# Inherent Optical Properties (IOPs)

## Lecture 1

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**Absorption properties**

**Scattering properties**

# ocean (water) color

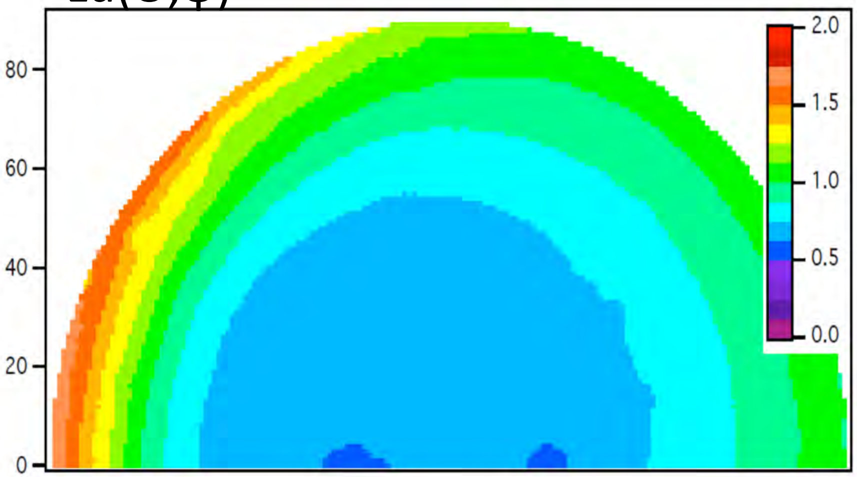




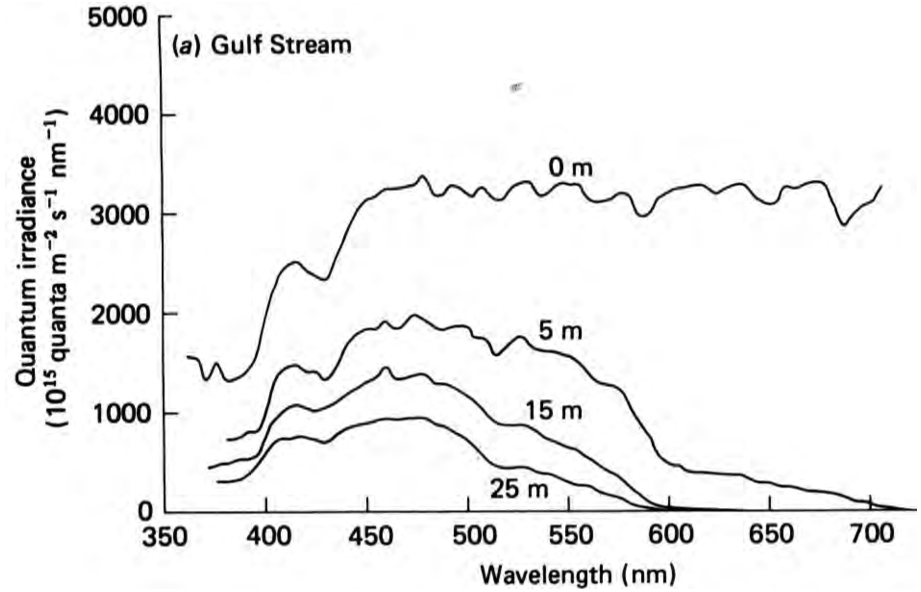



# light within water medium

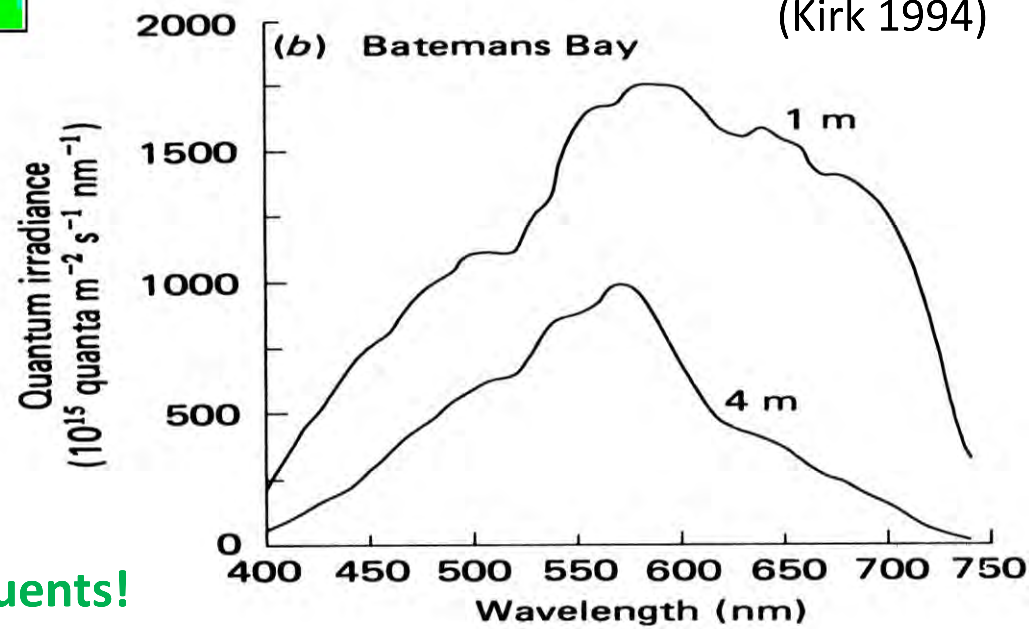
Lu(Θ,φ)



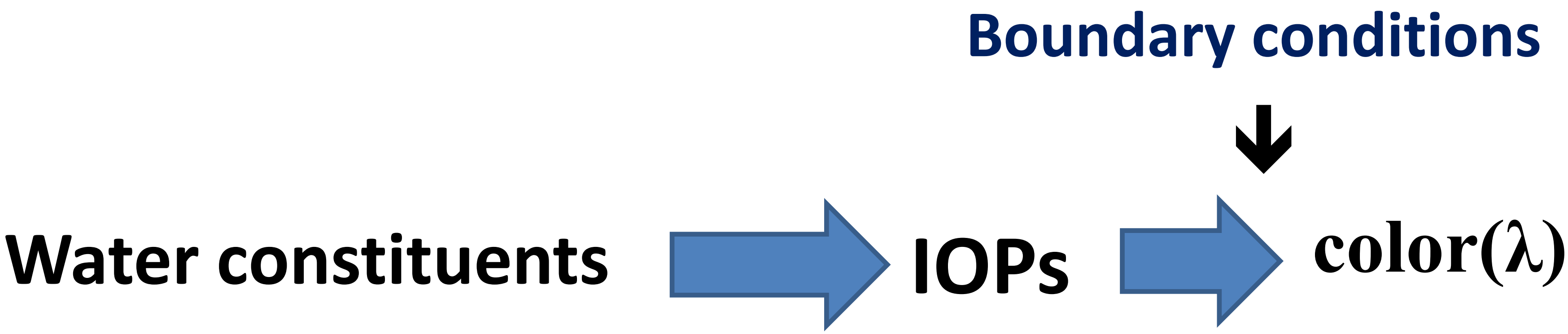

(Voss et al 2007)




(Kirk 1994)

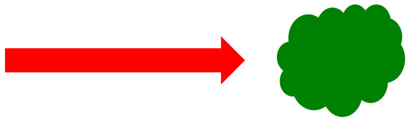



**They are modulated by water constituents!**


Boundary conditions
Water constituents
IOPs
color(λ)

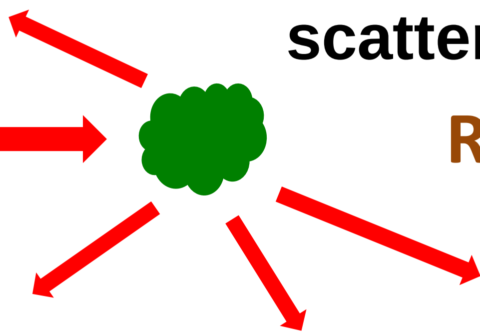
# Primary IOPs:

absorption



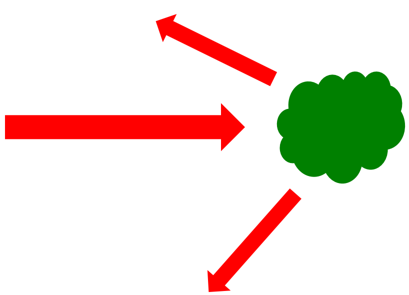
Transfer of energy

scattering



Redistribution of energy

backscattering



Scattering has angular dependence

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

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

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

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

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

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

**beam attenuation coefficient: $c = a + b$ (m-*1*)**

# IOPs are additive.

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



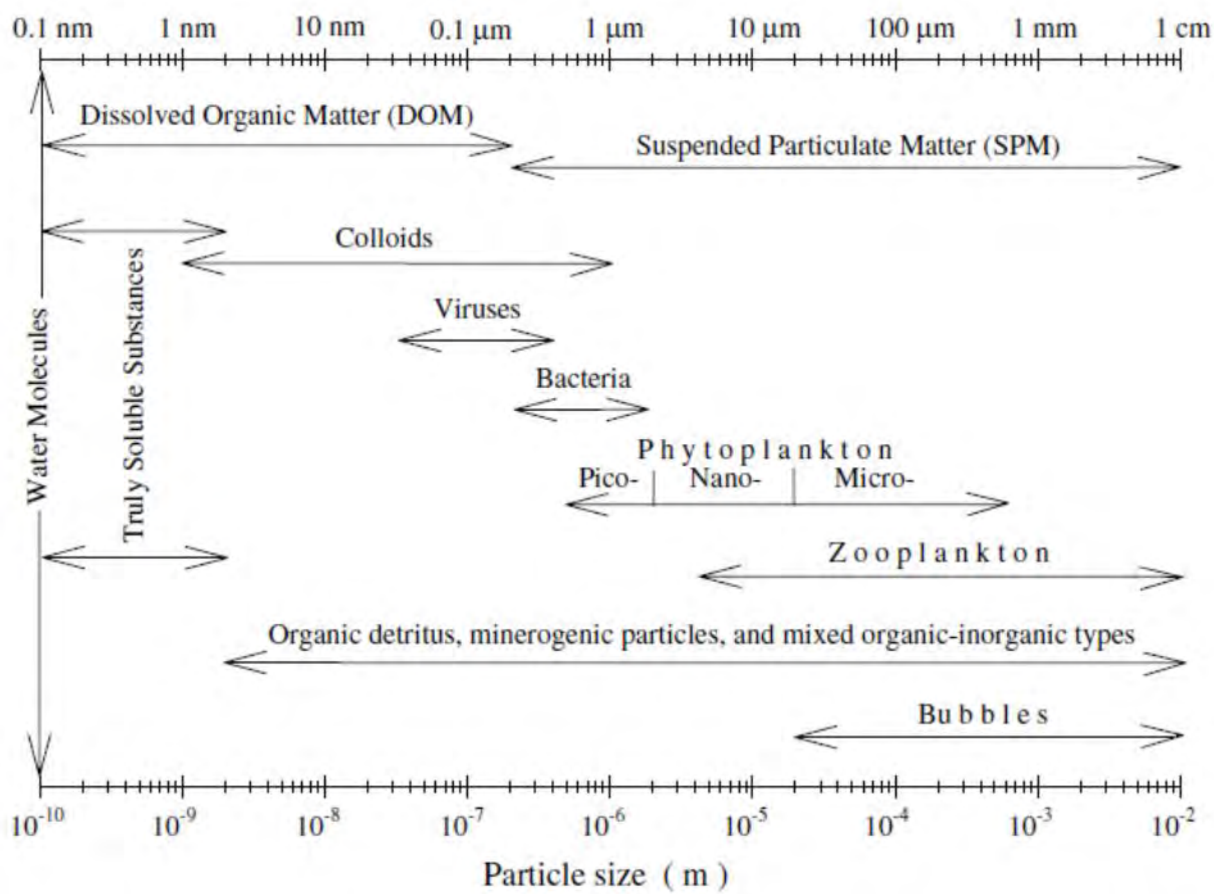



Fig. 1. Schematic diagram showing various seawater constituents in the broad size range from molecular size of the order of $10^{-10}$ m to large particles and bubbles of the order of $10^{-3}$–$10^{-2}$ m in size. The arrow ends generally indicate approximate rather than sharp boundaries for different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

# 1. absorption properties

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

**Very detailed:**

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

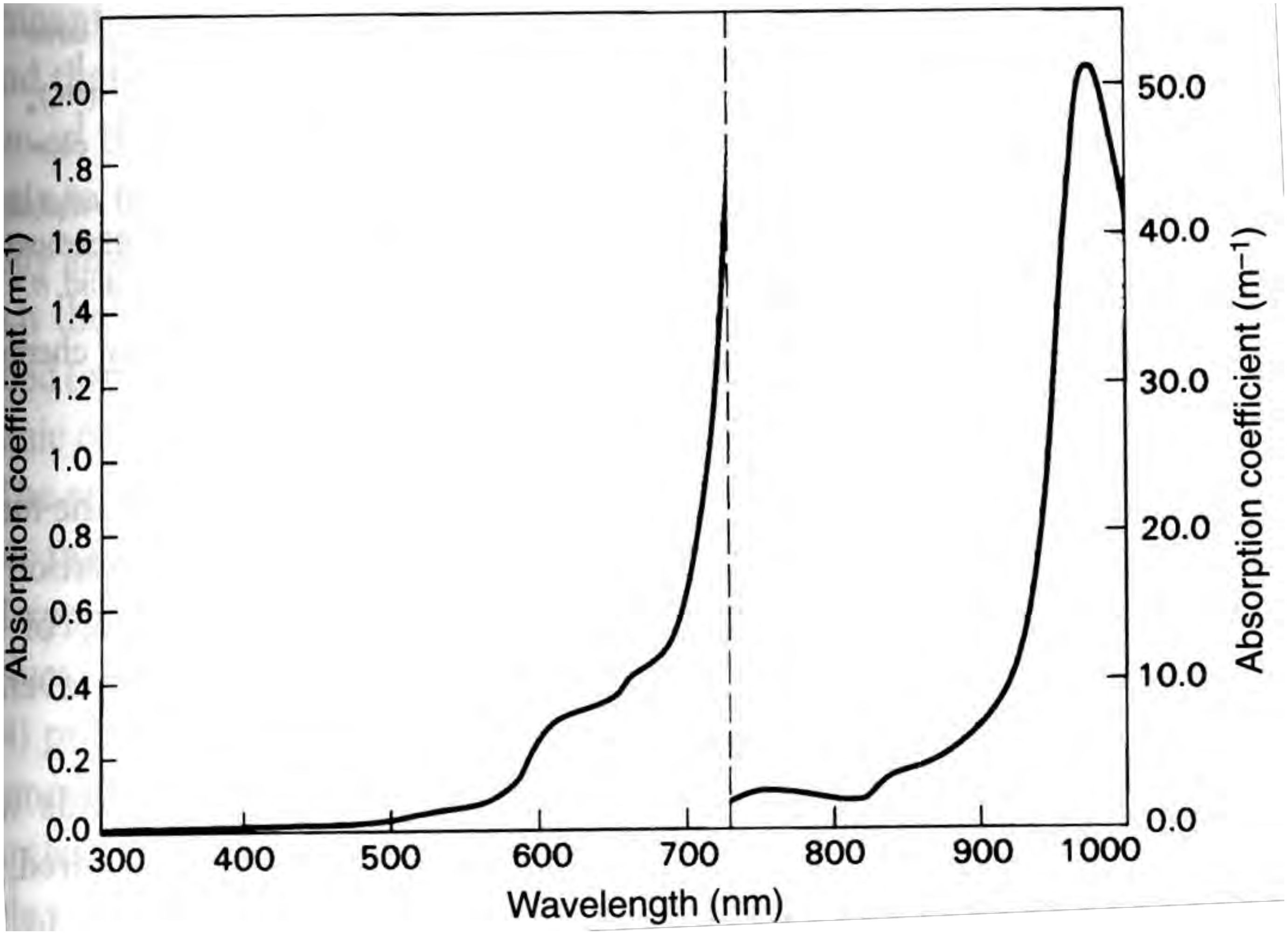
(Stramski et al 2001)

## Practical (and common) division:

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

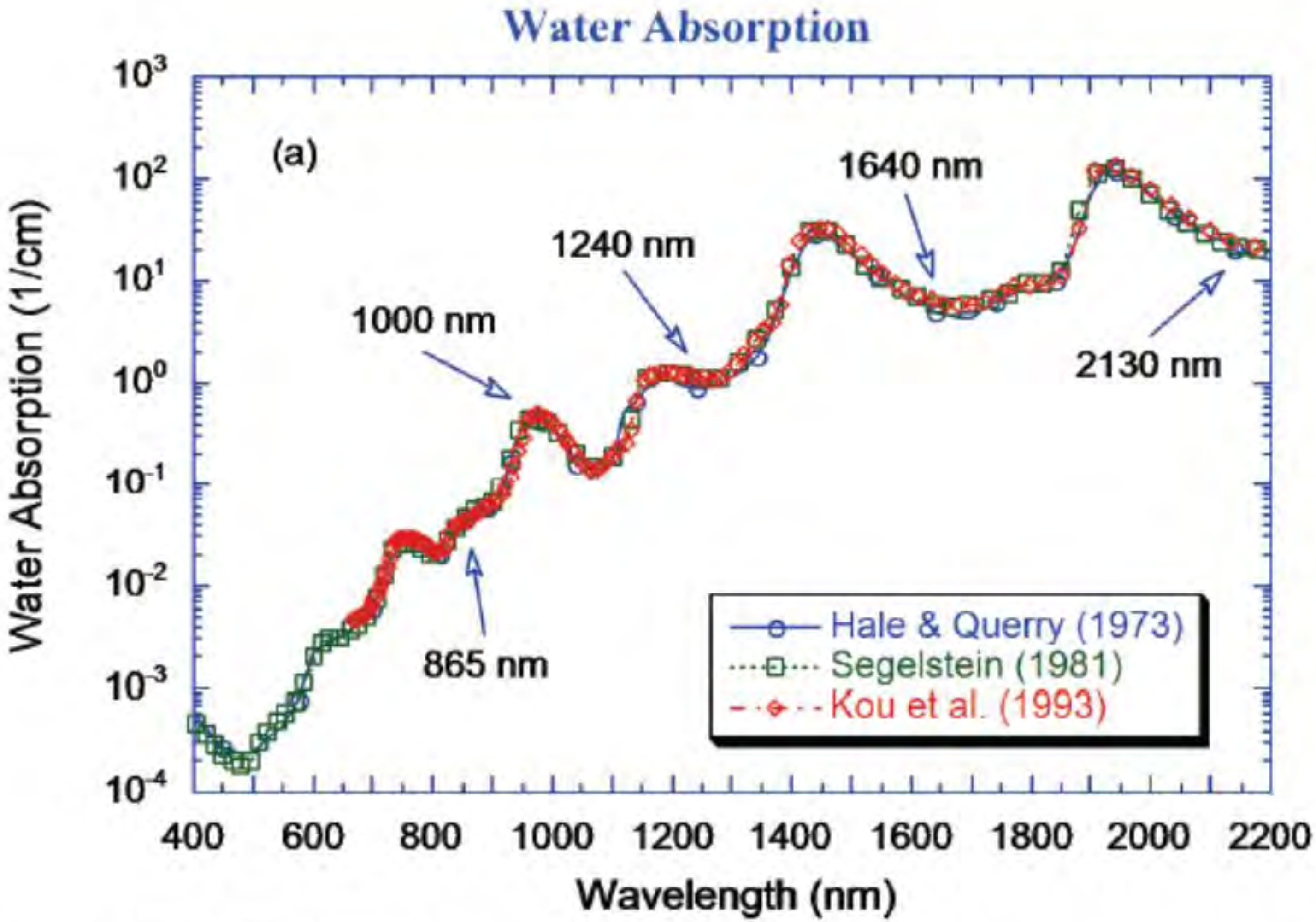
**Pure water (seawater):** $a_w$
**Particulate:** $a_p = a_{ph} + a_d$
**Pigments of living phytoplankton:** $a_{ph}$
**Detritus:** $a_d$
**Gelbstoff (yellow substance; colored dissolved organic matter):** $a_g$

