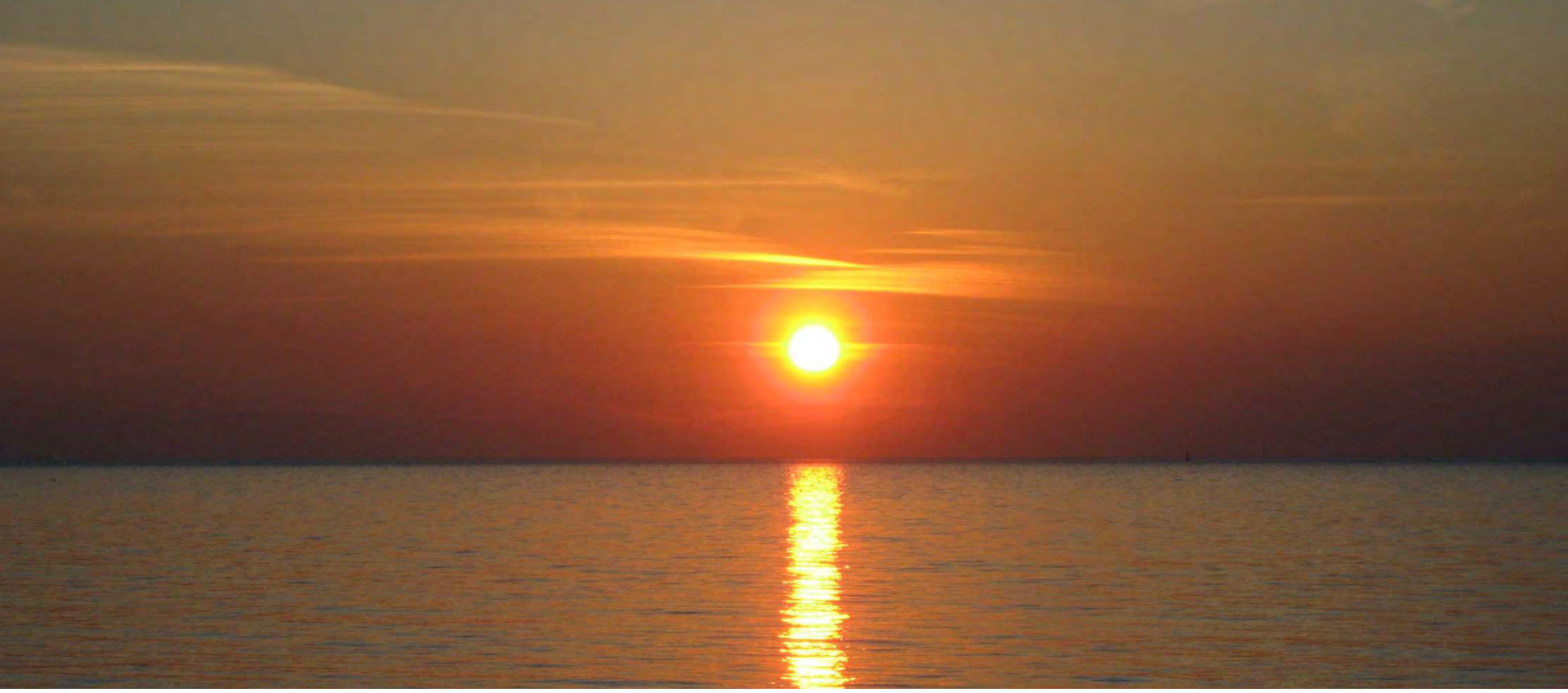
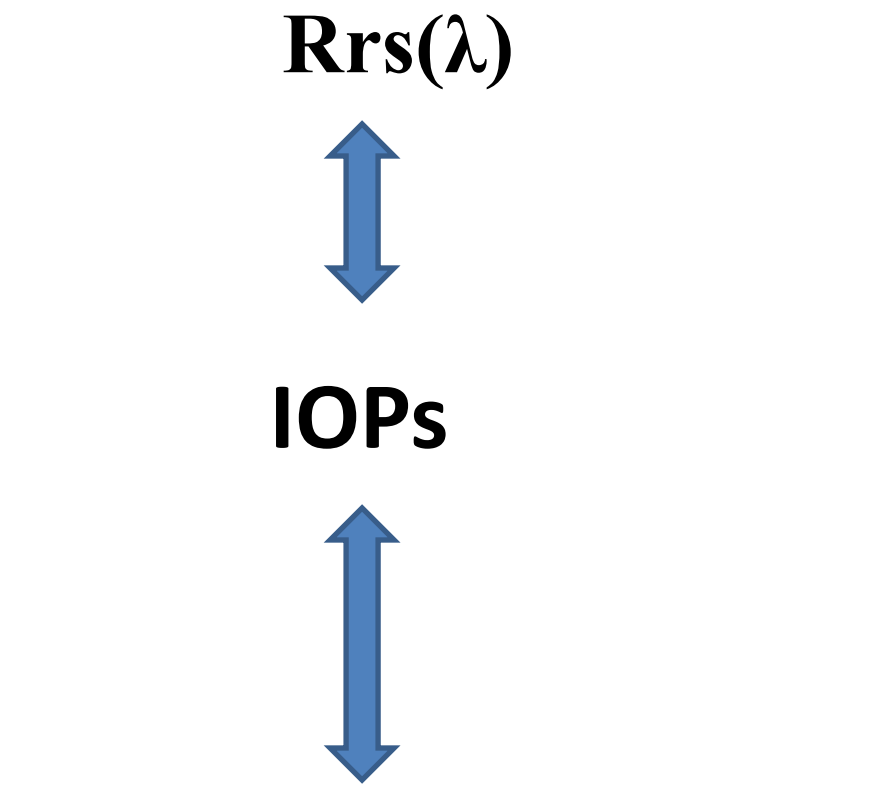


