近海海洋环境科学国家重点实验室（厦门大学）

State Key Laboratory of Marine Environmental Science
(Xiamen University)

Optical
Oceanography
Laboratory

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Inherent Optical Properties (IOPs)

Lecture 1: Basics

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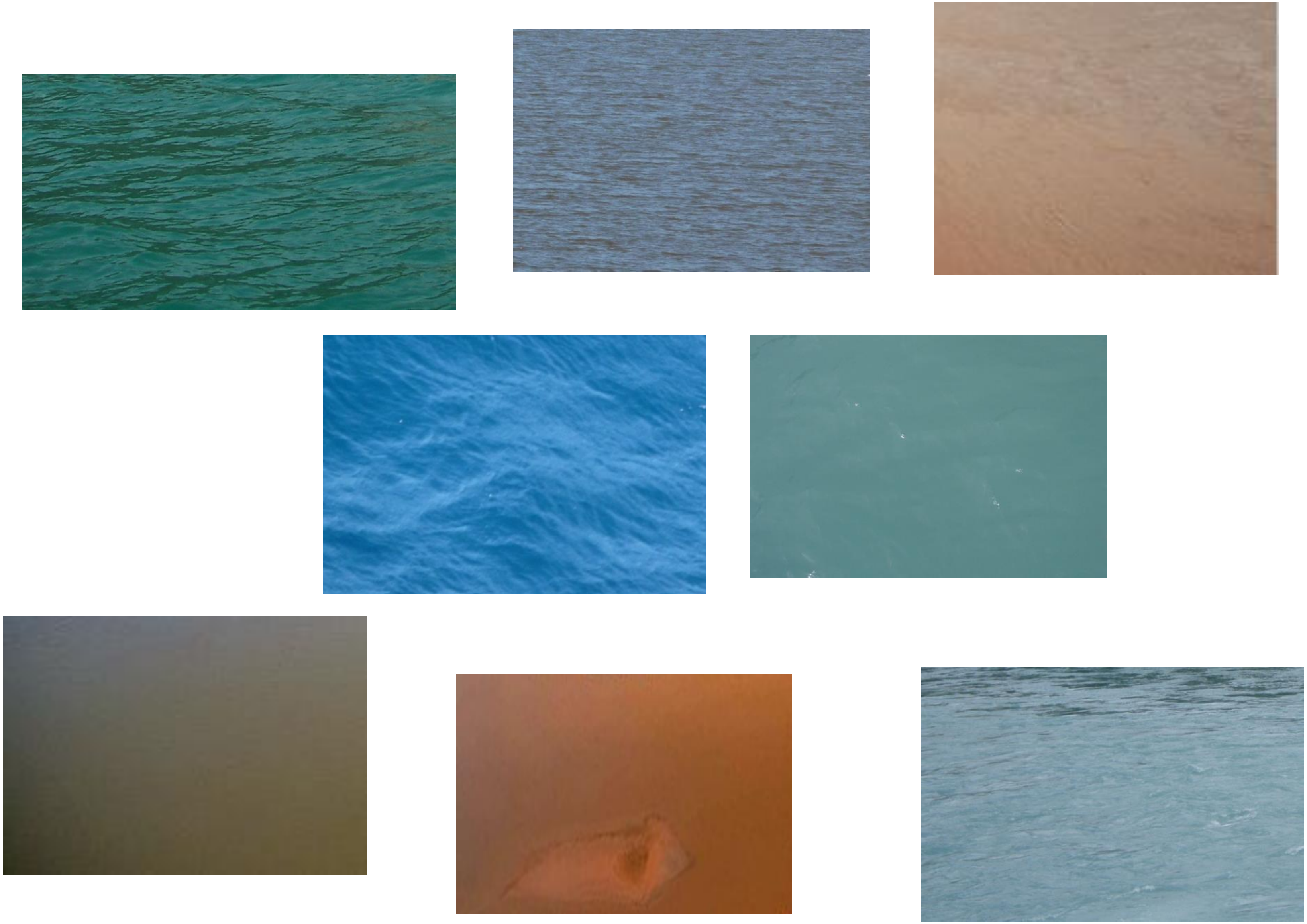
Research Interest:

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

Absorption properties

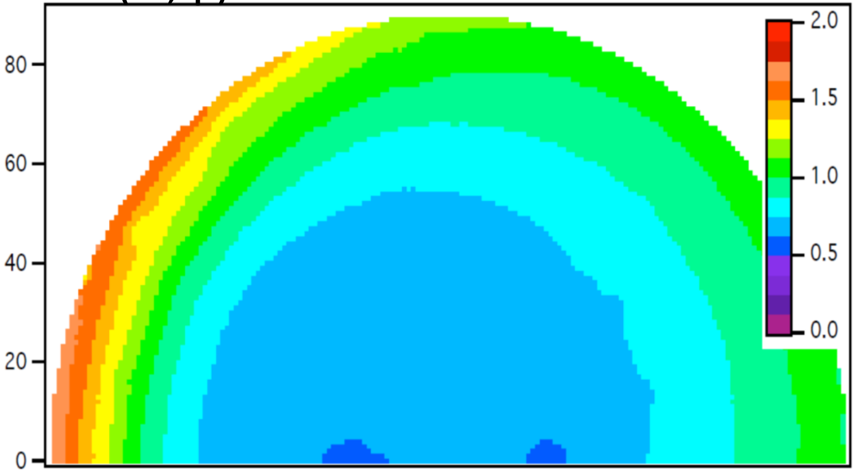
Scattering properties

ocean (water) color

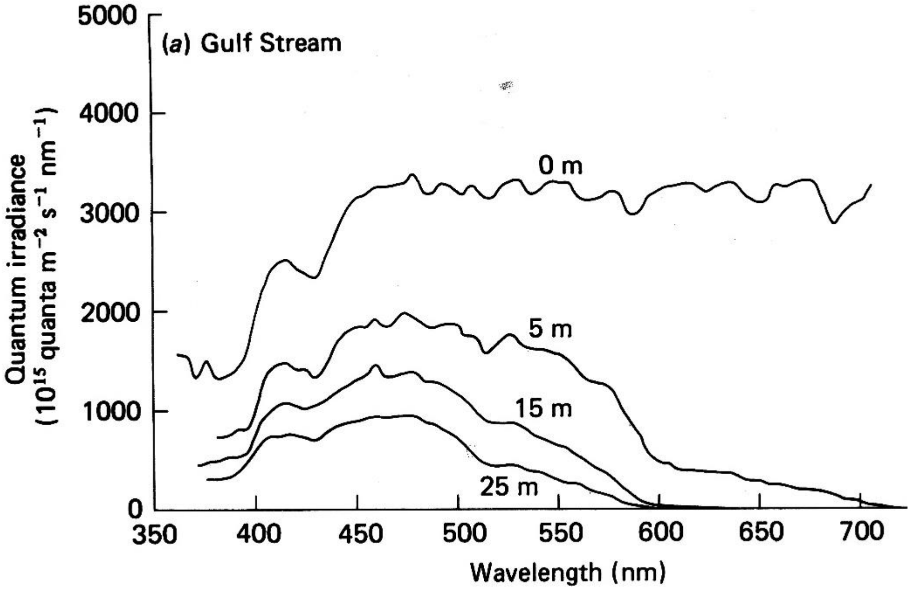


light within water medium

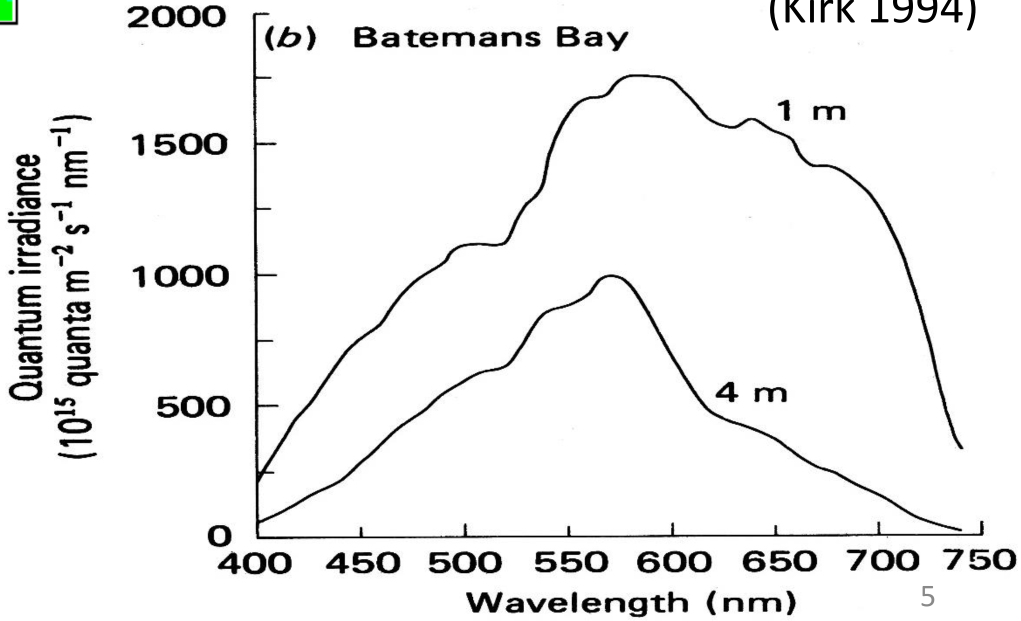
Lu(Θ,ϕ)



(Voss et al 2007)



(Kirk 1994)



They are modulated by inherent optical properties (IOPs)!

Boundary conditions

↓

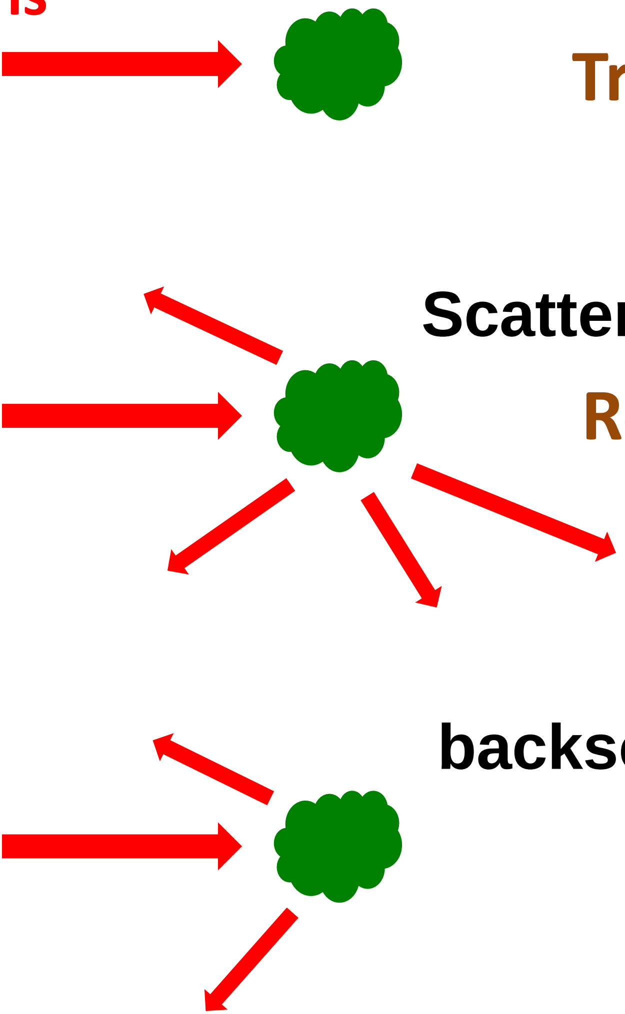
Water constituents → **IOPs** → **color**

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

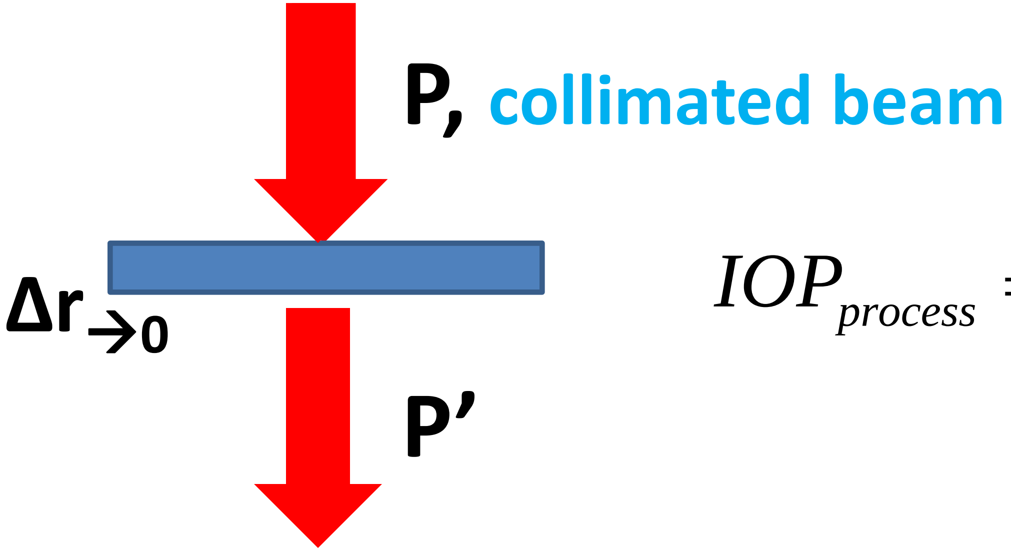
Scattering

Redistribution of energy

backscattering

Scattering has angular dependence

Definition of absorption and scattering **coefficients**



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

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

Units: Δr: infinitesimal (m)

a&b: m^{-1}

$a = 0.4\ \mathrm{m}^{-1}$

$b = 1.5\ \mathrm{m}^{-1}$

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

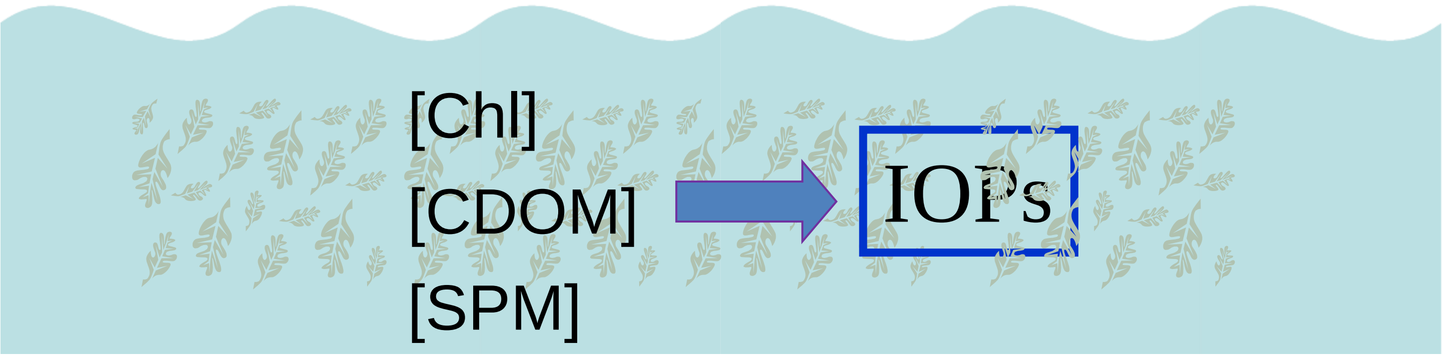
Volume Scattering Function (VSF): β ($m^{-1}\ sr^{-1}$)
(elastic)

↓

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})

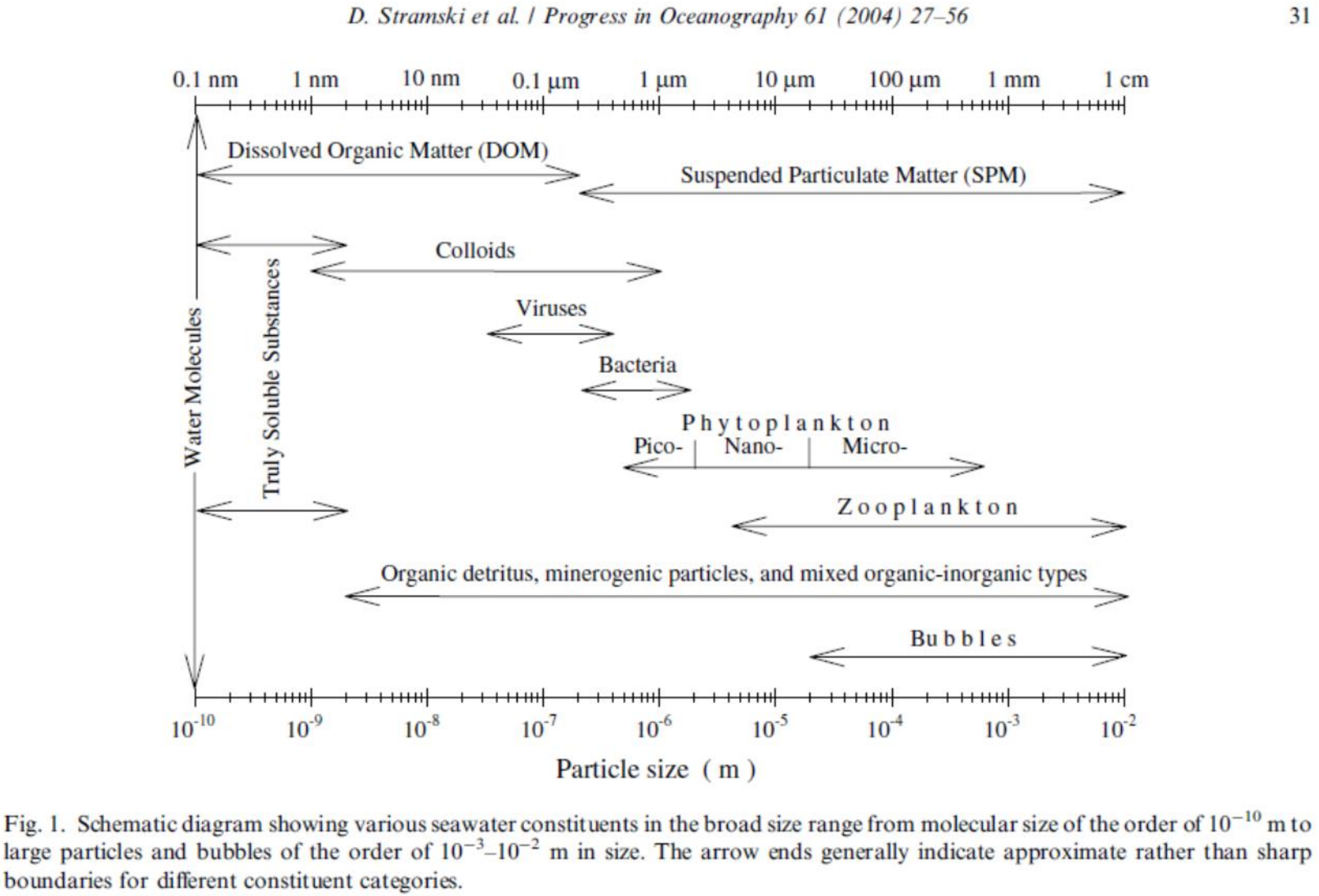


[Chl]
[CDOM]
[SPM]
→ IOPs

IOPs are additive

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

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



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.

1. absorption properties

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

Very detailed:

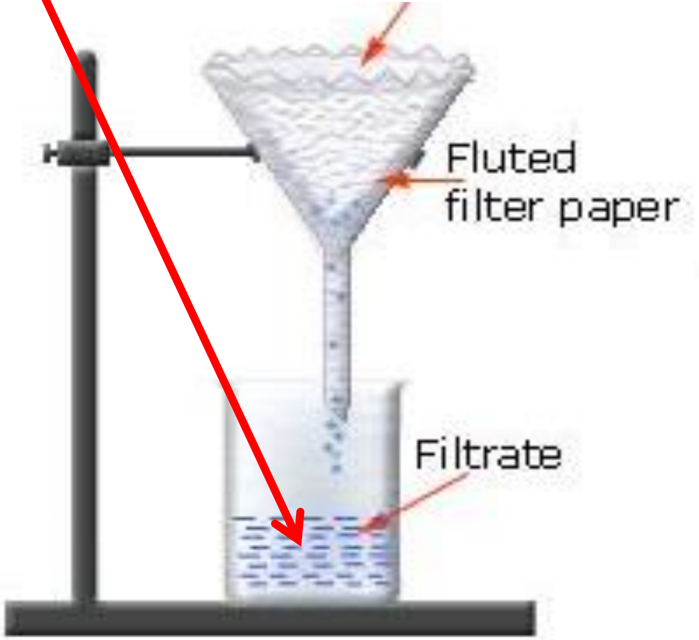
$$\begin{aligned} a(\lambda) &= a_w(\lambda) + \sum_{i=1}^{18} a_{\text{pla},i}(\lambda + a_{\text{det}}(\lambda) + a_{\text{min}}(\lambda) + a_{\text{CDOM}}(\lambda) \\ &= a_w(\lambda) + \sum_{i=1}^{18} N_{\text{pla},i}\sigma_{a,\text{pla},i}(\lambda) + N_{\text{det}}\sigma_{a,\text{det}}(\lambda) \\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

(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

Values of a_w?

130+ years of search for a_w

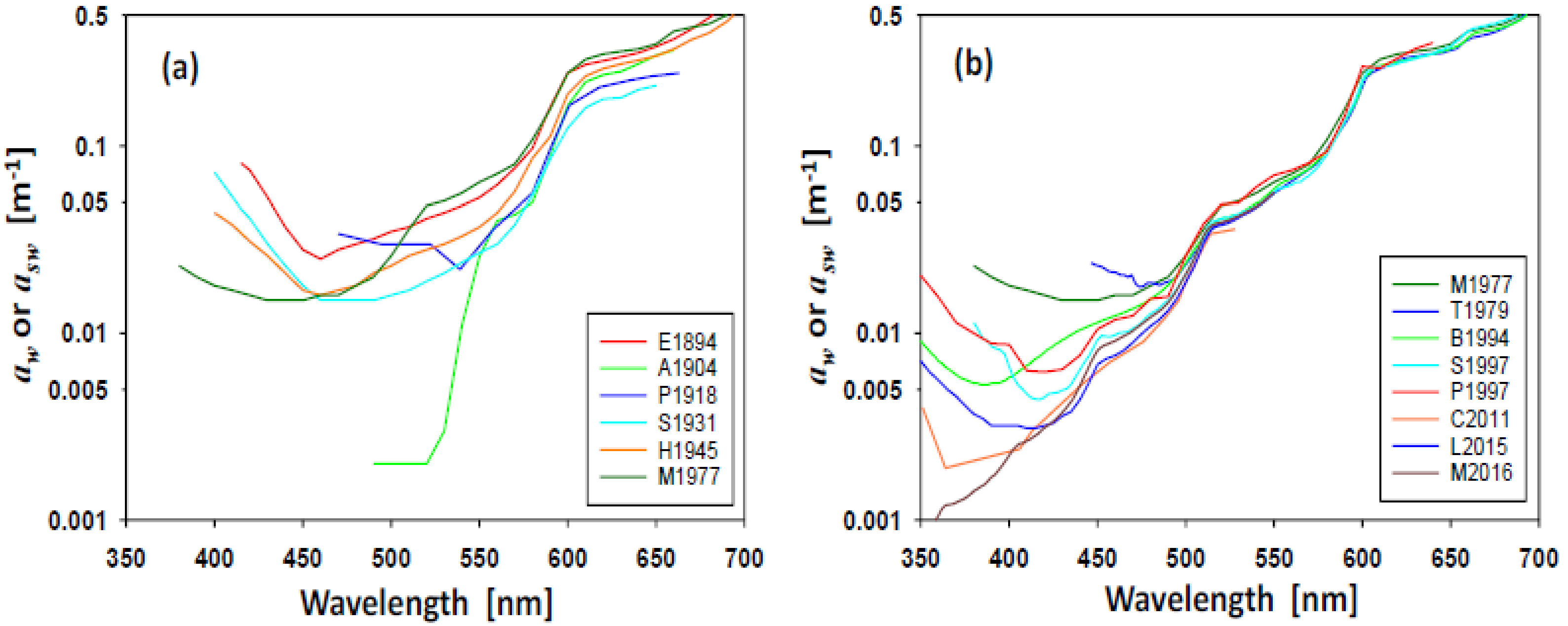
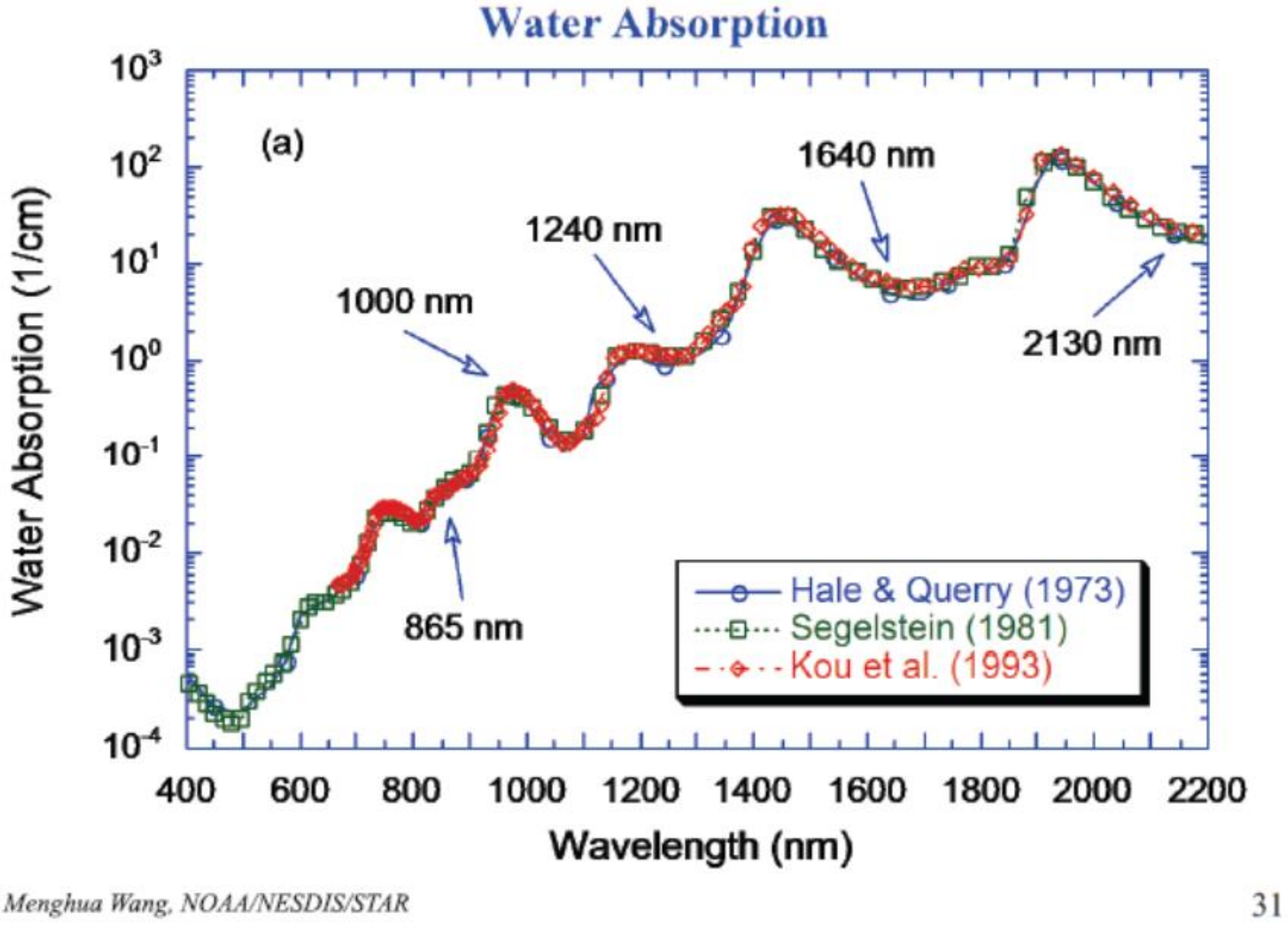


Fig. 1. Examples of historical measurements or determinations of a_w or a_{sw}. (a) Older data, (b) later data. The values of Morel and Prieur (1977) are included in both (a) and (b) for reference. E1894: Ewan (1894); A1904: Aufsess (1904); P1918: Pietenpol (1918); S1931: Sawyer (1931); H1945: Hulburt (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)

a_w spectrum


Water Absorption
(a)
1000 nm
1240 nm
1640 nm
2130 nm
865 nm
Water Absorption (1/cm)
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
400
600
800
1000
1200
1400
1600
1800
2000
2200
Wavelength (nm)
Hale & Querry (1973)
Segelstein (1981)
Kou et al. (1993)
Menghua Wang, NOAA/NESDIS/STAR
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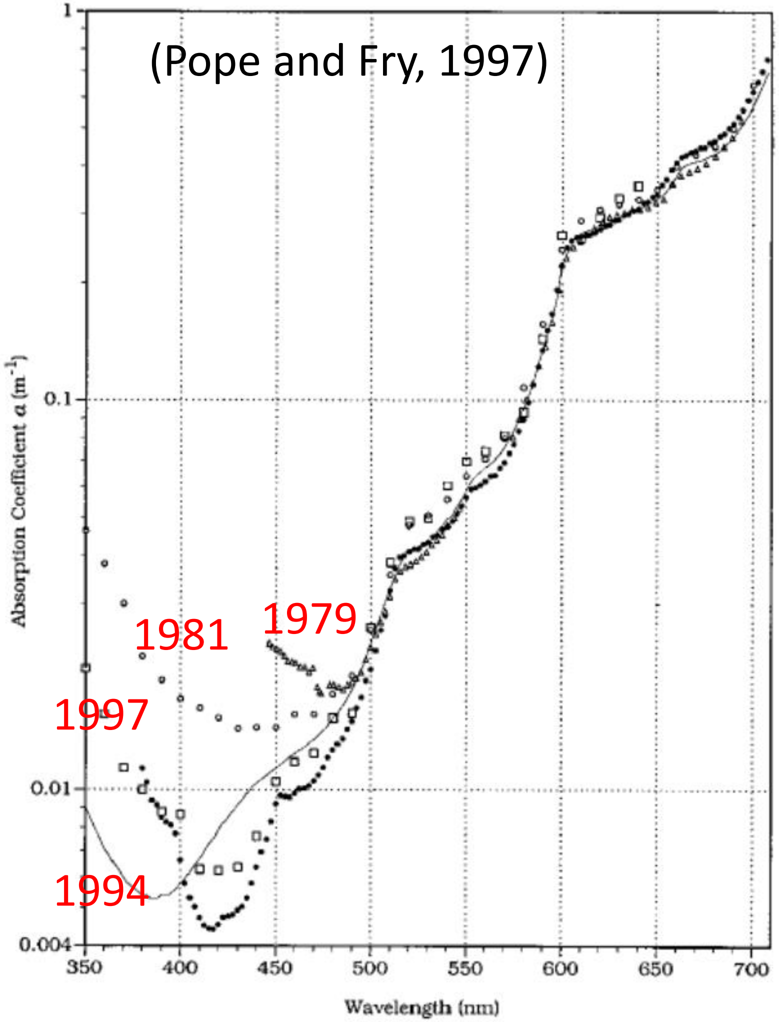
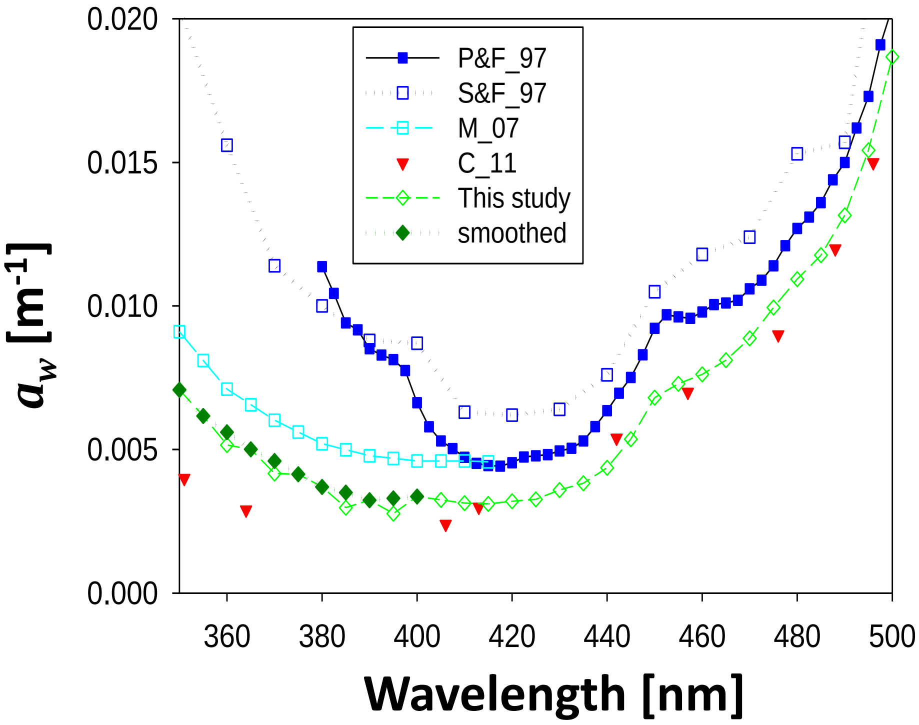
Uncertainties of a_w in the UV-blue