# $a_w$ spectrum



2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Absorption coefficient (m⁻¹)
50.0
40.0
30.0
20.0
10.0
0.0
Absorption coefficient (m⁻¹)
300
400
500
600
700
800
900
1000
Wavelength (nm)

# $a_w$



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

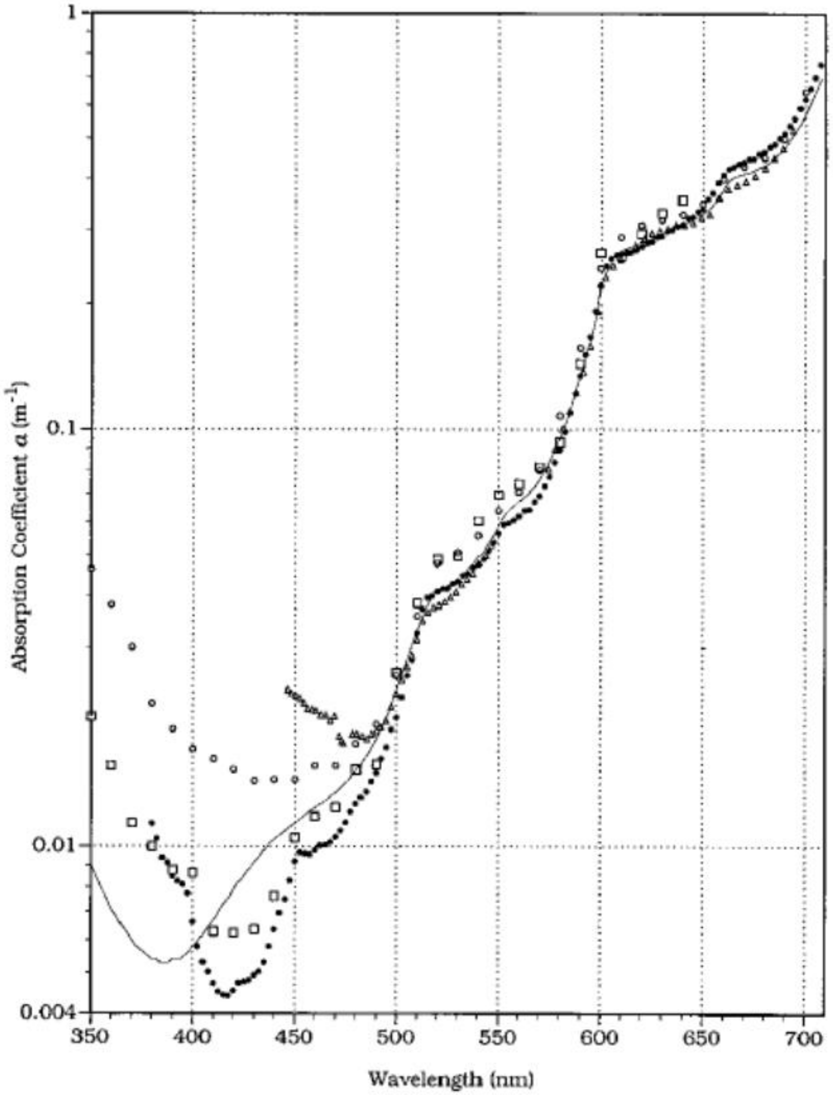
$a_w$

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)*

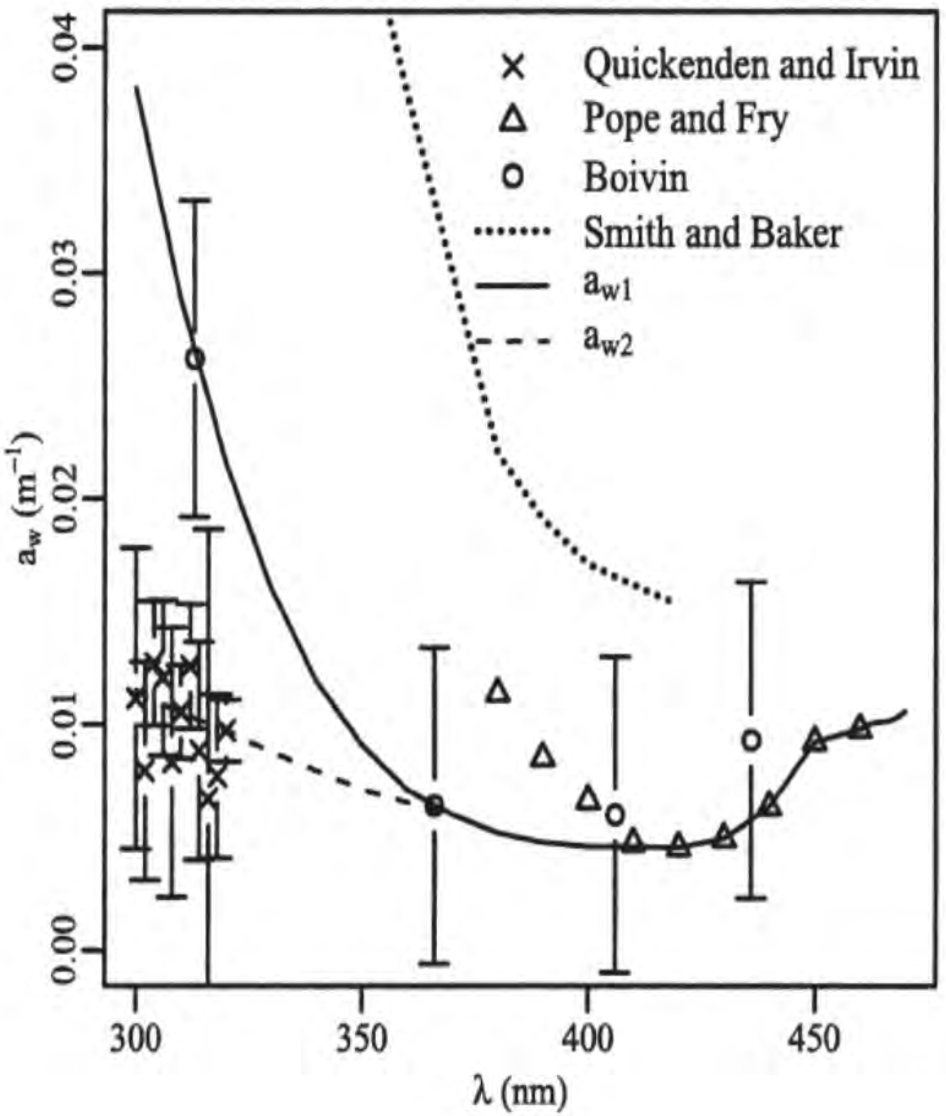
| λ (nm) | a ($m^{-1}$) | λ (nm) | a ($m^{-1}$) |
|---|---|---|---|
| 280 | 0.0239[ab] | 560 | 0.071 |
| 290 | 0.0140[ab] | 570 | 0.080 |
| 300 | 0.0085[ab] | 580 | 0.108 |
| 310 | 0.0082[ab] | 590 | 0.157 |
| 320 | 0.0077[ab] | 600 | 0.245 |
| 366 | 0.0055[a] | 610 | 0.290 |
| 380 | 0.023 | 620 | 0.310 |
| 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)

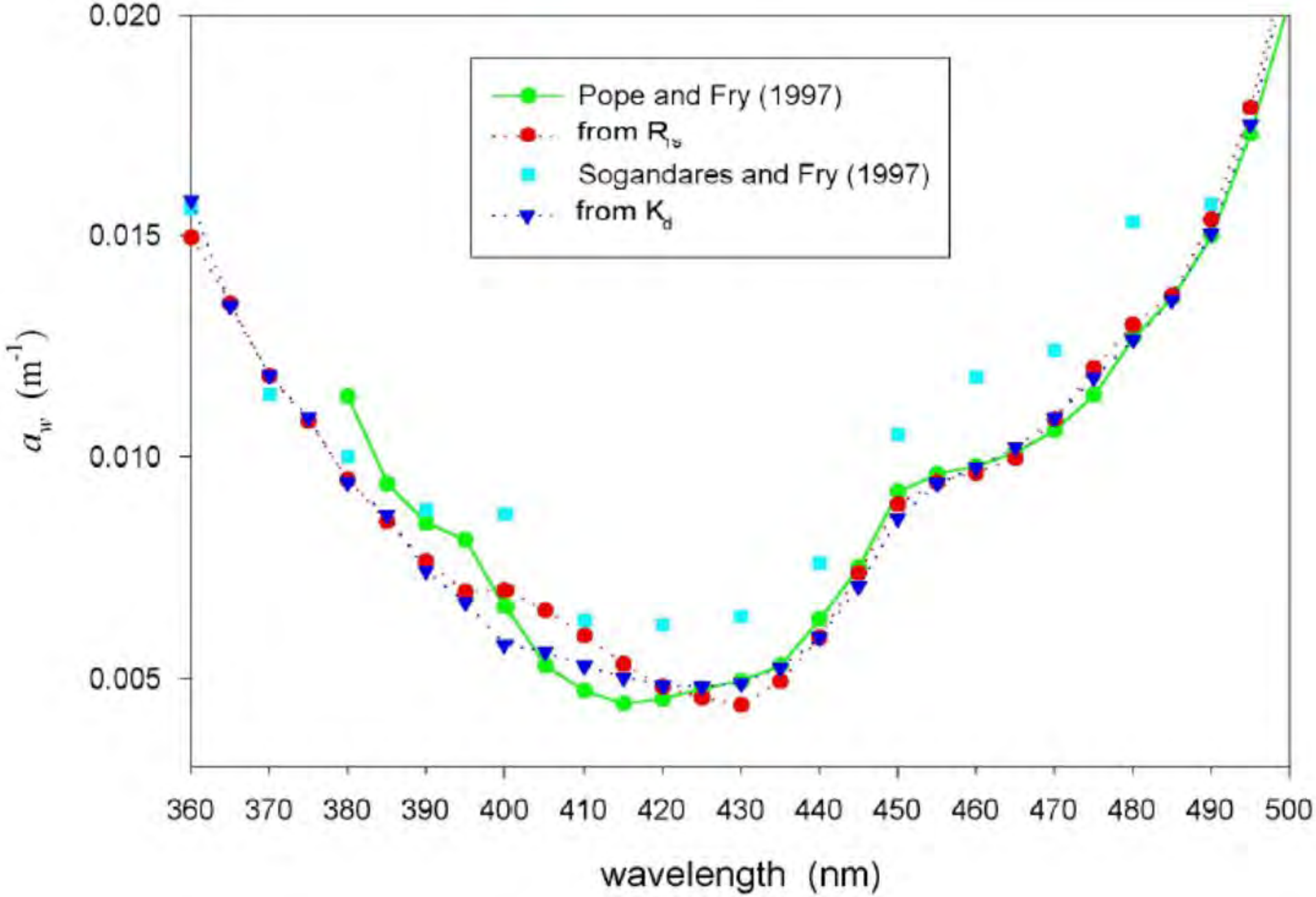
# Uncertainties of $a_w$:




(Pope and Fry, 1997)




(Morel et al 2007)




(Lee et al 2000)

# $a_w$ is temperature and salinity dependent

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

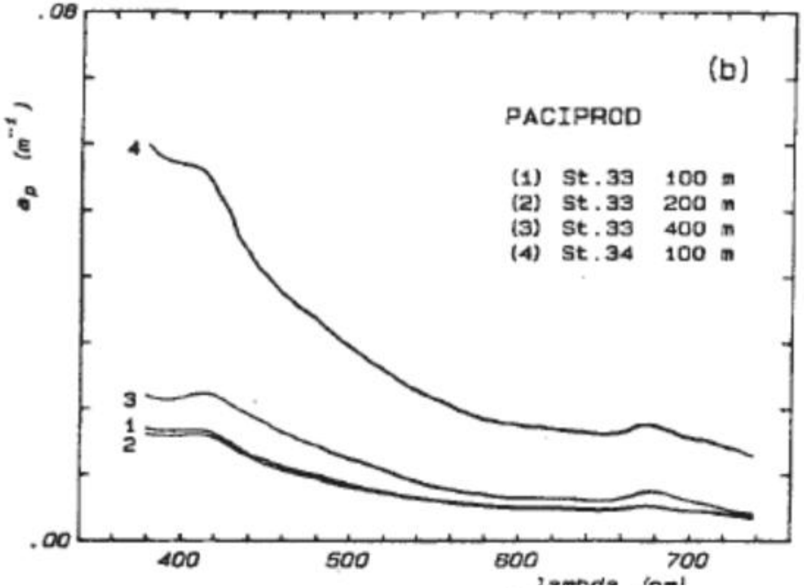
**Table 2. Linear Slopes of the Temperature Dependence of the Absorption Coefficient Measured in the Laboratory[a]**

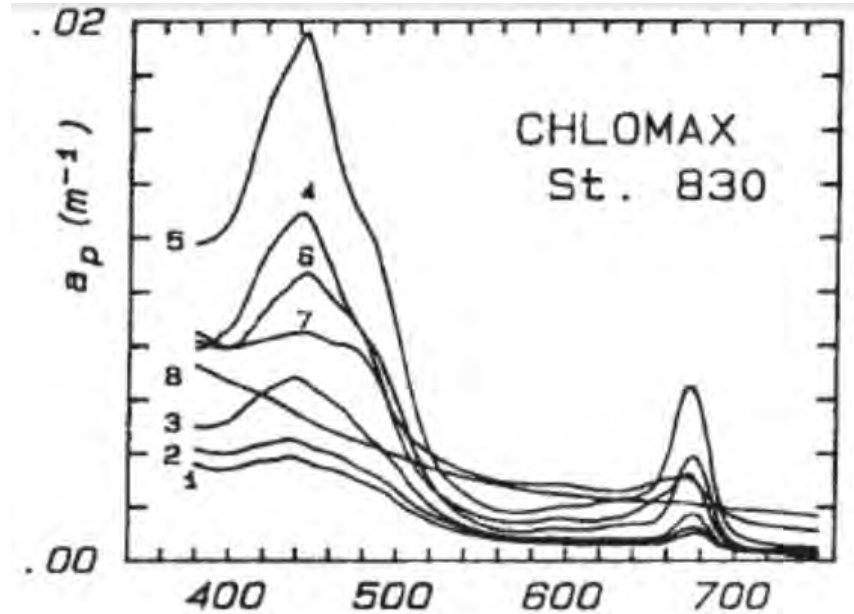
| Wavelength | $\Psi_T$, Pure Water | Standard Deviation, Pure Water | $\Psi_T$, Saltwater | Standard Deviation, Saltwater |
|---|---|---|---|---|
| 412 | 0.0001 | 0.0003 | 0.0003 | 0.0003 |
| 440 | 0.0000 | 0.0002 | 0.0002 | 0.0002 |
| 488 | 0.0000 | 0.0002 | 0.0001 | 0.0002 |
| 510 | 0.0002 | 0.0001 | 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 |

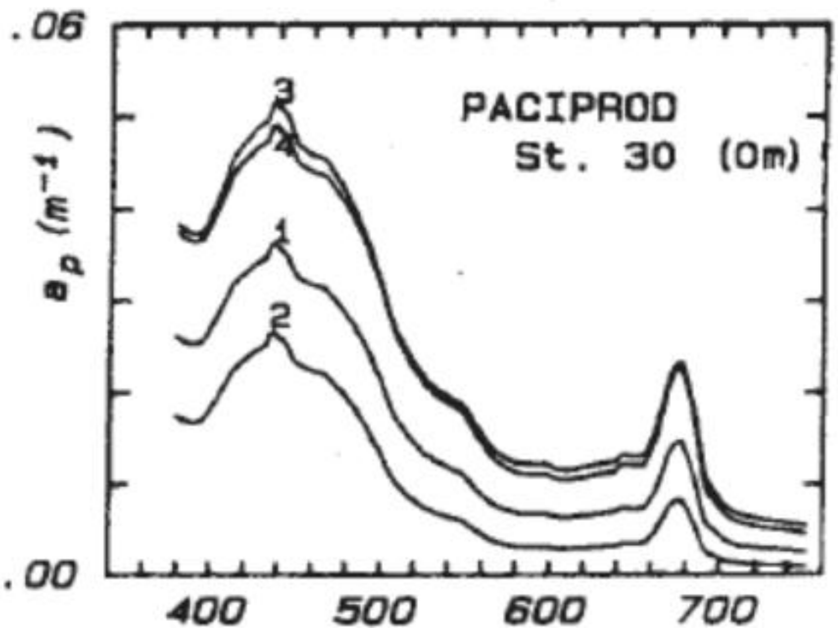
[a]For pure water the results of five tests are combined. The results of two tests were combined for the saltwater results. The absorption and attenuation meter results have been pooled together as well as pooling the common wavelengths between instruments. The standard deviations of the pooled values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

(Pegau et al 1997)