Inherent Optical Properties (IOPs)

Lecture 3: Applications


Rrs(λ)
IOPs
Physical-biogeochemical properties

1. Primary applications

2. Examples of other applications

1. Primary applications

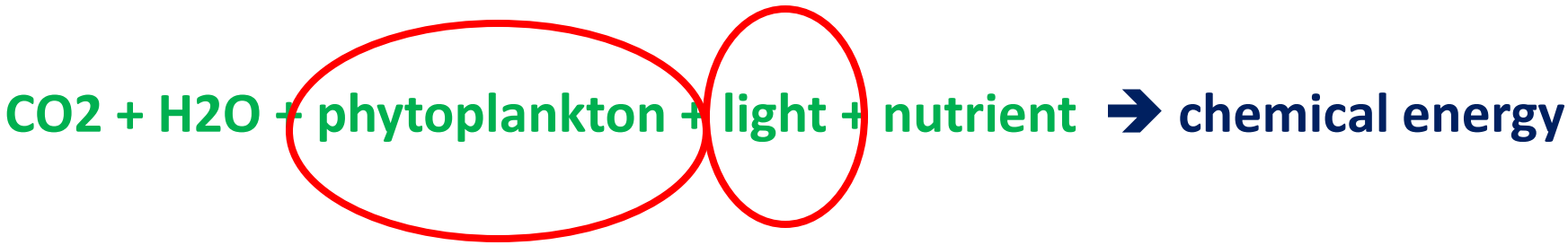
Estimation of Primary Production (PP)

