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Inherent Optical Properties (IOPs)

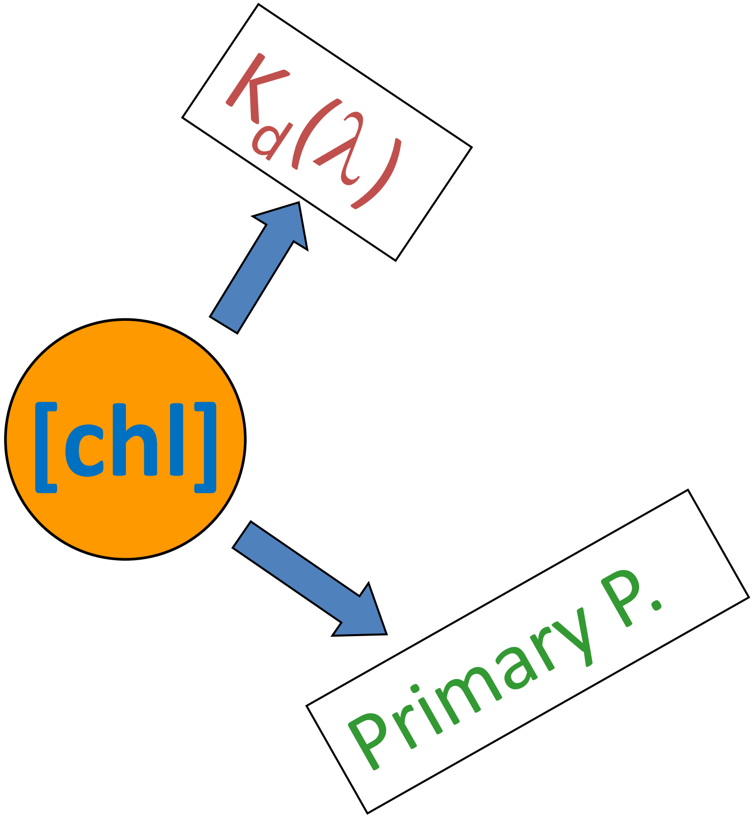
Lecture 3: Applications

Rrs(λ) ⟷ IOPs

What to do with the retrieved IOPs?

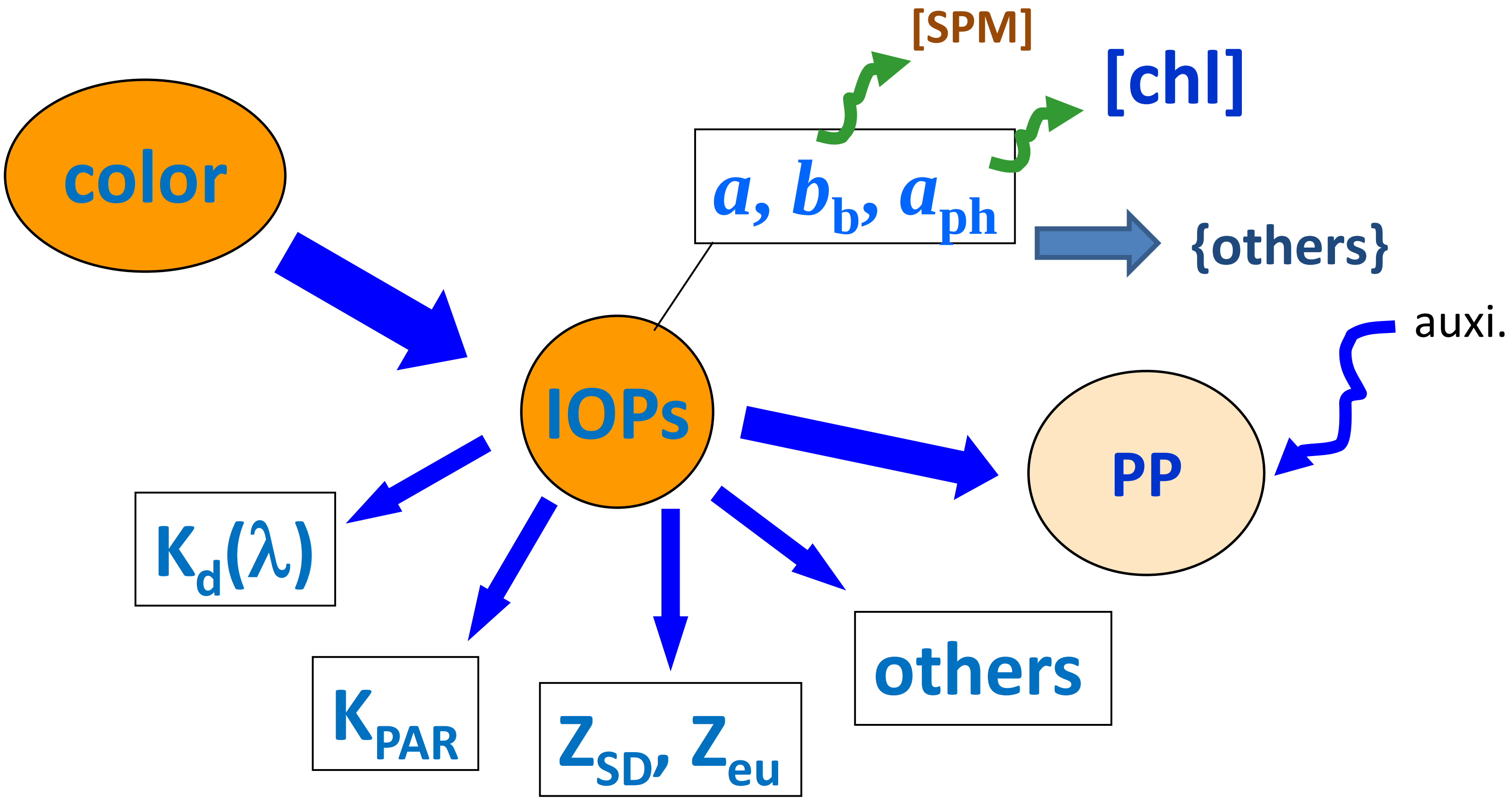
Traditional strategy: [chl] centered system

Ocean color spectrum ➔



Works for waters "Case-1" waters (where IOPs co-vary with [Chl]).

IOP-centered system:



No division of "Case-1" vs "Case-2" waters.

1. Estimation of diffuse attenuation coefficient ($K_d(\lambda)$)

2. Estimation of K_d(PAR) and euphotic-zone depth

3. Estimation of water clarity (Secchi disk depth)

4. Estimation of primary production

5. A few other examples

1. Estimation of diffuse attenuation coefficient ($K_d(\lambda)$)

Traditionally,

$$K_d(490) = A\left(\frac{L_w(\lambda_{blue})}{L_w(\lambda_{green})}\right)^B$$

Austin and Petzold (1981)

Or,

$$K_d(\lambda, [Chl]) = K_w(\lambda) + \chi(\lambda)[Chl]^{e(\lambda)} \qquad (2)$$

(Morel and Maritorena 2001)

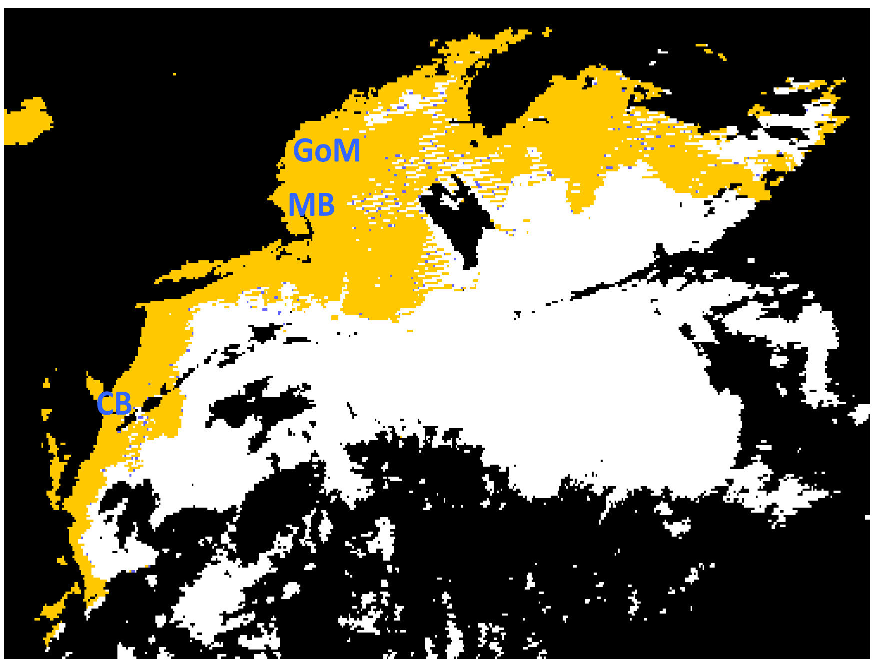
For "Case-1" waters

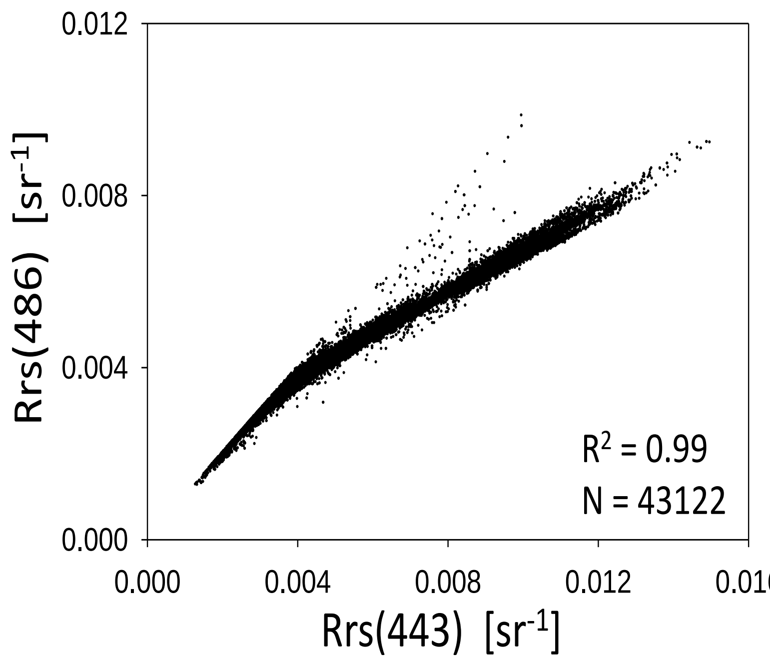
$$\log_{10}(K_{bio}(490)) = a_0 + \sum_{i=1}^{4} a_i \log_{10}\left(\frac{R_{rs}(\lambda_{\text{blue}})}{R_{rs}(\lambda_{\text{green}})}\right)$$

$$Kd\_490 = K_{bio}(490) + 0.0166$$

$$log_{10}(chlor\_a) = a_0 + \sum_{i=1}^{4} a_i log_{10}\left(\frac{R_{rs}(\lambda_{blue})}{R_{rs}(\lambda_{green})}\right)^i,$$

$Rrs(\lambda_{blue})$ = Rrs(443)>Rrs(486)





The standard K_d(490) and Chl products are 100% co-vary in coastal waters; further…

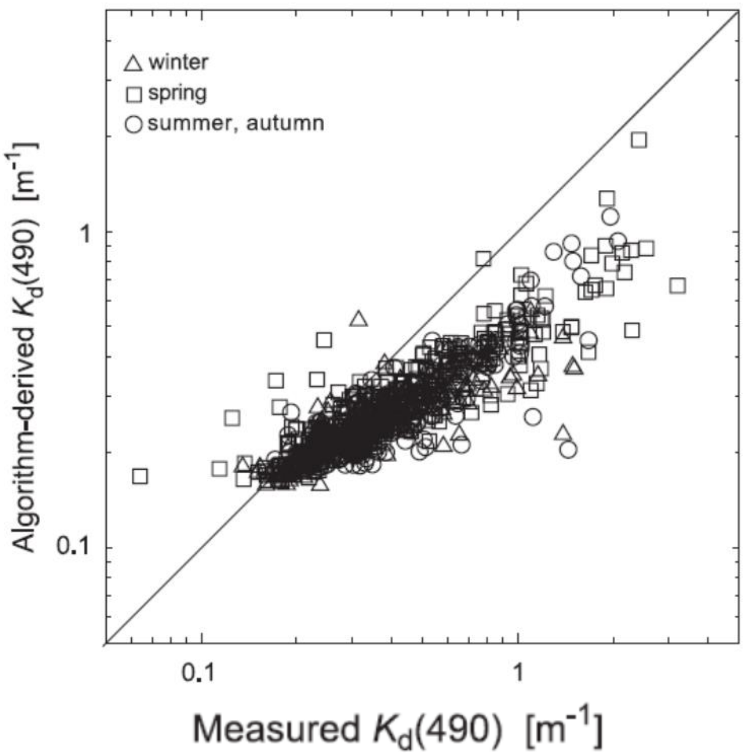
$$K_d(490) = Fun\left(\frac{R_{rs}(490)}{R_{rs}(555)}\right)$$

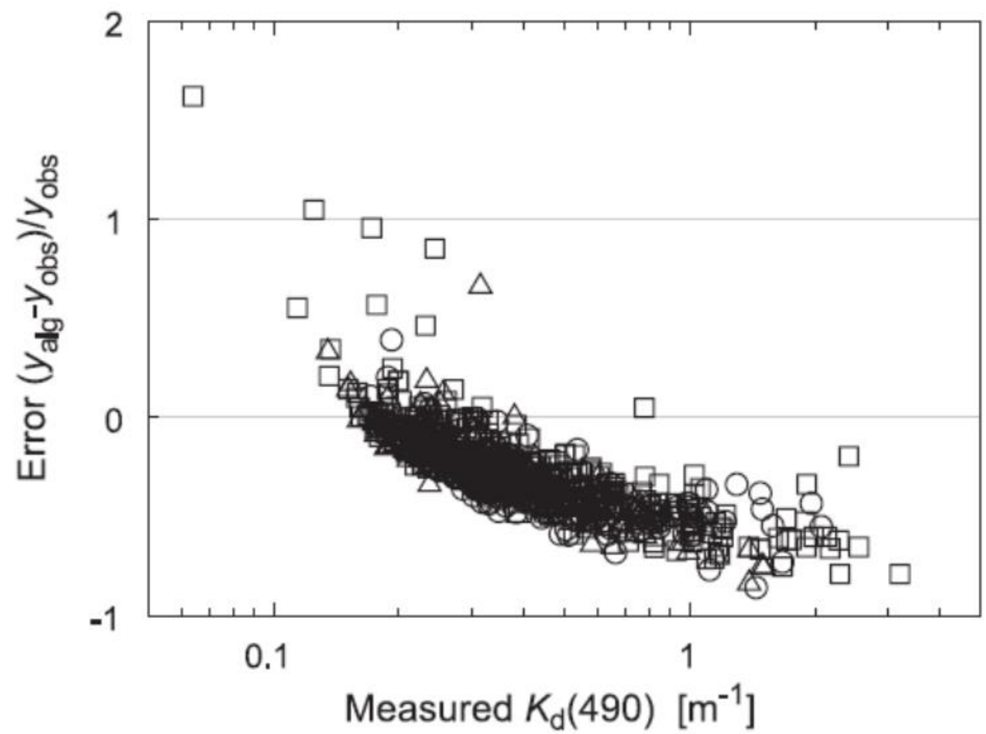
AOP: sun angle dependent

Nearly independent of sun angle

The two sides do not match in optical nature.

In addition, ratio-derived K_d has large uncertainties





(Darecki and Stramisk, 2004)

How to estimate $\mathbf{K_d(\lambda)}$ from IOPs?

What is the analytical relationship between $\mathbf{K_d}$ and IOPs?

Through Monte Carlo simulations:

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

(Kirk 1984)

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

(Gordon 1989)

Relationship based on radiative transfer?

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

(inelastic scattering omitted)

Integrate over the downwelling hemisphere:

(Aas, 1987)

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

Left side:

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

1st term on the right side:

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

2nd term on the right side:

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

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

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

$$K_d(\lambda, z) = -\frac{d\,E_d(\lambda, z)}{E_d(\lambda, z)\;dz}$$

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

$$K_d = \mathrm{m}_0\, a + \mathrm{v}\; b_b$$

$\mathrm{v} \neq \mathrm{m}_0$

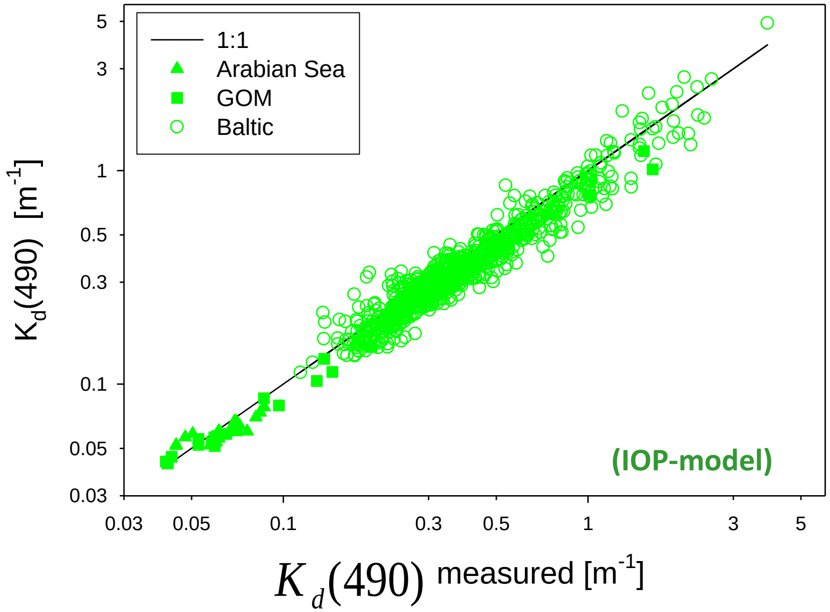
$$\mathrm{v} = m_1(1 - m_2 e^{-m_3 a})$$

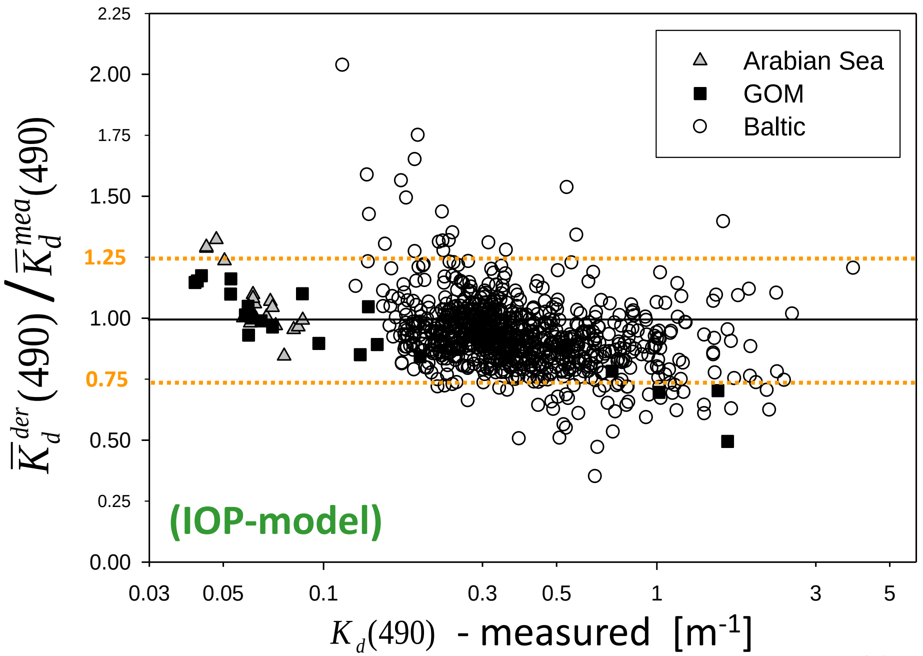
(*Lee et al. 2005, 2013*)

($m_{0,1,2}$ are wavelength independent)

R_{rs} → a&b_b → K_d

No division of “Case 1” vs “Case 2” waters.