# $a_p$ spectrum

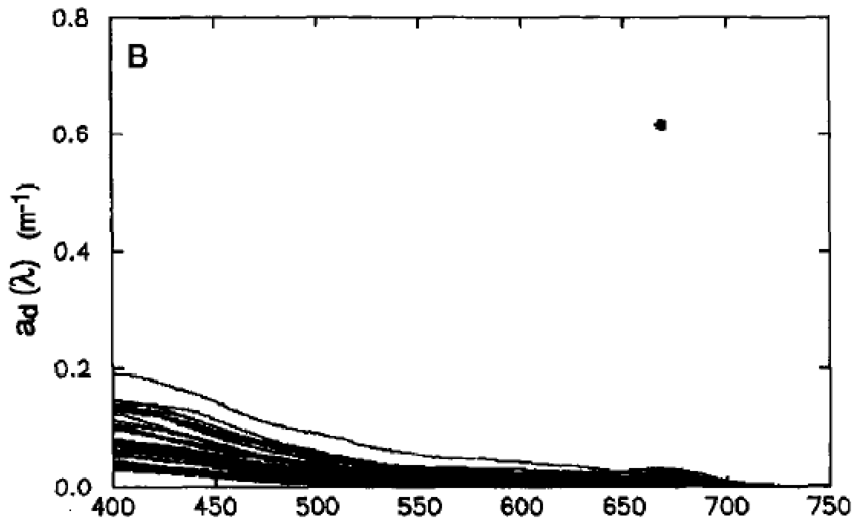


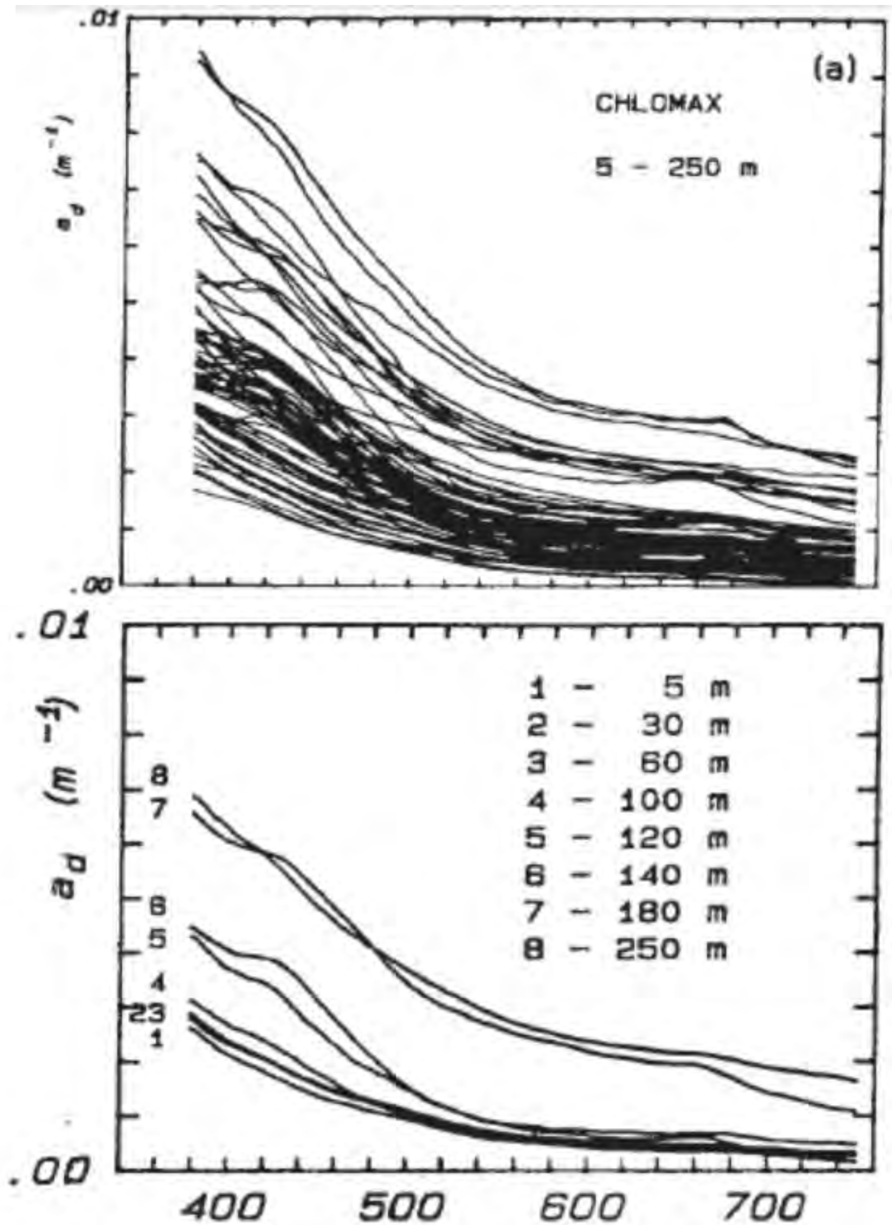




Bricaud and Stramski (1990)

# $a_d$ spectrum

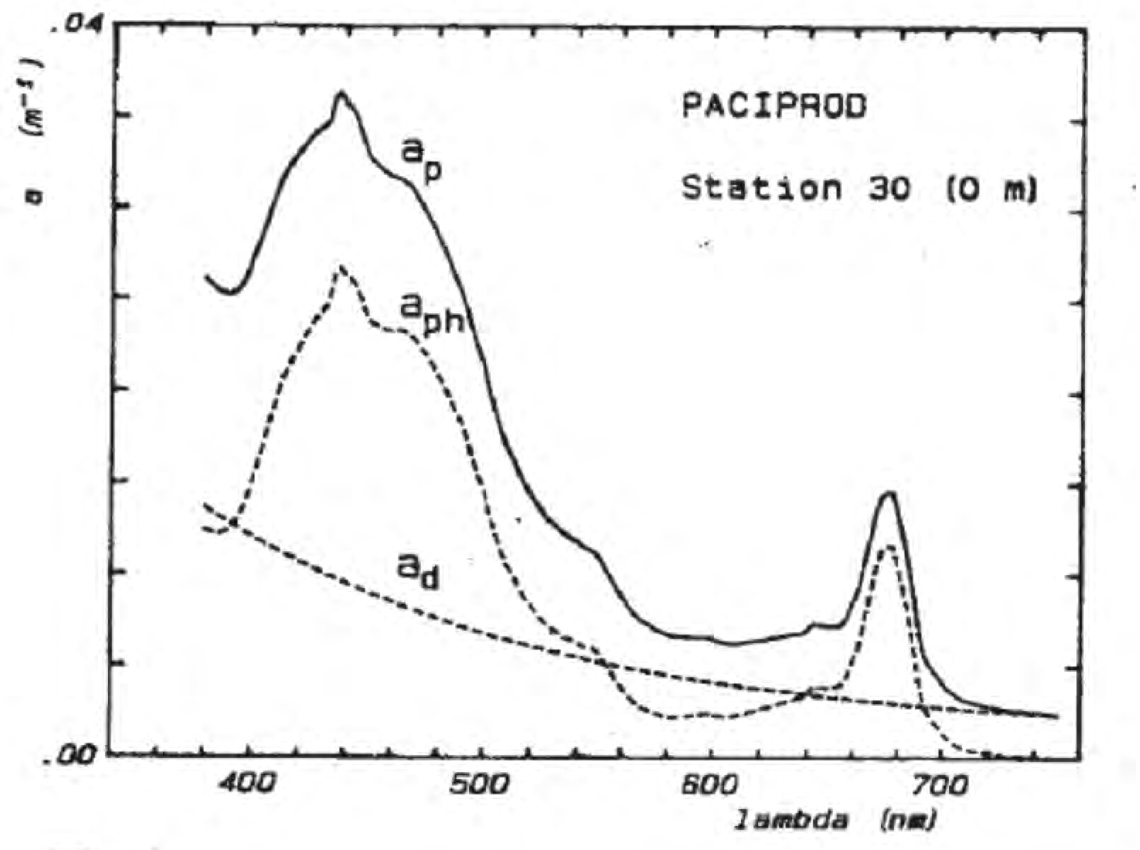


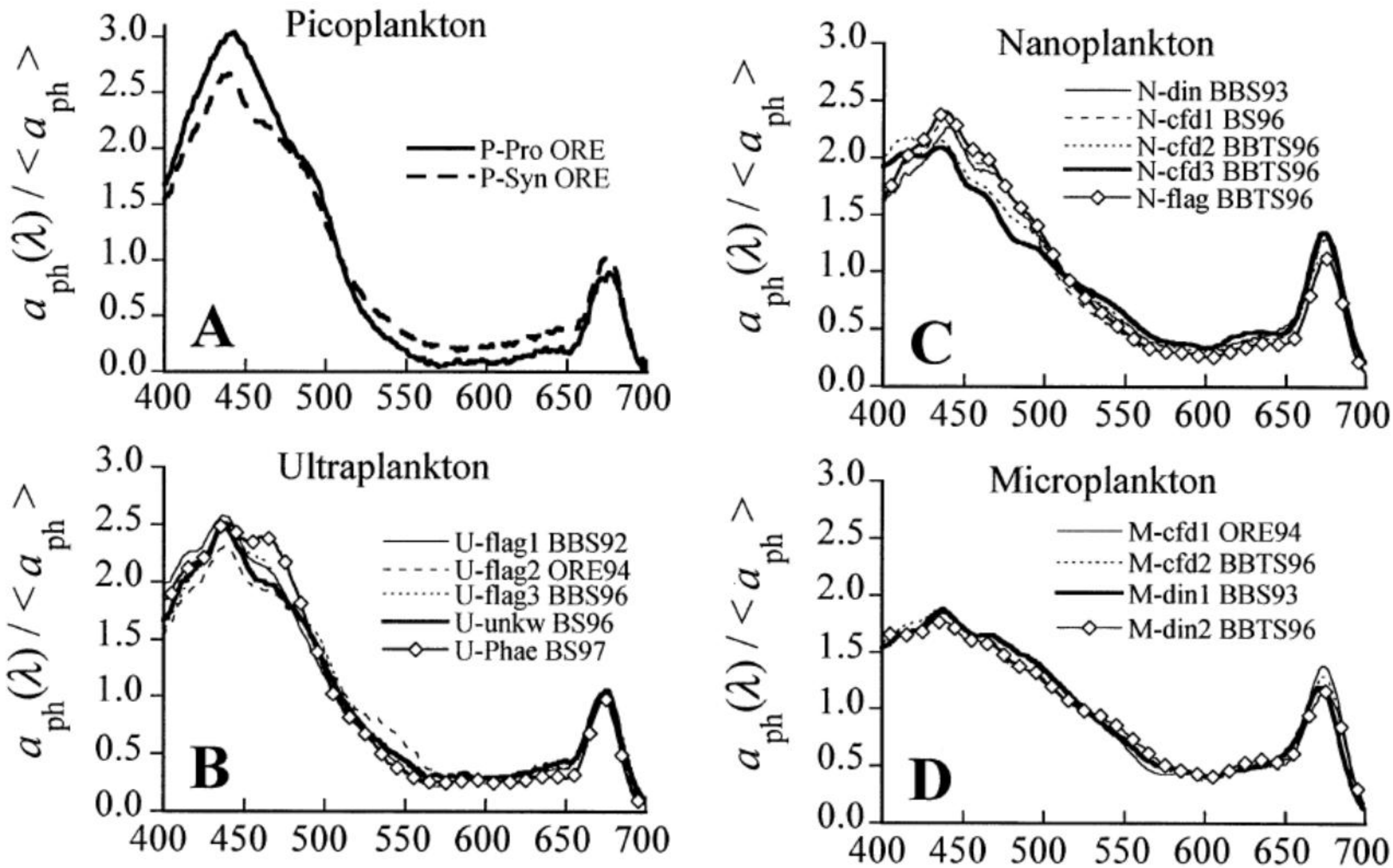

$$a_d = a_d(\lambda_0)e^{-S_d(\lambda-\lambda_0)}$$

**$S_d$: ~0.005 – 0.015 $nm^{-1}$**

# $a_{ph} = a_p - a_d$ spectrum

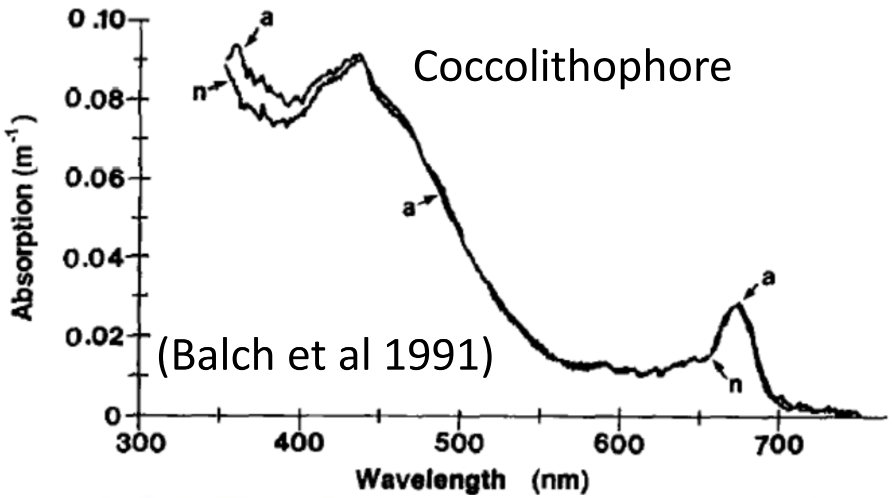


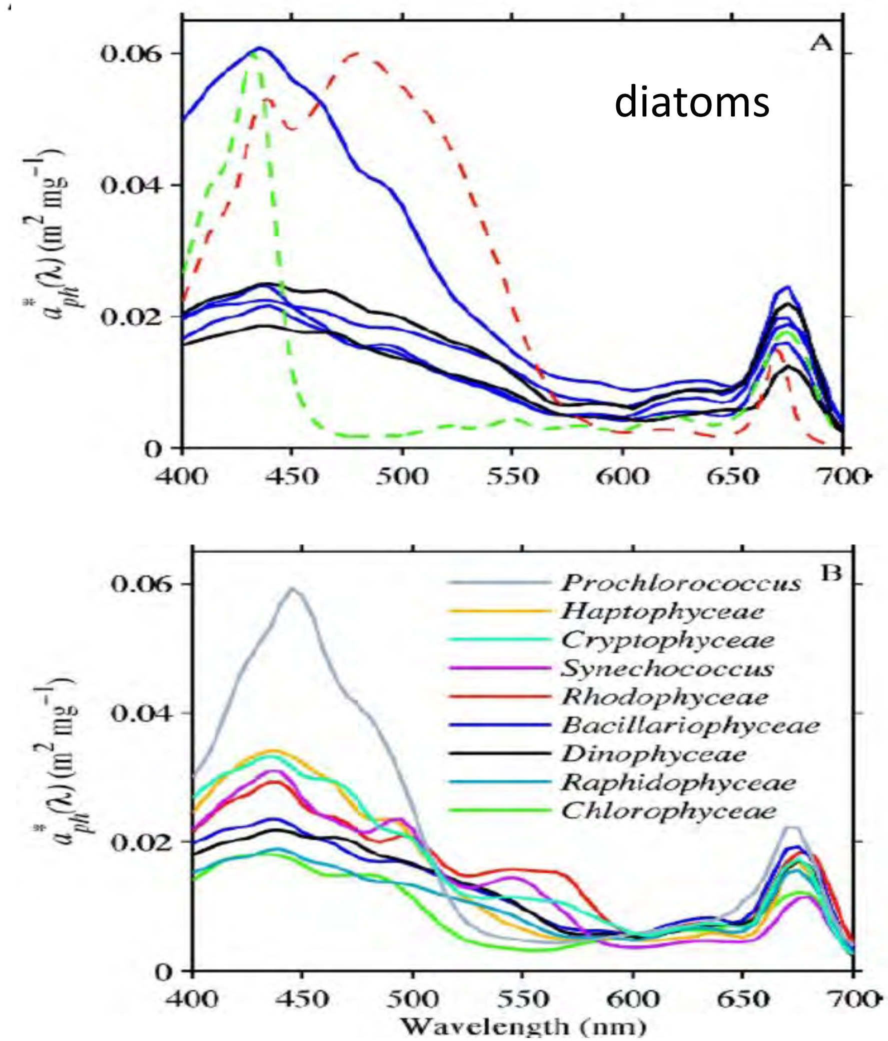
# Separated by size

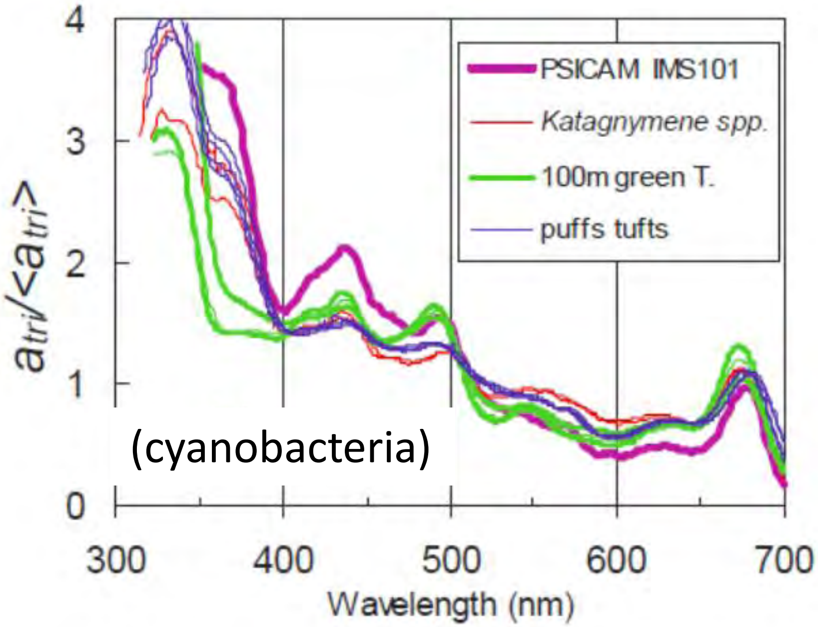



(Ciotti et al 2002)

