



Inherent Optical Properties (IOPs)

Lecture 3: Applications

$R_{rs}(\lambda)$  **IOPs**


What to do with the retrieved IOPs?

→ Chlorophyll concentration: [Chl]

Examples: Carder et al (1999), GSM (2002), GIOP (2013)

$$R_{rs}(\lambda) = F(a(\lambda), b_b(\lambda))$$

$$a(\lambda) = a_w(\lambda) + M_1 \langle a_{ph}(\lambda) \rangle + M_2 \langle a_{dg}(\lambda) \rangle$$


$$a_{ph}(\lambda)$$

$\langle a_{ph}(\lambda) \rangle$: **Varies with temperature in Carder et al (1999);**
Fixed globally in GSM (Maritorena et al 2002)
Varies with [Chl] in GIOP (Werdell et al 2013)

Why chlorophyll concentration?

1. Estimate Primary Production (PP)

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

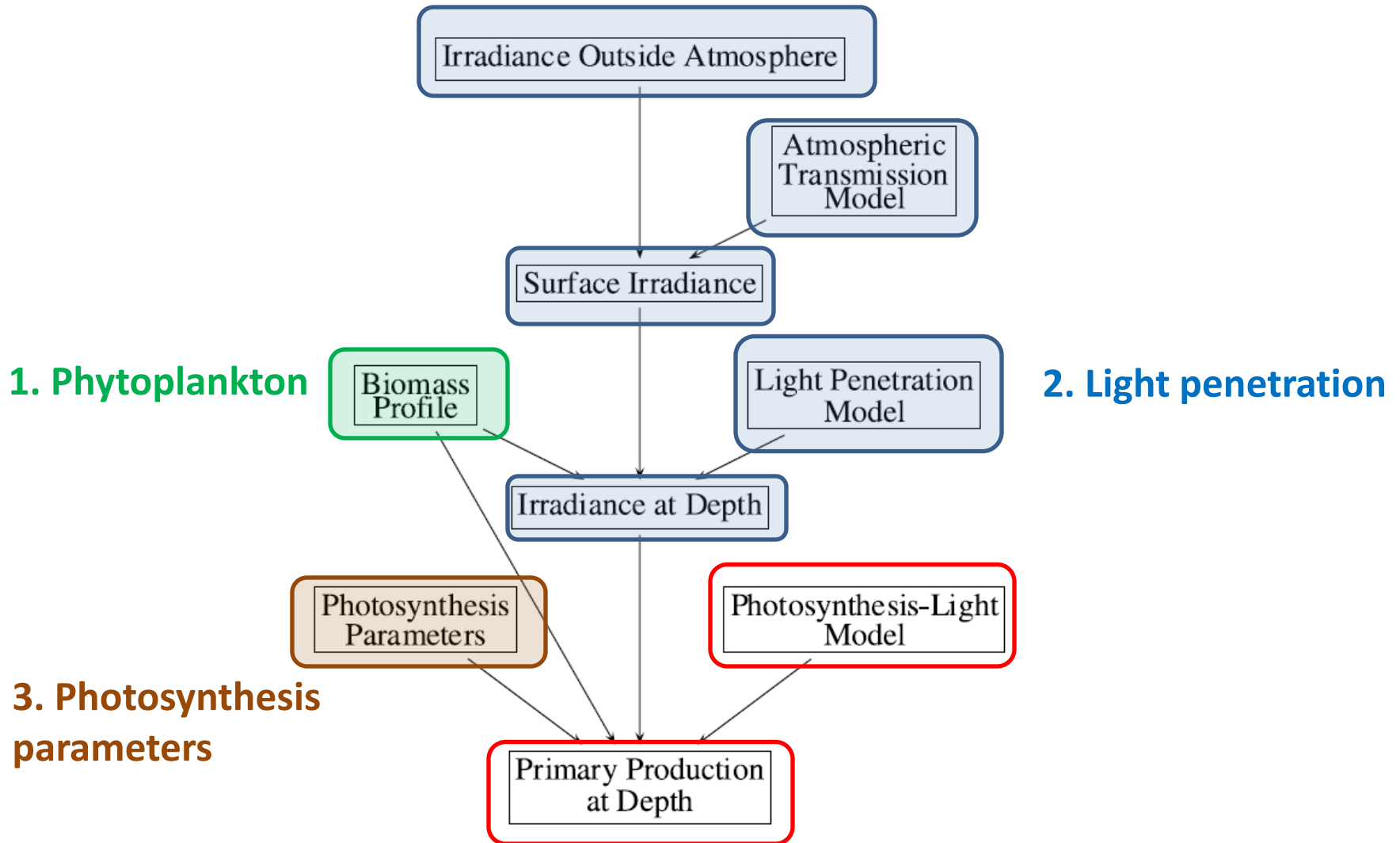
“On a global scale, marine phytoplankton consume fifty thousand million tones of carbon every year in a process referred to as **primary production.**” --
IOCCG Report #2

food chain; carbon cycle

Elements of photosynthesis:

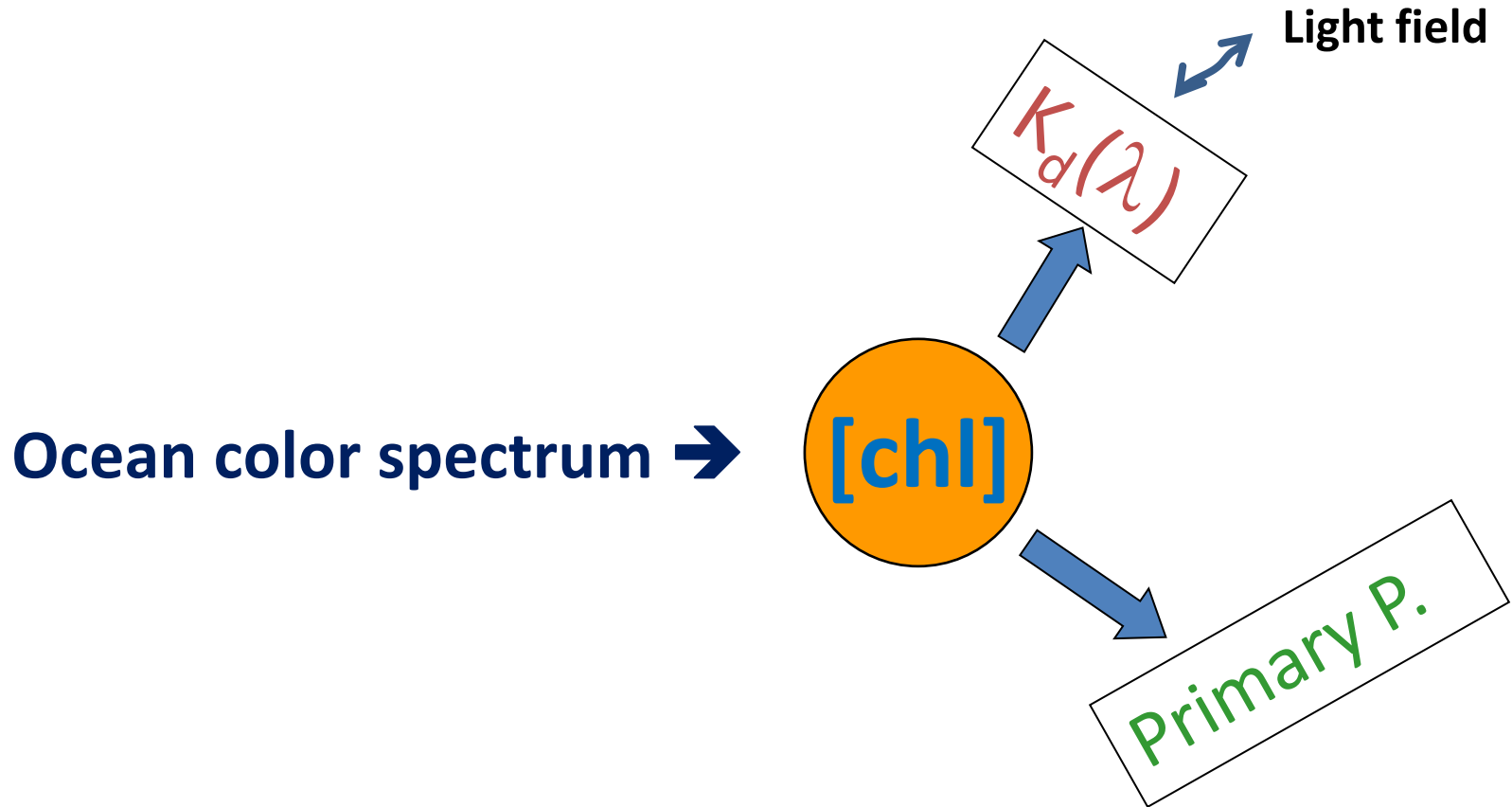
CO₂ + H₂O + phytoplankton + light + nutrient → chemical energy

Components for PP quantification:



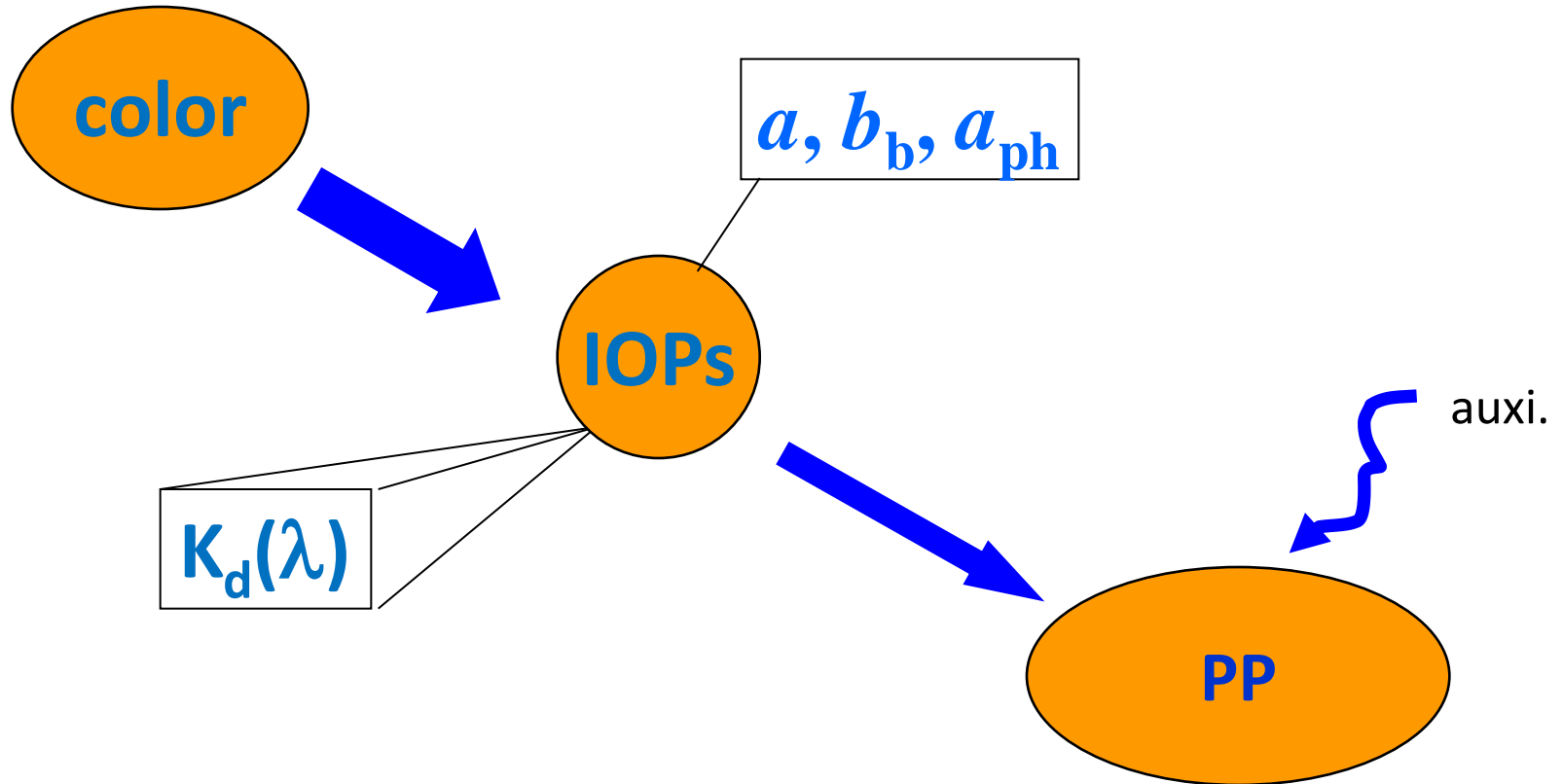
(Platt and Sathyendranath, 2007)

Traditional strategy: [chl] centered system



Works for waters where IOPs co-vary with [Chl].

IOP-based approach:



Works for most waters.

1.1 Estimation of diffuse attenuation coefficient (K_d) (for light field)

$$K_d(490) \propto \frac{Rrs(\lambda_1)}{Rrs(\lambda_2)}$$

Or,

$$K_d(\lambda) \propto Chl$$

$$K_d(490) = a_1 + a_2 X^{-a_3}$$

or

$$K_d(490) = b_1 X^{-b_2}$$

with

$$X = \frac{Lwn(488)}{Lwn(551)}$$

or

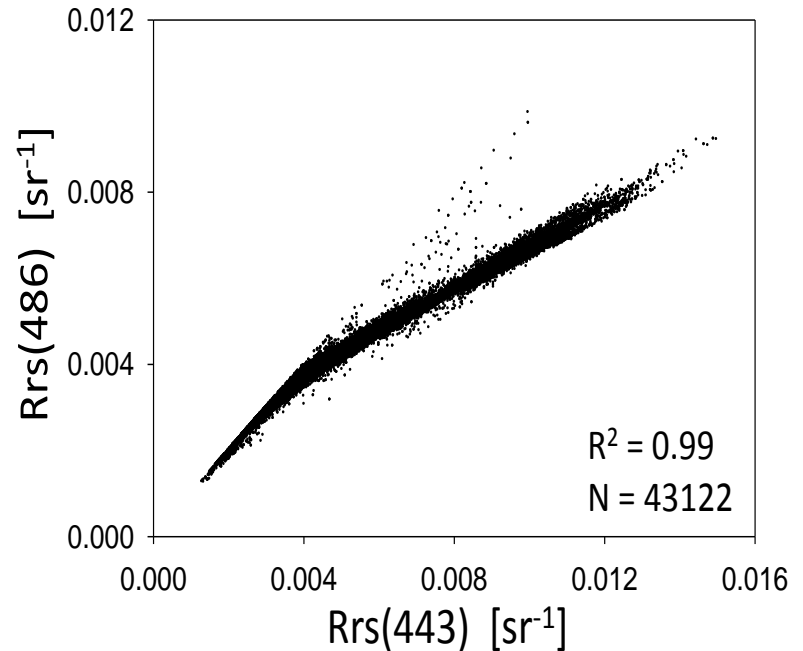
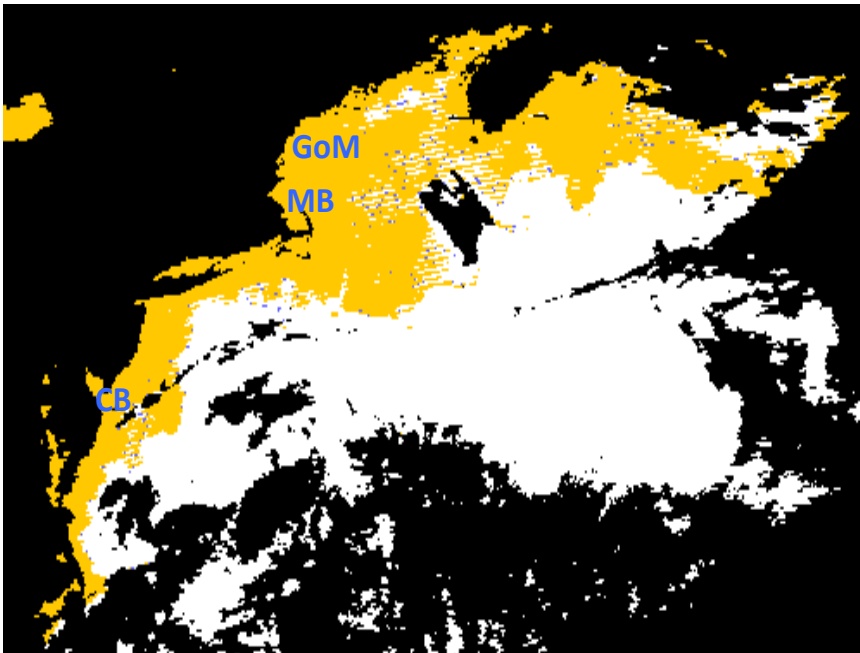
$$X = \frac{Rrs(488)}{Rrs(551)}$$