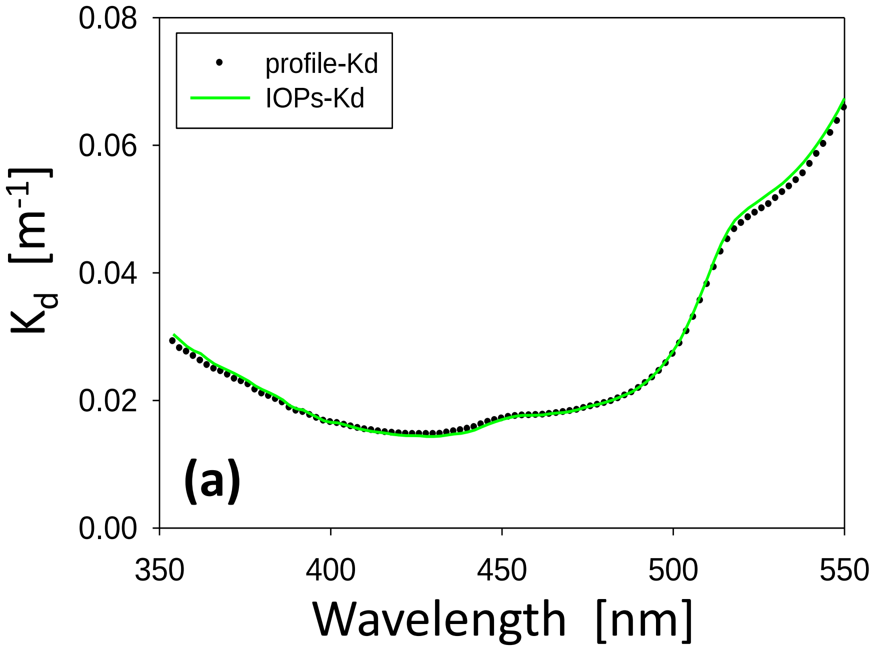


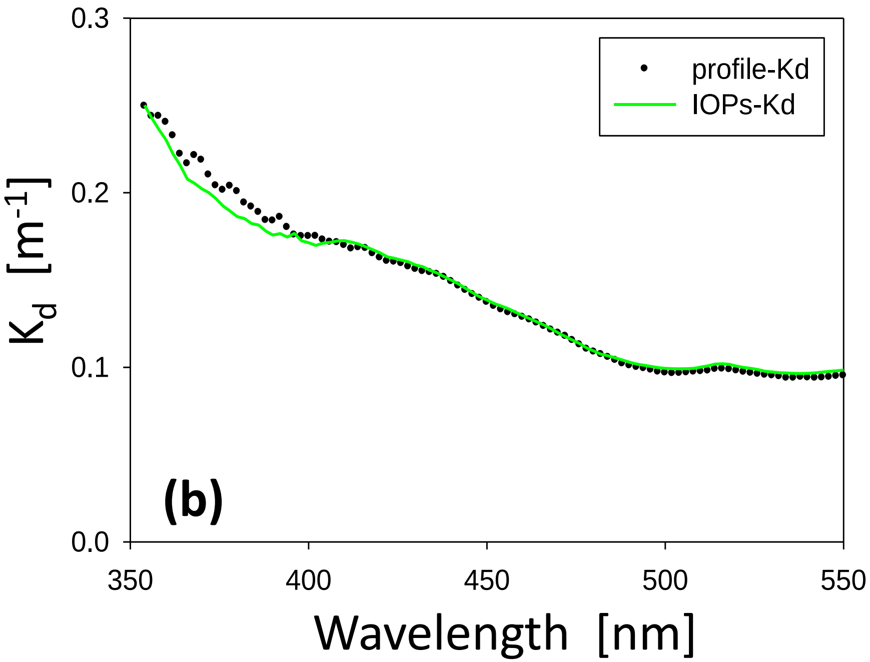


Oceanic & Coastal waters

(*Lee et al. 2005*)

K_d spectrum:





(Lee et al 2013)

2. Estimation of K_{PAR} and euphotic-zone depth

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

$$K_{PAR} = K_w + k_c C + K_x$$

Good for earlier days,
Not good for the 21st century

hence of K_{PAR}.

1. K_w is a value averaged over the whole spectrum. It is computed for a layer extending from zero to a certain depth Z within an ideally optically pure ocean. When computing this depth-averaged value, denoted $\bar{K}_w(0, Z)$, the spectral distribution of the light at the surface, $E_0(\lambda)$, and at the depth Z, $E_z(\lambda)$, intervenes according to

$$\bar{K}_w(0, Z) = -Z^{-1} \log \left\{ \left[\int_{400}^{700} E_0(\lambda) \exp\left[-K_w(\lambda) Z\right] d\lambda \right/ \int_{400}^{700} E_0(\lambda)\, d\lambda \right\} \quad (7)$$

In other words, $\bar{K}_w(0, Z)$ is no longer a constant as soon as it is computed for a layer of variable thickness. When Z increases, the remnant light tends to become monochromatic, with the irradiance maximum centered on the minimum of K_w, and the averaged value $\bar{K}_w(0, Z)$ decreases accordingly (see Figure 4; $E_0(\lambda)$ is taken from Figure 8).

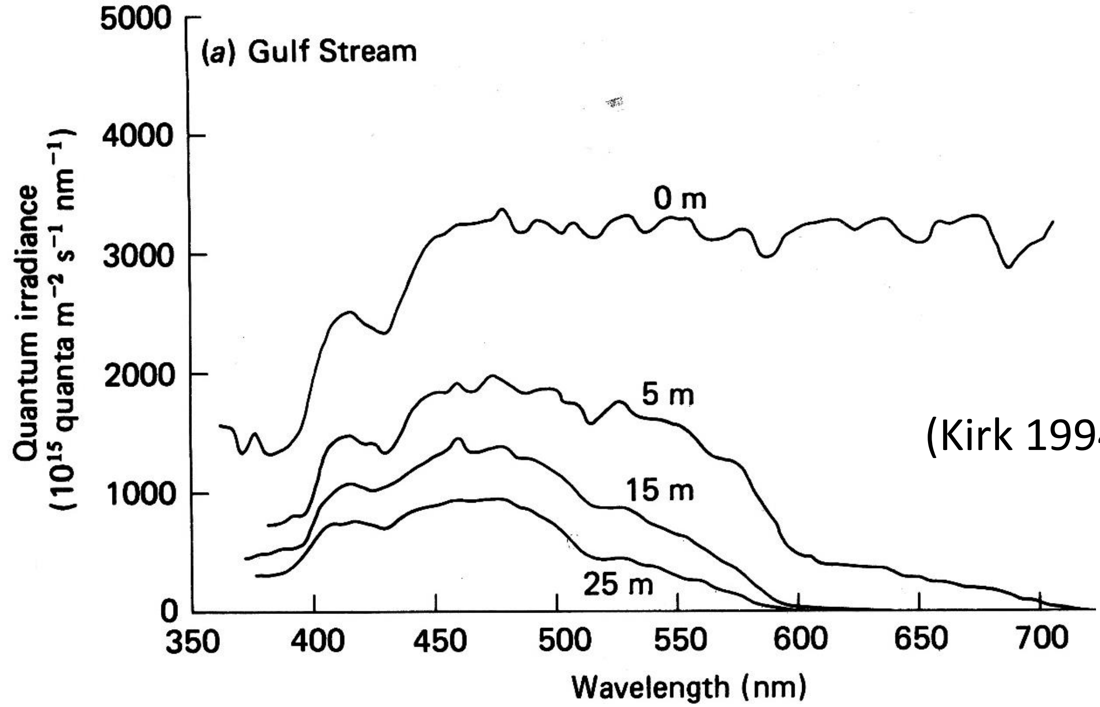
2. The constant coefficient k_c is also a doubly averaged value, over the spectrum and over the layer considered. The result of such averaging depends on the spectral composition of the underwater light and on its change with depth. Since the phytoplankton concentration depicted by C governs both

(Morel, 1988, JGR)

$$K_{PAR} = \frac{-1}{z} \ln\left(\frac{PAR(z)}{PAR(0)} \right) \qquad PAR(z) = \int_{400}^{700} E_0(\lambda,0)\, e^{-K(\lambda,z)z}\, d\lambda$$

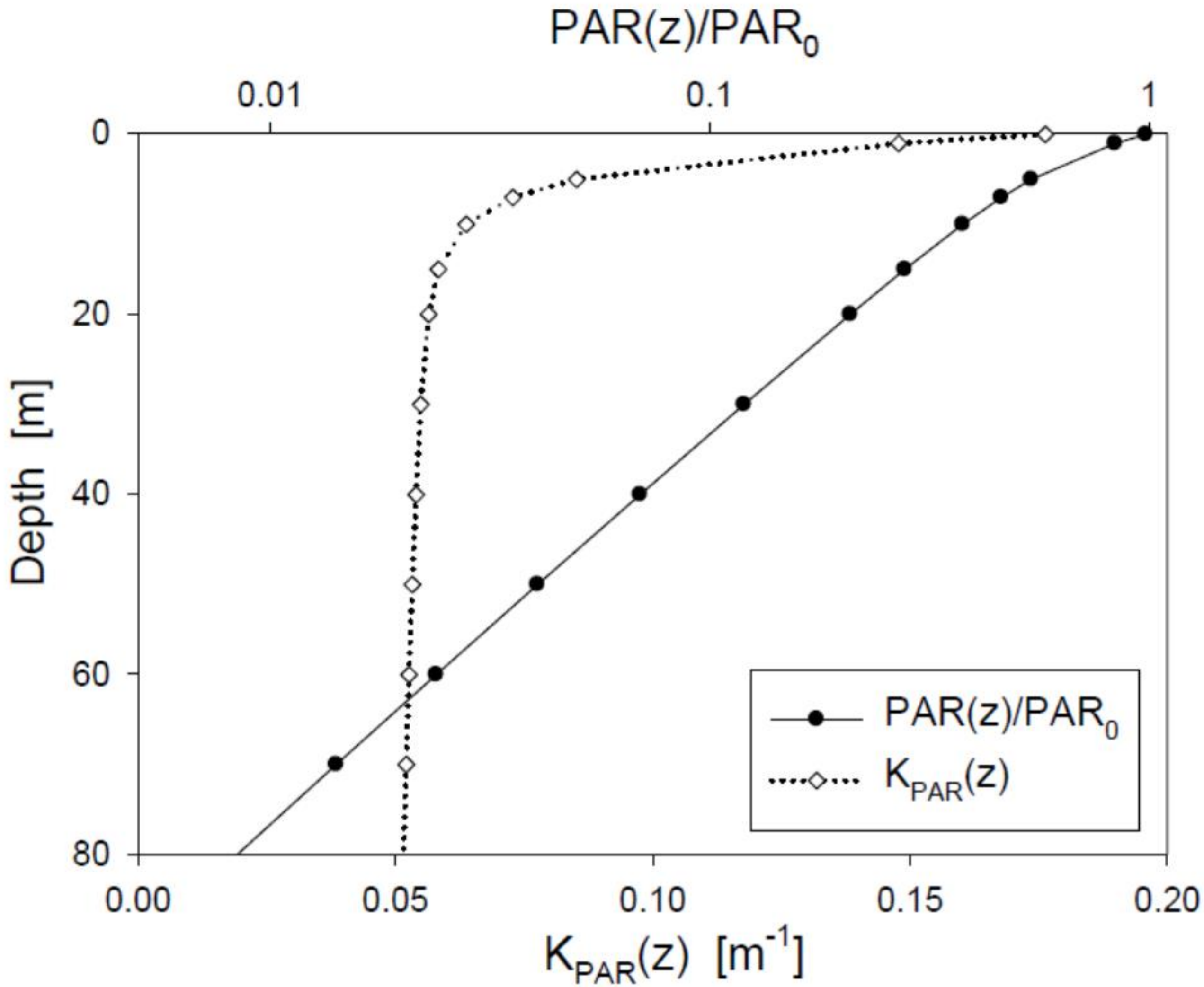
K_{PAR} is light-quality weighted!

Change of light with depth:



(Kirk 1994)

➔ **Light at deeper depth is associated with lower attenuation coefficient**


PAR(z)/PAR0
0.01
0.1
1
0
20
40
60
80
Depth [m]
PAR(z)/PAR0
KPAR(z)
0.00
0.05
0.10
0.15
0.20
KPAR(z) [m-1]

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

$$K_{PAR}(z) \approx K_1 + \frac{K_2}{(1+z)^{0.5}}$$

$$K_1 = f_1(a(490), b_b(490)$$

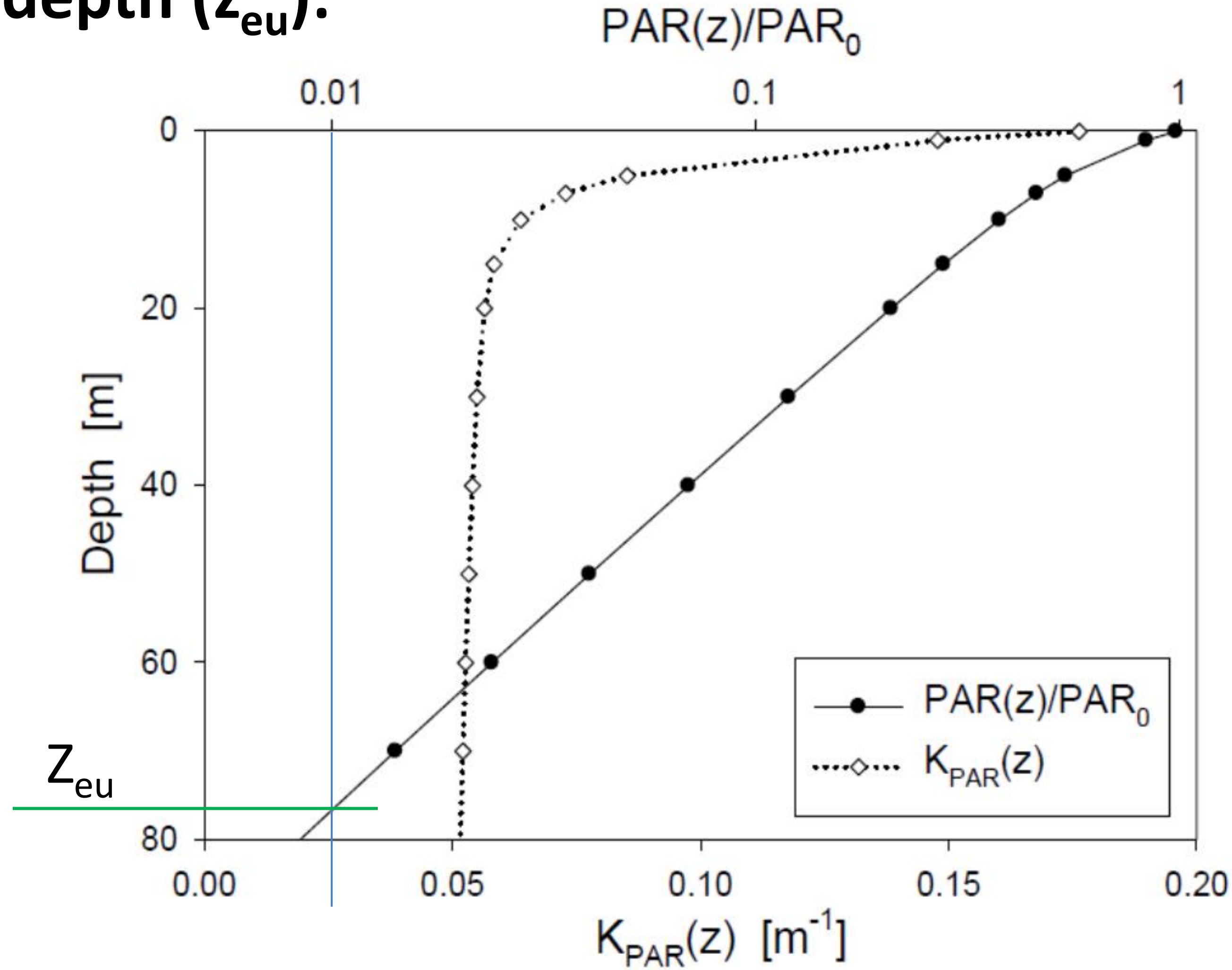
$$K_2 = f_2(a(490), b_b(490)$$

(Lee et al 2005)

Key:

K_{PAR} varies with depth, especially in the upper water column.