# By species or groups



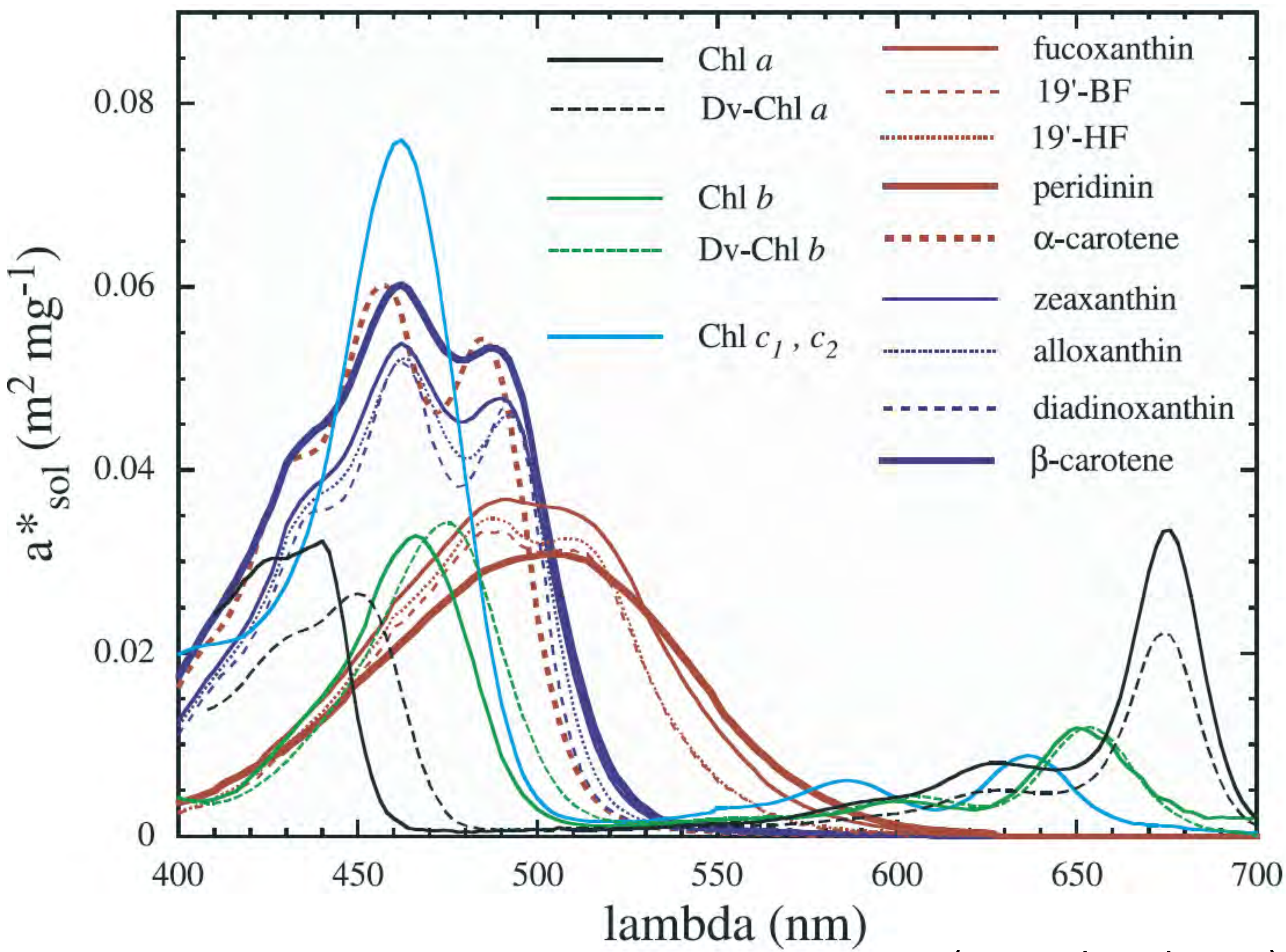




(Dierssen et al 2006)

(Dupouy et al 2008)

# Separated by pigments




(Bricaud et al 2004)

# Modeling $a_{ph}$ spectrum

## Example of one parameter hyperspectral $a_{ph}(\lambda)$ model:

Bricaud et al (1995):

$$a_{ph}(\lambda) = A_{ph}(\lambda)\,Chl^{1-B_{ph}(\lambda)}$$

Table 2. Spectral Values of the Constants Obtained When Fitting the Variations of $a^*_{ph}(\lambda)$ Versus the (chl $a$ + di a) Concentration ⟨Chl⟩ to Power Laws of the Form $a^*_{ph}(\lambda) = A(\lambda)\,\langle Chl\rangle^{-B(\lambda)}$ and Determination Coefficients on th Log-Transformed Data $r^2$

| λ, nm | A | B | $r^2$ | λ, nm | A | B |
|---|---|---|---|---|---|---|
| 400 | 0.0263 | 0.282 | 0.702 | 402 | 0.0271 | 0.281 |
| 404 | 0.0280 | 0.282 | 0.706 | 406 | 0.0290 | 0.281 |
| 408 | 0.0301 | 0.282 | 0.710 | 410 | 0.0313 | 0.283 |
| 412 | 0.0323 | 0.286 | 0.718 | 414 | 0.0333 | 0.291 |
| 416 | 0.0342 | 0.293 | 0.725 | 418 | 0.0349 | 0.296 |
| 420 | 0.0356 | 0.299 | 0.733 | 422 | 0.0359 | 0.306 |
| 424 | 0.0362 | 0.313 | 0.746 | 426 | 0.0369 | 0.316 |
| 428 | 0.0376 | 0.317 | 0.749 | 430 | 0.0386 | 0.314 |
| 432 | 0.0391 | 0.318 | 0.750 | 434 | 0.0395 | 0.324 |
| 436 | 0.0399 | 0.328 | 0.757 | 438 | 0.0401 | 0.332 |
| 440 | 0.0403 | 0.332 | 0.762 | 442 | 0.0398 | 0.339 |
| 444 | 0.0390 | 0.348 | 0.774 | 446 | 0.0383 | 0.355 |
| 448 | 0.0375 | 0.360 | 0.783 | 450 | 0.0371 | 0.359 |
| 452 | 0.0365 | 0.362 | 0.783 | 454 | 0.0358 | 0.366 |
| 456 | 0.0354 | 0.367 | 0.789 | 458 | 0.0351 | 0.368 |
| 460 | 0.0350 | 0.365 | 0.789 | 462 | 0.0347 | 0.366 |
| 464 | 0.0343 | 0.368 | 0.792 | 466 | 0.0339 | 0.369 |
| 468 | 0.0335 | 0.369 | 0.793 | 470 | 0.0332 | 0.368 |
| 472 | 0.0325 | 0.371 | 0.792 | 474 | 0.0318 | 0.375 |
| 476 | 0.0312 | 0.378 | 0.793 | 478 | 0.0306 | 0.379 |
| 480 | 0.0301 | 0.377 | 0.791 | 482 | 0.0296 | 0.377 |
| 484 | 0.0290 | 0.376 | 0.788 | 486 | 0.0285 | 0.373 |
| 488 | 0.0279 | 0.369 | 0.783 | 490 | 0.0274 | 0.361 |
| 492 | 0.0267 | 0.356 | 0.774 | 494 | 0.0258 | 0.349 |
| 496 | 0.0249 | 0.341 | 0.763 | 498 | 0.0240 | 0.332 |
| 500 | 0.0230 | 0.321 | 0.747 | 502 | 0.0220 | 0.311 |
| 504 | 0.0209 | 0.300 | 0.722 | 506 | 0.0199 | 0.288 |
| 508 | 0.0189 | 0.275 | 0.686 | 510 | 0.0180 | 0.260 |
| 512 | 0.0171 | 0.249 | 0.641 | 514 | 0.0163 | 0.237 |
| 516 | 0.0156 | 0.224 | 0.578 | 518 | 0.0149 | 0.211 |
| 520 | 0.0143 | 0.196 | 0.498 | 522 | 0.0137 | 0.184 |
| 524 | 0.0131 | 0.173 | 0.417 | 526 | 0.0126 | 0.162 |
| 528 | 0.0121 | 0.151 | 0.332 | 530 | 0.0117 | 0.139 |
| 532 | 0.0113 | 0.129 | 0.248 | 534 | 0.0108 | 0.119 |
| 536 | 0.0104 | 0.109 | 0.176 | 538 | 0.0100 | 0.100 |
| 540 | 0.0097 | 0.090 | 0.116 | 542 | 0.0093 | 0.081 |

Lee (1994); Lee et al (1998):

$$a_{ph}(\lambda) = \left(a_0(\lambda) + a_1(\lambda)\ln(P)\right)P$$

$$P = a_{ph}(440)$$

Table 2. Parameters for the Empirical $a_\phi(\lambda)$ Simulation by Eq. (12)[a]

| Wavelength | $a_0(\lambda)$ | $a_1(\lambda)$ |
|---|---|---|
| 390 | 0.5813 | 0.0235 |
| 400 | 0.6843 | 0.0205 |
| 410 | 0.7782 | 0.0129 |
| 420 | 0.8637 | 0.006 |
| 430 | 0.9603 | 0.002 |
| 440 | 1.0 | 0 |
| 450 | 0.9634 | 0.006 |
| 460 | 0.9311 | 0.0109 |
| 470 | 0.8697 | 0.0157 |
| 480 | 0.789 | 0.0152 |
| 490 | 0.7558 | 0.0256 |
| 500 | 0.7333 | 0.0559 |
| 510 | 0.6911 | 0.0865 |
| 520 | 0.6327 | 0.0981 |
| 530 | 0.5681 | 0.0969 |
| 540 | 0.5046 | 0.09 |
| 550 | 0.4262 | 0.0781 |
| 560 | 0.3433 | 0.0659 |
| 570 | 0.295 | 0.06 |
| 580 | 0.2784 | 0.0581 |

# Example of two parameter model:

(Ciotti et al 2002)

$$a_{\phi}(\lambda) = a_{\phi}(505)\cdot[S_f \cdot \bar{a}_{<pico>}(\lambda)] + [(1 - S_f)\cdot \bar{a}_{<micro>}(\lambda)]$$

Table 3. Basis vectors representing the normalized absorption for the smallest ($\bar{a}_{(pico)}(\lambda)$, *Prochlorococcus*) and biggest ($\bar{a}_{(micro)}(\lambda)$, average microplankton) cell sizes in our data set. Wavelength ($\lambda$) in nm. Basis vectors for $a^*_{ph}(\lambda)$ can be constructed by setting $\bar{a}_{(pico)}(676)$ to 0.023 $m^2\ mg^{-1}$, $\bar{a}_{(micro)}(674)$ to 0.0086 $m^2\ mg^{-1}$, and scaling for the other wavelengths accordingly.

| λ | Pico | Micro | λ | Pico | Micro | λ | Pico | Micro | λ | Pico | Micro | λ | Pico | Micro |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 400 | 1.682 | 1.574 | | | | | | | | | | | | |
| 402 | 1.734 | 1.584 | 462 | 2.526 | 1.623 | 522 | 0.544 | 1.013 | 582 | 0.111 | 0.459 | 642 | 0.191 | 0.528 |
| 404 | 1.800 | 1.600 | 464 | 2.455 | 1.616 | 524 | 0.522 | 0.992 | 584 | 0.072 | 0.452 | 644 | 0.174 | 0.526 |
| 406 | 1.890 | 1.617 | 466 | 2.402 | 1.606 | 526 | 0.486 | 0.977 | 586 | 0.073 | 0.452 | 646 | 0.197 | 0.528 |
| 408 | 1.978 | 1.633 | 468 | 2.331 | 1.592 | 528 | 0.448 | 0.959 | 588 | 0.073 | 0.449 | 648 | 0.176 | 0.538 |
| 410 | 2.057 | 1.654 | 470 | 2.281 | 1.568 | 530 | 0.391 | 0.944 | 590 | 0.099 | 0.443 | 650 | 0.168 | 0.549 |
| 412 | 2.162 | 1.669 | 472 | 2.205 | 1.542 | 532 | 0.375 | 0.927 | 592 | 0.070 | 0.433 | 652 | 0.160 | 0.574 |
| 414 | 2.269 | 1.674 | 474 | 2.136 | 1.509 | 534 | 0.336 | 0.909 | 594 | 0.095 | 0.424 | 654 | 0.217 | 0.605 |
| 416 | 2.327 | 1.684 | 476 | 2.063 | 1.481 | 536 | 0.305 | 0.888 | 596 | 0.085 | 0.416 | 656 | 0.244 | 0.655 |
| 418 | 2.398 | 1.697 | 478 | 2.049 | 1.459 | 538 | 0.292 | 0.868 | 598 | 0.090 | 0.406 | 658 | 0.286 | 0.720 |
| 420 | 2.457 | 1.708 | 480 | 1.998 | 1.437 | 540 | 0.288 | 0.847 | 600 | 0.086 | 0.401 | 660 | 0.381 | 0.798 |
| 422 | 2.533 | 1.710 | 482 | 1.930 | 1.415 | 542 | 0.261 | 0.826 | 602 | 0.068 | 0.400 | 662 | 0.437 | 0.889 |
| 424 | 2.614 | 1.716 | 484 | 1.918 | 1.399 | 544 | 0.245 | 0.806 | 604 | 0.078 | 0.403 | 664 | 0.520 | 0.979 |
| 426 | 2.663 | 1.737 | 486 | 1.897 | 1.387 | 546 | 0.214 | 0.785 | 606 | 0.069 | 0.408 | 666 | 0.660 | 1.068 |
| 428 | 2.749 | 1.763 | 488 | 1.867 | 1.377 | 548 | 0.194 | 0.764 | 608 | 0.090 | 0.416 | 668 | 0.716 | 1.147 |
| 430 | 2.804 | 1.793 | 490 | 1.812 | 1.367 | 550 | 0.187 | 0.737 | 610 | 0.096 | 0.429 | 670 | 0.824 | 1.207 |
| 432 | 2.840 | 1.812 | 492 | 1.776 | 1.349 | 552 | 0.138 | 0.711 | 612 | 0.094 | 0.443 | 672 | 0.846 | 1.243 |
| 434 | 2.915 | 1.827 | 494 | 1.701 | 1.338 | 554 | 0.137 | 0.682 | 614 | 0.084 | 0.458 | 674 | 0.816 | 1.249 |
| 436 | 2.947 | 1.830 | 496 | 1.648 | 1.319 | 556 | 0.111 | 0.653 | 616 | 0.105 | 0.473 | 676 | 0.891 | 1.227 |
| 438 | 2.978 | 1.834 | 498 | 1.522 | 1.301 | 558 | 0.094 | 0.626 | 618 | 0.128 | 0.487 | 678 | 0.869 | 1.174 |
| 440 | 3.014 | 1.824 | 500 | 1.439 | 1.271 | 560 | 0.095 | 0.604 | 620 | 0.119 | 0.495 | 680 | 0.812 | 1.096 |
| 442 | 3.032 | 1.800 | 502 | 1.373 | 1.242 | 562 | 0.070 | 0.580 | 622 | 0.126 | 0.499 | 682 | 0.741 | 1.004 |
| 444 | 3.011 | 1.771 | 504 | 1.270 | 1.222 | 564 | 0.053 | 0.555 | 624 | 0.138 | 0.504 | 684 | 0.605 | 0.893 |

# Multiple parameter model:

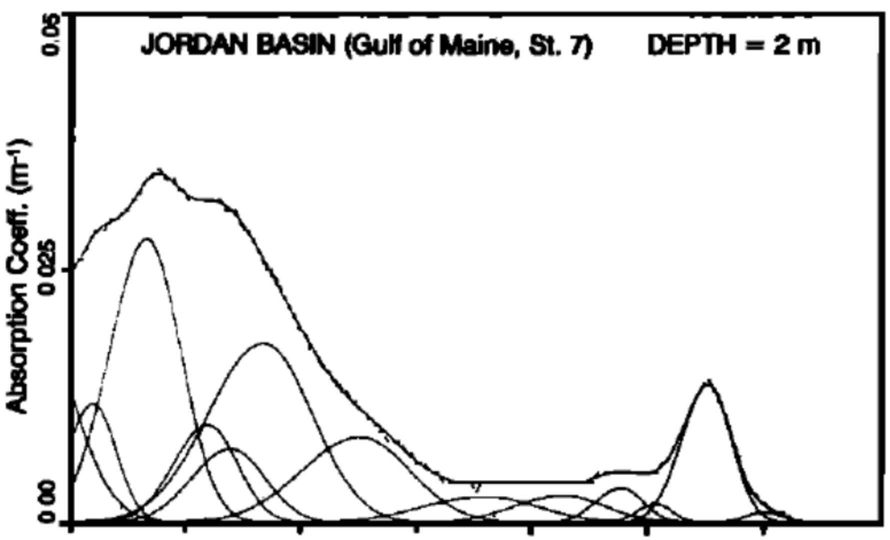
$$a_{ph}(\lambda) = \sum_{j=1}^{l} C_j a_j^*(\lambda_{mj}) \exp\left[\frac{(\lambda - \lambda_{mj})^2}{2\sigma_j^2}\right] \qquad (7)$$

TABLE 2. Input Values and Mean Characteristics of Gaussian Bands Reflecting Absorption by Chlorophylls and Carotenoids

| Characteristic | Gaussian Band Number and Associated Pigment Species | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 chl *a* | 2 chl *a* | 3 chl *a* | 4 chl *c* | 5 chl *b* | 6 carot. | 7 carot. | 8 chl *c* | 9 chl *a* | 10 chl *c* | 11 chl *b* | 12 chl *a* | 13 chl *a* |
| Input parameters | | | | | | | | | | | | | |
| Half width, nm | 53.8 | 21.3 | 32.1 | 27.2 | 45.0 | 45.4 | 45.9 | 46.3 | 35.0 | 28.9 | 24.4 | 21.6 | 33.5 |
| Center, nm | 384 | 413 | 435 | 461 | 464 | 490 | 532 | 583 | 623 | 644 | 655 | 676 | 700 |
| Output parameters | | | | | | | | | | | | | |
| Half width, nm | 43.2 | 22.7 | 34.5 | 29.3 | 36.0 | 46.8 | 49.6 | 46.8 | 38.0 | 24.9 | 25.4 | 24.7 | 29.0 |
| Center, nm | 381.5 | 410.8 | 433.5 | 459.2 | 466.6 | 487.8 | 532.0 | 585.6 | 620.6 | 640.7 | 652.9 | 675.6 | 699.8 |
| Specific absorption coefficient, $m^2$ (mg pigment)$^{-1}$ | 0.042 | 0.019 | 0.047 | 0.110 | 0.115 | 0.035 | 0.019 | 0.044 | 0.005 | 0.044 | 0.029 | 0.021 | 0.002 |

Specific absorption coefficients of each pigment are ratios of Gaussian band absorptions (in reciprocal meters) to high-performance liquid chromatography concentrations (in milligrams per cubic meter) of that pigment. Chl, chlorophyll; Carot., carotenoid.

