Optics of Marine Particles

Lecture 2

Dariusz Stramski

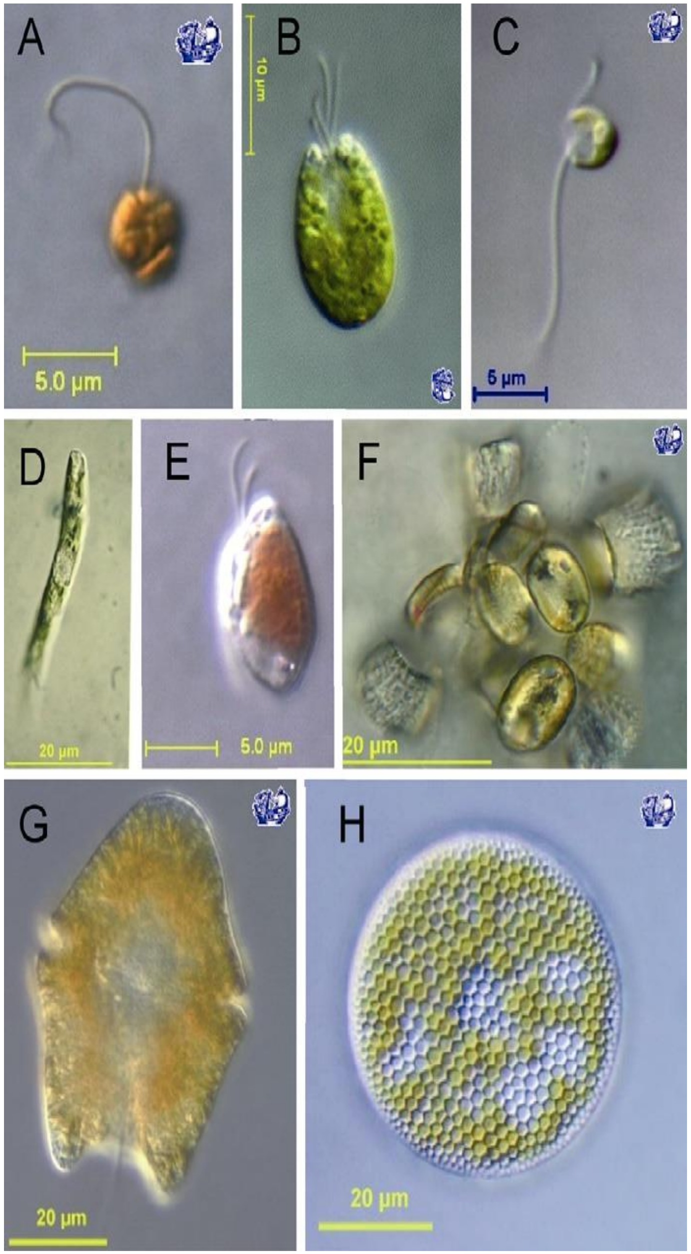
Scripps Institution of Oceanography
University of California San Diego
Email: dstramski@ucsd.edu

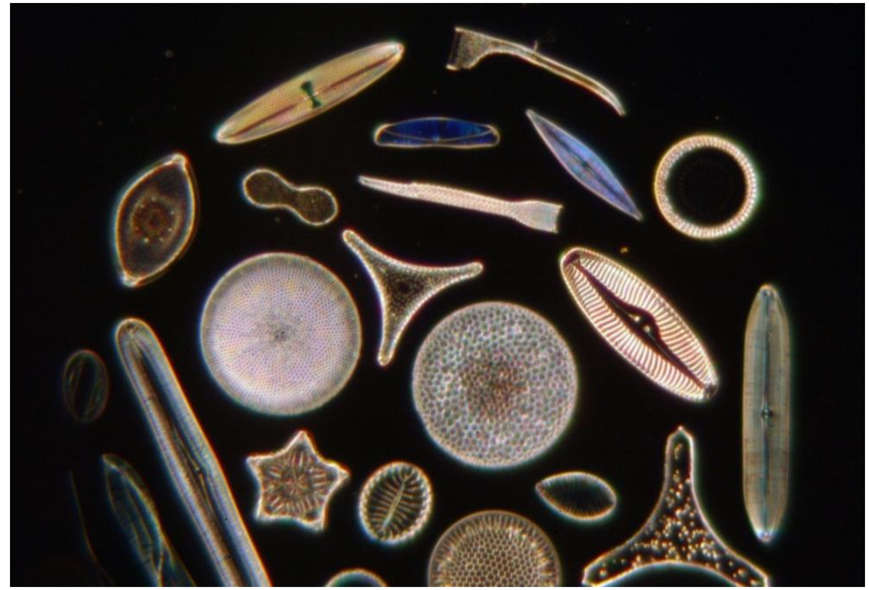
IOCCG Summer Lecture Series
22 July - 2 August 2014, Villefranche-sur-Mer, France

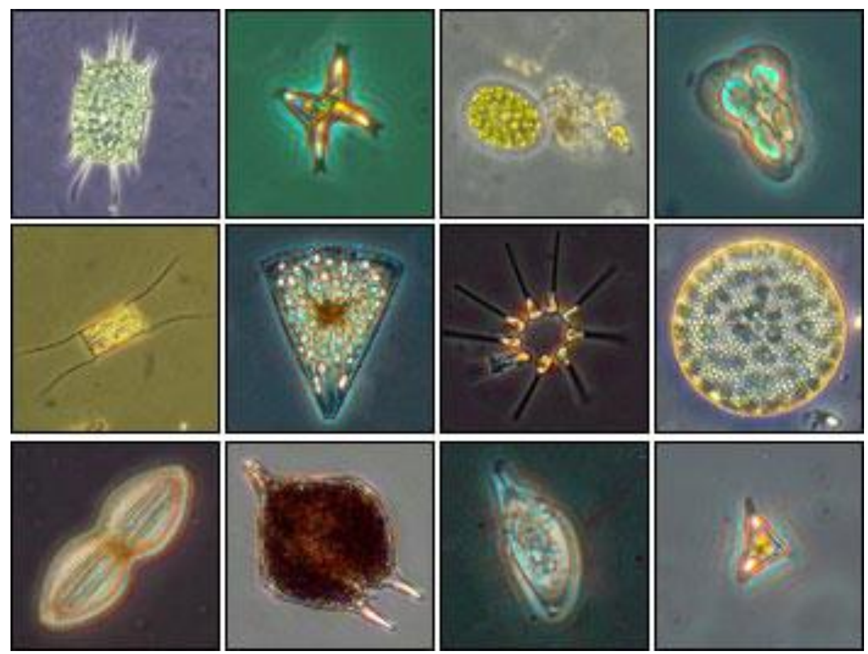
Suspended Particulate Matter

- Plankton microorganisms
- Biogenic detrital particles
- Mineral particles
- Colloidal particles
- Air bubbles

Plankton microorganisms







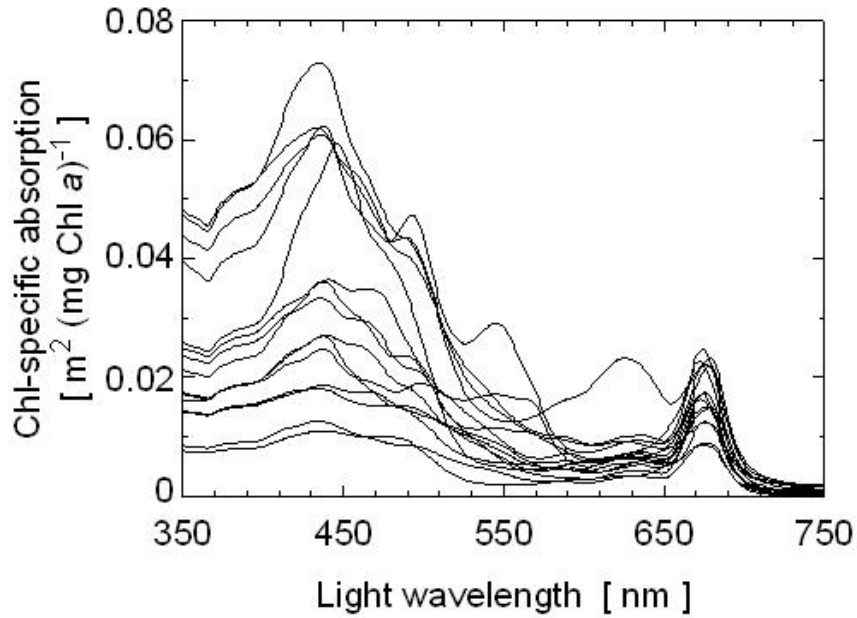
Plankton microorganisms

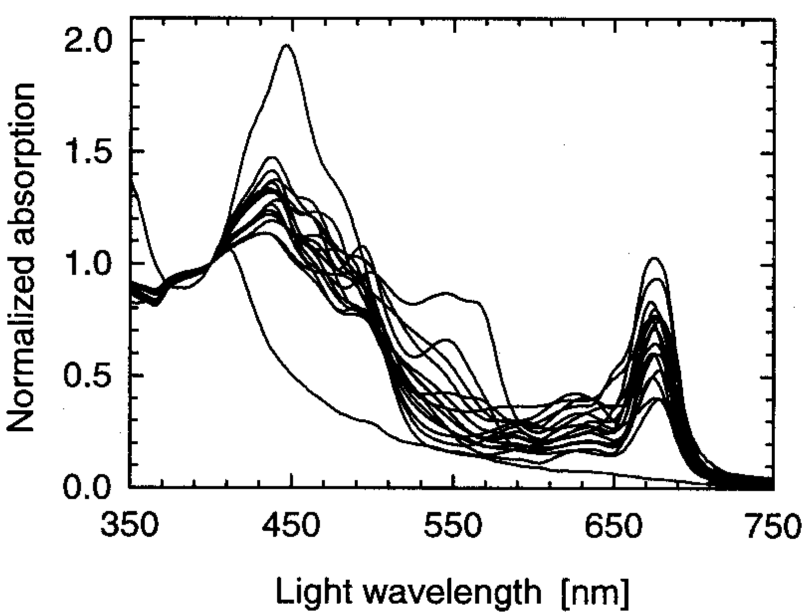
Table 1. Microbial components in the database and source of raw data. Values for the average equivalent spherical diameter (D), the real part of refractive index at 550 nm (n), and imaginary part of refractive index at 440 and 675 nm (n') are also given for each component.

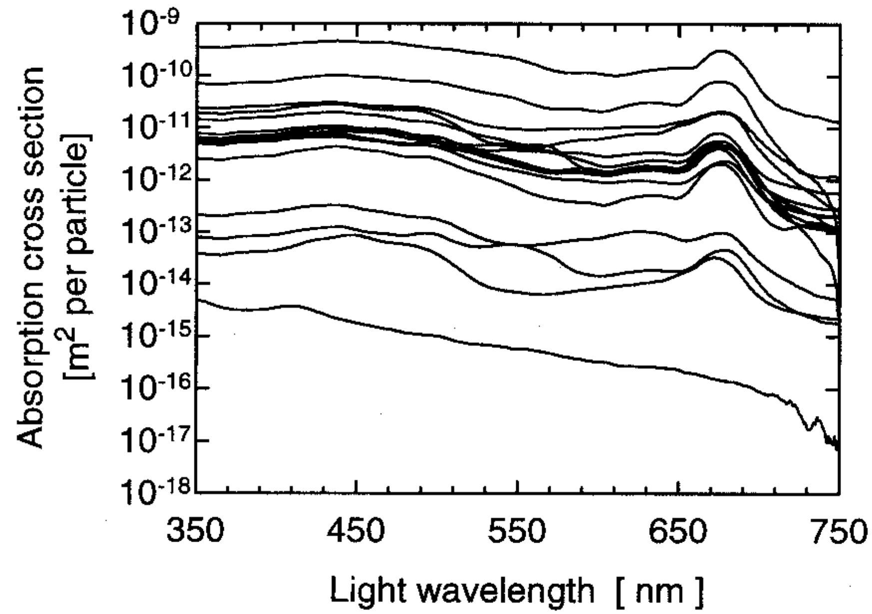
i	Label	Microbial species	D [μm]	n 550 nm	$n' \cdot 10^3$ 440 nm	$n' \cdot 10^3$ 675 nm	Source of raw data
1	VIRU	Viruses	0.07	1.050	0	0	Stramski and Kiefer, 1991
2	HBAC	Heterotrophic bacteria	0.55	1.055	0.509	0.057	Stramski and Kiefer, 1990
3	PROC	generic Prochlorophyte; the average of:	0.66	1.051	18.51	10.30	
		PMED - Prochlorococcus strain MED	0.59	1.055	23.25	13.77	Morel et al., 1993
		PNAS - average of Prochlorococcus strains NATL and SARG	0.70	1.046	13.78	6.687	Morel et al., 1993
4	SYNE	generic Synechococcus; the average of:	1.05	1.051	5.587	2.930	
		SM41 - Synechococcus strain MAX41 (Cyanophyceae)	0.92	1.047	5.415	2.905	Morel et al., 1993
		SM01 - Synechococcus strain MAX01 (Cyanophyceae)	0.94	1.049	4.505	2.547	Morel et al., 1993
		SROS - Synechococcus strain ROS04 (Cyanophyceae)	1.08	1.049	4.516	2.154	Morel et al., 1993
		SDC2 - Synechococcus strain DC2 (Cyanophyceae)	1.14	1.050	4.249	2.375	Morel et al., 1993
		S103 - Synechococcus strain WH8103 (Cyanophyceae)	1.14	1.062	9.251	4.668	Stramski et al., 1995
5	SYMA	generic phycocyanin-rich picophytoplankton; the average of:	1.41	1.055	6.495	2.757	
		SCYS - Synechocystis (Cyanophyceae)	1.39	1.050	4.530	1.910	Ahn et al., 1992
		MARI - Anacystis marina (Cyanophyceae)	1.43	1.060	8.460	3.603	Ahn et al., 1992
6	PING	Pavlova pinguis (Haptophyceae)	3.97	1.046	4.177	2.709	Bricaud et al., 1988
7	PSEU	Thalassiosira pseudonana (Bacillariophyceae)	3.99	1.045	9.231	7.397	Stramski and Reynolds, 1993
8	LUTH	Pavlova lutheri (Haptophyceae)	4.26	1.045	5.767	2.403	Bricaud et al., 1988
9	GALB	Isochrysis galbana (Haptophyceae)	4.45	1.056	7.673	5.101	Ahn et al., 1992
10	HUXL	Emiliania huxleyi (Haptophyceae)	4.93	1.050	5.012	2.950	Ahn et al., 1992
11	CRUE	Porphyridium cruentum (Rhodophyceae)	5.22	1.051	3.351	2.443	Bricaud et al., 1988
12	FRAG	Chroomonas fragarioides (Cryptophyceae)	5.57	1.039	4.275	2.904	Ahn et al., 1993
13	PARV	Prymnesium parvum (Haptophyceae)	6.41	1.045	2.158	1.329	Bricaud et al., 1988
14	BIOC	Dunaliella bioculata (Chlorophyceae)	6.71	1.038	10.49	7.839	Ahn et al., 1993
15	TERT	Dunaliella tertiolecta (Chlorophyceae)	7.59	1.063	6.260	5.076	Stramski et al., 1993
16	CURV	Chaetoceros curvisetum (Bacillariophyceae)	7.73	1.024	2.877	1.480	Bricaud et al., 1988
17	ELON	Hymenomonas elongata (Haptophyceae)	11.77	1.046	13.87	7.591	Ahn et al., 1992
18	MICA	Prorocentrum micans (Dinophyceae)	27.64	1.045	2.466	1.710	Ahn et al., 1992

(Stramski et al., 2001)

Interspecies variability in absorption

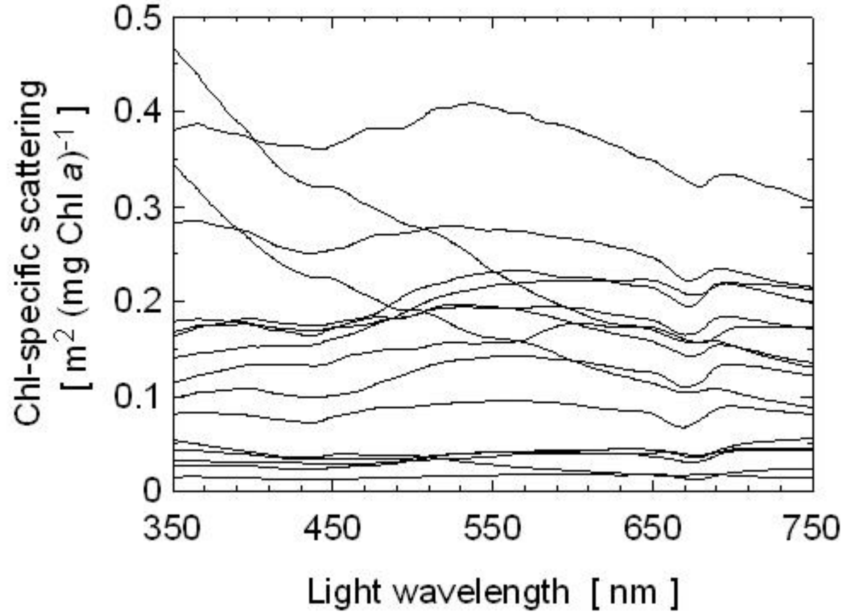


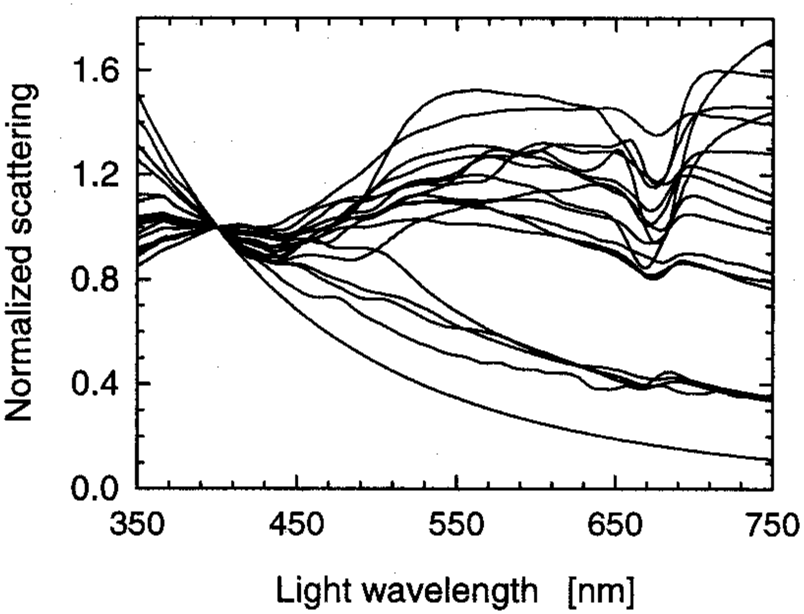


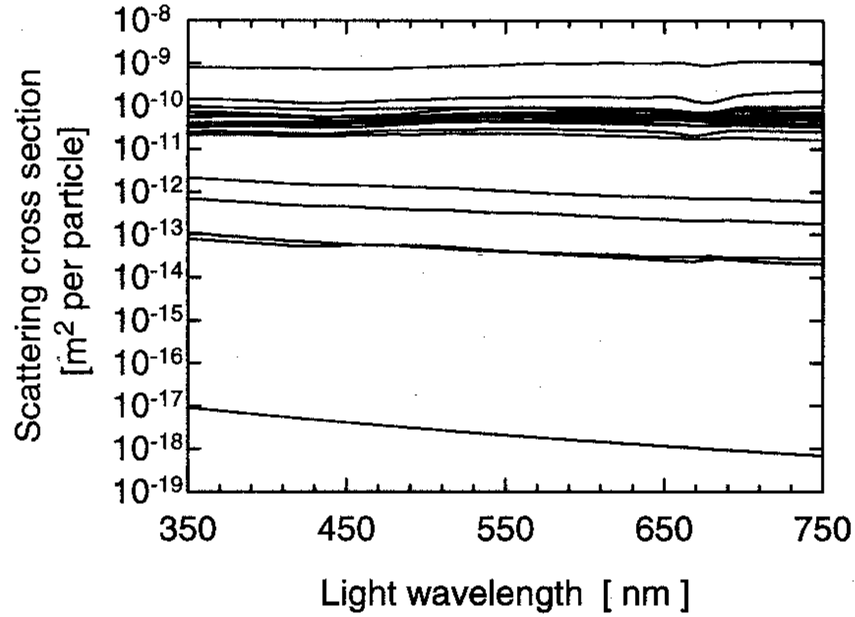


(Stramski et al. 2001)