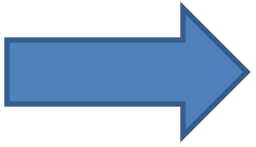
$$\log_{10}(K_{bio}(490)) = a_0 + \sum_{i=1}^4 a_i \log_{10} \left(\frac{R_{rs}(\lambda_{blue})}{R_{rs}(\lambda_{green})} \right)$$

$$Kd_{490} = K_{bio}(490) + 0.0166$$

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

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





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

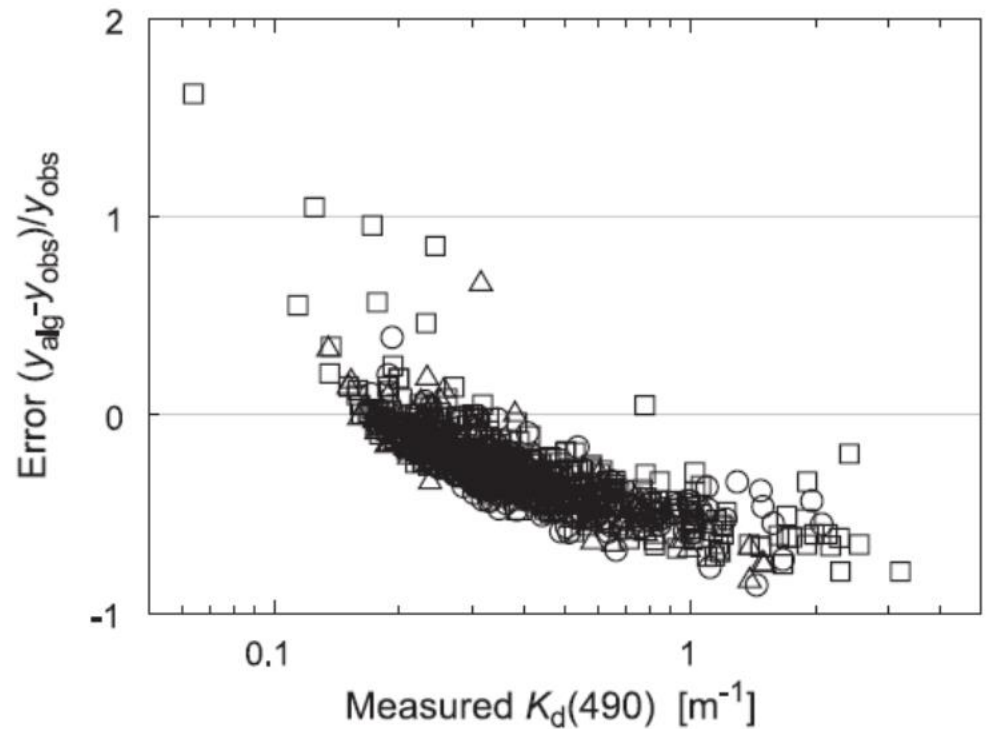
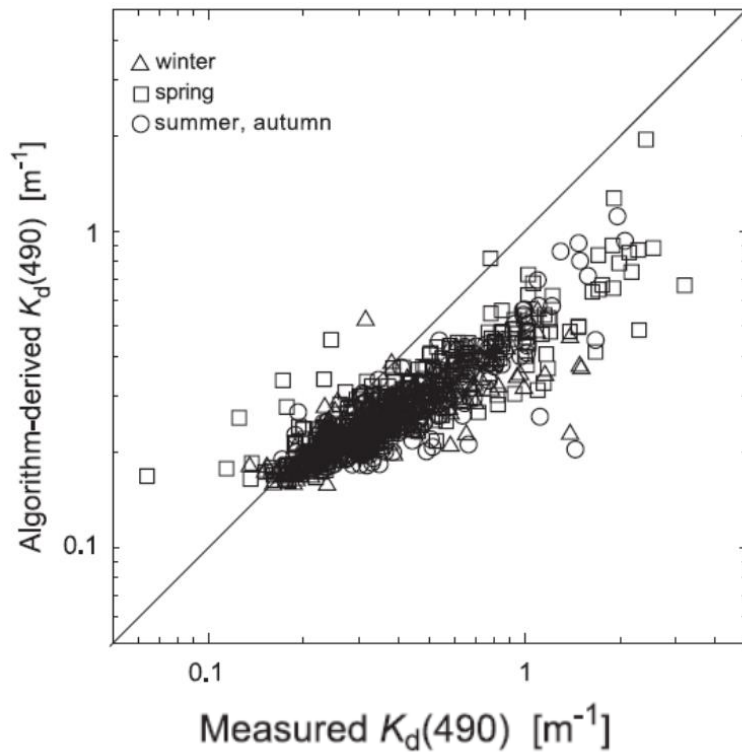
$$K_d(490) = Fun\left(\frac{R_{rs}(490)}{R_{rs}(555)}\right)$$

AOP: sun angle dependent

Nearly independent of sun angle

The two sides do **not** match in optical attributes.

In addition, ratio-derived K_d has large uncertainties



(Darecki and Stramisk, 2004)

Via radiative transfer equation:

$$K_d = m_0 a + v b_b$$

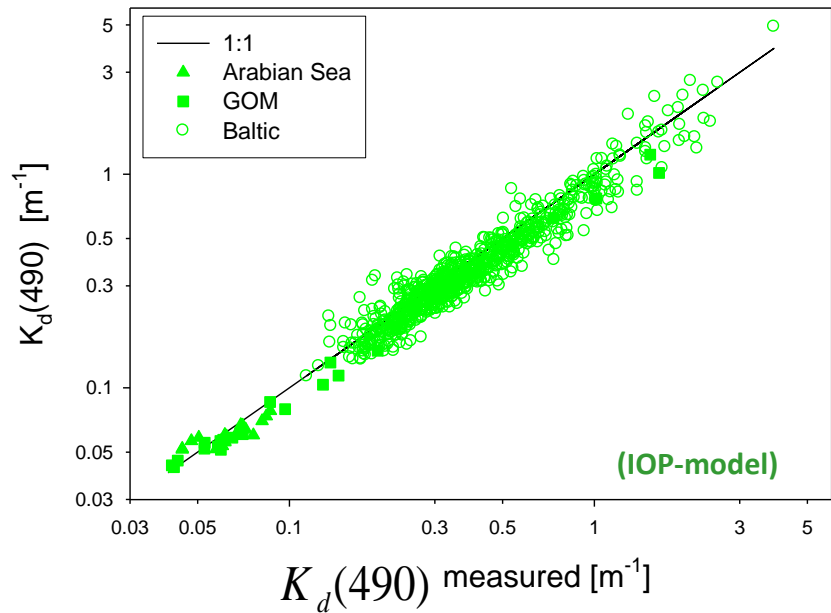
$$v = m_1 (1 - m_2 e^{-m_3 a})$$

(Lee et al. 2005, 2013)

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

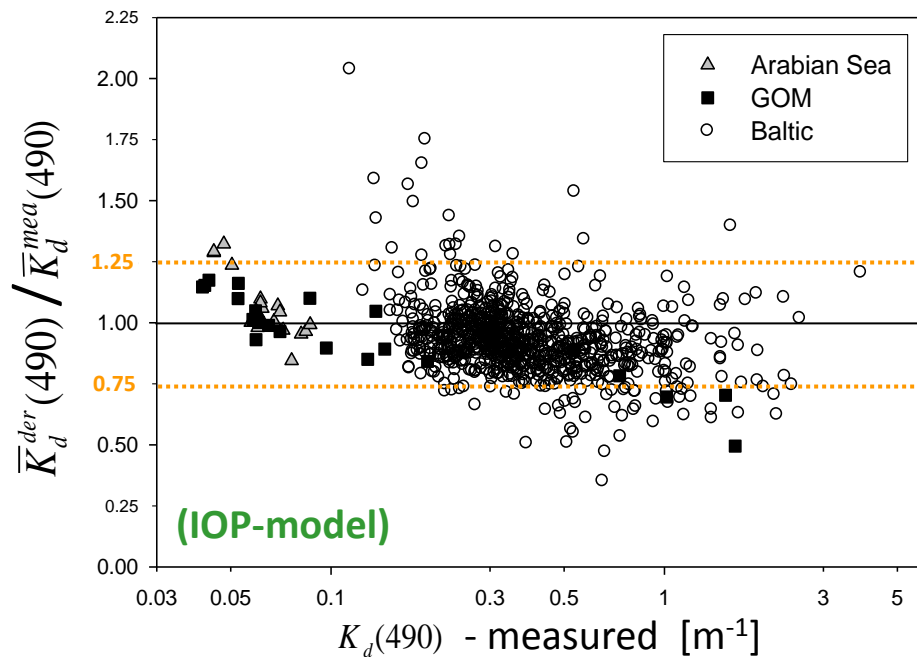


No division of “Case 1” or “Case 2” waters.

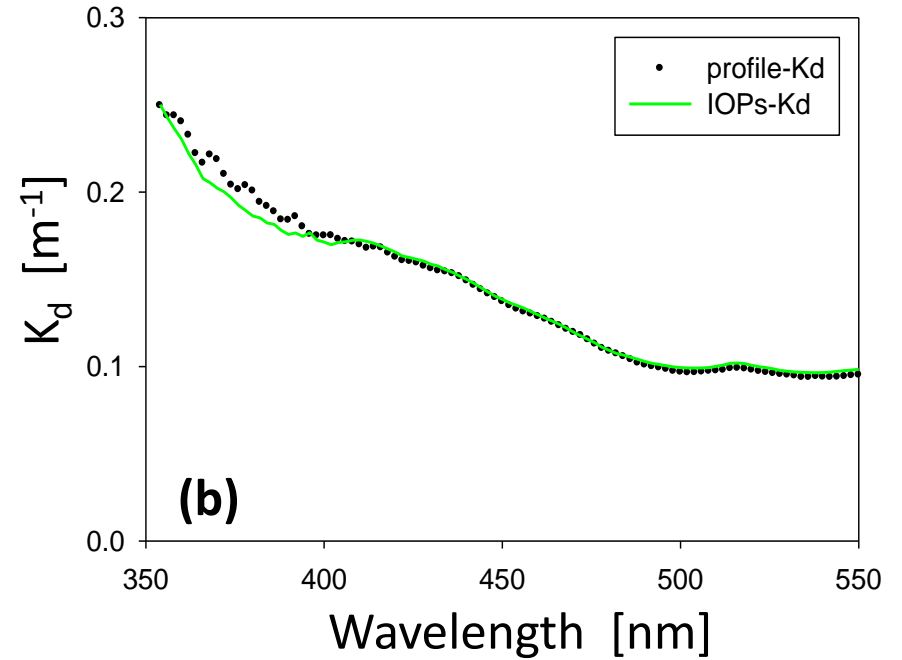
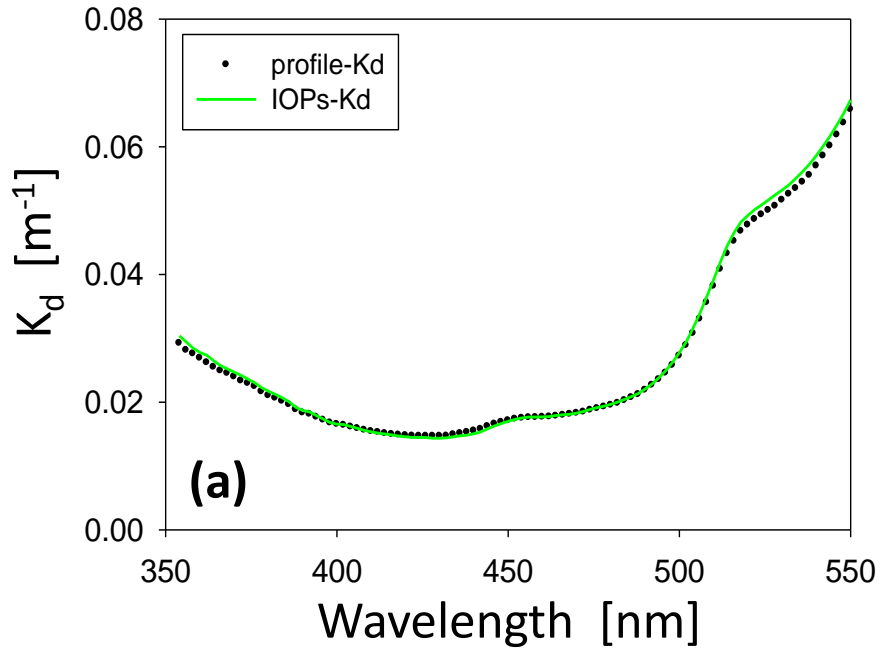


Oceanic & Coastal waters

(Lee et al. 2005)



Kd spectrum:



(Lee et al 2013)

1.2 Attenuation of PAR (K_{PAR}) and euphotic depth

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

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

Good for earlier days,
Not so 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

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

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)

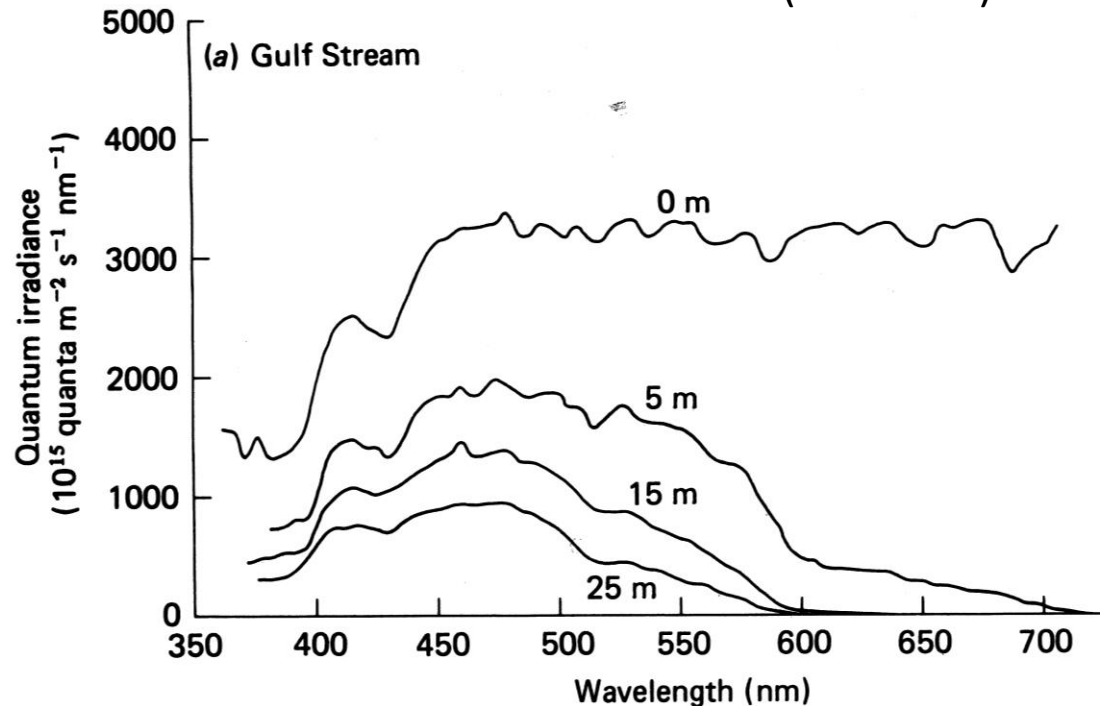
$$K_{PAR} = \frac{-1}{z} \ln \left(\frac{PAR(z)}{PAR(0)} \right)$$

$$PAR(z) = \int_{400}^{700} E_0(\lambda, 0) e^{-K(\lambda, z)z} d\lambda$$

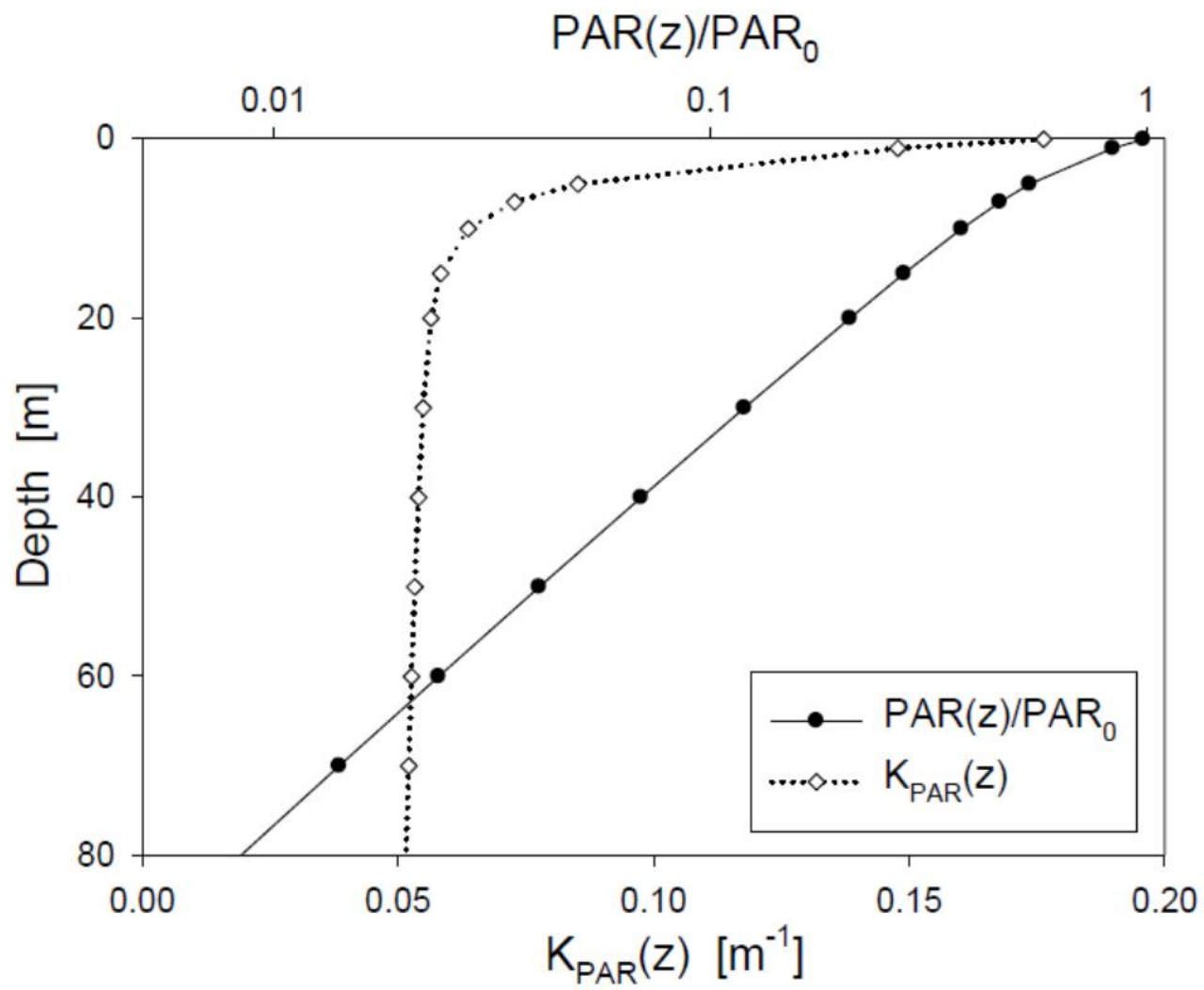
K_{PAR} is light-quality weighted!