(Hoepffner and Sathyendranath, 1993)

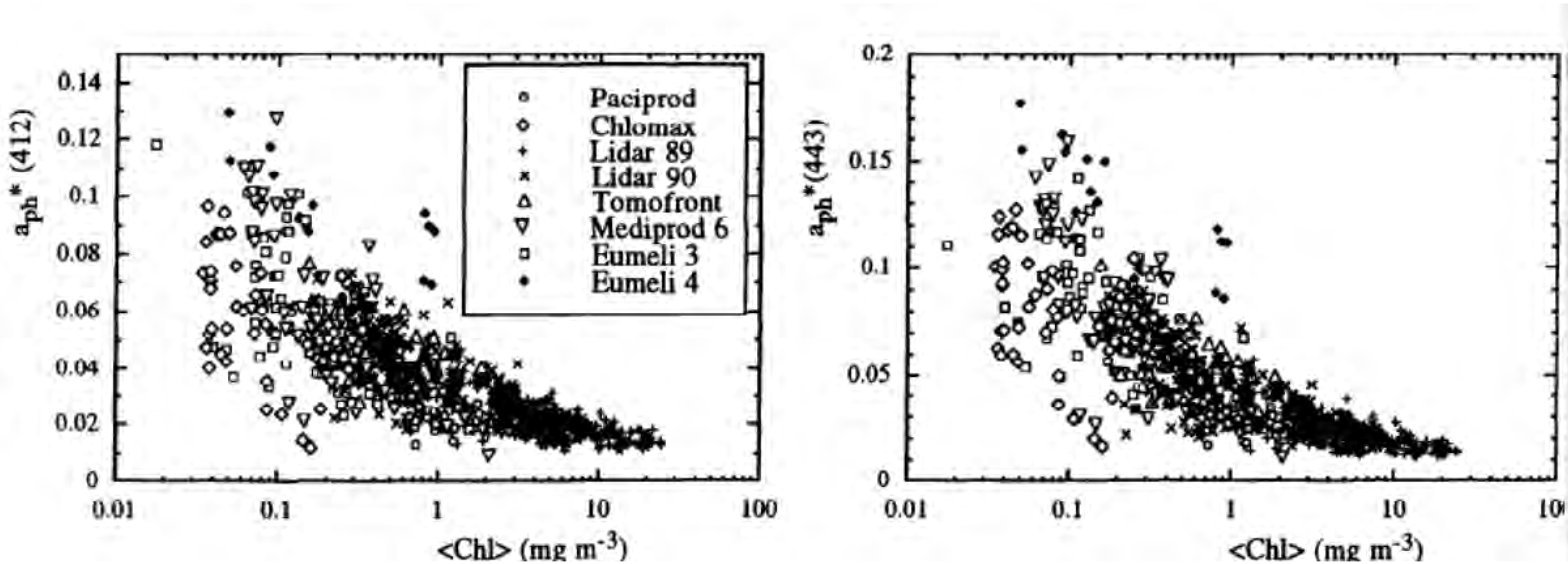


# Package effect

Specific absorption/scattering coefficient =

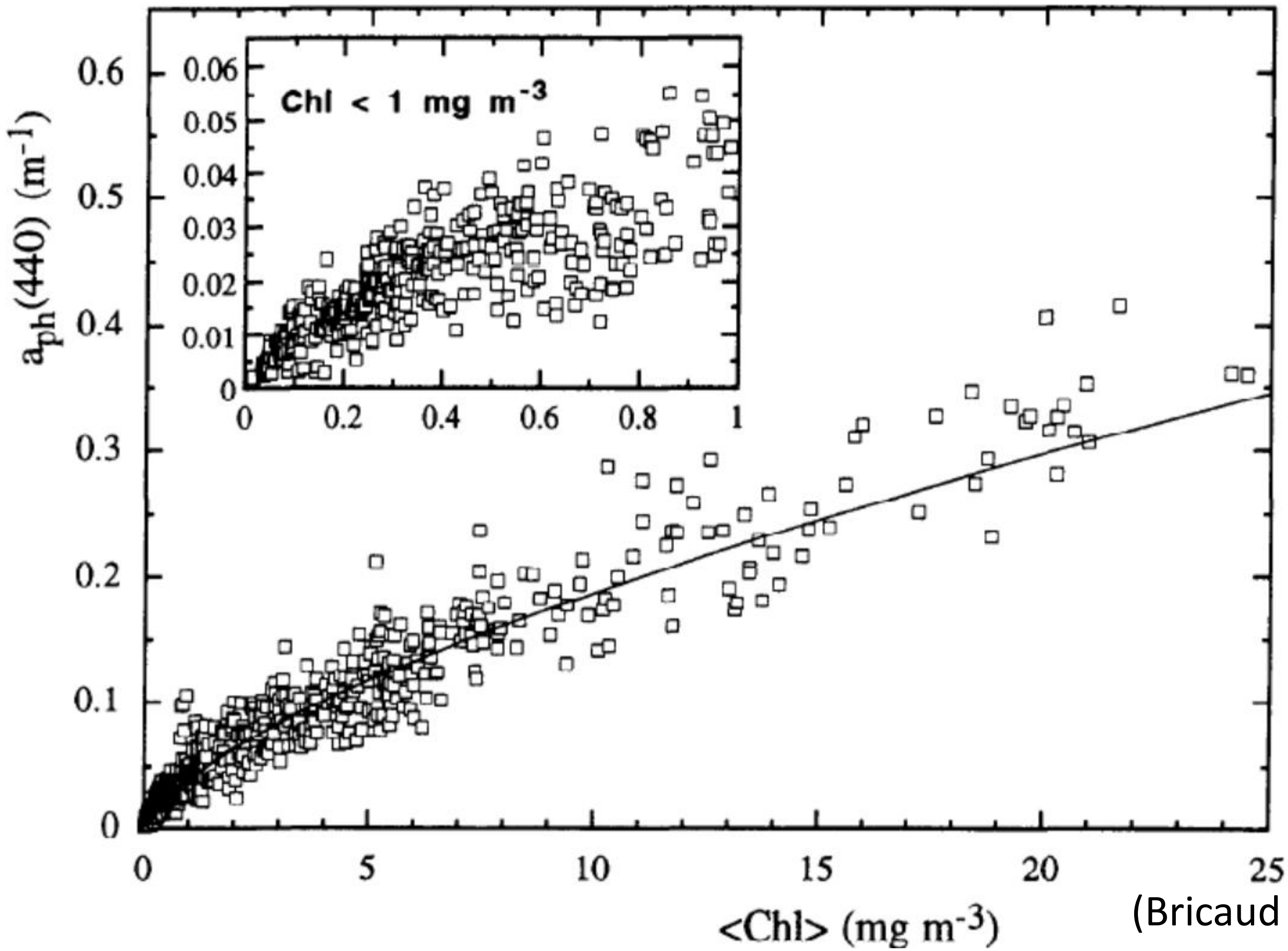
**Concentration normalized absorption/scattering coefficient**

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




(Bricaud et al 1995)

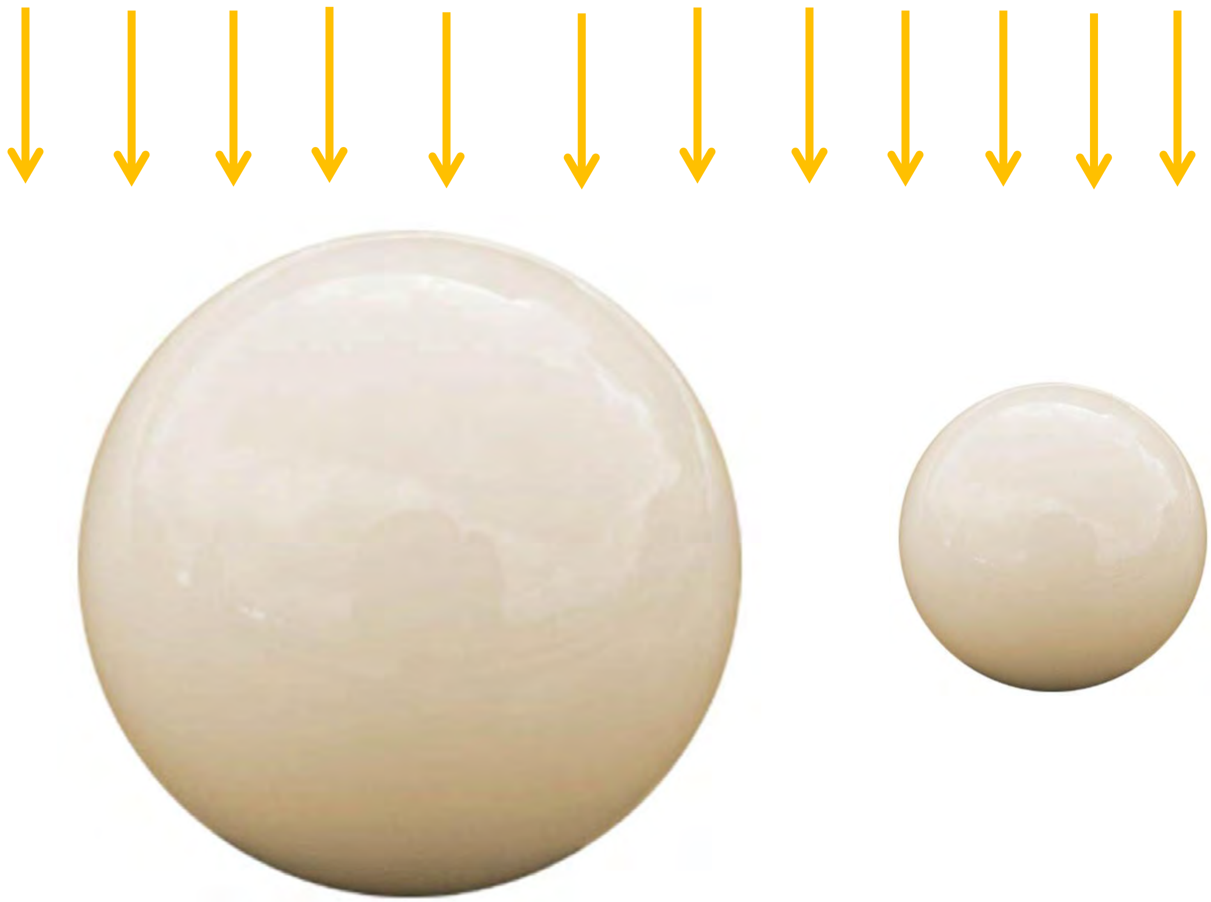
**Chl ↑ → specific optical property ↓**




(Bricaud et al 1995)

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

# Simplified case:



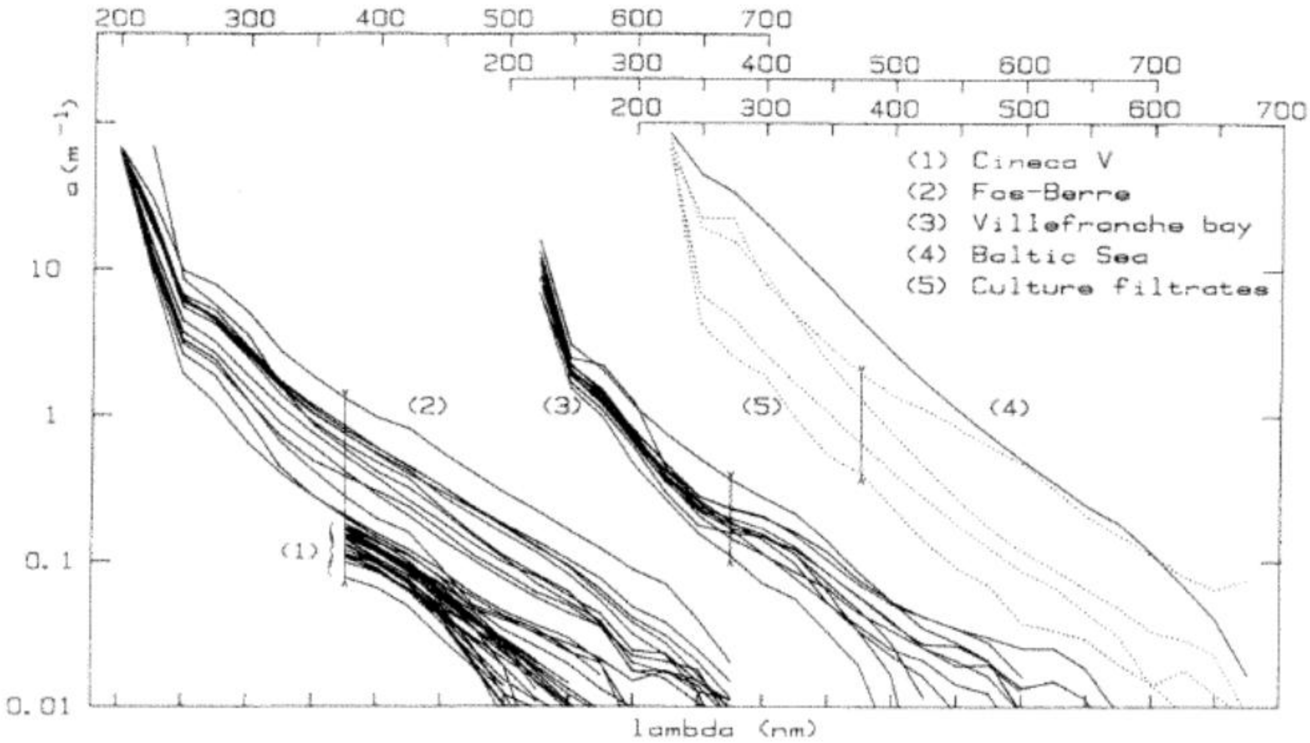
$$a \propto \rho S$$

$$W \propto \rho V$$

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

# $a_g$ spectrum

Absorption spectra of yellow substance (gelbstoff)

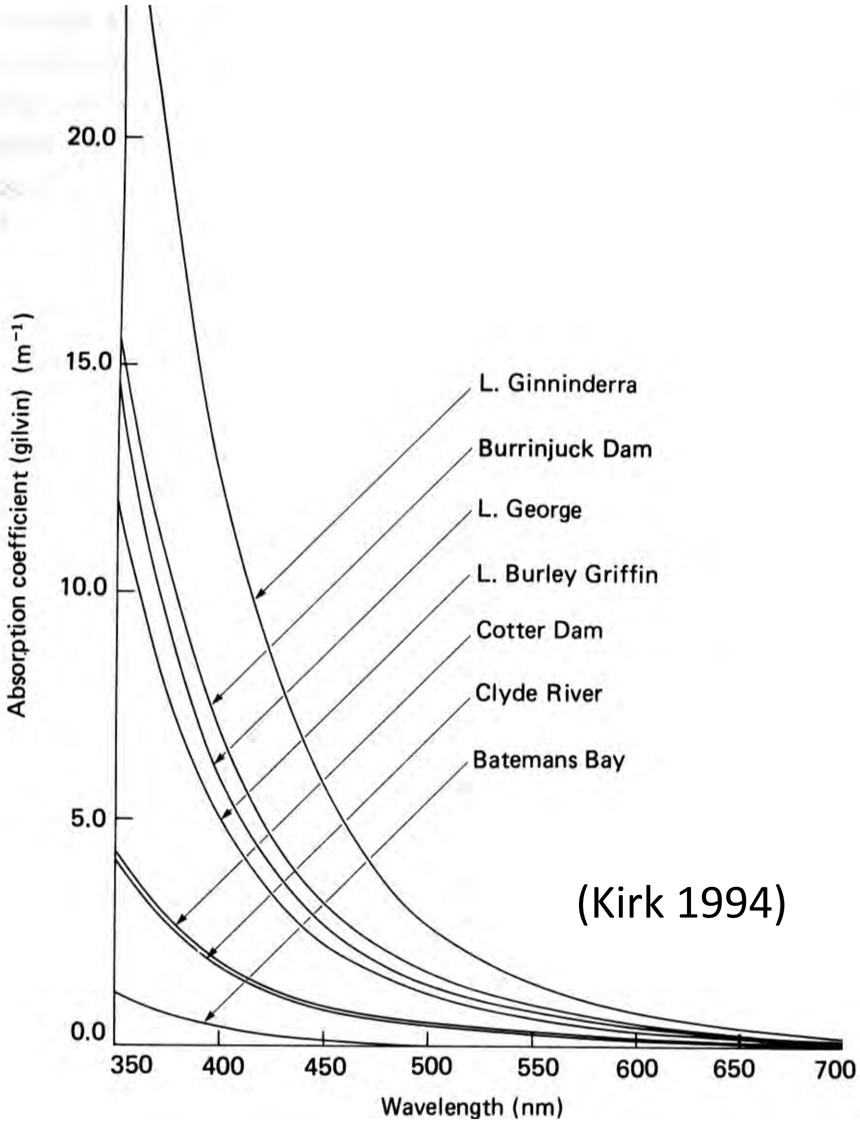



(Bricaud et al 1981)

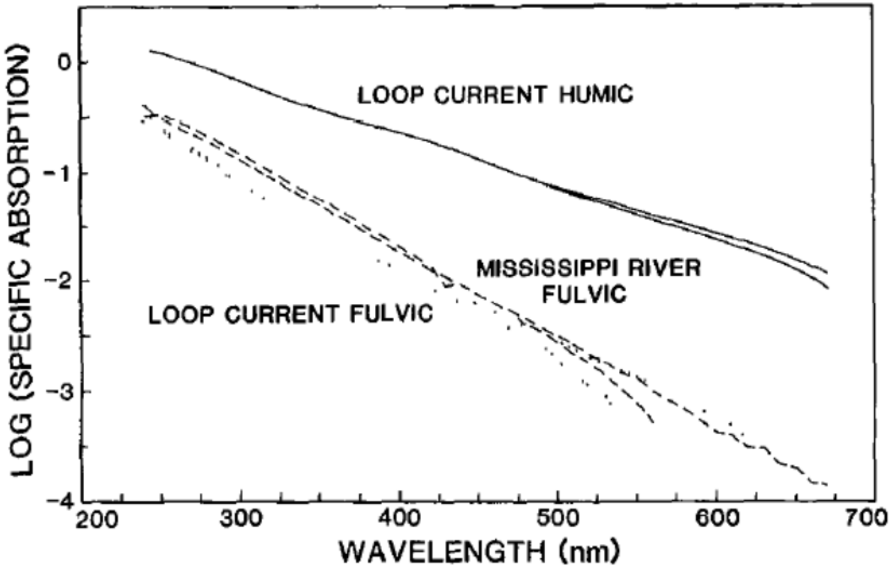
# $a_g$ spectrum

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

**$S_g$: ~0.01 – 0.03 nm$^{-1}$**




(Kirk 1994)




(Carder et al 1989)