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

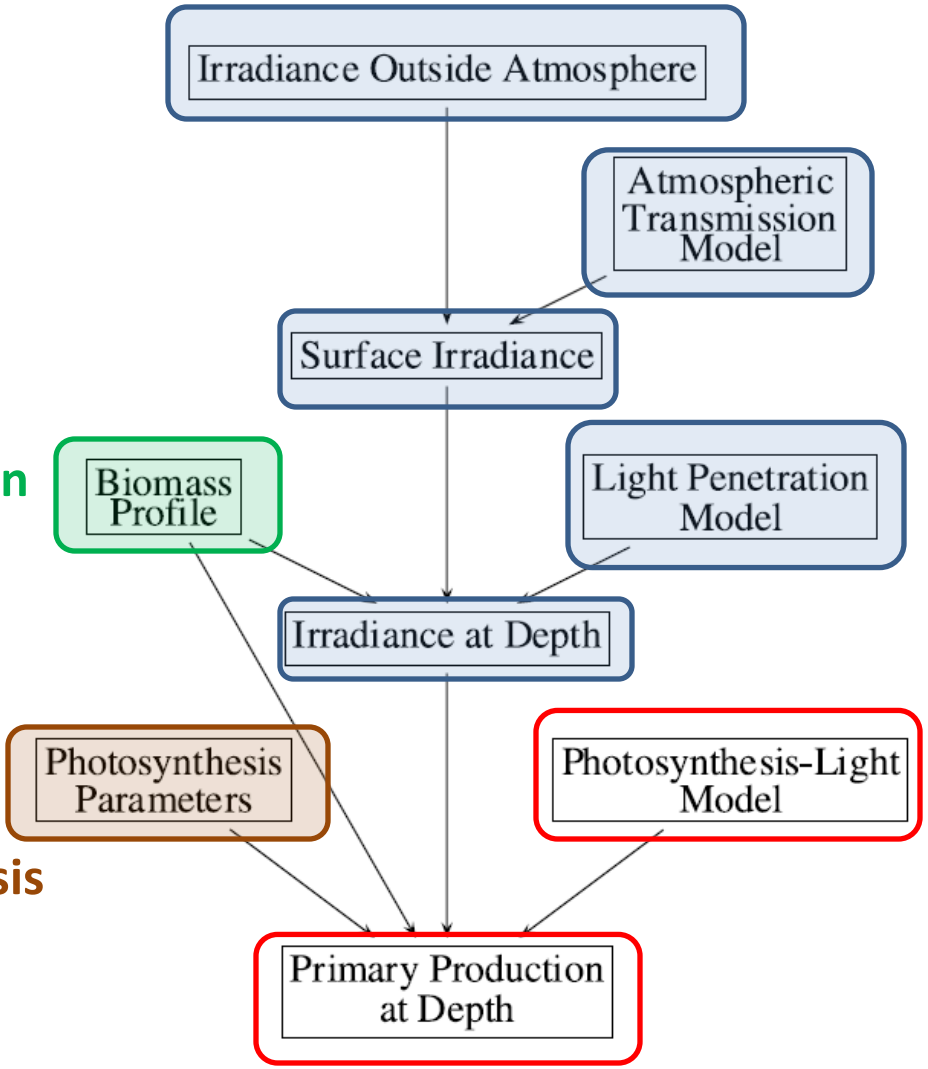
"On a global scale, marine phytoplankton consume fifty thousand million tones of carbon every year in a process referred to as **primary production**." **-- IOCCG Report #2**

food chain; carbon cycle

Elements of photosynthesis:



Components for PP quantification:



1. Phytoplankton

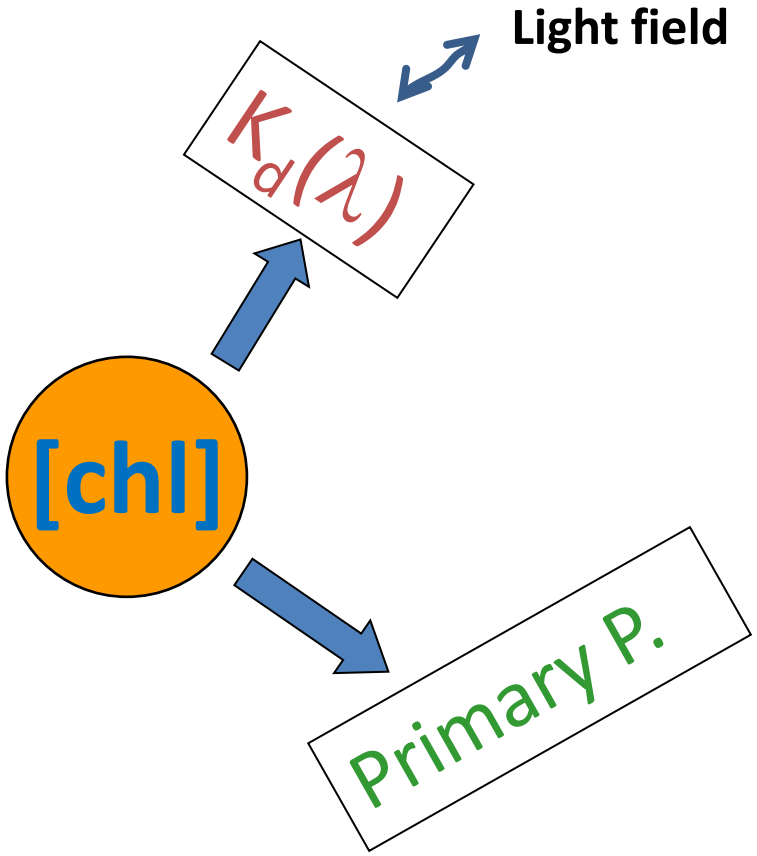
2. Light penetration

3. Photosynthesis parameters

(Platt and Sathyendranath, 2007)