Euphotic depth (z_{eu}):



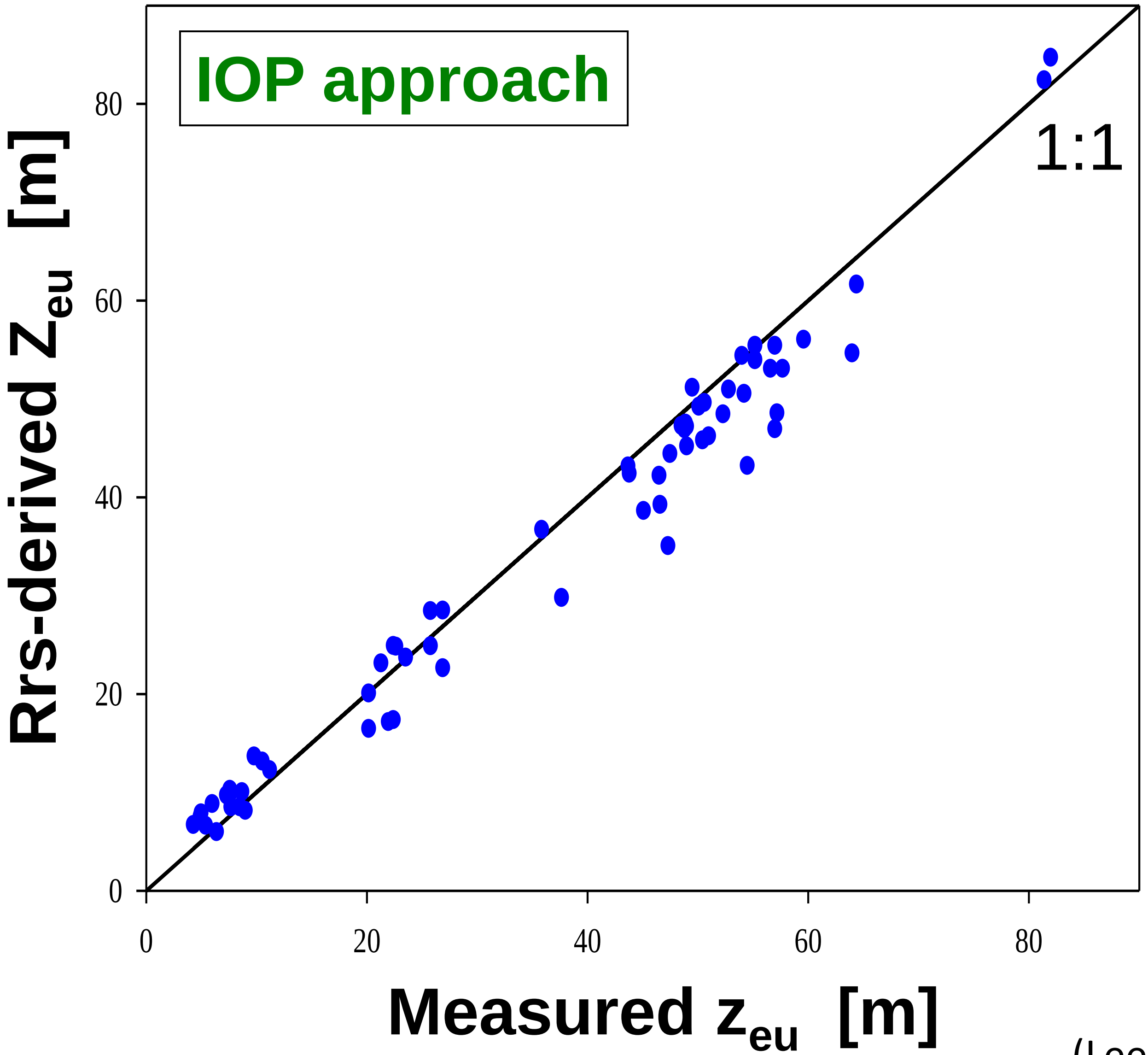
$$\frac{PAR(z)}{PAR(0)} = 1\%$$

$$z_{eu} = \frac{4.6}{K_{PAR}(z_{eu})}$$

$$\left\{K_1(a(490)\&b_b(490)) + \frac{K_2(a(490)\&b_b(490))}{(1+z_{eu})^{0.5}}\right\} z_{eu} = 4.6$$

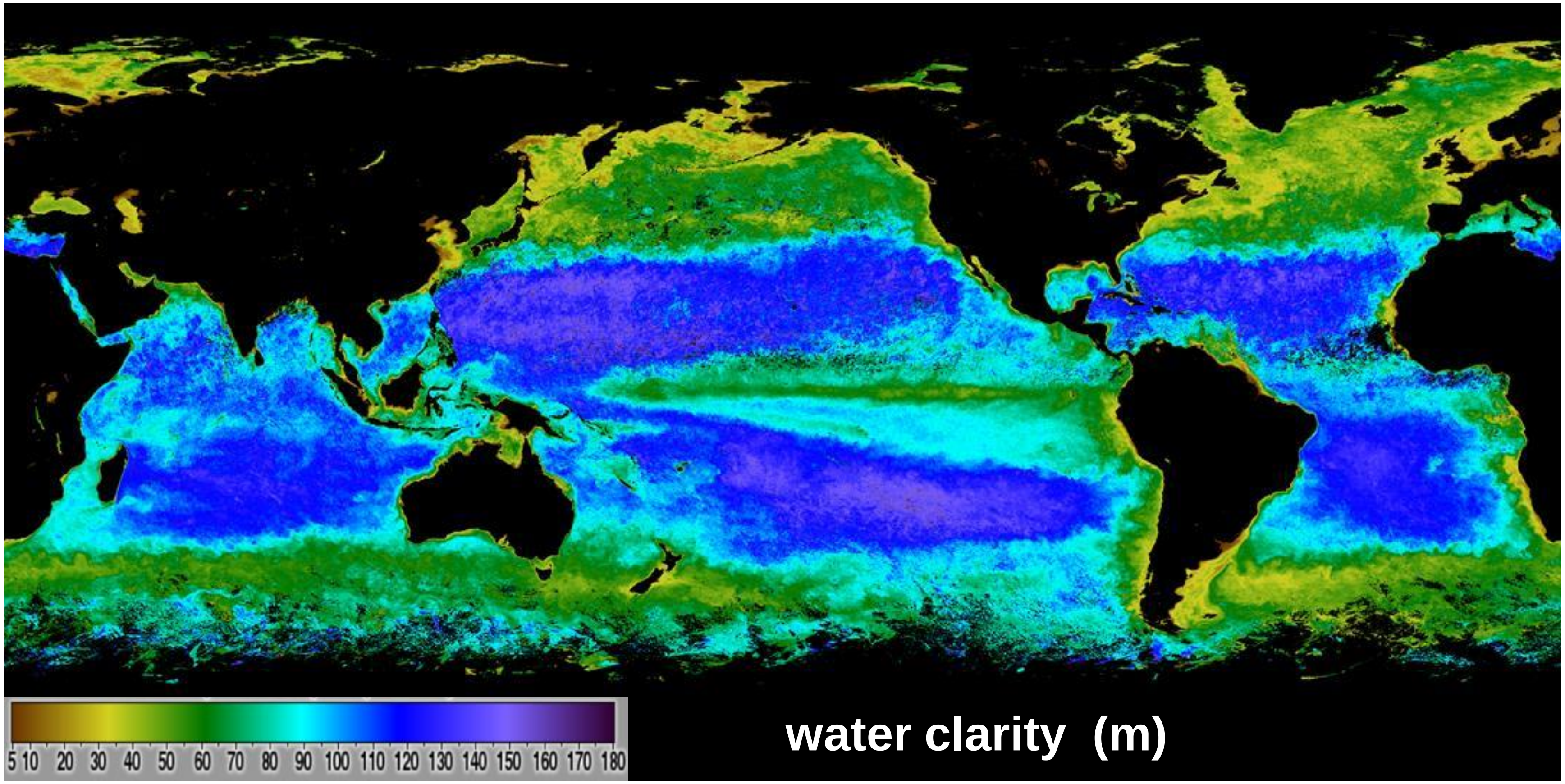
(or 5.3 if defined as 0.5%)

$$R_{rs}(\lambda) \rightarrow a(\lambda)\&b_b(\lambda) \rightarrow K_{PAR}(z) \rightarrow z_{eu}$$



(Lee et al 2005)

Global distribution of Z_{eu}



3. Estimation of water clarity (Secchi disk depth)

Empirical relationships for Z_{SD} derived from measurements:

Formula	Z_{SD} range (m)	Reference
$Z_{SD} = 1.7/K_{PAR}$	1.9 - 35	Poole and Atkins (1929)
$Z_{SD} = 1.44/K_{PAR}$	2 - 12	Holmes (1970)
$Z_{SD} = 1.7/K_{PAR}$	0.1 - 35	Idso (1974)
$Z_{SD} = 1.54/K_{PAR}$	6 - 46	Megard and Berman (1989)
$Z_{SD} = 1.27/K_{PAR}$	0.2 – 2.2	Gallegos et al. (1990)
$Z_{SD} = 1.86/K_{PAR}$	2.3 – 14.7	Kolengings et al. (1991)
$Z_{SD}^{1.16} = 1.48/K_{PAR}$	1.2 - 5	Montes-Hugo et al. (2005)
$Z_{SD} = 1.36/K_{PAR}$	0.1 - 42	Lugo-Fernandez (2008)
$Z_{SD}^{0.76} = 2/K_{PAR}$	0.2 - 6	Padial and Thomaz (2008)
$Z_{SD} = 1.8/K_{PAR}$	0.6 – 4.2	Bracchini et al. (2009)
$Z_{SD}^{0.85} = 1.76/K_{PAR}$	1.7 – 7.0	Ficek and Zapadka (2010)
$Z_{SD} = 1.4/K_{PAR}$	0.5 – 2.5	Gallegos et al. (2011)
$Z_{SD} = 1.37/K_{PAR}$	0.1 – 2.4	Zhang et al. (2012)

$$K_D(\mathrm{m}^{-1}) = 0.11 + \frac{1.28}{D(\mathrm{m})}$$

(Sathyendranath and Varadachari, 1982)

(Lee et al 2018)

$$Z_{SD} = (1.4\sim1.7)/K_{PAR}$$

The theoretical relationship:

(Duntley 1952; Preisendorfer 1986; Zaneveld and Pegau 2003; Aas 2014)

$$Z_{SD} = \frac{\Gamma}{K_d + c}$$

$c \gg K_d$

$$\Gamma = \ln\left(\frac{C_i}{C_t}\right)$$

(~5 – 10)

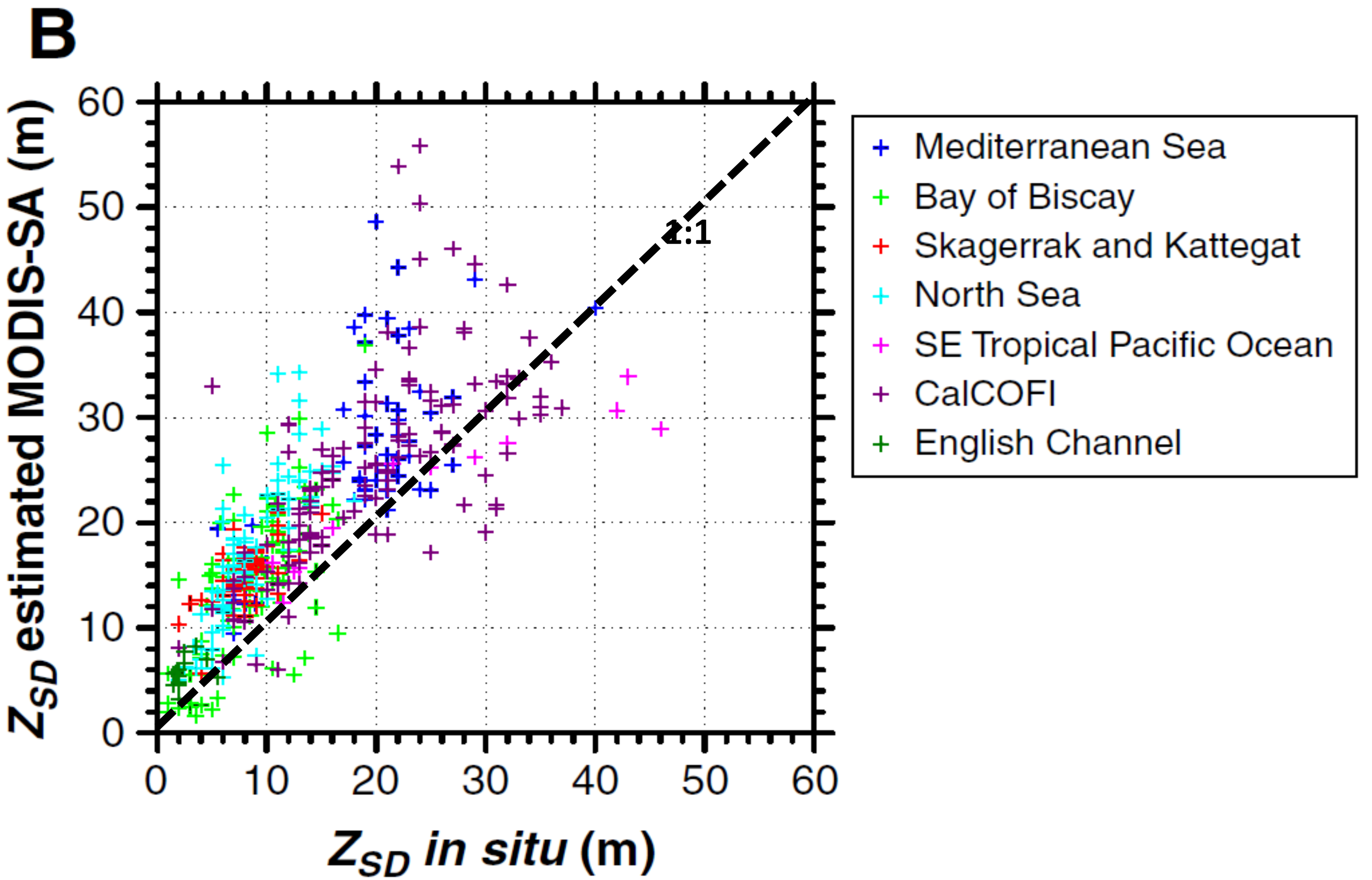
$$C_i = \frac{r_T - r_B}{r_B}$$

K_d: Diffuse attenuation coefficient
c: Beam attenuation coefficient
C_i: Inherent contrast
C_t: Contrast threshold of human eye; ~2%

$Z_{SD} = (1.4\text{-}1.7)/K_{PAR}$

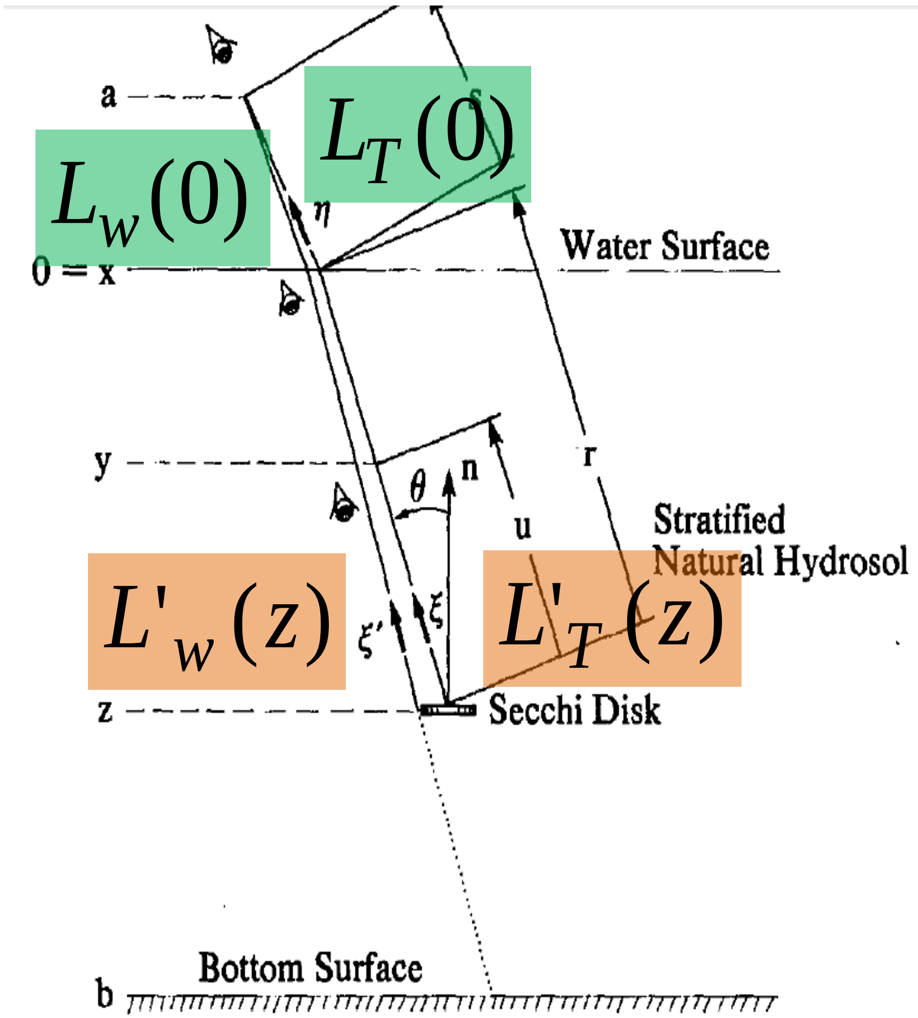
Theory and observation do <u>not match.</u>

Results based on classical theory



(Doron et al 2011)

Where the *c* comes from?