Interspecies variability in scattering

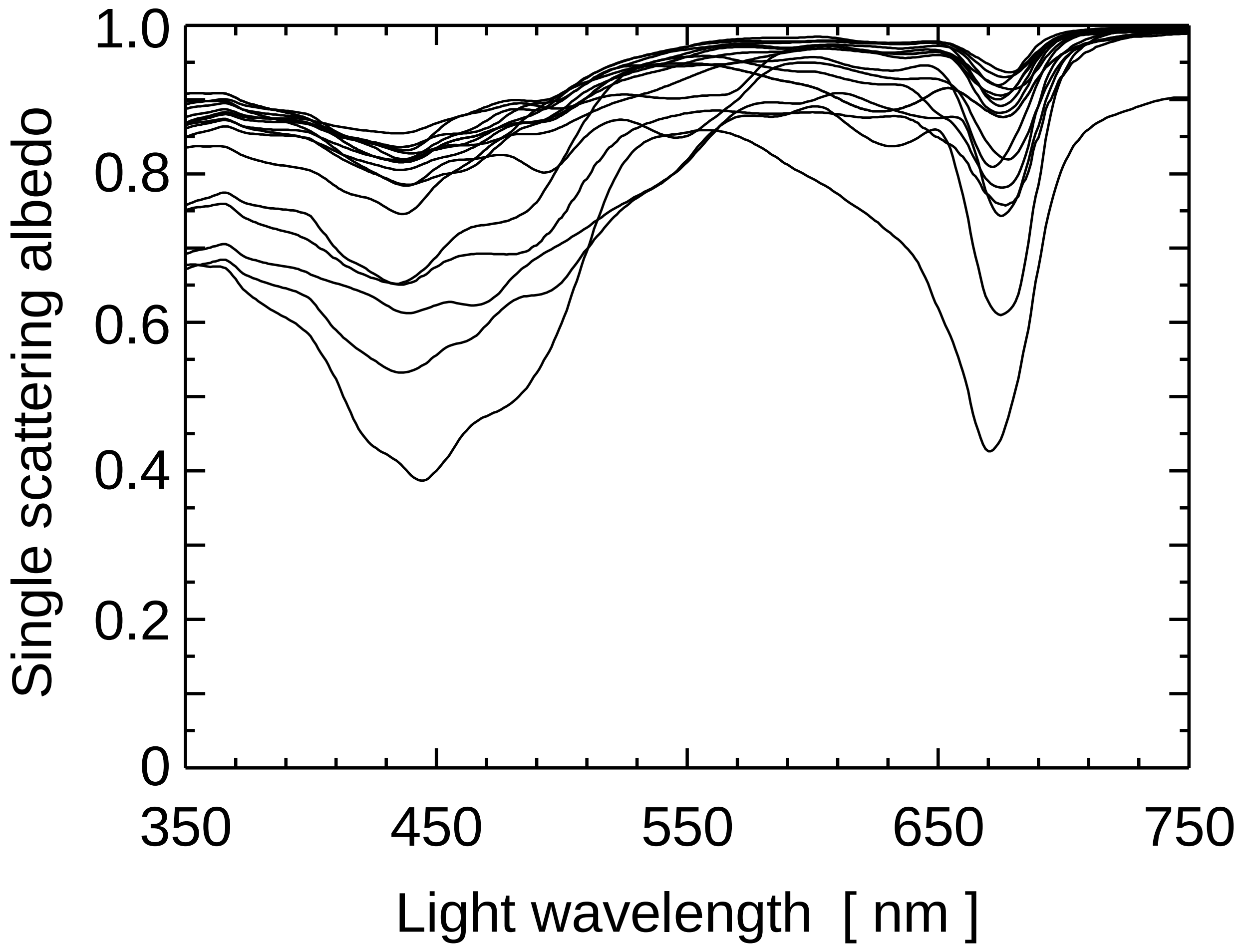






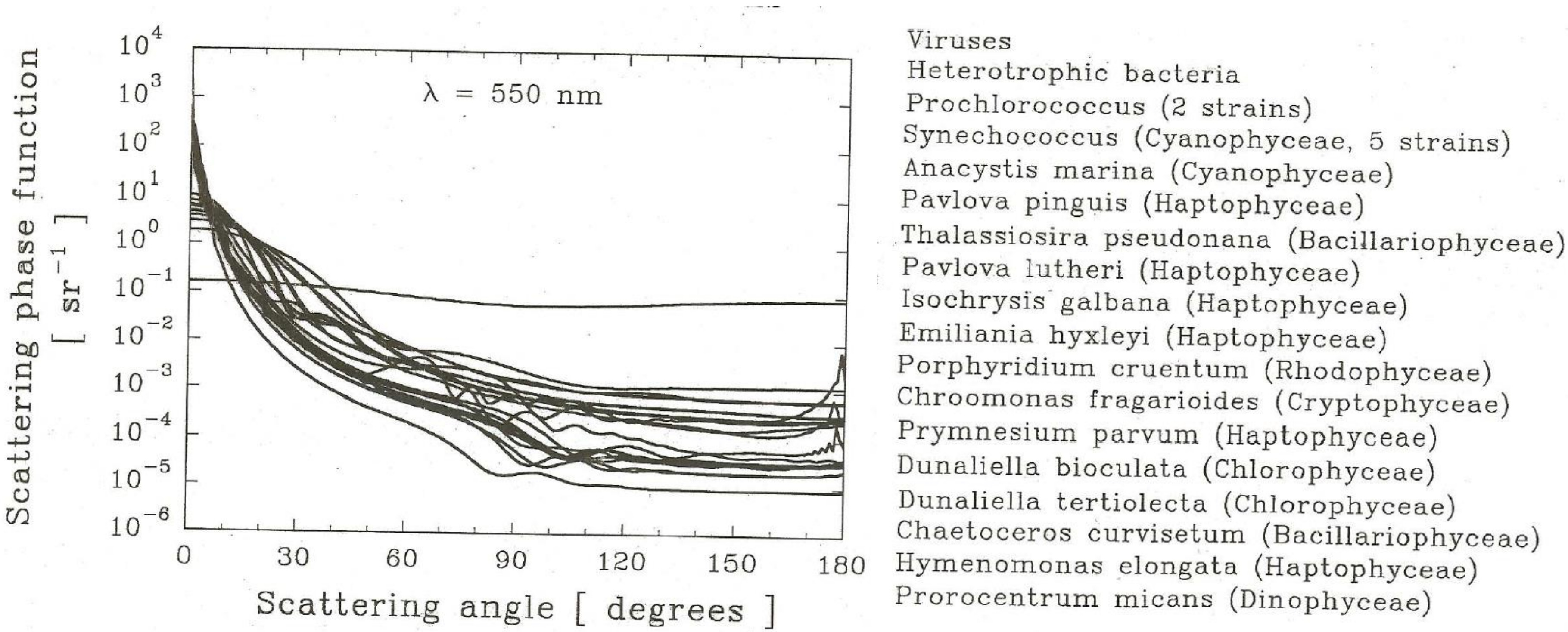
(Stramski et al. 2001)

Interspecies variability in single scattering albedo



(based on data from Stramski et al. 2001)

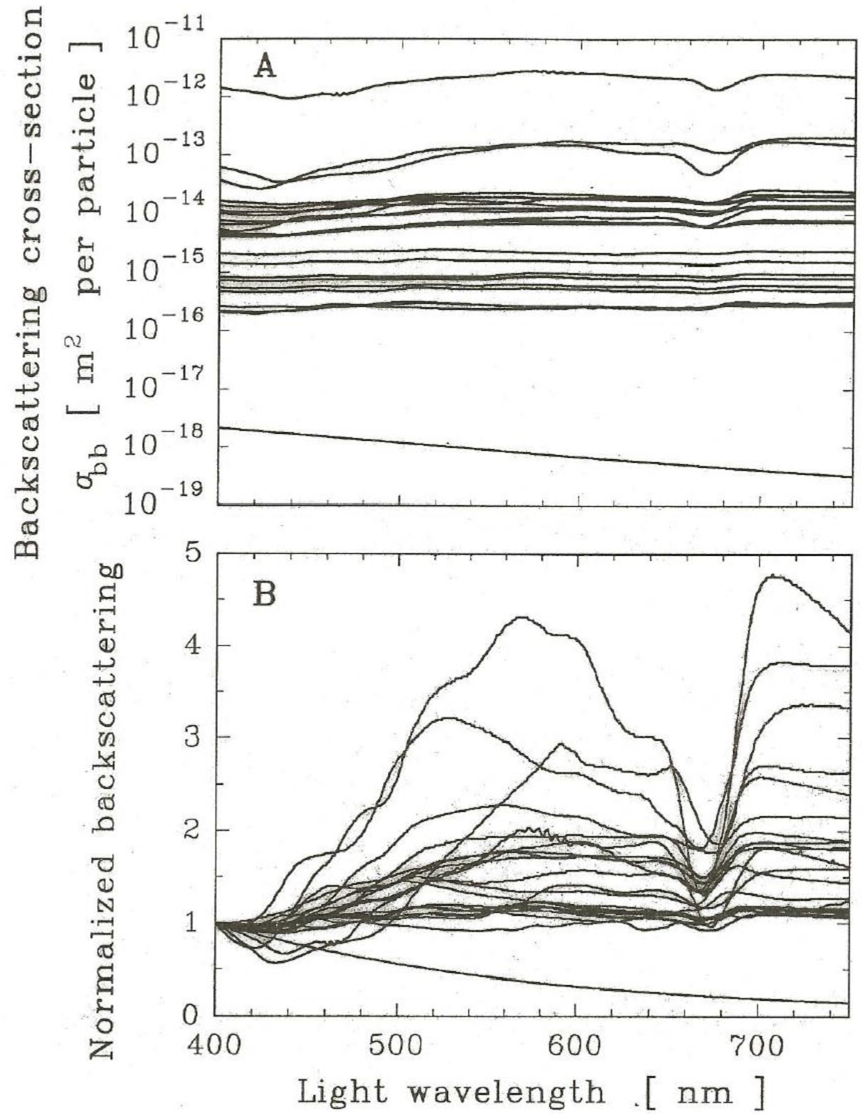
Mie calculations of scattering phase function for plankton microorganisms



(Stramski et al. 2001)

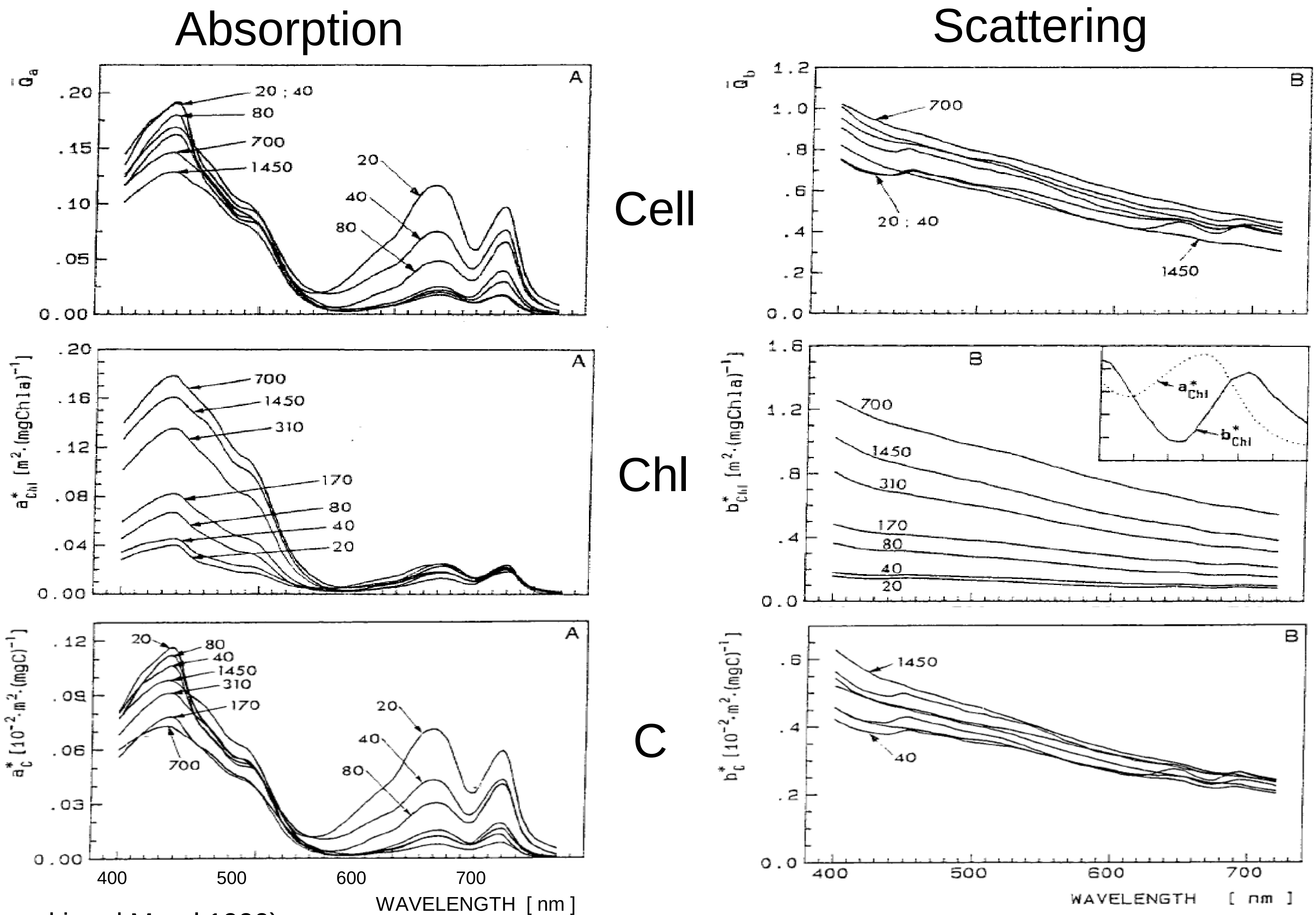
Backscattering properties of plankton microorganisms

(subject to uncertainties associated with Mie scattering calculations for homogeneous spheres)



(Stramski et al. 2001)

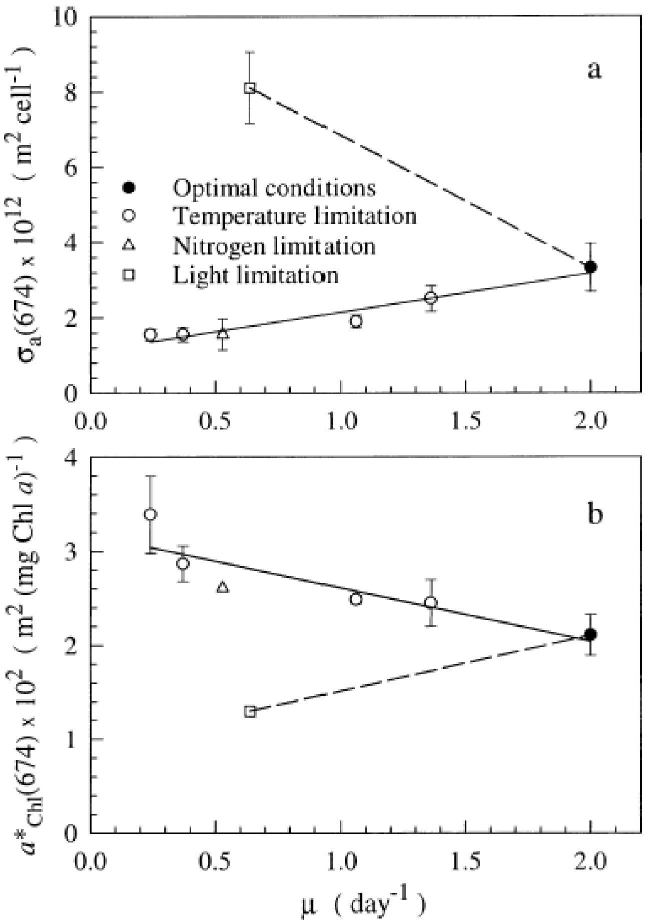
Intraspecies variability due to irradiance - *Synechocystis*



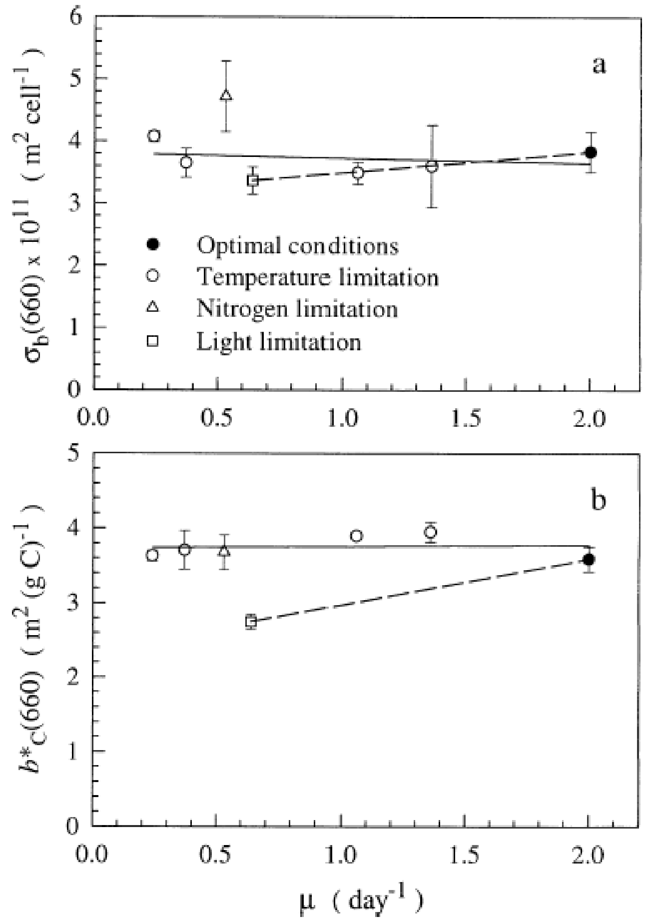
(Stramski and Morel 1990)

Intraspecies variability due to temperature, nitrogen, and light limitation – *Thalassiosira pseudonana*