Change of light with depth:

(Kirk 1994)



→ Light at deeper depth is associated with lower attenuation coefficient



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

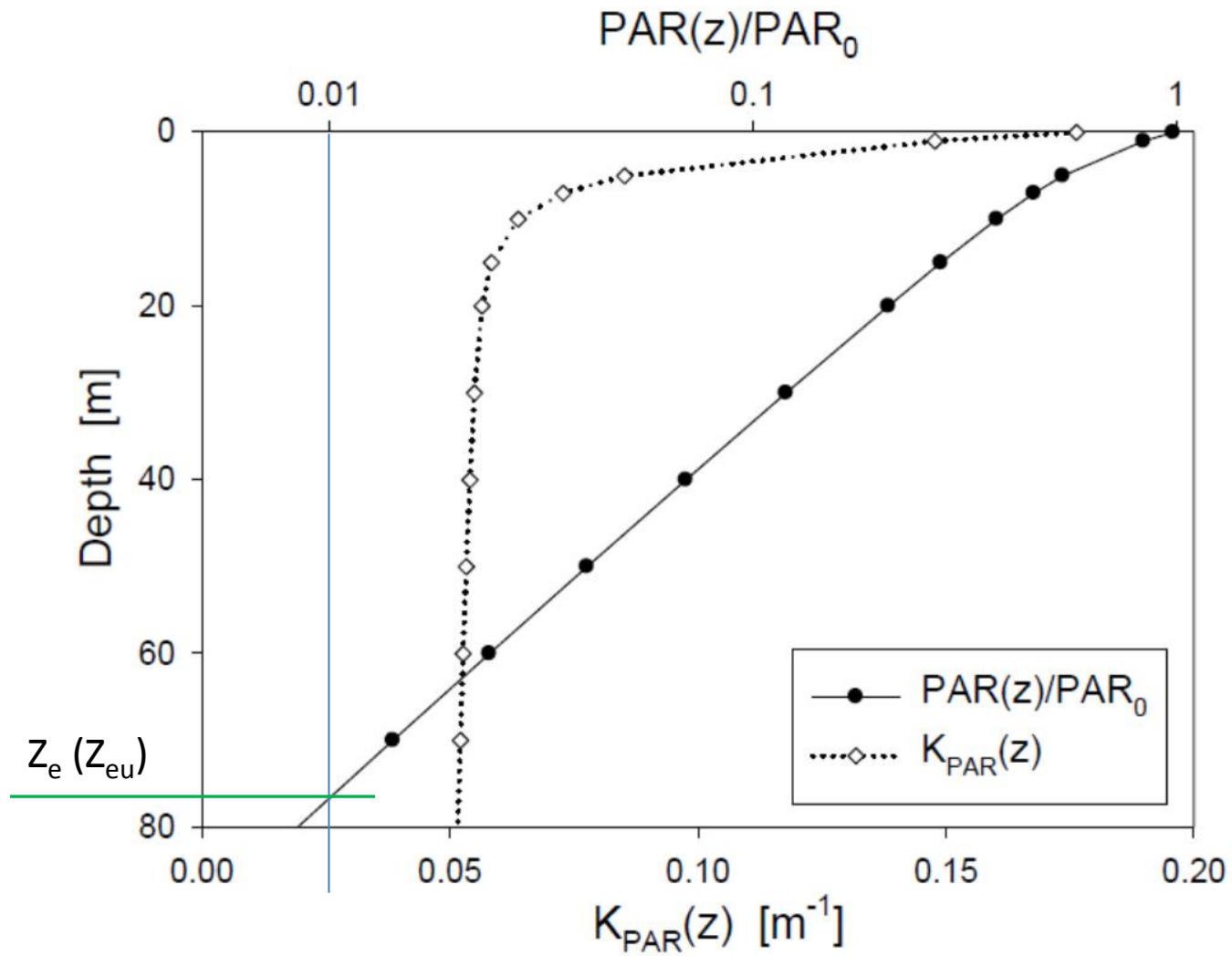
$$K_{PAR}(z) \approx K_1 + \frac{K_2}{(1+z)^{0.5}}$$

Key:

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

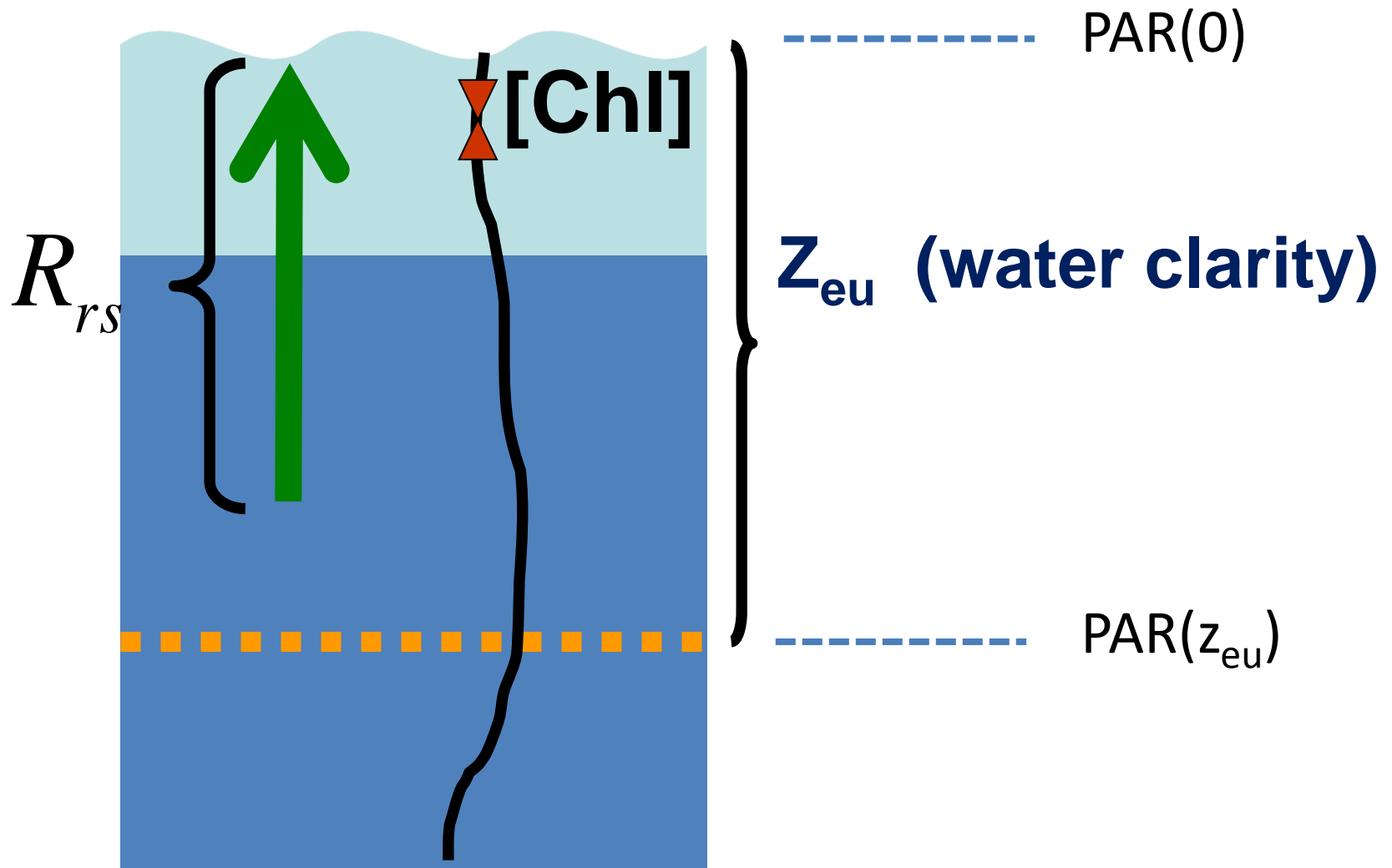
Euphotic depth (z_{eu}):

$$\frac{PAR(z)}{PAR(0)} = 1\% \quad \rightarrow \quad z_{eu} = \frac{4.6}{K_{PAR}(z_{eu})}$$



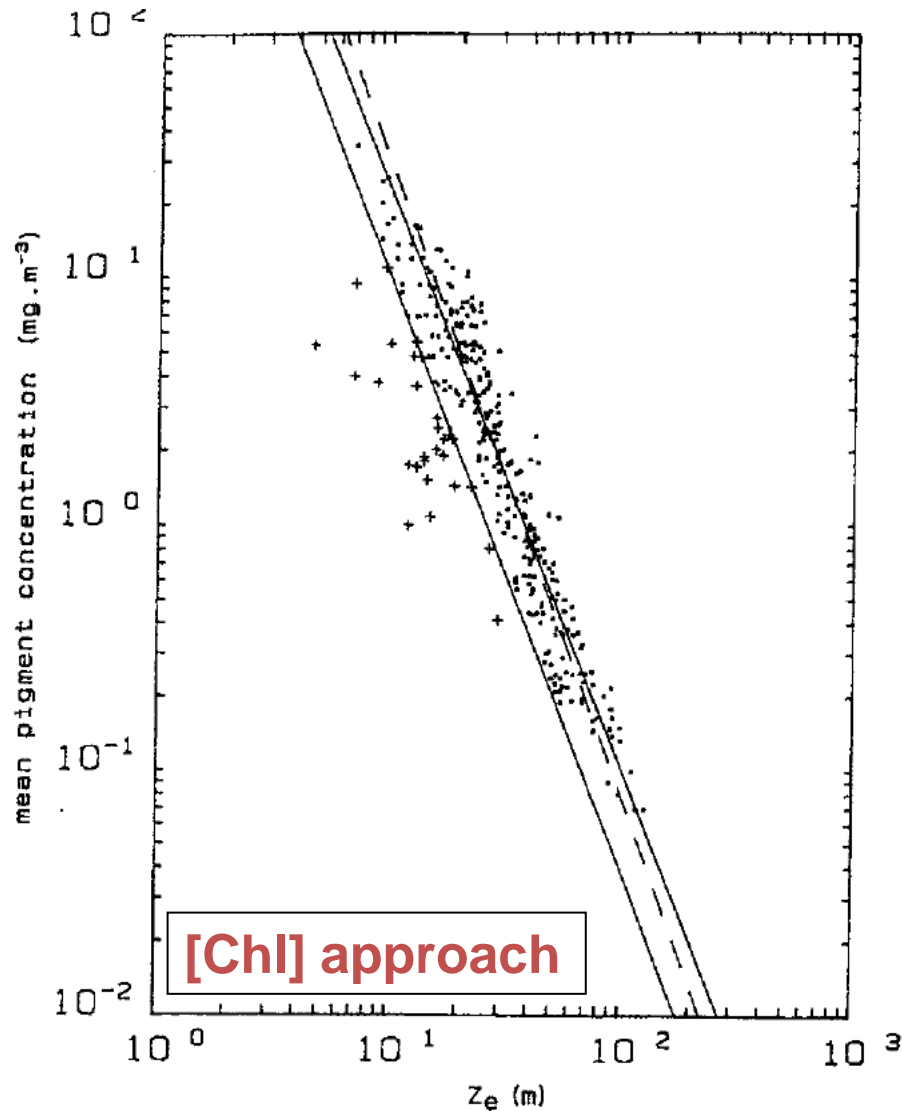
$$\frac{PAR(z_{eu})}{PAR(0)} = 1\%$$

Euphotic depth (Z_{eu})



[Chl] (empirical) approach:

$$R_{rs}(\lambda) \rightarrow [\text{Chl}] \rightarrow z_{eu}$$



$$Z_e = 38.0C^{-0.428}$$

(Morel 1988)

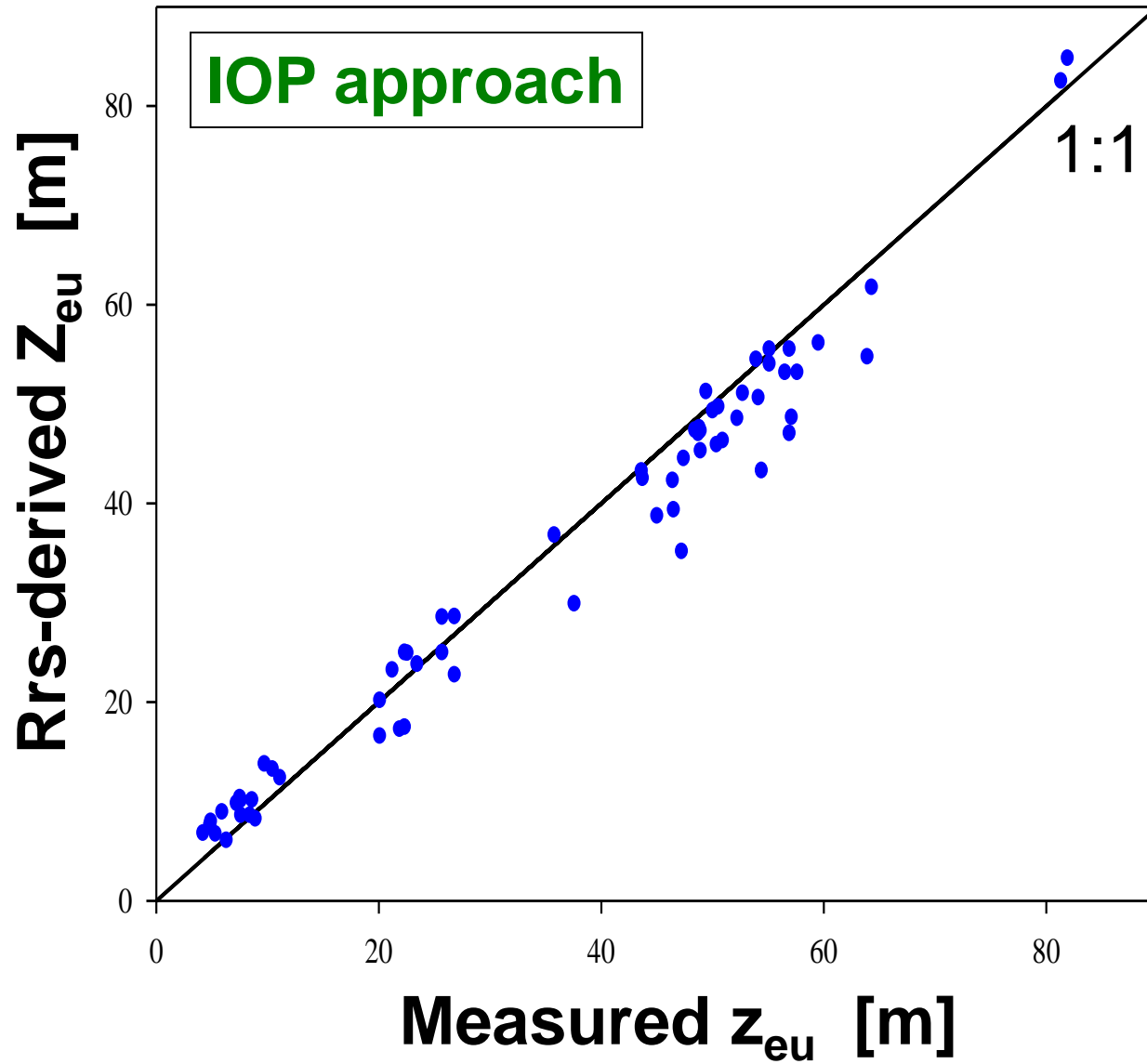
IOP approach:

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



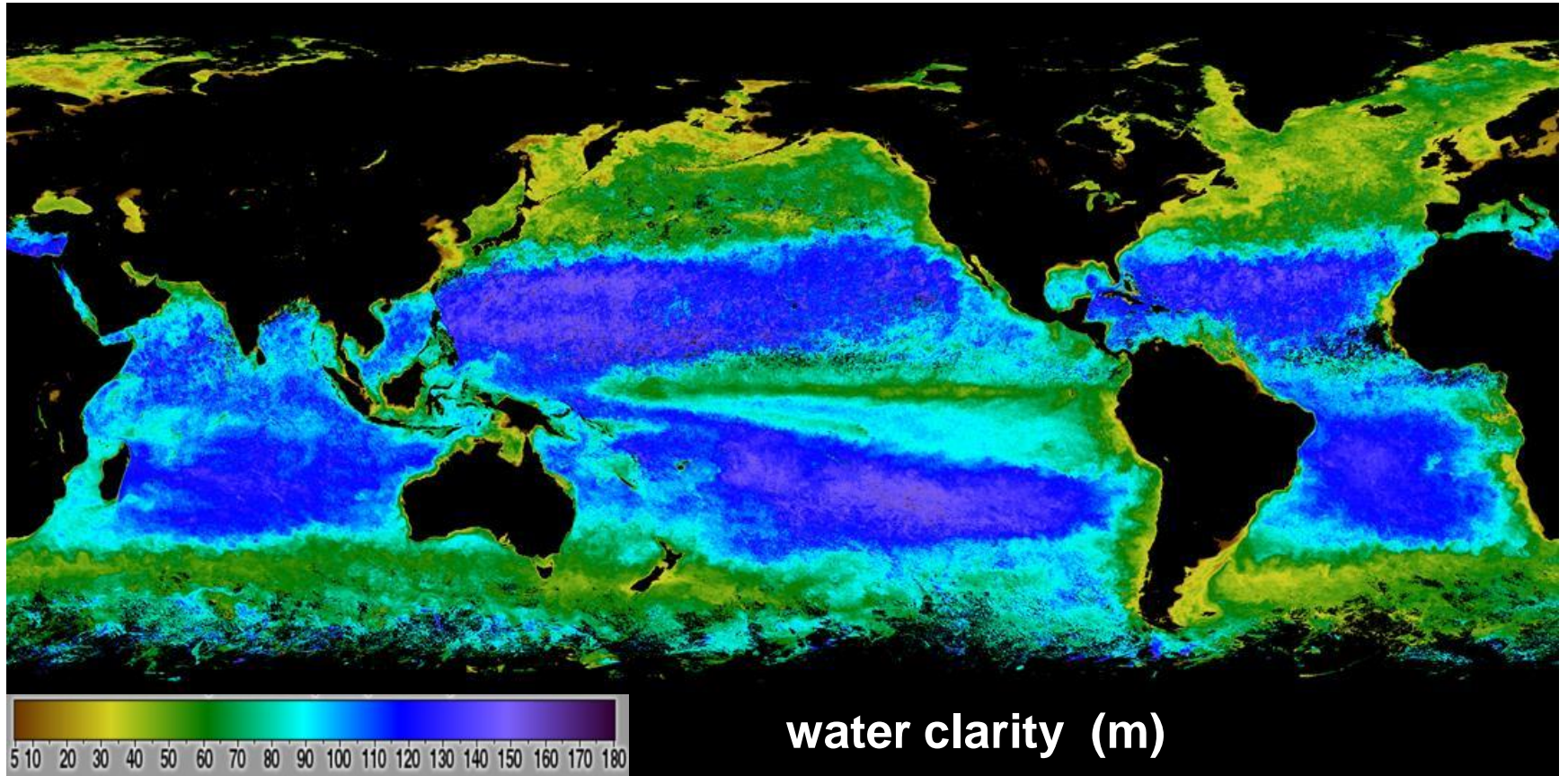
$$K_{PAR}(z) = K_1(a(490) \& b_b(490)) + \frac{K_2(a(490) \& b_b(490))}{(1+z)^{0.5}}$$

Water clarity (z_{eu})



(Lee et al 2005)

Global distribution of Z_{eu}

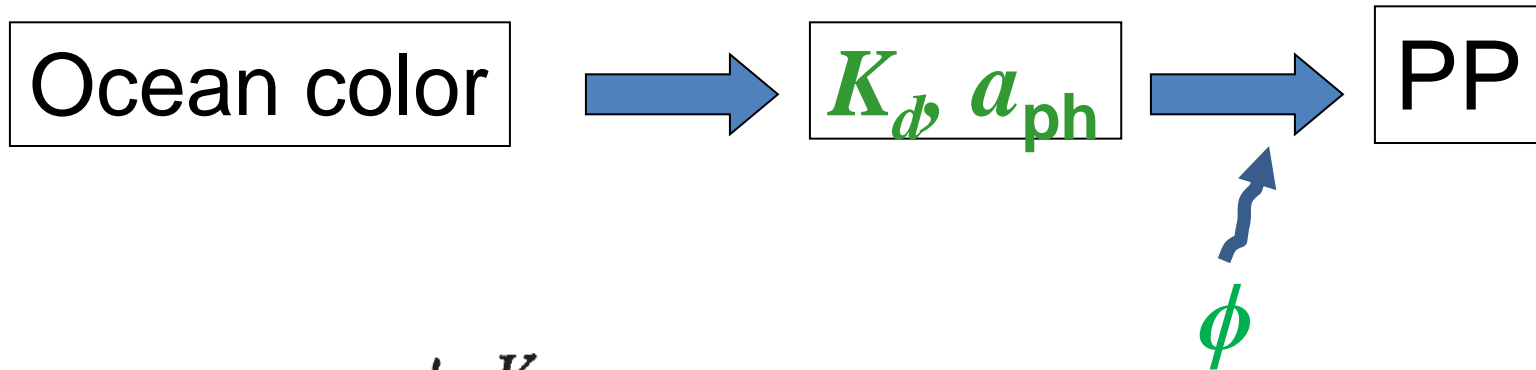


1.3 IOP based PP estimation:

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

represents 'photosynthesis'

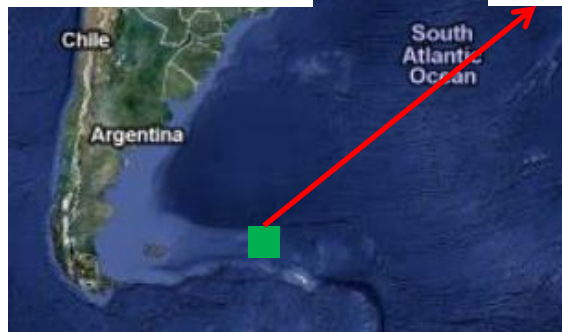
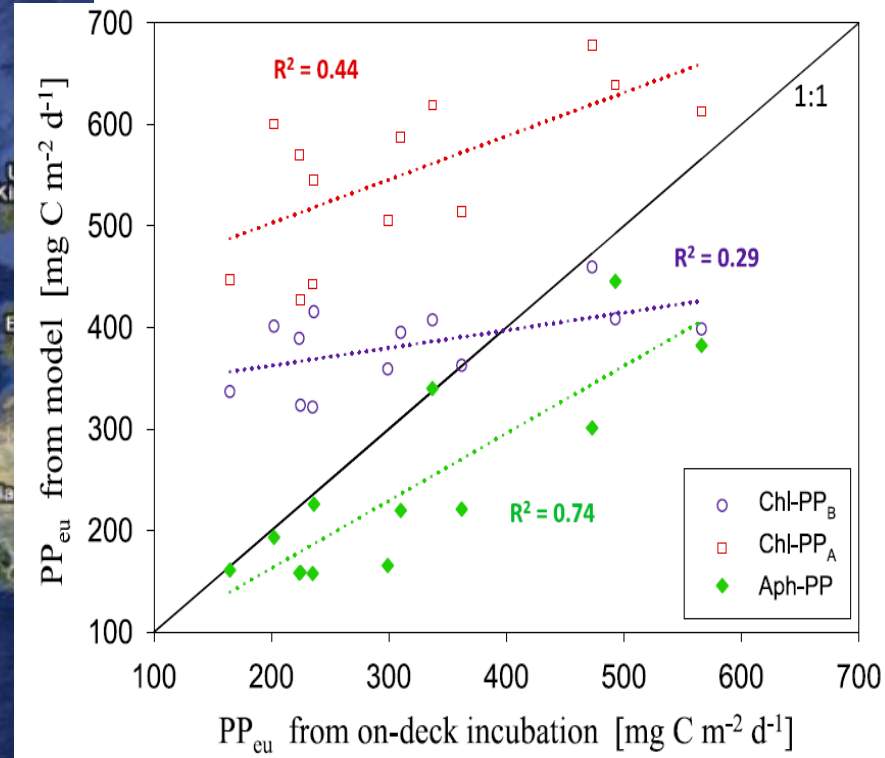
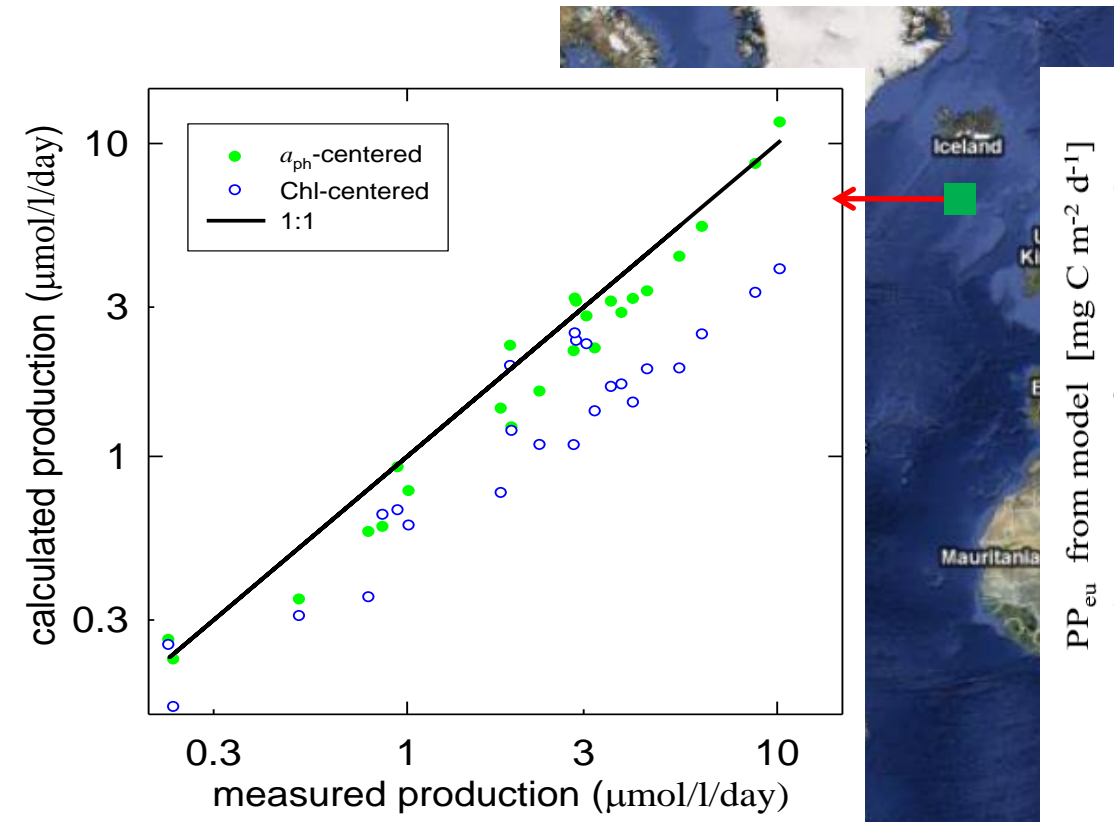
ϕ : quantum yield of photosynthesis



$$\phi(E_0) = \frac{\phi_m K_\phi}{K_\phi + E_0} \quad (2)$$

(Kiefer and Mitchell, 1983, L&O)

Remotely-estimated PP compared with measured PP



(Lee et al., Appl. Opt., 1996)

(Lee et al., JGR, 2011)

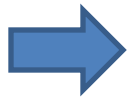
Why a_{ph} based approach is likely better?

Essence of present satellite
Chl product:

$$Chl = fun\left(\frac{R_{rs}(\lambda_1)}{R_{rs}(\lambda_2)}\right)$$

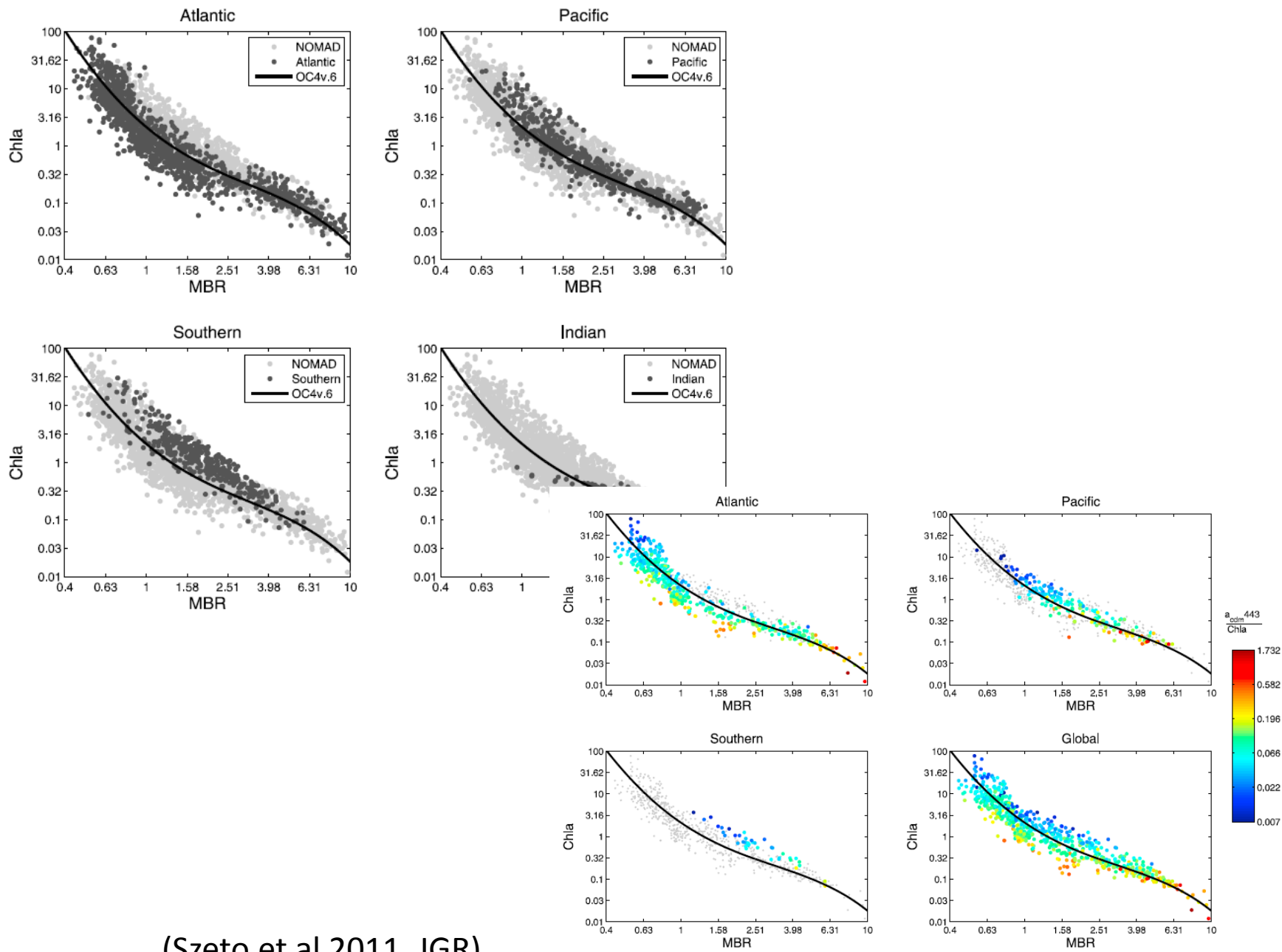
$$R_{rs} \approx G \frac{b_b}{a + b_b}$$

$$\frac{R_{rs}(440)}{R_{rs}(550)} \approx \frac{a(550) b_{bw}(440) + b_{bp}(440)}{a(440) b_{bw}(550) + b_{bp}(550)}$$



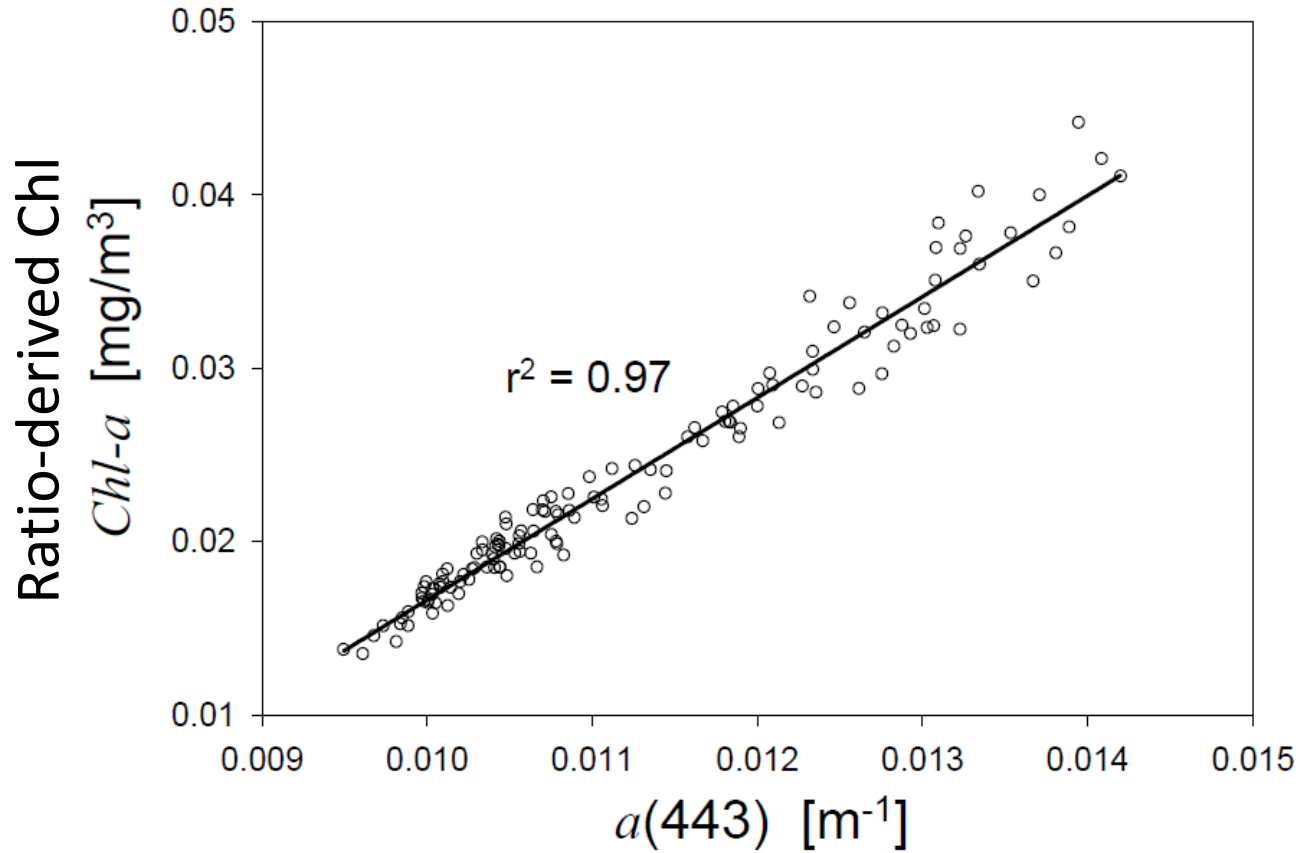
$$\frac{R_{rs}(440)}{R_{rs}(550)} \propto \frac{a(550)}{a(440)} = \frac{a_w(550) + a_{dg}(550) + a_{ph}^*(550) Chl}{a_w(440) + a_{dg}(440) + a_{ph}^*(440) Chl}$$

Change of R_{rs} band ratio not necessarily represents change of [Chl]!



