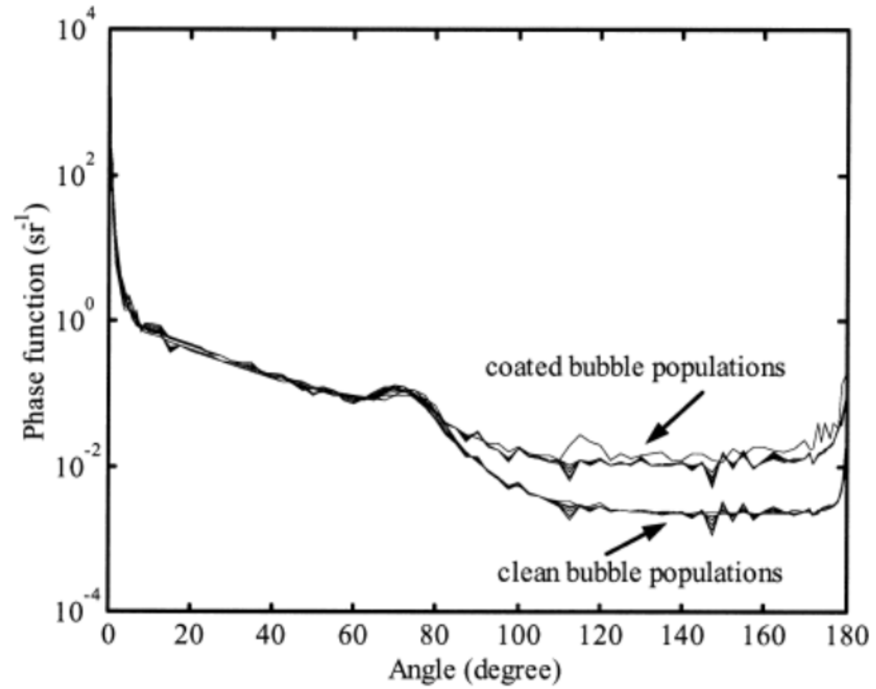
$$b_{bp}(\lambda) = b_0 \left(\frac{\lambda_0}{\lambda} \right)^{\eta}$$