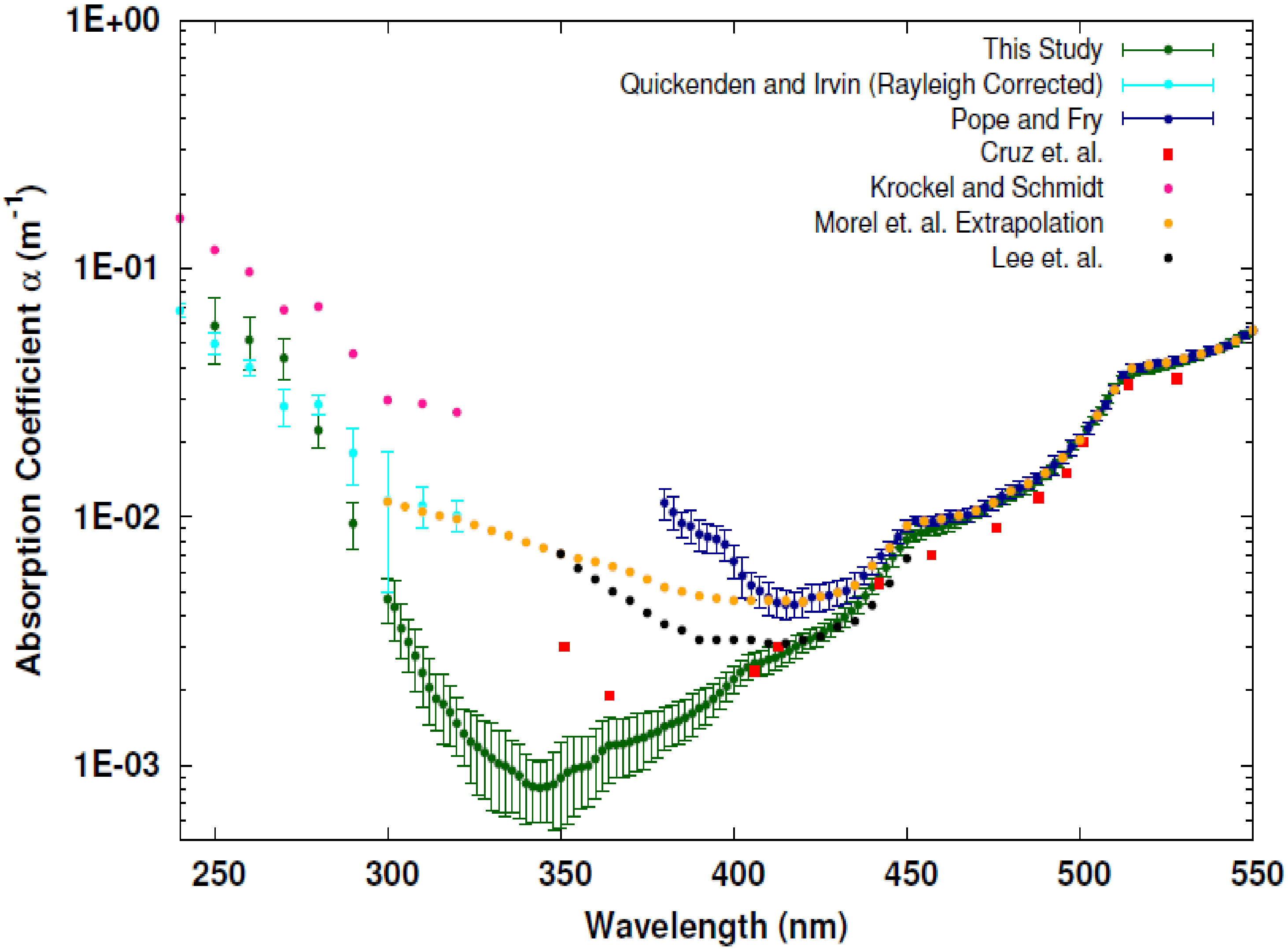


(Pope and Fry, 1997)

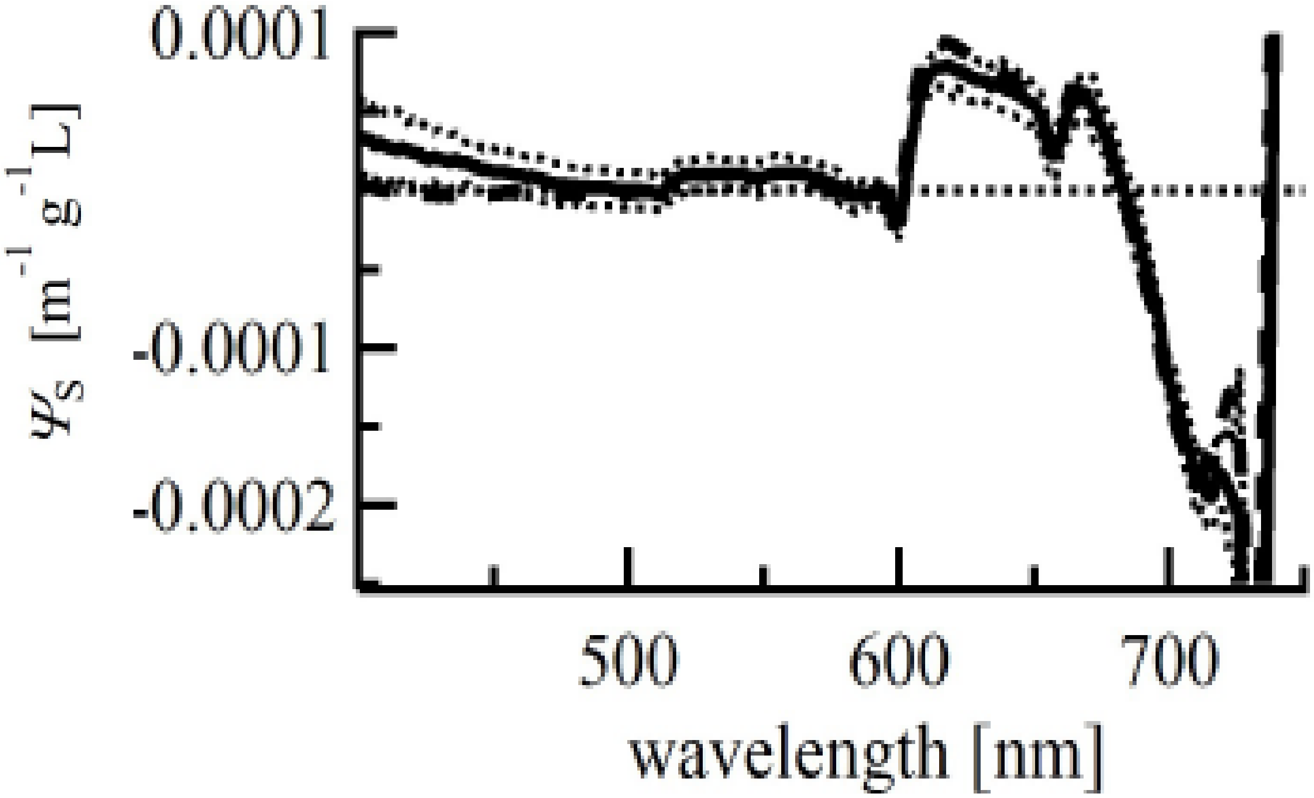
Fig. 10. Present results (●) for the absorption of pure water plotted with those from Buiteveld *et al.*[2] (smooth curve), Tam and Patel[4] (△), Smith and Baker[6] (○), and Sogandares and Fry[3] (□).



(Lee et al 2015)

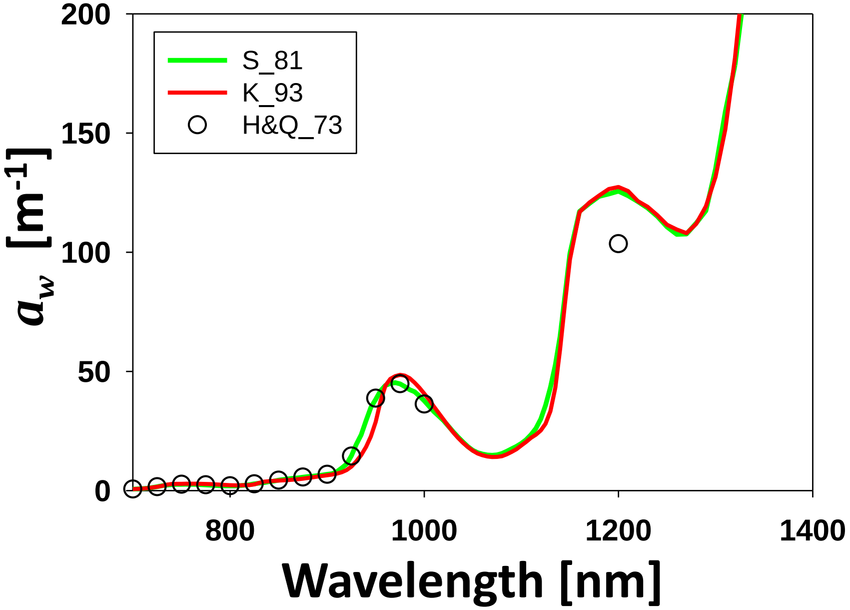


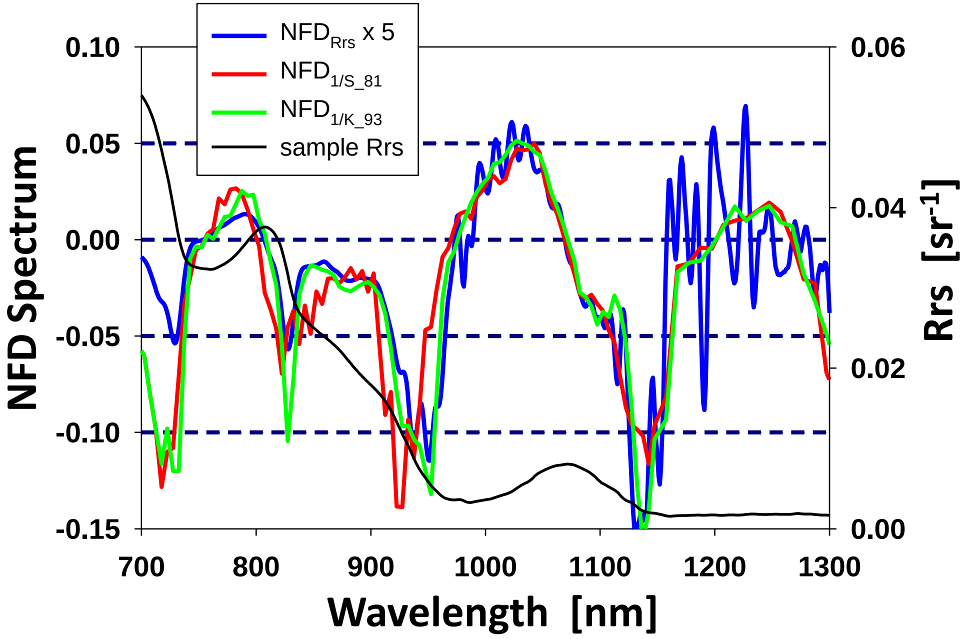
(Mason et al, 2016)



(Rottgers et al. 2014)

In the NIR-SWIR range …





(Lee et al 2016)

H&Q_73: Hale and Querry 1973

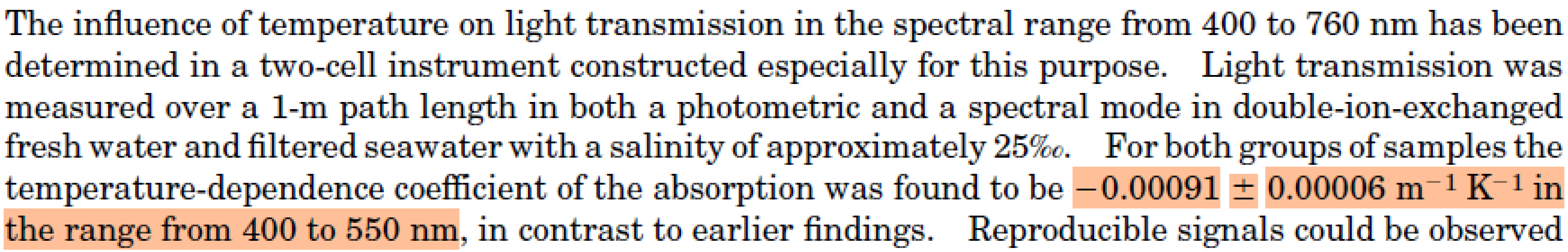
S_81: Segelstein 1981

K_93: Kou et al 1993 √

$a_{\mathrm{w,sw}}$ 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 $-0.00091 \pm 0.00006\ \mathrm{m^{-1}\,K^{-1}}$ in the range from 400 to 550 nm, in contrast to earlier findings. Reproducible signals could be observed

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

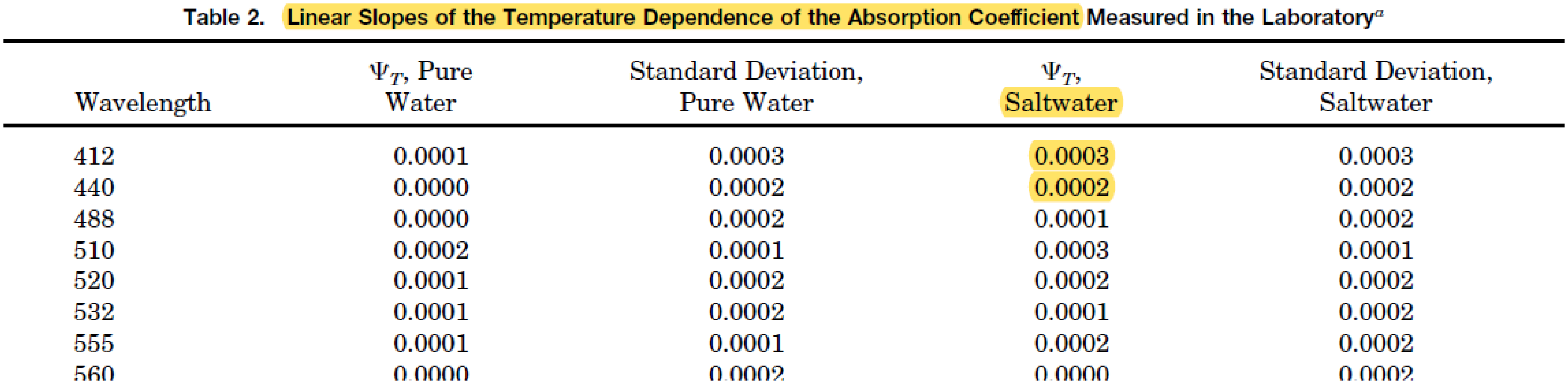


Table 2. Linear Slopes of the Temperature Dependence of the Absorption Coefficient Measured in the Laboratory[a]

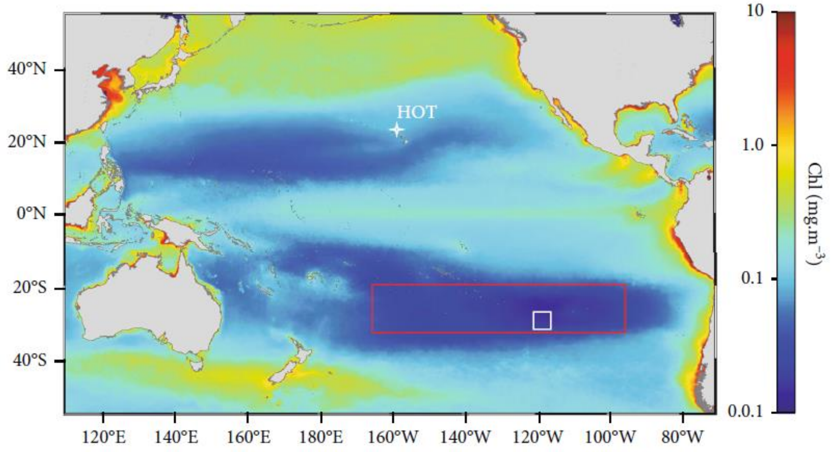
Wavelength	Ψ_T, Pure Water	Standard Deviation, Pure Water	Ψ_T, Saltwater	Standard Deviation, Saltwater
412	0.0001	0.0003	0.0003	0.0003
440	0.0000	0.0002	0.0002	0.0002
488	0.0000	0.0002	0.0001	0.0002
510	0.0002	0.0001	0.0003	0.0001
520	0.0001	0.0002	0.0002	0.0002
532	0.0001	0.0002	0.0001	0.0002
555	0.0001	0.0001	0.0002	0.0002
560	0.0000	0.0002	0.0000	0.0002

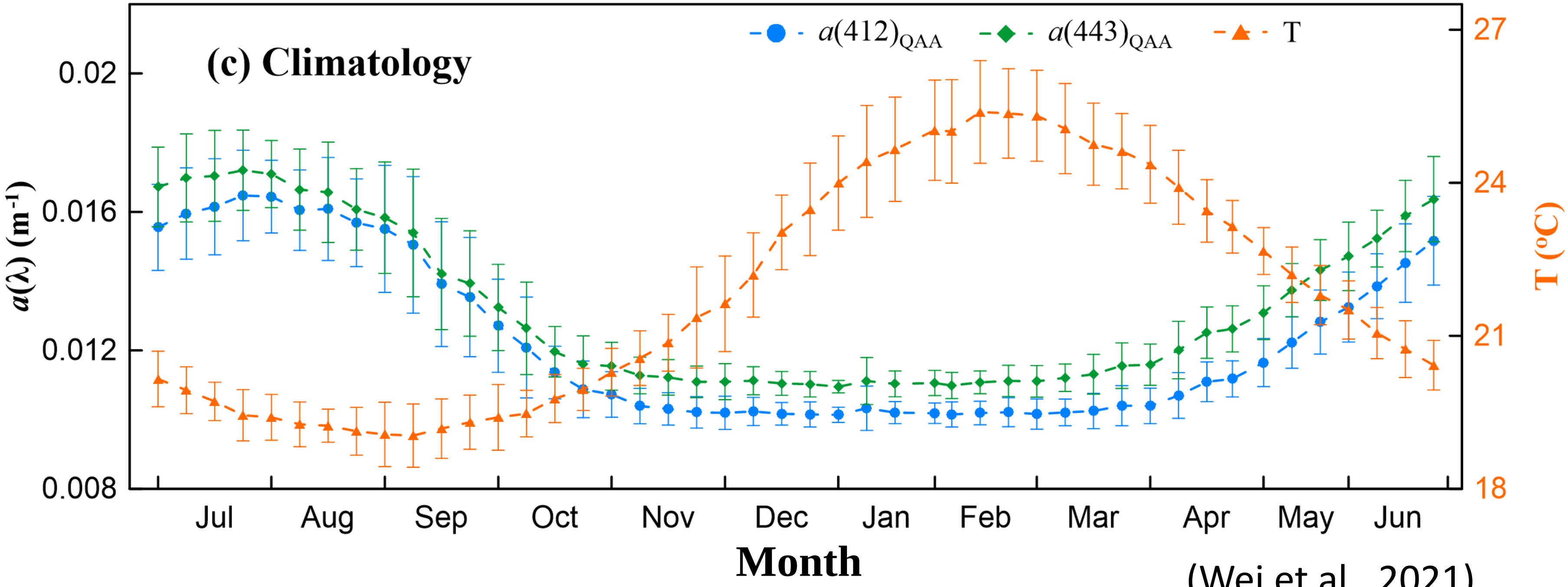
(Pegau et al., Appl. Opt., 1997)

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

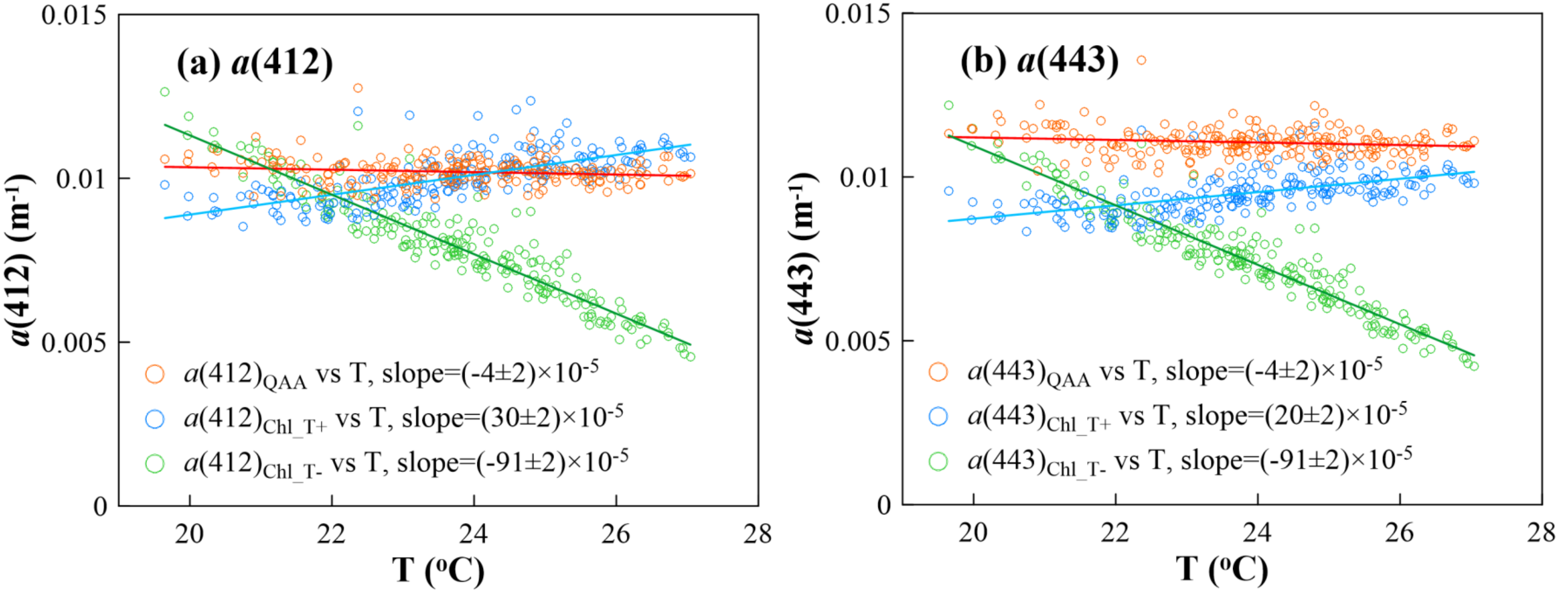
(Rottgers et al. 2014)

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





(Wei et al., 2021)

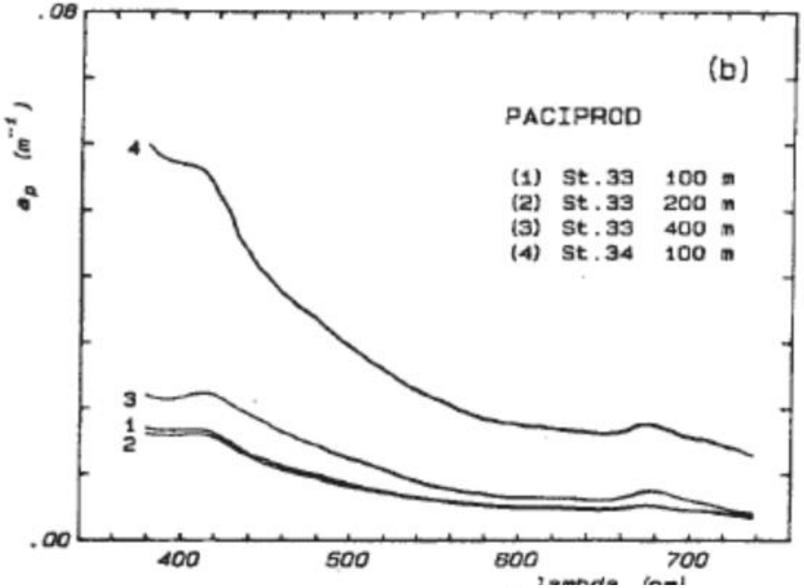


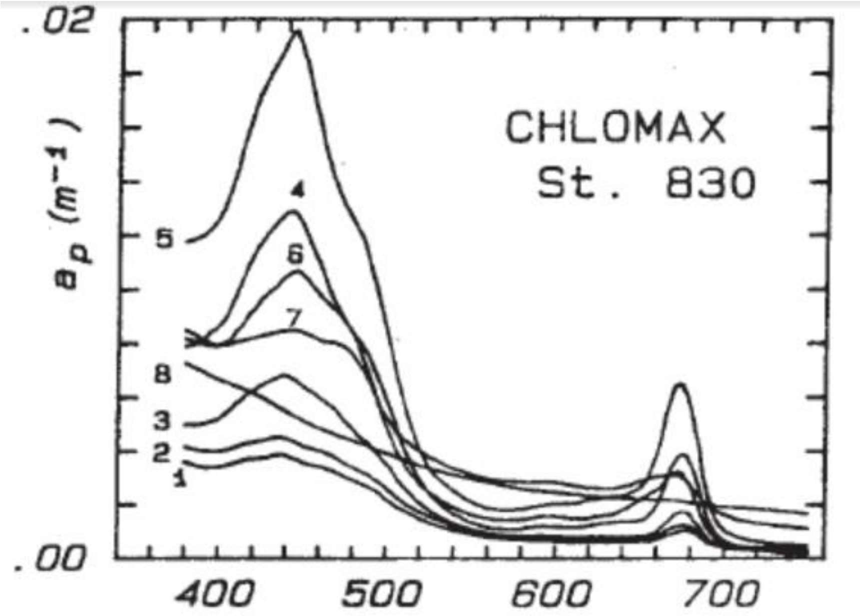
(Wei et al., 2021)

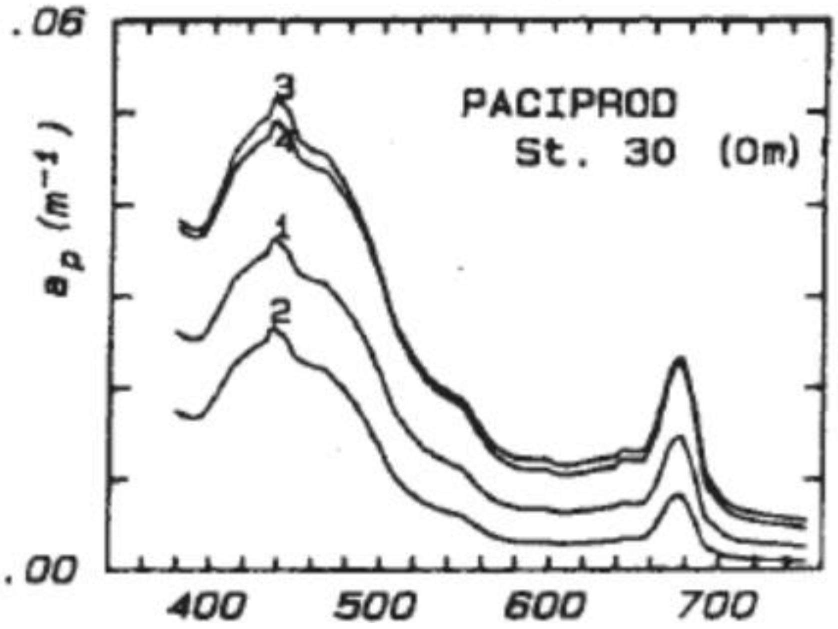
- **$a(\lambda)_{Chl\_T-}$: a(412) is expected to decrease by ~56%**
- **$a(\lambda)_{Chl\_T+}$: a(412) is expected to increase by ~26%.**

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

a_p spectrum



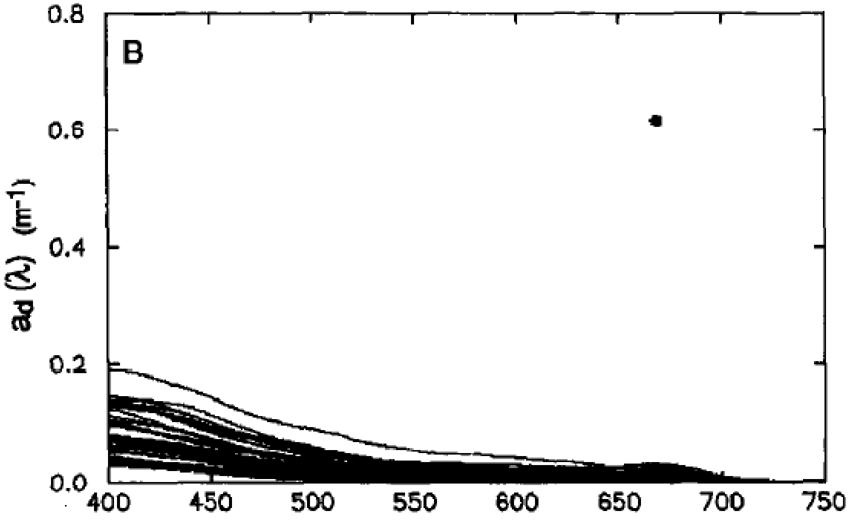


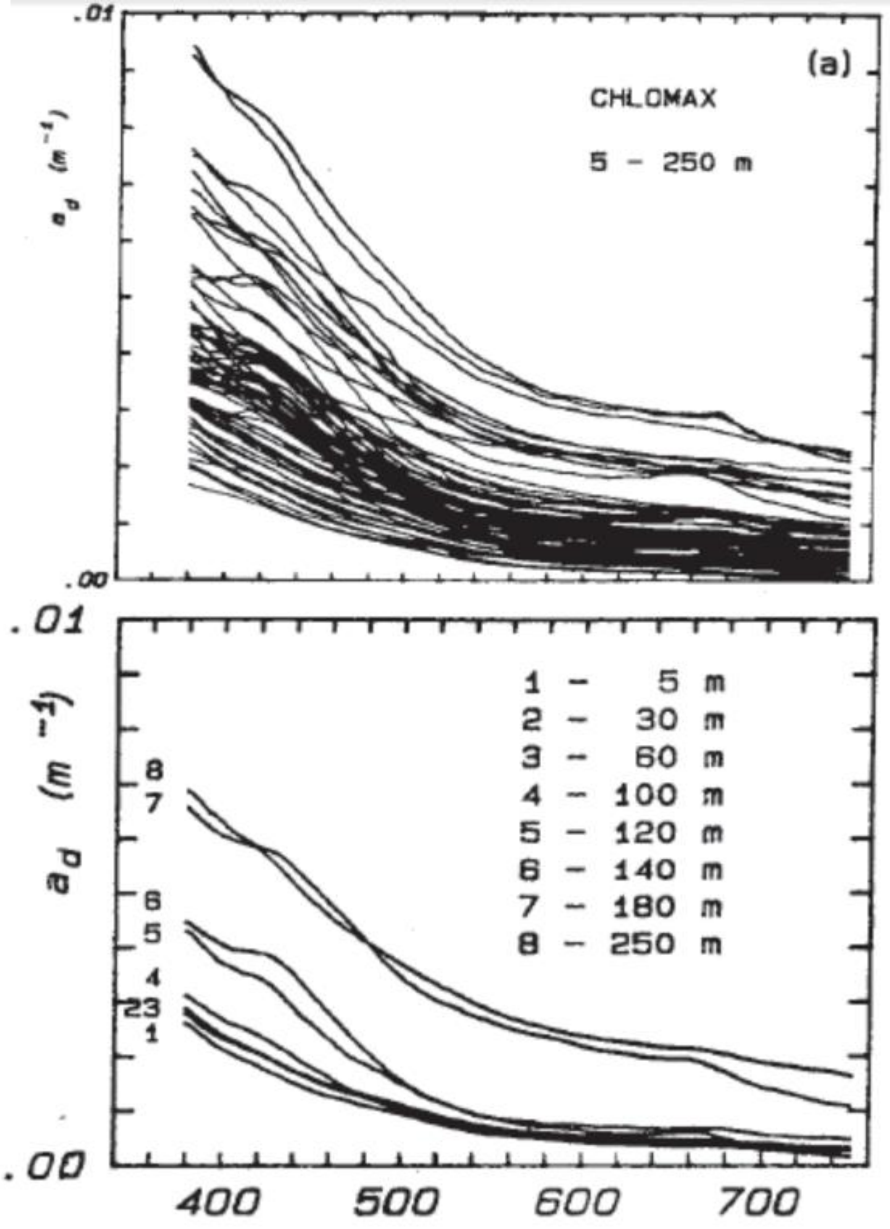


Bricaud and Stramski (1990)