(Szeto et al 2011, JGR)

The change of Rrs ratio really reflects change of total absorption!



(Lee et al, 2010, JGR)

Brief summary about current satellite Chl product:

- The map of Rrs ratio represents a map of total absorption coefficient.
- The GSM-derived Chl represents more of phytoplankton absorption coefficient.

To accurately retrieve spatially and temporally varying Chl from OCS Rrs, we need:

1. Remove the influence of detritus/CDOM and particles
2. Take into account the spatial/temporal variation of a^*_{ph}

A promising effort:

Semianalytic Moderate-Resolution Imaging Spectrometer algorithms for chlorophyll a and absorption with bio-optical domains based on nitrate-depletion temperatures

K. L. Carder, F. R. Chen, Z. P. Lee, and S. K. Hawes

Department of Marine Science, University of South Florida, St. Petersburg

D. Kamykowski

Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh

(Carder et al, 1999, JGR)

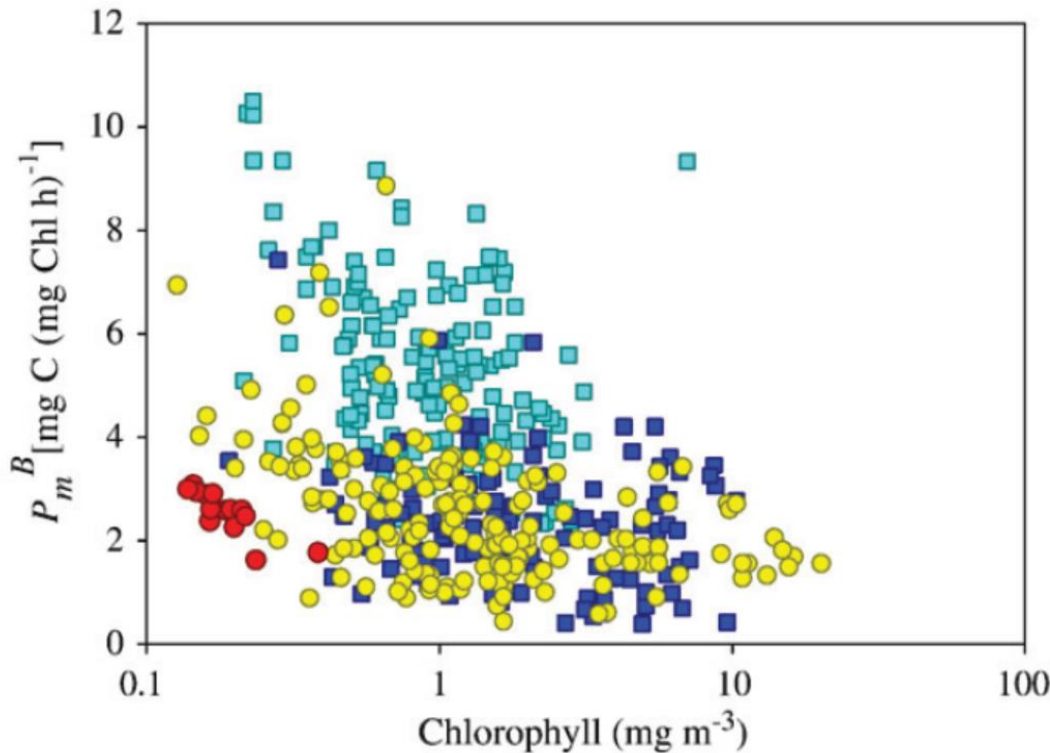
(Behrenfeld and Falkowski, 1997)

II. Time-integrated models (TIMs)

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

IV. Depth-integrated models (DIMs)

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



$$p^b \propto \phi_m a_{ph}^*$$

P^b is also dependent on a_{ph}^* , which is not a constant either for a given Chl nor for varying Chl!

(Platt et al 2008, RSE)

Another example of using remotely sensed IOPs for PP

“Carbon” based Production Model (CbPM)

$$\mu = 2 \times \text{Chl} : C_{\text{sat}} / [0.022 + (0.045 - 0.022) \exp^{-3I_g}] \times (1 - \exp^{-3I_g}).$$

(Behrenfeld et al 2005; Westberry et al 2008)

$$\mu = \frac{\text{Chl}}{C} / f(I_g)$$

actually a_{ph} from GSM
 b_{bp}

‘IOP-based growth rate’

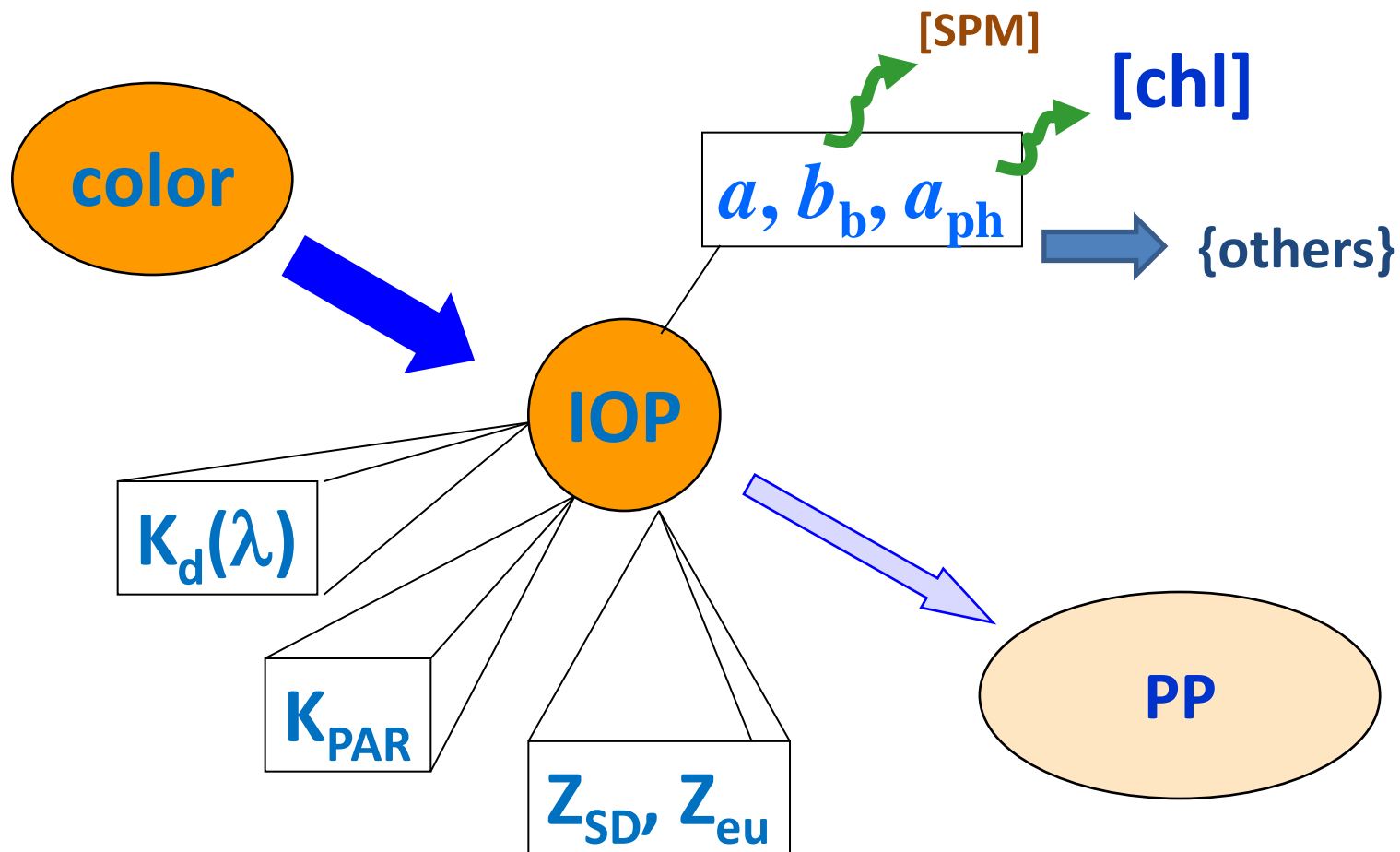
$$\text{NPP} = C \times \mu \times Z_{\text{eu}} \times h(I_0),$$

$$\text{NPP} \propto \text{Chl} \times Z_{\text{eu}} \times h(I_0) / f(I_g)$$

a_{ph} from GSM

‘IOP-based NPP’

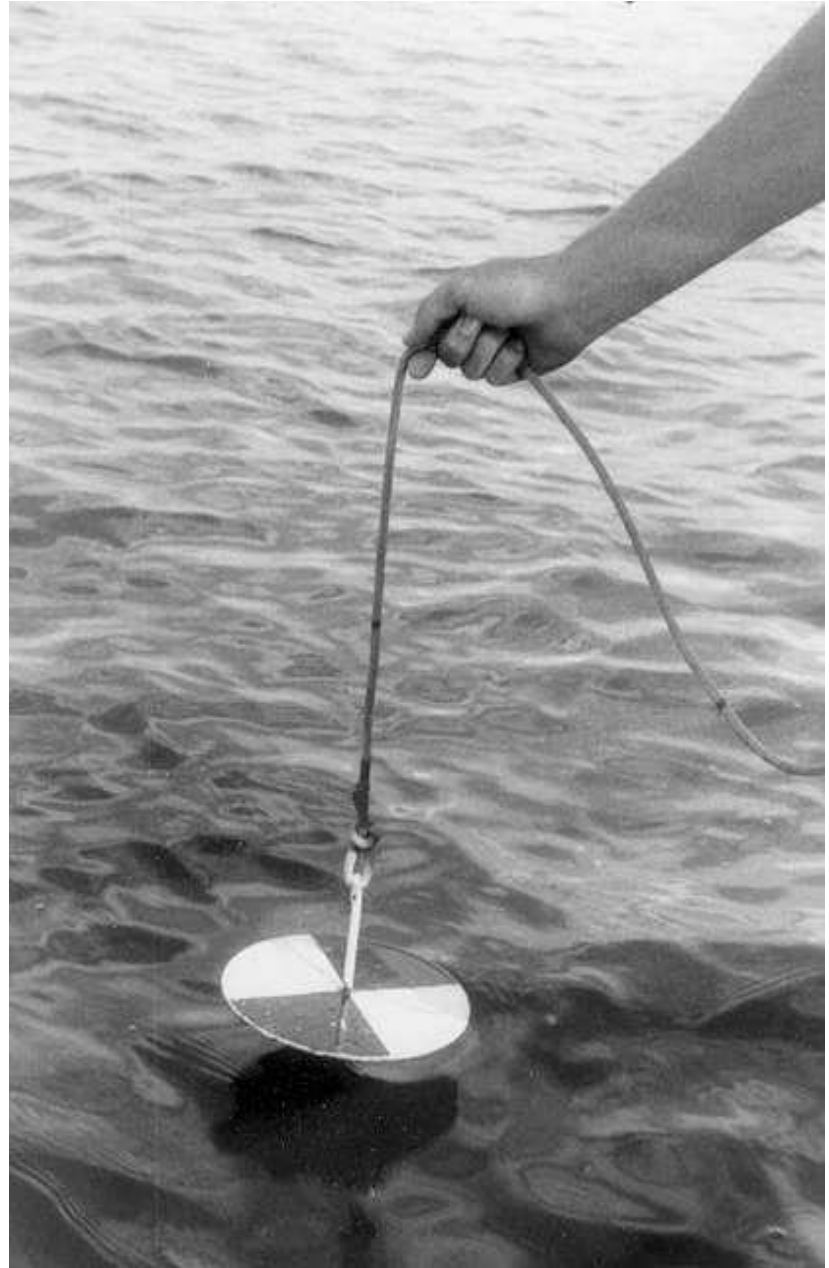
2. Example of other applications of IOP products



Works for most waters.

2.1 Secchi depth (Z_{SD})

Water clarity

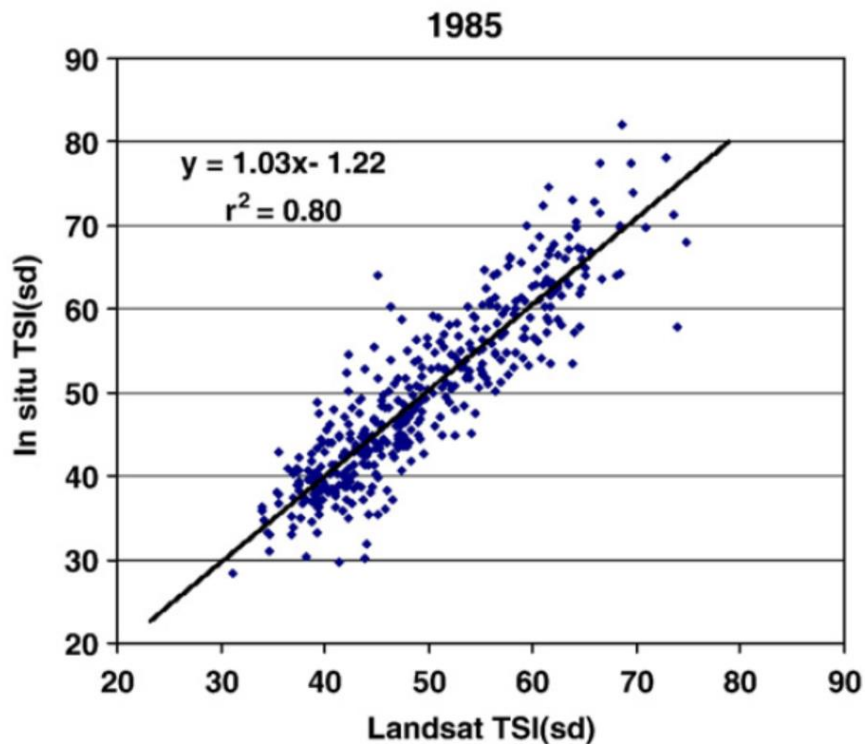


empirical approach:

least-squares multiple regression using the general form:

$$\ln(\text{SD}) = a(\text{TM1}/\text{TM3}) + b(\text{TM1}) + c$$

where a , b and c are coefficients fit to the calibration data by the regression analysis, $\ln(\text{SD})$ is the natural logarithm of Secchi depth for a given lake, and TM1 and TM3 are the Landsat brightness values for the selected lake pixels in the blue and red bands, respectively. Kloiber



(Olmanson et al 2008)

The theoretical relationship:

(Duntley 1952; Preisendorfer 1986; Aas 2014)

$$Z_{SD} = \frac{\Gamma}{K_d + c} \quad \Gamma = \ln\left(\frac{C_i}{C_t}\right) \quad C_i = \frac{r_T - r_w}{r_w}$$

$c \gg K_d$ ($\sim 5 - 10$)

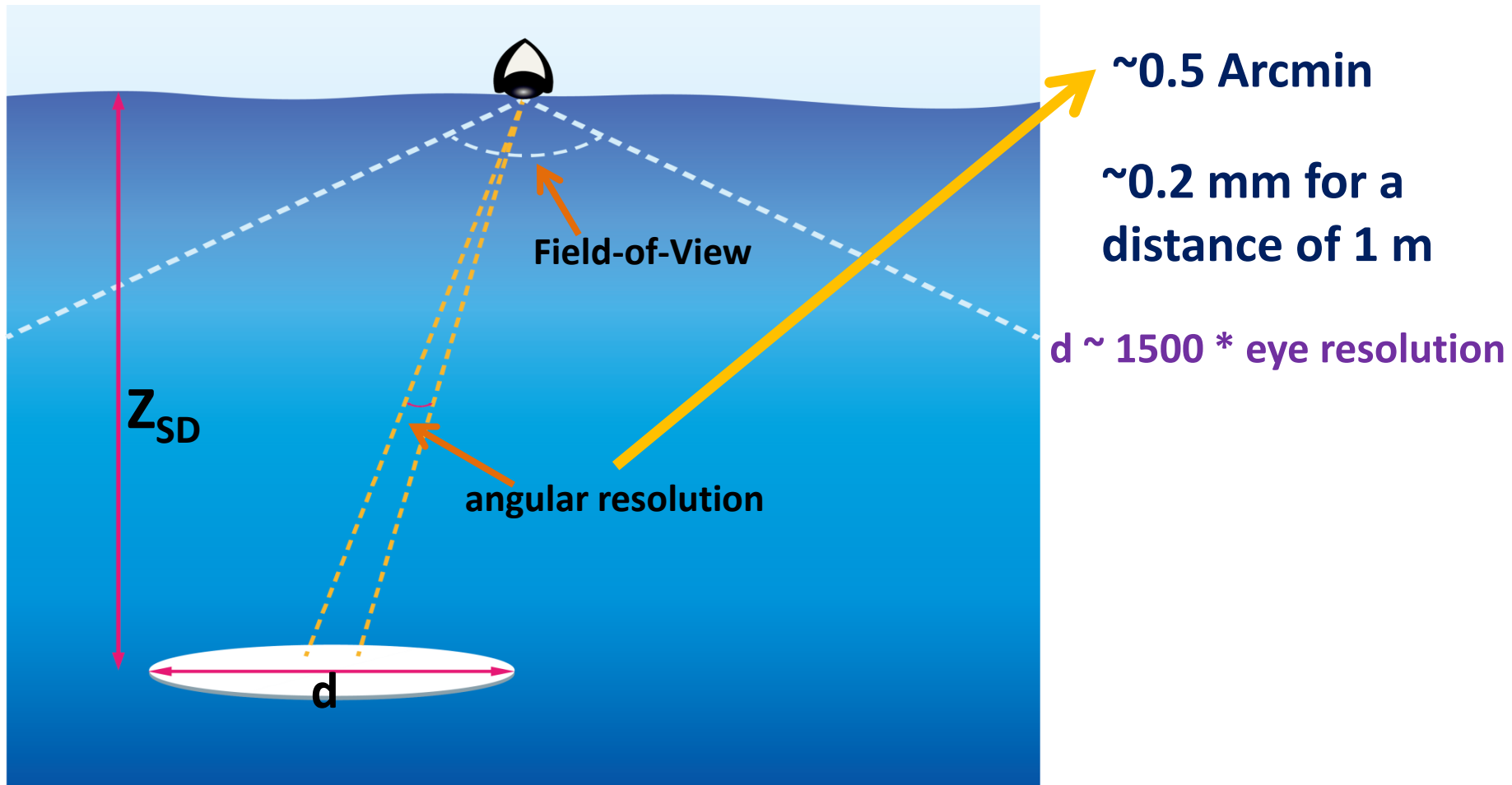
K_d : Diffuse attenuation coefficient

c : Beam attenuation coefficient

C_i : Inherent contrast

C_t : Contrast threshold of human eye; $\sim 2\%$

Secchi disk vs the resolution of eye “sensor”