Absorption vs. growth rate



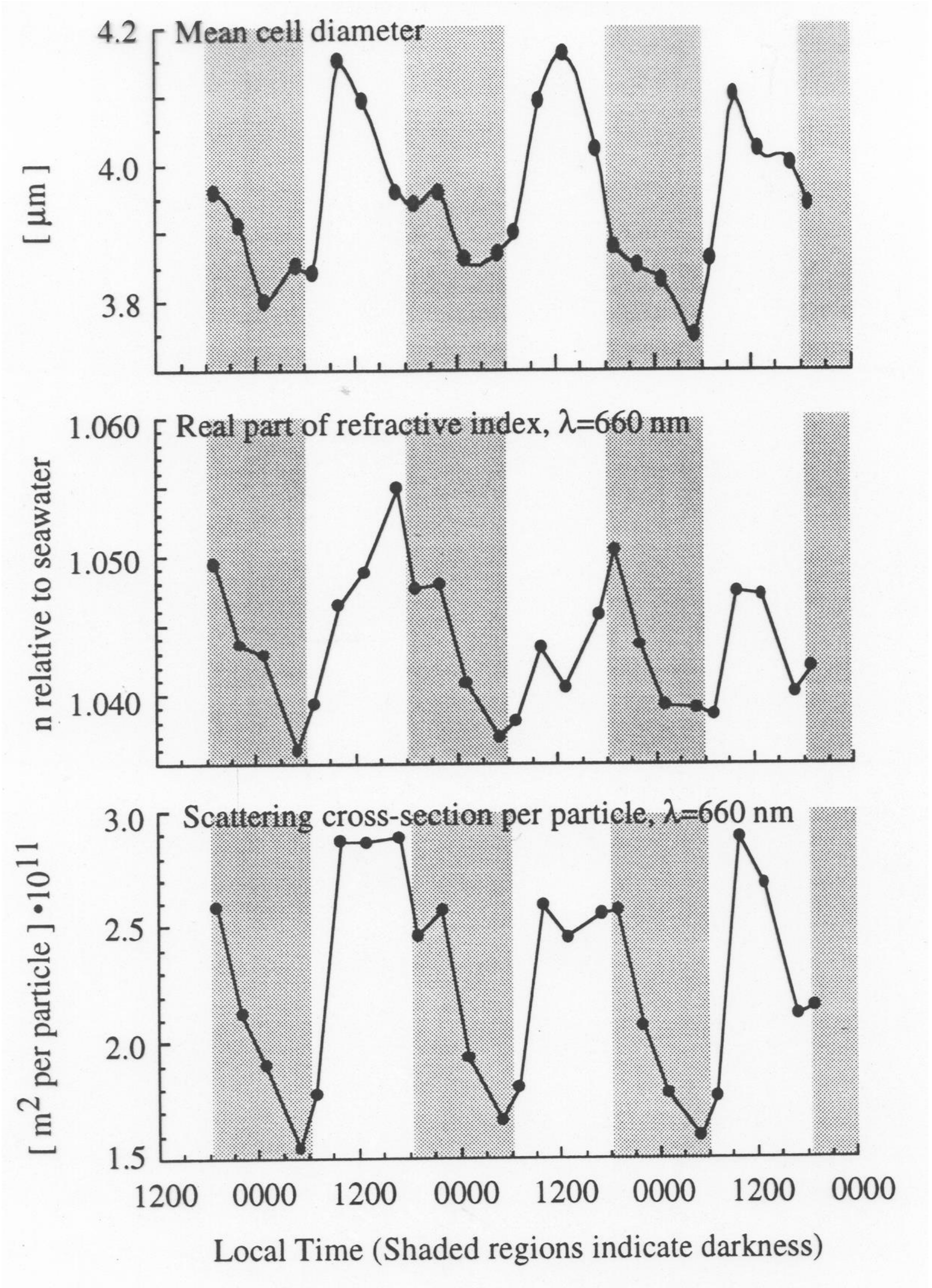
Scattering vs. growth rate



(Stramski et al. 2002)

Intraspecies variability over a diel cycle

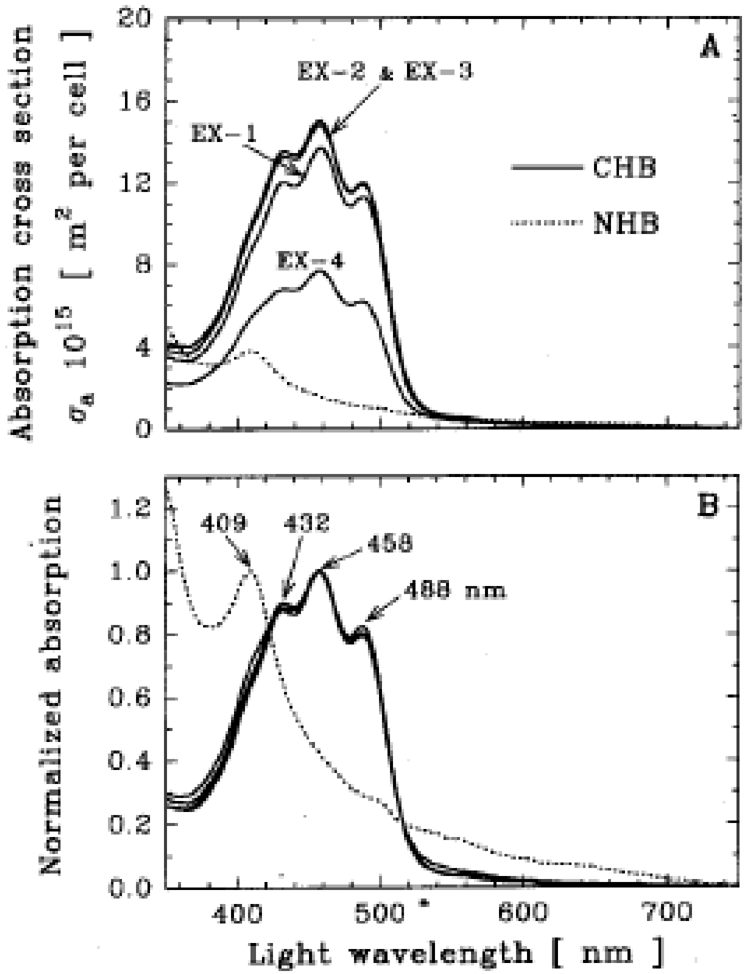
Thalassiosira pseudonana



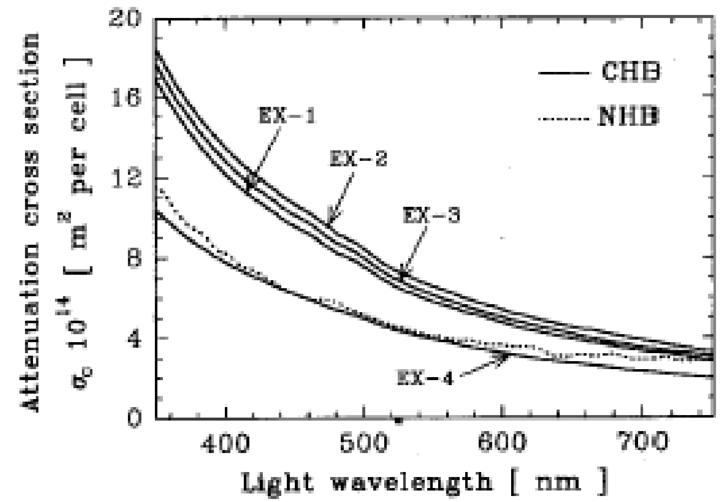
(Stramski and Reynolds 1993)

Optical variability for heterotrophic bacteria

Absorption



Beam attenuation



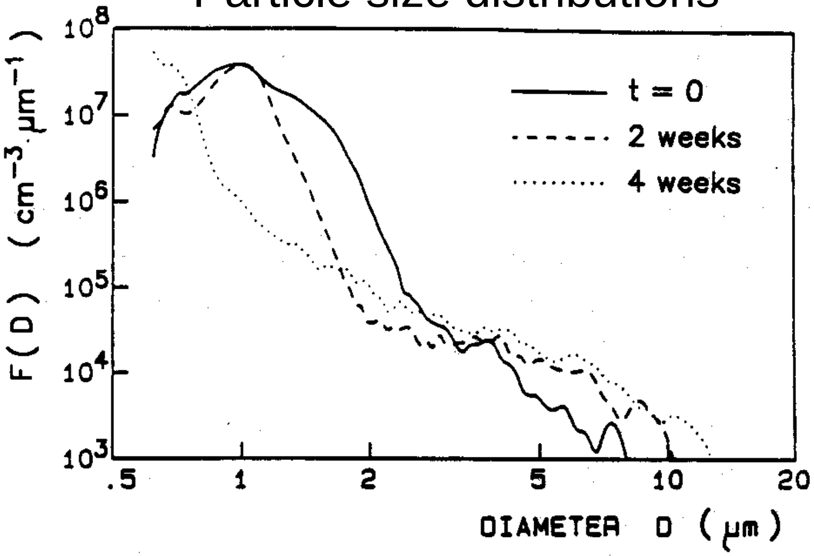
CHB Carotenoid-rich bacteria:
grown in nutrient-enriched seawater [EX-1 (light-dark cycle), EX-2 and EX-3 (dark)], and in nutrient-poor seawater (EX-4)

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

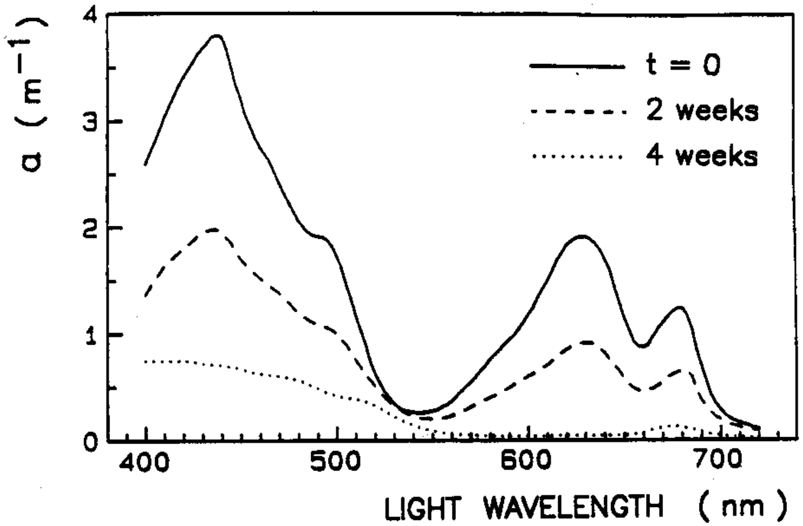
(Stramski and Kiefer 1998)

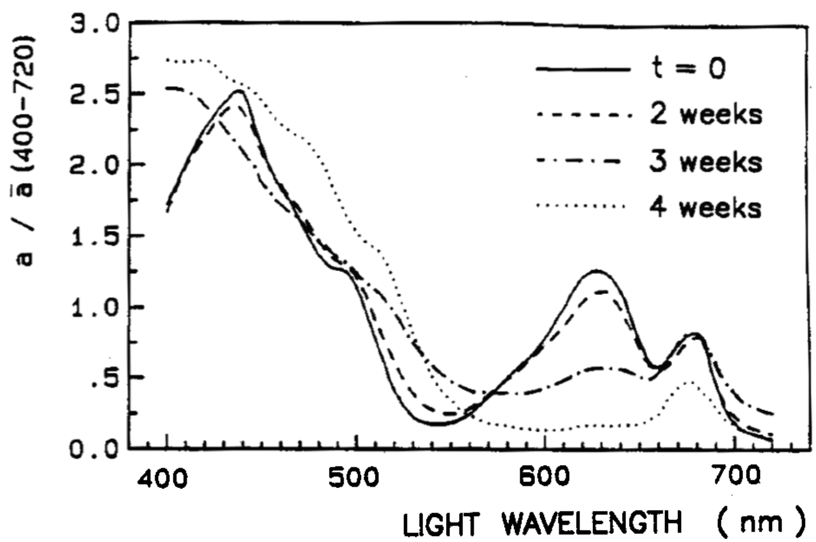
Prey-predator interactions (cyanobacteria and ciliates)

Particle size distributions

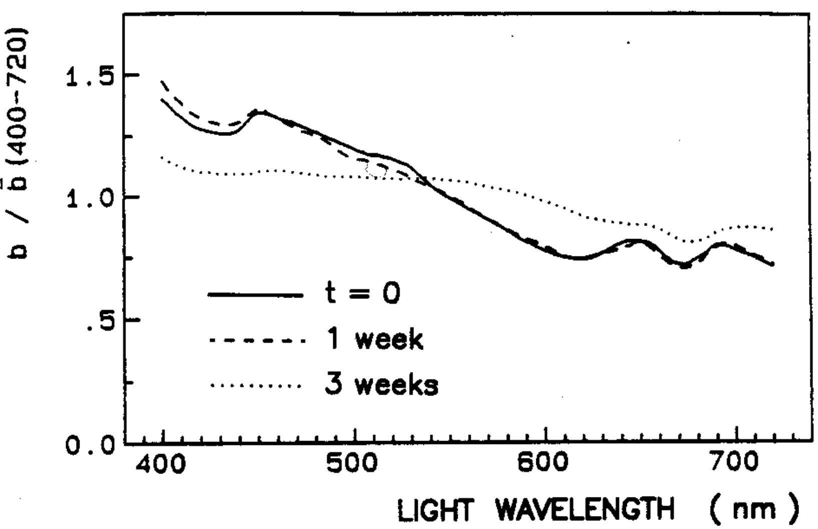


Absorption spectra





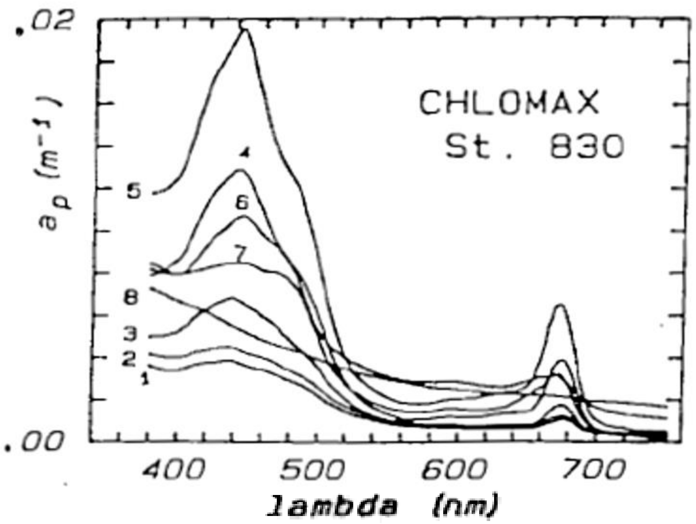
Scattering spectra

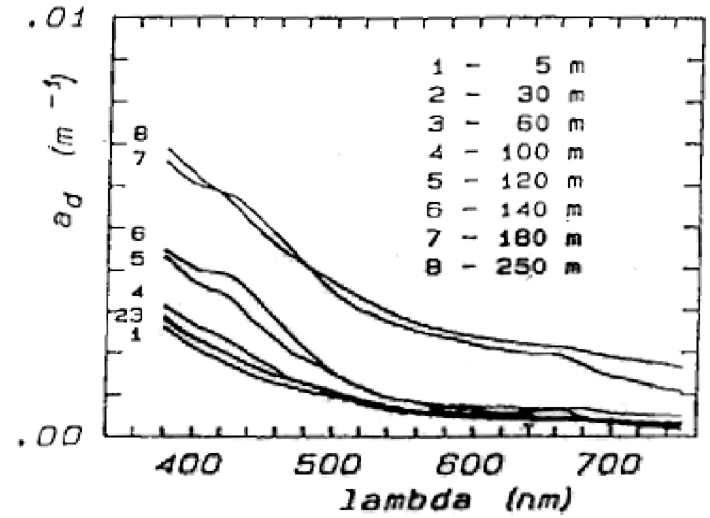


(Stramski et al. 1992)

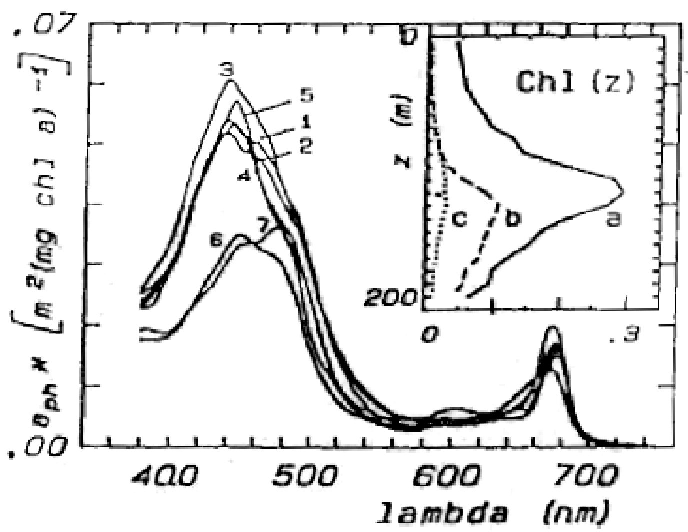
Examples of particulate absorption coefficients

a_p, $a_{d\ or\ NAP}$, a_{ph} (data from the Sargasso Sea)