(google)

a_d spectrum



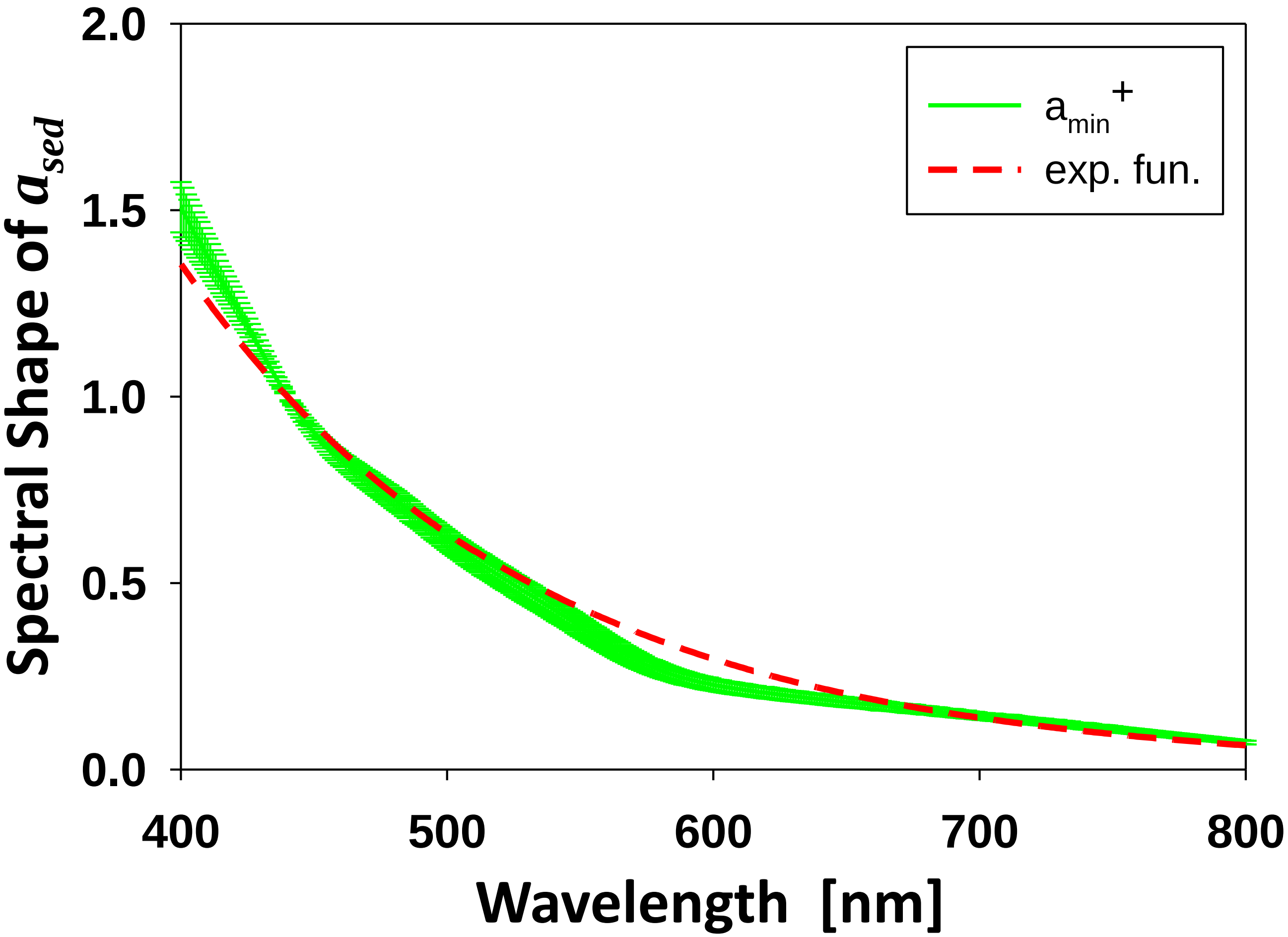


$$a_d = a_d(\lambda_0)\, e^{-S_d(\lambda-\lambda_0)}$$

S_d: ~0.005 – 0.015 nm^{-1}

Bricaud and Stramski (1990)

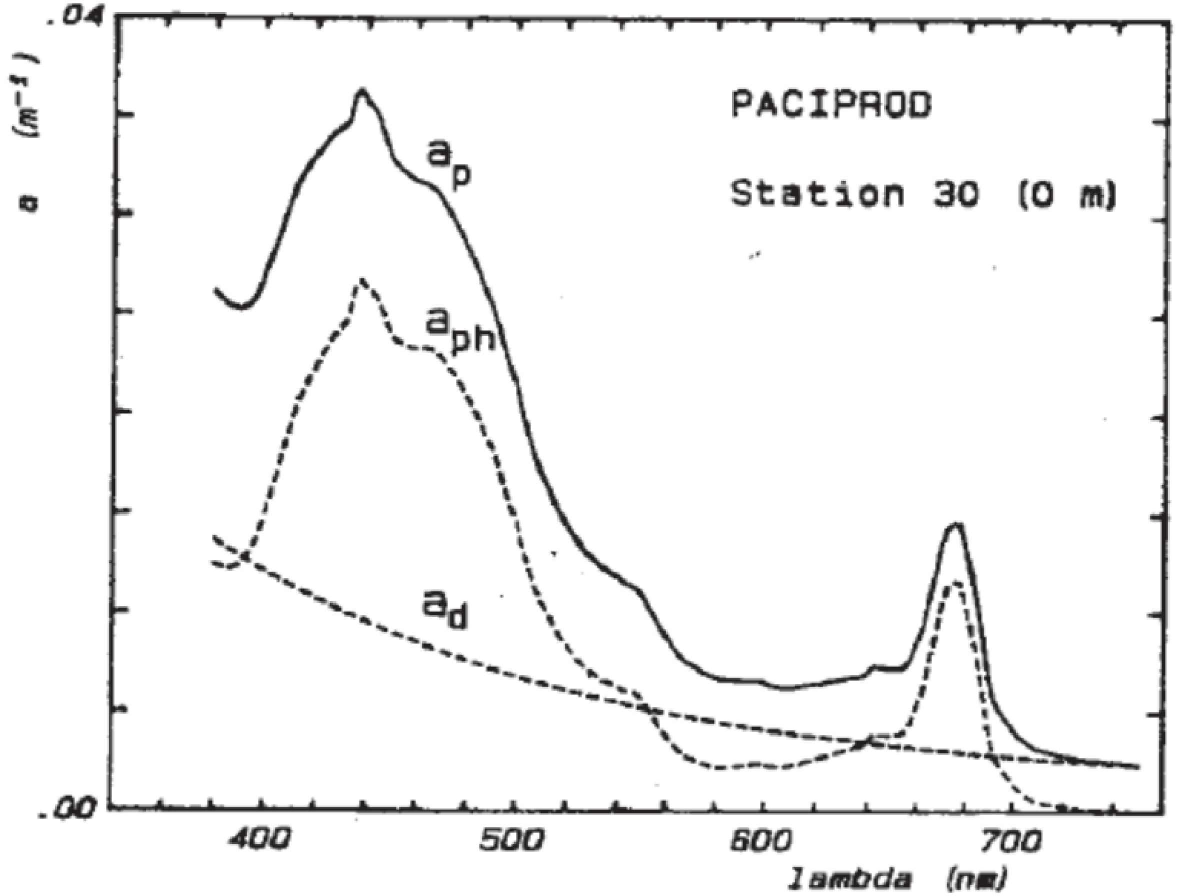
Mineral dominated particles



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

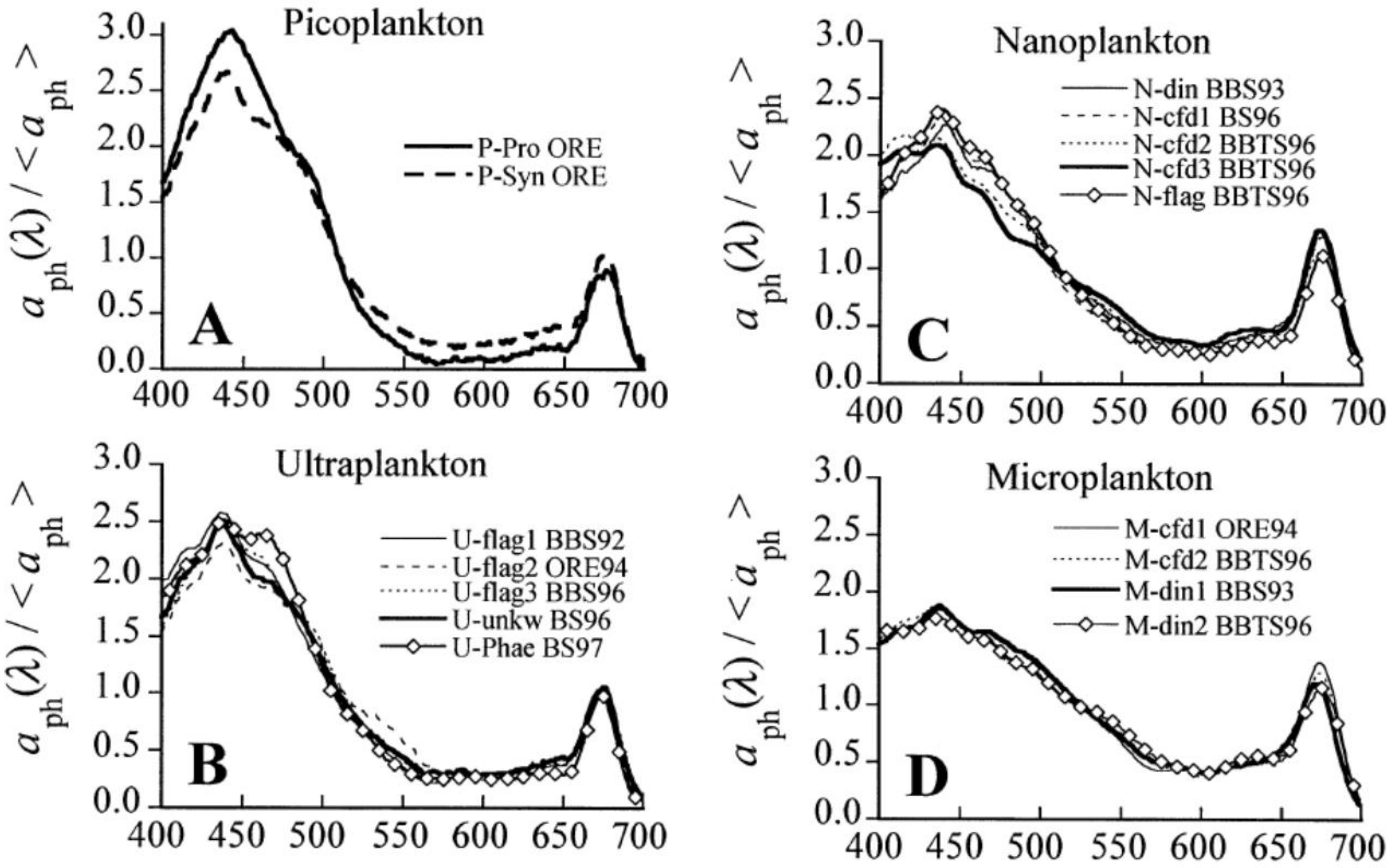
(Lee et al. 2016)

$a_{ph} = a_p - a_d$ spectrum



Bricaud and Stramski (1990)

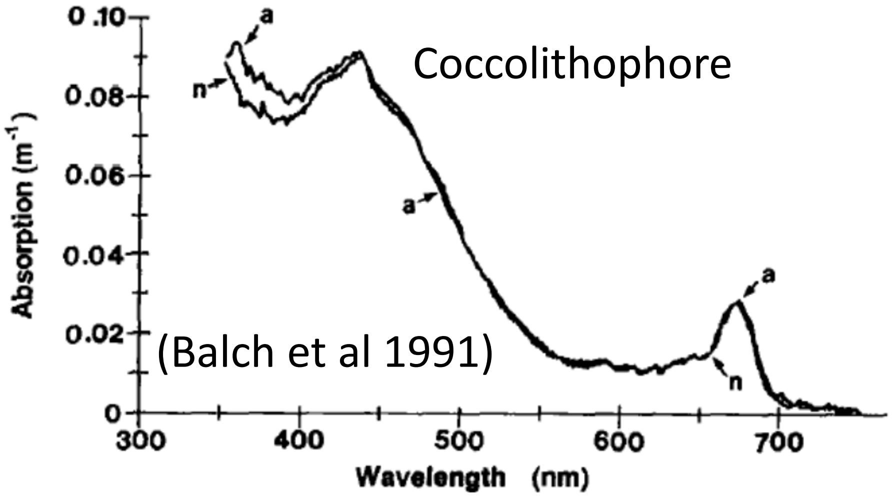
Separated by size



(Ciotti et al 2002)

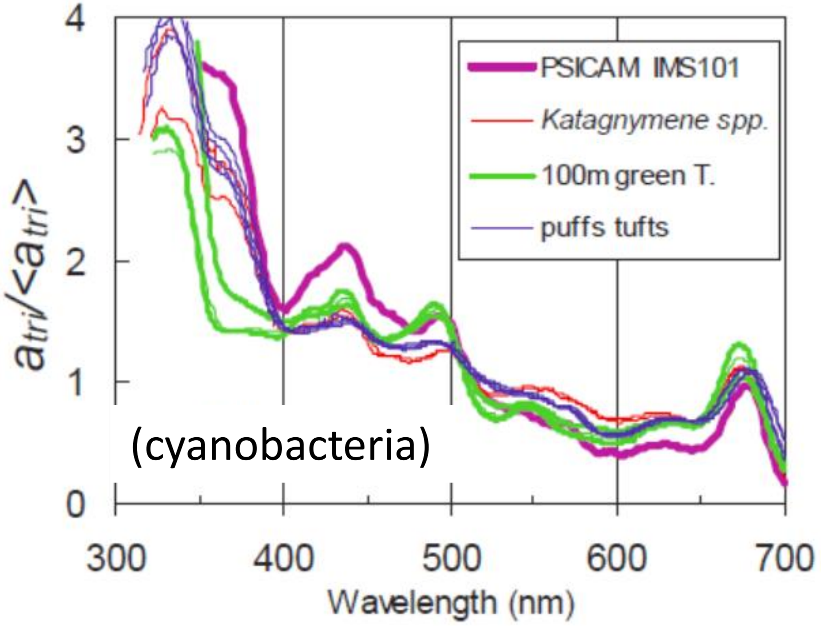
“fatness”

By species or groups



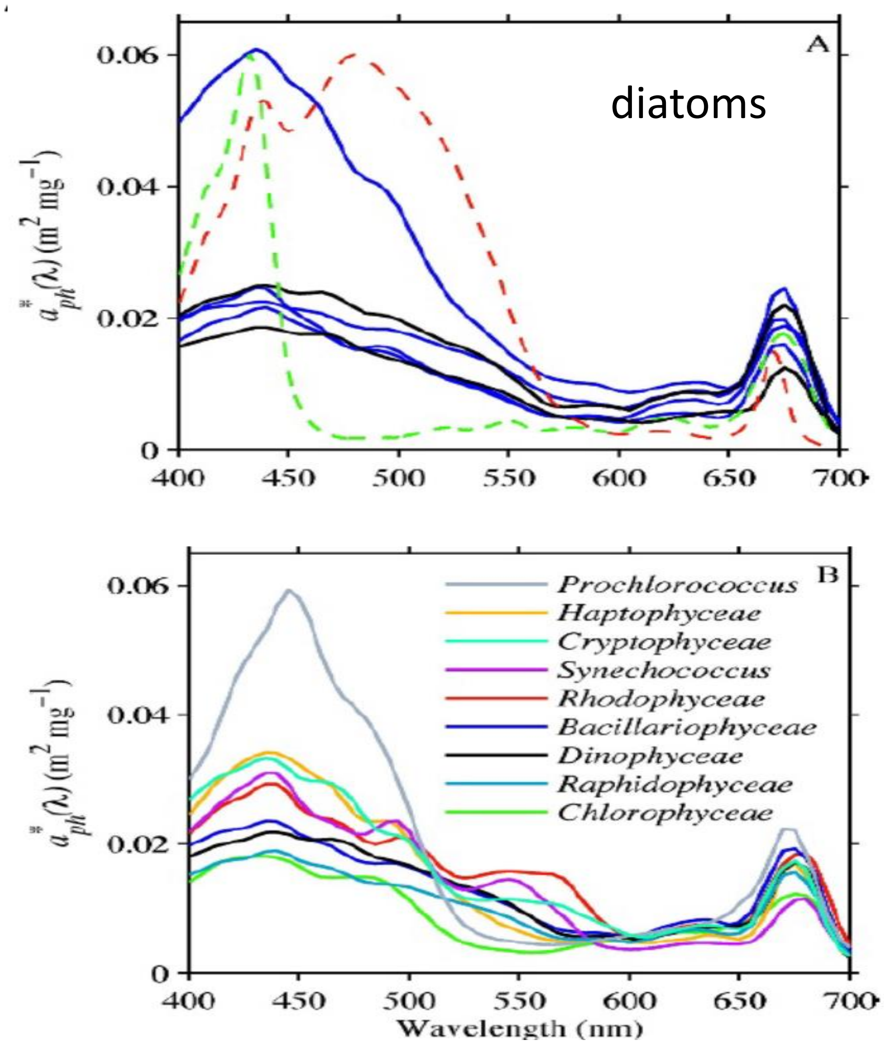
Coccolithophore

(Balch et al 1991)



(cyanobacteria)

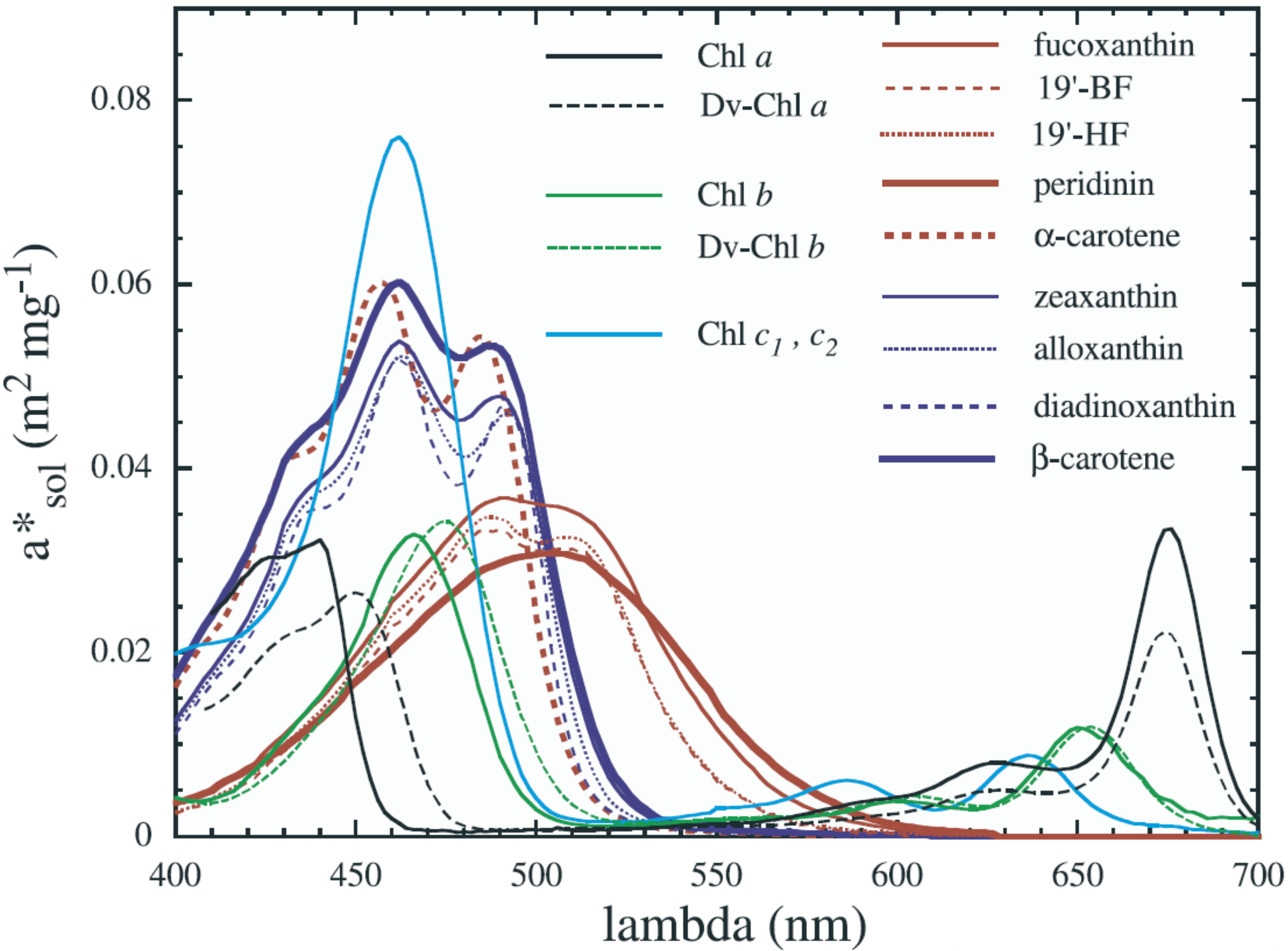
(Dupouy et al 2008)



diatoms

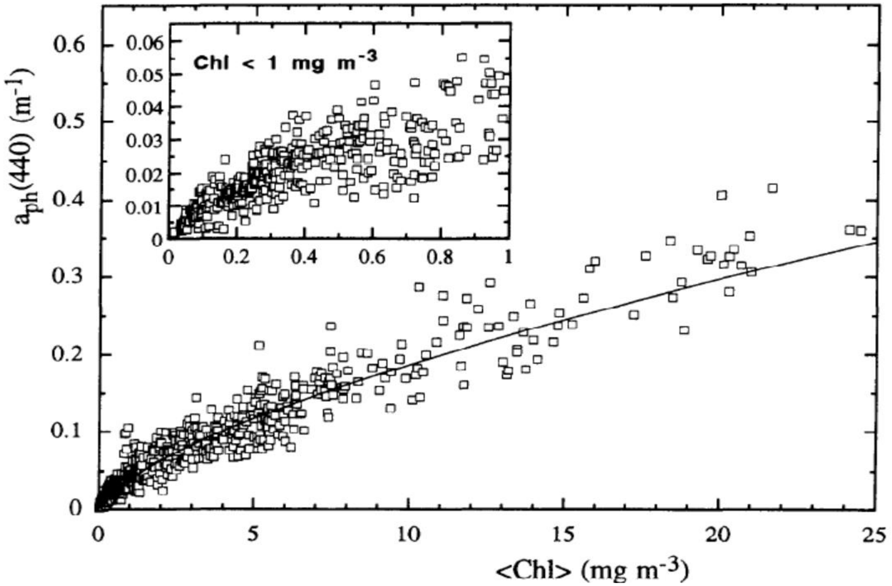
(Dierssen et al 2006)

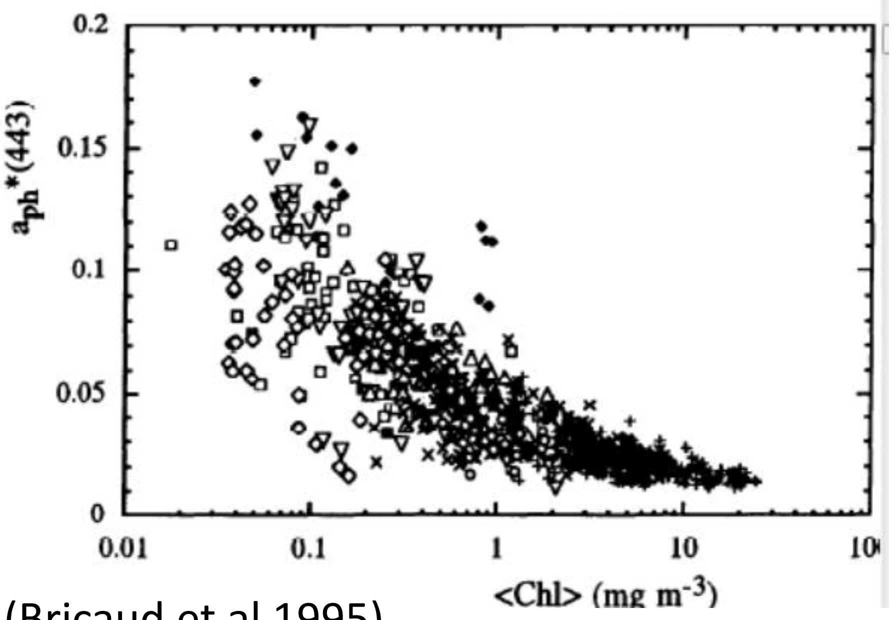
Contribution of various pigments



(Bricaud et al 2004)

Package effect





(Bricaud et al 1995)

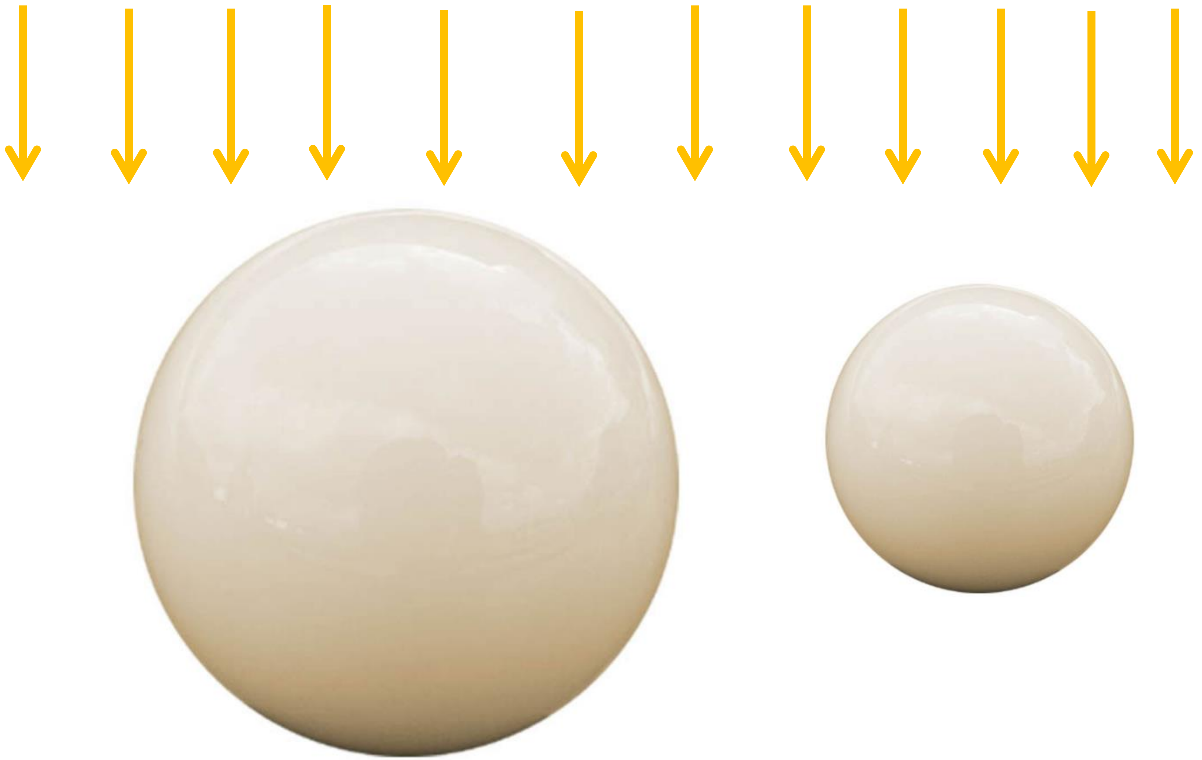
Increase of absorption is NOT linearly proportionally to Chl concentration!

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

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

Chl ↑ → specific optical property ↓

Simplified case:



$$a \propto \sigma S$$

$$W \propto \rho V$$

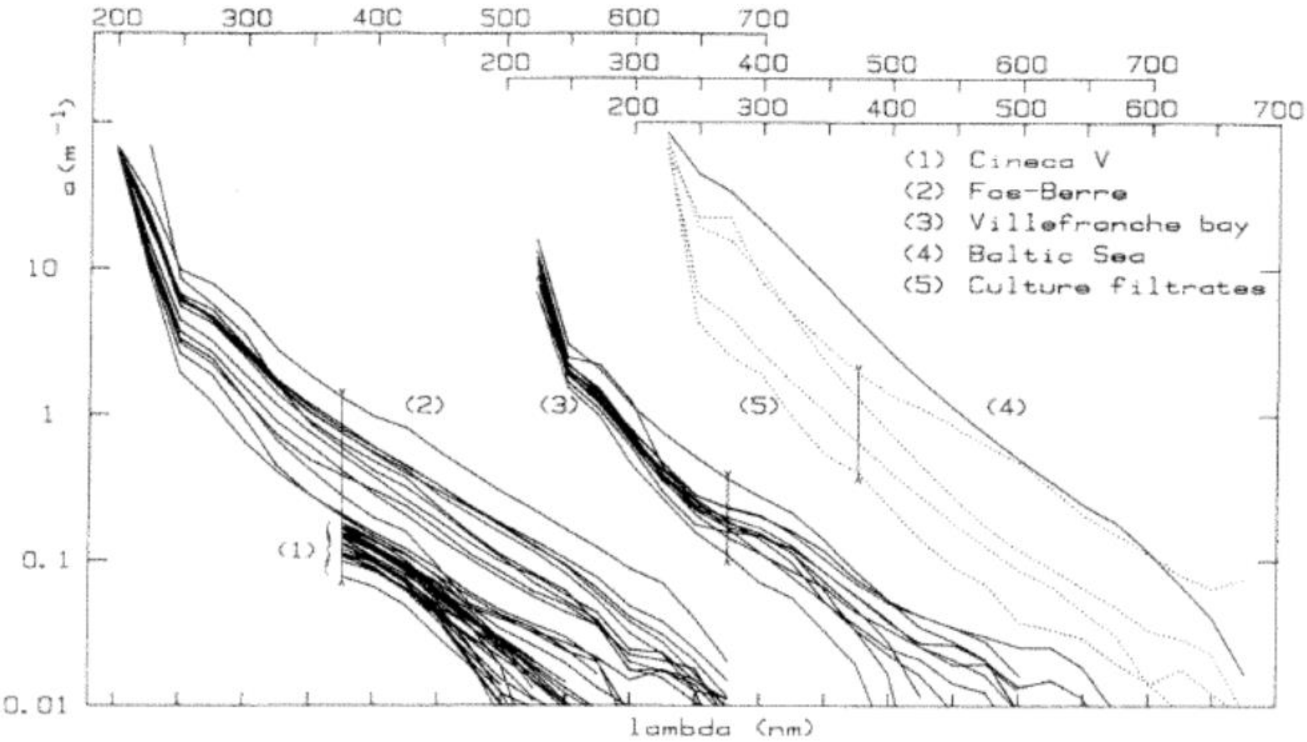
$$a^{*}_{ph} \propto \frac{a}{W} = \frac{\sigma}{\rho}\frac{S}{V} \propto \frac{1}{d}$$

S: cross section
V: volume
W: weight

Size matters on efficiency!

a_g spectrum

Absorption spectra of yellow substance (gelbstoff)

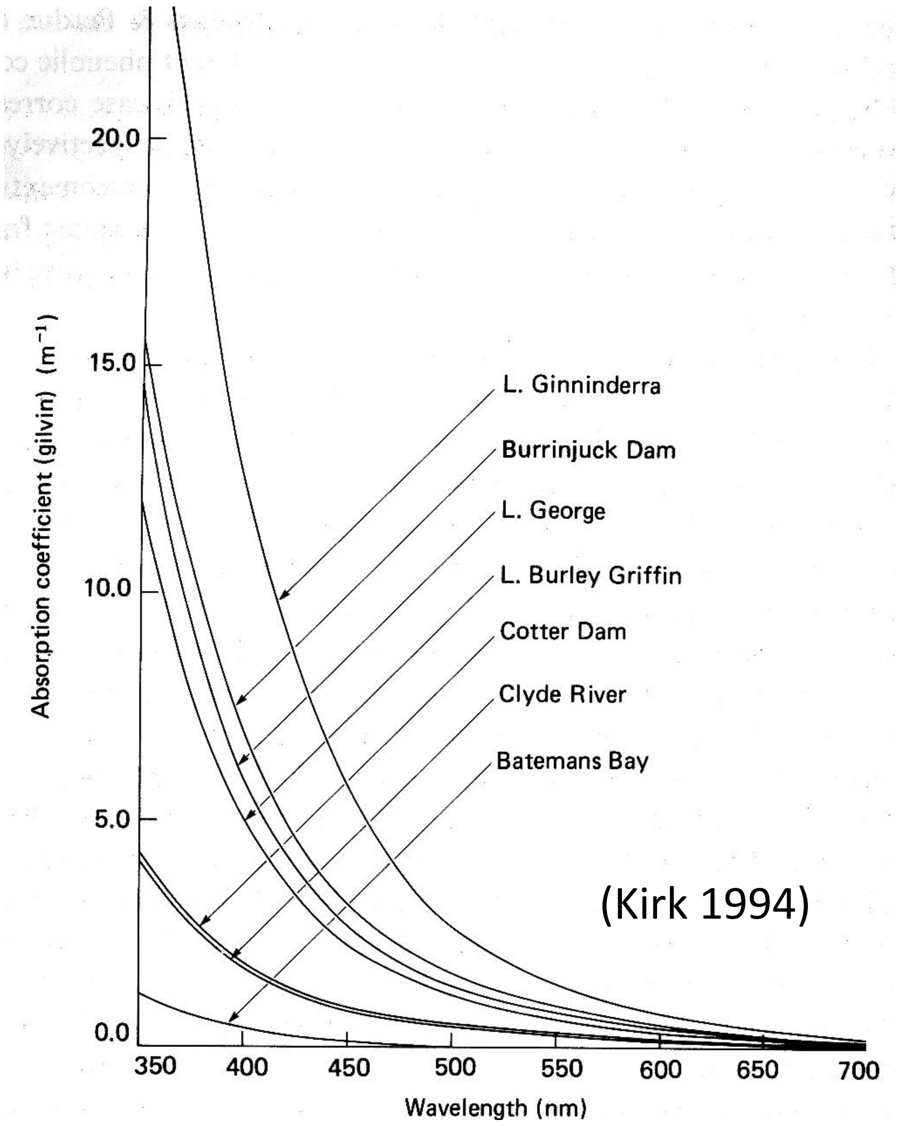


(Bricaud et al 1981)

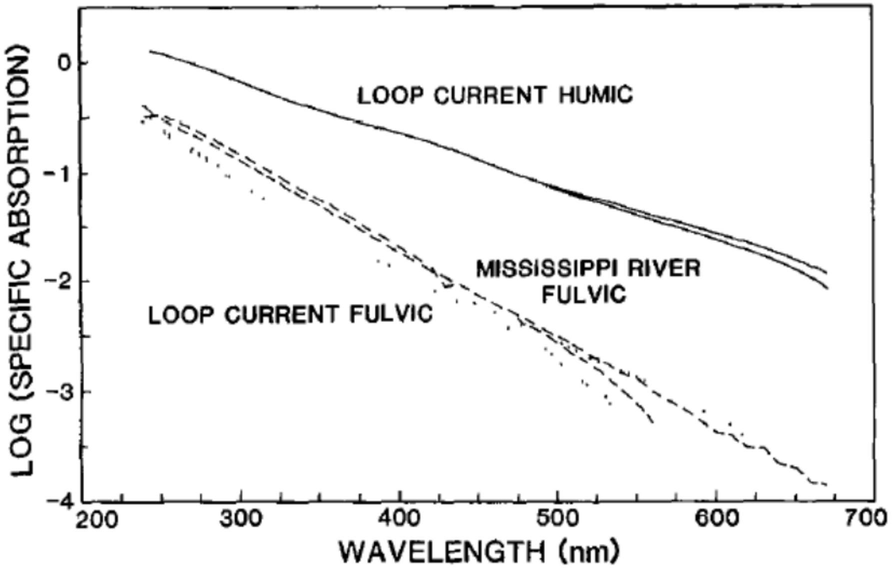
a_g spectrum

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

S_g: ~0.01 – 0.03 nm^{-1}



(Kirk 1994)