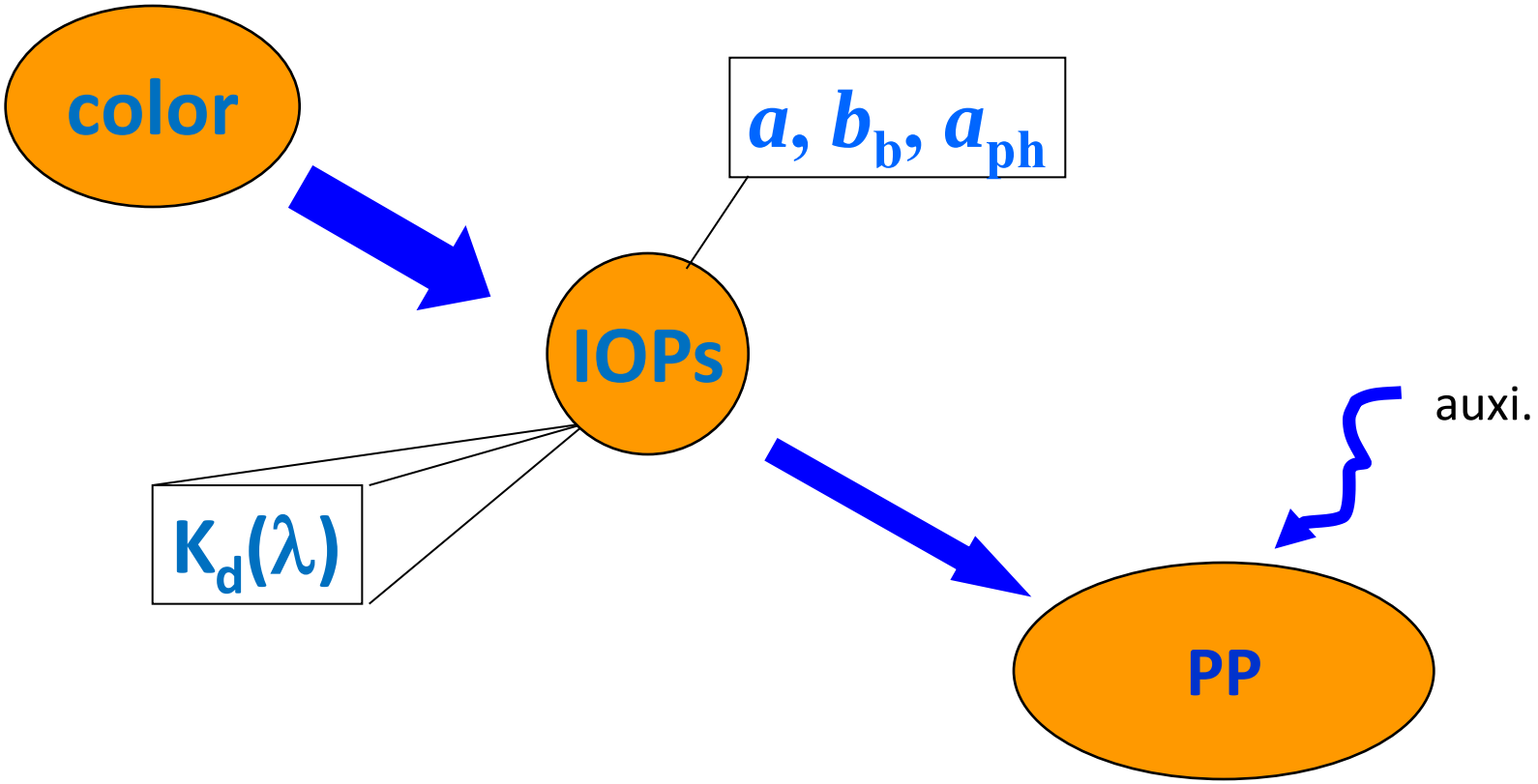
Traditional strategy: [chl] centered system

Ocean color spectrum ➔



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)

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

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

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

Aas (1987) two-stream solution:

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

$$\begin{cases} \dfrac{d}{dz}E_u = -(a + r_u b_b)E_{ou} + r_d\, b_b E_{od} \\ \dfrac{d}{dz}E_d = r_u b_b E_{ou} \quad -(a + r_d b_b)E_{od} \end{cases}$$

$$\frac{d}{dz}E_d = -cE_{od} + (b - r_d b_b)E_{od} + r_u b_b E_{ou}$$

$$\frac{d}{dz}E_d = -(a + r_d b_b)E_{od} + r_u b_b E_{ou}$$

$$\frac{d}{dz}E_d = -\frac{a + r_d b_b}{\mu_d}E_d + \frac{r_u b_b}{\mu_u}E_u$$

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

Approximation:

$$K_d = D_d(a + b_b)$$

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

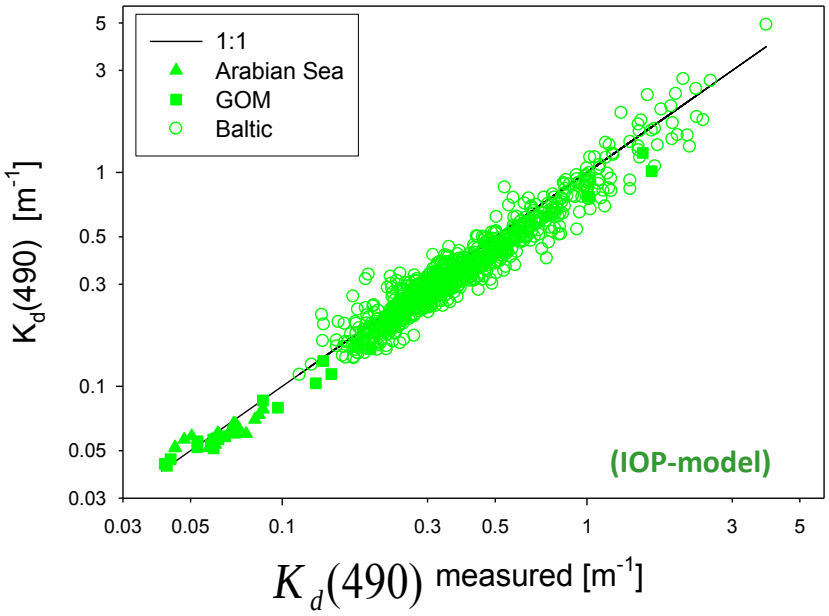
$$\mathrm{v} = m_1(1 - m_2 e^{-m_3 a})$$

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

R_{rs} → $a \& b_b$ → K_d

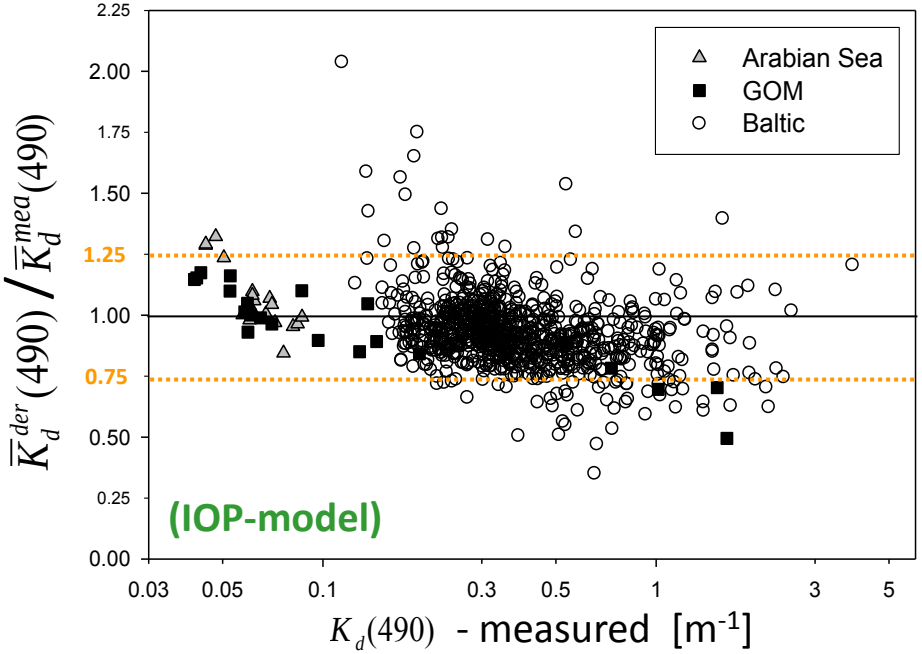
No division of "Case 1" or "Case 2" waters.

(*Lee et al. 2004a*)