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

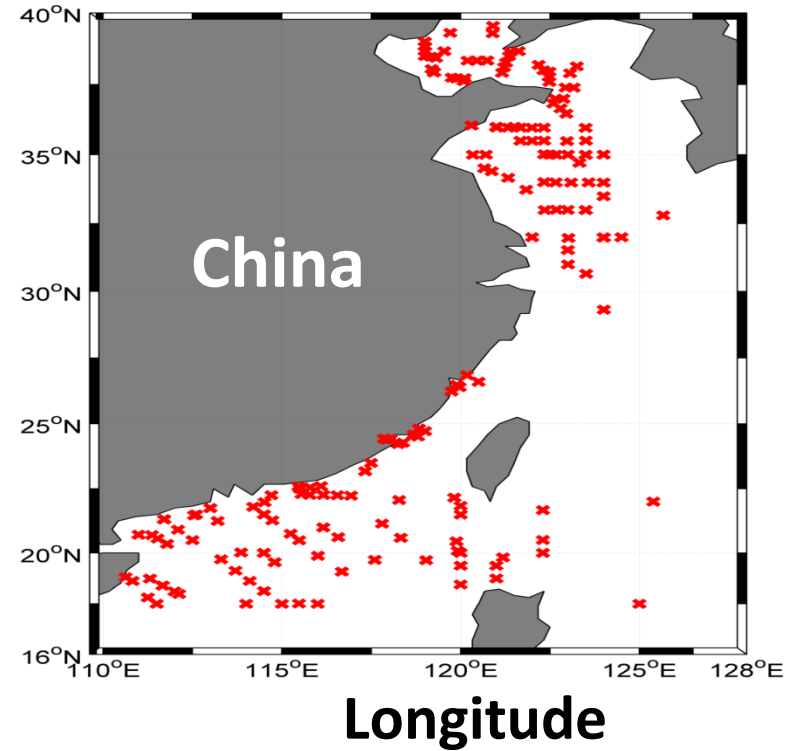
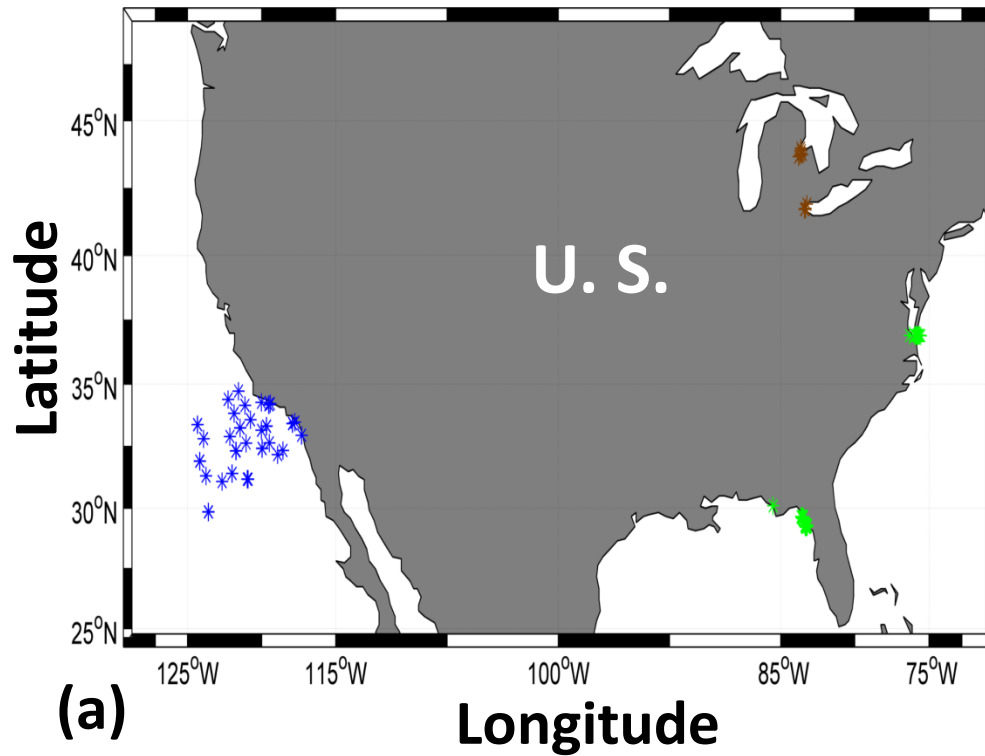
New theoretical relationship for Z_{SD} :

$$Z_{SD} \approx \frac{1}{2.5K_d^{tr}} \ln \left(\frac{|r_T - r_w^{tr}|}{0.013} \right)$$

K_d^{tr} : attenuation coefficient in the transparent window

(Lee et al 2015)

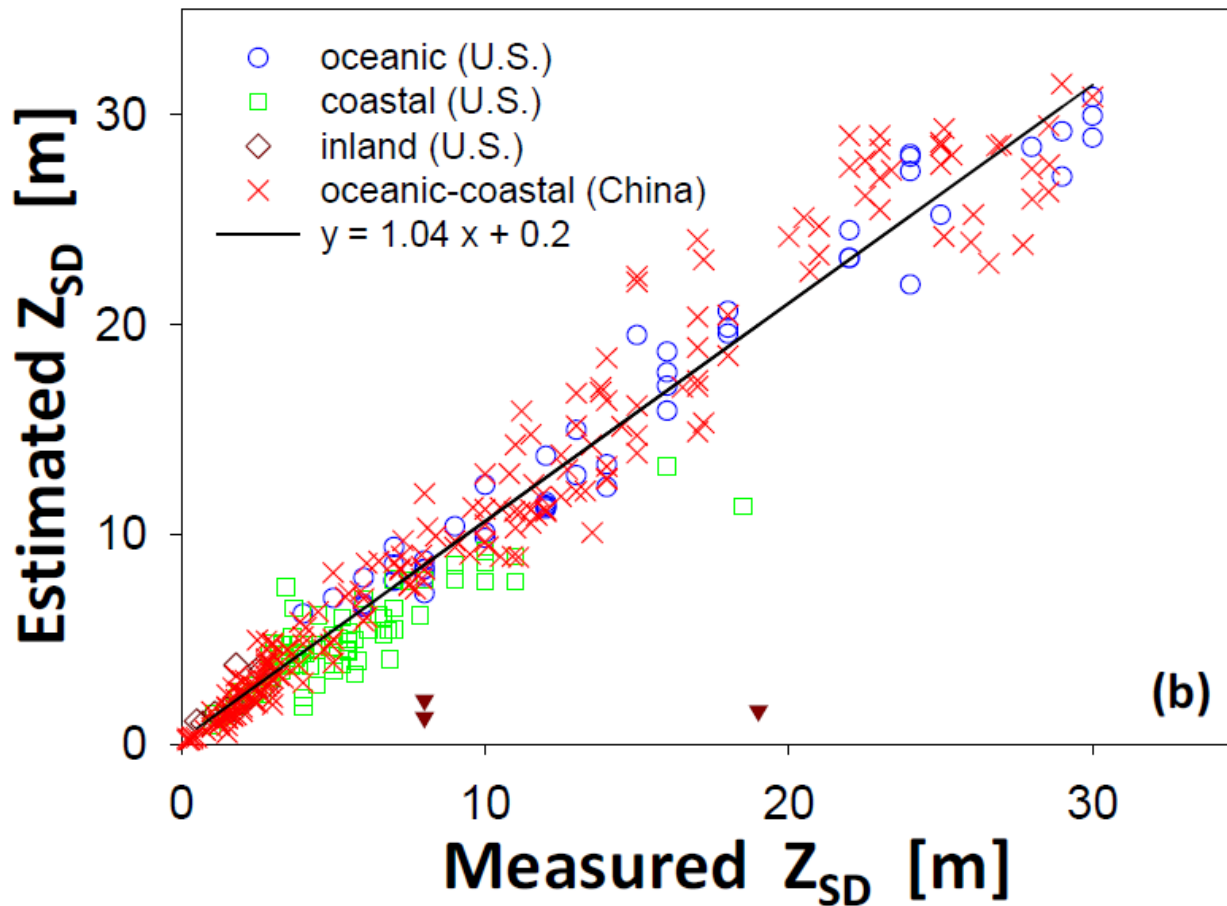
Verification of the new Secchi disk theory



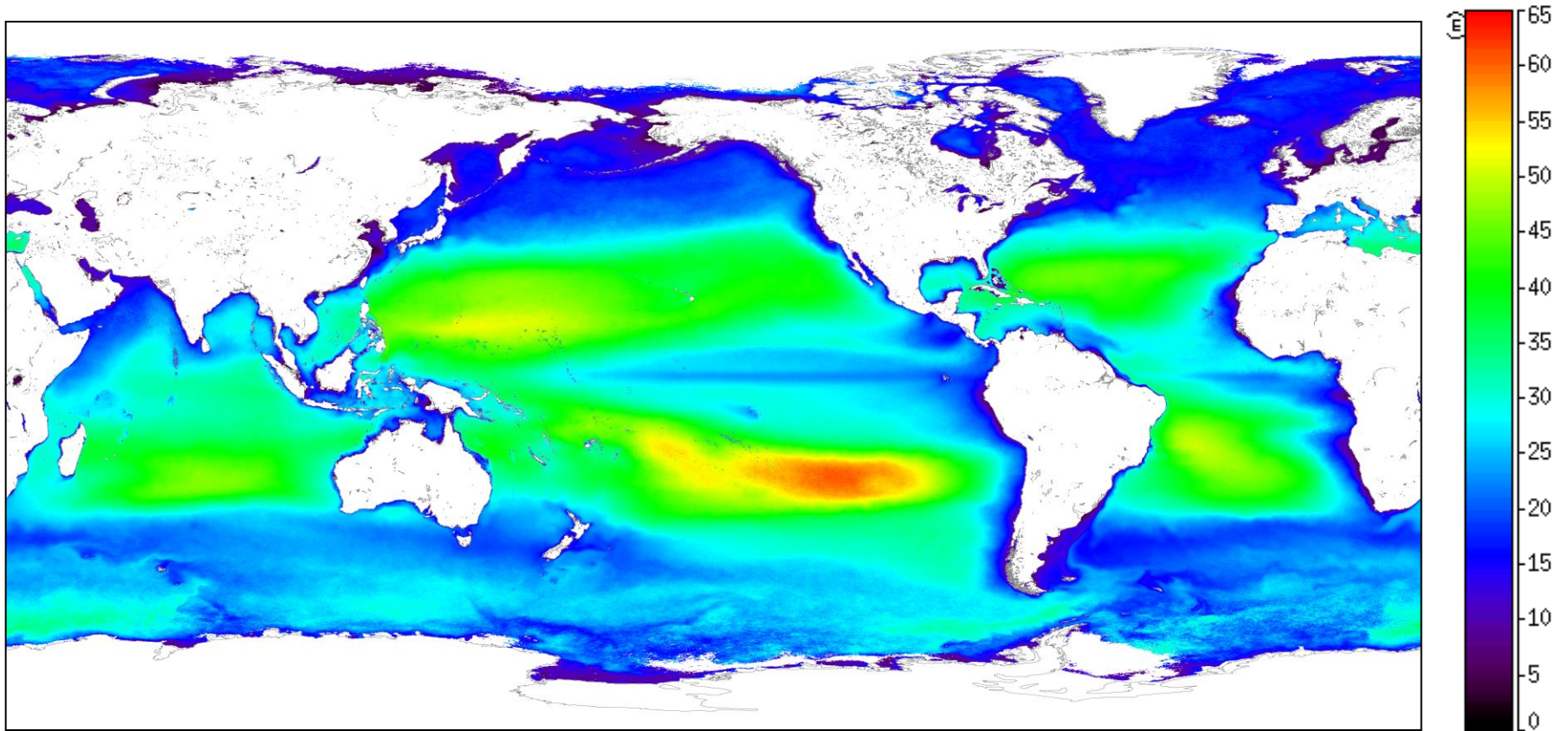
Verification of the new Secchi disk theory

QAA (2002) Lee et al (2013)