(Carder et al 1989)

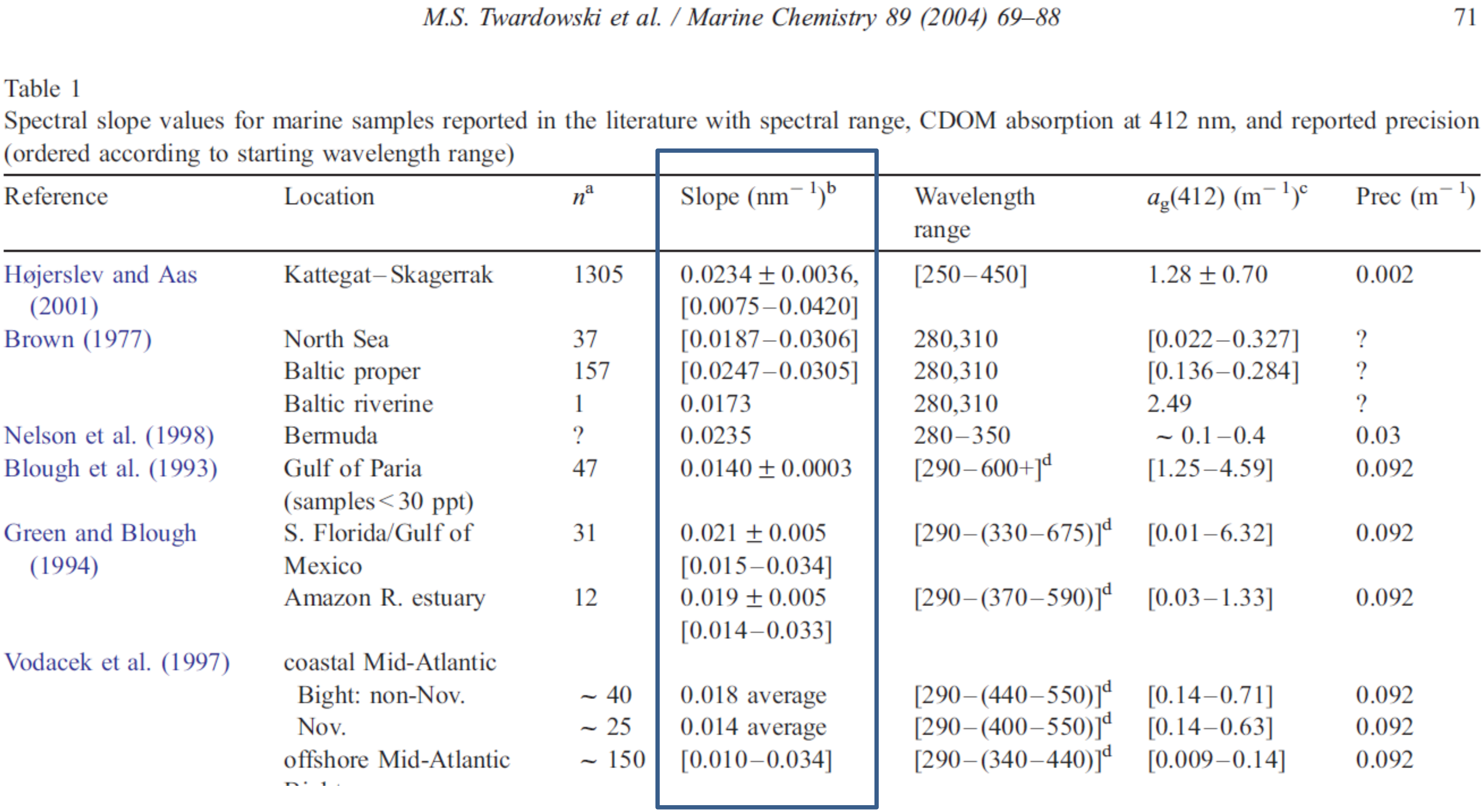


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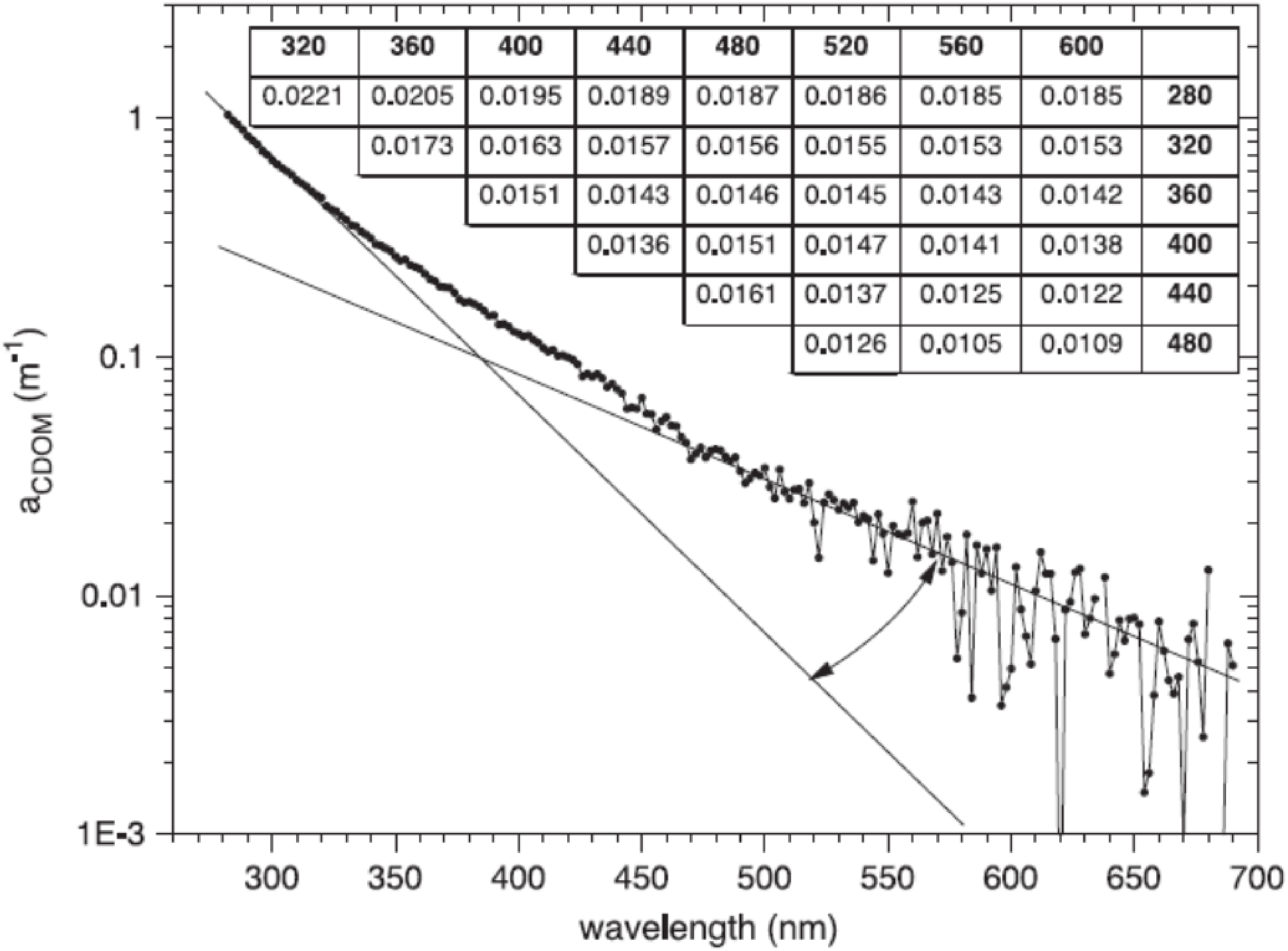
Table 1
Spectral slope values for marine samples reported in the literature with spectral range, CDOM absorption at 412 nm, and reported precision (ordered according to starting wavelength range)

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	∼ 150	[0.010–0.034]	[290–(340–440)]^d	[0.009–0.14]	0.092

(Twardowski et al 2004)

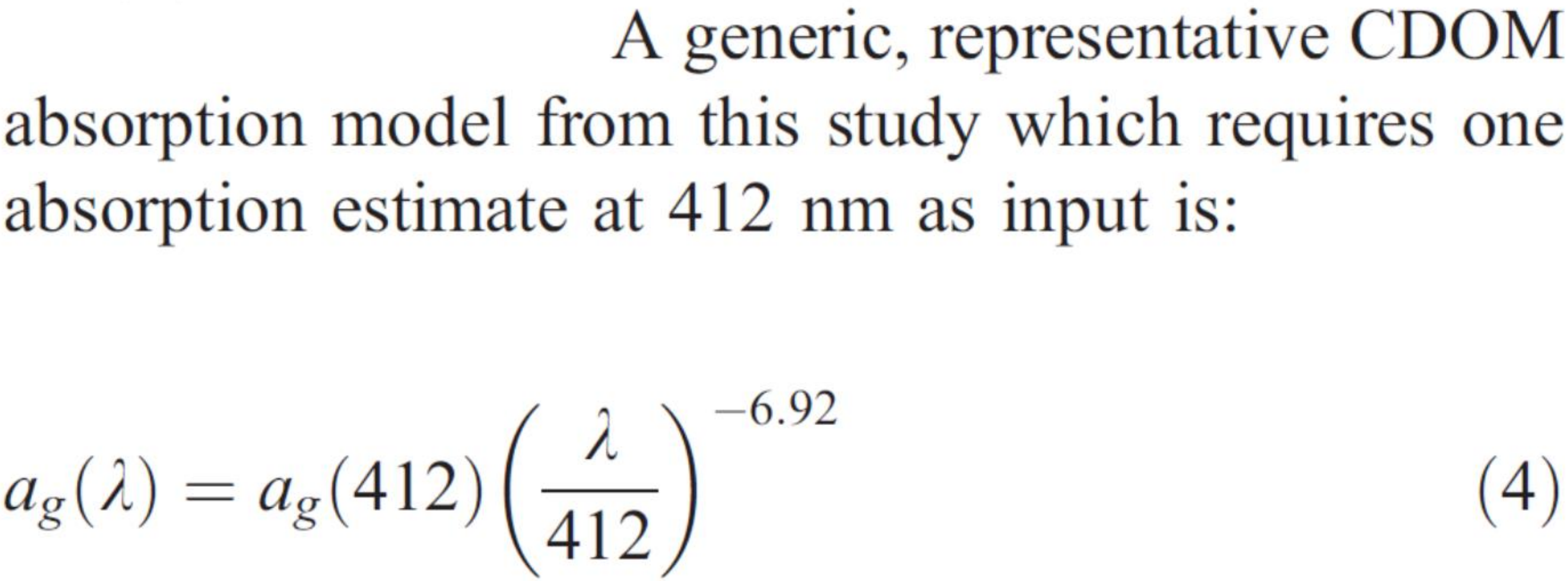
Slope changes with wavelength range



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:

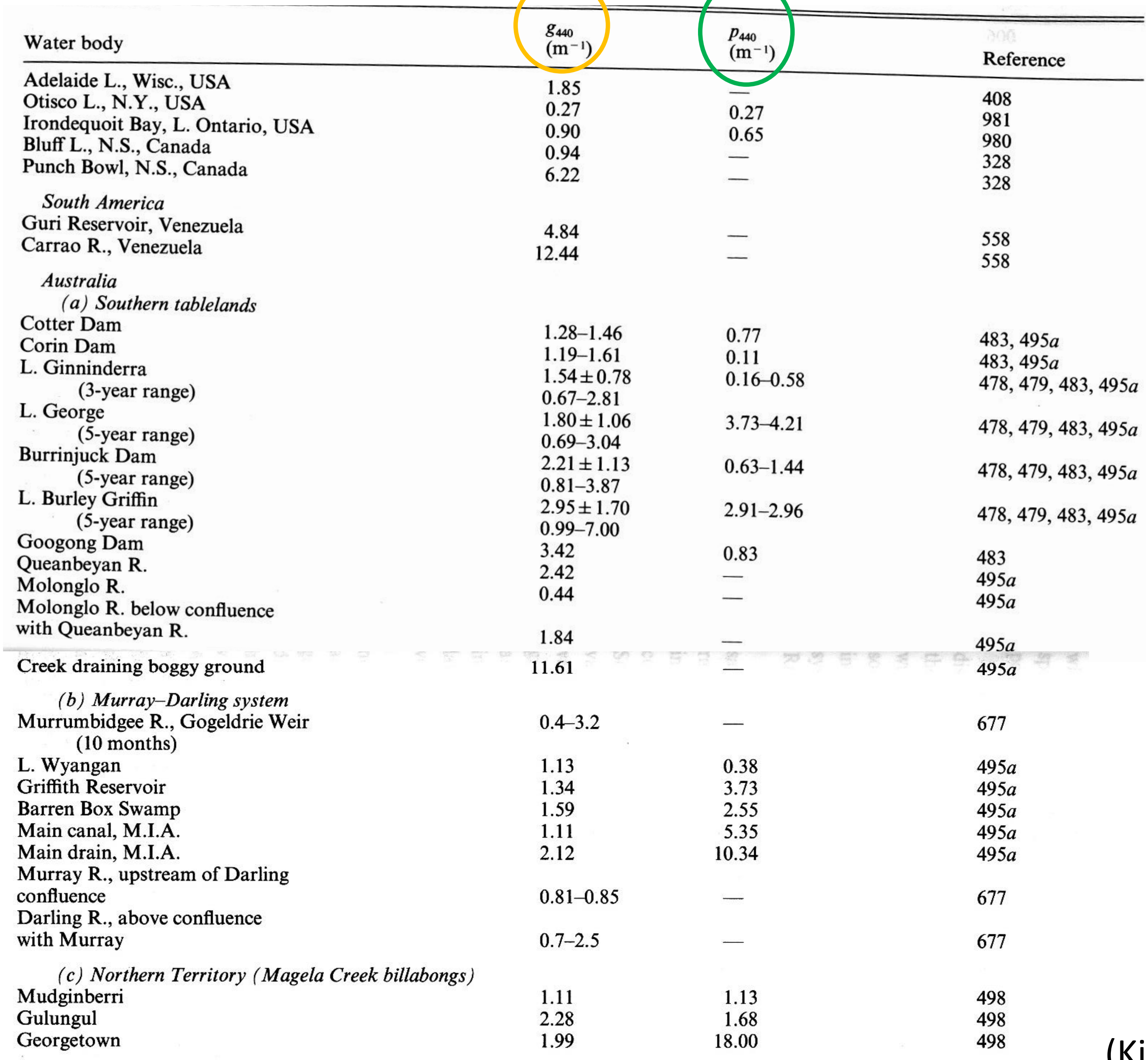


A generic, representative CDOM absorption model from this study which requires one absorption estimate at 412 nm as input is:

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

(Twardowski et al 2004)

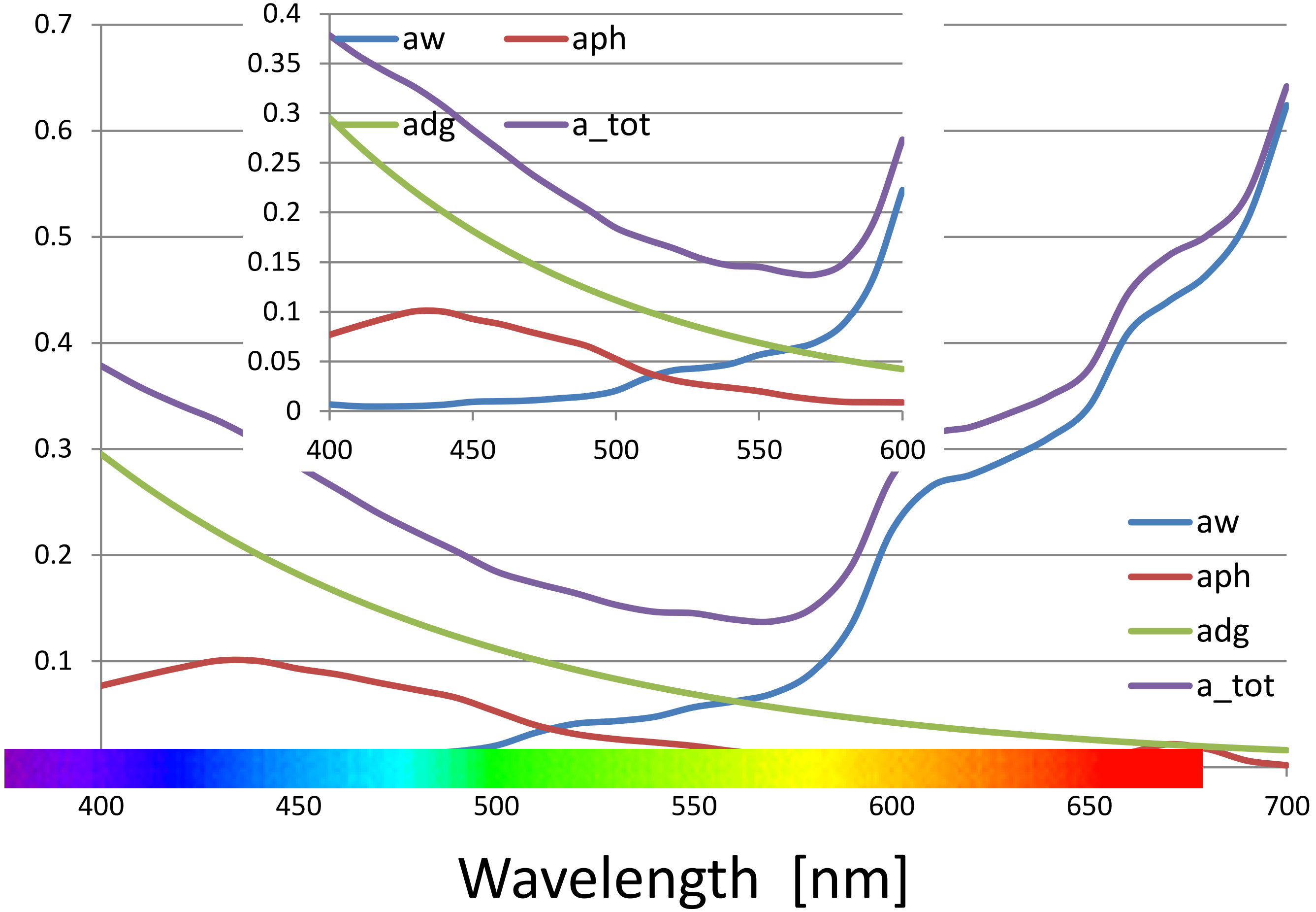
Values of a_{ph} and a_g of natural waters



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

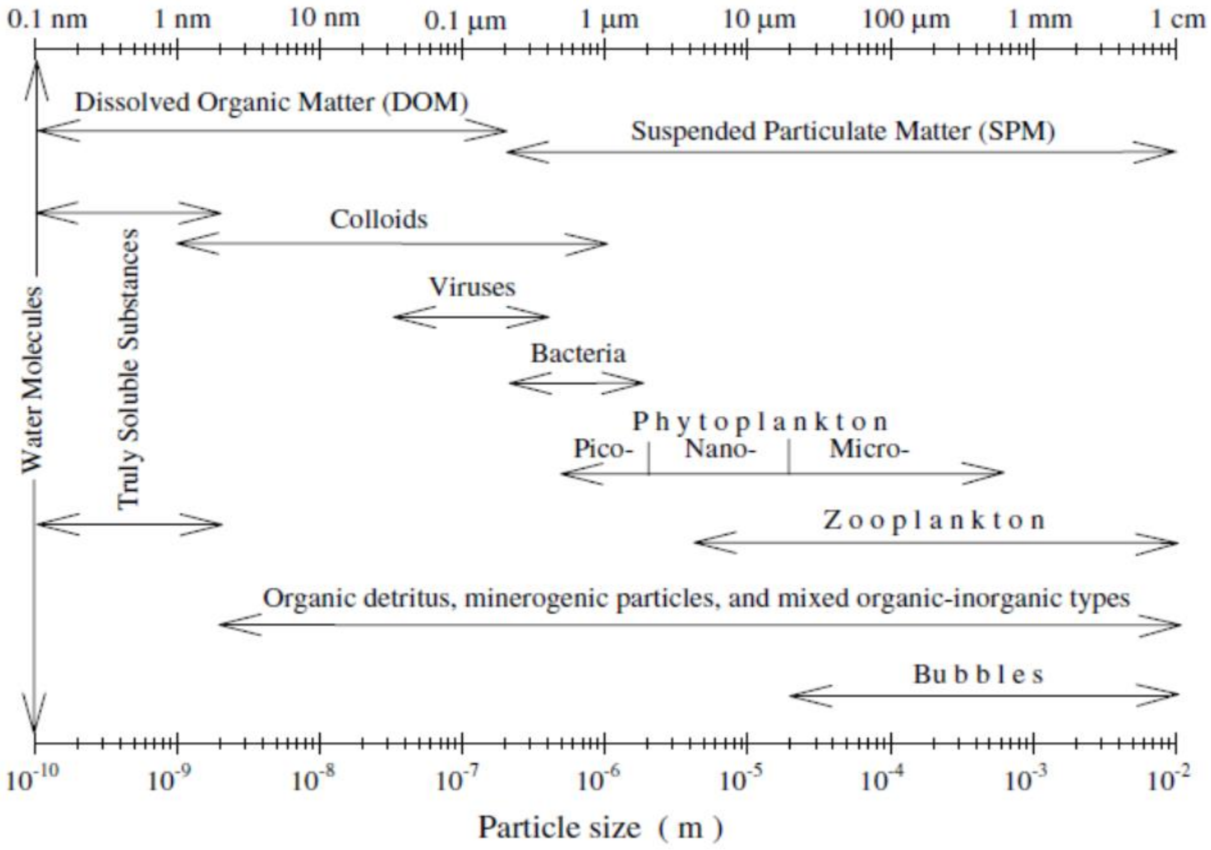
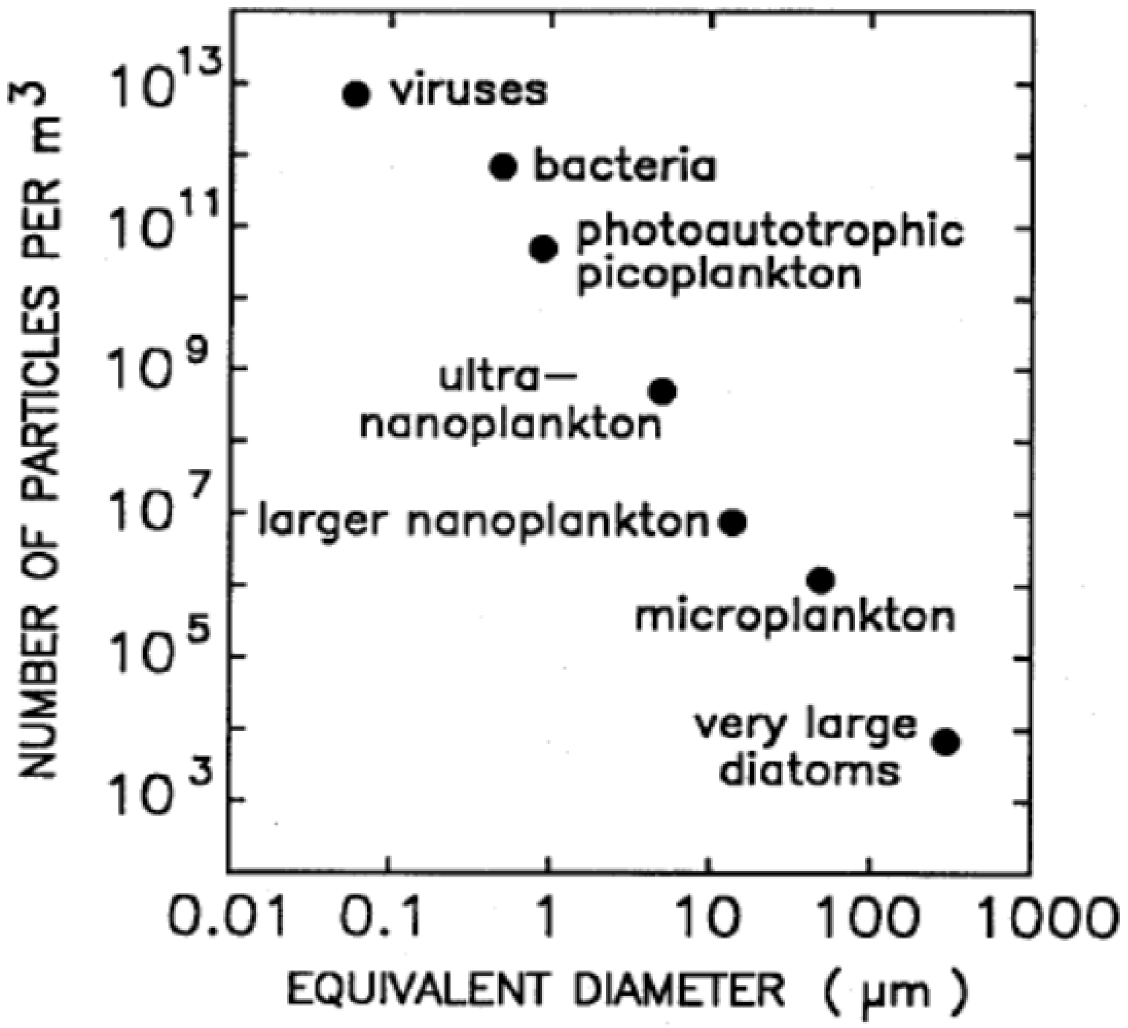


Fig. 1. Schematic diagram showing various seawater constituents in the broad size range from molecular size of the order of 10^{-10} m to large particles and bubbles of the order of 10^{-3}–10^{-2} m in size. The arrow ends generally indicate approximate rather than sharp boundaries for different constituent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

Size distribution



(Stramski and Kiefer 1991)

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

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

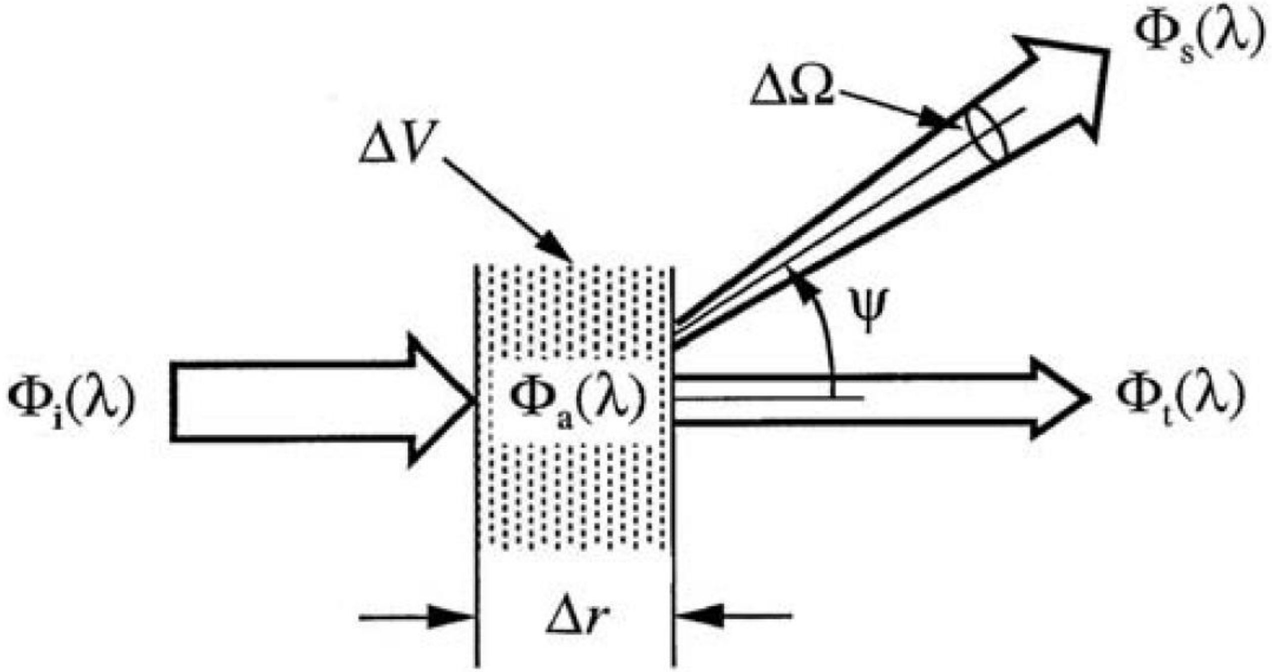
Turbulence

$$b = b_w + b_p$$

Or,

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

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



(Mobley 1994)

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

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

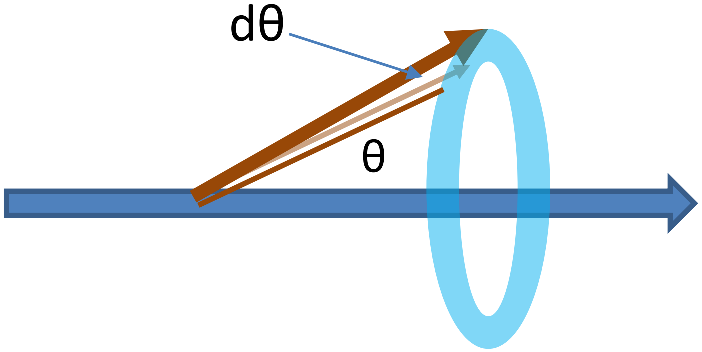
Volume Scattering Function (VSF): β (m^{-1} sr^{-1})

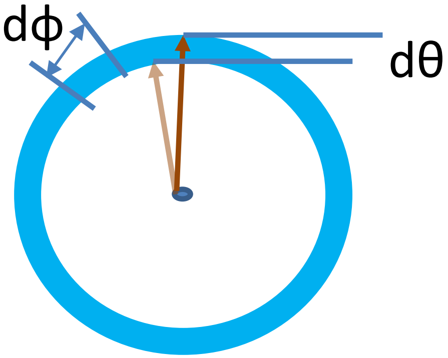
Scattering coefficient: b (m^{-1})

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

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

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





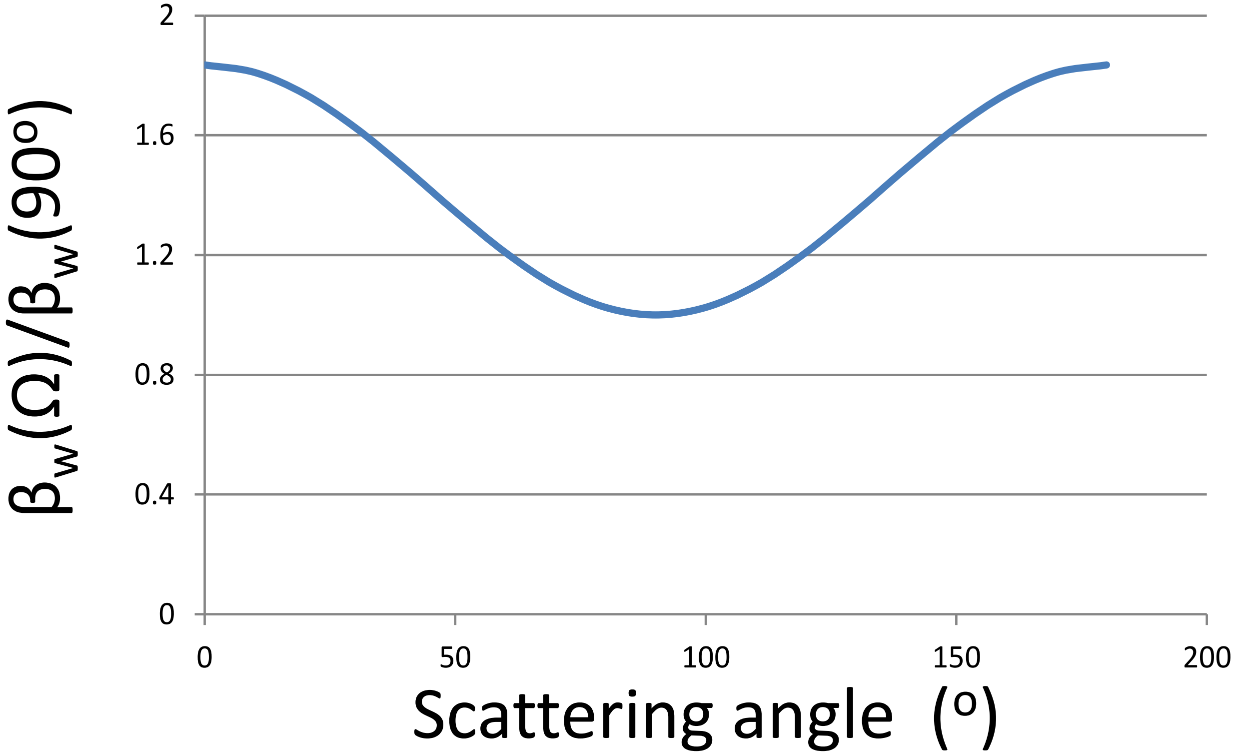
$$b = \int_0^{\pi}\int_0^{2\pi} \beta \sin(\theta)\, d\theta d\phi = 2\pi \int_0^{\pi} \beta \sin(\theta)\, d\theta$$