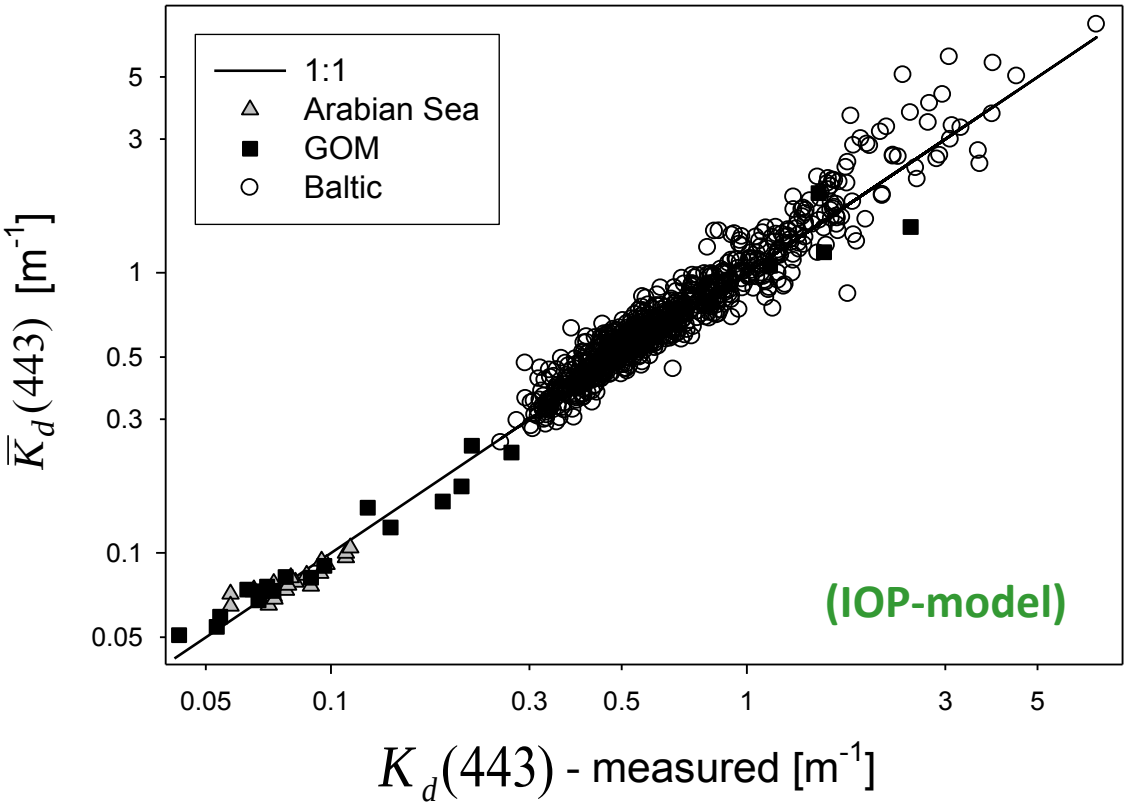


Oceanic & Coastal waters

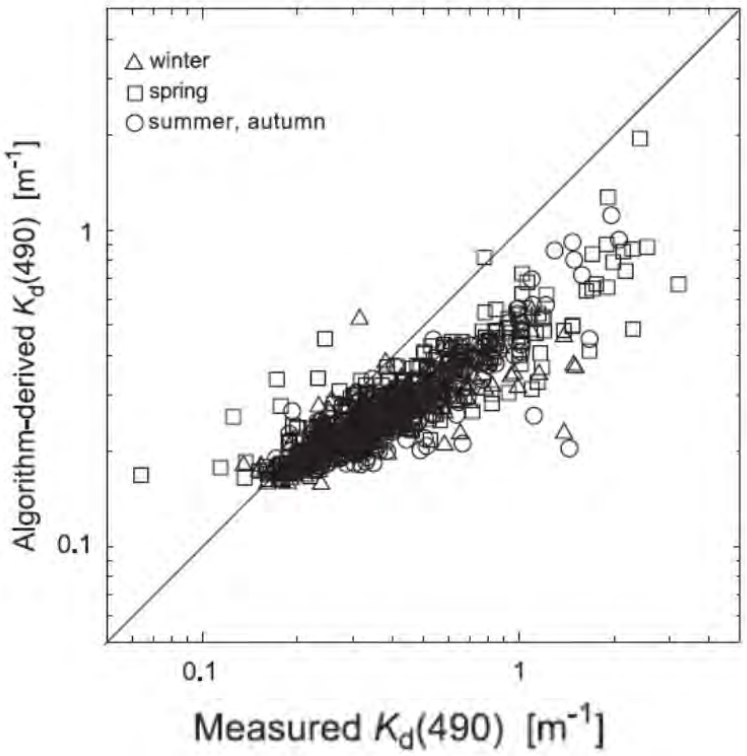
(*Lee et al. 2004a*)