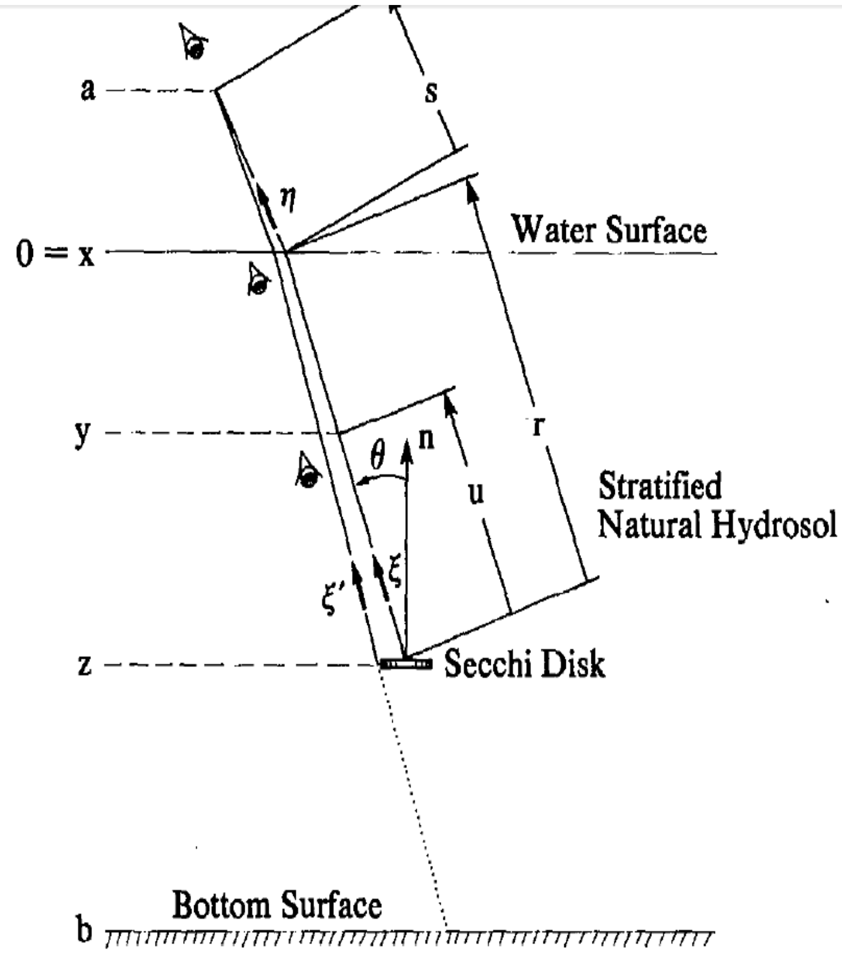


Geometry of the Secchi Disk Sighting

(Preisendorfer, 1986)

$$d\frac{L_T(z,\xi)}{dz} = -c\,L_T(z,\xi) + \int_{4\pi} L'_T(z)\beta d\omega$$

$$d\frac{L_w(z,\xi')}{dz} = -c\,L_w(z,\xi') + \int_{4\pi} L'_w(z)\beta d\omega$$



Geometry of the Secchi Disk Sighting

Assume:

$$\int L'_T(z)\,\beta\,dw = \int L'_w(z)\,\beta\,dw$$

$$d\,\frac{L_T(z,\xi)}{dz} = -c\,L_T(z,\xi) + \int_{4\pi} L'_T(z)\beta d\omega$$

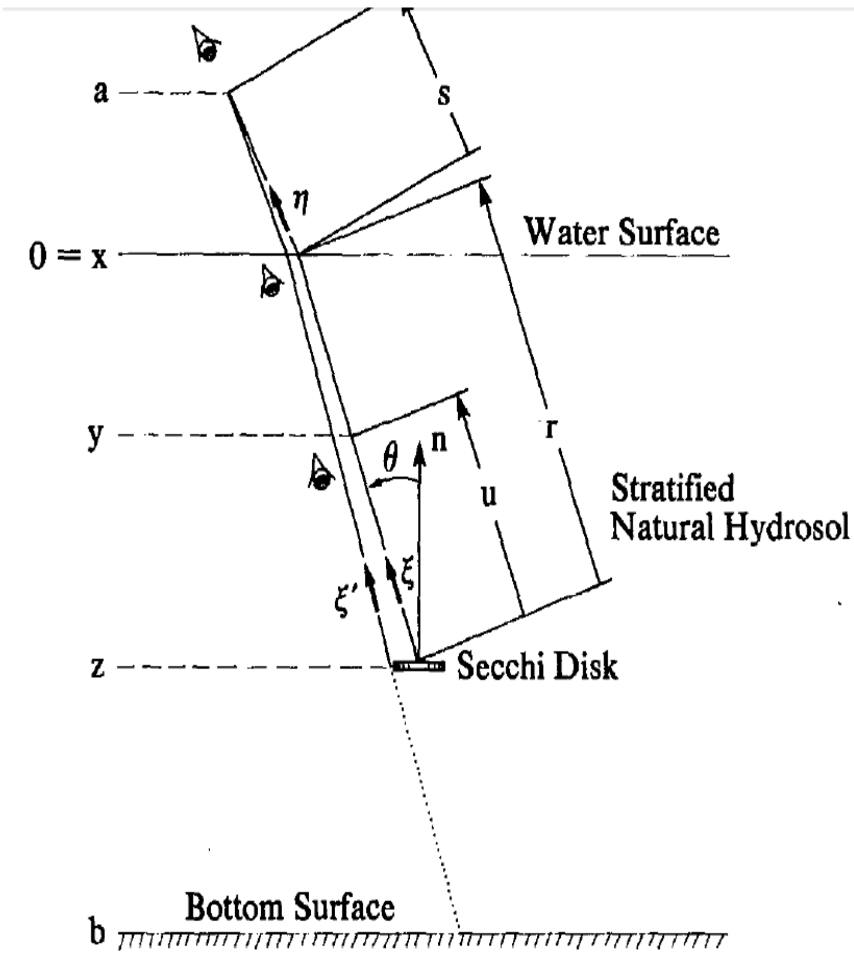
$$d\,\frac{L_w(z,\xi')}{dz} = -c\,L_w(z,\xi') + \int_{4\pi} L'_w(z)\beta d\omega$$

⬇

$$d\,\frac{L_T(z) - L_w(z)}{dz} = -c(L_T(z) - L_w(z))$$

⬇

$$Z_{SD} = \frac{1}{(c+K)} ln\left(\frac{C_i}{C_t}\right) = \frac{\Gamma}{(c+K)}$$



Geometry of the Secchi Disk Sighting

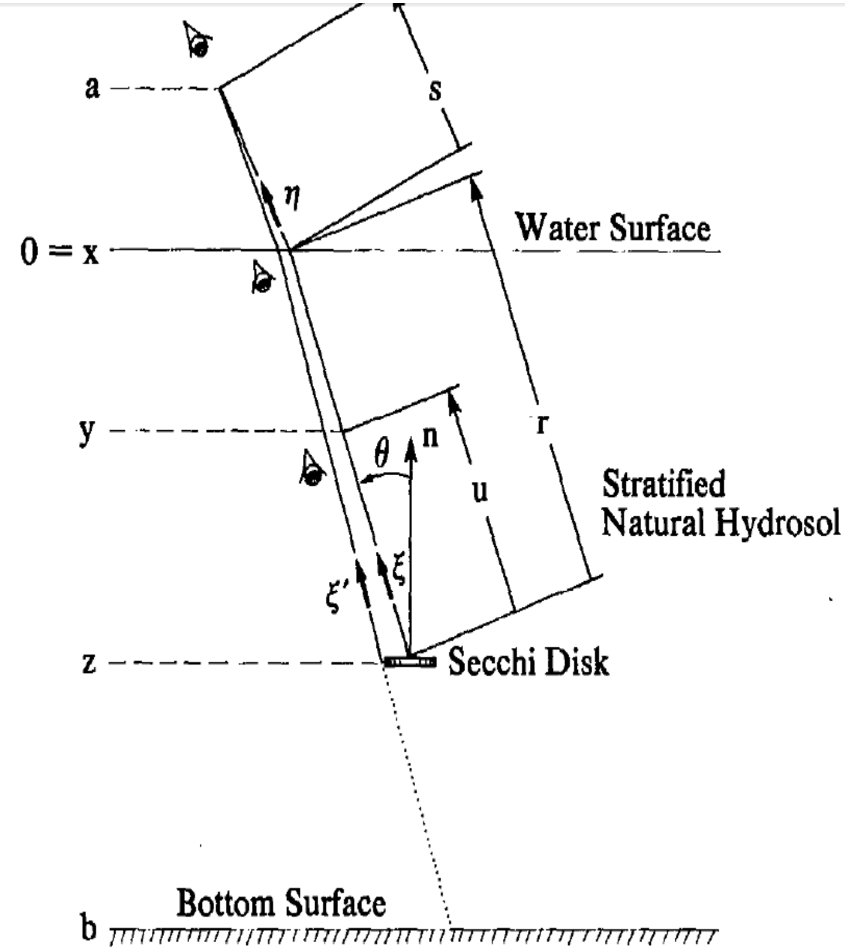
$$\int L'_T(z)\,\beta\,dw = \int L'_w(z)\,\beta\,dw \quad ??$$

Point source:

$$\int L'_T(z)\beta dw = \int L'_w(z)\beta dw$$

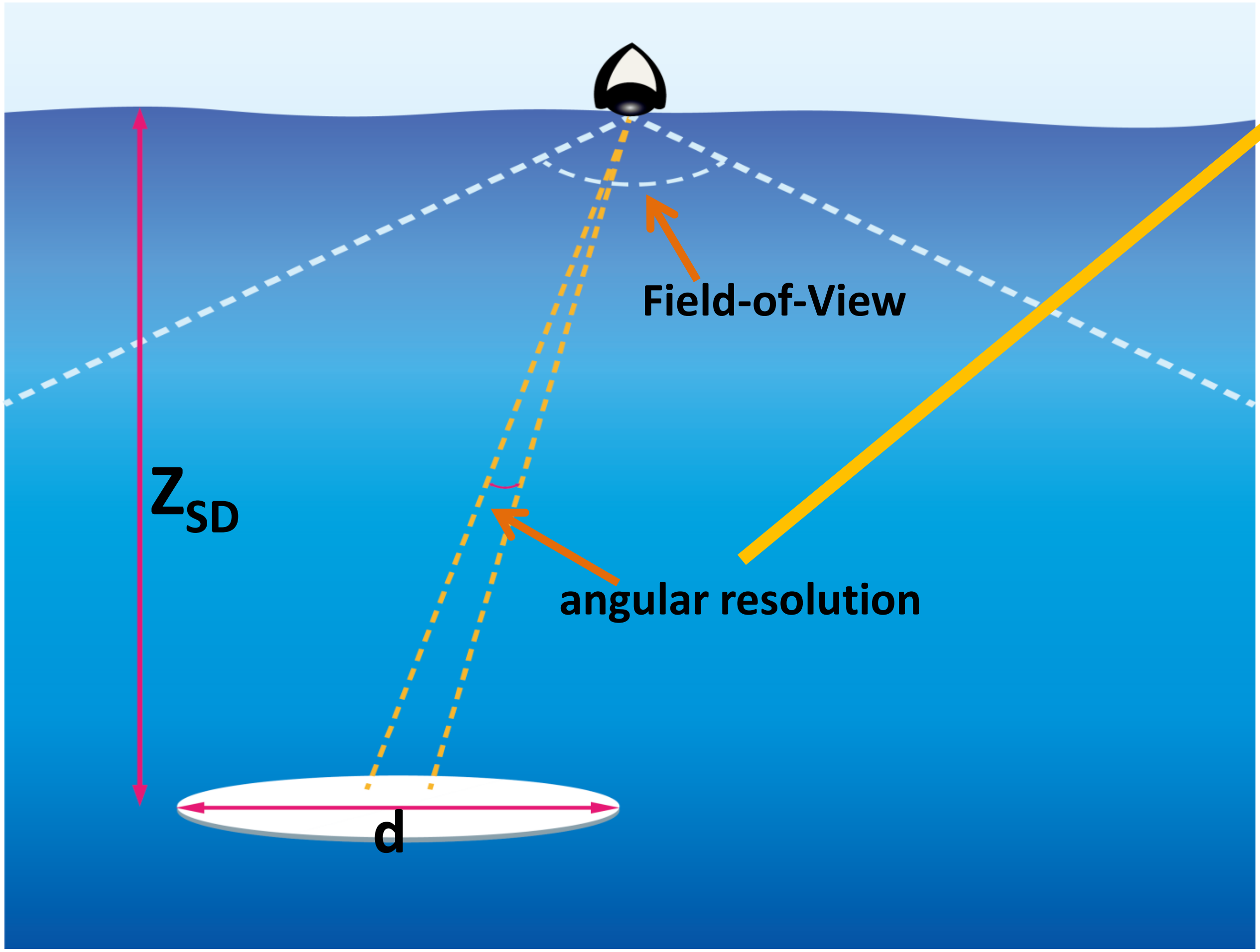
Does this assumption hold for observing a Secchi disk?

Is a Secchi disk a point to our eye?



Geometry of the Secchi Disk Sighting

Secchi disk vs the resolution of eye "sensor"



~0.5 Arcmin

~0.2 mm for a distance of 1 m

d ~ 1500 * eye resolution

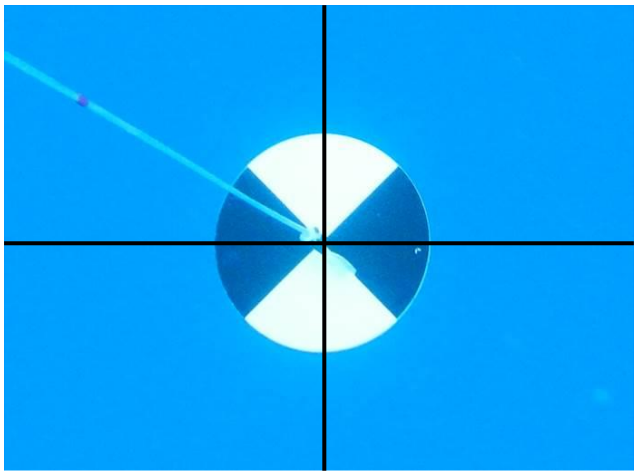
Z_{SD}: up to ~50 m

d ~ 30 * eye resolution

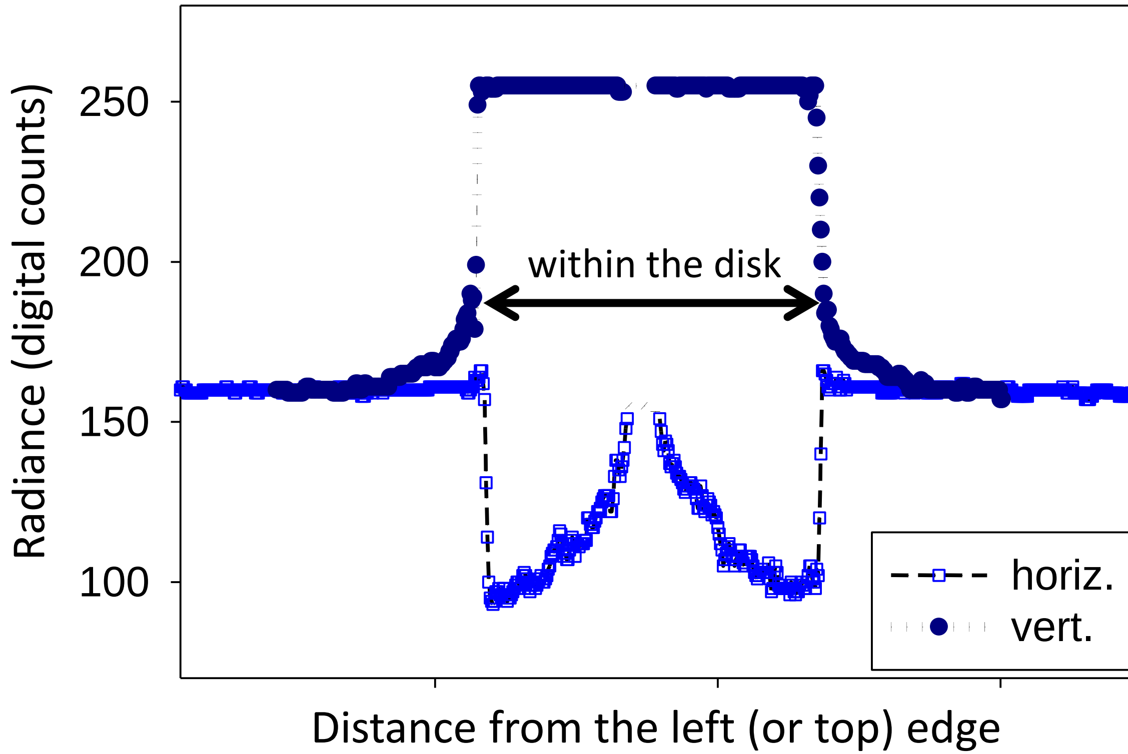
For a radiance sensor with a 5° resolution, the equivalent target is ~ 120-m wide when viewed 1 m away.

➡ A Secchi disk is **NOT** a point source for human eyes.