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

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

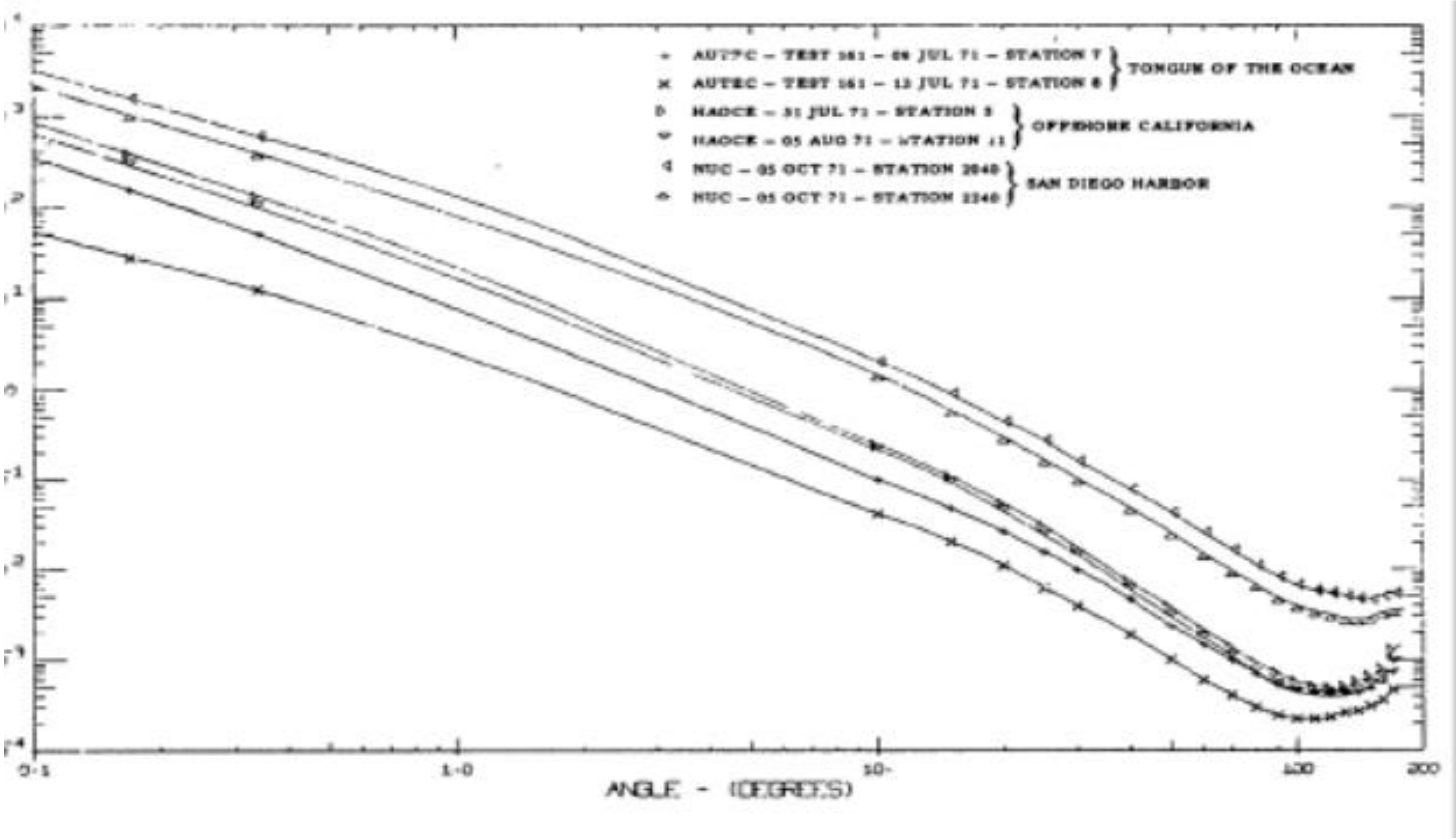
Scattering of water molecules

VSF of pure water (β_w)



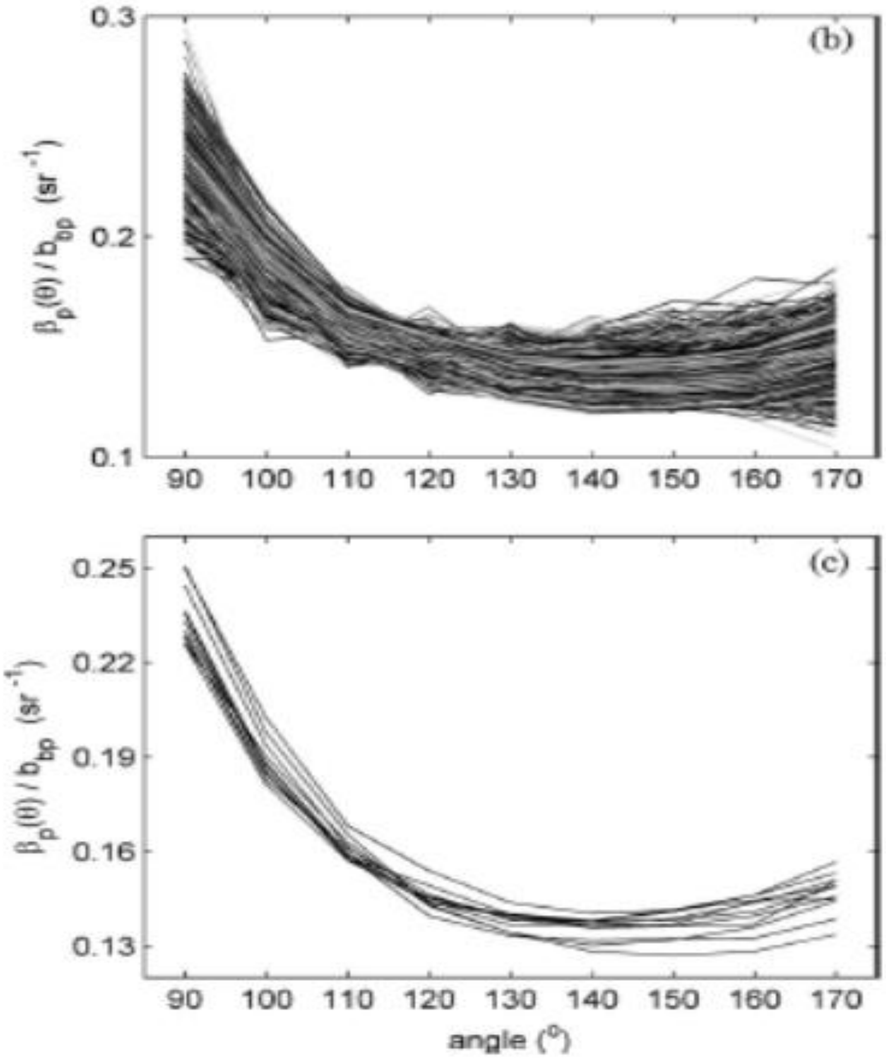
$$b_w = 2\ b_{bw}$$

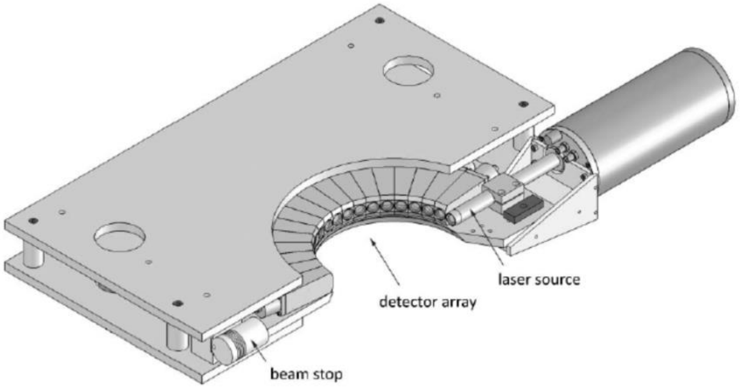
Volume Scattering Function with particles



(Petzold 1972)

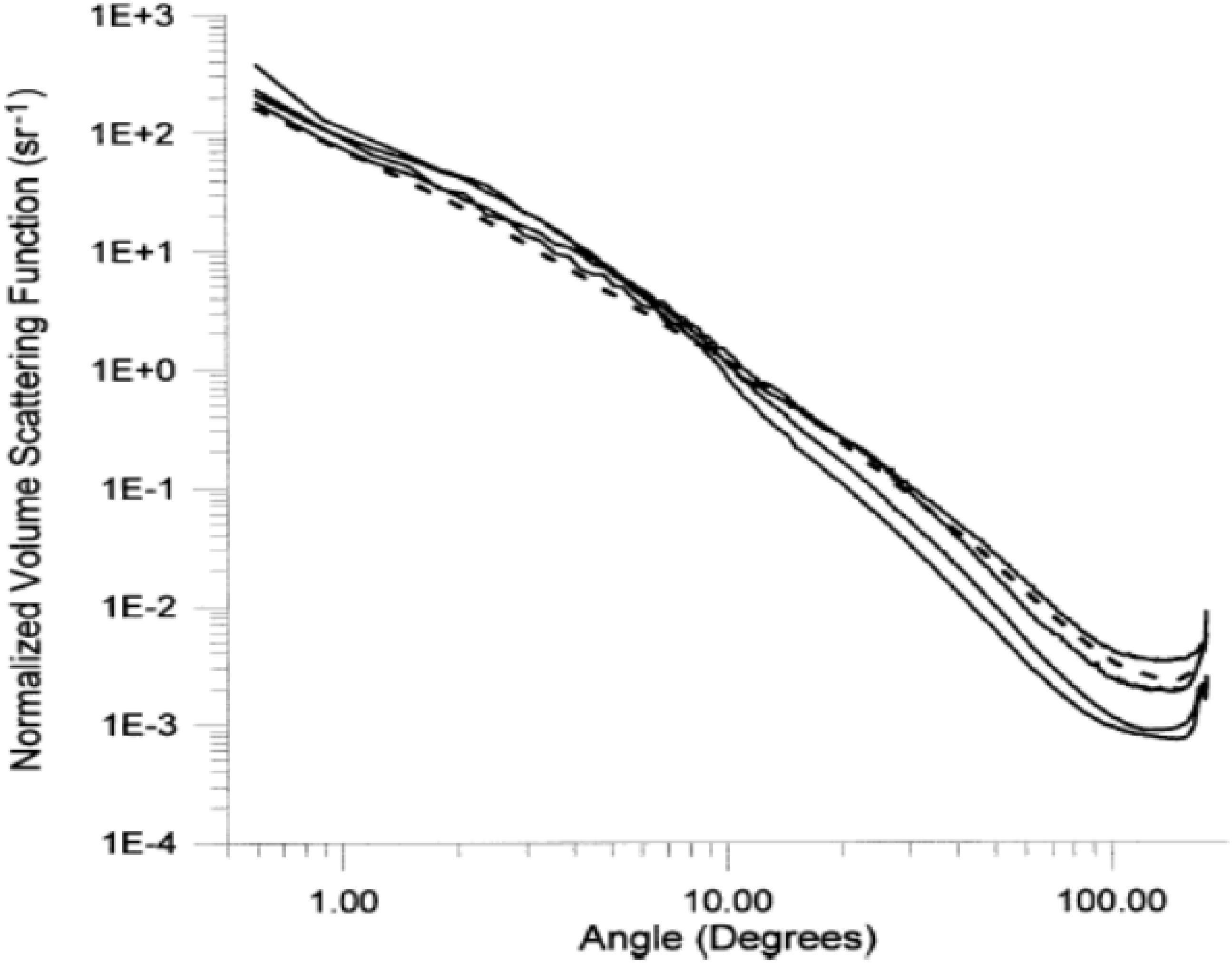
MASCOT measurements



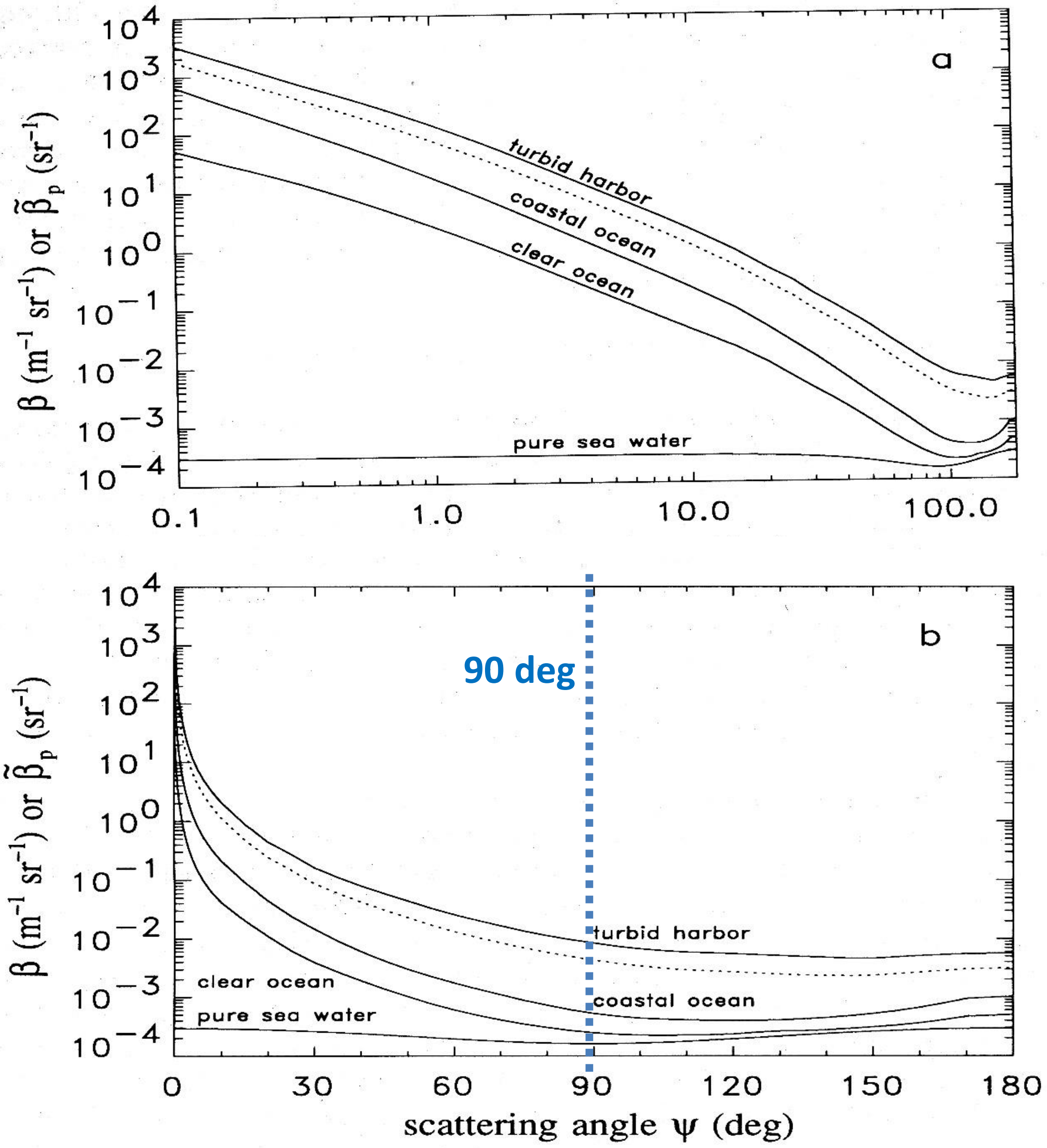


(Sullivan and Twardowski, 2009)

MVSM measurements



(Lee and Lewis, 2003)



(Mobley 1994)

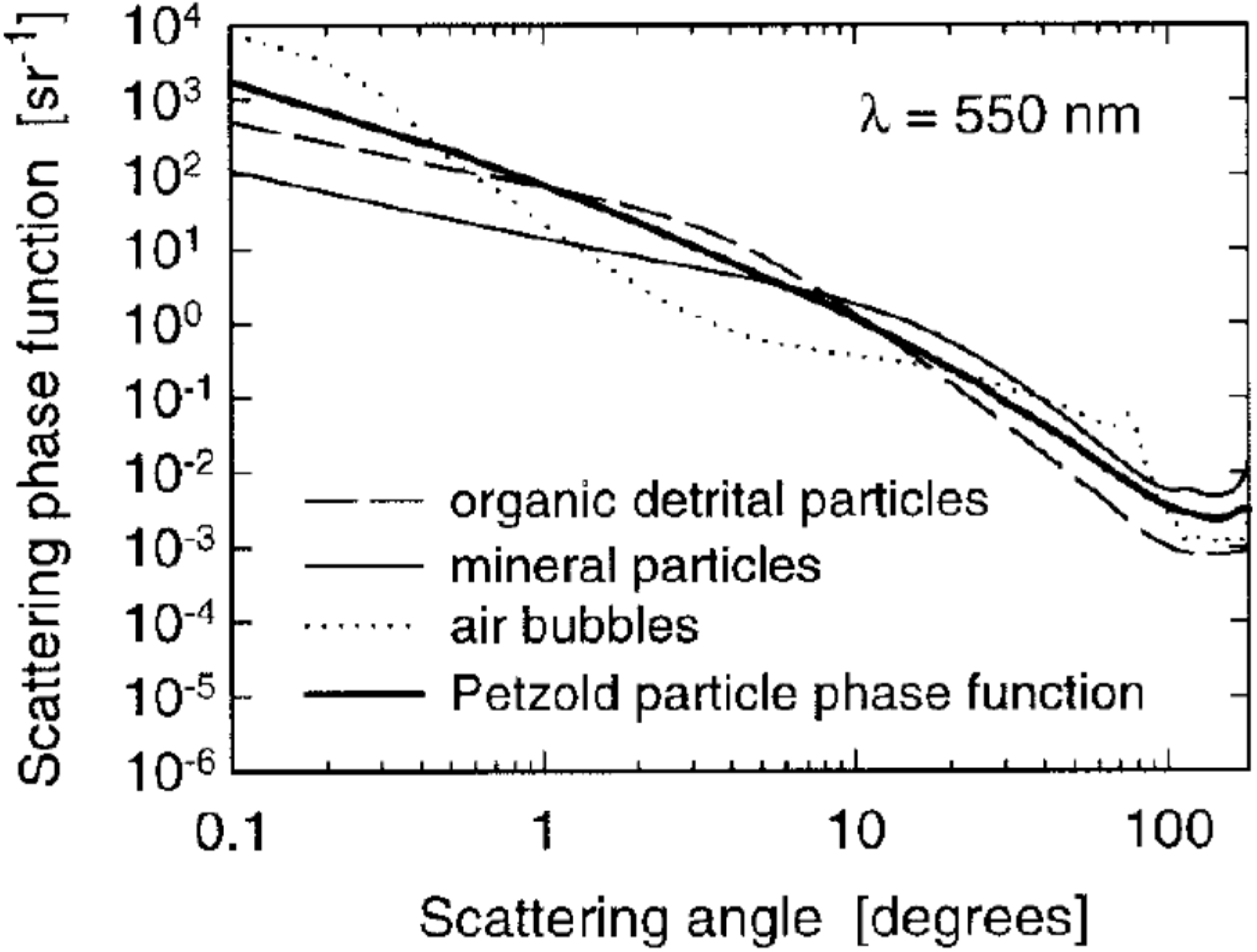
β shape changes in a narrow range in the backward domain

Particles are strongly forward scatters!

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

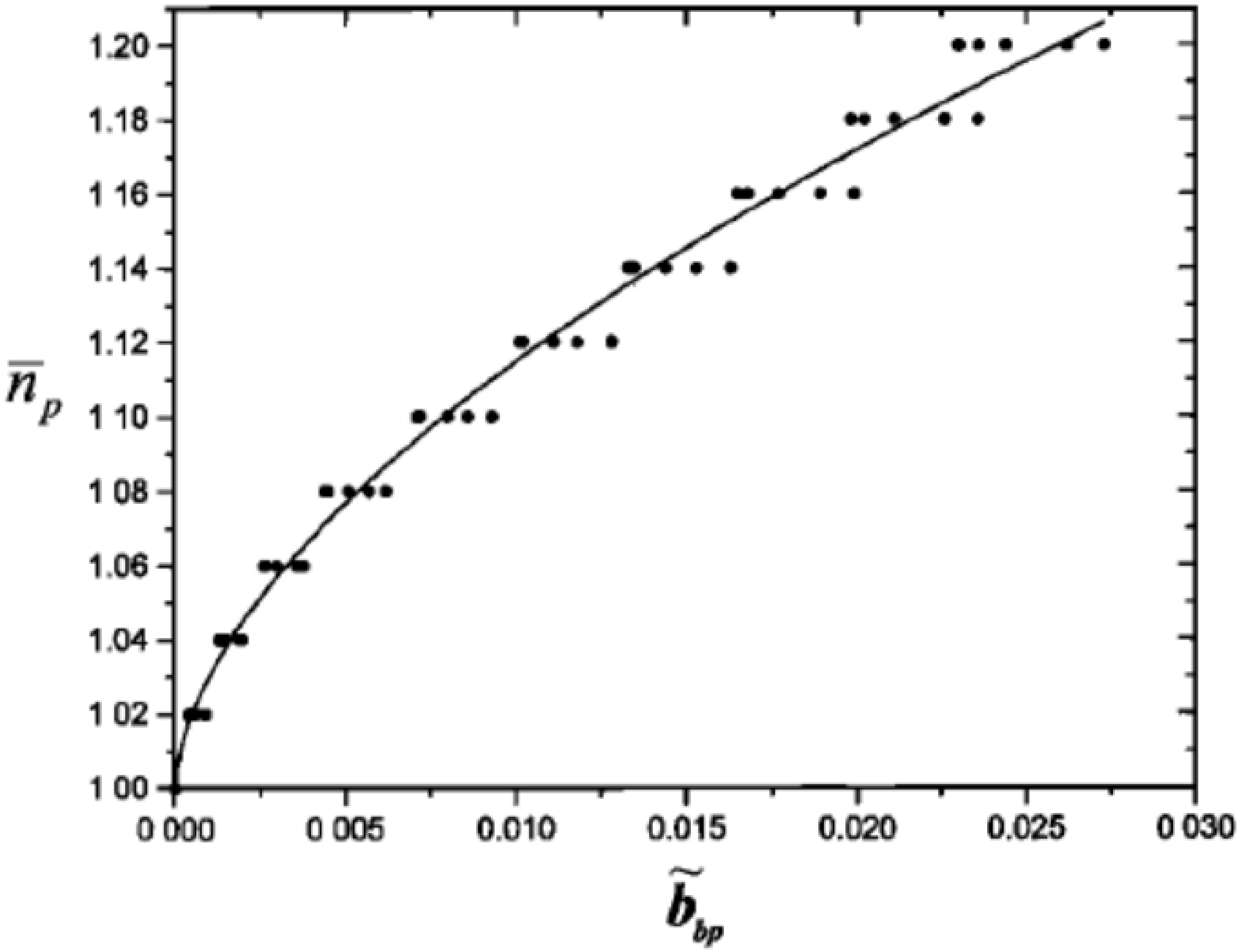
$$\tilde{b}_{bw} = 0.5;$$

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



(Stramski et al 2001)

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

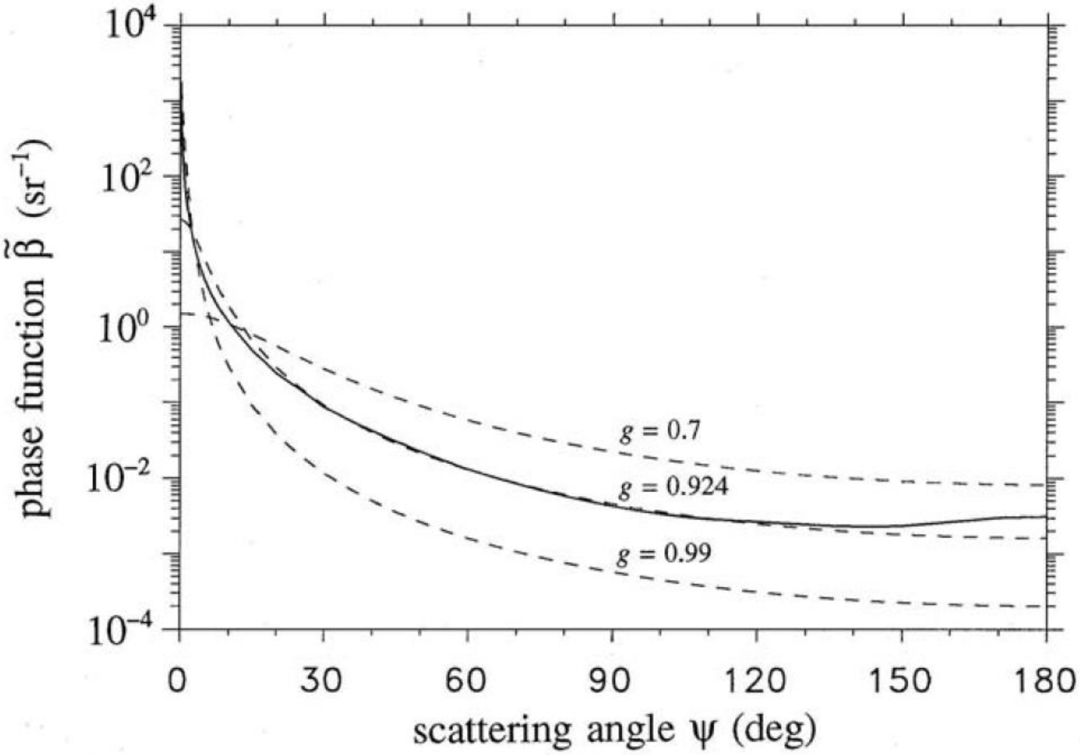


Twardowski et al (2001)

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)

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

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

Mathematical models of VSF

Kopelevich (1983): **combination of large and small particles**

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

Spectral dependence

Morel 1974:

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

Shifrin: 1988

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

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

Value and spectrum of seawater b_{bw}:

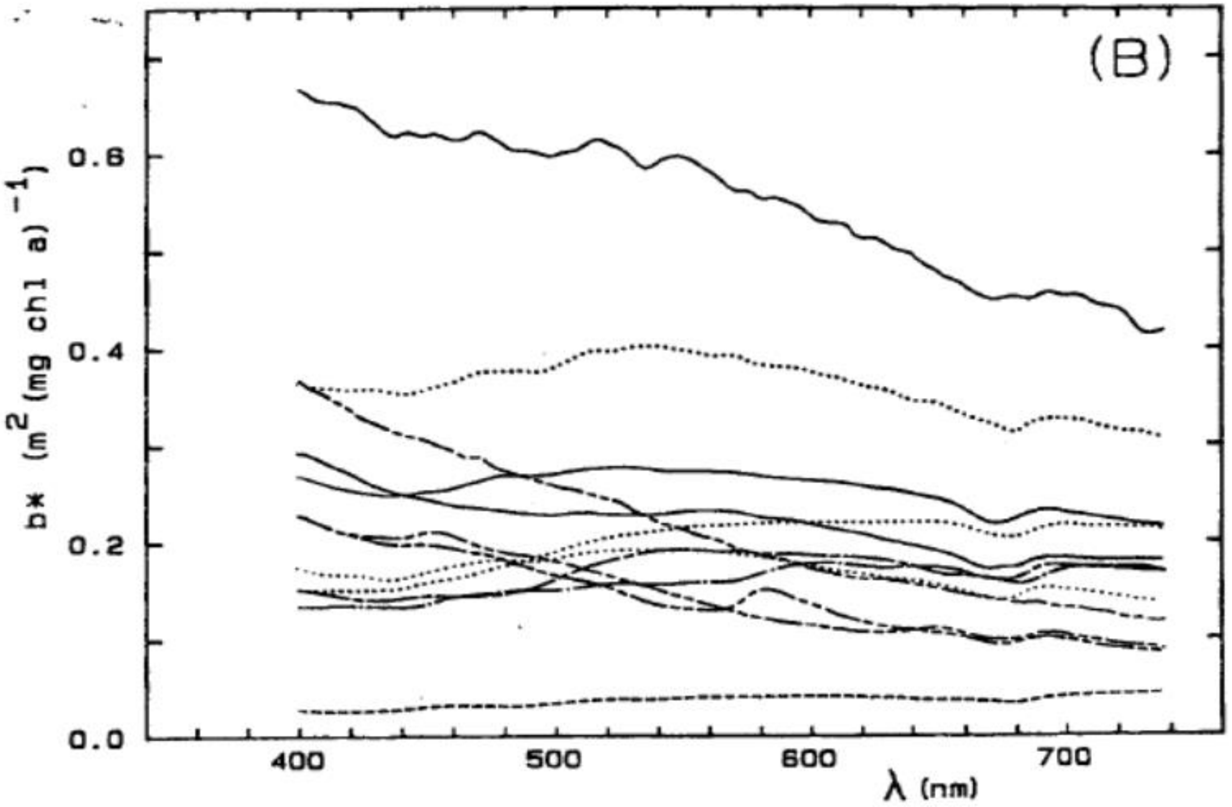
$$b_{bw}(\lambda) = 0.0023\left(\frac{450}{\lambda}\right)^{4.32}$$

(Morel 1974)

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

(Zhang et al, 2009)

Spectrum of scattering coefficient

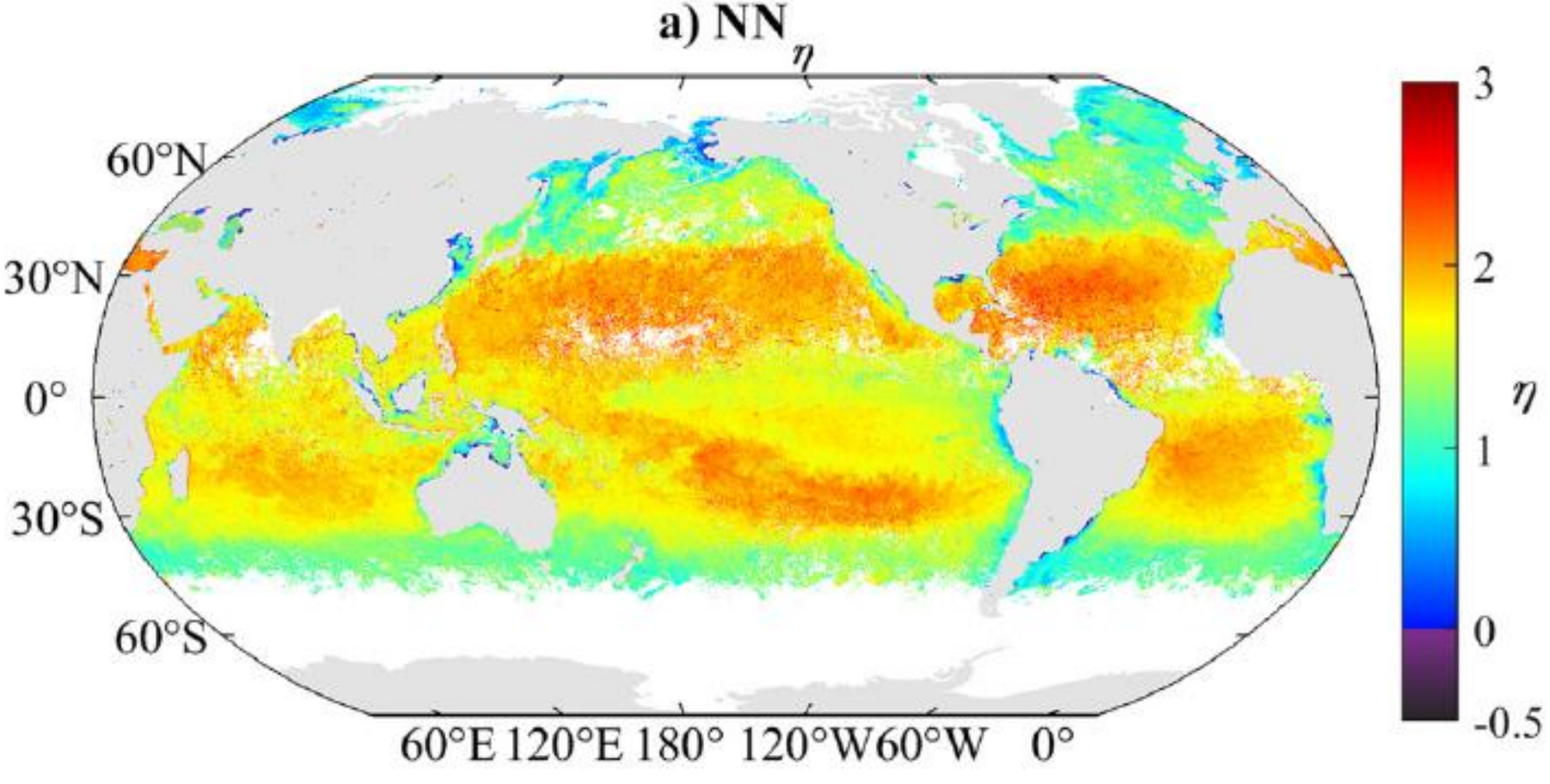


(Bricaud et al 1988)

weakly wavelength dependent

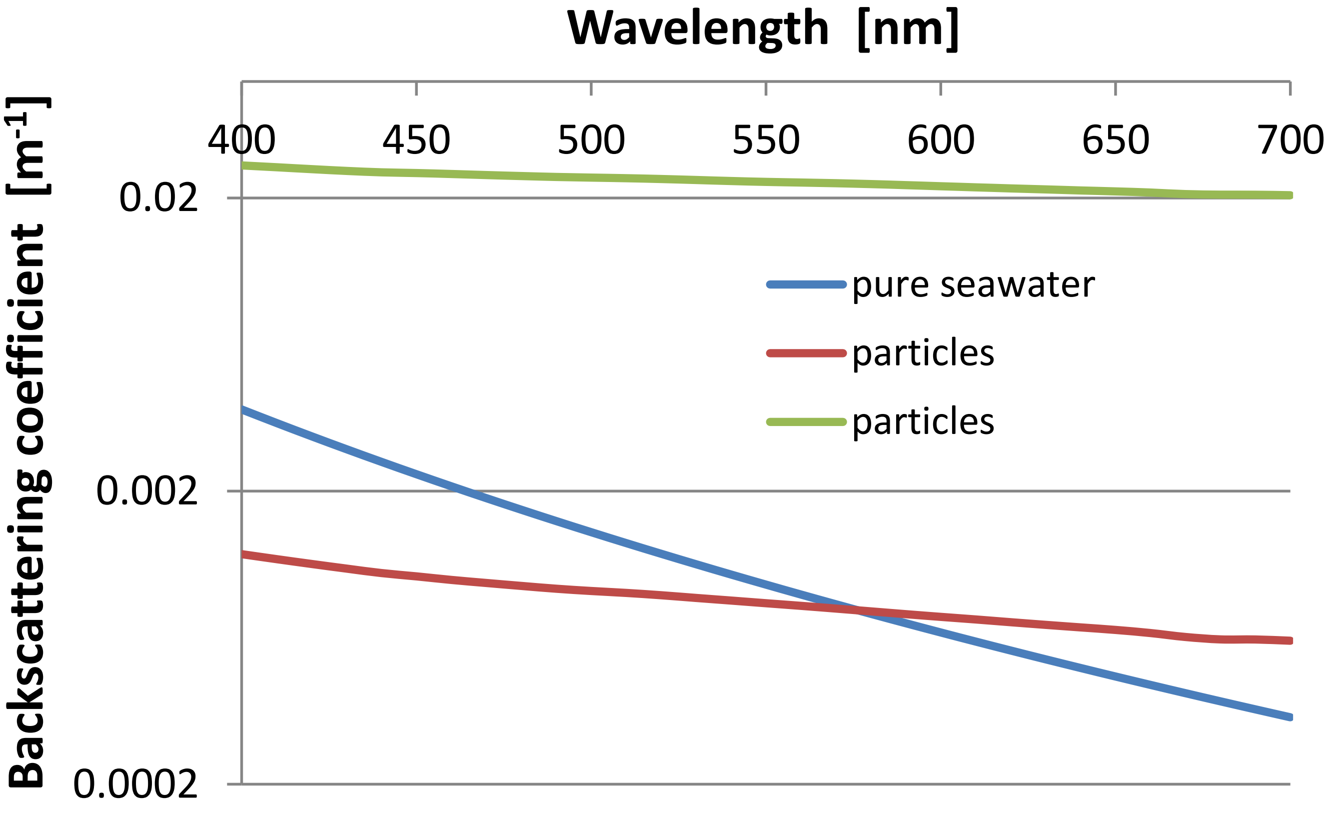
$$b_{bp}(\lambda) = b_{bp}(\lambda_0)\left(\frac{\lambda_0}{\lambda}\right)^{\eta}$$