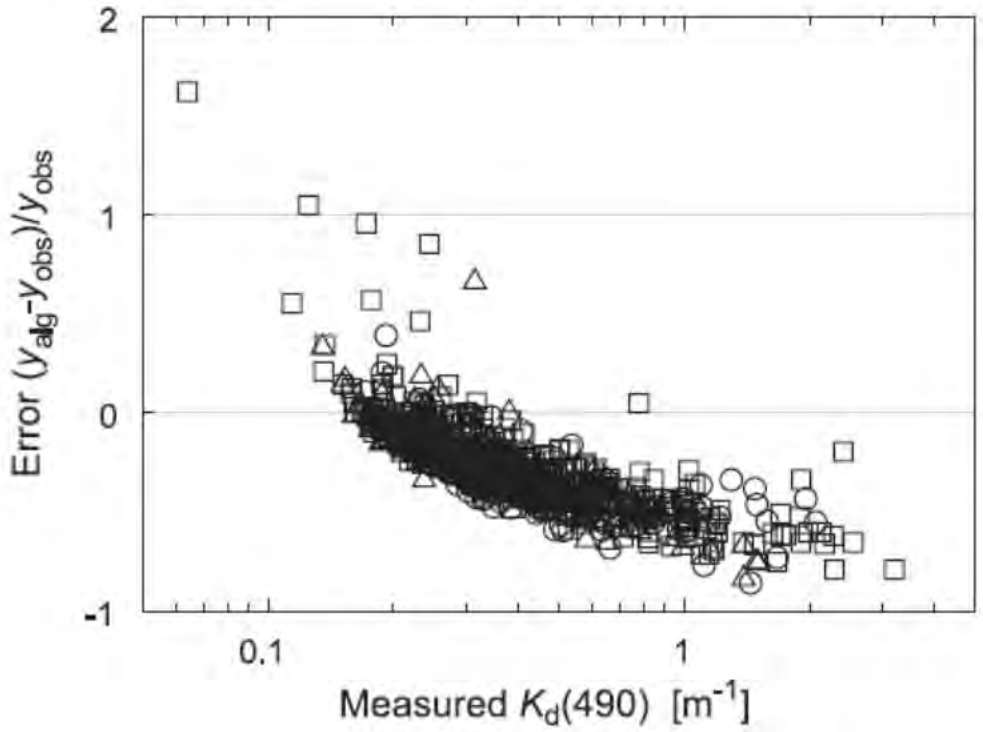


Other wavelength:



Ratio-derived Kd





(Darecki and Stramisk, 2004)

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

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

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)

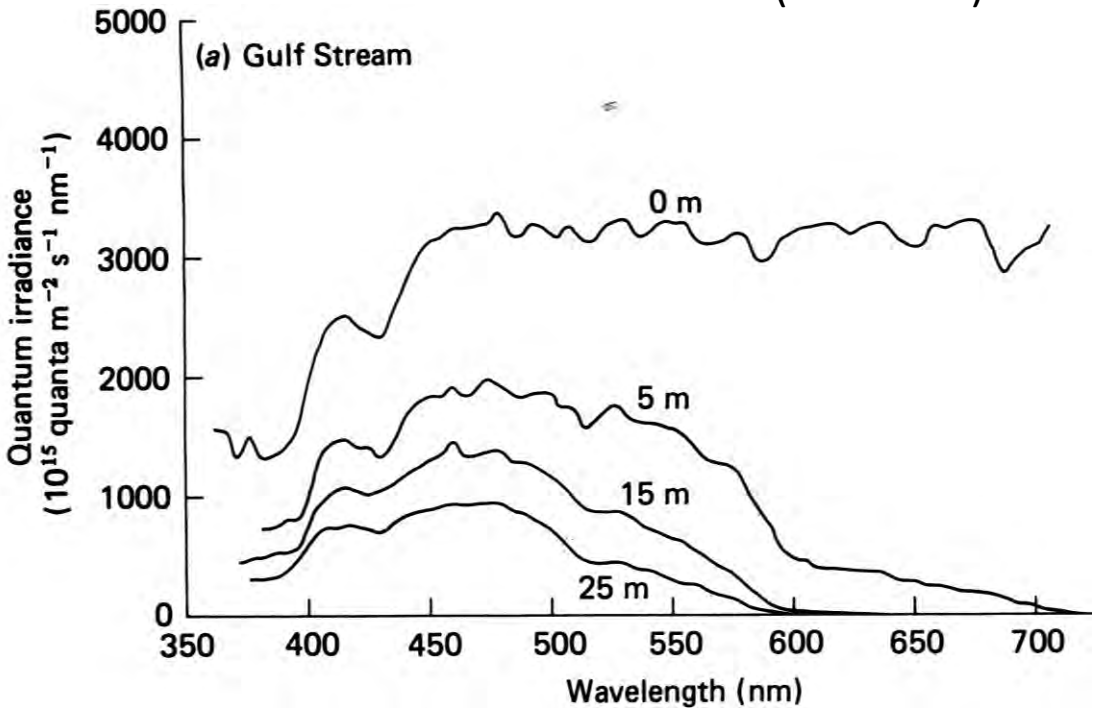
$$K_{PAR} = \frac{-1}{z} \ln\left(\frac{PAR(z)}{PAR(0)}\right)$$