Spatial variation of radiance around a Secchi disk:



(Lee et al 2015)



$$\int L'_T(z)\,\beta\,dw \neq \int L'_w(z)\,\beta\,dw$$

$$d\frac{L_T(z,\xi)}{dz} = -c\,L_T(z,\xi) + \int_{4\pi} L'_T(z)\beta d\omega$$

$$d\frac{L_w(z,\xi')}{dz} = -c\,L_w(z,\xi') + \int_{4\pi} L'_w(z)\beta d\omega$$

$$\int L'_T(z)\beta\, dw \neq \int L'_w(z)\beta\, dw$$

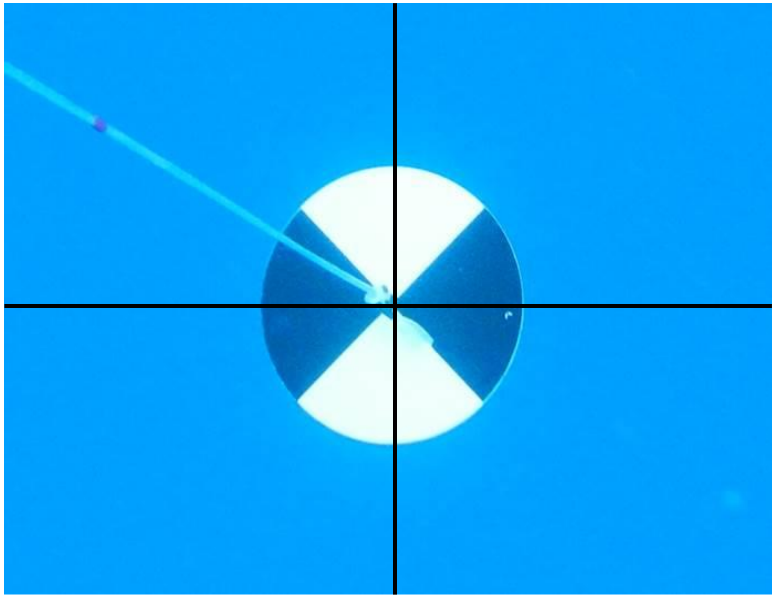
$$d\frac{L_T(z) - L_w(z)}{dz} \neq -c\big(L_T(z) - L_w(z)\big)$$

$$Z_{SD} \neq \frac{\Gamma}{K + c}$$

Quantification of contrast:

$$C_i = \frac{r_T - r_B}{r_B}$$

r_T: **reflectance of target**
r_B: **reflectance of background**



r_B **?**

Contrast for detection:

$$L^C = L_T - L_B$$

d ~ 50 * the resolution of "eye sensor"

↓

A Secchi disk is a sinking "bottom" to human eye

- **Use the most transparent (tr) band to sight the disk**
- **Following "brightness consistency"**

Radiative transfer of shallow bottom:

$$L_T^{tr}(0^-) = r_w^{tr} \times E_d^{tr}(0^-)\left(1 - e^{-(K_d^{tr}+K_L^{tr})z}\right) + r_T \times E_d^{tr}(0^-)e^{-(K_d^{tr}+K_L^{tr})z}$$

$K_{d,L}^{tr}$: **attenuation coefficient in the transparent window**

Adjacent water:

$$L_w^{tr}(0^-) = r_w^{tr} E_d^{tr}(0^-)$$

Contrast in radiance:

$$L^C = L_T^{tr}(0^-) - L_w^{tr}(0^-) = r_w^{tr} \times E_d^{tr}(0^-)\left(-e^{-(K_d^{tr}+K_L^{tr})z}\right) + r_T \times E_d^{tr}(0^-)e^{-(K_d^{tr}+K_L^{tr})z}$$

Eye-adapted Contrast:

$$C_a^r = \frac{L_T^{tr}(0^-) - L_w^{tr}(0^-)}{E_d^{tr}(0^-)}$$

$$L_T^{tr}(0^-) - L_w^{tr}(0^-) = r_w^{tr} \times E_d^{tr}\,(0^-)\left(-e^{-(K_d^{tr}+K_L^{tr})z}\right) + r_T \times E_d^{tr}\,(0^-)e^{-(K_d^{tr}+K_L^{tr})z}$$

⇓

$$C_a^r = (r_T - r_w^{tr})e^{-(K_d^{tr}+K_L^{tr})z}$$

$$C_a^r = C_t^r \quad \Rightarrow \quad \boldsymbol{Z_{SD}}$$

C_t^r : Contrast threshold in reflectance

New theoretical relationship for Z_{SD}:

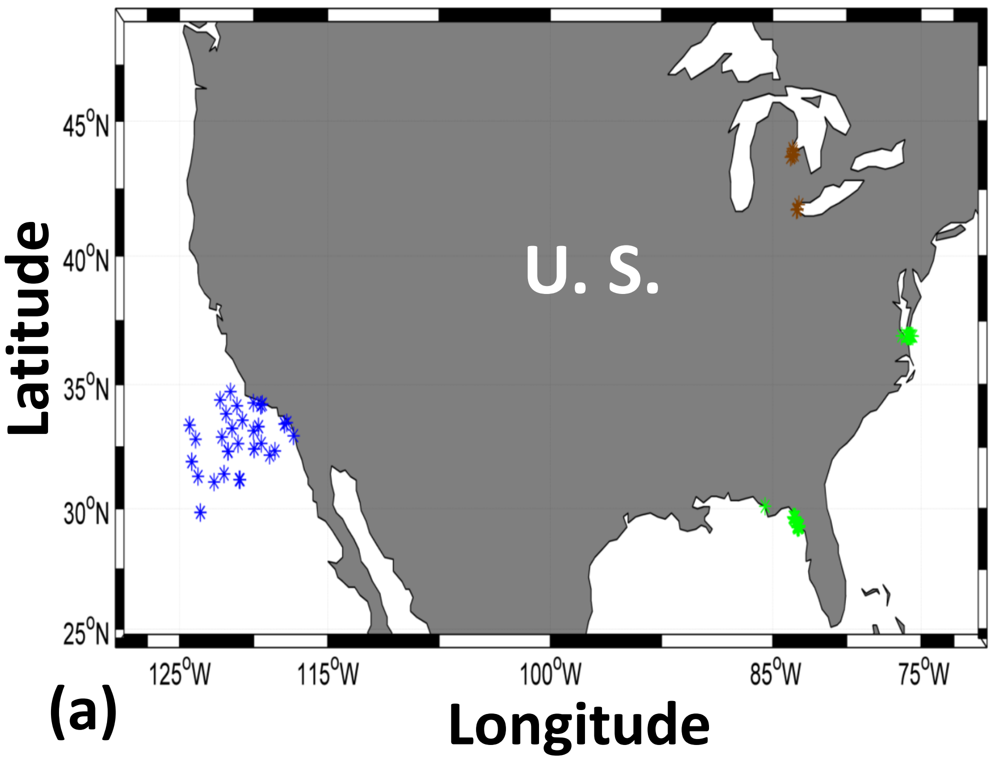
$$Z_{SD} = \frac{1}{K_d^{tr} + K_L^{tr}} \ln\left(\frac{1}{C_t^r} \left(r_T - r_w^{tr} \right) \right)$$

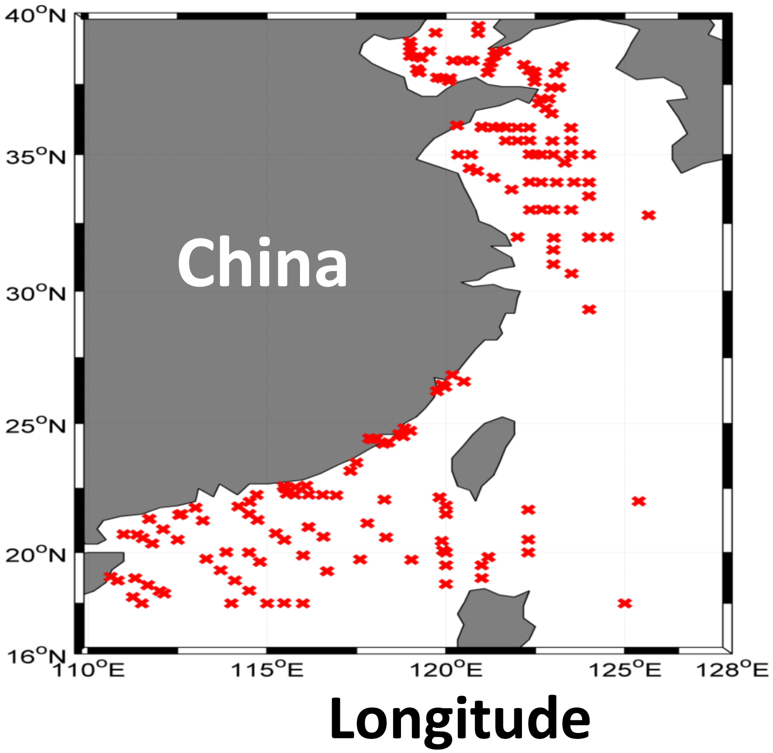
$$Z_{SD} \approx \frac{1}{K_d^{tr}} \approx \frac{1.4}{K_{PAR}}$$

R_{rs} → $a\&b_b$ → K_d → Z_{SD}

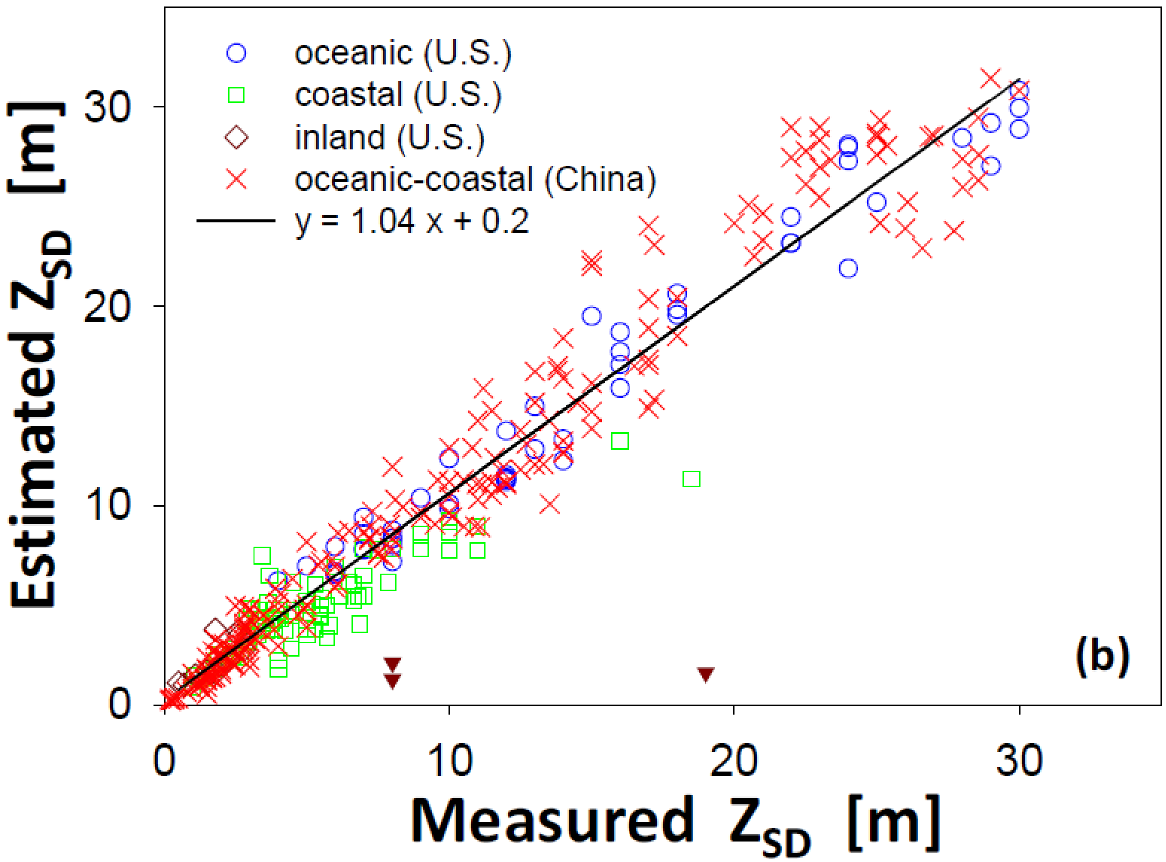
(Lee et al 2015)

Verification of the new Secchi disk theory



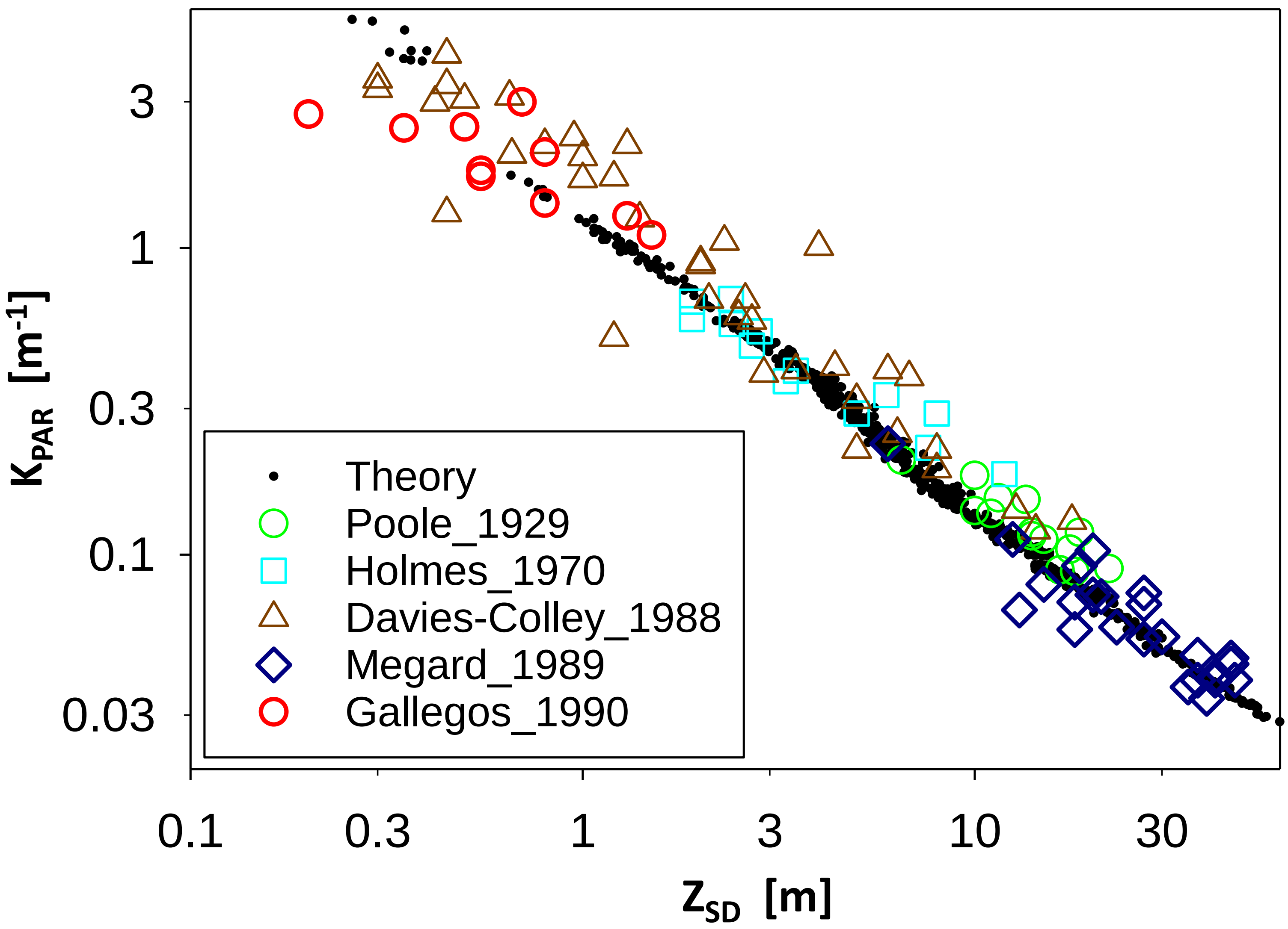


Verification of the new Secchi disk theory



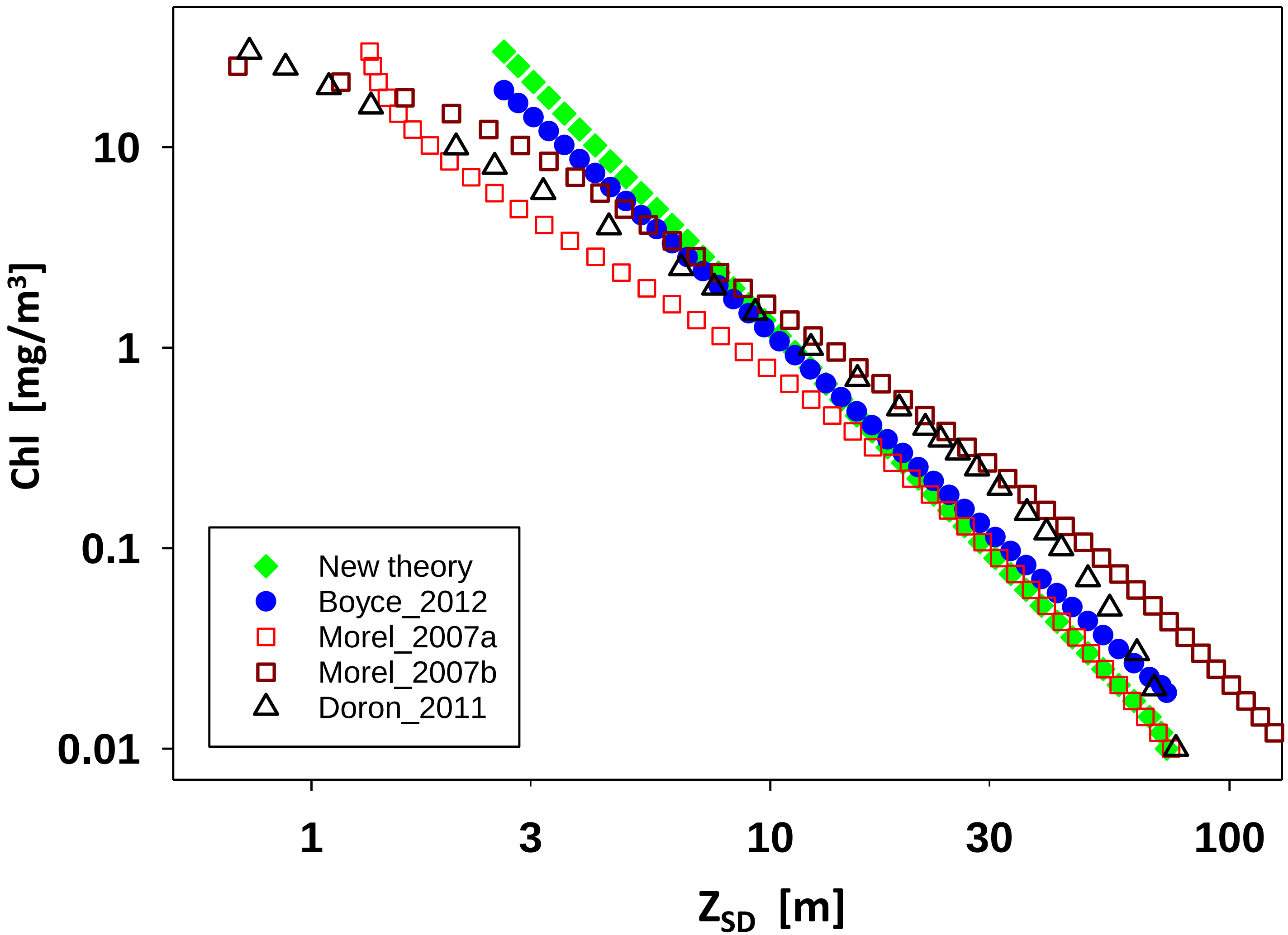
(Lee et al 2015)