Table 1

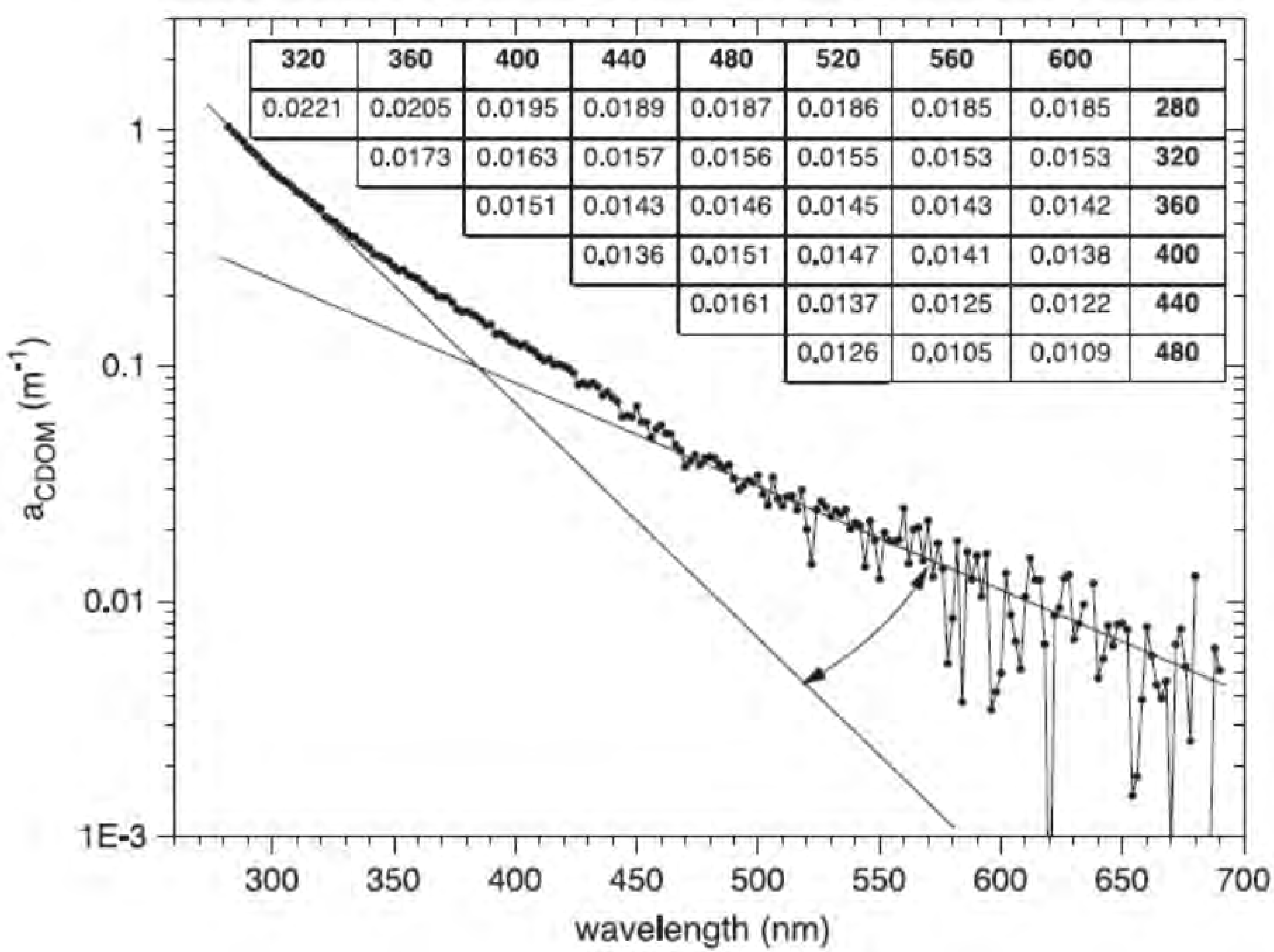
Spectral slope values for marine samples reported in the literature with spectral range, CDOM absorption at 412 nm, and reported precision (ordered according to starting wavelength range)

| 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 |
| 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 | |
|---|---|---|---|---|---|---|---|---|
| 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:

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

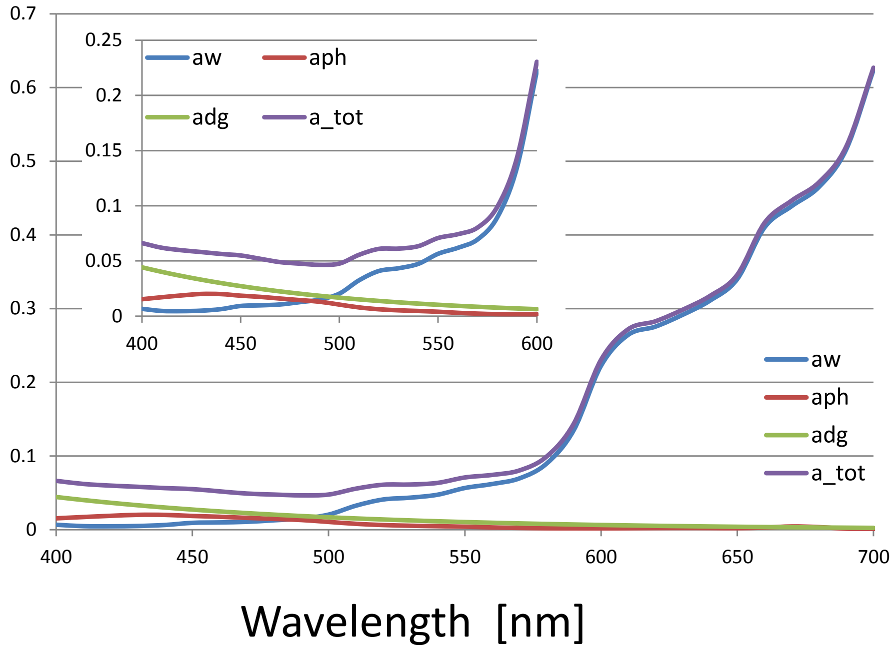
(Twardowski et al 2004)

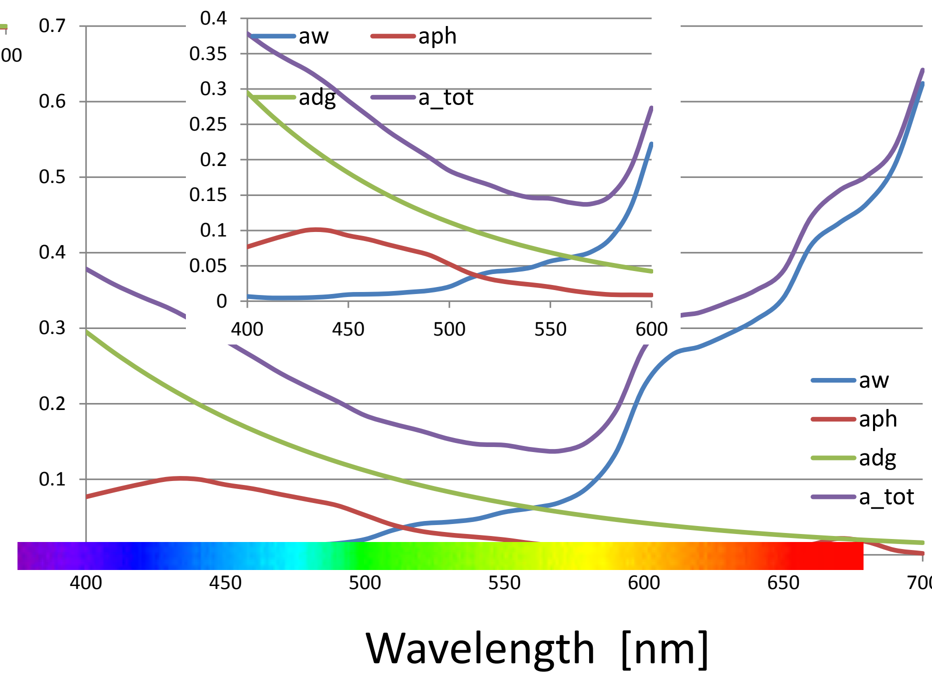
# Values of $a_{ph}$ and $a_g$ of natural waters

| 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 of optically active components



# 2. Scattering properties

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

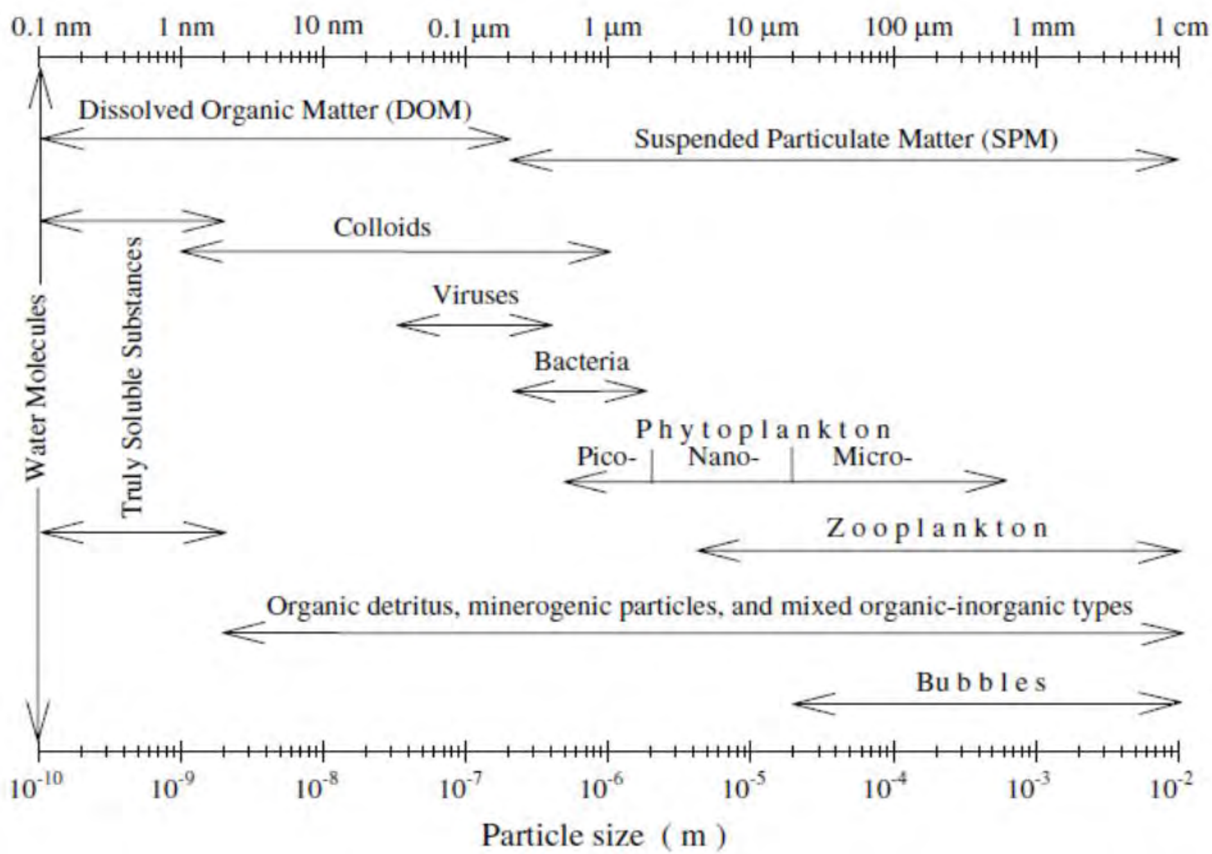
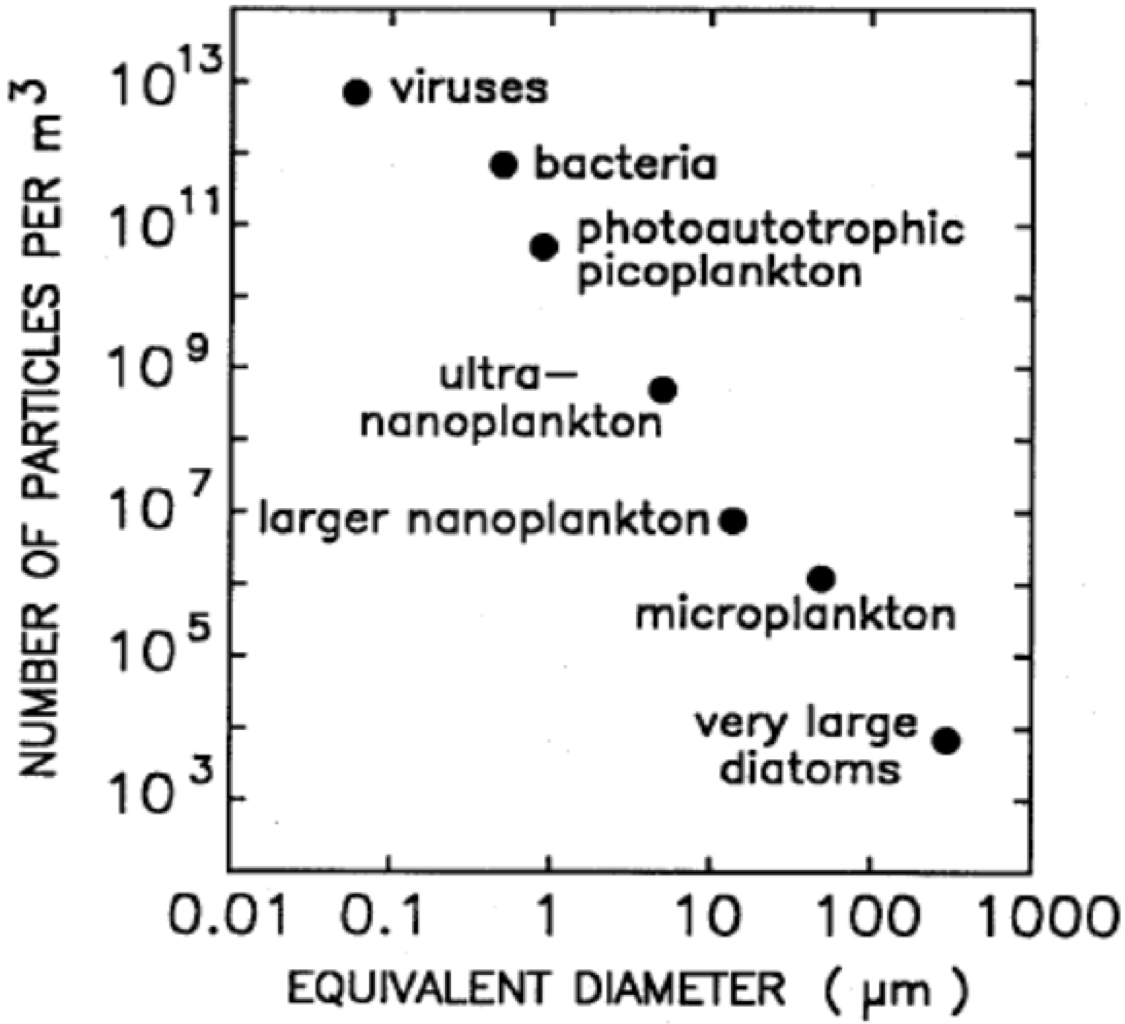



Fig. 1. Schematic diagram showing various seawater constituents in the broad size range from molecular size of the order of $10^{-10}$ m to large particles and bubbles of the order of $10^{-3}$–$10^{-2}$ m in size. The arrow ends generally indicate approximate rather than sharp boundaries for different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

# Size distribution




(Stramski and Kiefer 1991)