η: ~0-2.0



(Yu et al. 2023)

b_b spectrum contrast

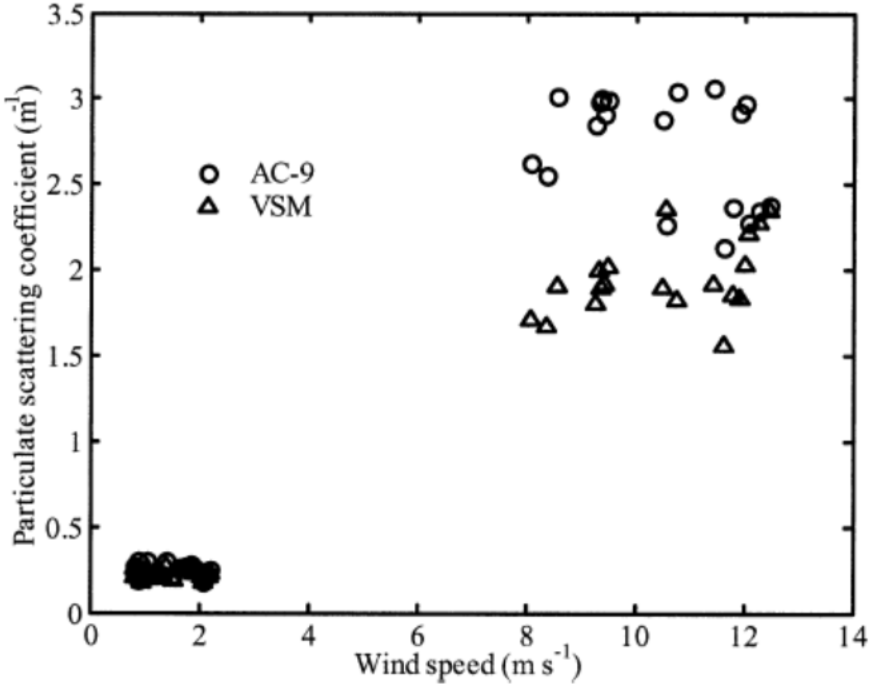


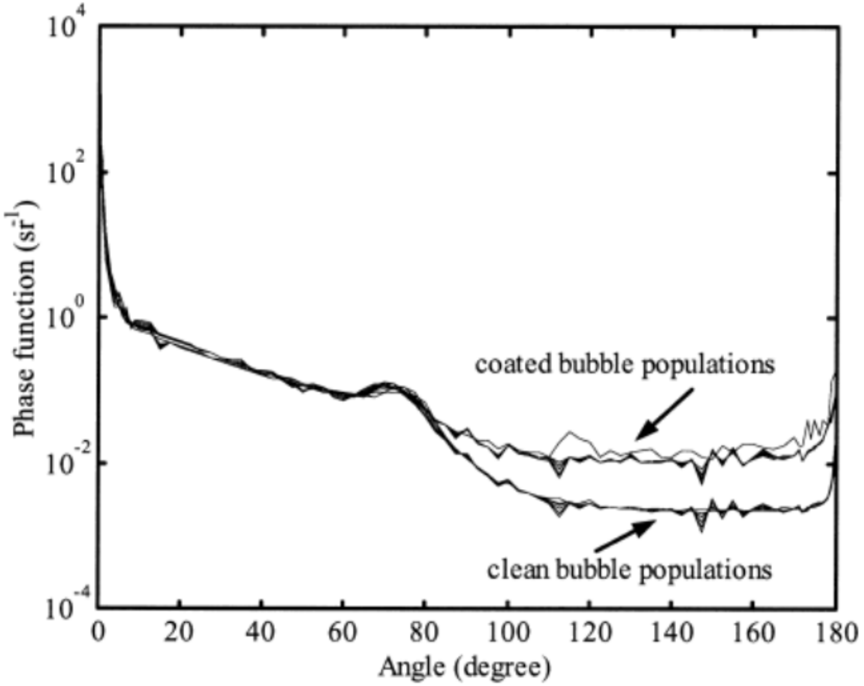
$$b_{bp}(\lambda) = b_0 \left(\frac{\lambda_0}{\lambda} \right)^{\eta}$$

b_{bw}: ~0.0001 – 0.004 m^{-1}

η: ~0-2.0

bubbles

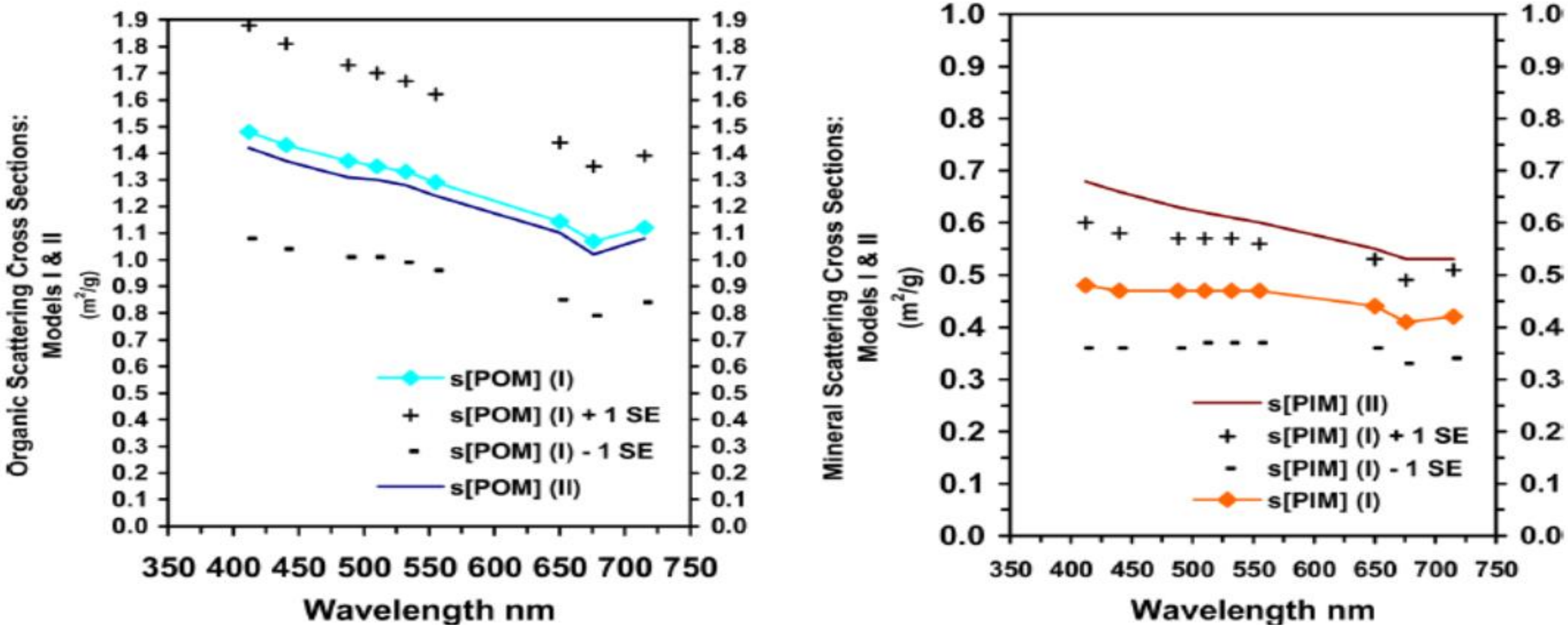




(Zhang et al 2002)

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

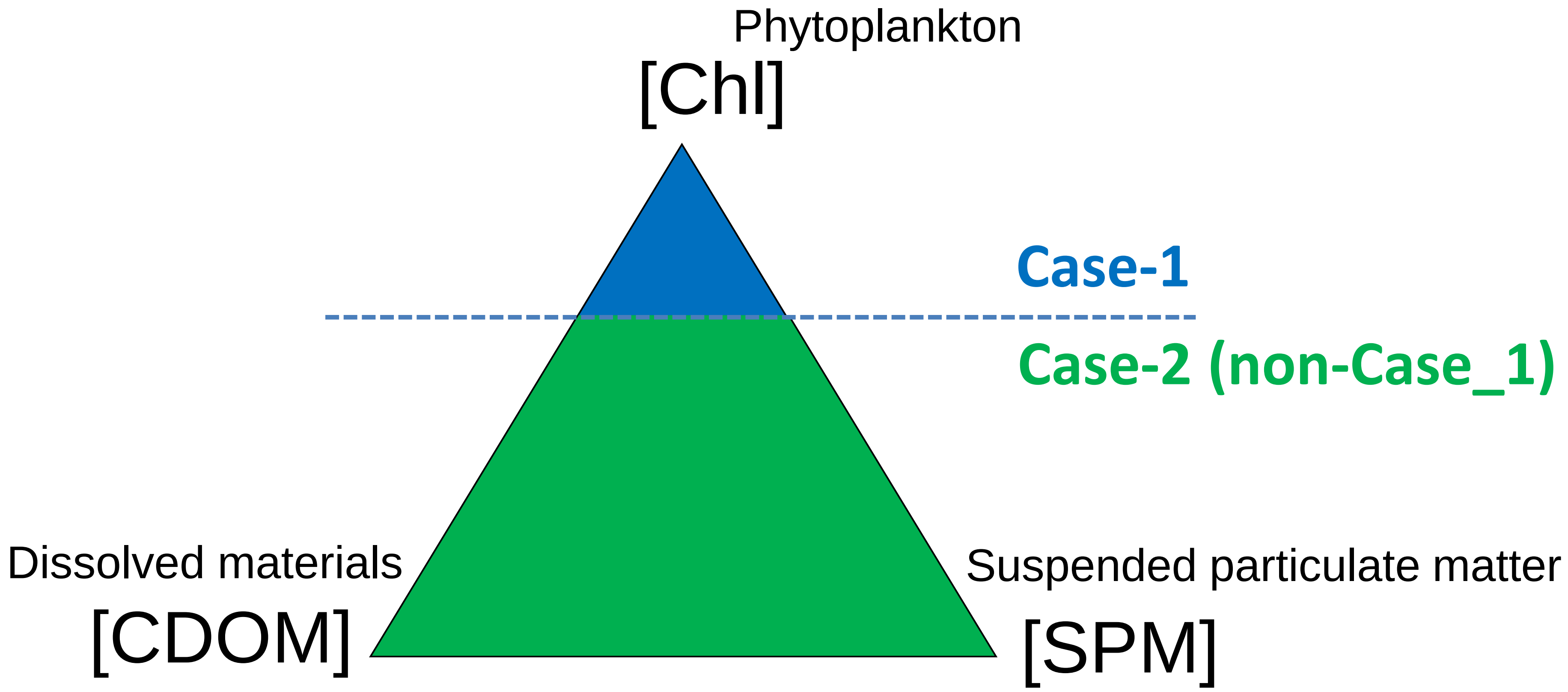
Organic vs inorganic separation



(Stavn and Richter 2008)

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.

(IOCCG Report #3, 2000)

Has nothing to do with location or value of [Chl].

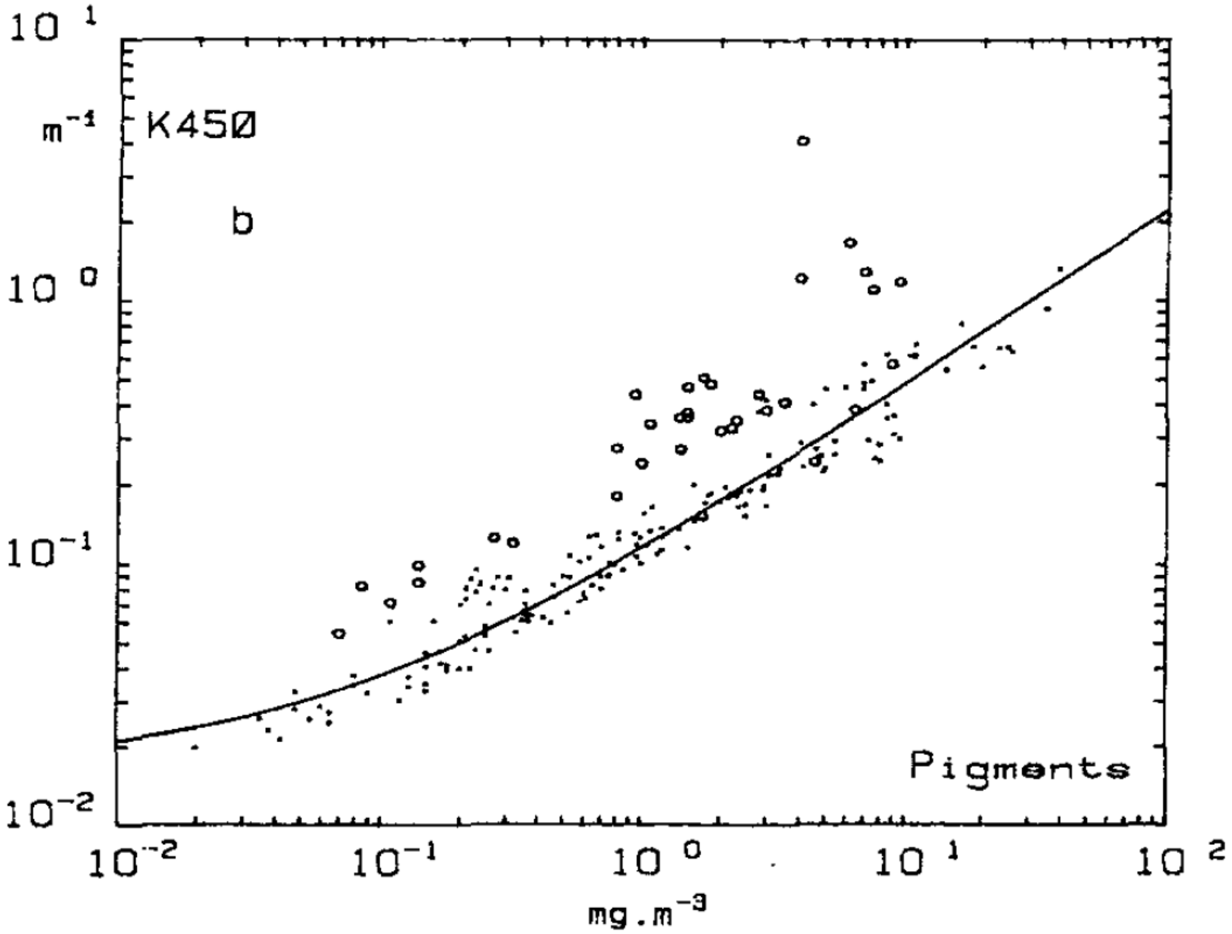
Quantitatively

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

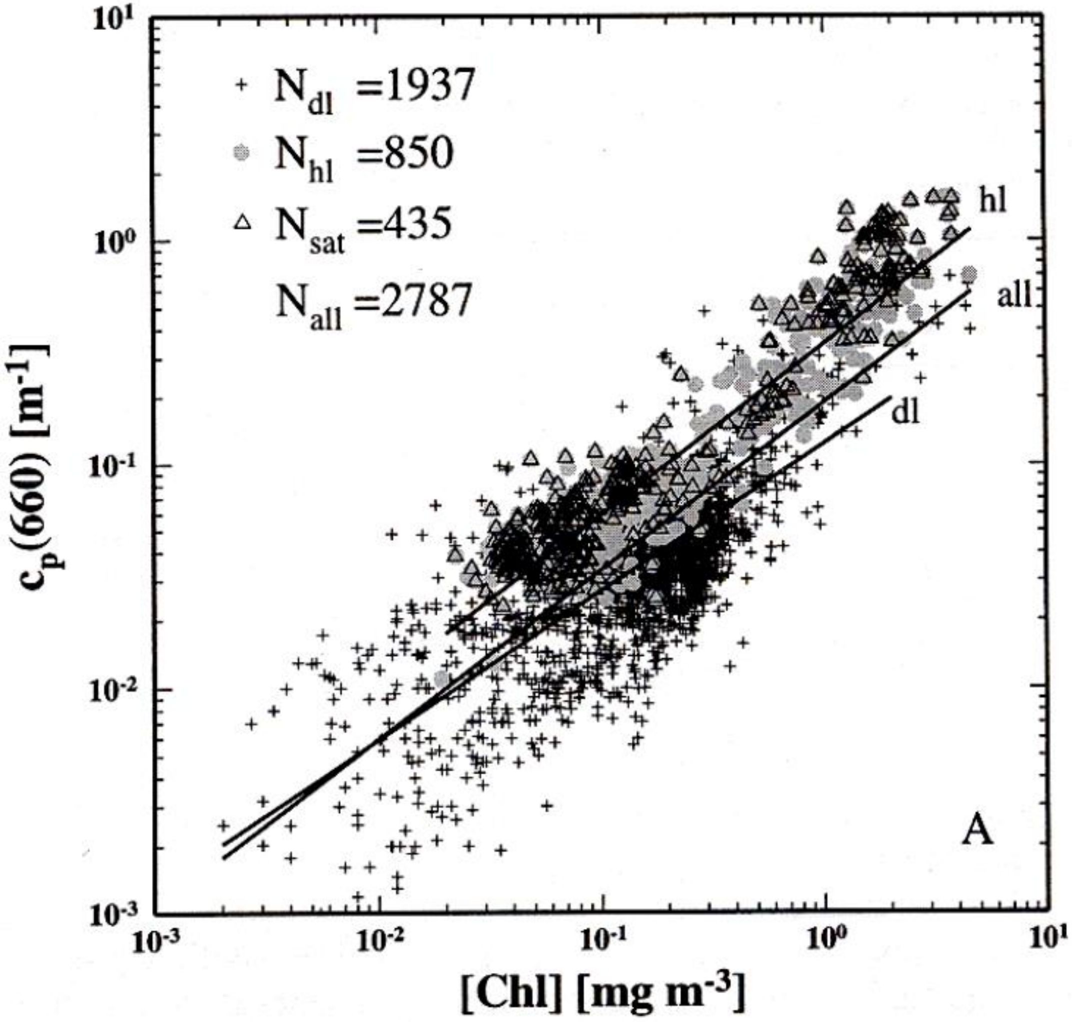
André Morel

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

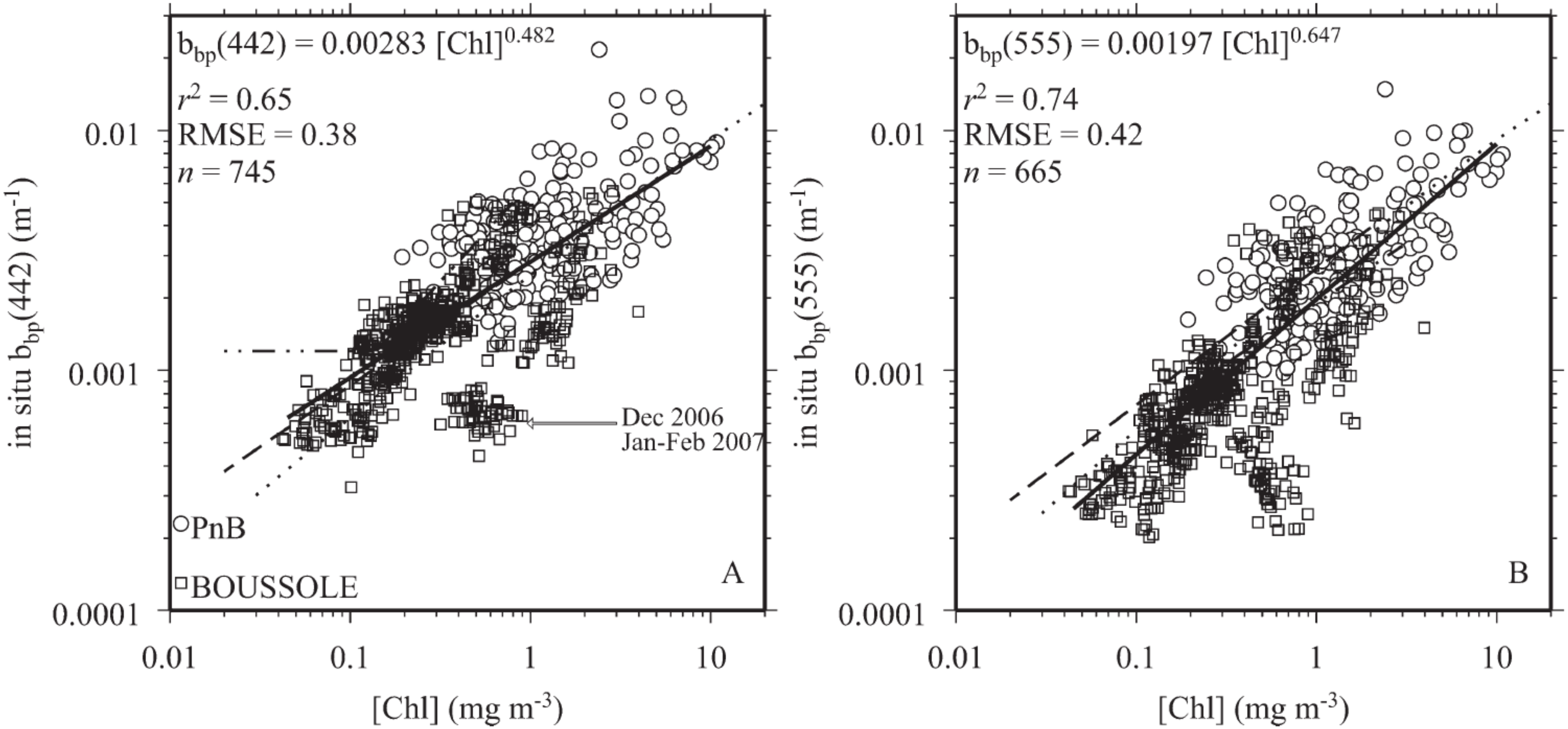
$$K(\lambda) = K_w(\lambda) + K_{\text{bio}}(\lambda).$$



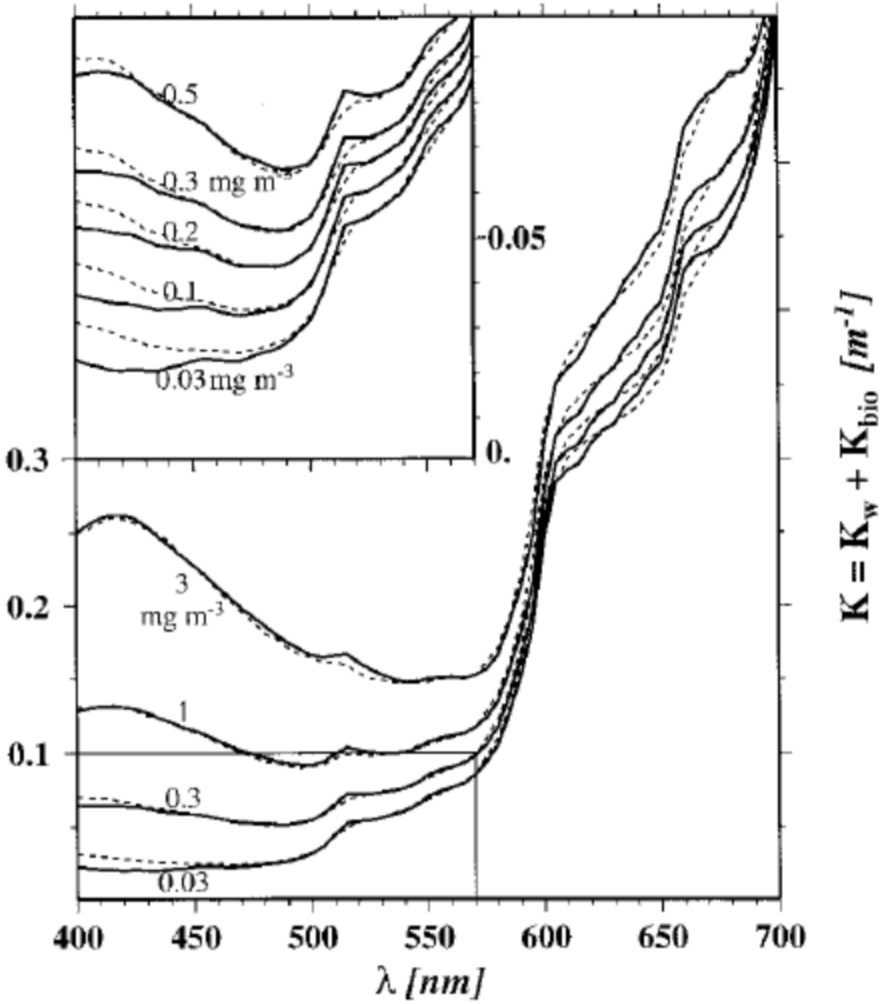
(Morel 1988)

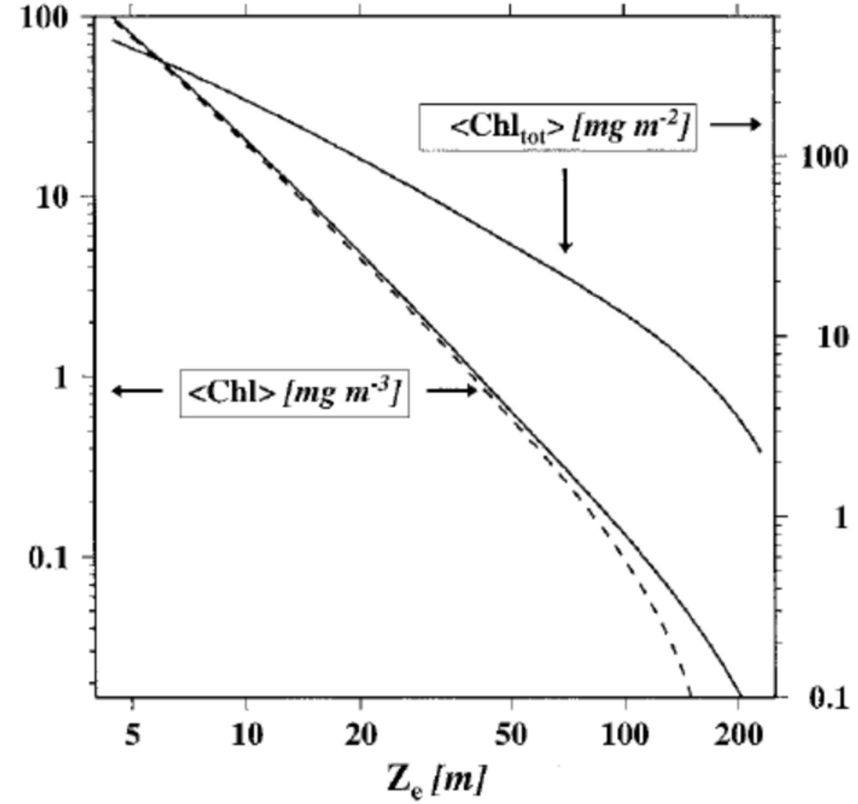


(Loisel and Morel, 1998)

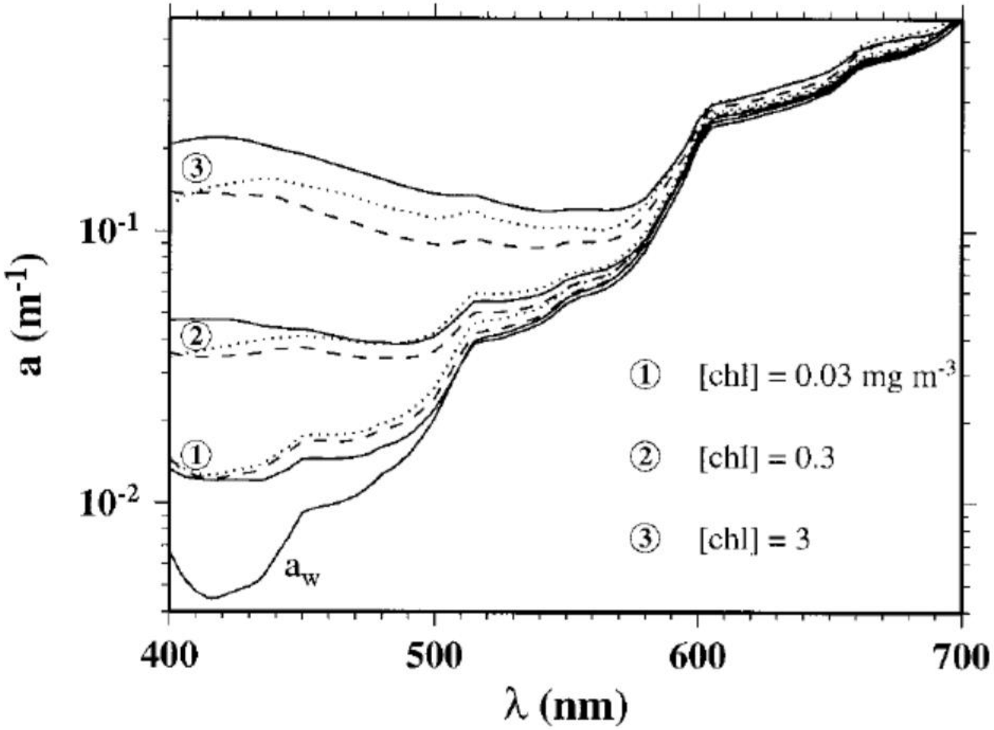


(Antoine et al., 2011)

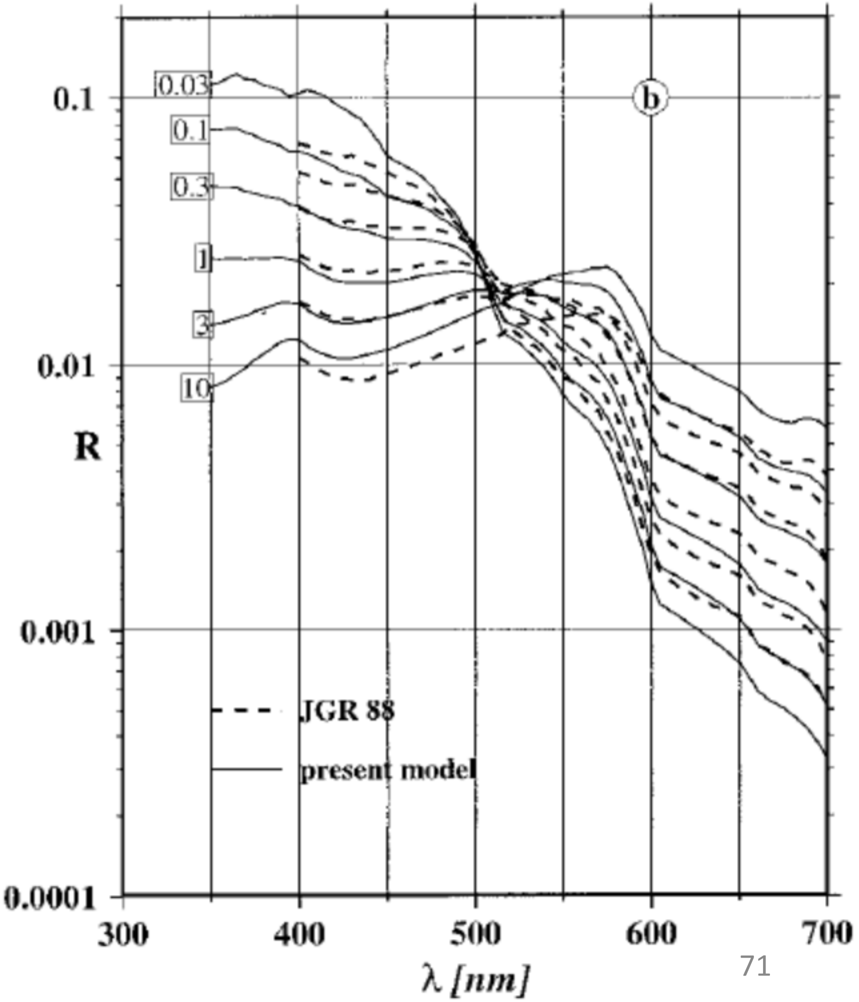




(Morel 1988,2001)



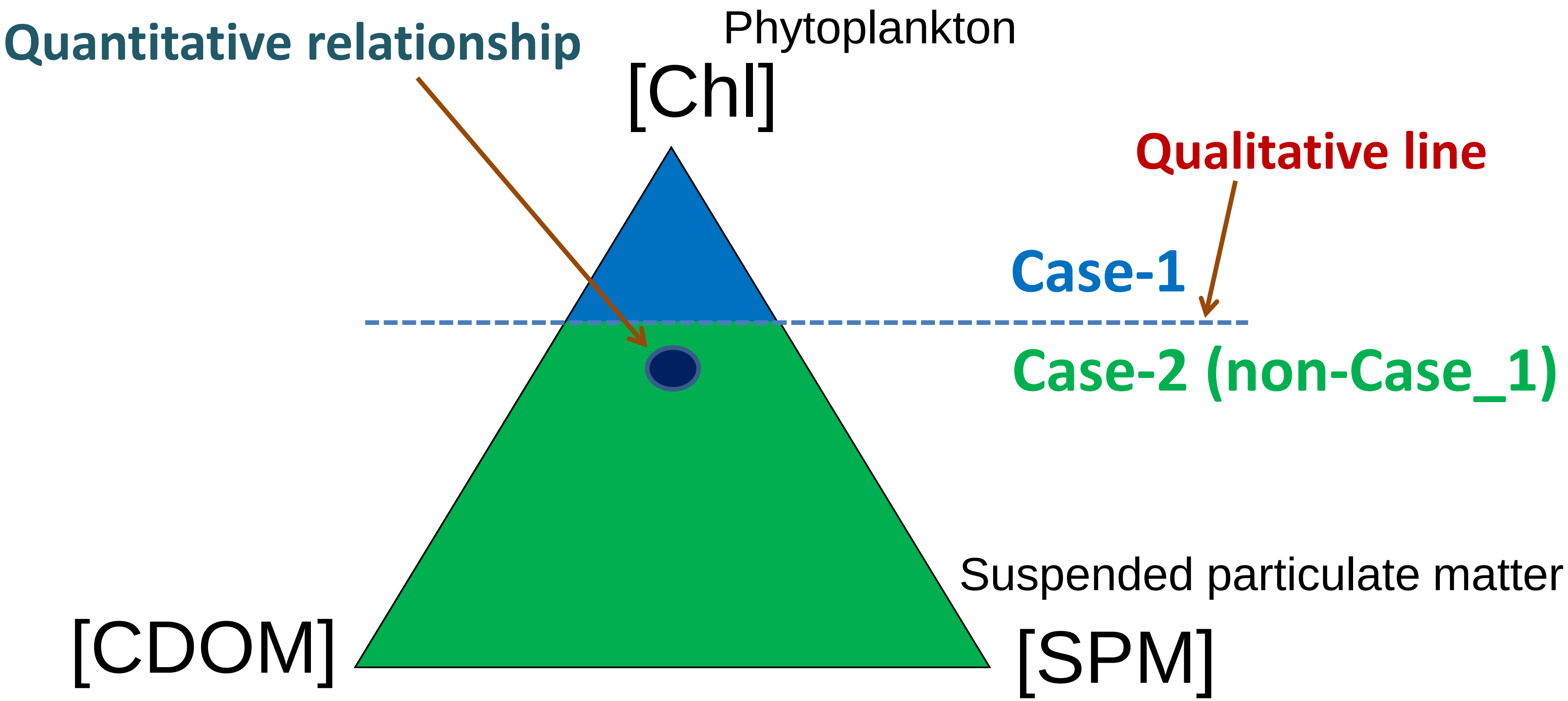
(Morel and Maritorena 2001)



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

One-variable water.