With K_d^{tr} as the minimum K_d among 410, 440, 490, 530, and 550 nm



(Lee et al 2018)

Z_{SD} vs Chl for “Case-1” waters



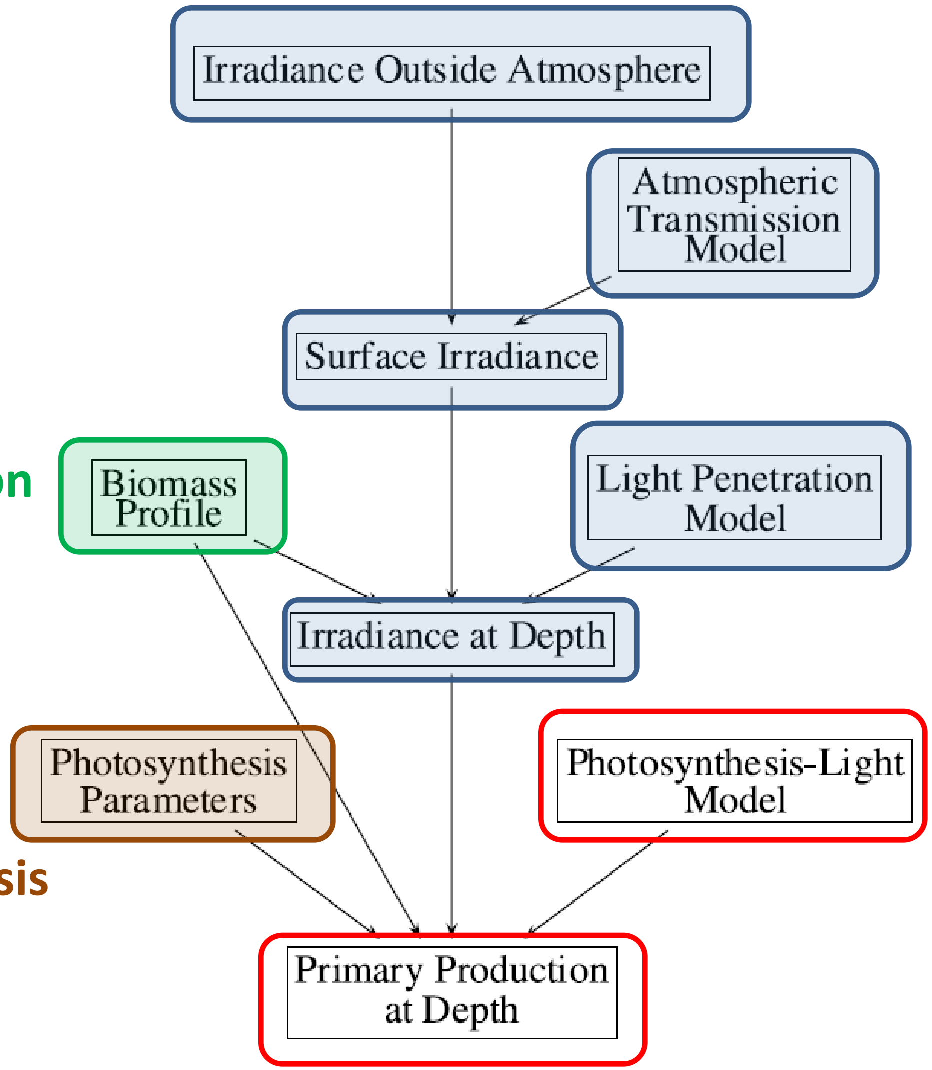
(Lee et al 2018)

4. Estimation of primary production

"One of the principal applications of satellite ocean color data is to derive net **primary production** (NPP)." --- McClain (Annu. Rev. Mar. Sci., 2009)

"On a global scale, marine phytoplankton consume fifty thousand million tones of carbon every year in a process referred to as **primary production." -- IOCCG Report #2**

Components for PP estimation:



1. Phytoplankton

2. Light at depth

3. Photosynthesis parameters

(from Platt and Sathyendranath)

Traditionally Chl is used to represent phytoplankton

I. Wavelength-resolved models (WRMs)

$$\sum PP = \int_{\lambda=400}^{700} \int_{t=\text{sunrise}}^{\text{sunset}} \int_{z=0}^{Z_{eu}} \Phi(\lambda, t, z) \times \mathrm{PAR}(\lambda, t, z) \times a^*(\lambda, z) \times \underline{\mathrm{Chl}(z)}\, d\lambda\, dt\, dz - R$$

II. Wavelength-integrated models (WIMs)

$$\sum PP = \int_{t=\text{sunrise}}^{\text{sunset}} \int_{z=0}^{Z_{eu}} \varphi(t, z) \times \mathrm{PAR}(t, z) \times \underline{\mathrm{Chl}(z)}\, dt\, dz - R$$

II. Time-integrated models (TIMs)

$$\sum PP = \int_{z=0}^{Z_{eu}} P^b(z) \times \mathrm{PAR}(z) \times DL \times \underline{\mathrm{Chl}(z)}\, dz$$

IV. Depth-integrated models (DIMs)

$$\sum PP = P^b_{opt} \times f[\mathrm{PAR}(0)] \times DL \times \underline{\mathrm{Chl}} \times Z_{eu}$$

(Behrenfeld and Falkowski, 1997)

I. Wavelength-resolved models (WRMs)

$$\sum PP = \int_{\lambda=400}^{700} \int_{t=\text{sunrise}}^{\text{sunset}} \int_{z=0}^{Z_{eu}} \Phi(\lambda, t, z) \times \text{PAR}(\lambda, t, z) \times a^*(\lambda, z) \times \text{Chl}(z)\, d\lambda\, dt\, dz - R$$

Quantum yield of photosynthesis

$$a^*(\lambda) = \frac{a_{ph}(\lambda)}{Chl}$$

a_{ph}: Absorption coefficient of phytoplankton

II. Wavelength-integrated models (WIMs)

$$\sum PP = \int_{t=\text{sunrise}}^{\text{sunset}} \int_{z=0}^{Z_{eu}} \varphi(t, z) \times \text{PAR}(t, z) \times \text{Chl}(z)\, dt\, dz - R$$

Centered on Chl

I. Wavelength-resolved models (WRMs)

$$\sum PP = \int_{\lambda=400}^{700} \int_{t=\text{sunrise}}^{\text{sunset}} \int_{z=0}^{Z_{eu}} \Phi(\lambda, t, z) \times \text{PAR}(\lambda, t, z) \times a^*(\lambda, z) \times \text{Chl}(z)\, d\lambda\, dt\, dz - R$$

$$\sum PP = \int \int \phi(\lambda, t, z) \times PAR(\lambda, t, z) \times a_{ph}(\lambda, z) d\lambda dt - R$$

Centered on a_{ph}

$$\sum PP = \int_{t=\text{sunrise}}^{\text{sunset}} \int_{z=0}^{Z_{eu}} \varphi(t, z) \times \mathrm{PAR}(t, z) \times \mathrm{Chl}(z)\, \mathrm{d}t\, \mathrm{d}z$$

$$\sum PP = \int \int \phi(\lambda, t, z) \times PAR(\lambda, t, z) \times a_{ph}(\lambda, z) d\lambda dt$$

Contrast in mathematics and physics of the two approaches:

φ vs ϕ:

φ involves both ϕ and a^*.

Chl vs a_{ph}:

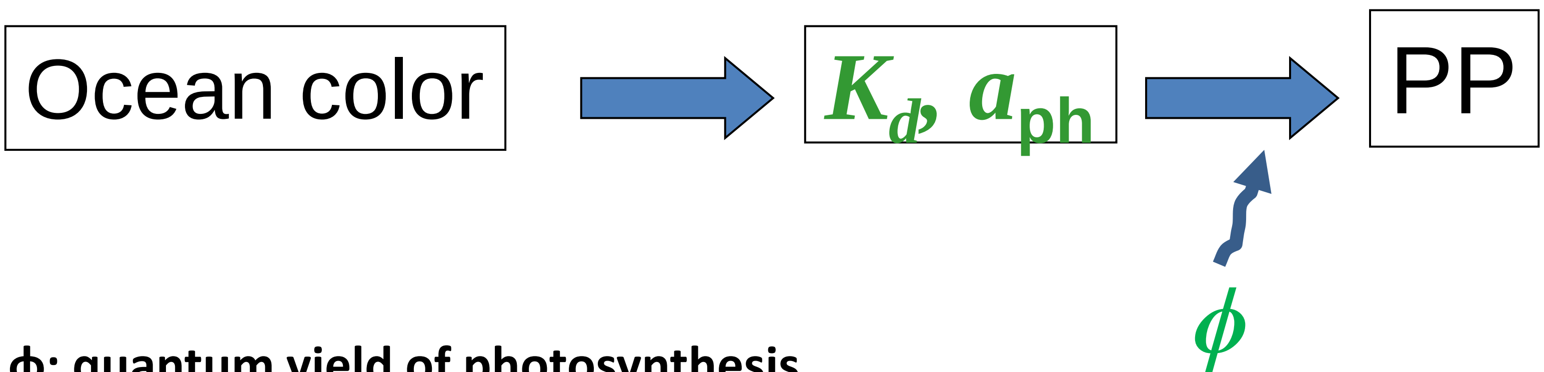
Chl is a biological property; could not be directly obtained from OC remote sensing.

a_{ph} is an optical property; ocean color measures optical property.

Absorption based model for PP

$$PP(z) = \iint \phi \times E_0(\lambda, t, z) \times a_{ph}(\lambda, z)\, d\lambda\, dt$$

A more direct representation of photosynthesis.

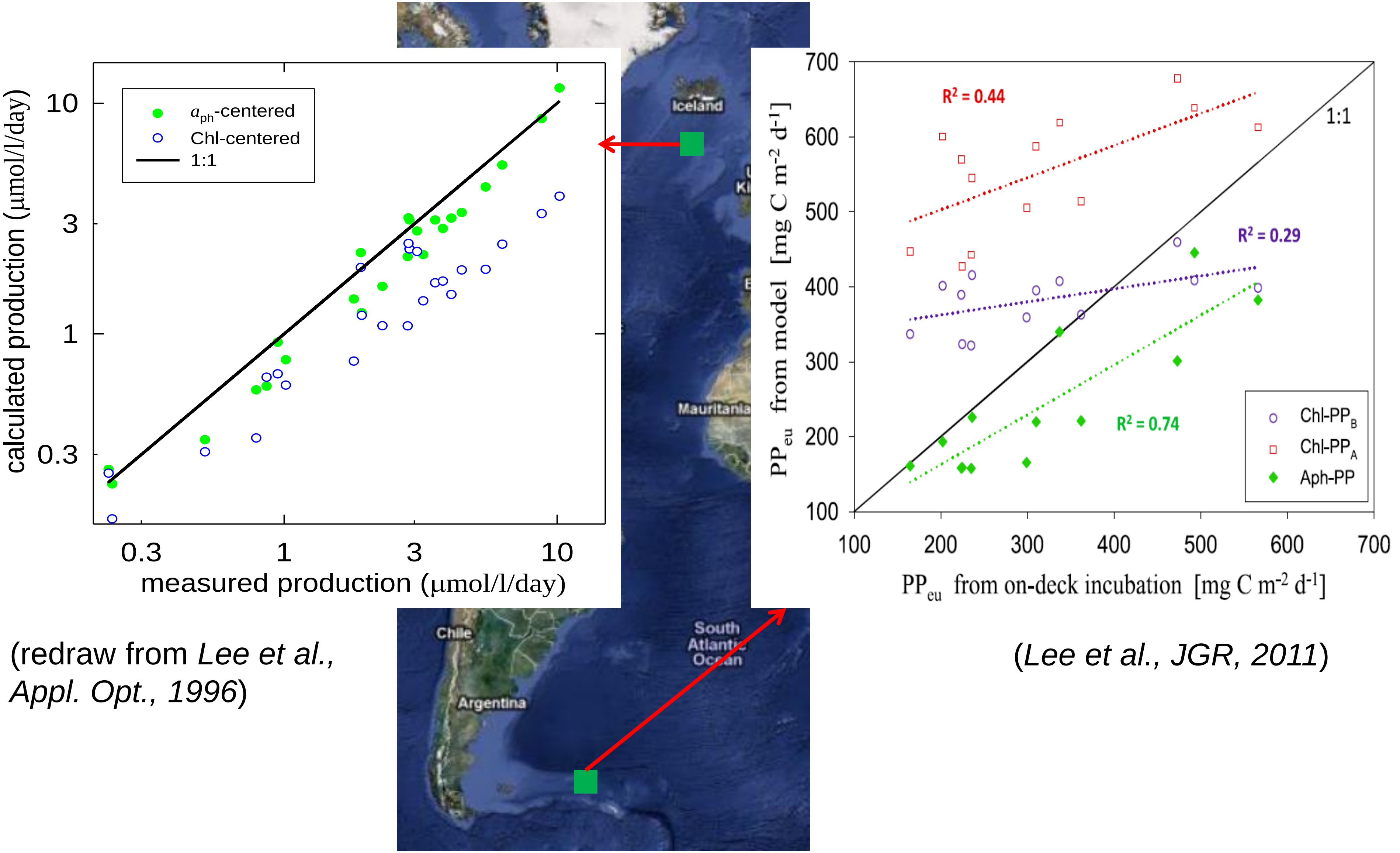


ϕ: quantum yield of photosynthesis

$$\phi(E_o) = \frac{\phi_m K_\phi}{K_\phi + E_o} \qquad (2)$$

(Kiefer and Mitchell, 1983, L&O)

Remotely-estimated PP compared with measured PP

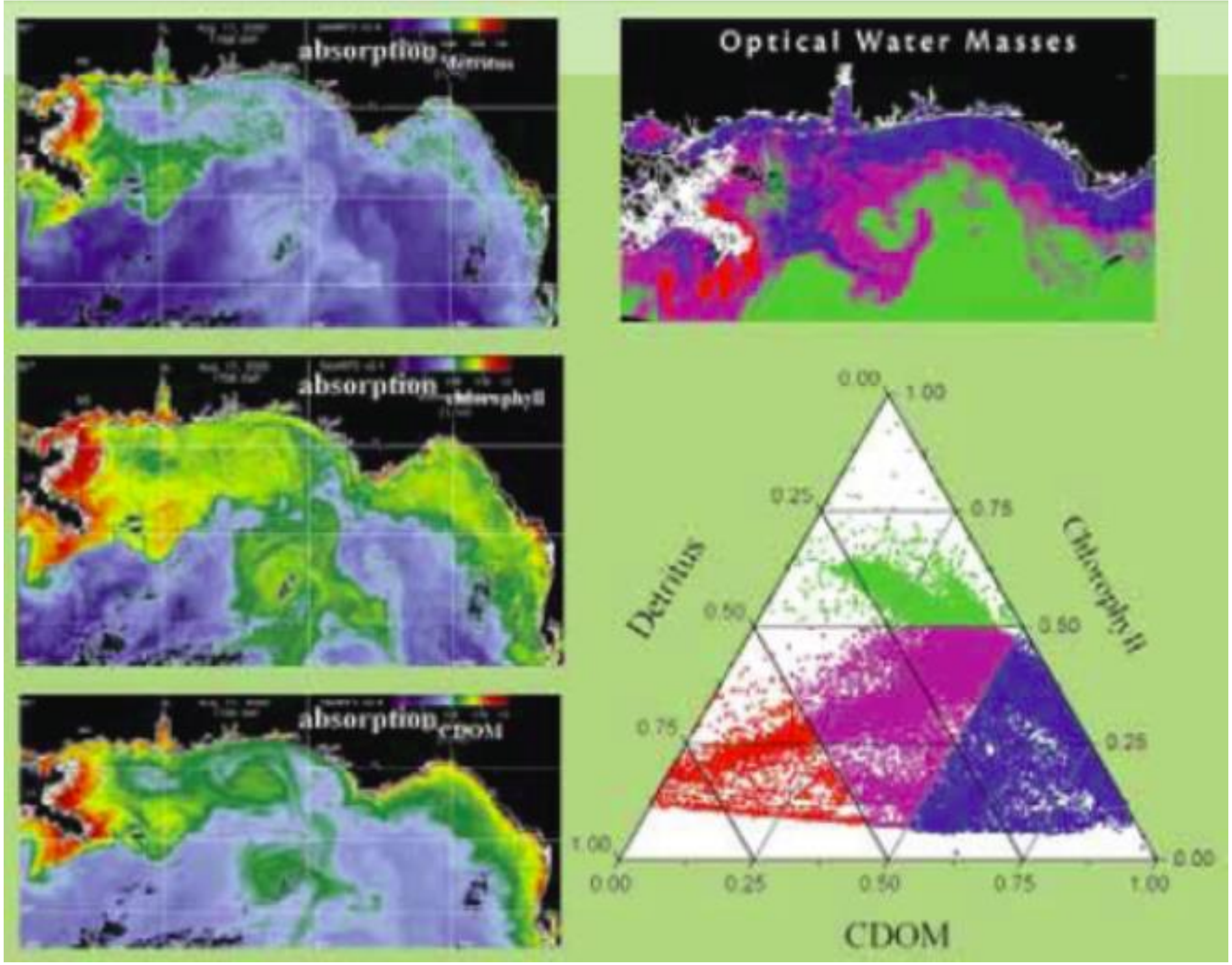


(redraw from *Lee et al., Appl. Opt., 1996*)