$$b = b_w + \sum b_{xi} \qquad b_b = b_w + \sum b_{bxi}$$

**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 used terms for scattering:

**Molecules**

**Suspended 'particles'**

**Bubbles**

**Turbulence**

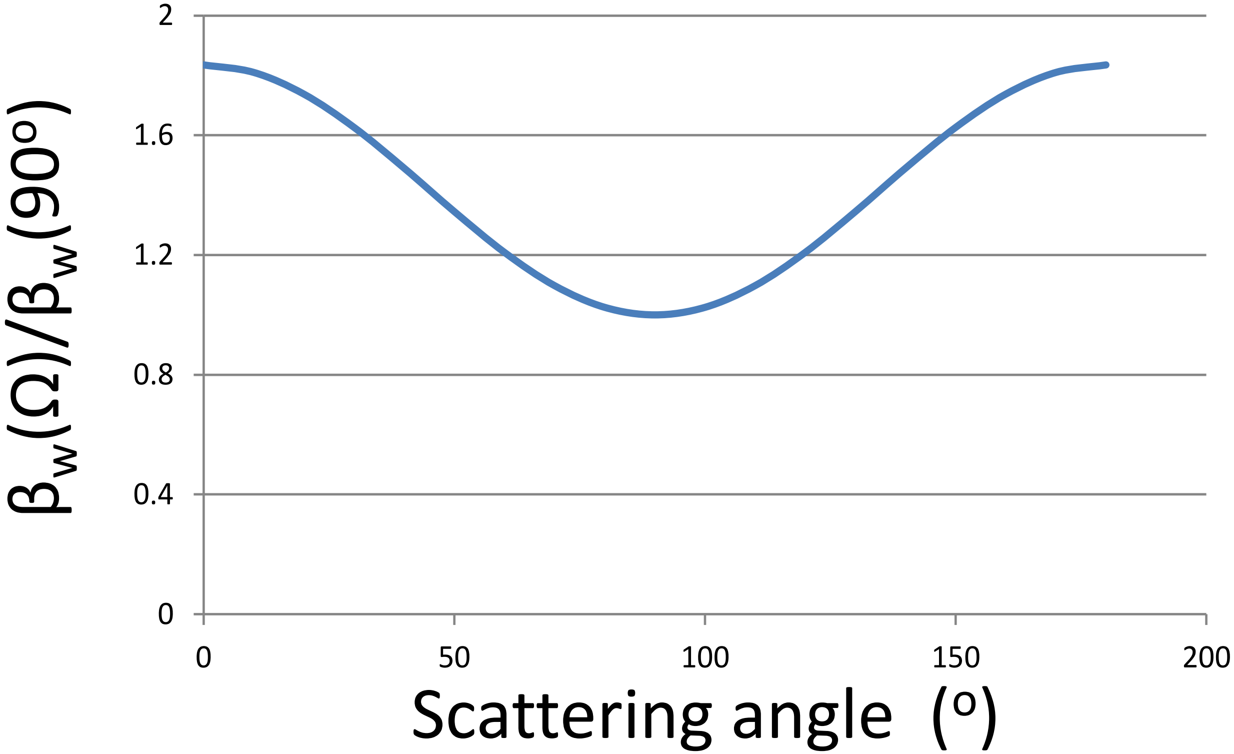
$$b = b_w + b_p$$

Or,

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

# Scattering of water molecules

## VSF of pure water ($\beta_w$)




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

# 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 $b_{bw}$:

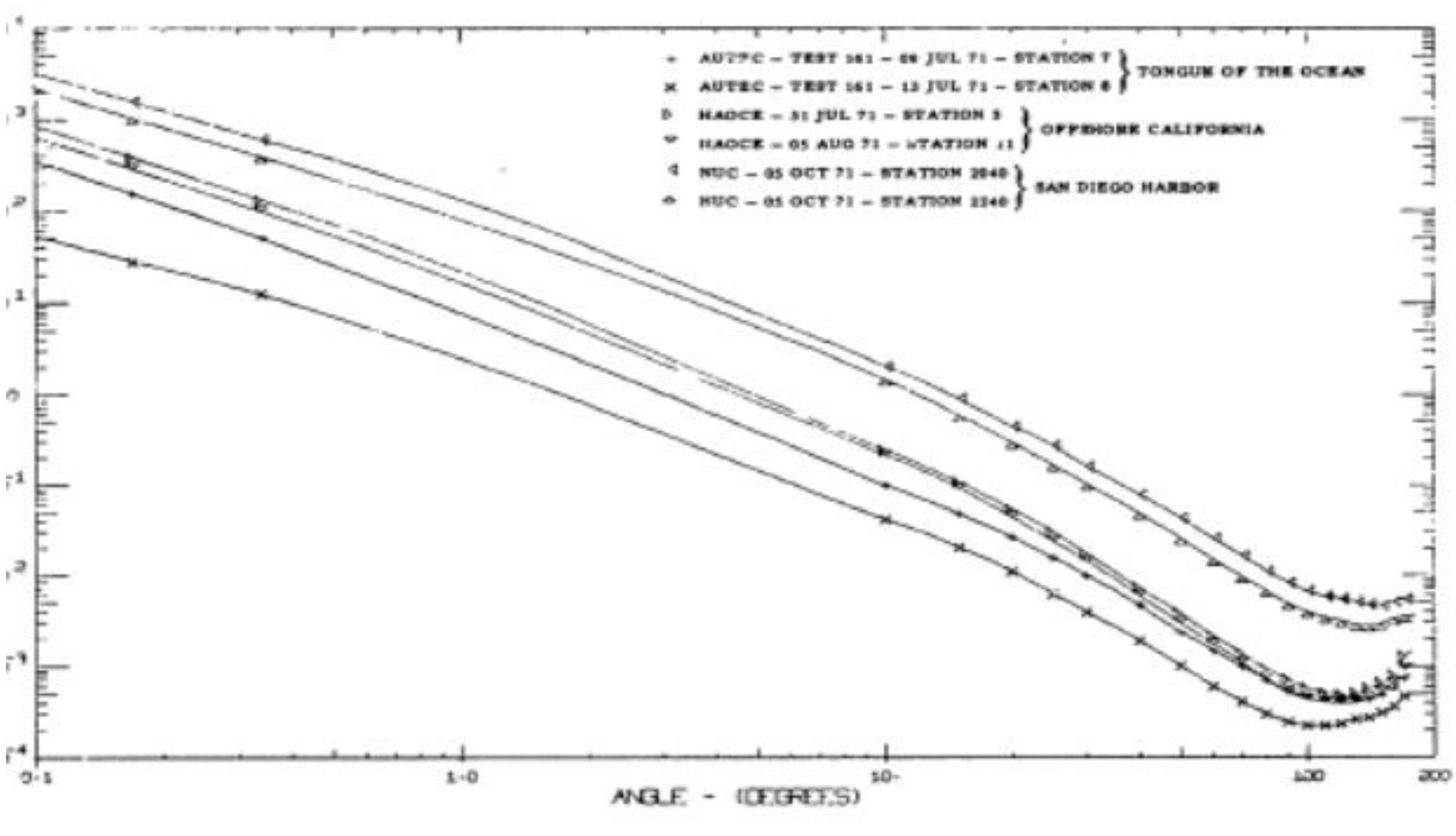
$$b_{bw}(\lambda) = 0.0023\left(\frac{450}{\lambda}\right)^{4.32}$$

(Morel 1974)

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

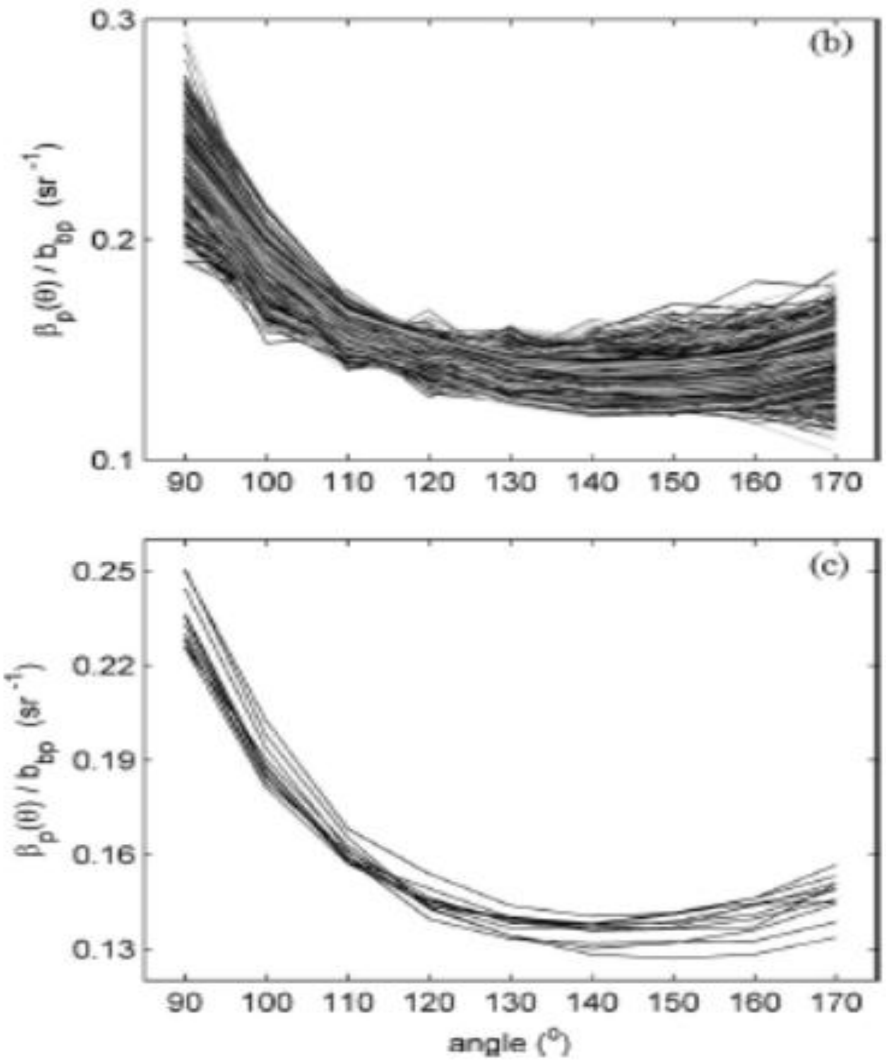
(Zhang et al 2009)

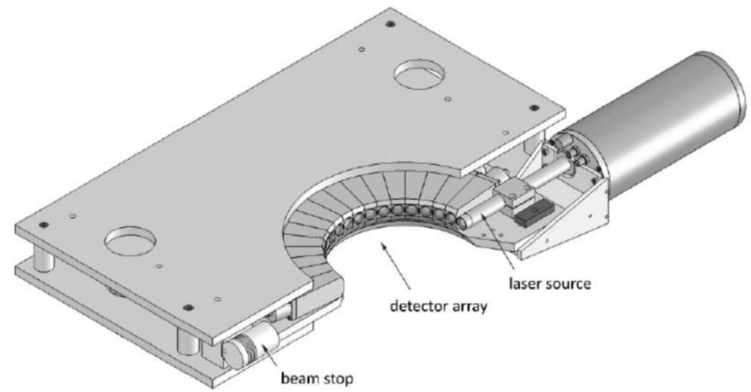
# Volume Scattering Function with particles




(Petzold 1972)

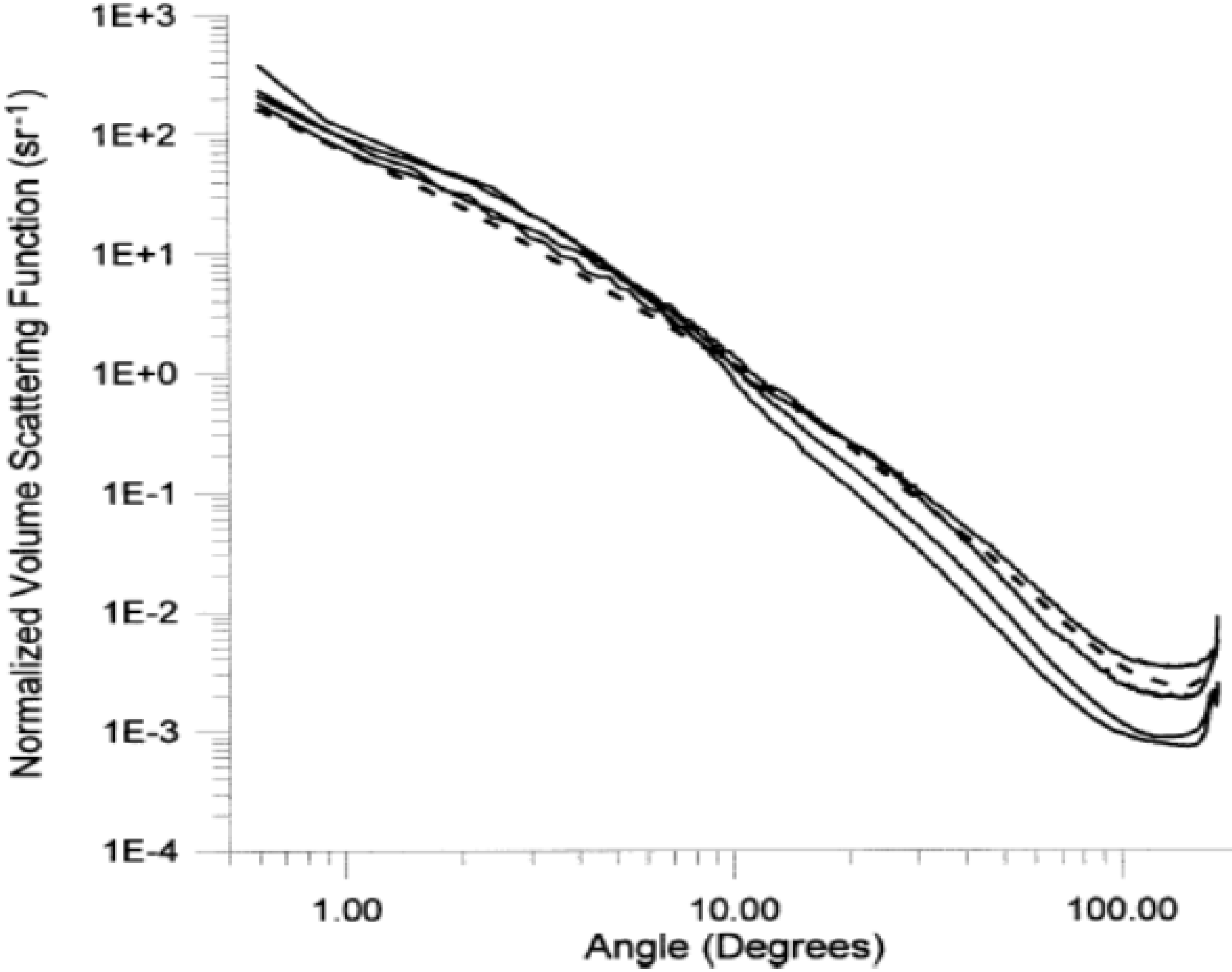
# MASCOT measurements



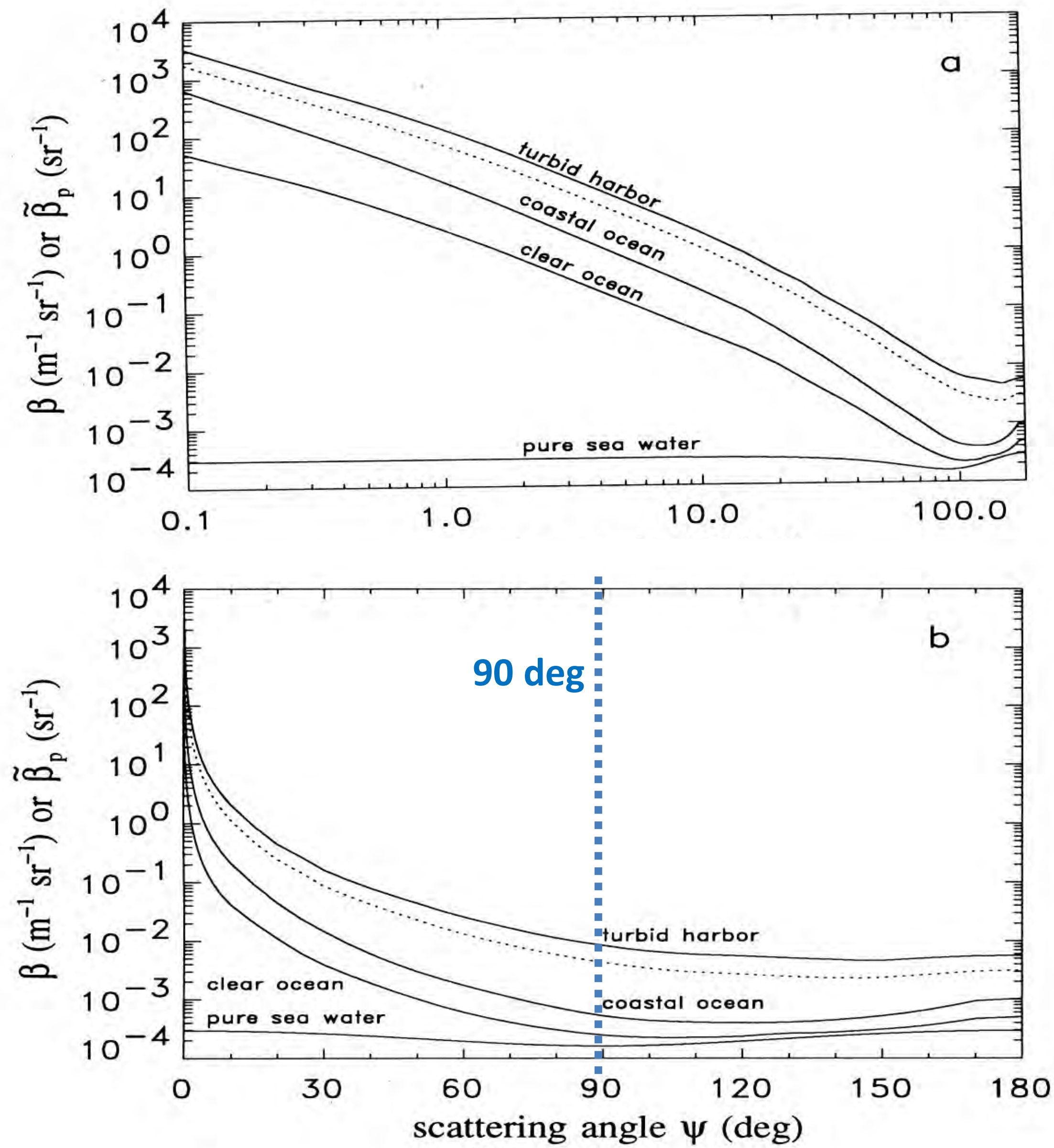




(Sullivan and Twardowski, 2009)

# MVSM measurements




(Lee and Lewis, 2003)




(Mobley 1994)

**β shape changes in a narrow range in the backward domain**

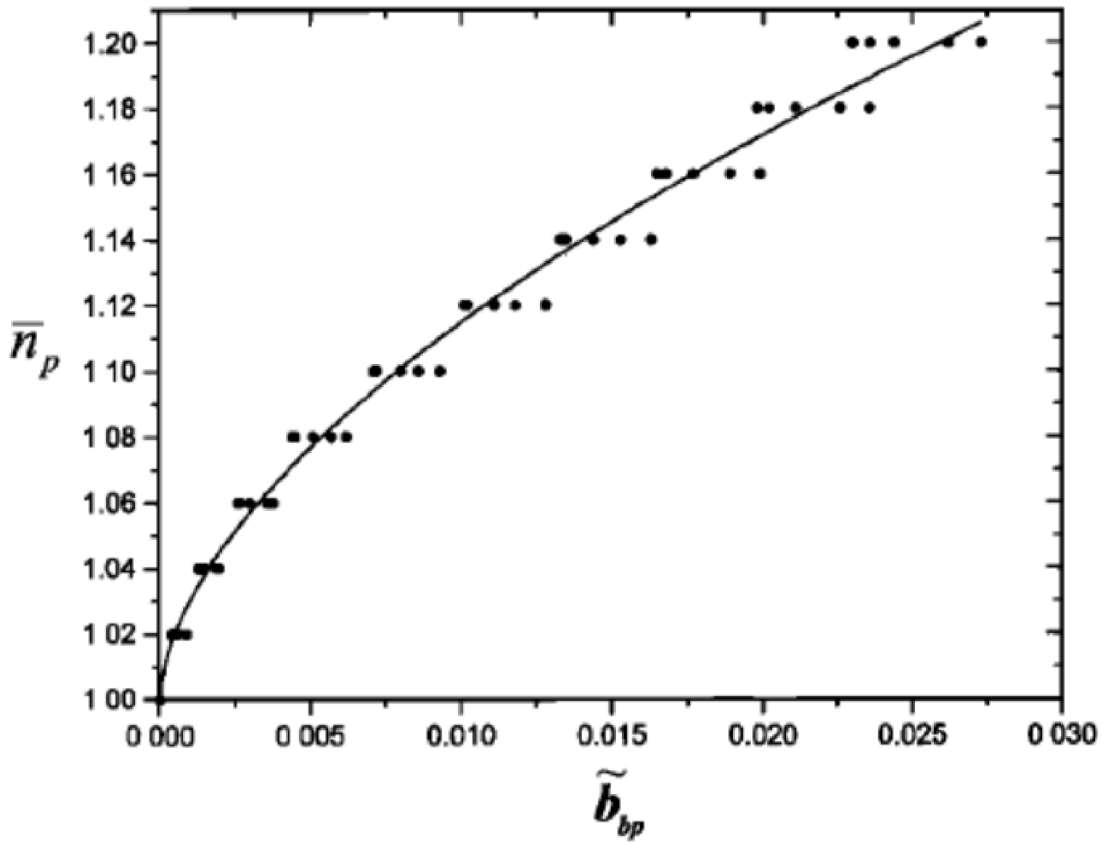
**Particles are strongly forward scatters!**