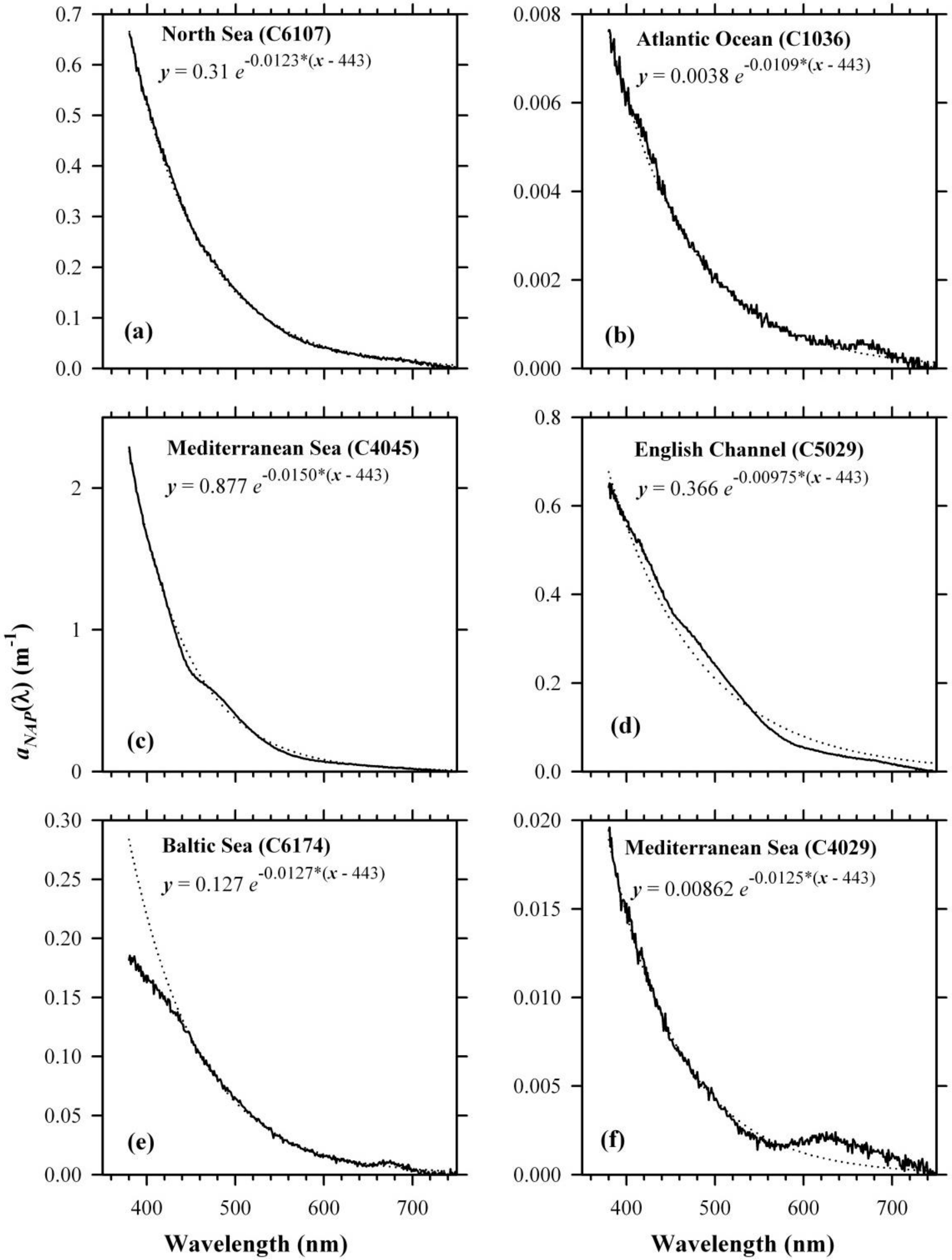


$$a_{ph} = a_p - a_{d\ or\ NAP}$$



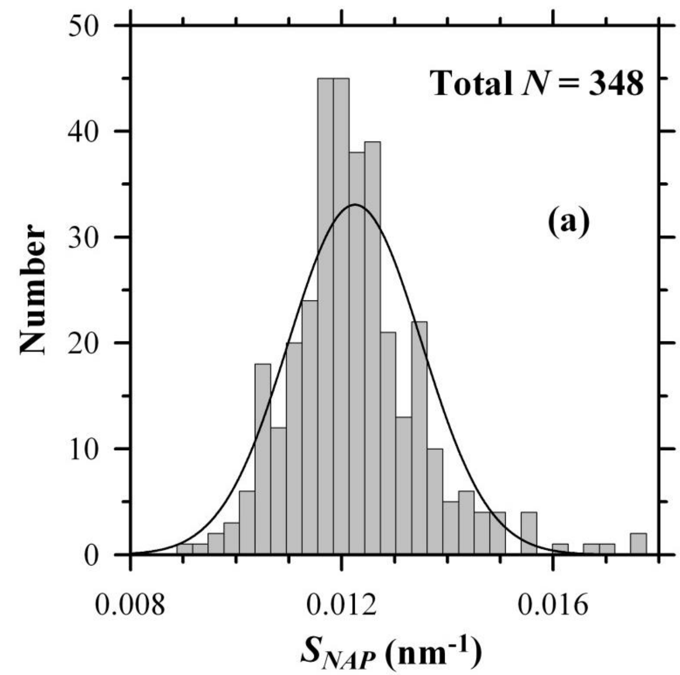
(Bricaud and Stramski 1990)

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

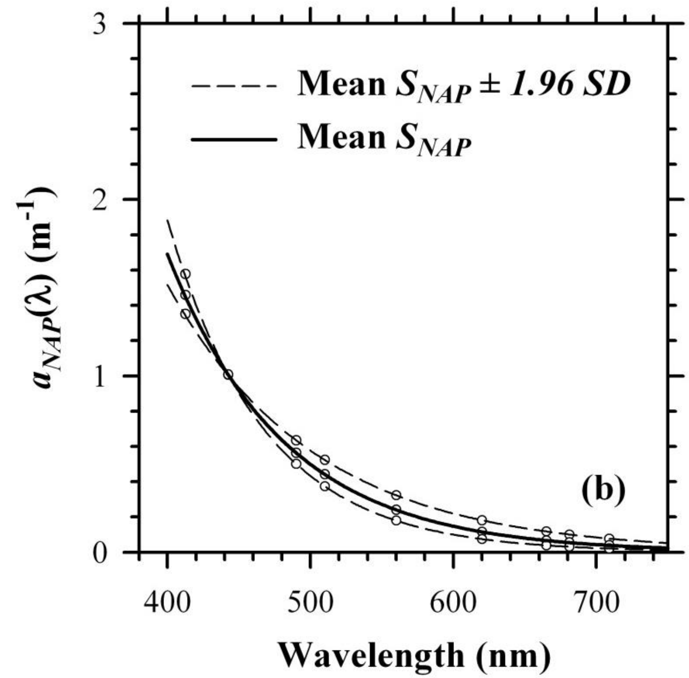


(Babin et al. 2003)

Frequency distribution of spectral slope of NAP absorption



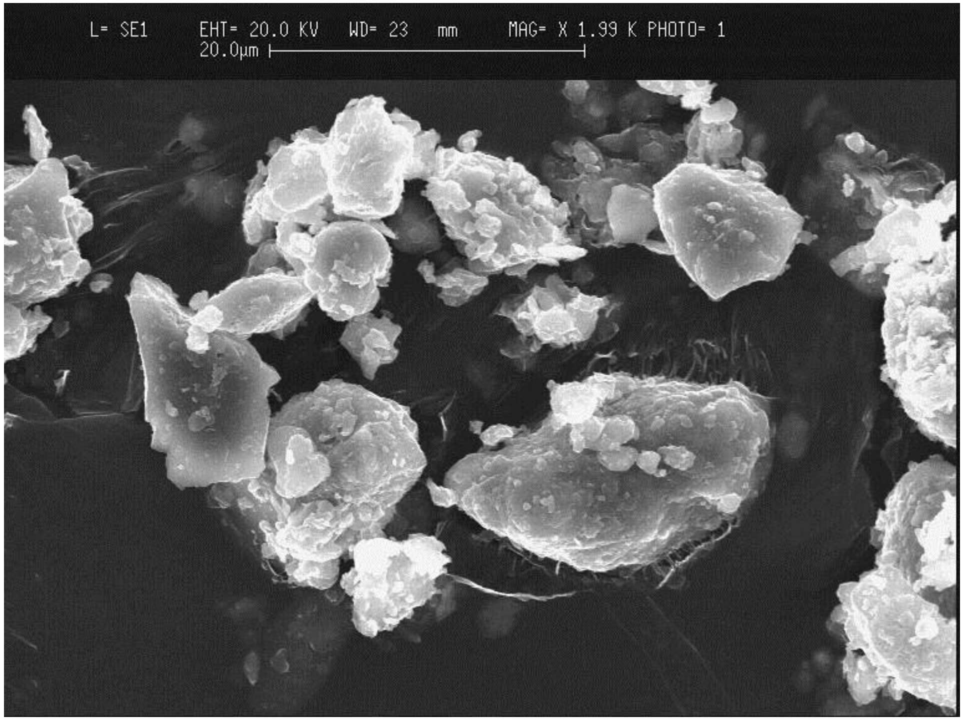
NAP absorption spectra calculated with $a_{NAP}(443)=1\ m^{-1}$ and $S_{NAP} = 0.0123\ nm^{-1}$ (±1.96 standard deviation, where $SD=0.0013\ nm^{-1}$)

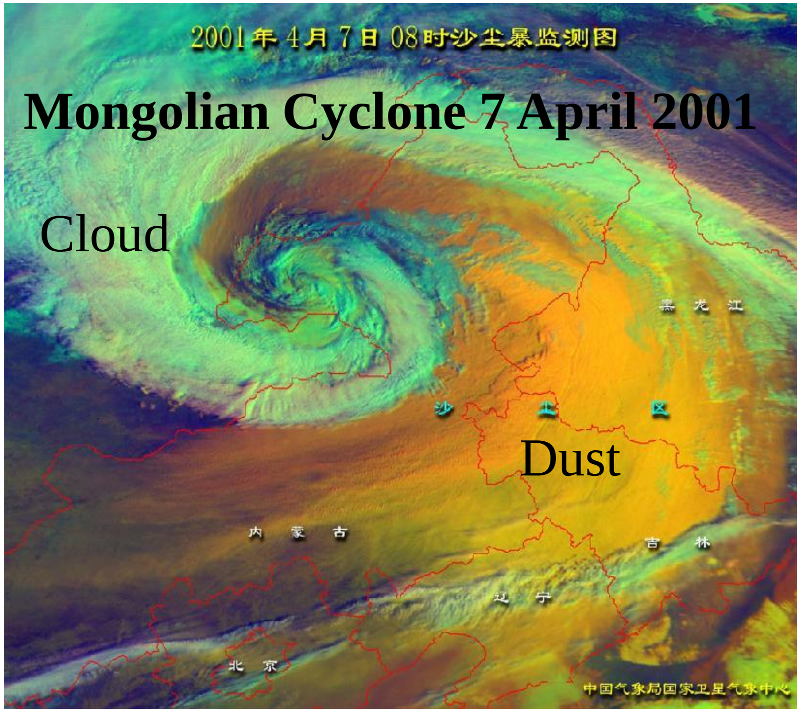


(Babin et al. 2003)

Mineral particles

Saharan dust



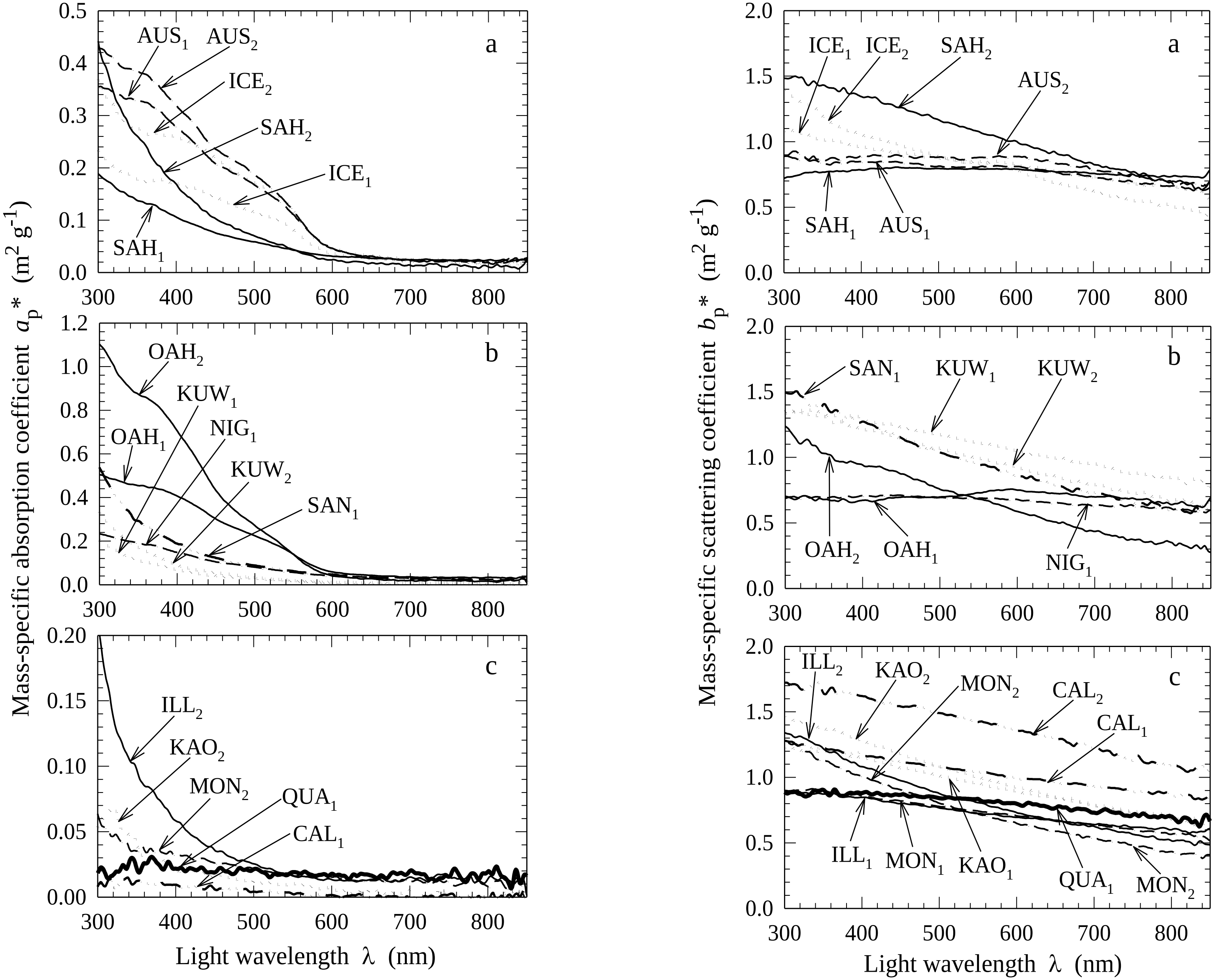


Terrigenous mineral-rich particulate matter

Sample ID	Description	Origin
ILL_1	illite	Source Clay Minerals Repository, University of Missouri (ref. IMt-1)
ILL_2	as above but different PSD	as above
KAO_1	kaolinite (poorly crystallized)	as above (ref. KGa-2)
KAO_2	as above but different PSD	as above
MON_1	Ca-montmorillonite	as above (ref. SAz-1)
MON_2	as above but different PSD	as above
CAL_1	calcite	natural crystal
CAL_2	as above but different PSD	as above
QUA_1	quartz	natural crystal
SAH_1	atmospheric dust from Sahara	red rain event, Villefranche-sur-Mer, France
SAH_2	as above but different PSD	as above
AUS_1	surface soil dust	cliff shore, Palm Beach near Sydney, Australia
AUS_2	as above but different PSD	as above
ICE_1	ice-rafted particles	glacier runoff, Kongsfjord, Spitsbergen
ICE_2	as above but different PSD	as above
OAH_1	surface soil dust	Oahu, Hawaii Islands
OAH_2	as above but different PSD	as above
KUW_1	surface soil dust	Kuwait (eastern part, close to ocean)
KUW_2	as above but different PSD	as above
NIG_1	surface soil dust	southwest Nigeria
SAN_1	atmospheric dust	San Diego, California

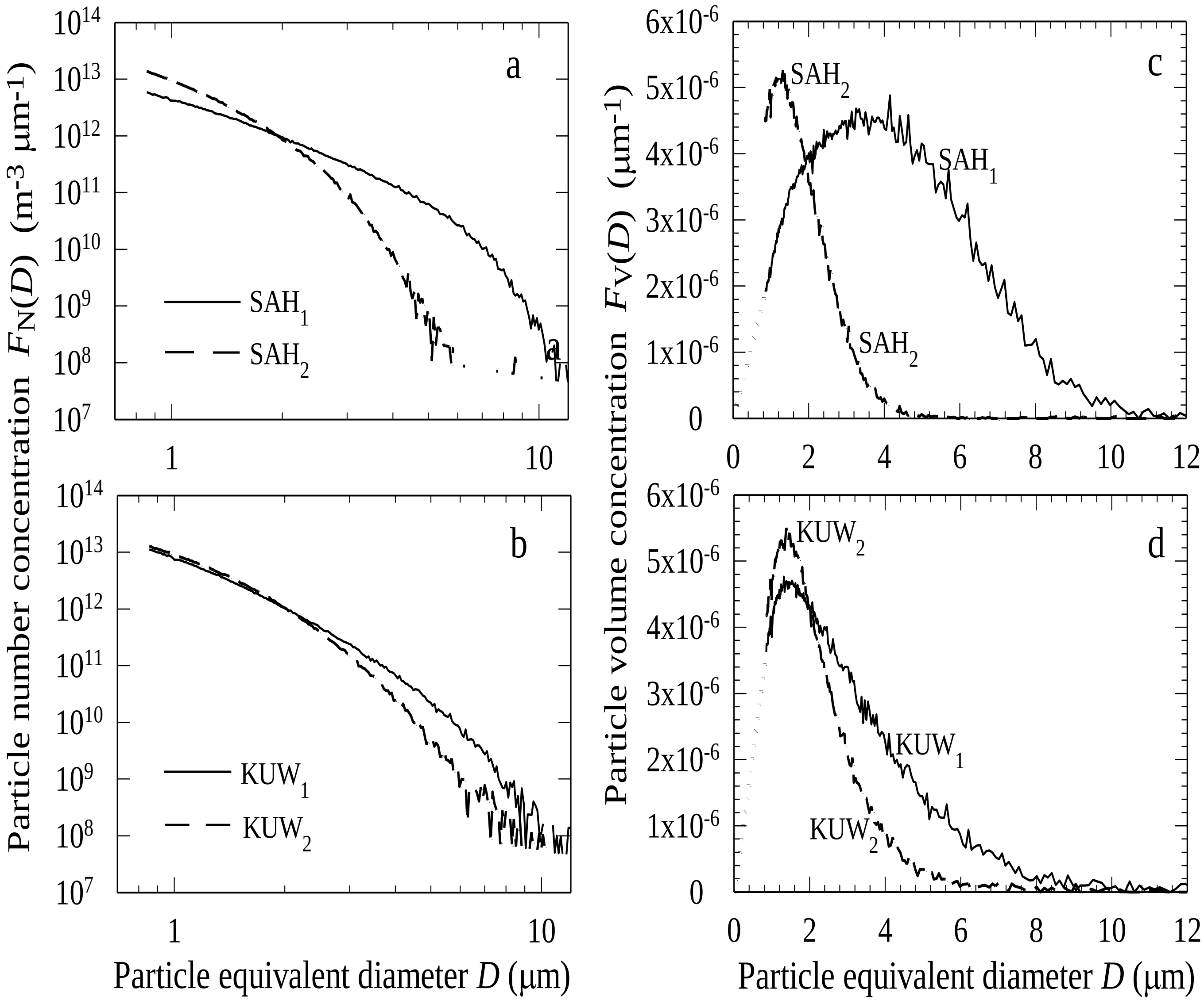
(Stramski et al. 2007)

Mass-specific absorption   Mass-specific scattering



(Stramski et al. 2007)