(*Lee et al., JGR, 2011*)

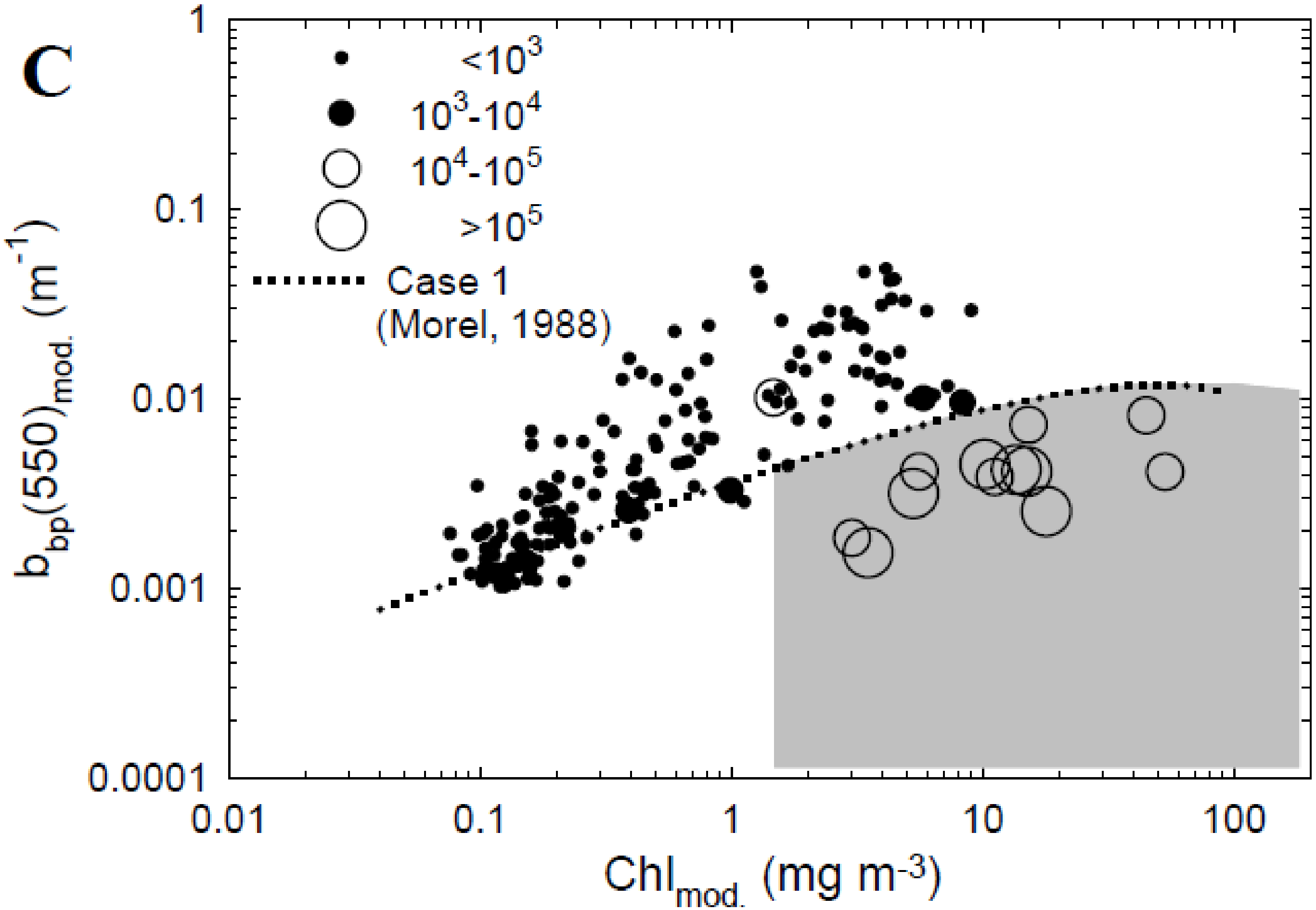
5. A few other examples

5a. Water mass classification



(Arnone et al 2004)

5b. HAB identification-1

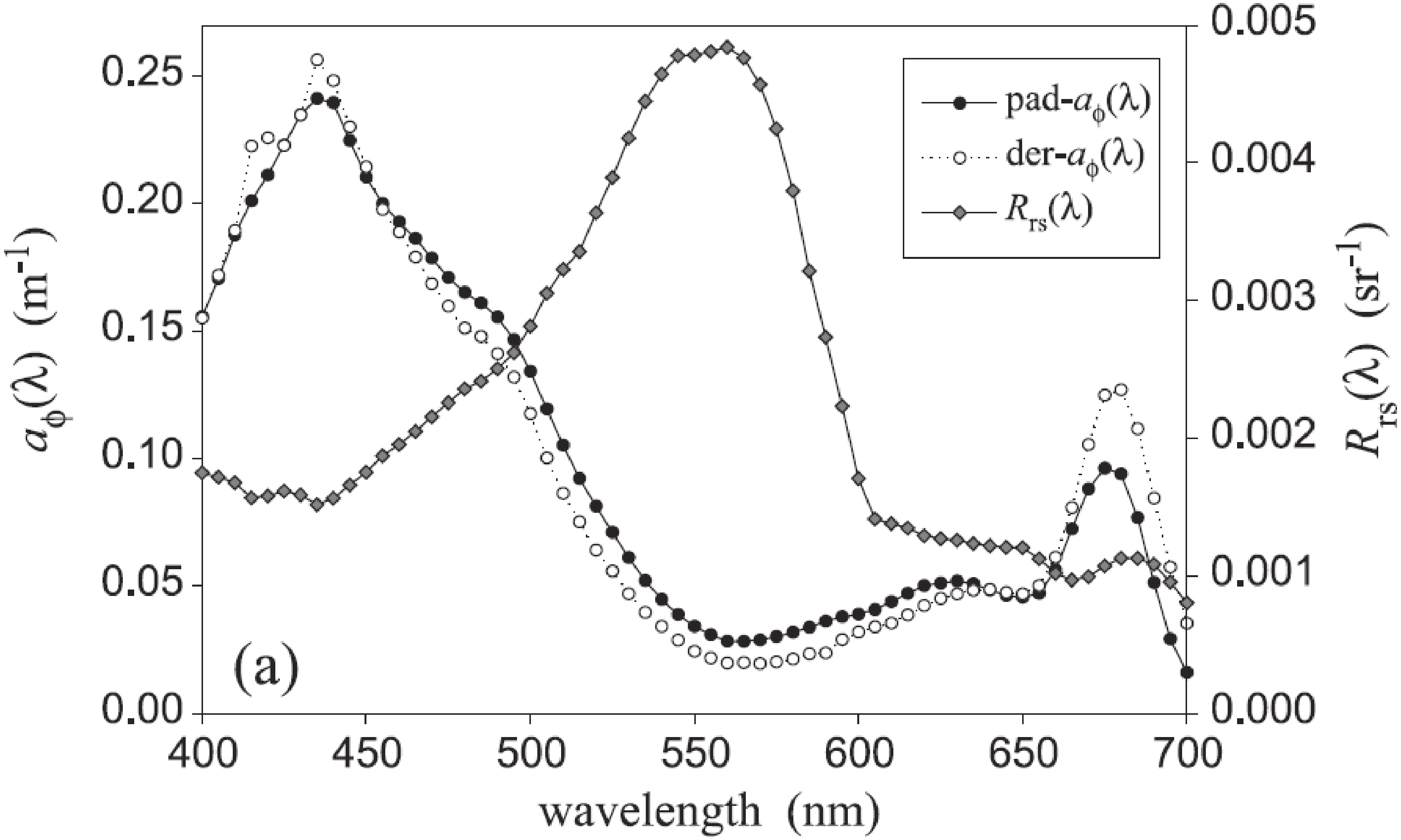


(Carnizzaro et al 2008)

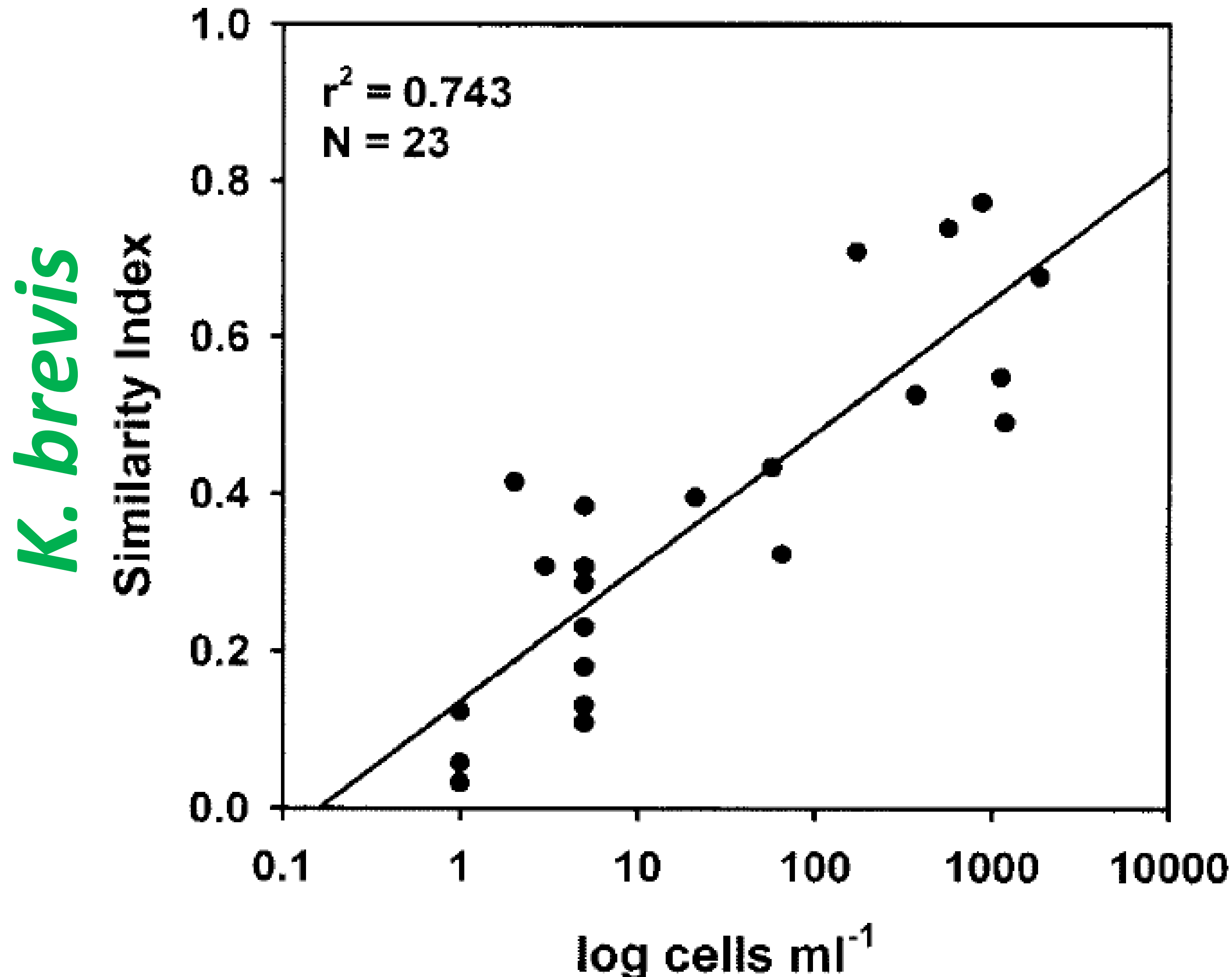
5c. HAB identification-2

QAA

$$R_{rs}(\lambda) \rightarrow a_{ph}(\lambda) = a(\lambda) - a_{dg}(\lambda) - a_w(\lambda)$$



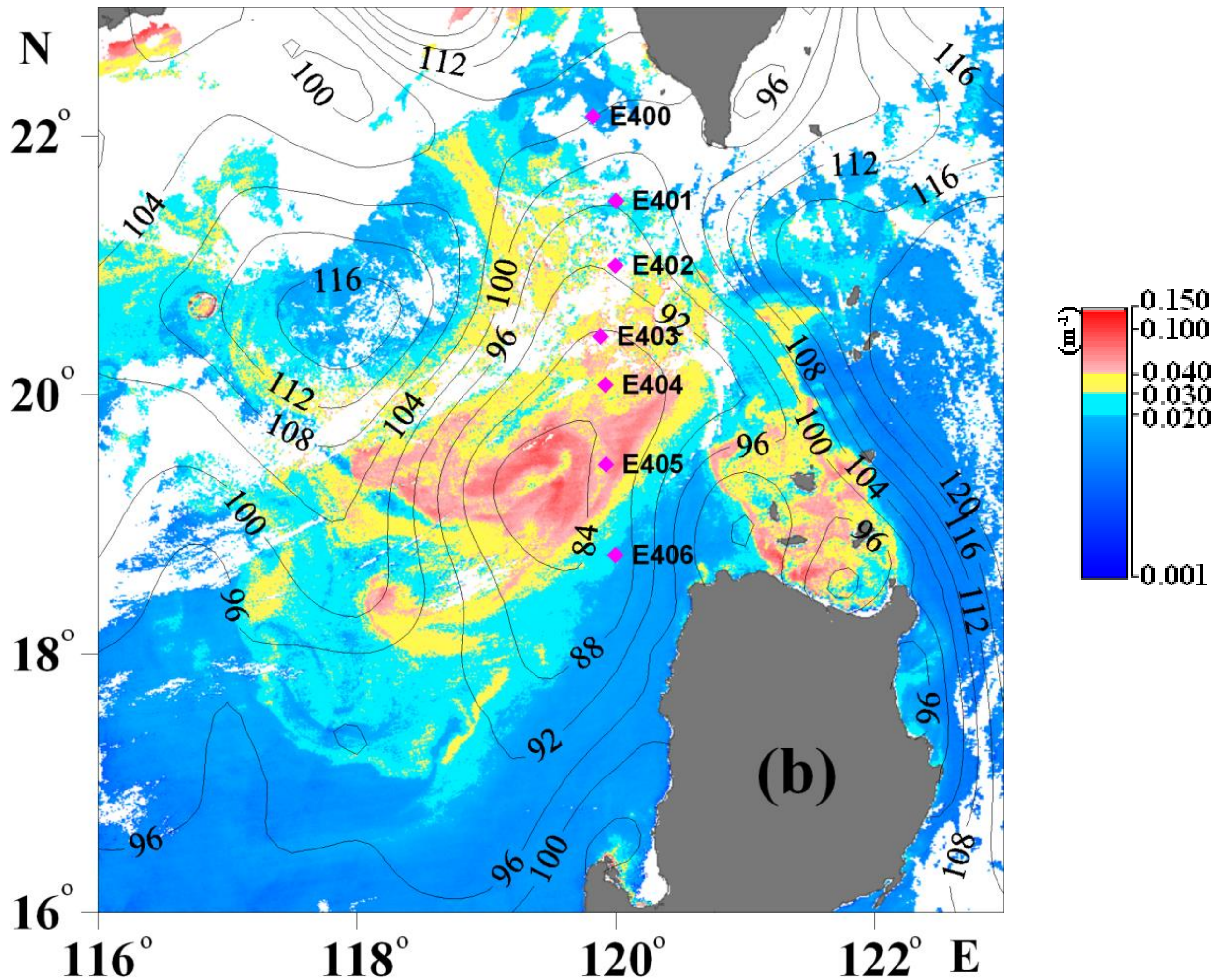
(Lee and Carder 2004)



(Craig et al 2006)

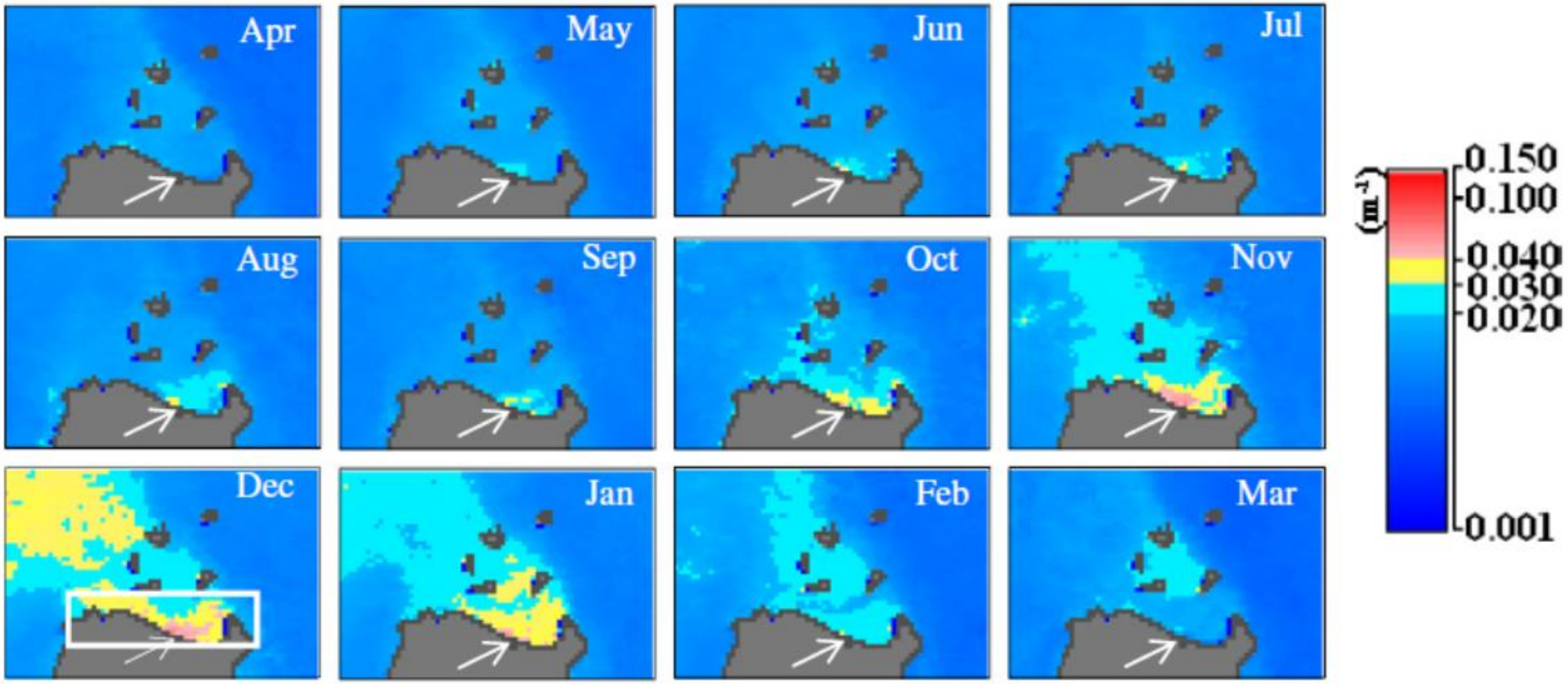
5d. Bloom dynamics

Distribution of a_{ph}(440) at Luzon Street



(Shang et al, 2012)