$$R_{rs} \rightarrow a \& b_b \rightarrow K_d$$

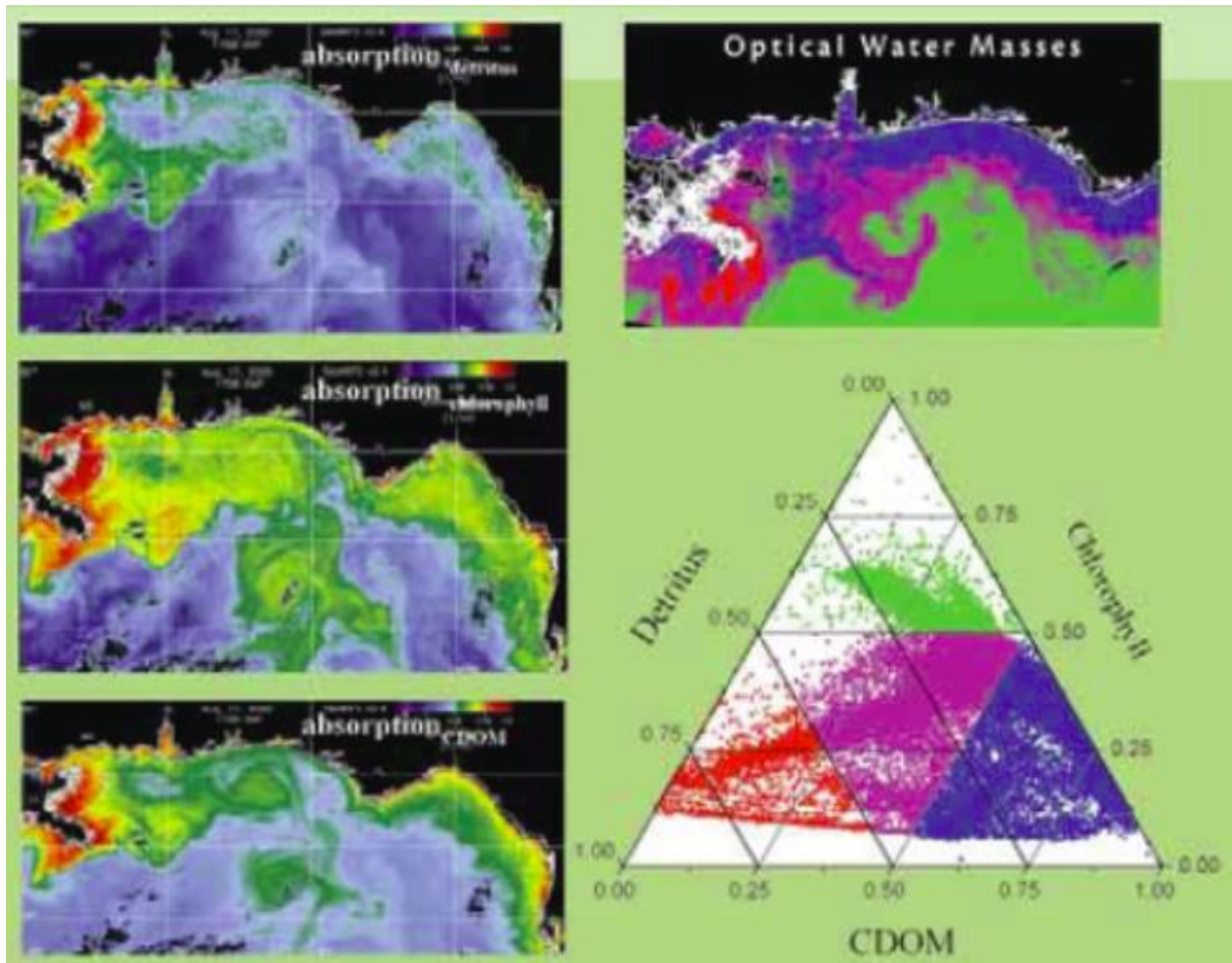


Global Z_{SD}



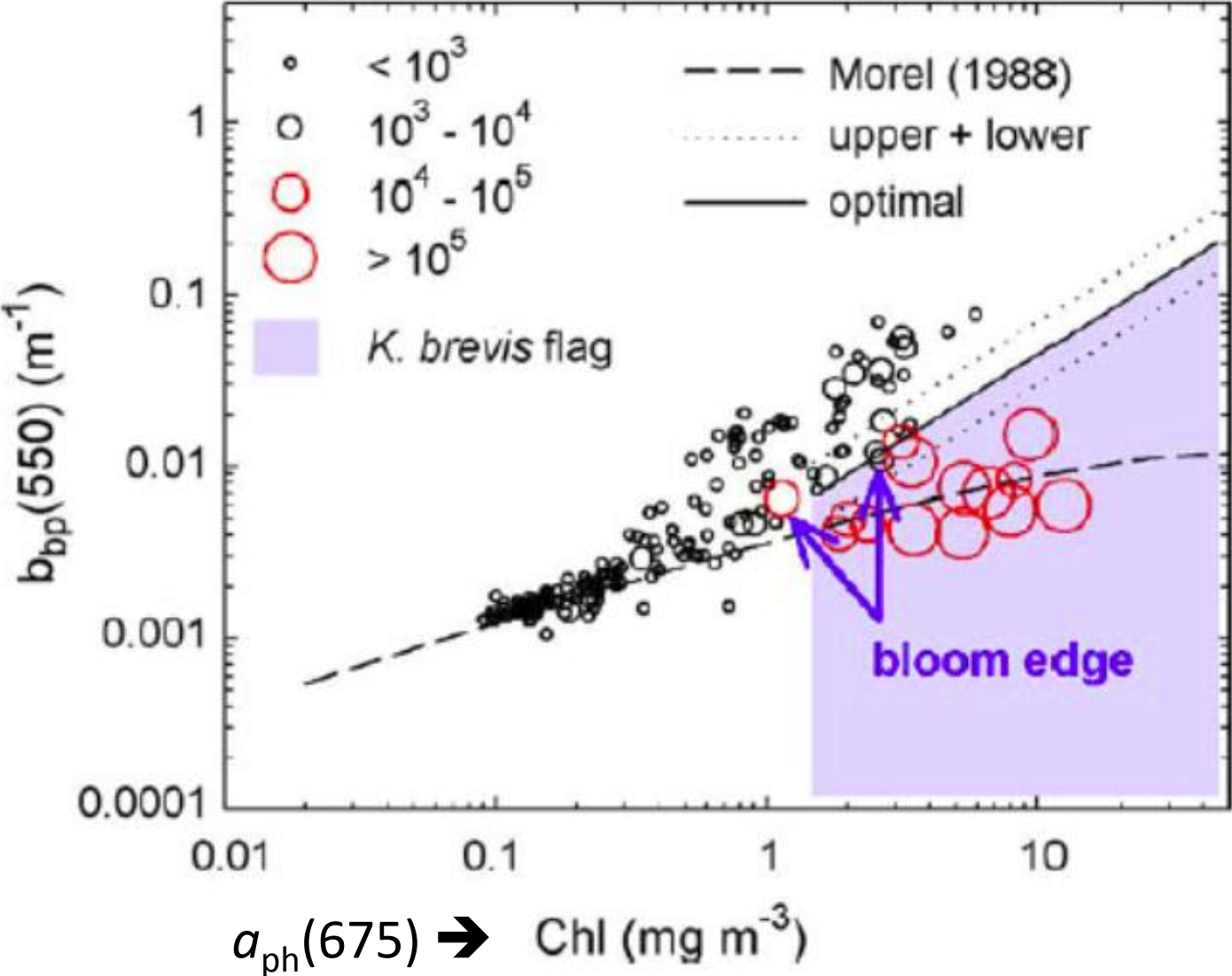
A much more straightforward product for water clarity!

2.2 Water mass classification



(Arnone et al 2004)

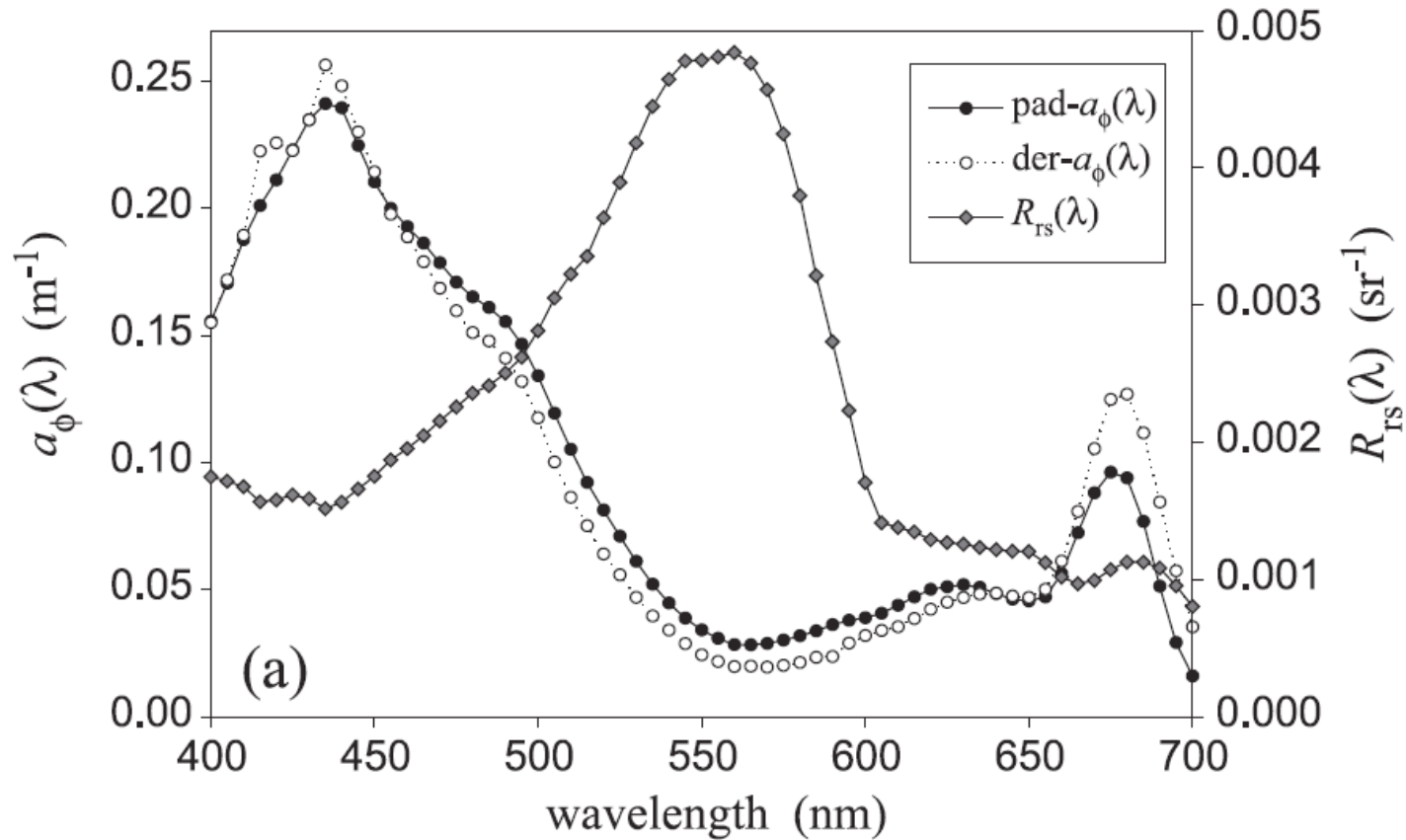
2.3 HAB identification-1



(Carnizzaro et al 2006)

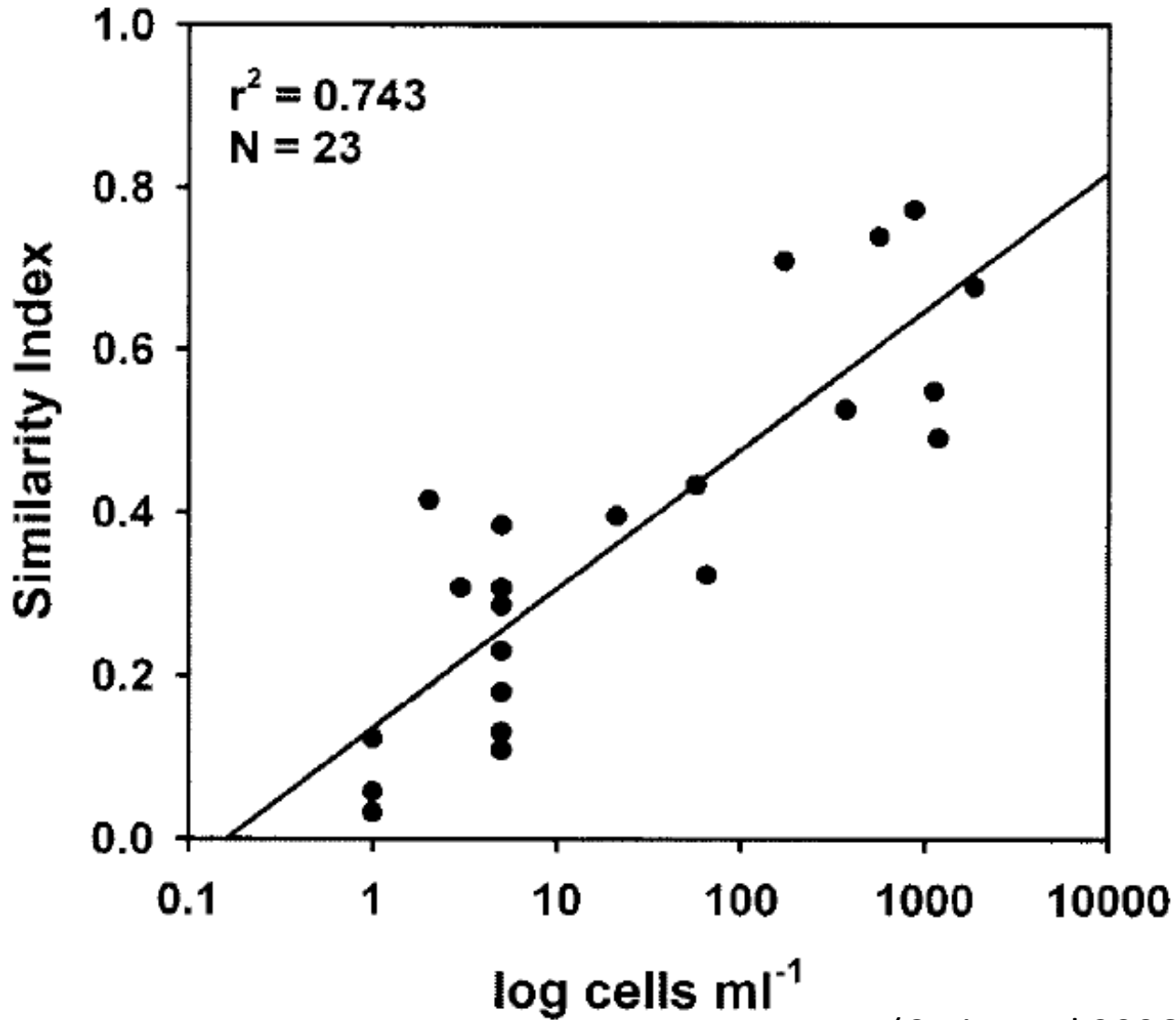
2.3 HAB identification-2

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



(Lee and Carder 2004)

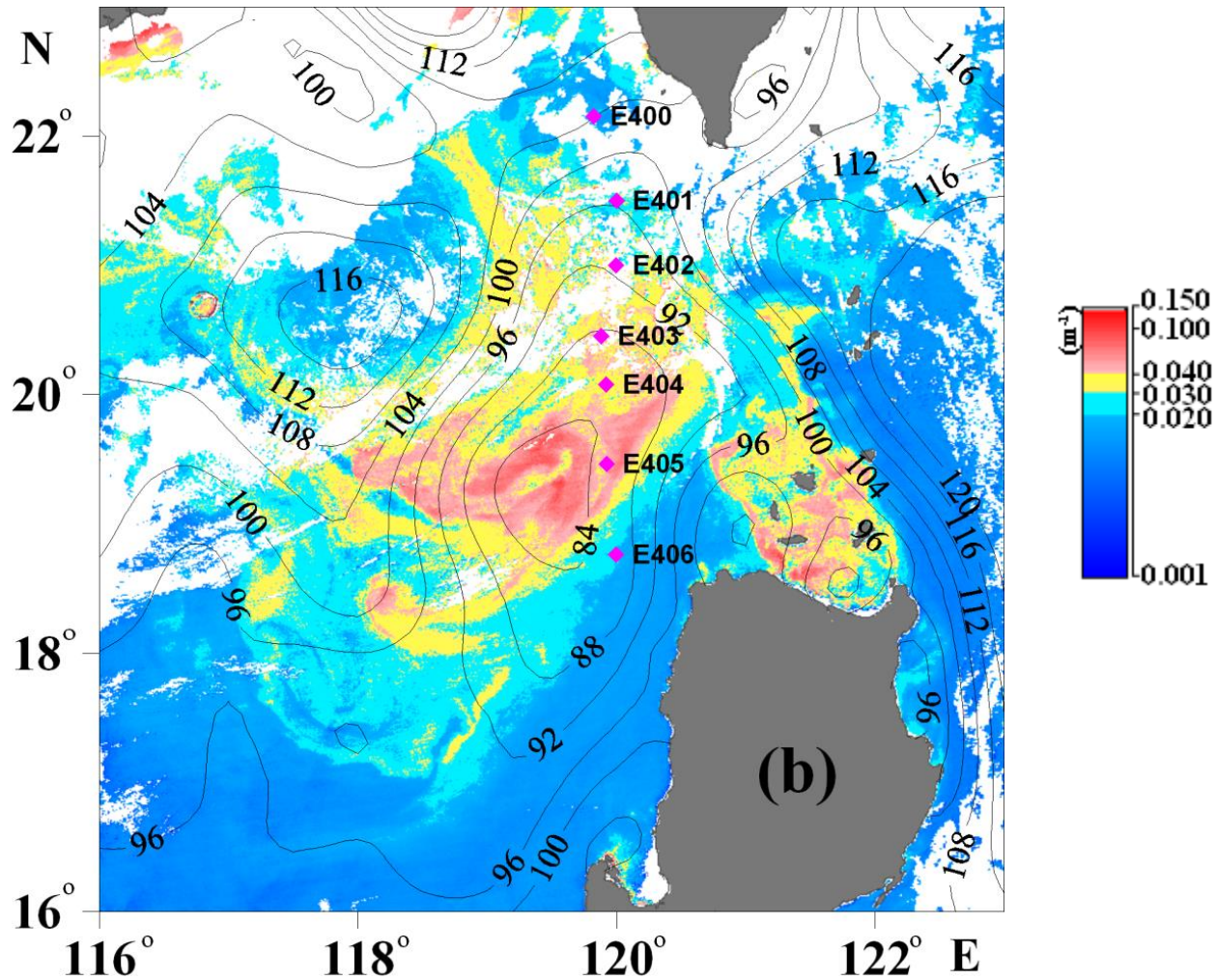
K. brevis



(Craig et al 2006)

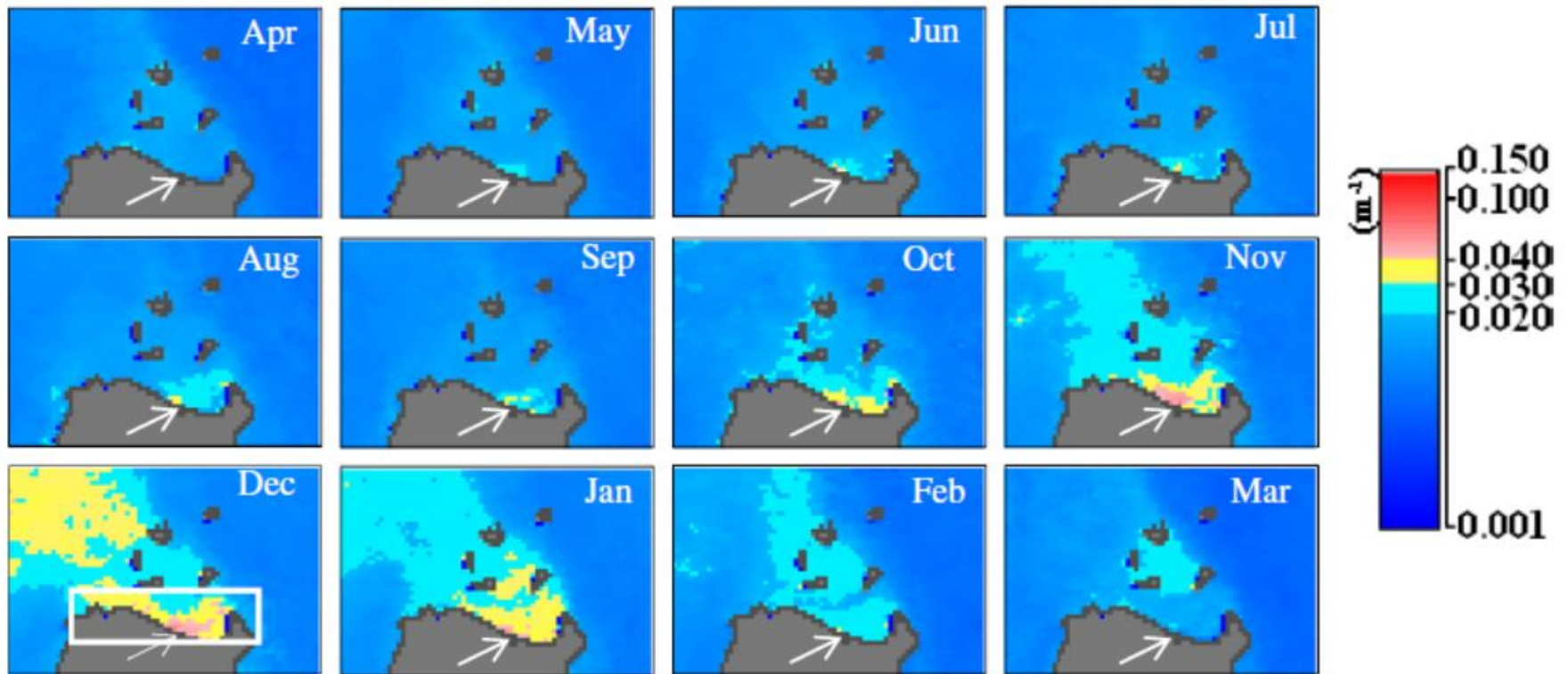
2.4 Bloom dynamics

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)