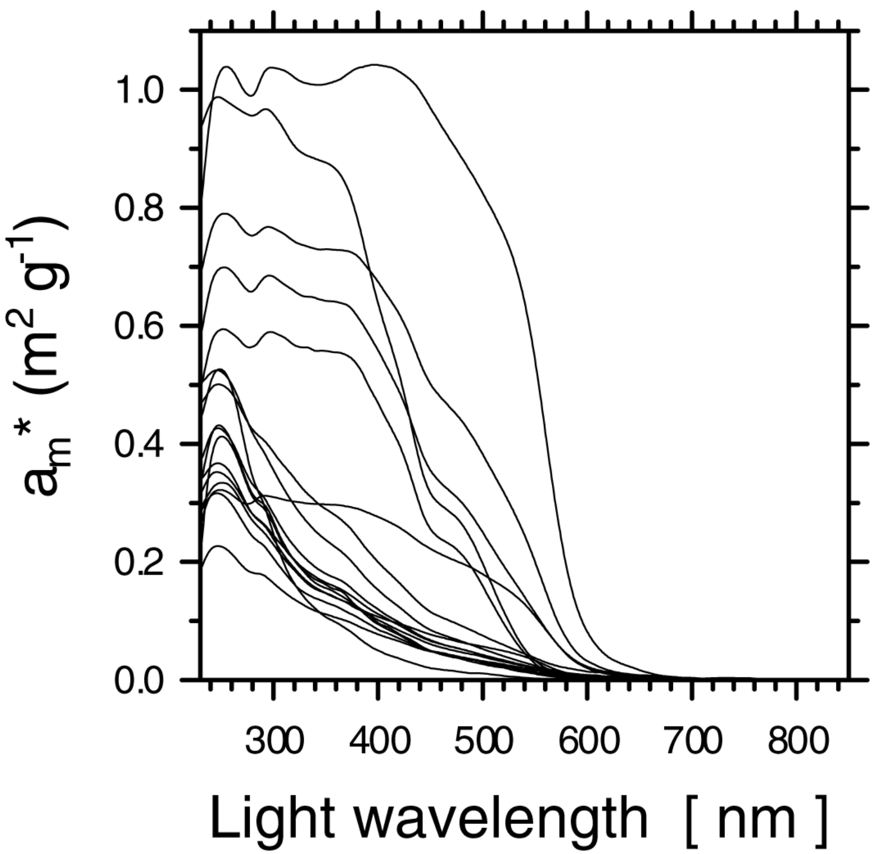
Particle Size Distributions



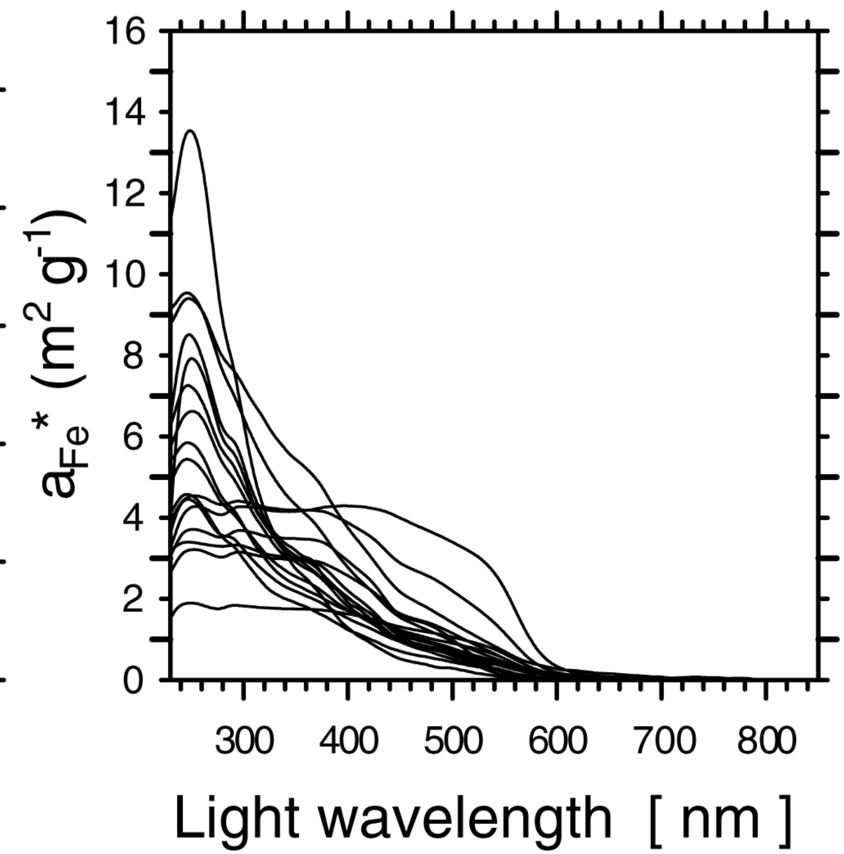
(Stramski et al. 2007)

Absorption of mineral-rich particulate assemblages

Mass-specific absorption



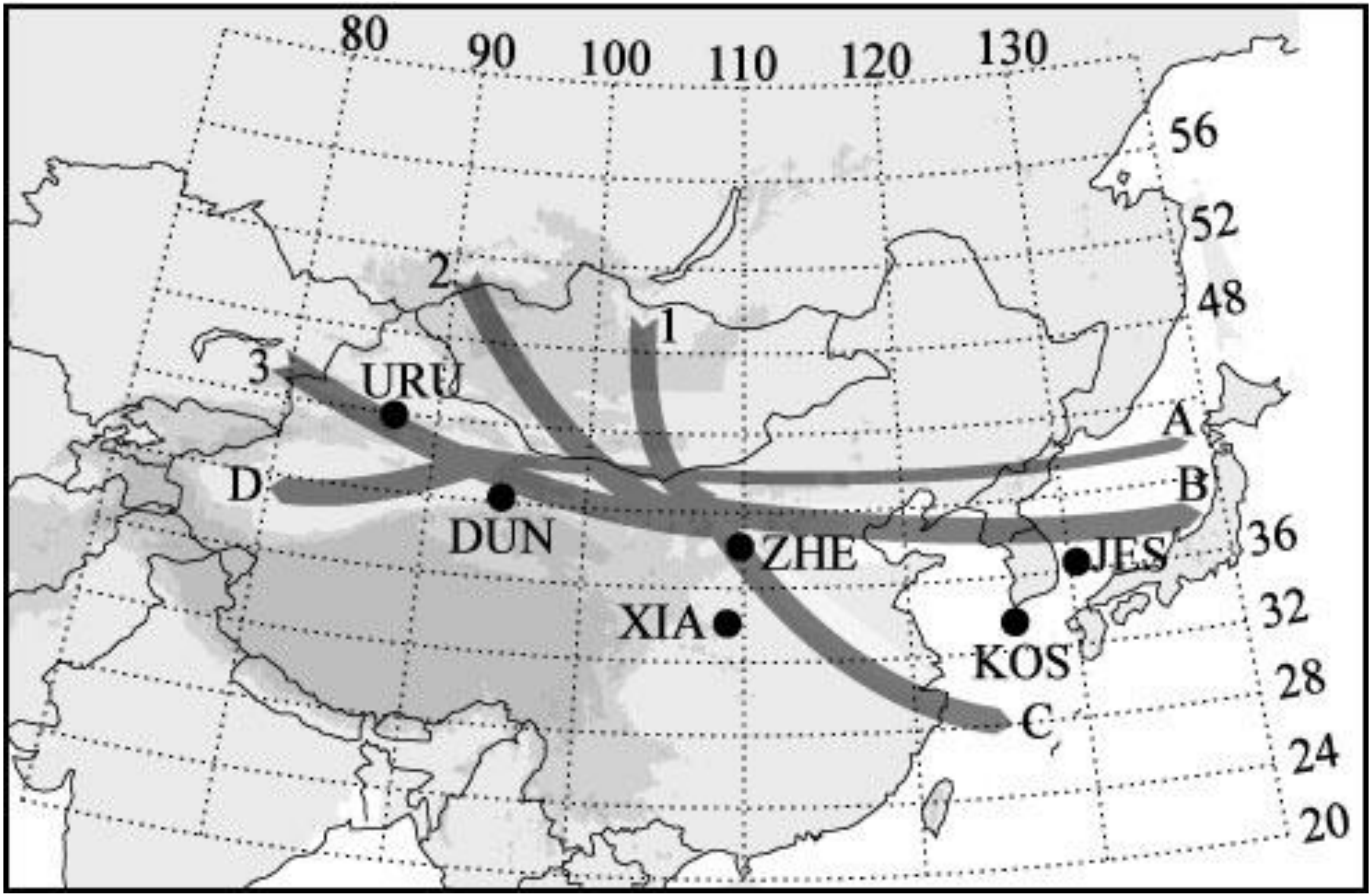
Fe-specific absorption



(Babin and Stramski 2004)

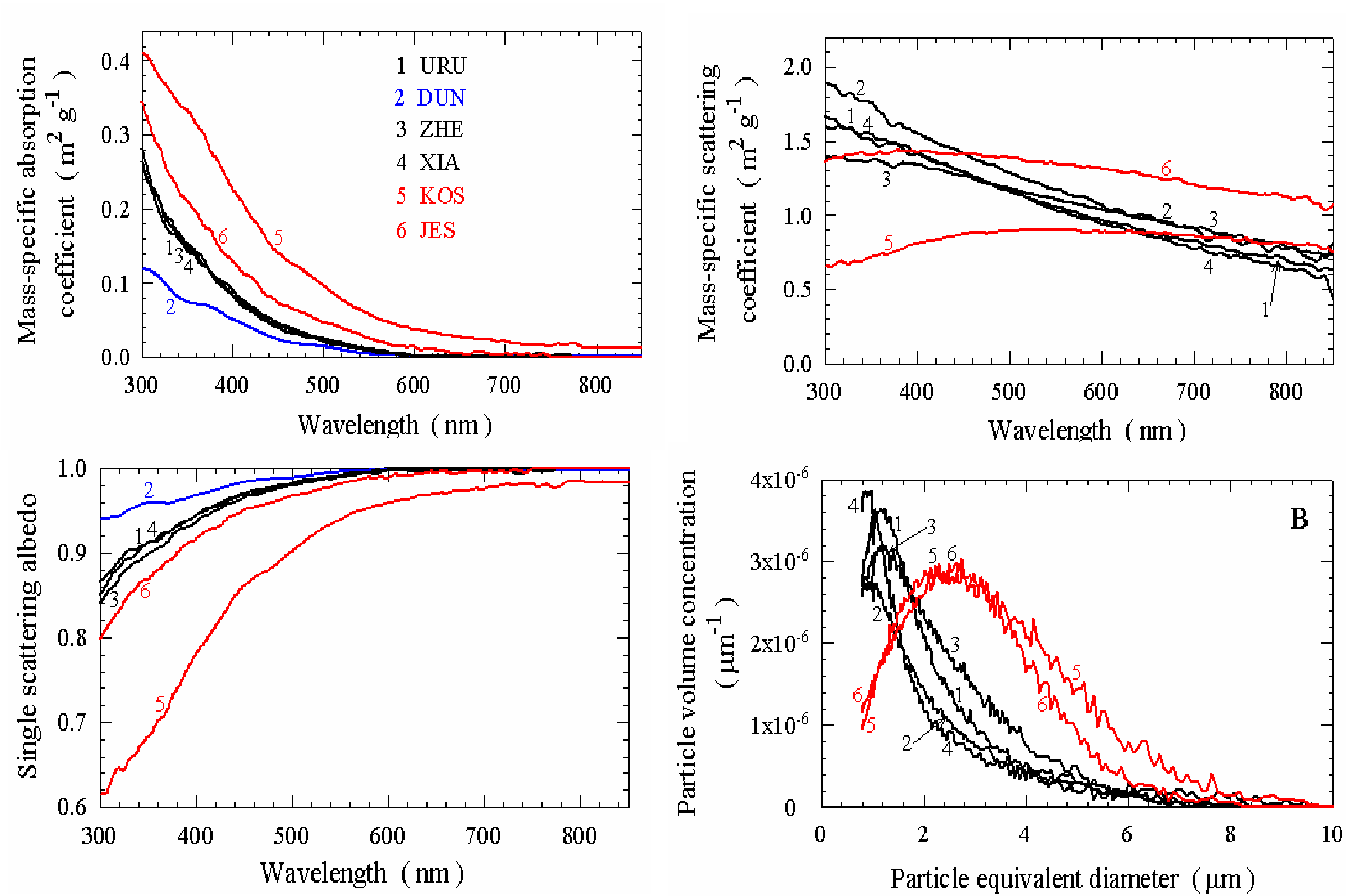
(Babin and Stramski 2004)

Asian dust - sampling locations



(Stramski et al. 2004)

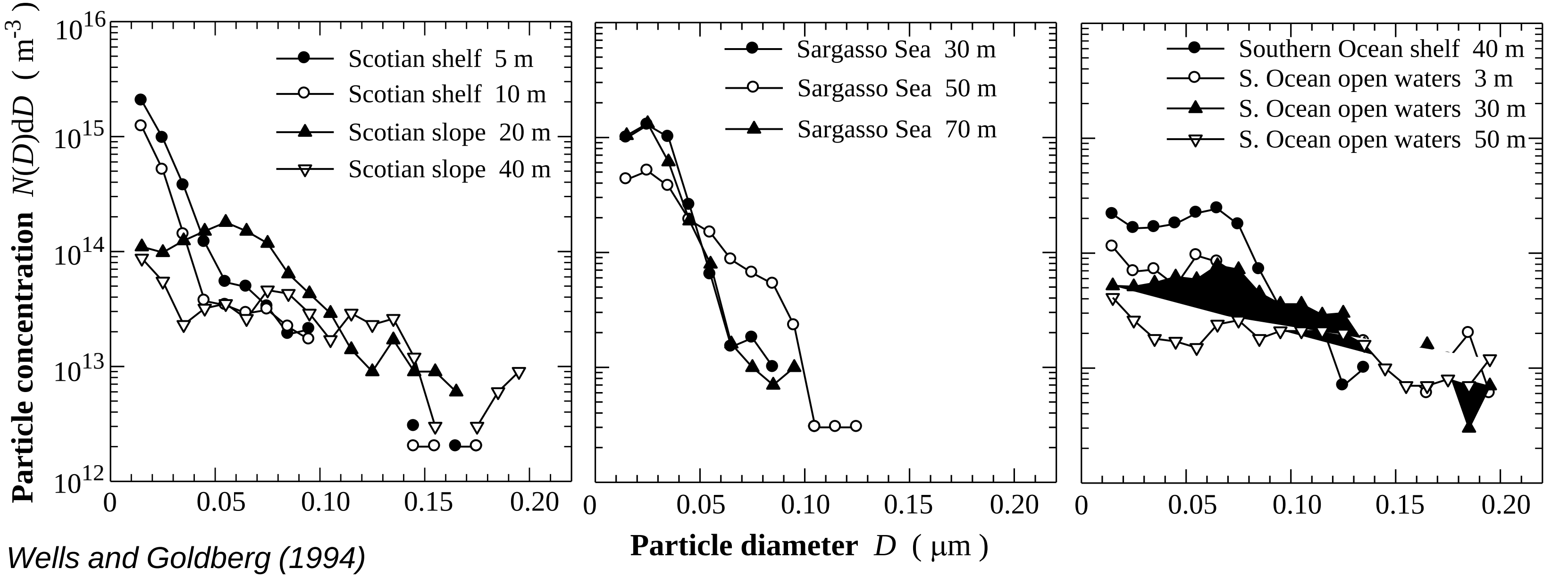
Asian mineral-rich dust



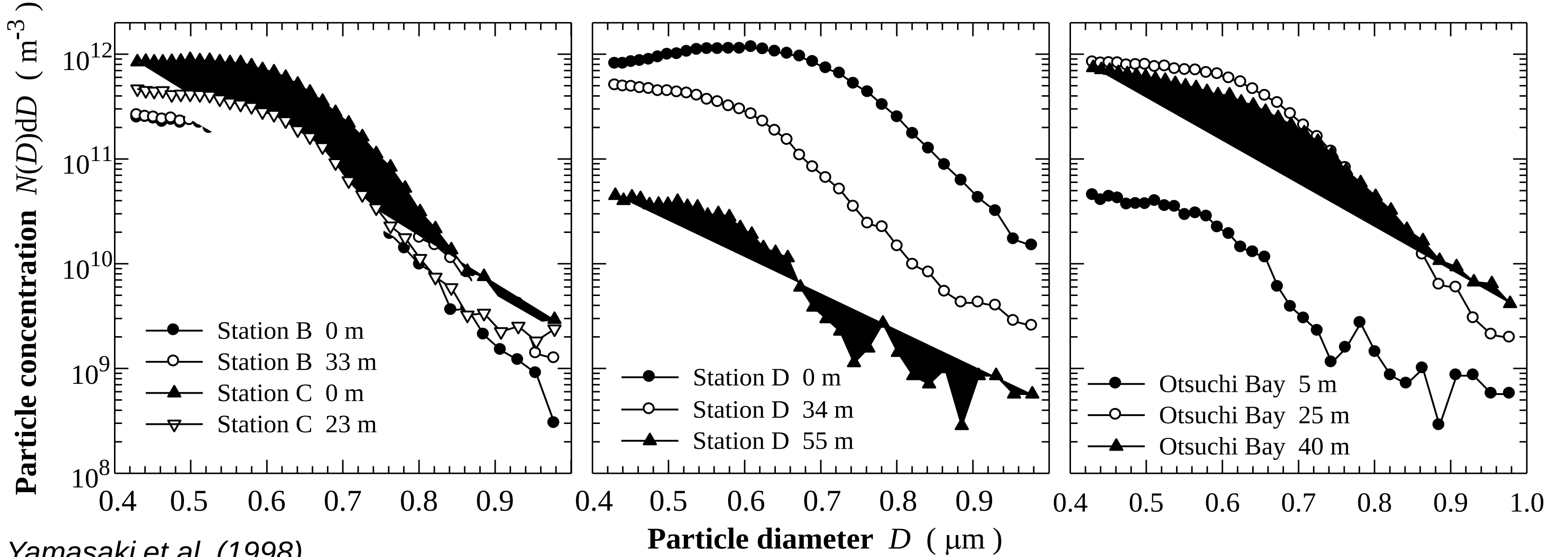
(Stramski et al. 2004)

Colloidal particles (< 1 μm in size) undergoing Brownian motion

Size distributions of colloids



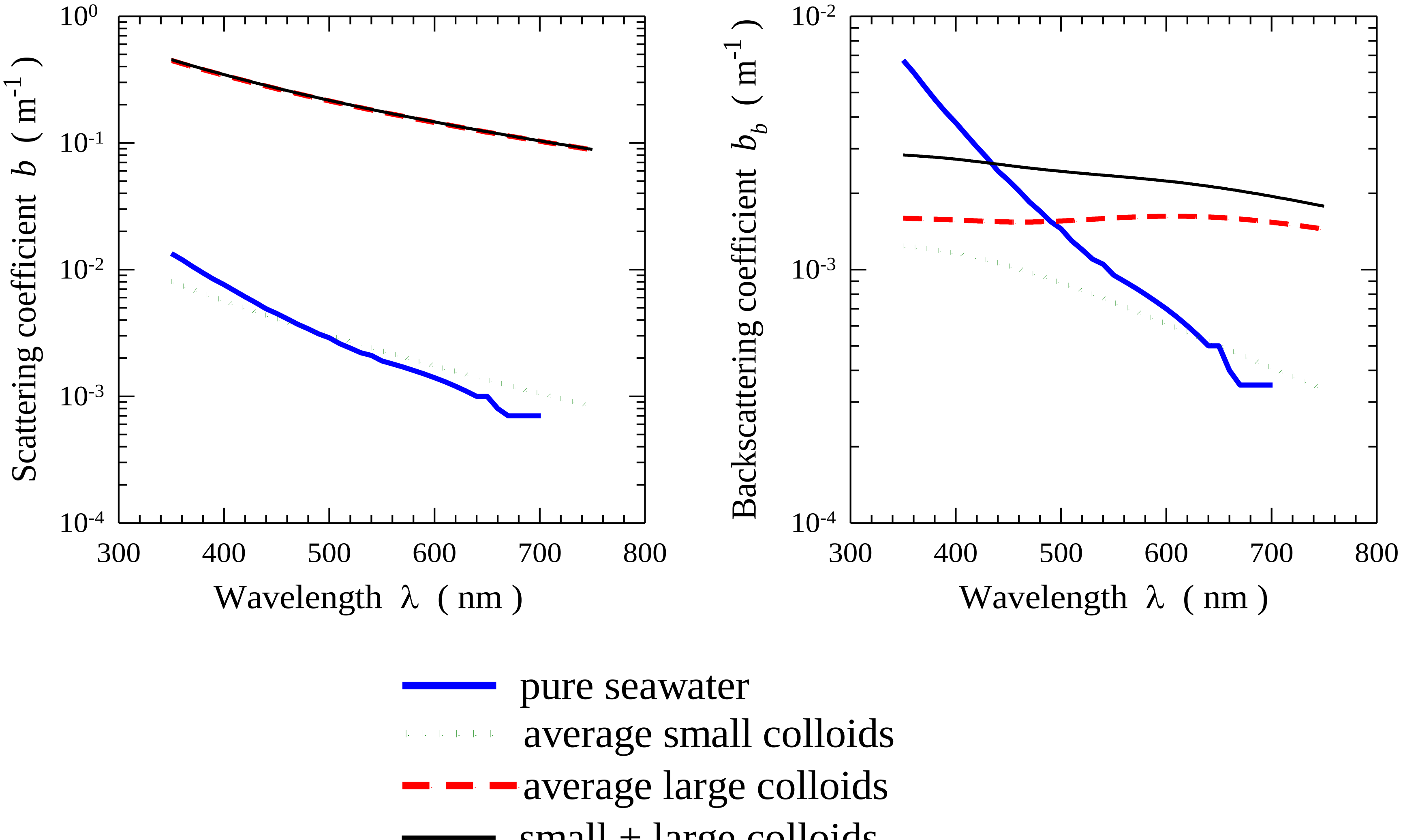
Wells and Goldberg (1994)