Monthly distribution of a_{ph}(440) at Luzon Street



(Shang et al, 2012)

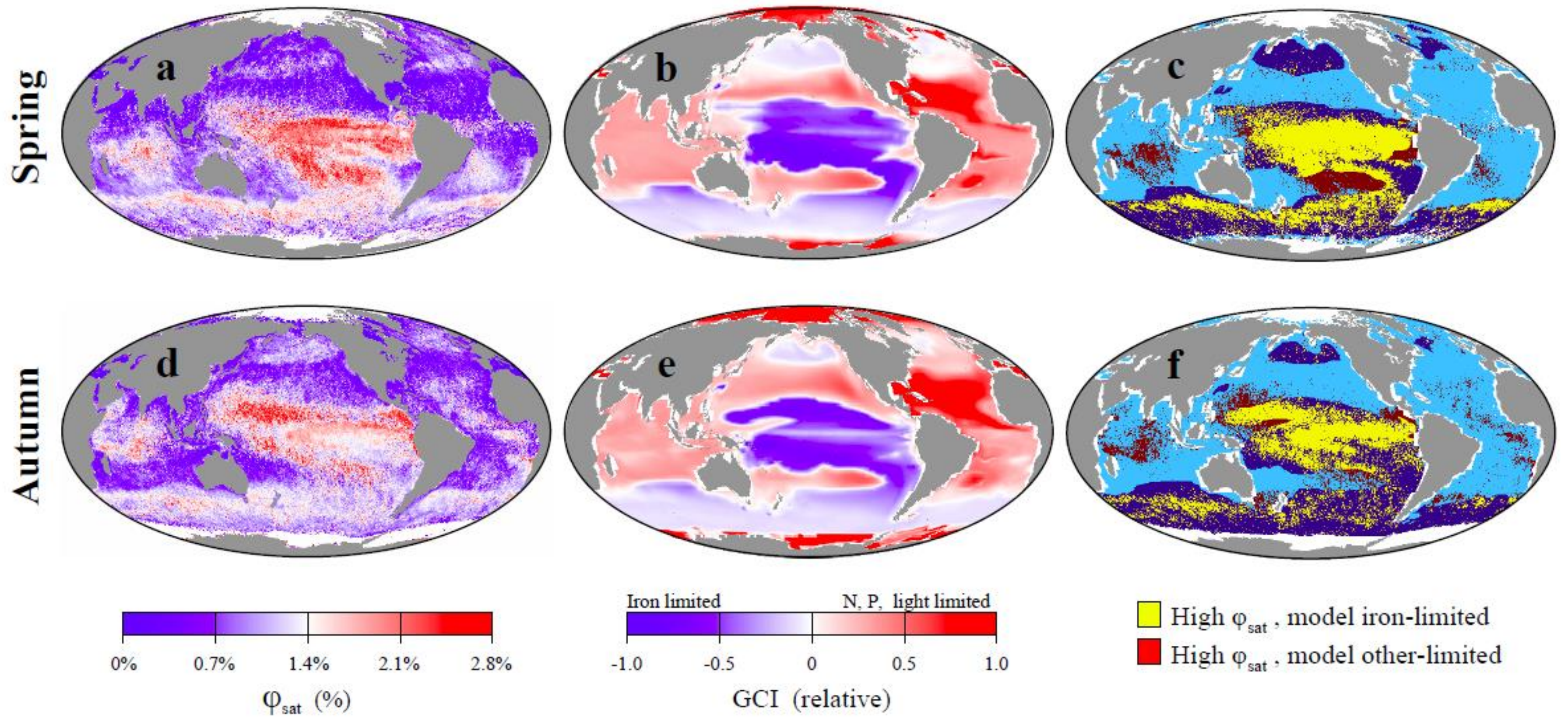
5e. Global physiology of ocean phytoplankton

IOP

$$F_{sat} = Chl_{sat} \times \langle a^*_{ph} \rangle \times \phi \times S, \quad (2)$$

ϕ: quantum yield of fluorescence

(Behrenfeld et al 2009)



(Behrenfeld et al 2009)

5f. Salinity estimation

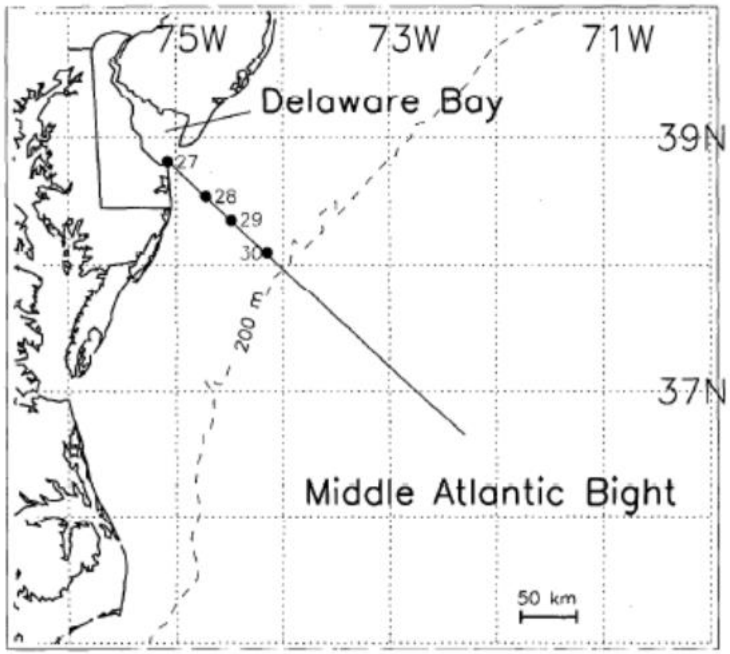
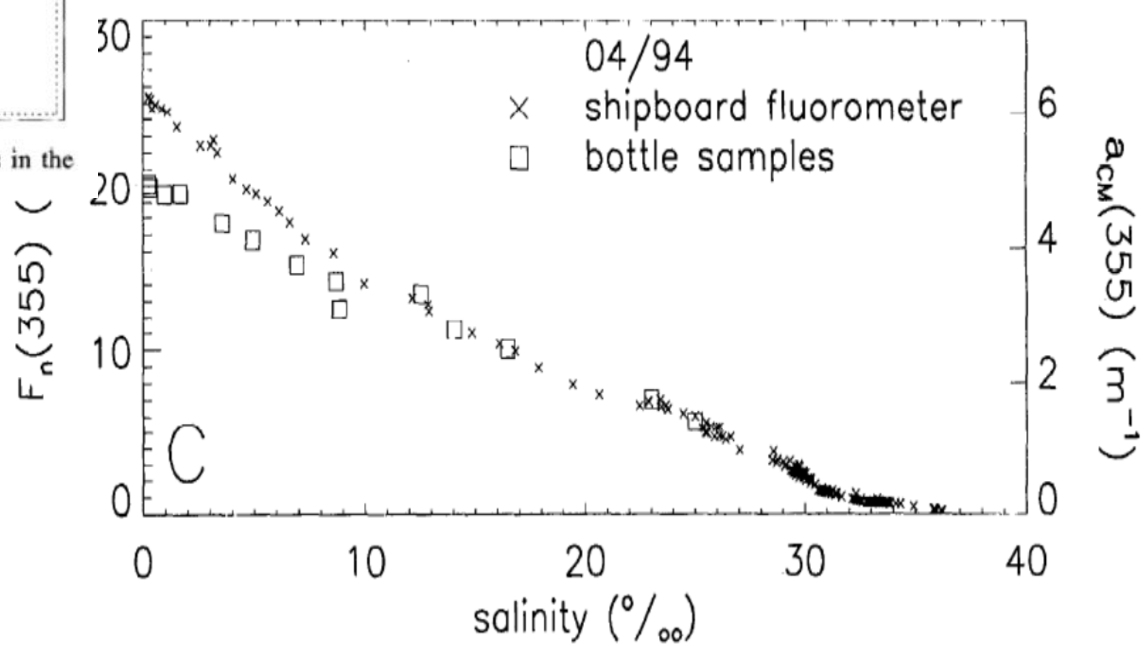
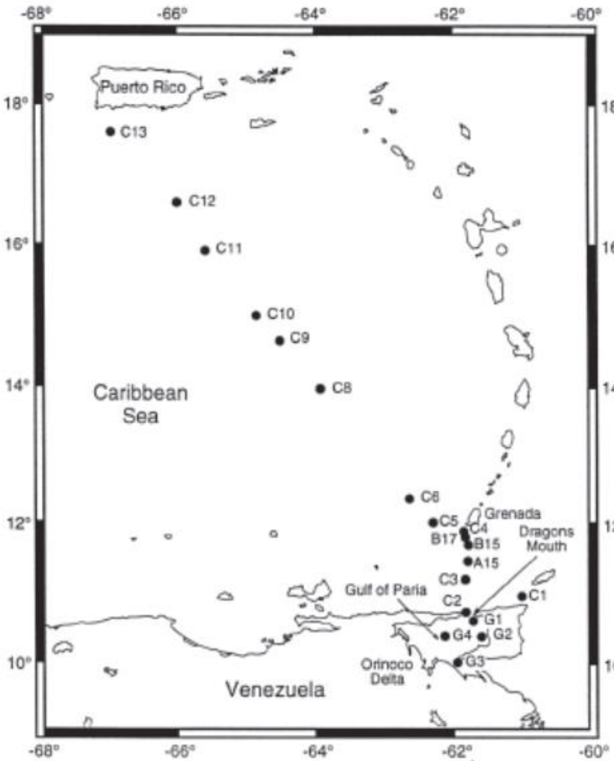
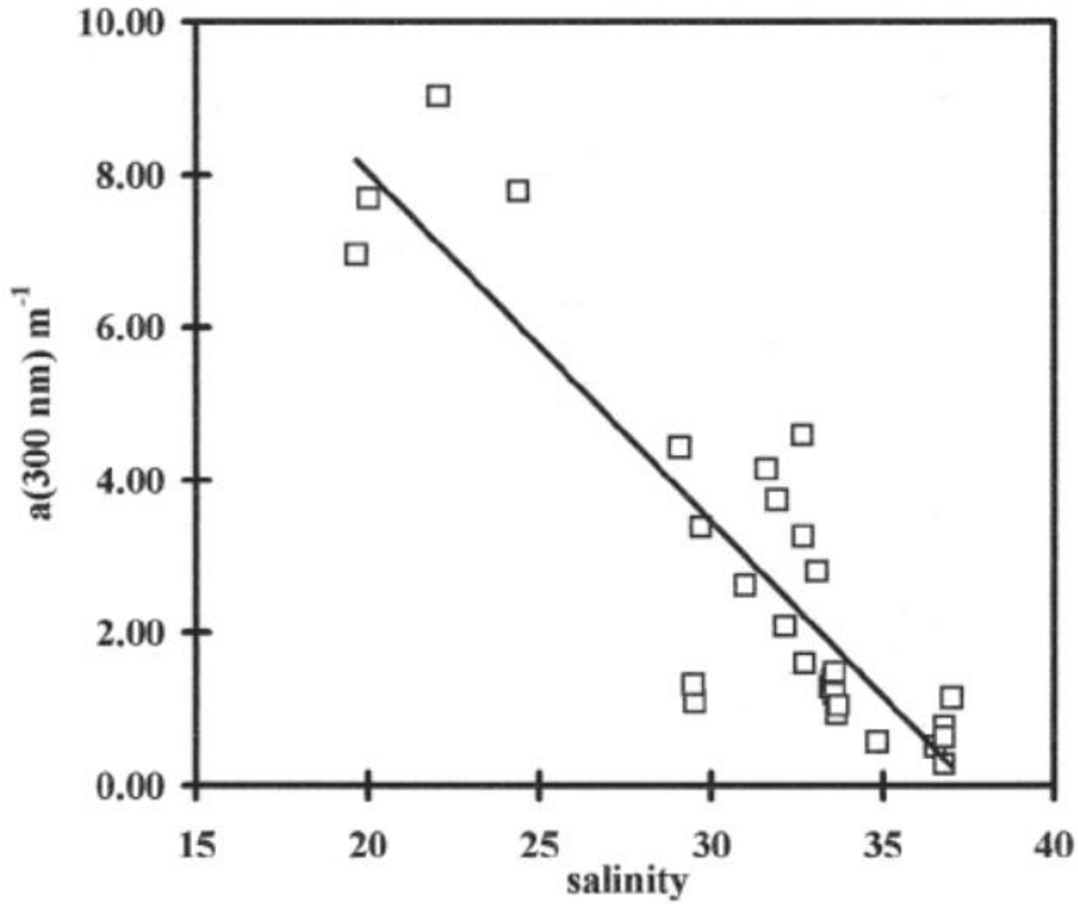


Fig. 1. Locations of the transect and hydrocast stations in the Middle Atlantic Bight.



(Vodacek et al 1997)

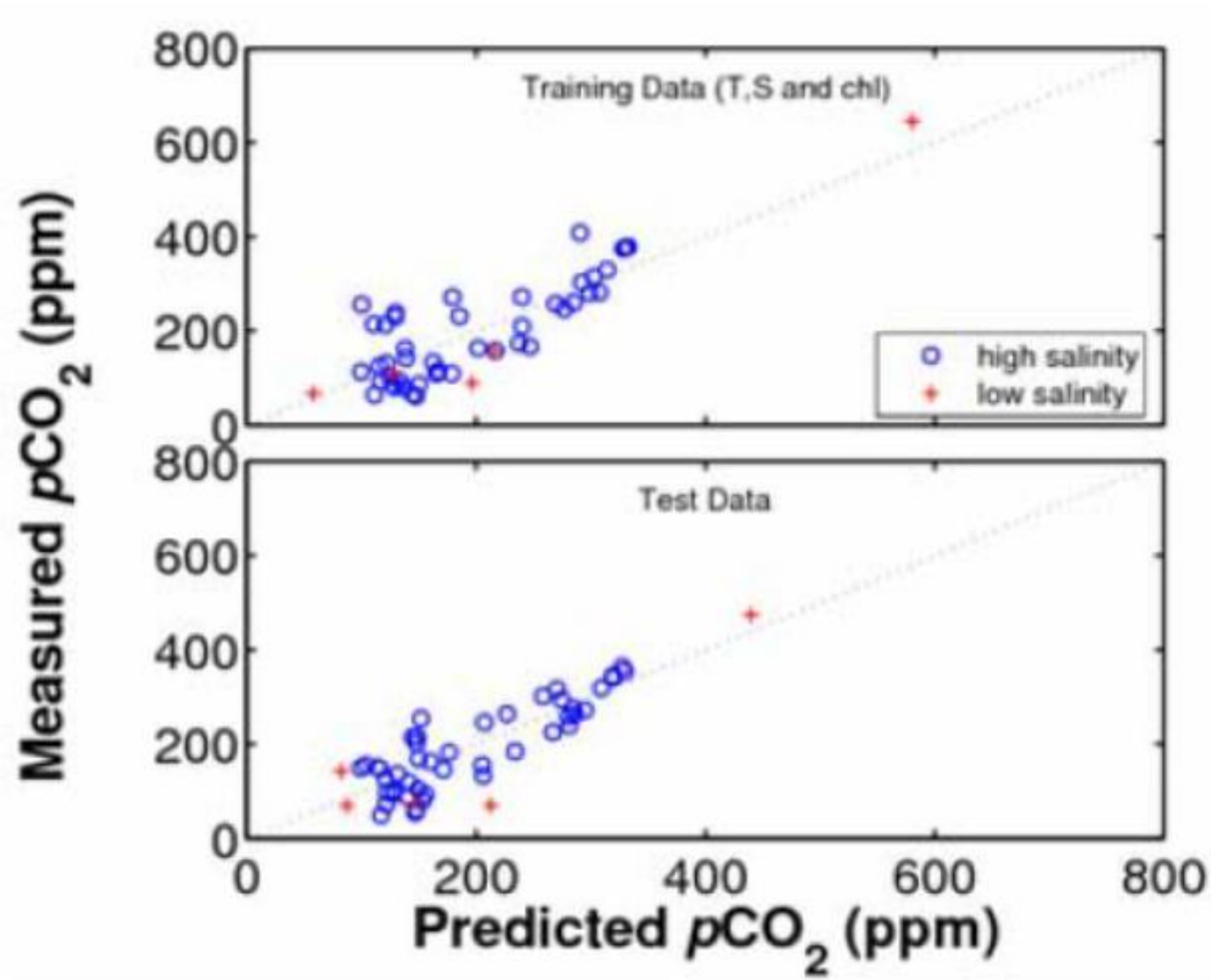




$$\mathrm{SSS} = x\, a_{\mathrm{CDOM}} + y$$

(Castellio et al 1999)

5g. pCO2 estimation



Lohrenz and Cai (2006)

pCO2 = f(T, S, Chl)

Key Points:

1. Many applications traditionally built around remotely-sensed [Chl] can be built around remotely-sensed IOPs, and no need to limit to "Case-1" waters.

2. Remote sensing and applications centered around IOPs avoided, when necessary, concentration-normalized optical properties.

3. With IOPs as the inputs, many products, e.g. K_d, Z_{eu}, Z_{SD}, could be estimated semi-analytically and more accurately.

4. When IOPs are known, many other applications could be carried out. Be creative.

Thank you!

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