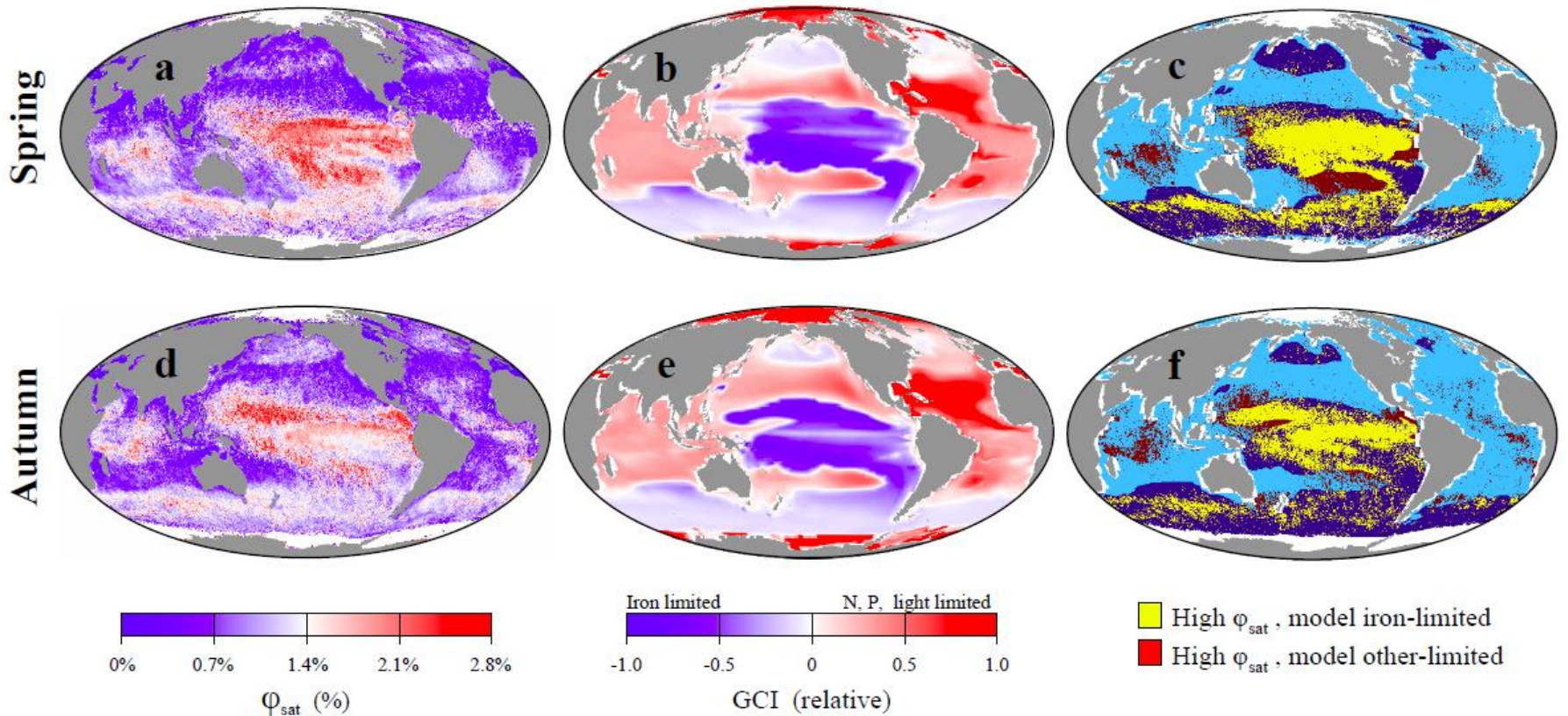
2.5 Global physiology of ocean phytoplankton

IOP

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

ϕ : quantum yield of fluorescence

(Behrenfeld et al 2009)



(Behrenfeld et al 2009)

2.6 Salinity estimation

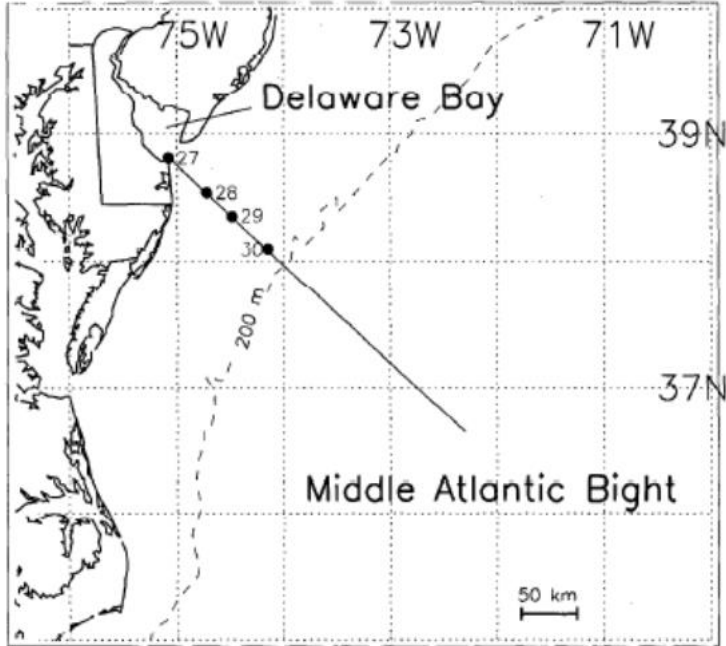
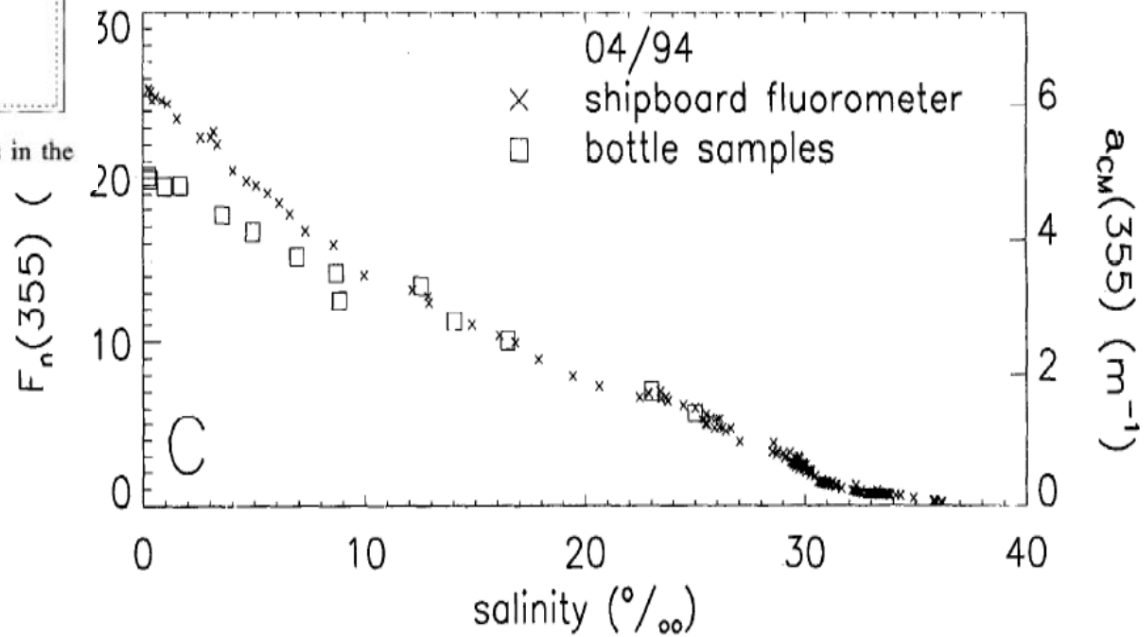
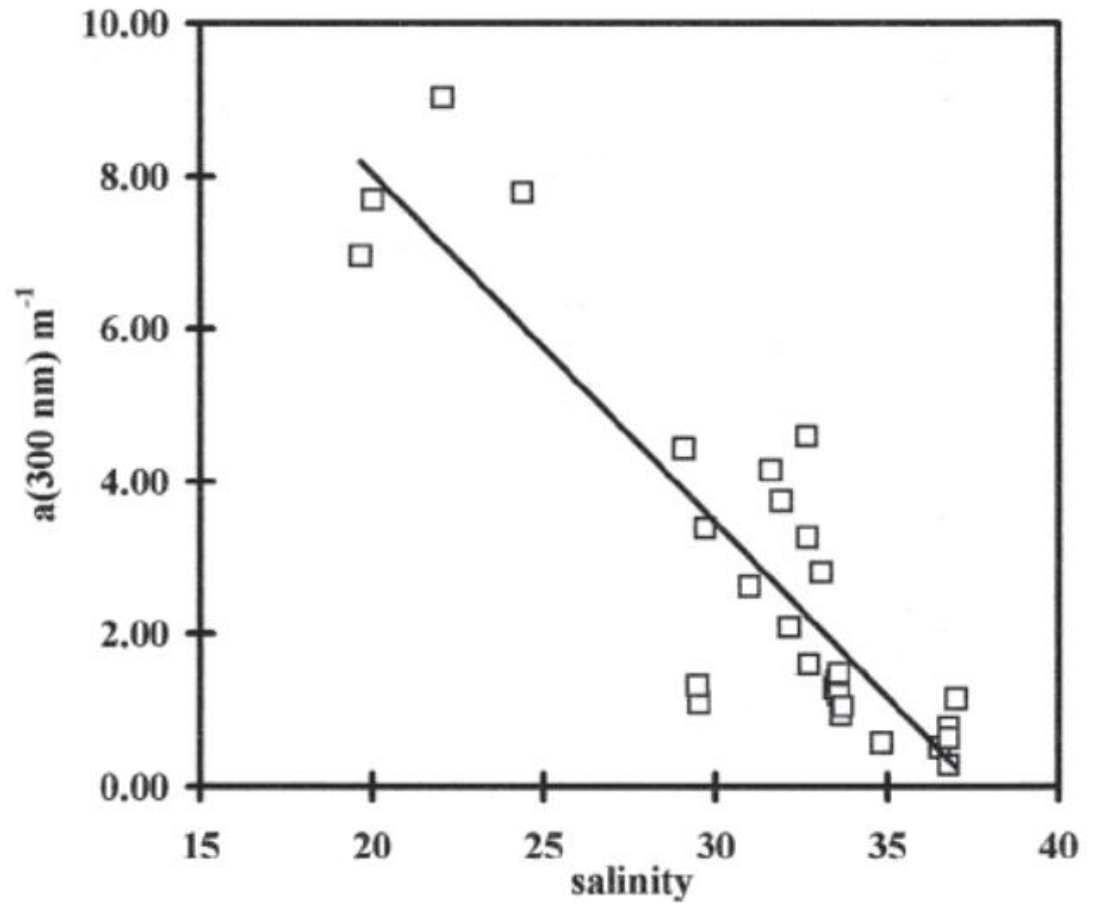
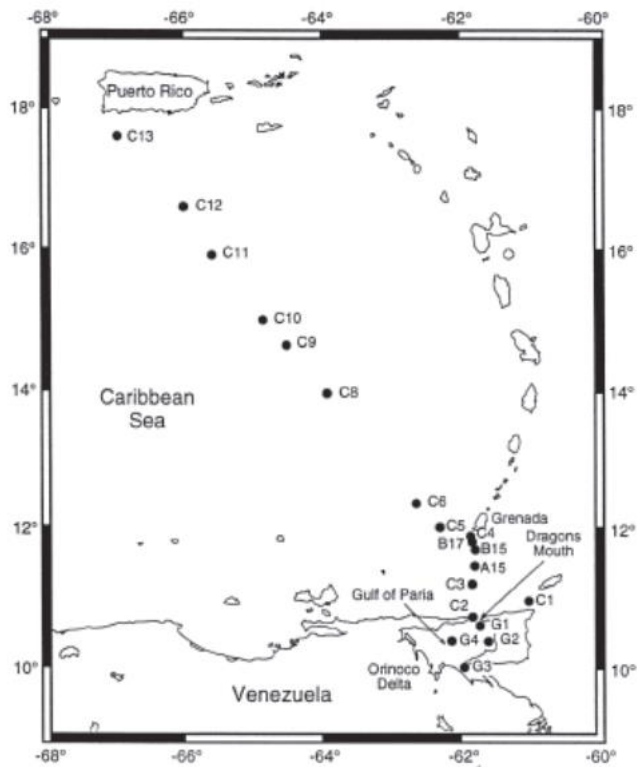


Fig. 1. Locations of the transect and hydrocast stations in the Middle Atlantic Bight.



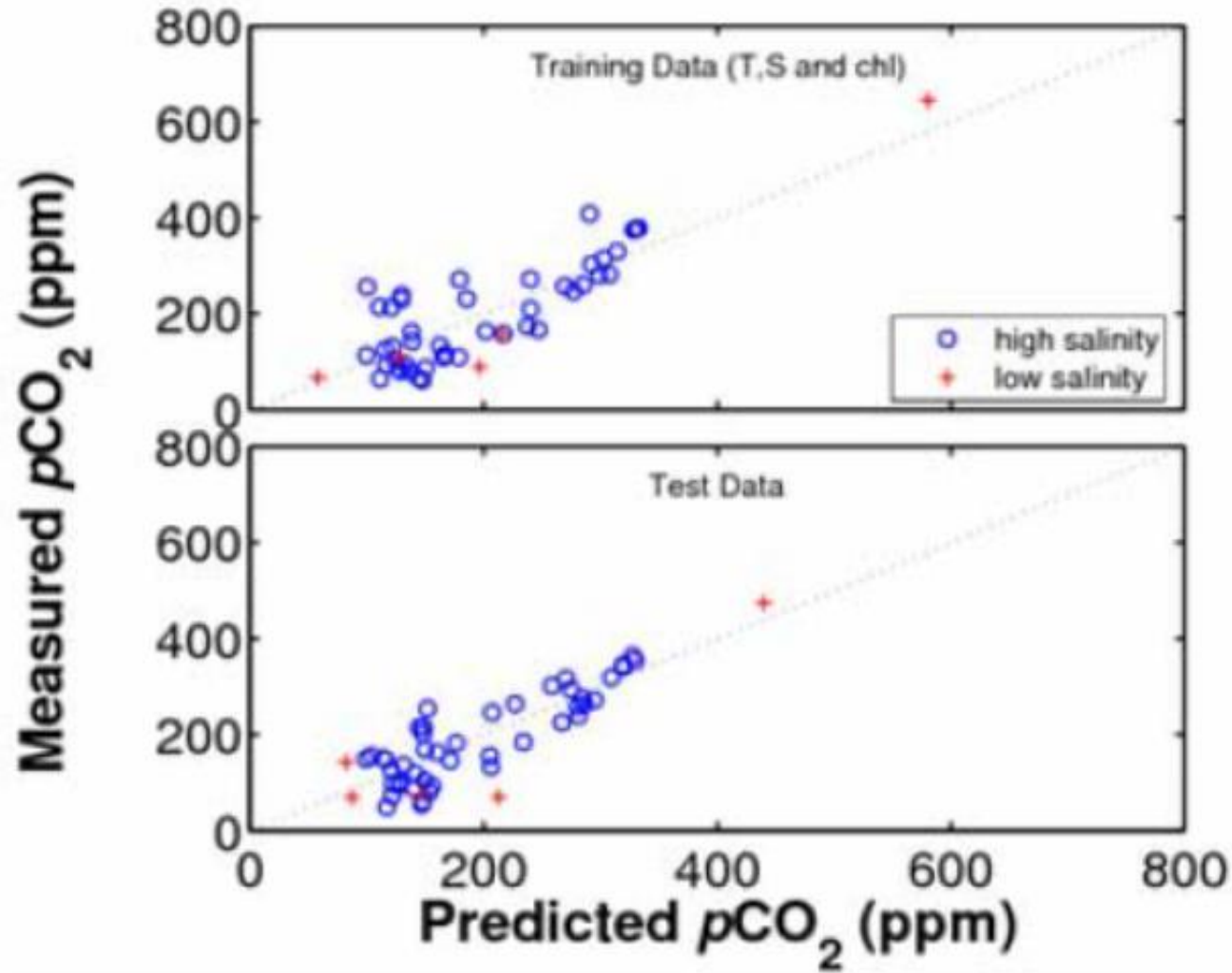
(Vodacek et al 1997)



$$SSS = X a_{\text{CDOM}} + y$$

(Castellio et al 1999)

2.7 pCO₂ estimation



Key Points:

1. Many applications traditionally built around [Chl] can be built around IOPs.
2. Remote sensing and applications centered around IOPs avoided, when necessary, concentration-normalized optical properties.
3. With IOPs as inputs, many products, e.g. K_d , Z_{eu} , Z_{sd} , PP , could be estimated easily and more accurately.
4. When IOPs are known, many other applications could be carried out. **Be creative!!!**

Thank you!