Yamasaki et al. (1998)

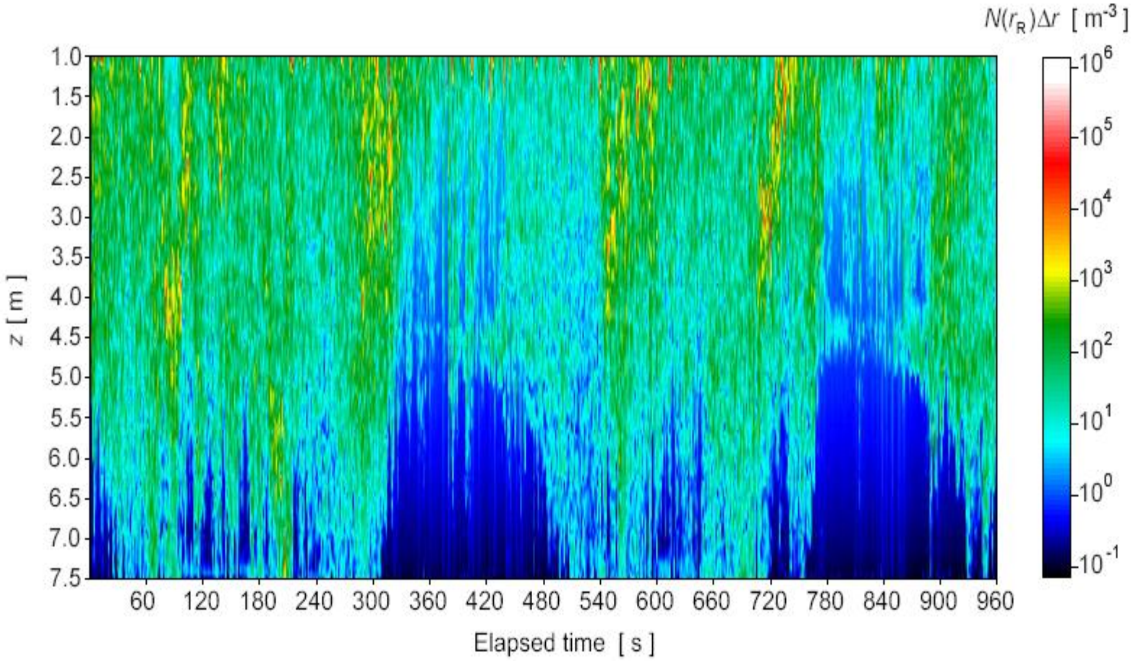
Results for colloidal particles

scattering | backscattering



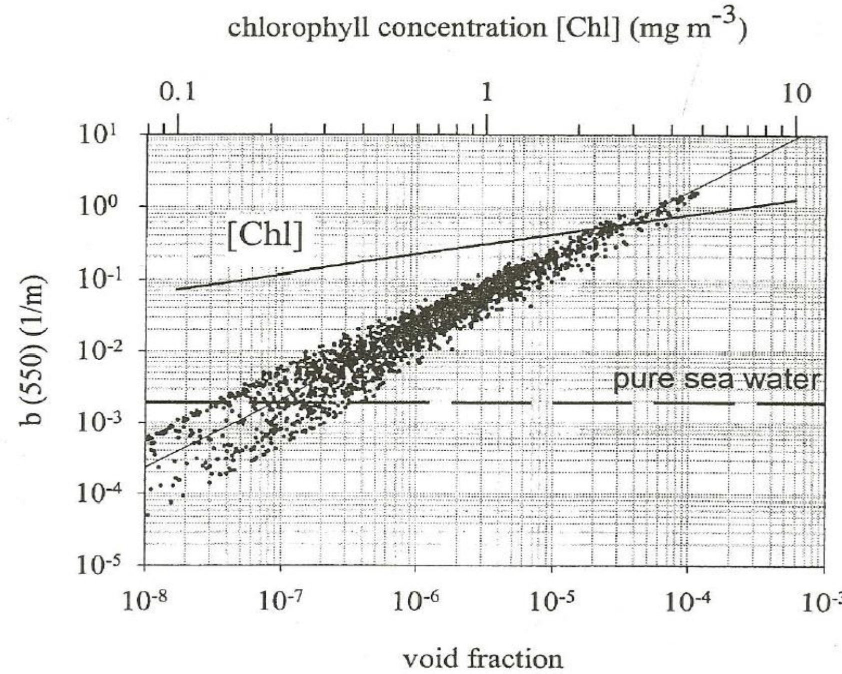
(Stramski and Woźniak 2005)

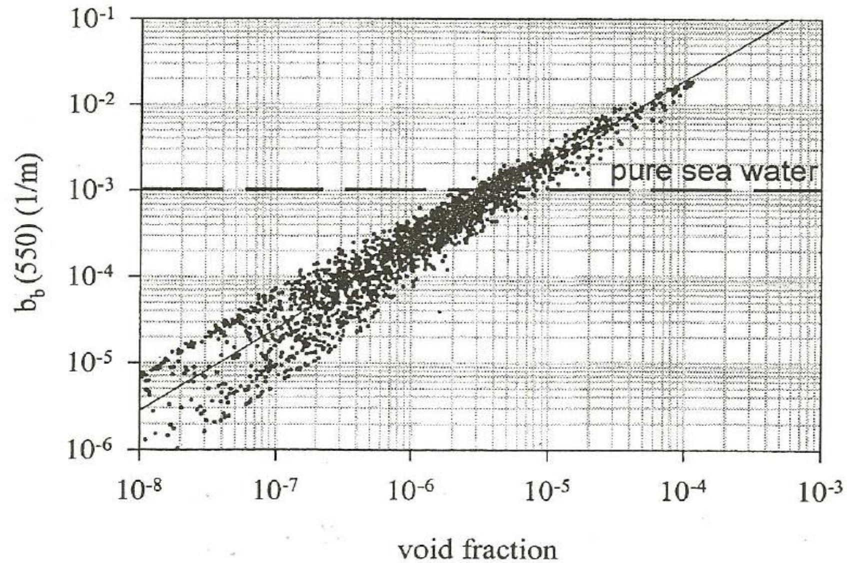
Light scattering by bubbles entrained by wave breaking



(Stramski and Tęgowski 2001)

Scattering and backscattering by bubbles as a function of void fraction





(Terrill et al. 2001)

Traditional approach

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

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

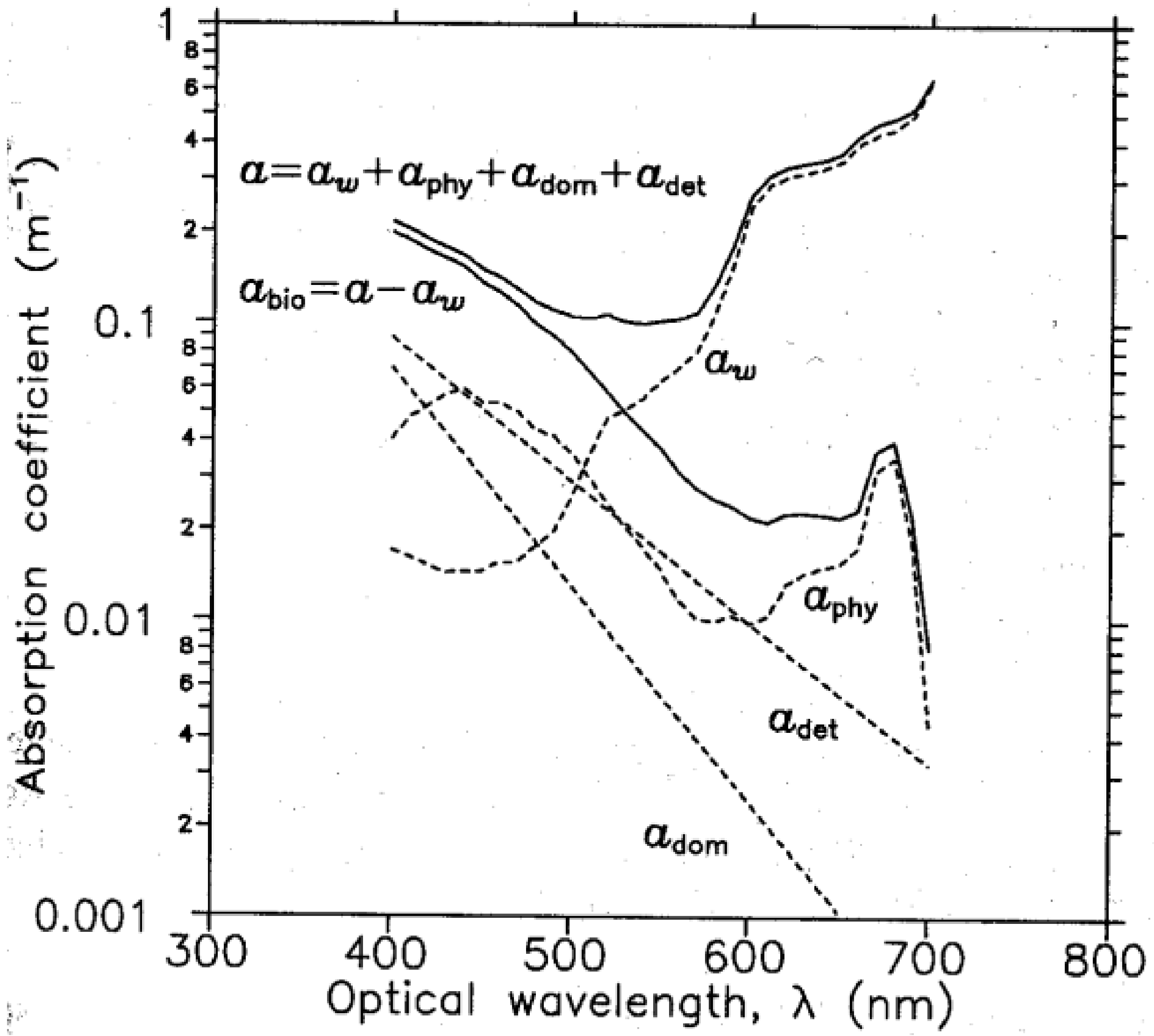
$$IOP_p(\lambda) = IOP_{ph}(\lambda) + IOP_{NAP}(\lambda)$$

Example IOPs:

absorption coefficient, scattering coefficient,

beam attenuation coefficient, volume scattering function

A four-component model of absorption



Chlorophyll-based approach

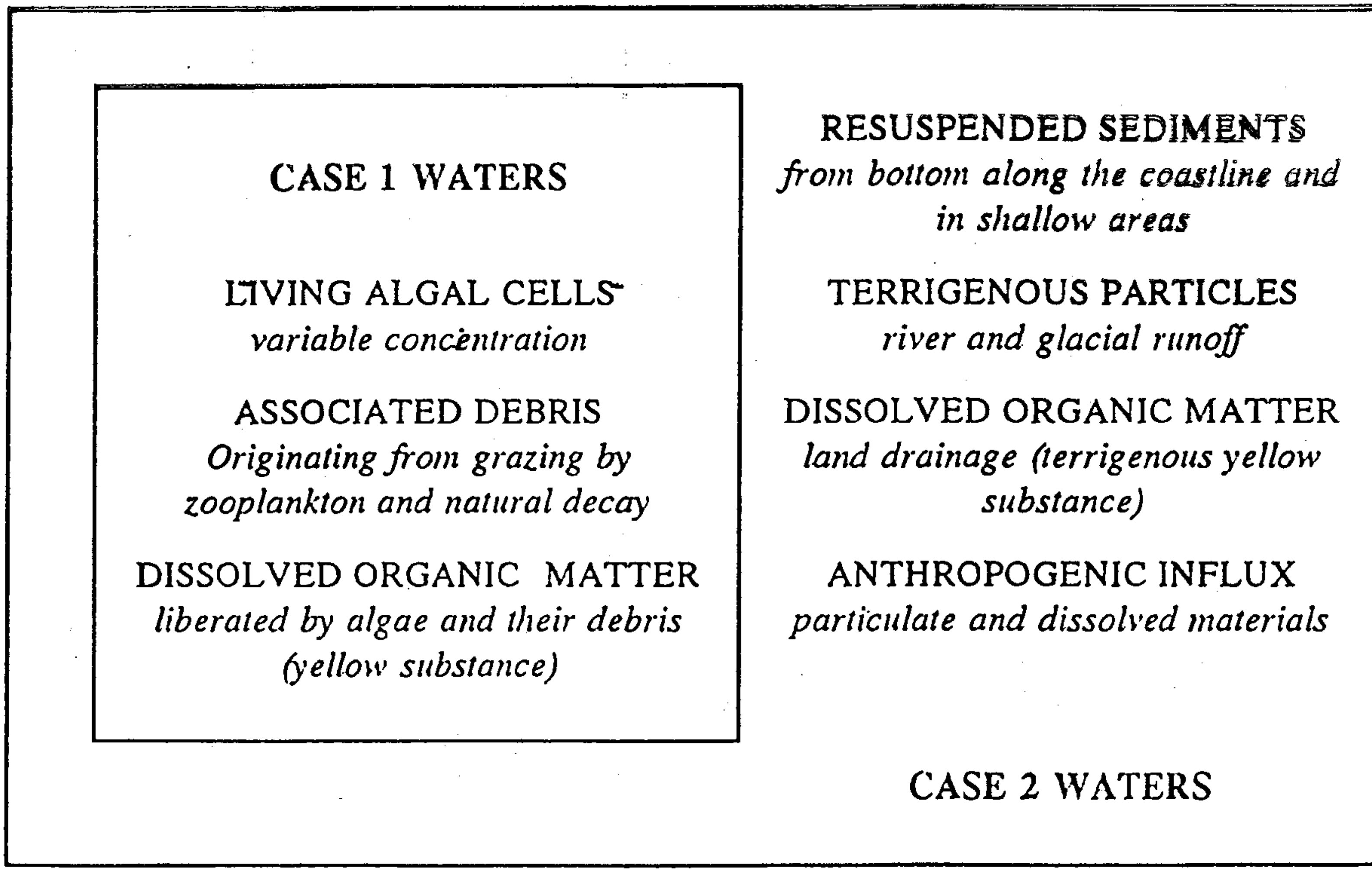
$$IOP(\lambda) = IOP_w(\lambda) + f\,[\,Chla\,]$$

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

$$a_p(\lambda) = f\,[\,Chla\,]$$

$AOP(\lambda)$ (*e.g.*, ocean reflectance) $= f\,[\,Chla\,]$

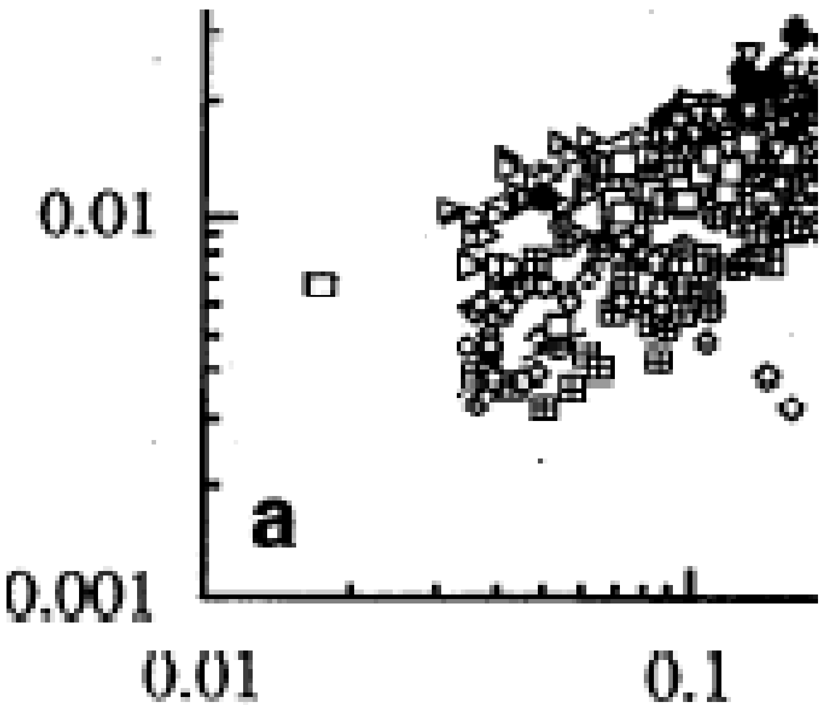
Case 1 and Case 2 Waters

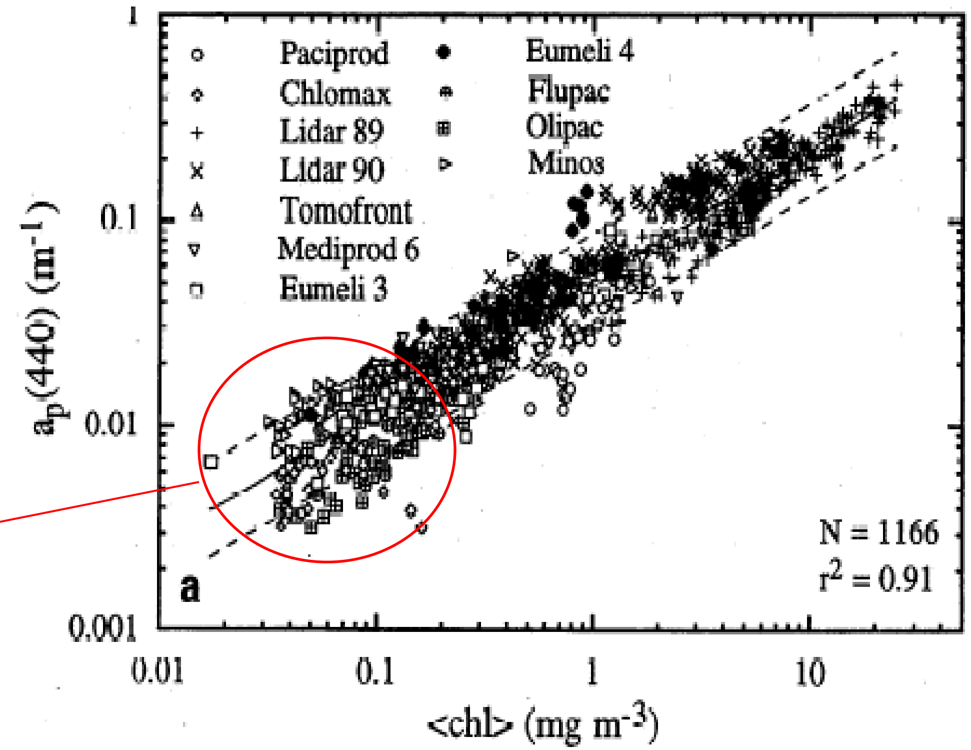


Morel and Prieur (1977); Gordon and Morel (1983)