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

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

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

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




Twardowski et al (2001)

# Examples of β model

**Henyey-Greenstein (1941)**

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

**Beardsley and Zaneveld (1969)**

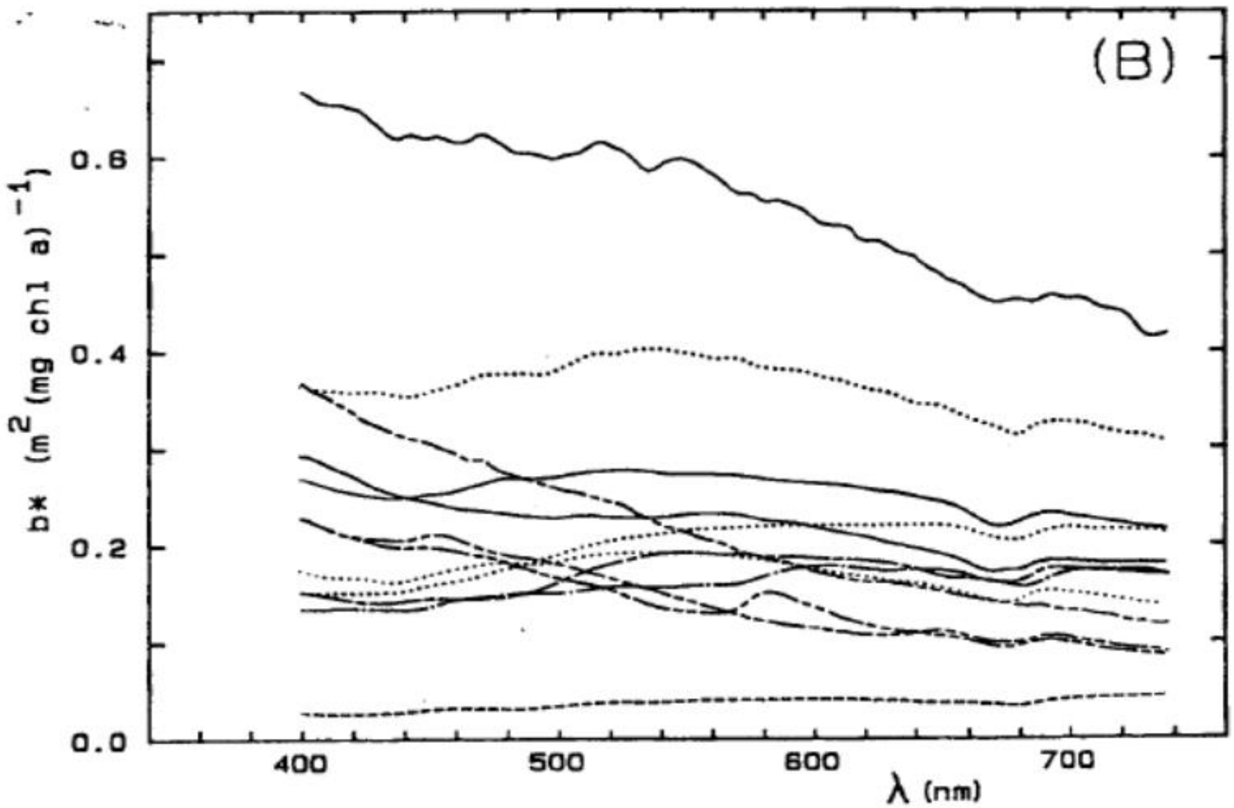
$$\beta \sim \frac{1}{(1-\varepsilon_f\cos\psi)^4(1+\varepsilon_b\cos\psi)^4}$$

**Fournier and Forand (1994)**

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

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

# Spectrum of scattering coefficient



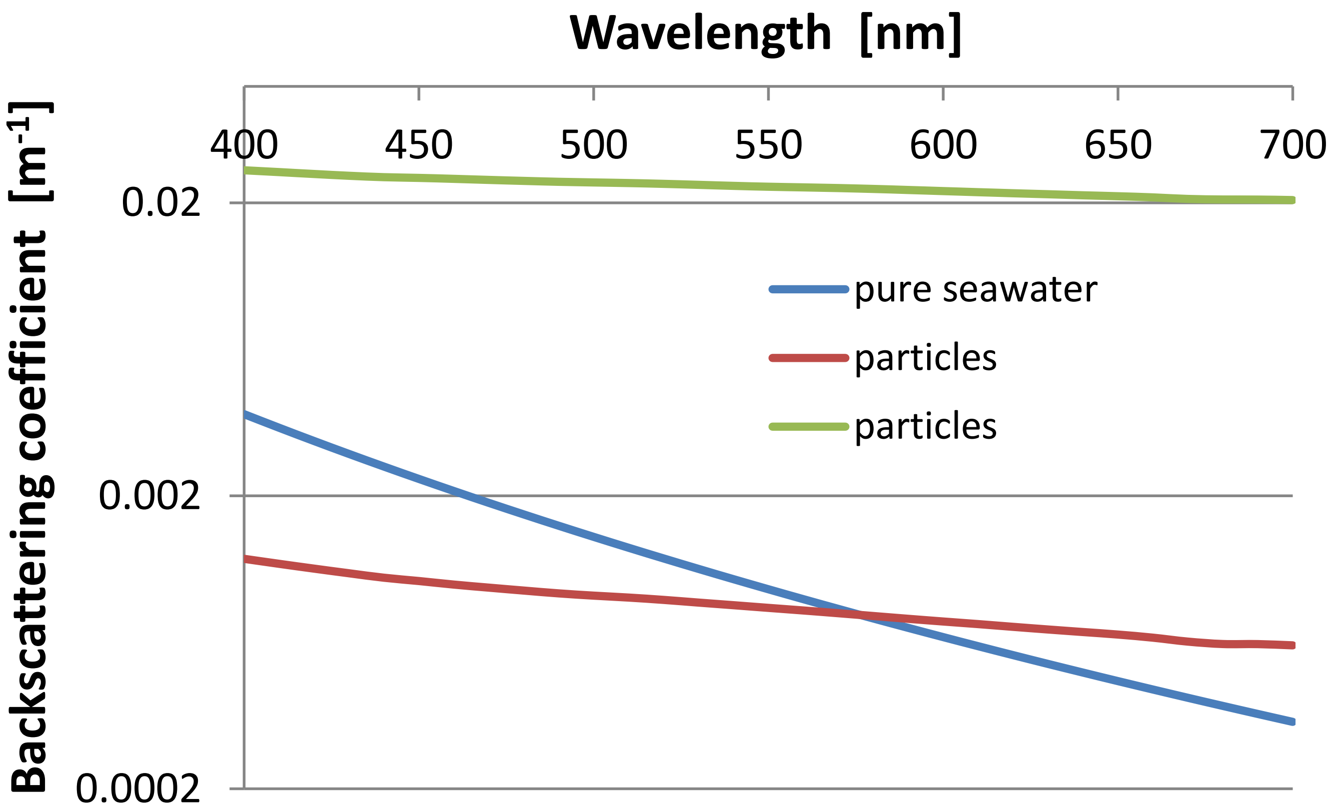

(Bricaud et al 1988)

**vary weakly with wavelength**

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

(Gould et al 1999)

# $b_b$ spectrum contrast

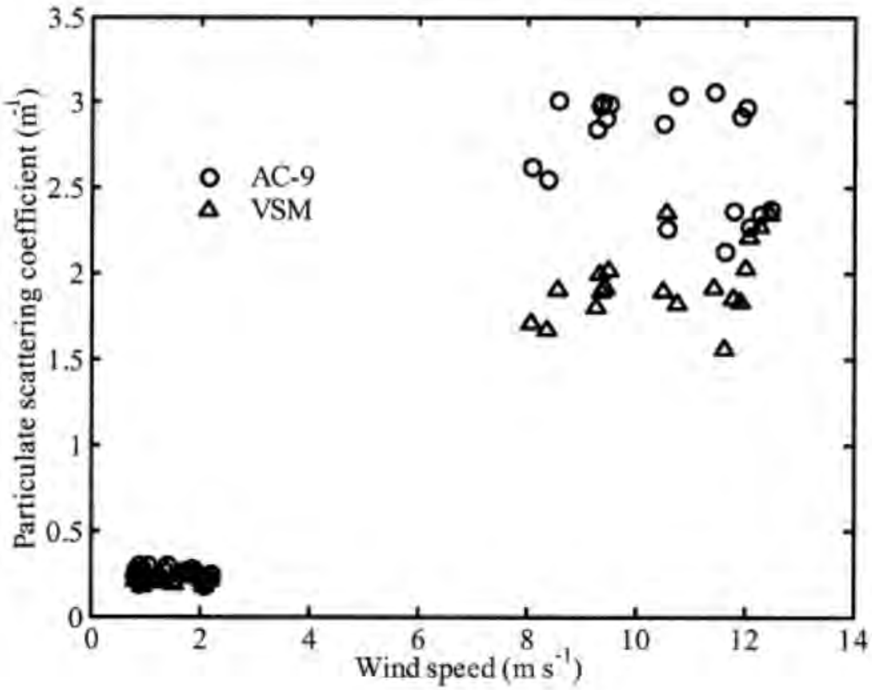


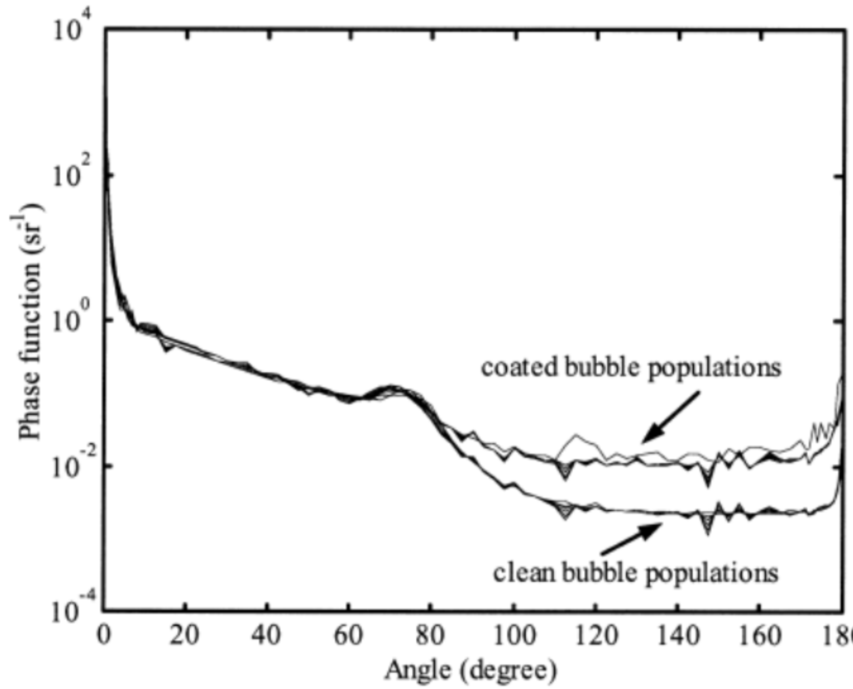

$$b_{bp}(\lambda) = b_0 \left( \frac{\lambda_0}{\lambda} \right)^{\eta}$$

**$b_{bw}$: ~0.0001 – 0.004 $m^{-1}$**

**η: ~0-2.0**

# bubbles

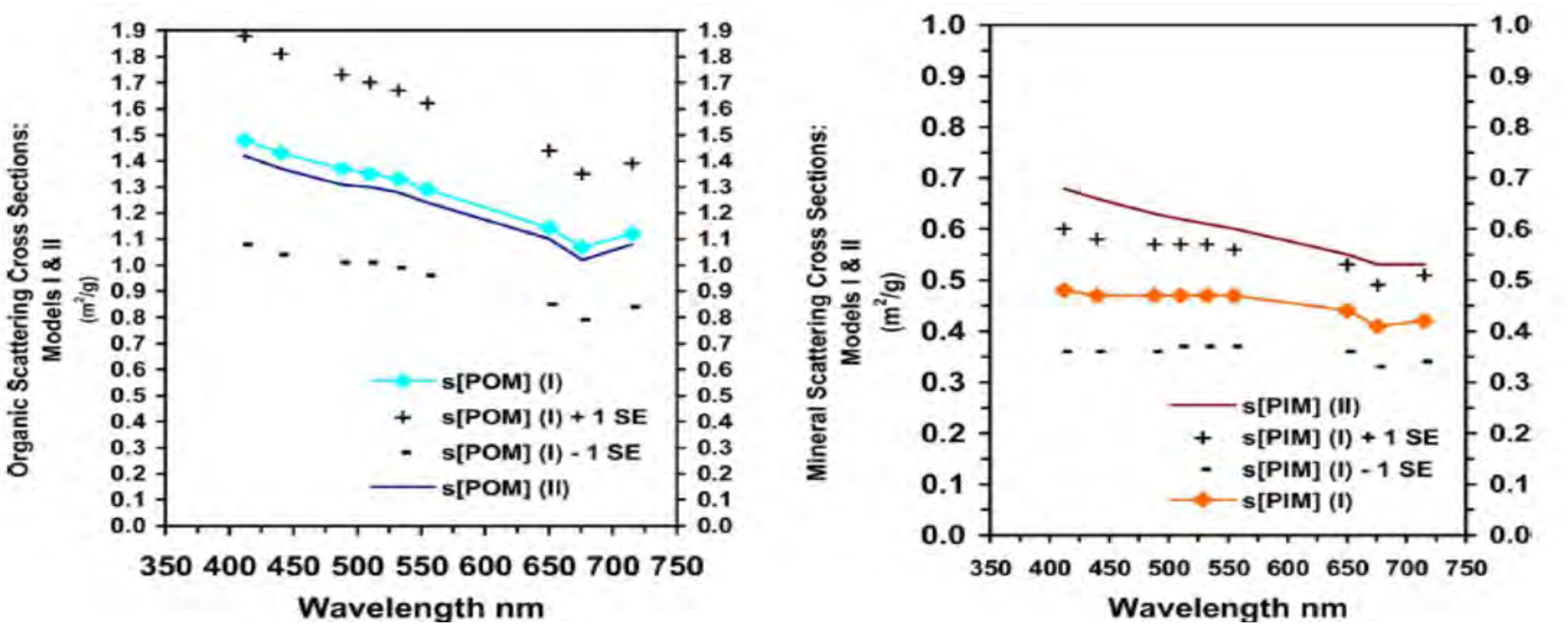


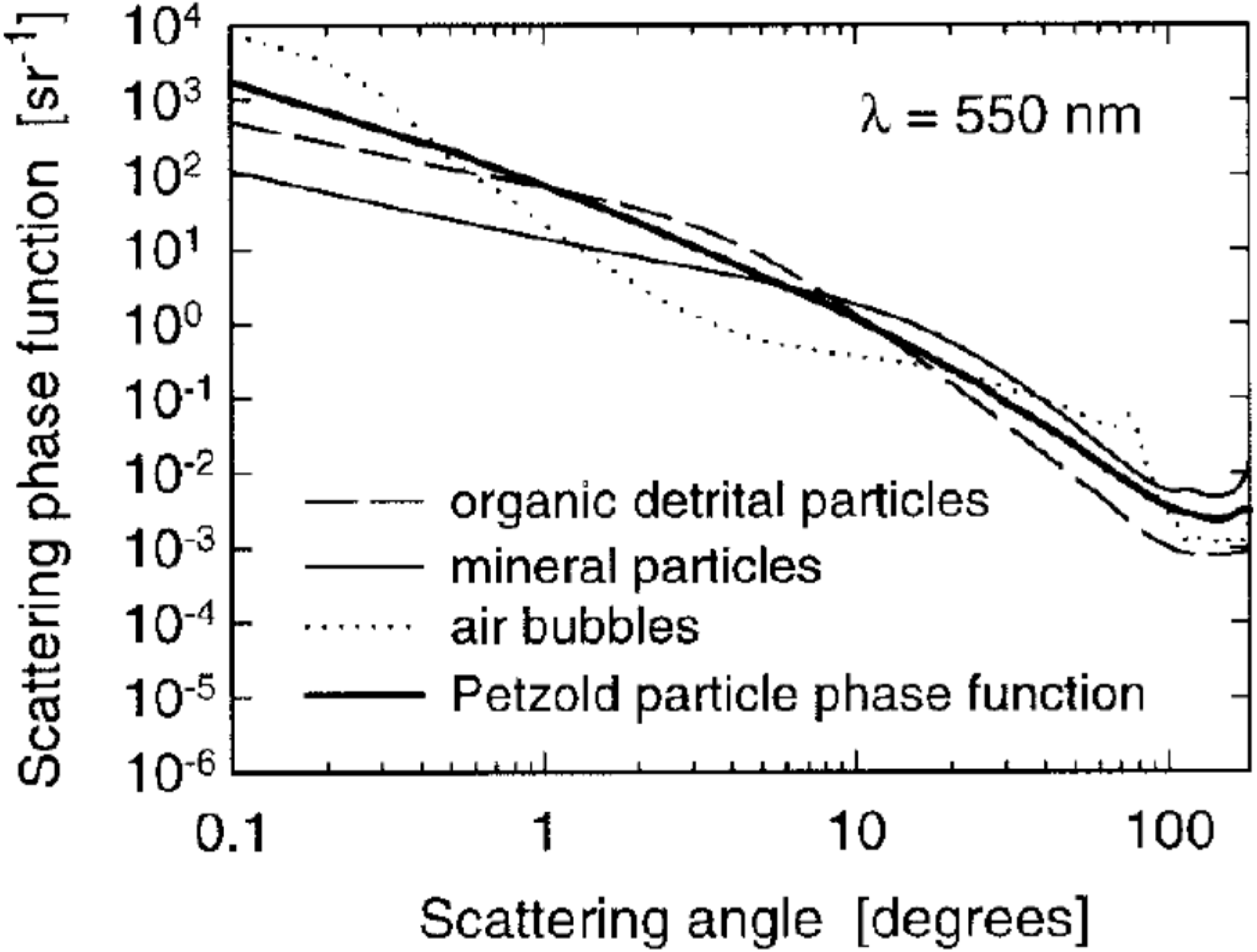

(Zhang et al 2002)

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

# Organic vs inorganic separation




(Stavn and Richter 2008)




(Stramski et al 2001)

# Light scattering by microorganisms in the open ocean

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

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Progress in Oceanography 61 (2004) 27–56

Oceanography

www.elsevier.com/locate/pocean

Review

# The role of seawater constituents in light backscattering in the ocean

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Received 3 November 2003; revised 4 July 2004; accepted 9 July 2004

Available online 19 August 2004

# 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, refractive index, and abundance.