Case-1 / Case-2 concept



Quantitative relationship

Phytoplankton

[Chl]

Qualitative line

Case-1

Case-2 (non-Case_1)

Suspended particulate matter

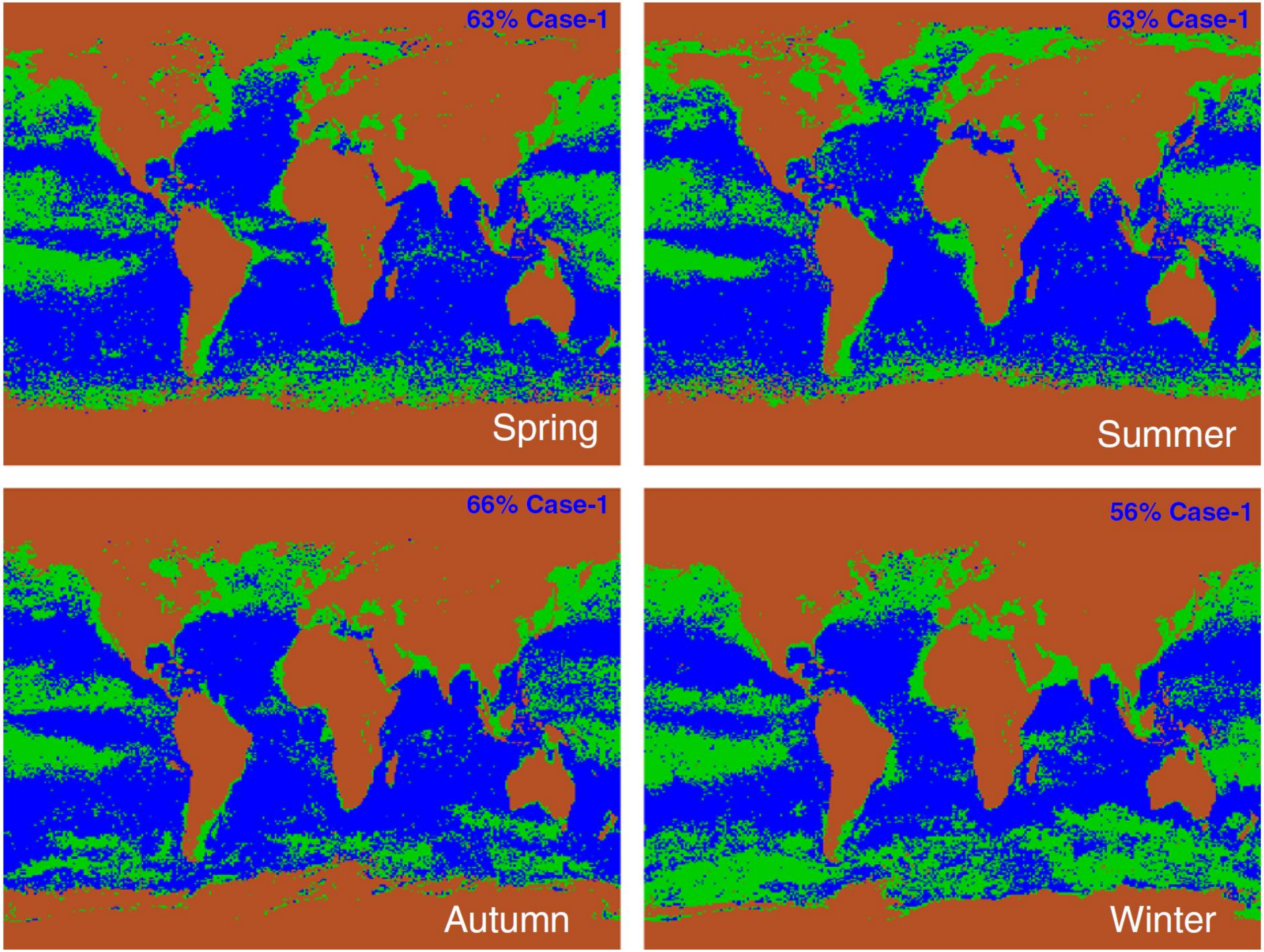
[CDOM]

[SPM]

Quantitative Case-1:

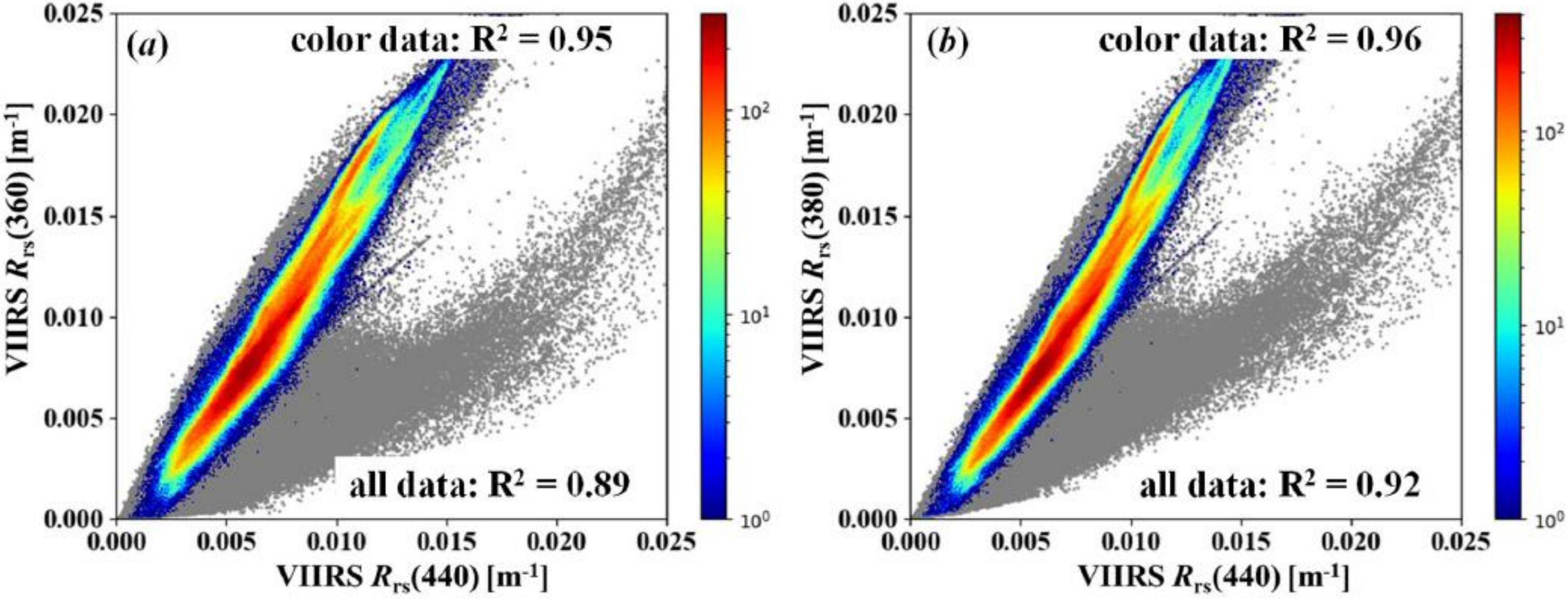
IOPs, AOPs = empirical function([Chl])

Global distribution of “Case-1” waters



(Lee and Hu, 2006)

UV bands?



(Wang et al 2021)

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, constituents.

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.

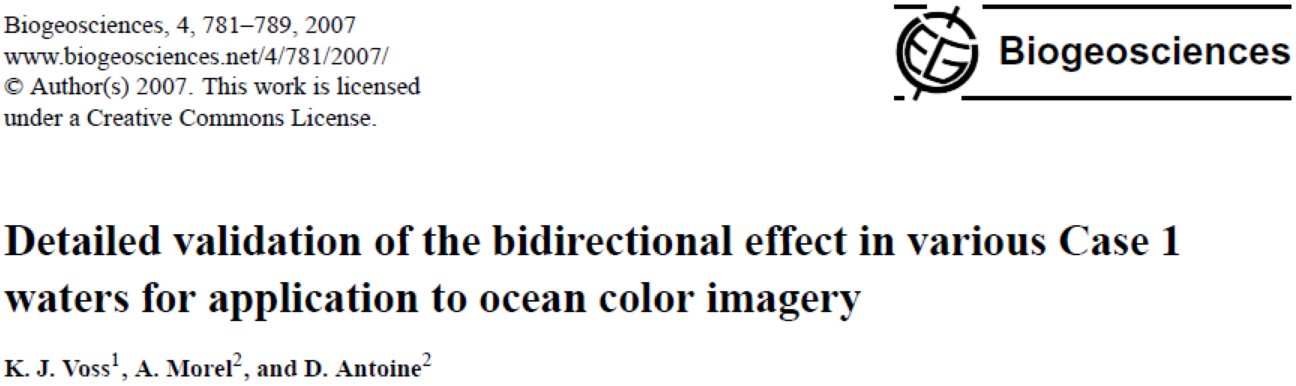
6. Spectrally,
water molecules are strong absorber in the longer wavelengths;
phytoplankton absorption generally has two distinct peaks with a stronger peak centered around 440 nm and weaker peak centered around 675 nm; have varying spectral shapes
detritus and gelbstoff are strong absorbers in the shorter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

7. “Case-1” definition is not based on location, nor based on values of [Chl].

There are statistical relationships between IOPs/AOPs and [Chl] for “Case-1” waters, but inversely, oceanic waters are not necessarily “Case-1”, coastal/inland waters are not necessarily “Case-2”.

References (in the order of citation):



Biogeosciences, 4, 781–789, 2007
www.biogeosciences.net/4/781/2007/
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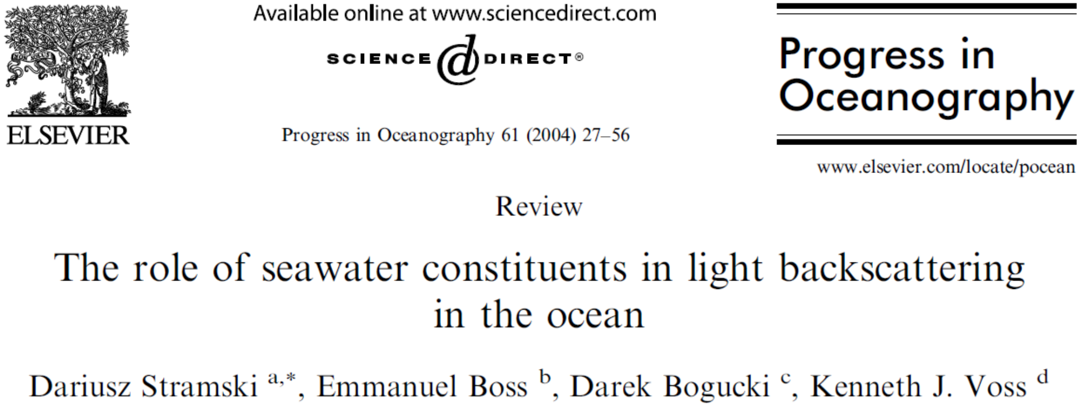
Biogeosciences

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

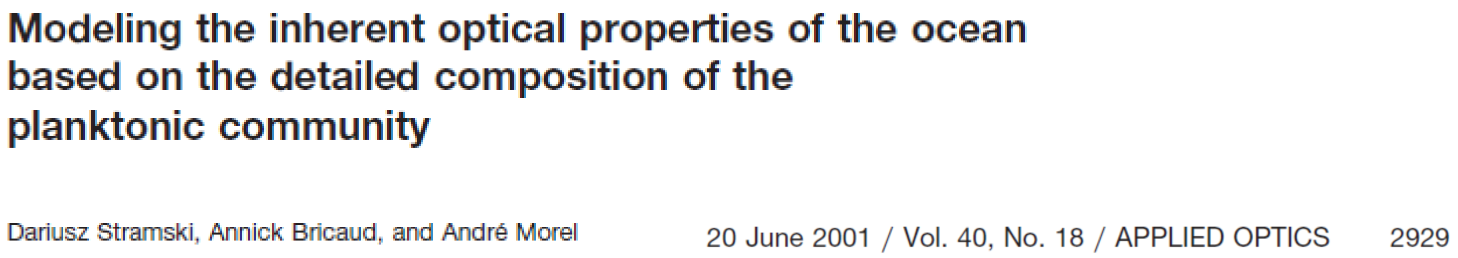
Progress in Oceanography

www.elsevier.com/locate/pocean

Review

The role of seawater constituents in light backscattering in the ocean

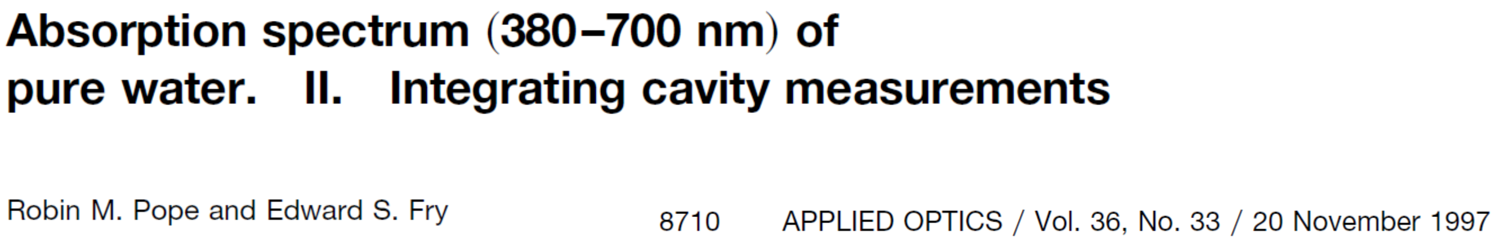
Dariusz Stramski [a,*], Emmanuel Boss [b], Darek Bogucki [c], Kenneth J. Voss [d]



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

Dariusz Stramski, Annick Bricaud, and André Morel

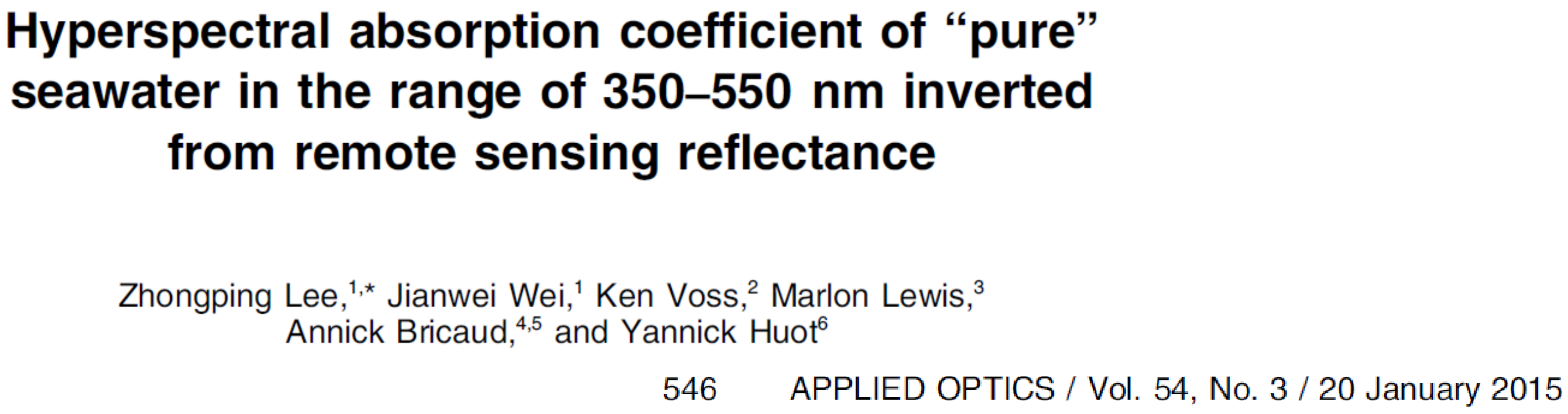
20 June 2001 / Vol. 40, No. 18 / APPLIED OPTICS 2929



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

Robin M. Pope and Edward S. Fry

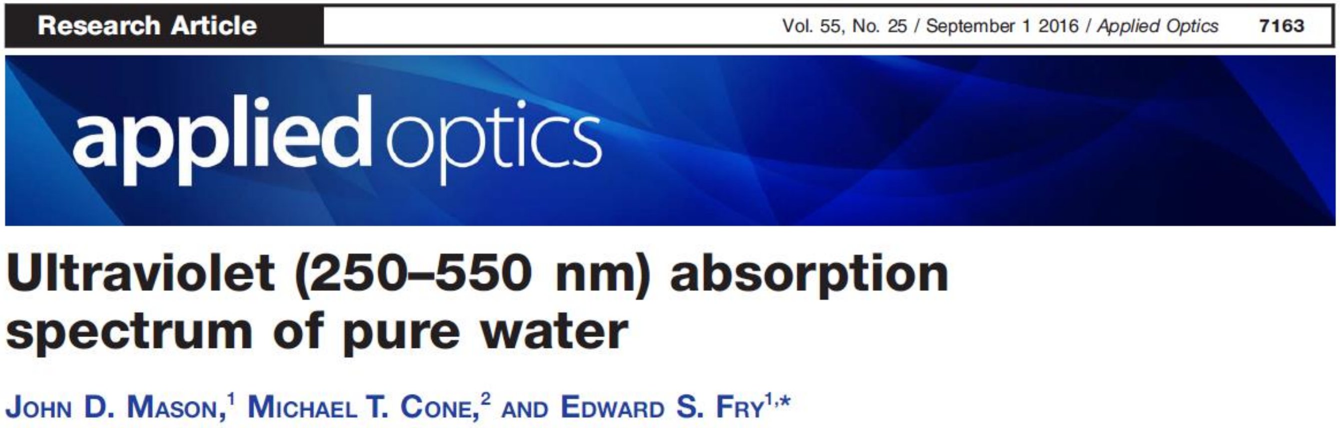
8710 APPLIED OPTICS / Vol. 36, No. 33 / 20 November 1997



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]

546 APPLIED OPTICS / Vol. 54, No. 3 / 20 January 2015

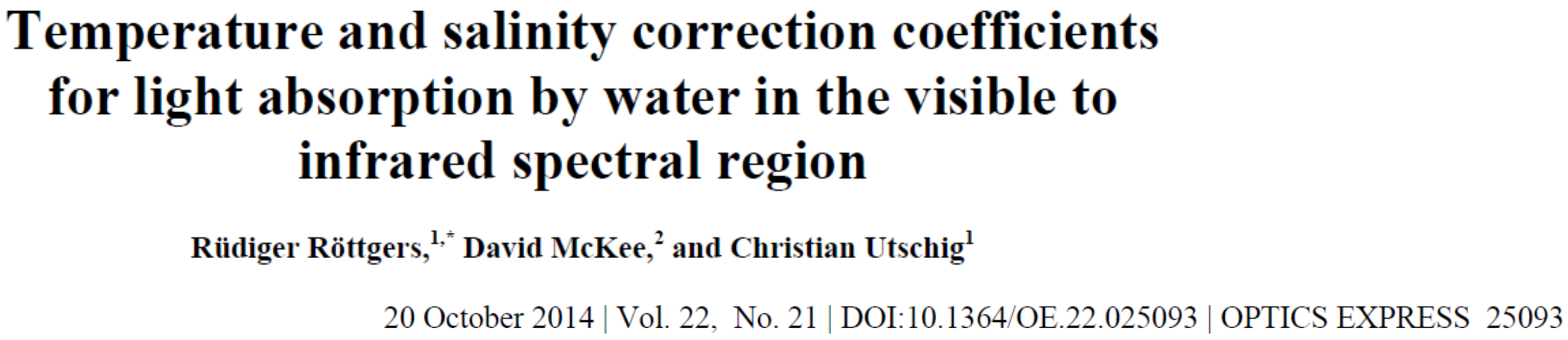


Research Article Vol. 55, No. 25 / September 1 2016 / *Applied Optics* **7163**

applied optics

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

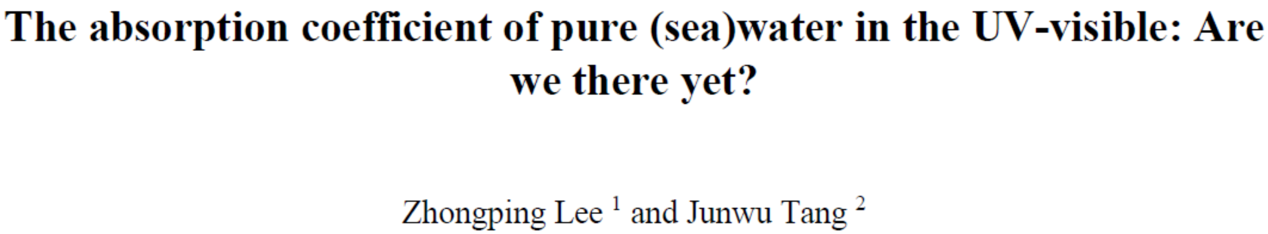
JOHN D. MASON,[1] MICHAEL T. CONE,[2] AND EDWARD S. FRY[1,*]



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

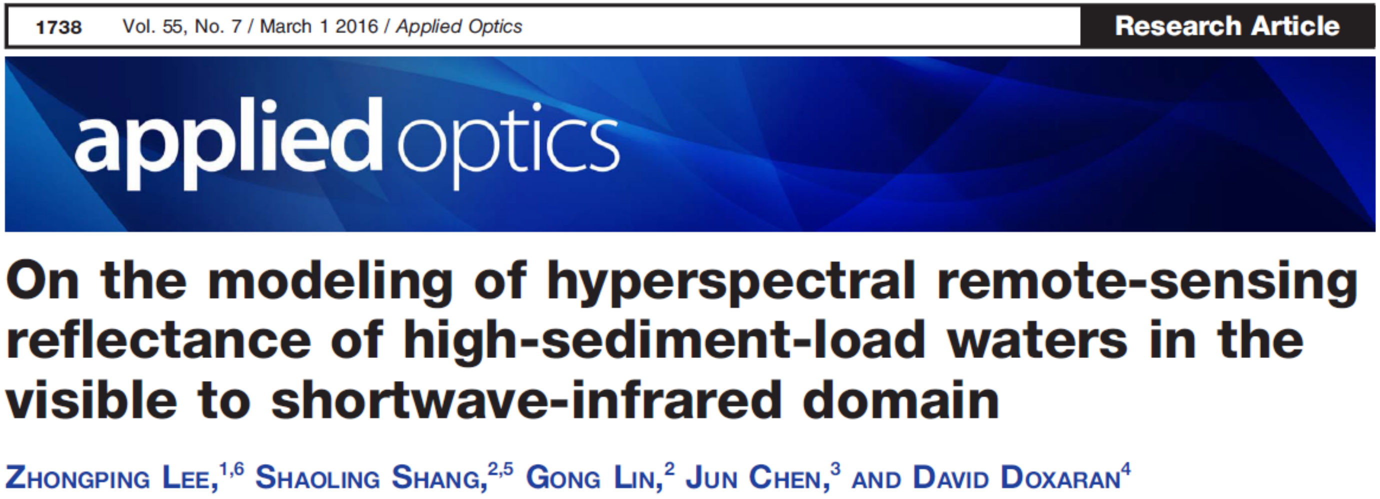
Rüdiger Röttgers,[1,*] David McKee,[2] and Christian Utschig[1]

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

applied optics

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]

Refractive indices of water and ice in the 0.65- to 2.5-μm spectral range

Linhong Kou, Daniel Labrie, and Petr Chylek

1 July 1993 / Vol. 32, No. 19 / APPLIED OPTICS 3531

Temperature influence on light absorption by fresh water and seawater in the visible and near-infrared spectrum

Ib Trabjerg and Niels K. Højerslev

20 May 1996 / Vol. 35, No. 15 / APPLIED OPTICS 2653

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

Journal of Remote Sensing
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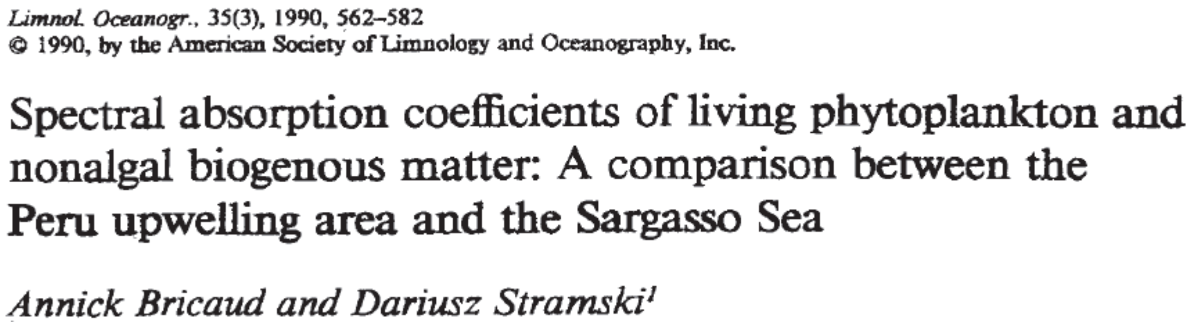
Research Article

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

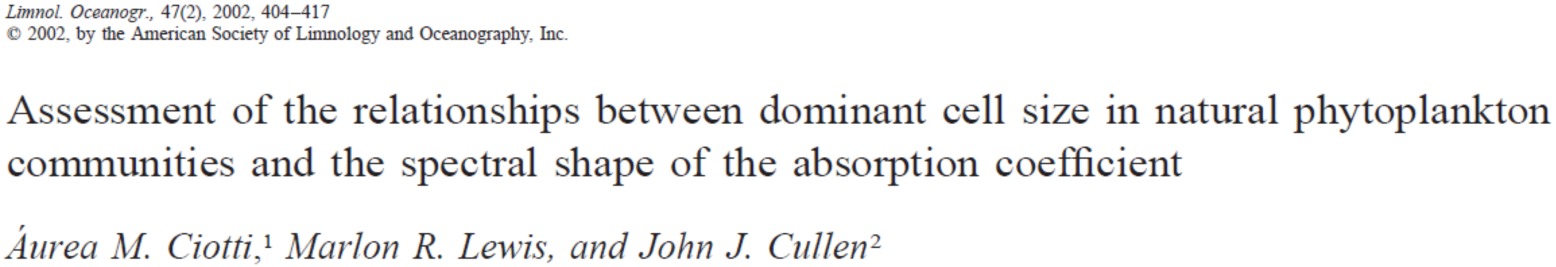
**Guomei Wei,[1,2] Zhongping Lee,[3] Xiuling Wu,[1] Xiaolong Yu,[1] Shaoling Shang,[1]
and Ricardo Letelier[4]**



Limnol. Oceanogr., 35(3), 1990, 562–582

Spectral absorption coefficients of living phytoplankton and nonalgal biogenous matter: A comparison between the Peru upwelling area and the Sargasso Sea

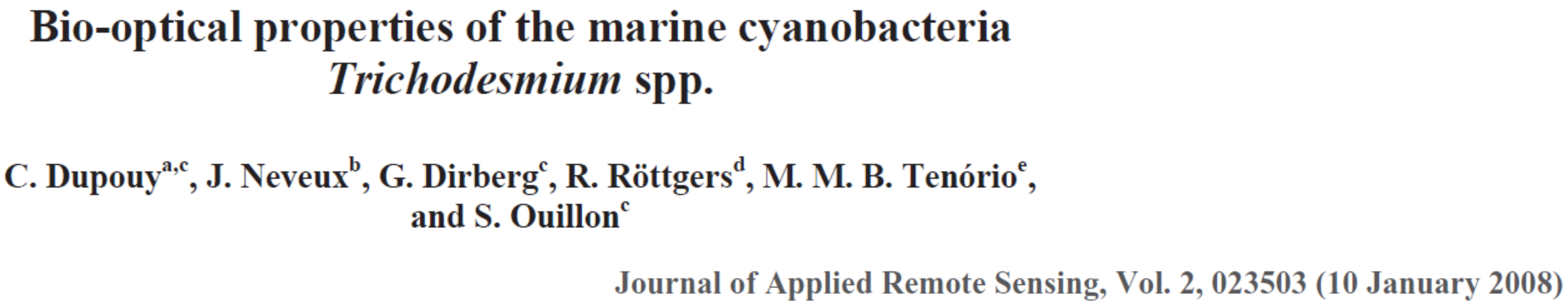
Annick Bricaud and Dariusz Stramski[1]



Limnol. Oceanogr., 47(2), 2002, 404–417

Assessment of the relationships between dominant cell size in natural phytoplankton communities and the spectral shape of the absorption coefficient

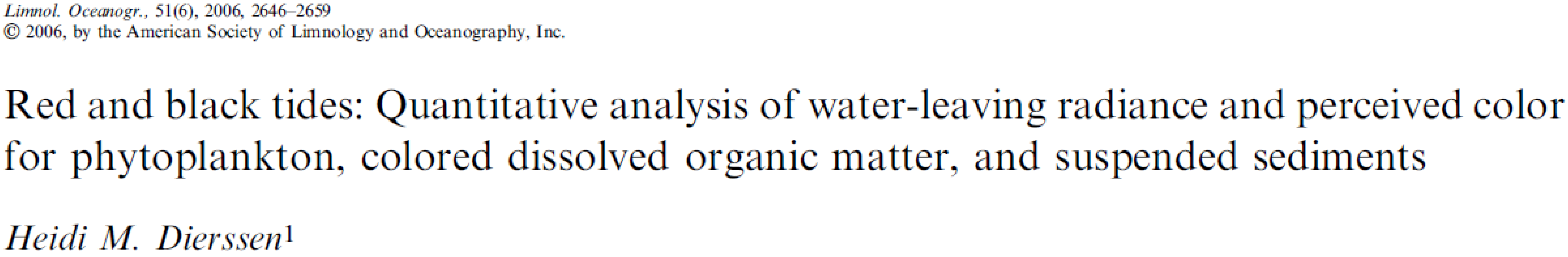
Áurea M. Ciotti,[1] *Marlon R. Lewis, and John J. Cullen*[2]



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]