Absorption vs. chlorophyll-a

~ 4-fold variation



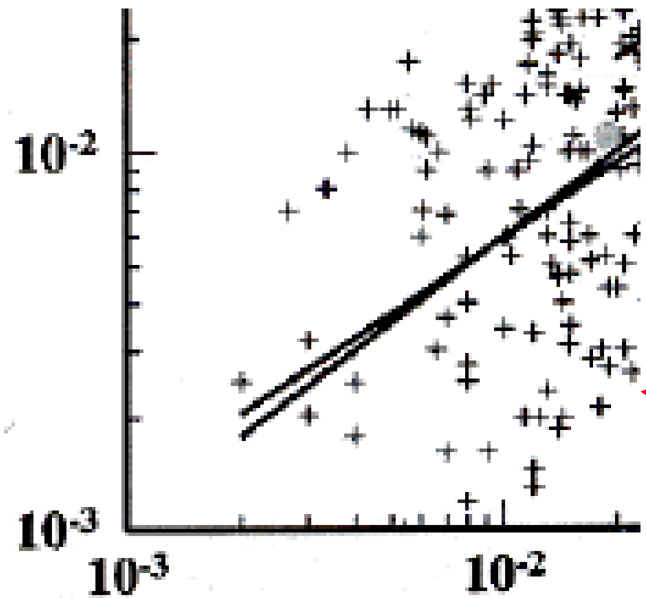


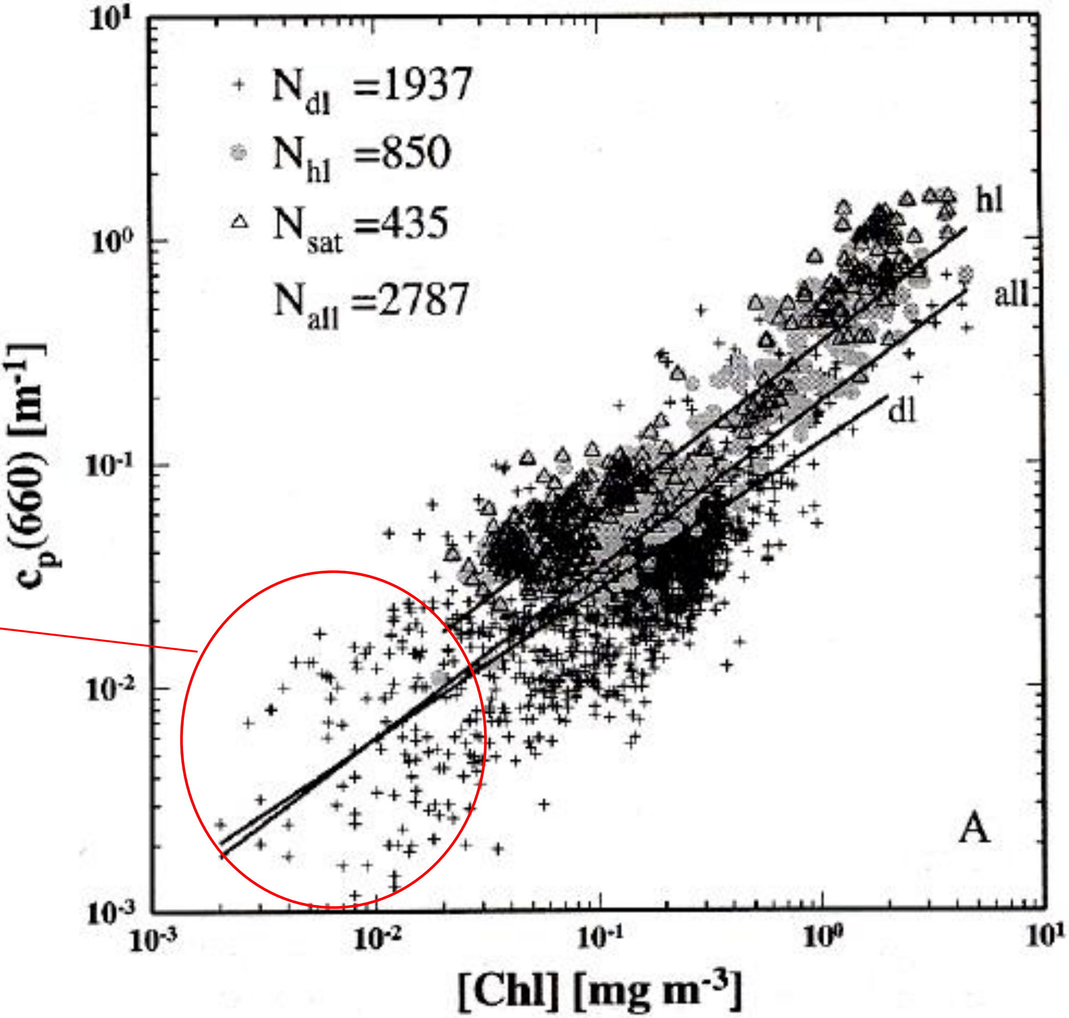
Cruise	Location
PACIPROD	Peru upwelling
CHLOMAX	Sargasso Sea
LIDAR 89	St. Lawrence estuary and gulf
LIDAR 90	St. Lawrence estuary and gulf
TOMOFRONT	northwestern Mediterranean
MEDIPROD 6	southwestern Mediterranean
EUMELI 3	tropical North Atlantic
EUMELI 4	tropical North Atlantic
FLUPAC	equatorial and subequatorial Pacific
OLIPAC	equatorial and subequatorial Pacific
MINOS	eastern and western Mediterranean

(Bricaud et al. 1998)

Beam attenuation vs. chlorophyll

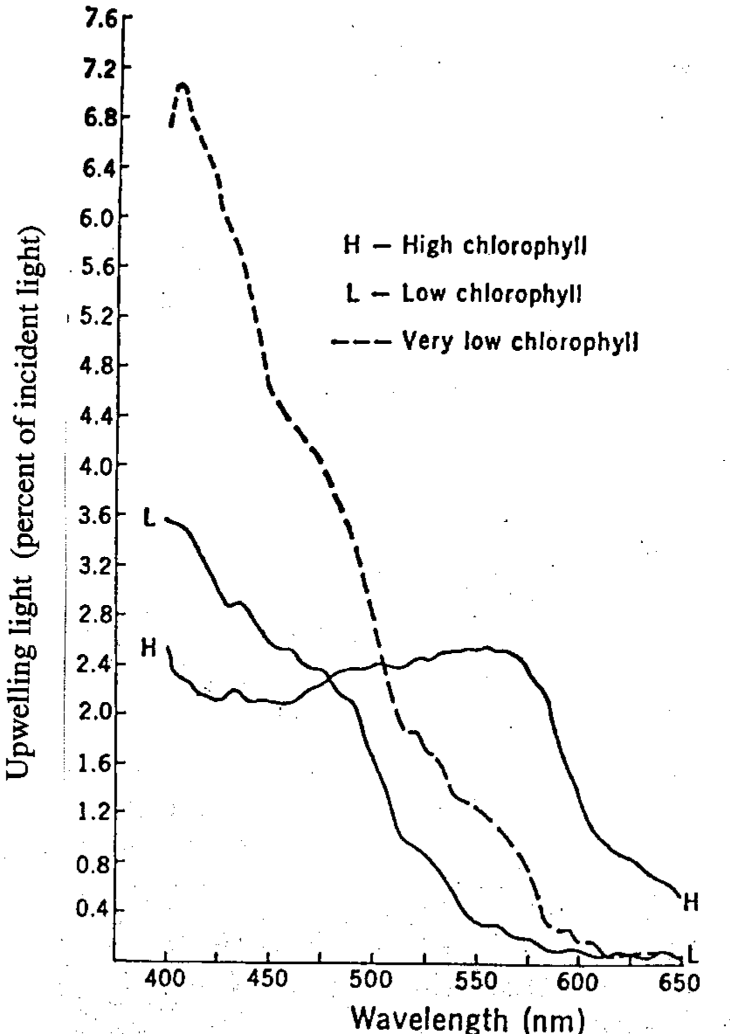
> 10-fold variation





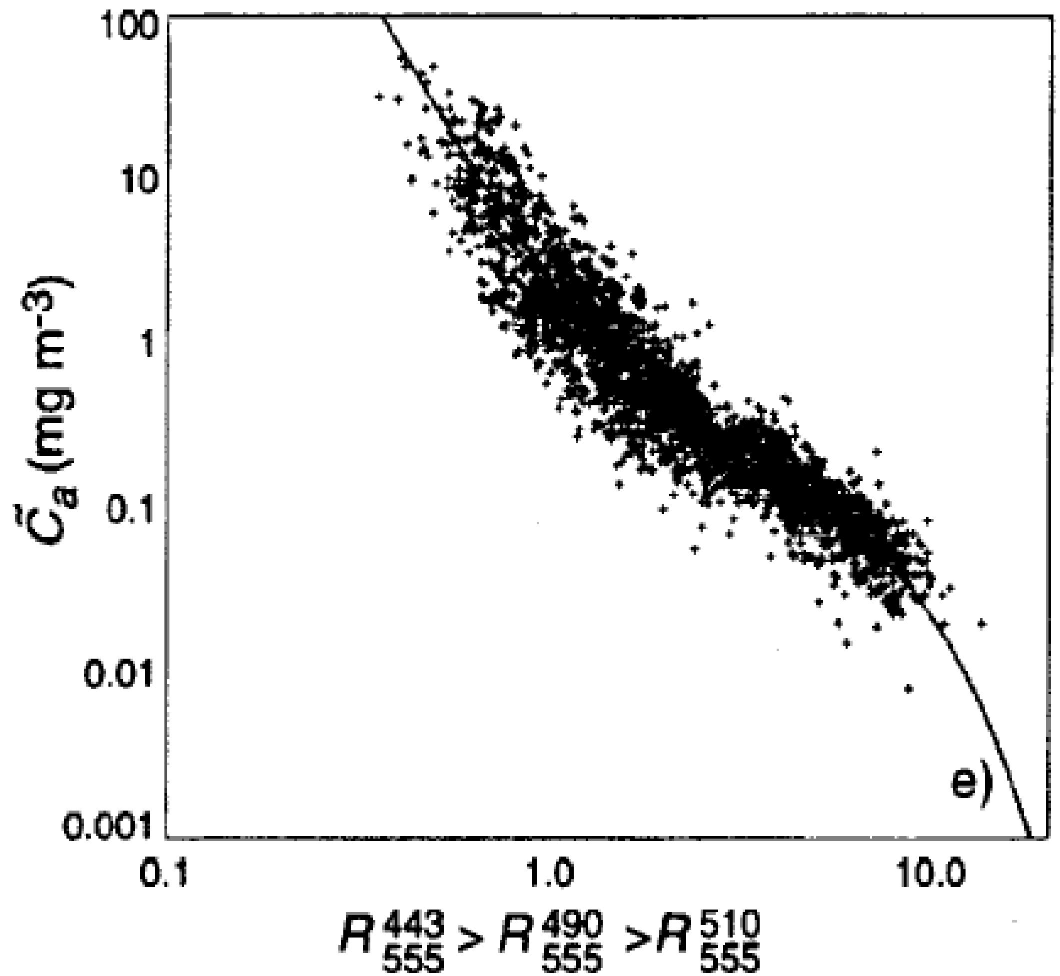
(Loisel and Morel 1998)

Chlorophyll Algorithm



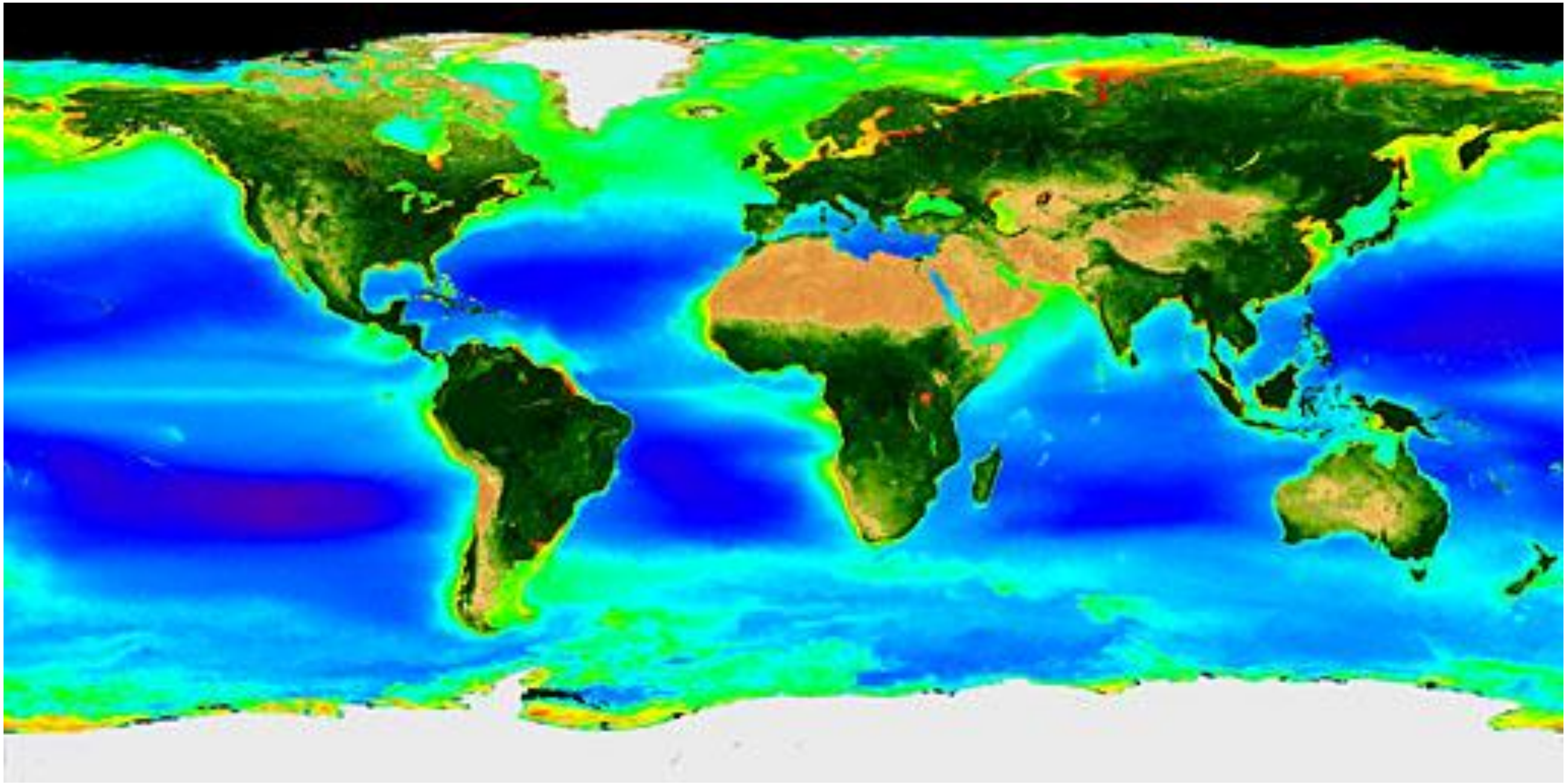
(Clarke, Ewing & Lorenzen 1970)

OC4 Algorithm



(O'Reilly et al. 2000)

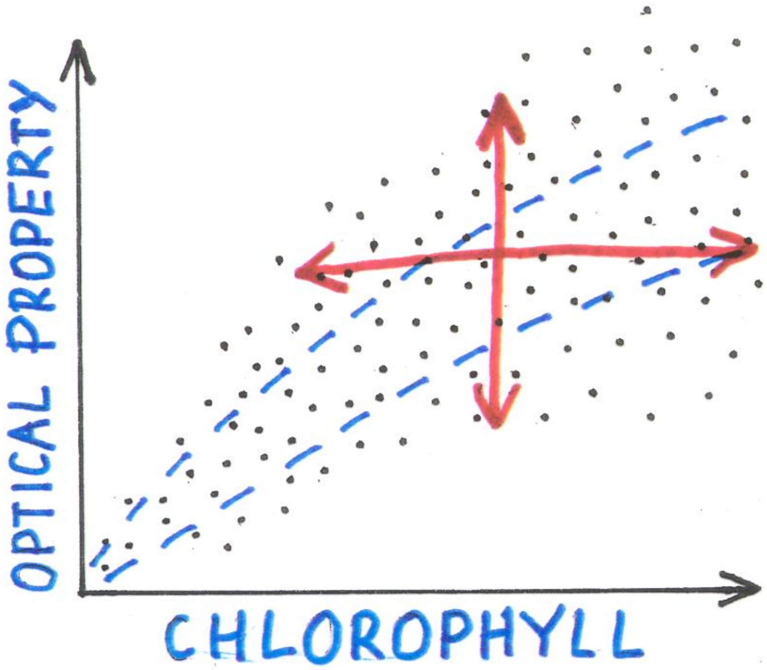
Global distribution of phytoplankton chlorophyll in the world's oceans from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) based on Sep 1997 - Feb 2007 data



Courtesy of NASA

Chlorophyll-based approach: Summary

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



Reductionist approach

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

$$IOP_{\mathrm{p}}(\lambda) = \sum_{k} IOP_{k,pla}(\lambda) \quad \text{plankton}$$

$$+ \sum_{m} IOP_{m,min}(\lambda) \quad \text{minerals}$$

$$+ \sum_{n} IOP_{n,det}(\lambda) \quad \text{detritus}$$

Example criteria

- Manageable number of components
- The sum of components should account for the total bulk particulate and optical properties as accurately as possible
- The components should play specific well-defined roles in ocean optics and biogeochemistry

Example reductionist model of particle functional types (PFTs)

Living Particles

Autotrophs

1. Picophytoplankton <2-3 μm (prokaryotes and eukaryotes)
2. Small nanophytoplankton ~2-8 μm
3. Coccolithophores
4. Large nanophytoplankton ~8-20 μm
5. Microphytoplankton 20-200 μm