b_{bw}: ~0.0001 – 0.004 m^{-1}

η: ~0-2.0

bubbles

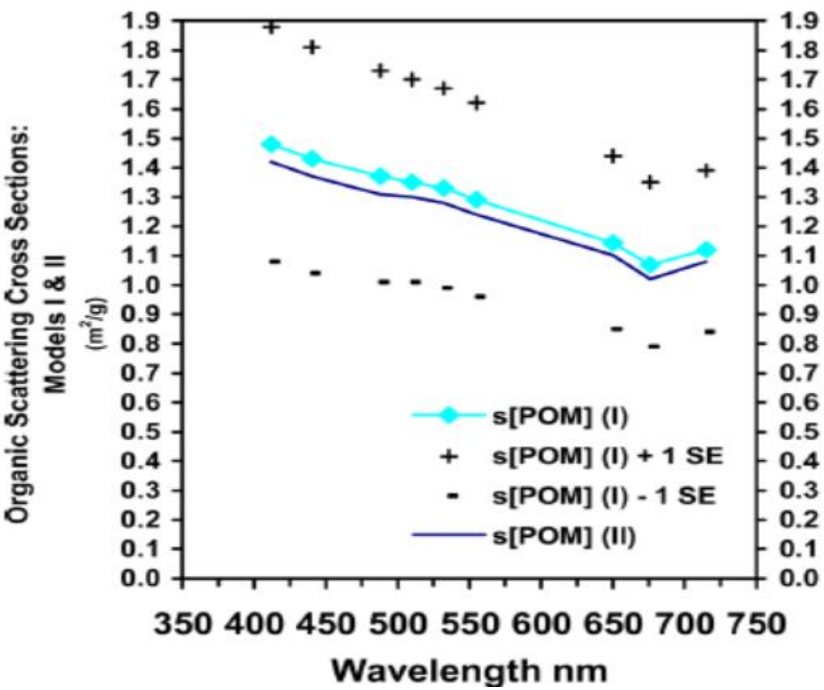


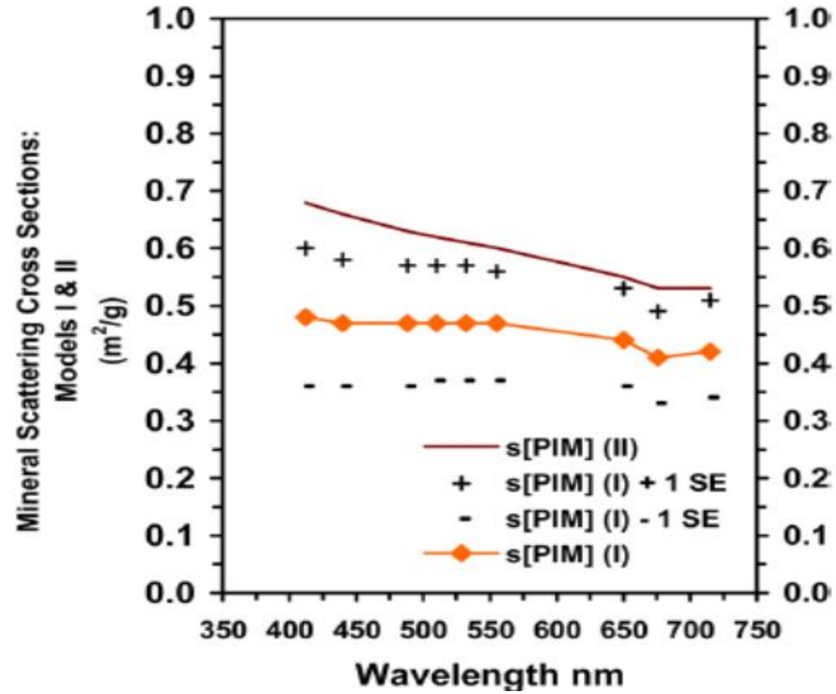


(Zhang et al 2002)

Not known the spectral characteristics of bubble scattering, considered spectrally flat

Organic vs inorganic separation





(Stavn and Richter 2008)

Light scattering by microorganisms in the open ocean

DARIUSZ STRAMSKI and DALE A. KIEFER

Department of Biological Sciences, University of Southern California, Los Angeles, California 90089-0371, U.S.A.

(Prog. Oceanog. 28, 343-383, 1991)

Oceanography

ELSEVIER

Progress in Oceanography 61 (2004) 27–56

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]

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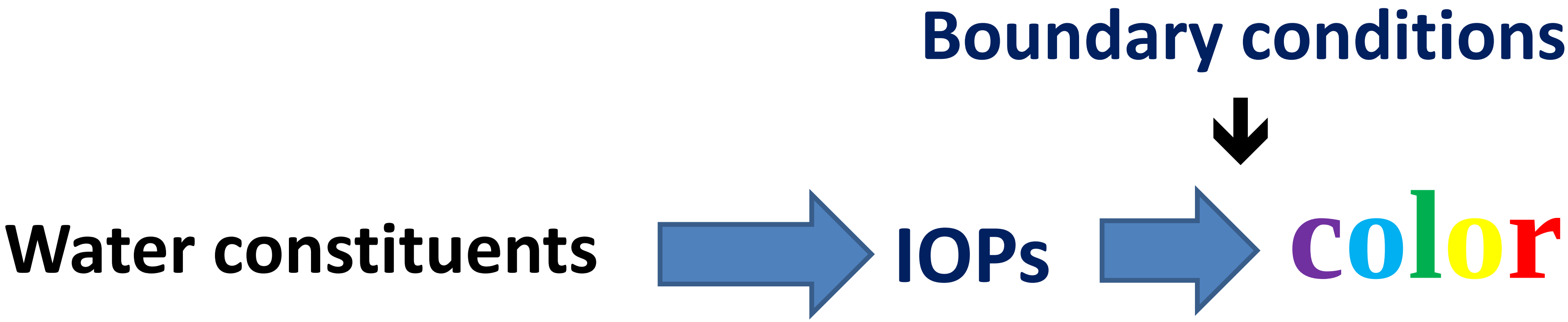
Received 3 November 2003; revised 4 July 2004; accepted 9 July 2004
Available online 19 August 2004



How marine constituents determine IOPs?

Optical Modeling of Spectral Backscattering and Remote Sensing Reflectance From *Emiliania huxleyi* Blooms

Griet Neukermans[1] and Georges Fournier[2]*

(2018, Frontiers in Marine Science)

Light scattering by marine algae: two-layer spherical and nonspherical models

Arturo Quirantes[a,*], Stewart Bernard[b]

(2004 J. QSRT)

Modeling the inherent optical properties of aquatic particles using an irregular hexahedral ensemble

Guanglang Xu[a,*], Bingqiang Sun[b], Sarah D. Brooks[a], Ping Yang[a,b], George W. Kattawar[b,c], Xiaodong Zhang[d]

(2017 J. QSRT)

Contrast between IOPs and AOPs

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

2. IOPs are additive; but not AOPs.

$$a = a_w + a_p + a_g$$

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

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

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

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.