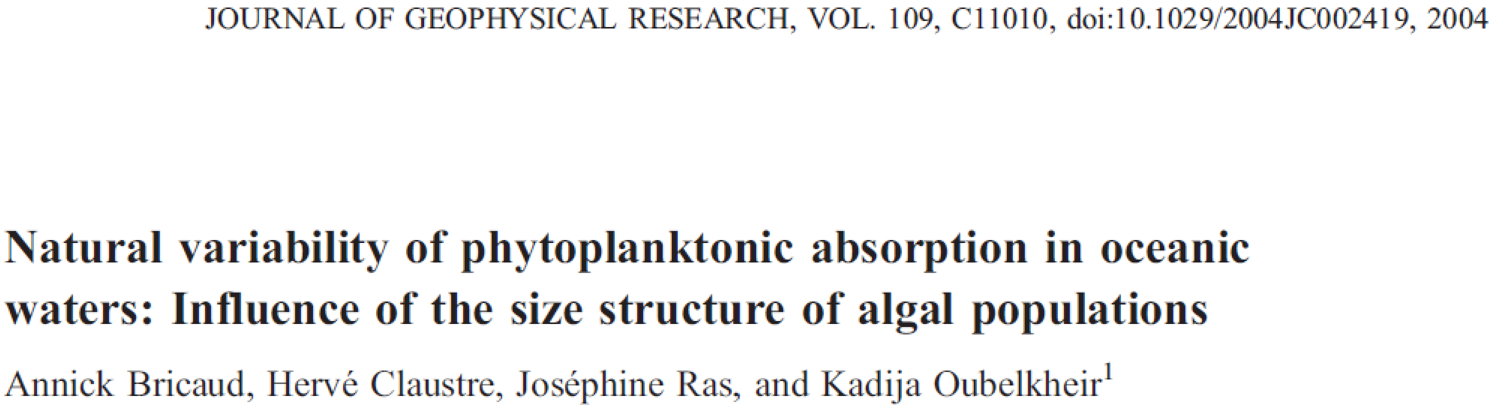
Journal of Applied Remote Sensing, Vol. 2, 023503 (10 January 2008)



Limnol. Oceanogr., 51(6), 2006, 2646–2659

Red and black tides: Quantitative analysis of water-leaving radiance and perceived color for phytoplankton, colored dissolved organic matter, and suspended sediments

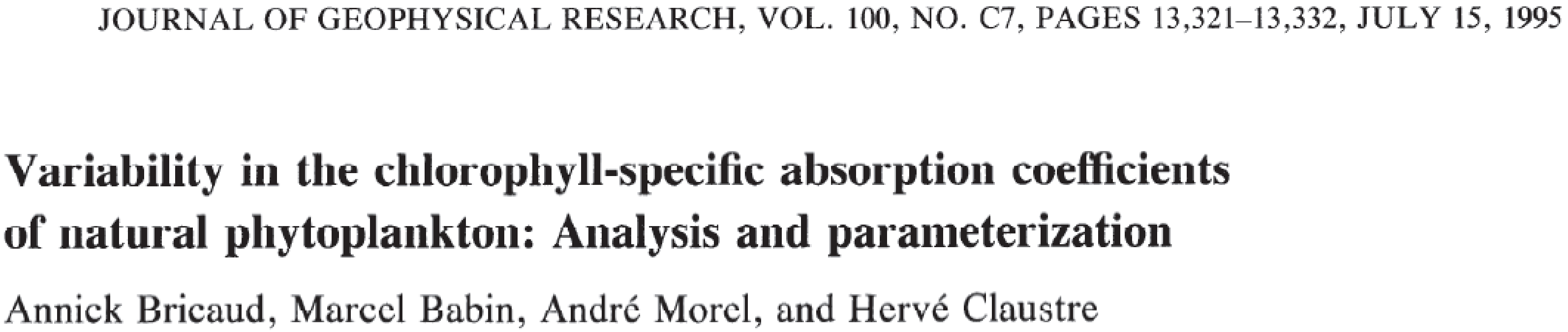
Heidi M. Dierssen[1]



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, C11010, doi:10.1029/2004JC002419, 2004

Natural variability of phytoplanktonic absorption in oceanic waters: Influence of the size structure of algal populations

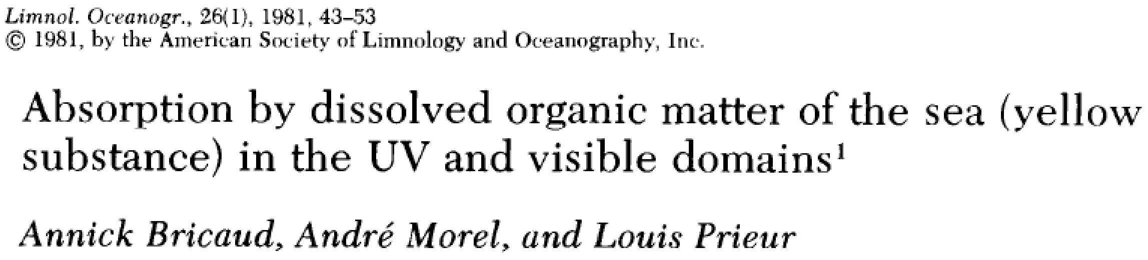
Annick Bricaud, Hervé Claustre, Joséphine Ras, and Kadija Oubelkheir[1]



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. C7, PAGES 13,321–13,332, JULY 15, 1995

Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: Analysis and parameterization

Annick Bricaud, Marcel Babin, André Morel, and Hervé Claustre



Limnol. Oceanogr., 26(1), 1981, 43–53
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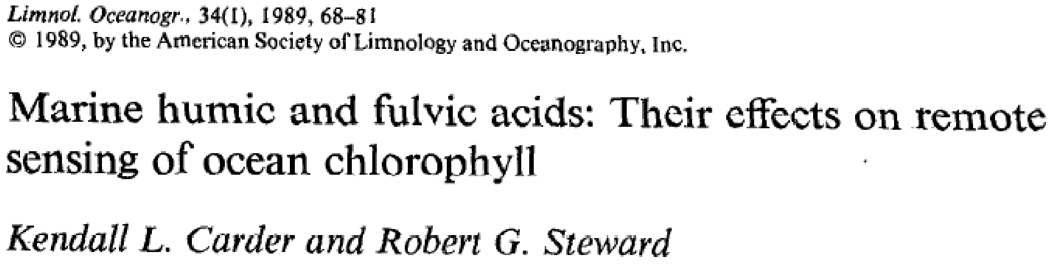
Absorption by dissolved organic matter of the sea (yellow substance) in the UV and visible domains[1]

Annick Bricaud, André Morel, and Louis Prieur



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Marine humic and fulvic acids: Their effects on remote sensing of ocean chlorophyll

Kendall L. Carder and Robert G. Steward

[BOOK] **Light** and photosynthesis in aquatic ecosystems
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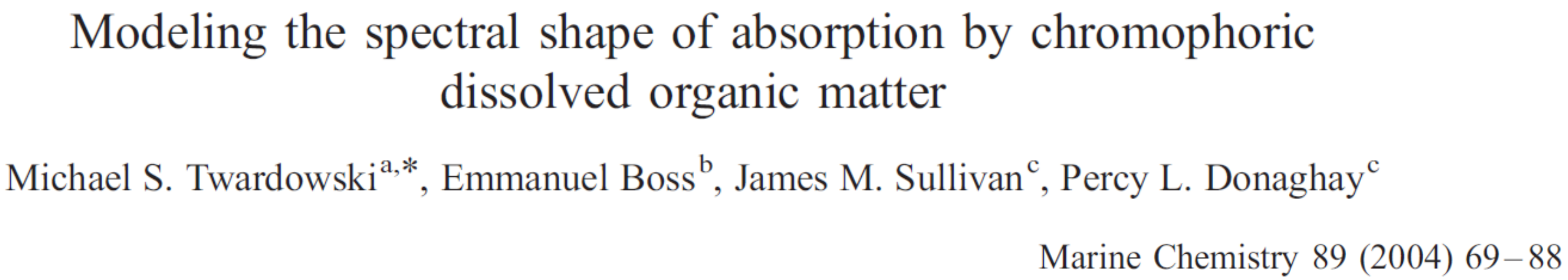
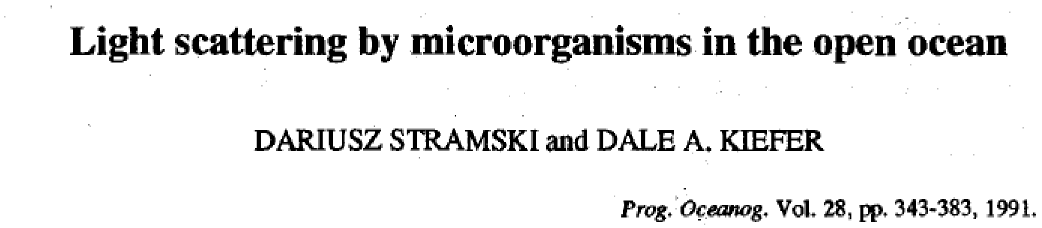


Modeling the spectral shape of absorption by chromophoric dissolved organic matter

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

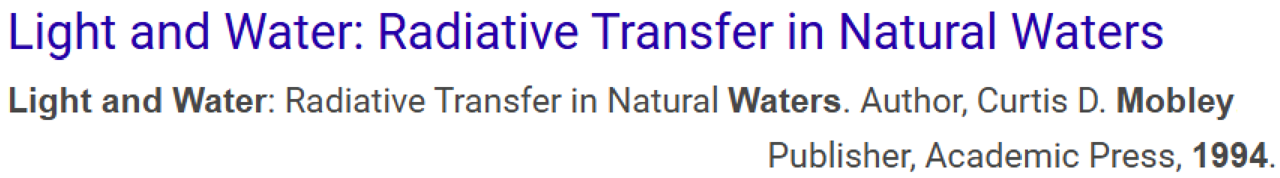
Marine Chemistry 89 (2004) 69–88



Light scattering by microorganisms in the open ocean

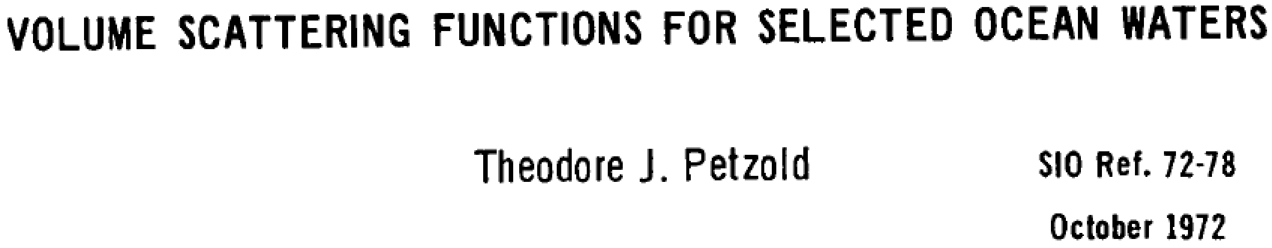
DARIUSZ STRAMSKI and DALE A. KIEFER

Prog. Oceanog. Vol. 28, pp. 343-383, 1991.



Light and Water: Radiative Transfer in Natural Waters

Light and Water: Radiative Transfer in Natural **Waters**. Author, Curtis D. **Mobley**
Publisher, Academic Press, **1994**.

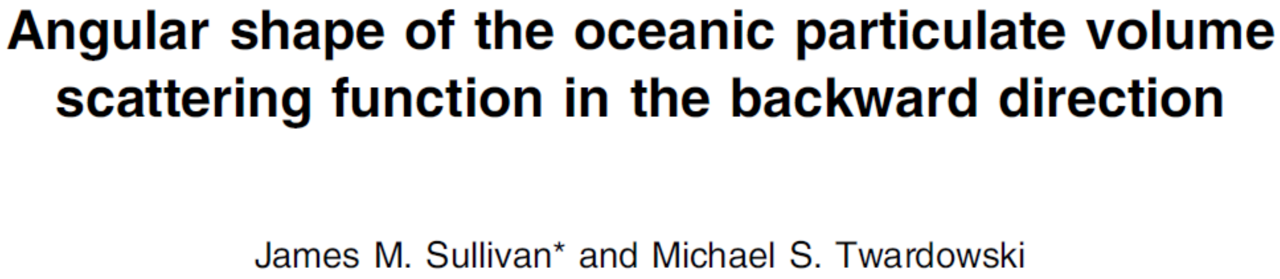


VOLUME SCATTERING FUNCTIONS FOR SELECTED OCEAN WATERS

Theodore J. Petzold

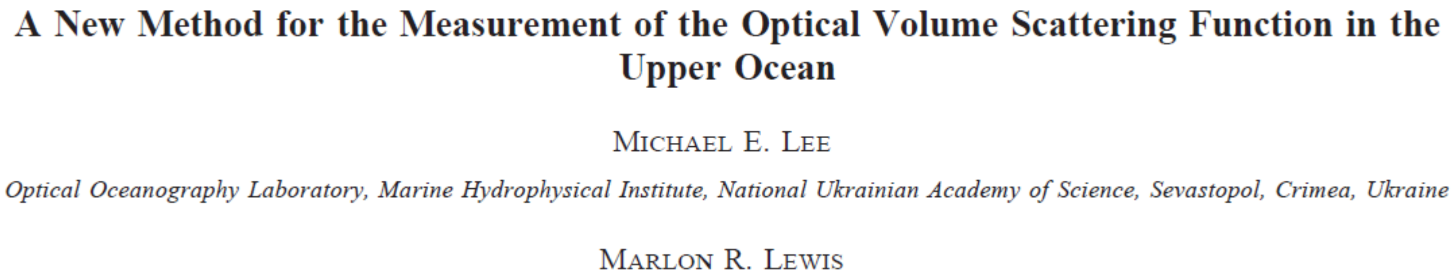
SIO Ref. 72-78

October 1972



Angular shape of the oceanic particulate volume scattering function in the backward direction

James M. Sullivan* and Michael S. Twardowski

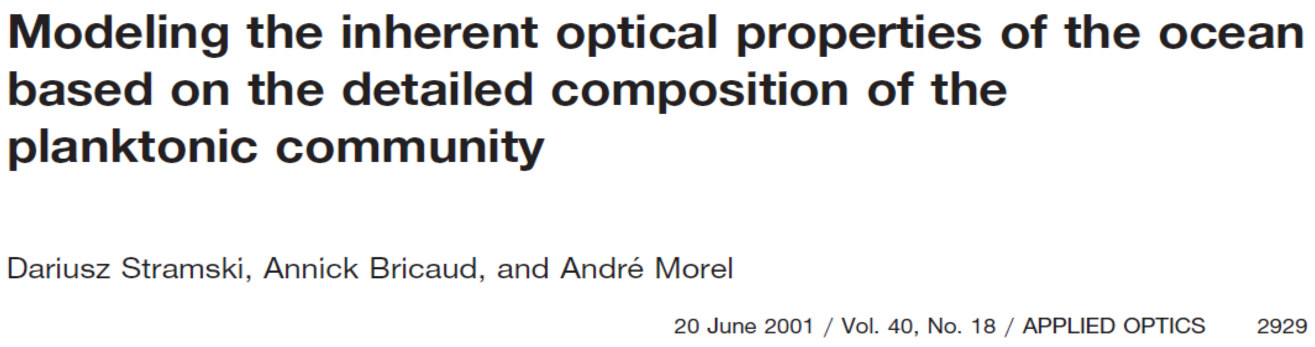


A New Method for the Measurement of the Optical Volume Scattering Function in the Upper Ocean

Michael E. Lee

Optical Oceanography Laboratory, Marine Hydrophysical Institute, National Ukrainian Academy of Science, Sevastopol, Crimea, Ukraine

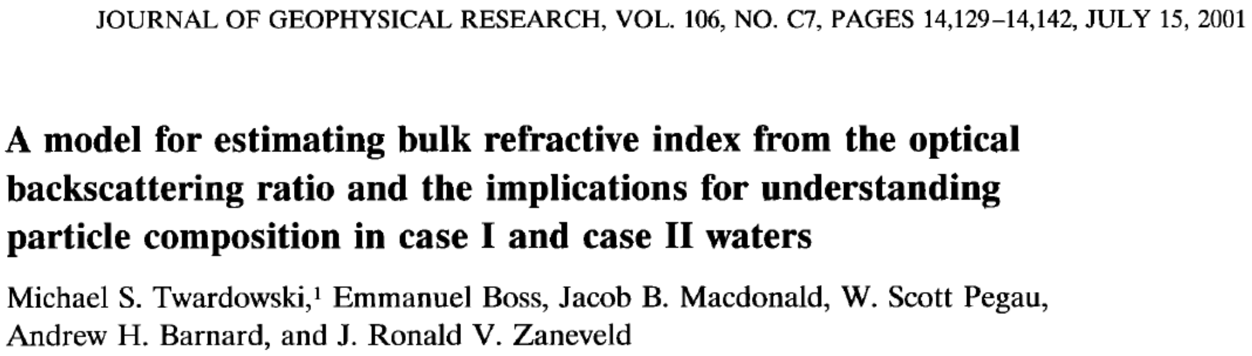
Marlon R. Lewis



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

Dariusz Stramski, Annick Bricaud, and André Morel

20 June 2001 / Vol. 40, No. 18 / APPLIED OPTICS 2929



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. C7, PAGES 14,129–14,142, JULY 15, 2001

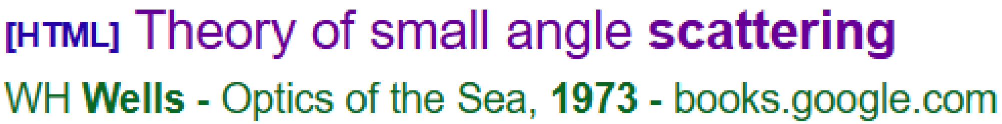
A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in case I and case II waters

Michael S. Twardowski,[1] Emmanuel Boss, Jacob B. Macdonald, W. Scott Pegau, Andrew H. Barnard, and J. Ronald V. Zaneveld

Journal of the Optical Society of America Vol. 59, Issue 4, pp. 373-377 (1969) • https://doi.org/10.1364/JOSA.59.000373

Theoretical Dependence of the Near-Asymptotic Apparent Optical Properties on the Inherent Optical Properties of Sea Water*

George F. Beardsley and J. Ronald V. Zaneveld



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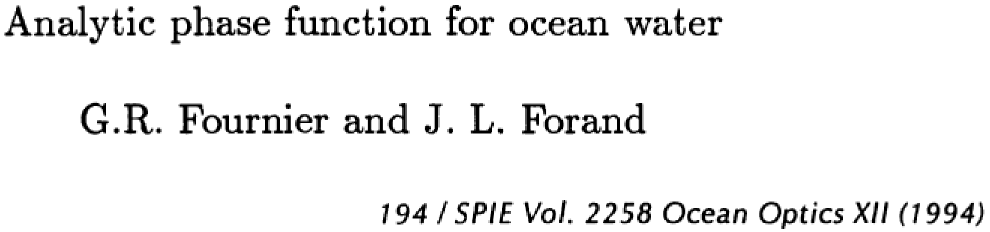

Analytic phase function for ocean water

G.R. Fournier and J. L. Forand

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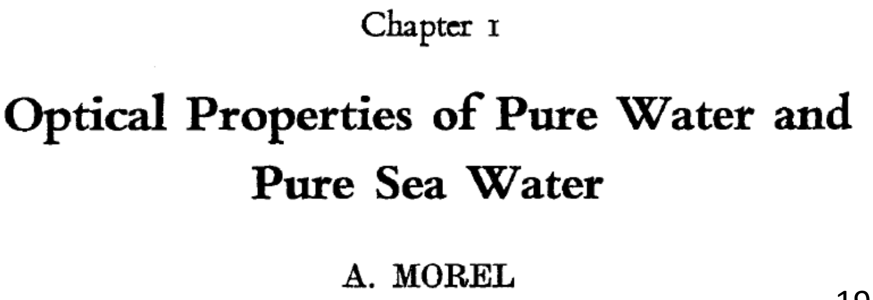

Chapter 1

Optical Properties of Pure Water and Pure Sea Water

A. MOREL

1974

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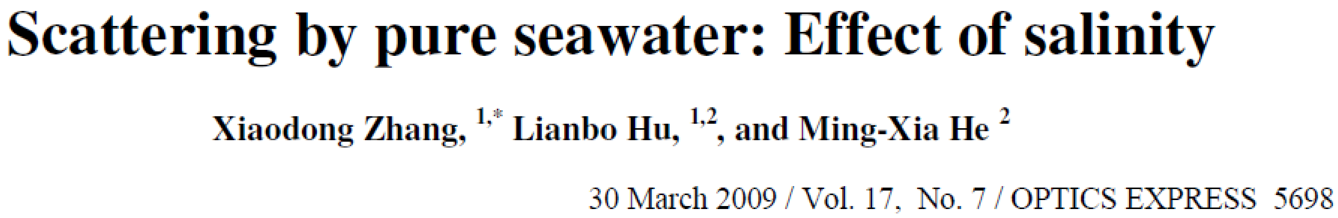
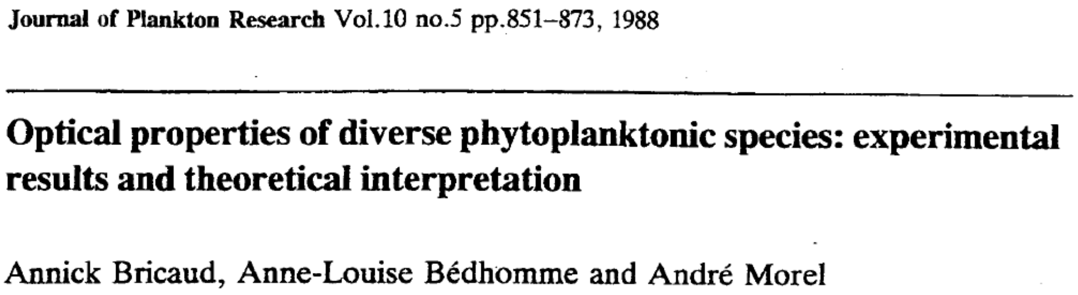


Scattering by pure seawater: Effect of salinity

Xiaodong Zhang,[1,*] Lianbo Hu,[1,2], and Ming-Xia He[2]

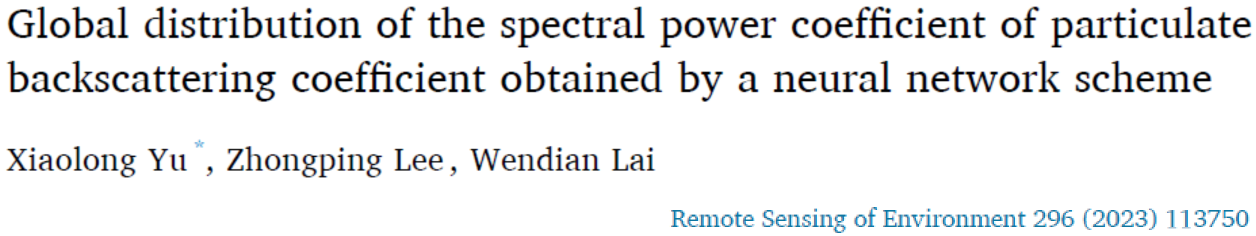
30 March 2009 / Vol. 17, No. 7 / OPTICS EXPRESS 5698



Journal of Plankton Research Vol.10 no.5 pp.851–873, 1988

Optical properties of diverse phytoplanktonic species: experimental results and theoretical interpretation

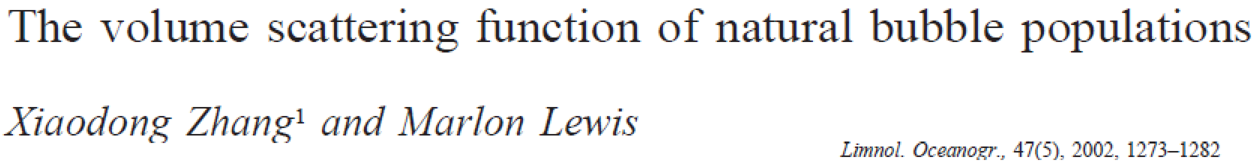
Annick Bricaud, Anne-Louise Bédhomme and André Morel



Global distribution of the spectral power coefficient of particulate backscattering coefficient obtained by a neural network scheme

Xiaolong Yu*, Zhongping Lee, Wendian Lai

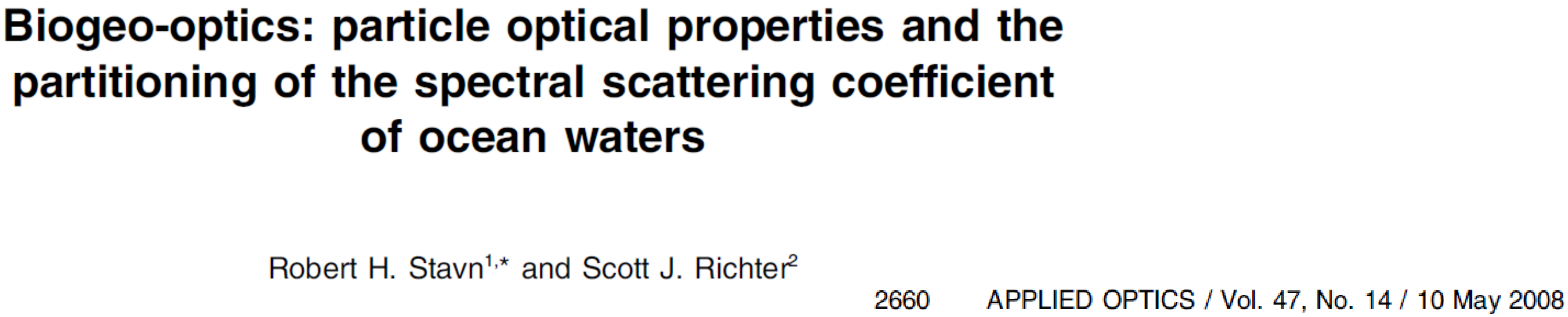
Remote Sensing of Environment 296 (2023) 113750



The volume scattering function of natural bubble populations

Xiaodong Zhang[1] and Marlon Lewis

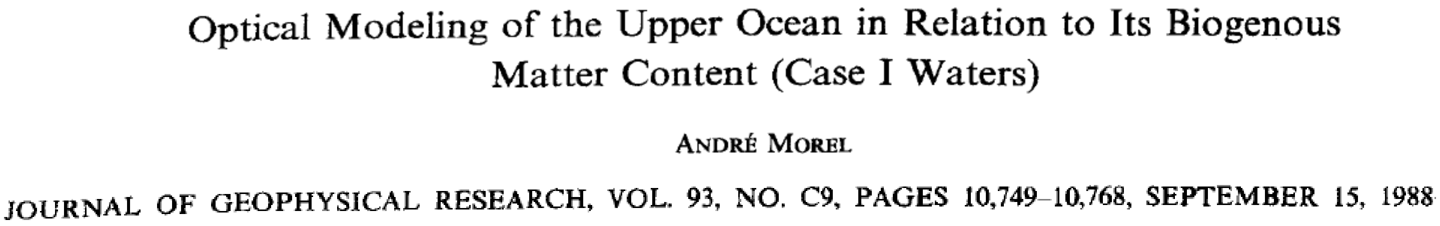
Limnol. Oceanogr., 47(5), 2002, 1273–1282



Biogeo-optics: particle optical properties and the partitioning of the spectral scattering coefficient of ocean waters

Robert H. Stavn[1,*] and Scott J. Richter[2]

2660 APPLIED OPTICS / Vol. 47, No. 14 / 10 May 2008



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

ANDRÉ MOREL

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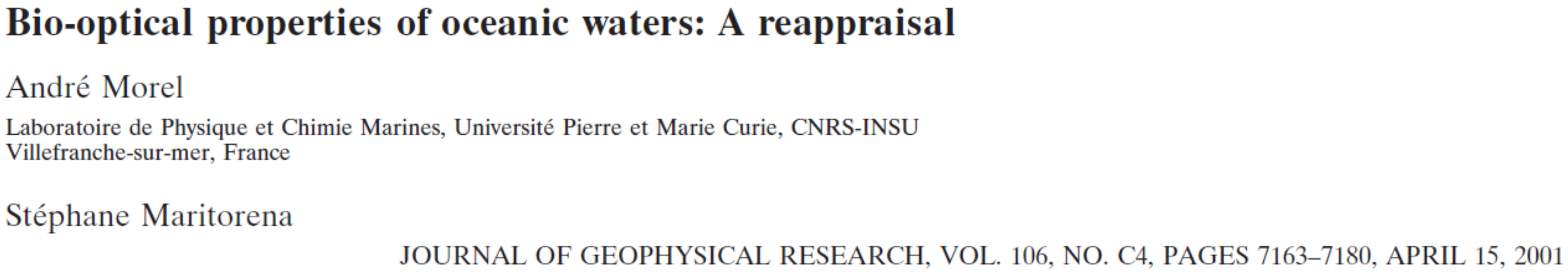

Bio-optical properties of oceanic waters: A reappraisal

André Morel

Laboratoire de Physique et Chimie Marines, Université Pierre et Marie Curie, CNRS-INSU
Villefranche-sur-mer, France

Stéphane Maritorena

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

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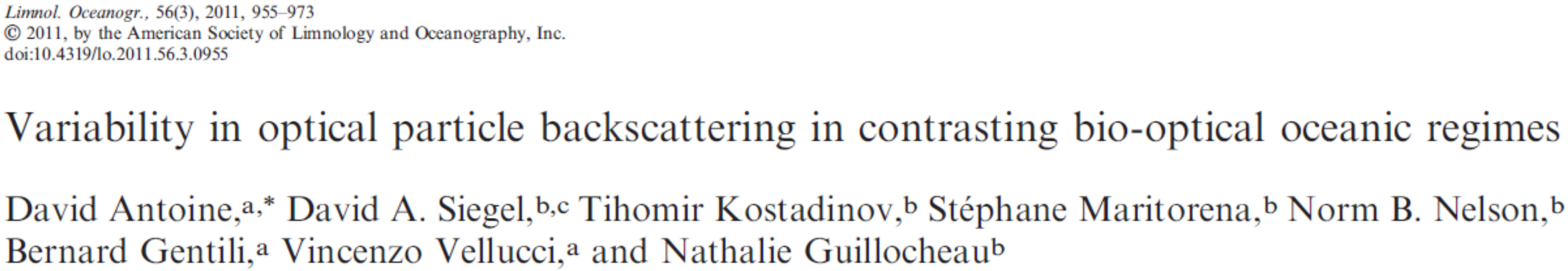
Light scattering and chlorophyll concentration in case 1 waters: A reexamination

Hubert Loisel and André Morel

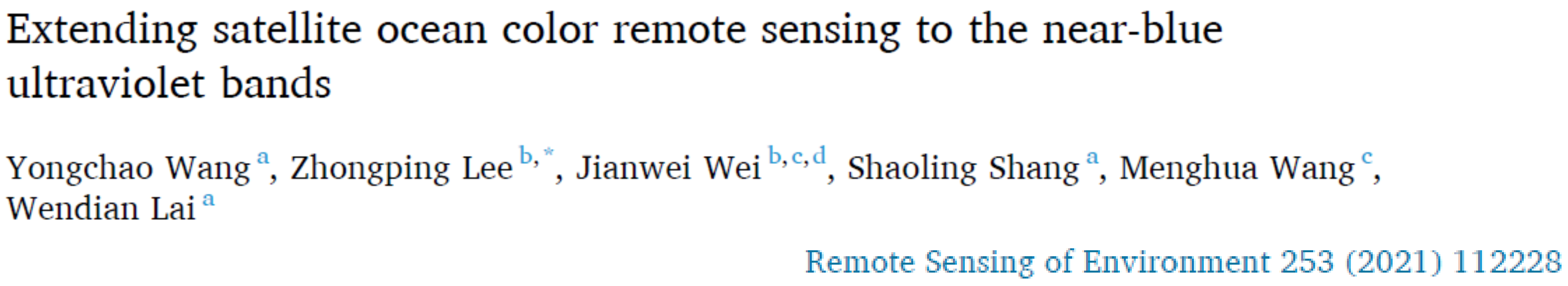


Limnol. Oceanogr., 56(3), 2011, 955–973

doi:10.4319/lo.2011.56.3.0955

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

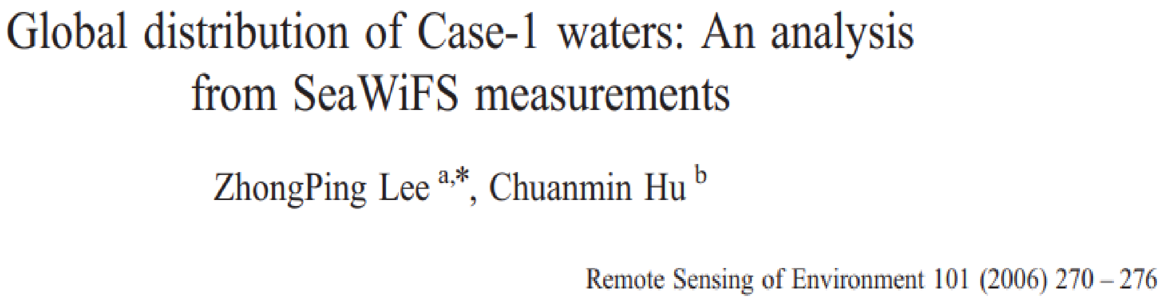
David Antoine,[a,*] David A. Siegel,[b,c] Tihomir Kostadinov,[b] Stéphane Maritorena,[b] Norm B. Nelson,[b]
Bernard Gentili,[a] Vincenzo Vellucci,[a] and Nathalie Guillocheau[b]



Extending satellite ocean color remote sensing to the near-blue ultraviolet bands

Yongchao Wang [a], Zhongping Lee [b,*], Jianwei Wei [b,c,d], Shaoling Shang [a], Menghua Wang [c], Wendian Lai [a]

Remote Sensing of Environment 253 (2021) 112228



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