Heterotrophs

6. Bacteria ~0.5 μm
7. Microzooplankton O(1-100) μm

Non-Living Particles

Organic

8. Small colloids 0.02-0.2 μm
9. Coarse colloids 0.2-1μm
10. Detritus >1μm

Inorganic

11. Colloidal/Clay minerals <2μm
12. Larger (Silt and Sand-sized) minerals >2μm

Challenge: Characterization of PFT properties

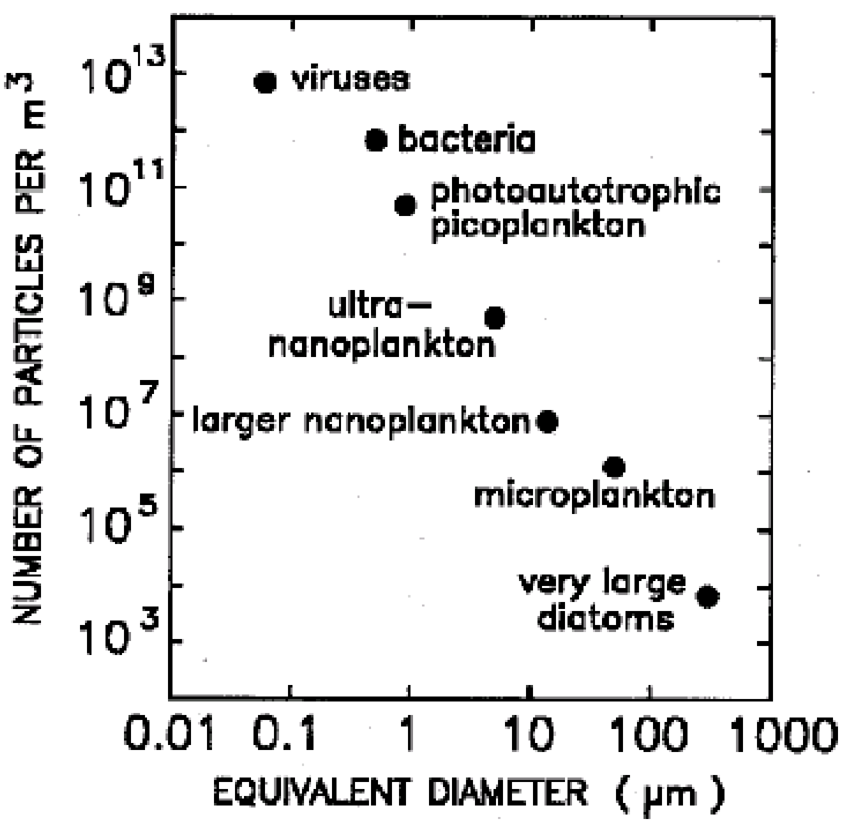
e.g., optical cross-sections $\sigma_i(\lambda)$

concentration in seawater N_i

Multi-component model of bulk IOPs

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

$N_i \longrightarrow$



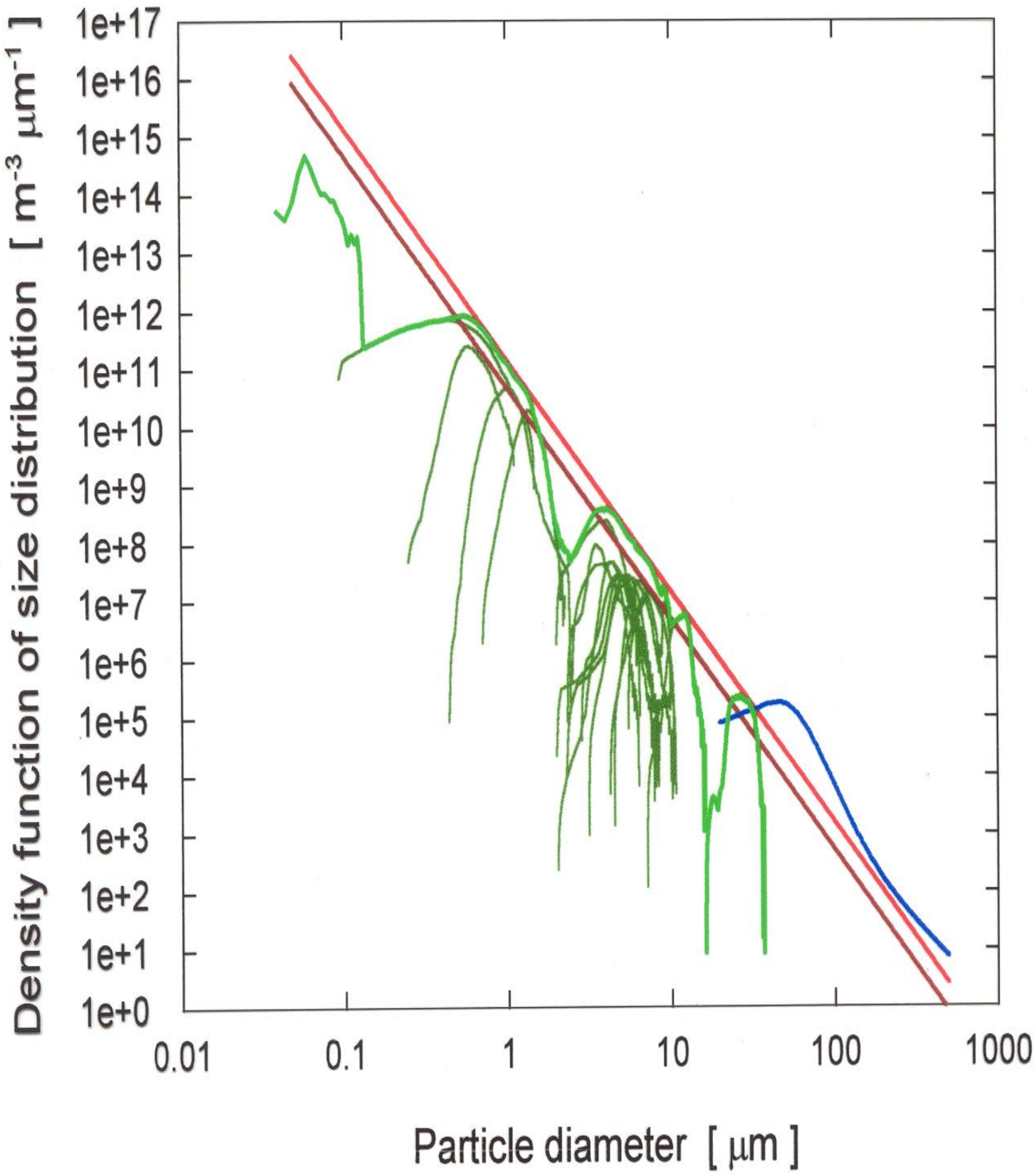
Example IOP model with detailed description of plankton community

i	Component	Concentration [particles/m^3]	*Chl* [mg m^{-3}]
1	VIRU	$1.0 \cdot 10^{13}$	0
2	HBAC	$4.0 \cdot 10^{11}$	0
3	PROC	$7.0 \cdot 10^{10}$	0.1026
4	SYNE	$2.0 \cdot 10^{10}$	0.0403
5	SYMA	$8.0 \cdot 10^{9}$	0.0360
Σ	Picoplankton	$4.98 \cdot 10^{11}$	0.1789
6	PING	$4.5056 \cdot 10^{8}$	0.0540
7	PSEU	$0.9808 \cdot 10^{8}$	0.0303
8	LUTH	$0.9924 \cdot 10^{8}$	0.0107
9	GALB	$0.4839 \cdot 10^{8}$	0.0155
10	HUXL	$0.4339 \cdot 10^{8}$	0.0104
11	CRUE	$0.4496 \cdot 10^{8}$	0.0129
12	FRAG	$0.4768 \cdot 10^{8}$	0.0157
13	PARV	$0.6247 \cdot 10^{8}$	0.0181
14	BIOC	$0.3966 \cdot 10^{8}$	0.0900
15	TERT	$0.3570 \cdot 10^{8}$	0.0609
16	CURV	$0.2987 \cdot 10^{8}$	0.0099
Σ	Small Nanoplankton	$1.0 \cdot 10^{9}$	0.3284
17	ELON	$1.7 \cdot 10^{7}$	0.1595
18	MICA	$2.0 \cdot 10^{6}$	0.0508
Σ	Total Plankton	$1.0499019 \cdot 10^{13}$	0.7176
19	DET	$3.3 \cdot 10^{14}$	0
20	MIN	$1.1 \cdot 10^{14}$	0
Σ	Total Non-living Particles	$4.4 \cdot 10^{14}$	0
21	BUB	$7.1 \cdot 10^{6}$	0

(Stramski et al. 2001)

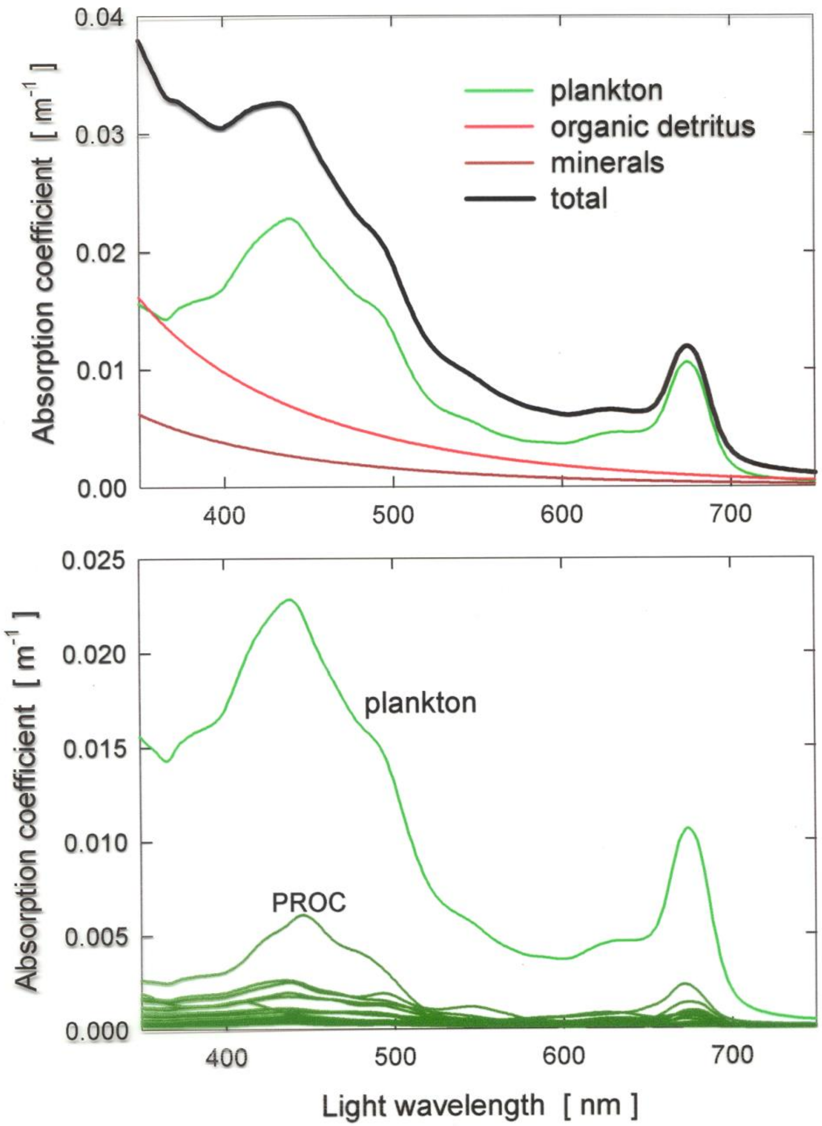
Size distribution

18 planktonic components
composite plankton
mineral particles
organic detritus
air bubbles

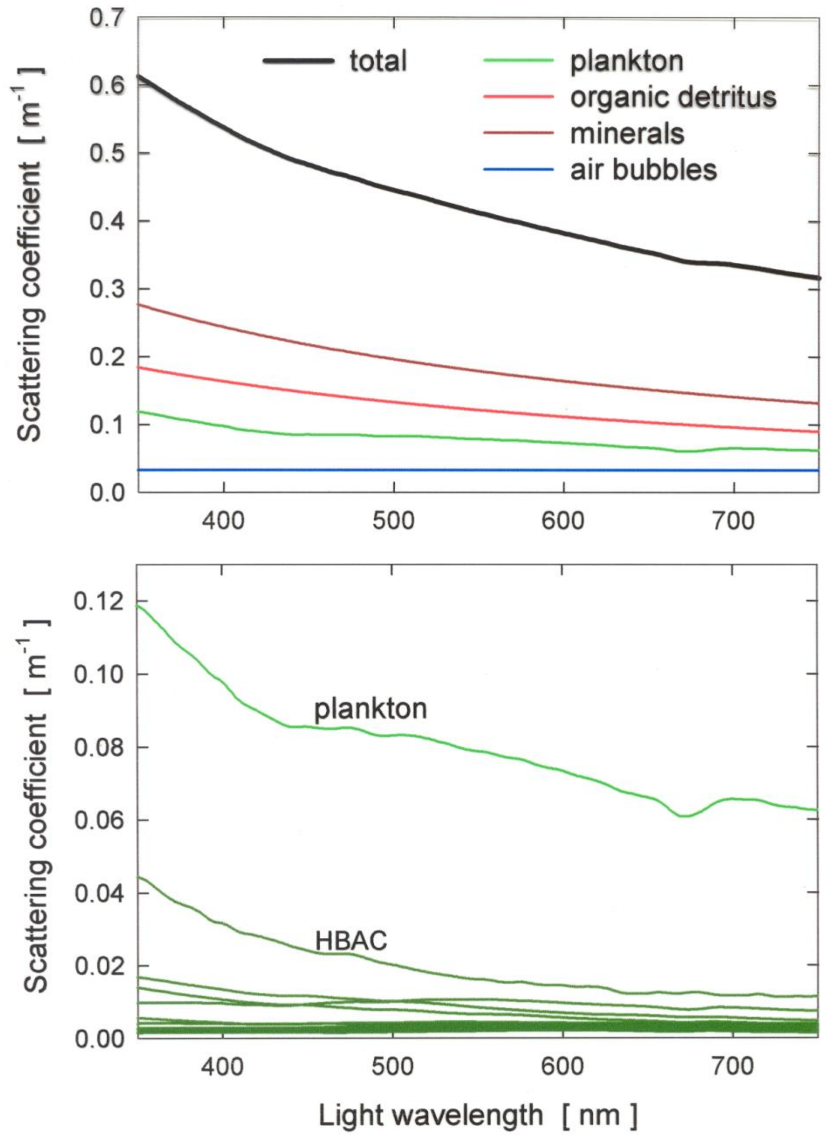


(Stramski et al. 2001)

Absorption



Scattering



(Stramski et al. 2001)

Reductionist IOP/radiative transfer/reflectance model

Input to radiative transfer model

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

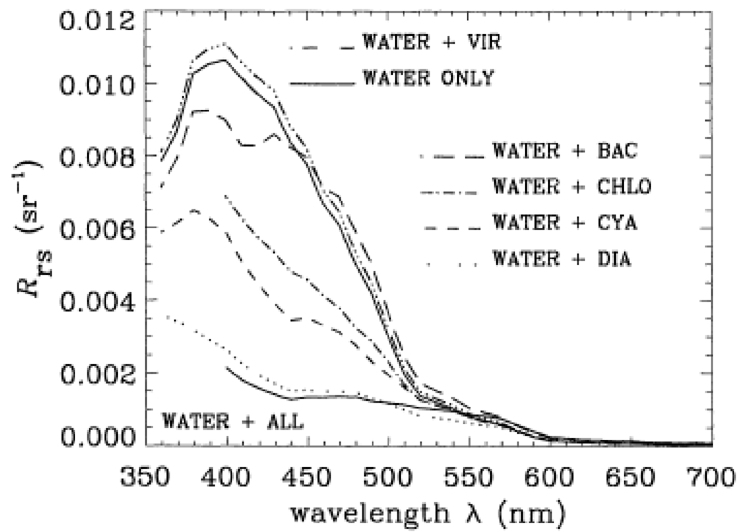
Output, *e.g*. ocean reflectance

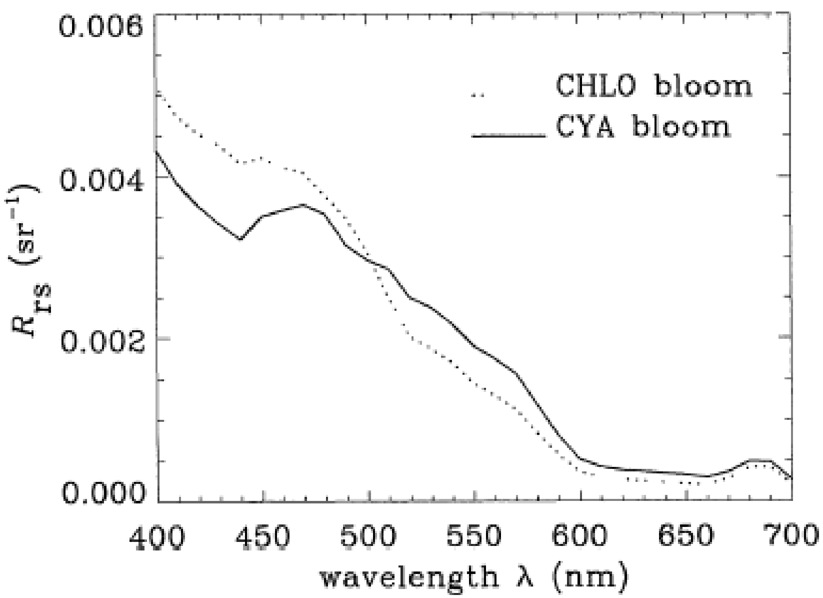
$$R(\lambda) = f\,[\sum_{i=1}^{j} N_{\mathrm{i}}\,\overline{\sigma}_{i,a}(\lambda), \sum_{i=1}^{j} N_{\mathrm{i}}\,\overline{\sigma}_{i,b}(\psi,\lambda)]$$

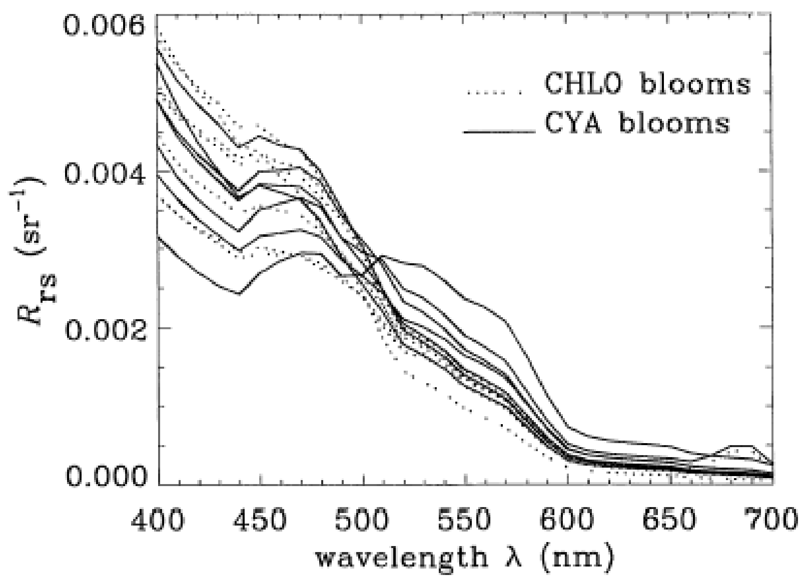
- In what ways does variability in detailed seawater composition determine variability in ocean reflectance?
- What information about water constituents and optical properties can we hope to extract from remotely sensed reflectance?

Multi-component IOP database → Radiative transfer model

Viruses	3×10^{9}–1×10^{14} particles m^{-3}	
Heterotrophic bacteria	1×10^{11}–2×10^{12}	
Cyanobacteria	1×10^{9}–1×10^{11}	($Chl^* = 4.63\times10^{-12}$)
Small diatoms	3×10^{8}–1×10^{10}	($Chl^* = 3.09\times10^{-10}$)
Chlorophytes	1×10^{7}–4×10^{8}	($Chl^* = 1.71\times10^{-9}$)
Detritus (DET)	$a_{DET}(400)$ = 0.2–0.6 of $a_{MICROBE}(400)$	
	b_{DET} = 0.2–0.6 of $b_{MICROBE}(400)$	
Yellow matter (CDOM)	$a_{CDOM}(400)$ = 0.2–0.4 of $a_{MICROBE}(400)$	
	$b_{CDOM} = 0$	







(Stramski and Mobley 1997; Mobley and Stramski 1997)

Reductionist approach:
What do we need to do?

- Optical measurements
  include $\beta(\psi, \lambda)$; target specific water constituents
- Particle identification and characterization
  particle species composition, size distribution,
  particle chemistry, biology, mineralogy, etc.
- Laboratory experiments (not just field experiments)
- New techniques and instrumentation

The complexity of seawater as an optical medium should not deter us from pursuing the proper course in future research

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

Steven Weinberg

1979 Nobel Prize in Physics