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

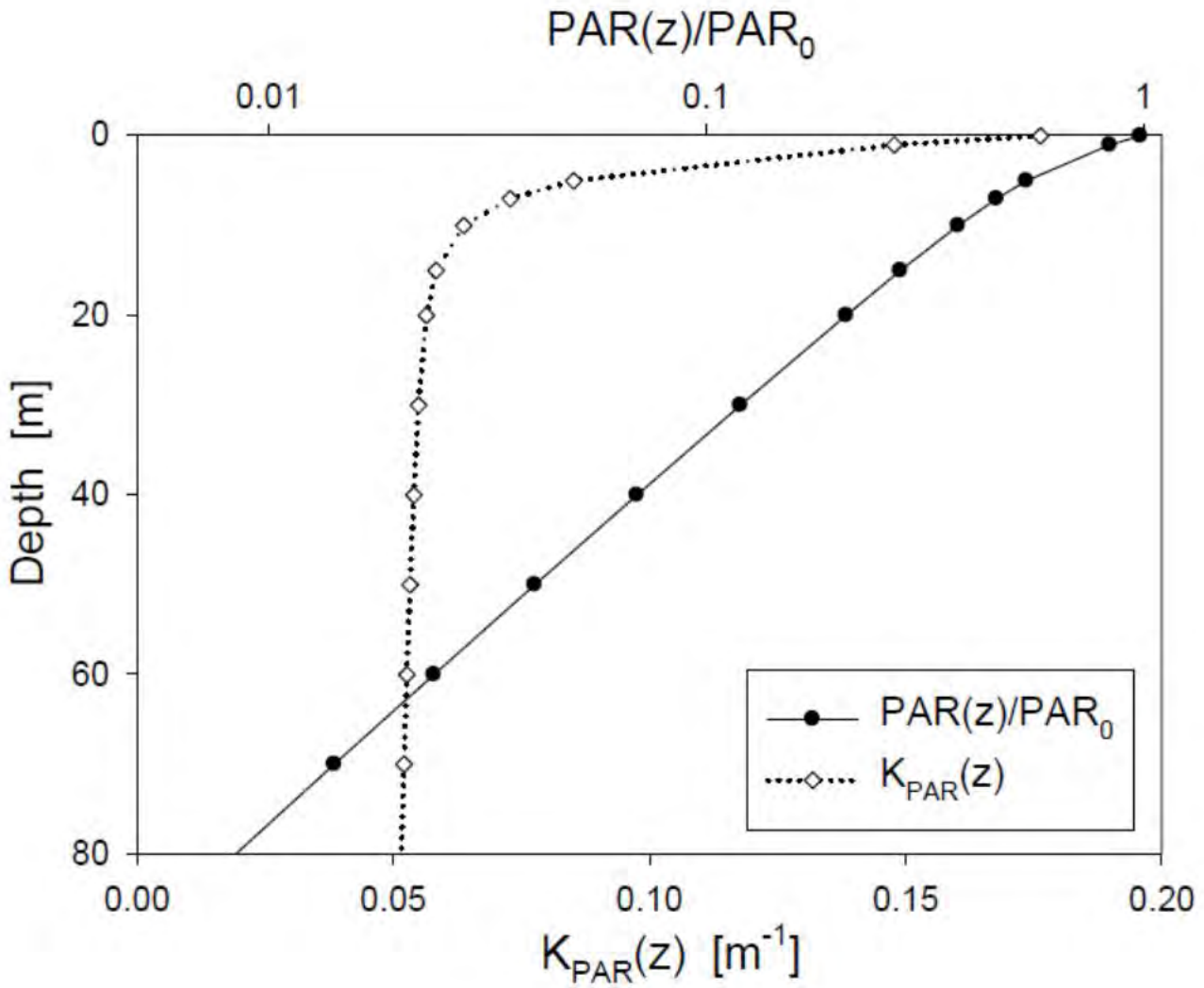
K_{PAR} is light-quality weighted!

Change of light with depth:

(Kirk 1994)



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


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

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

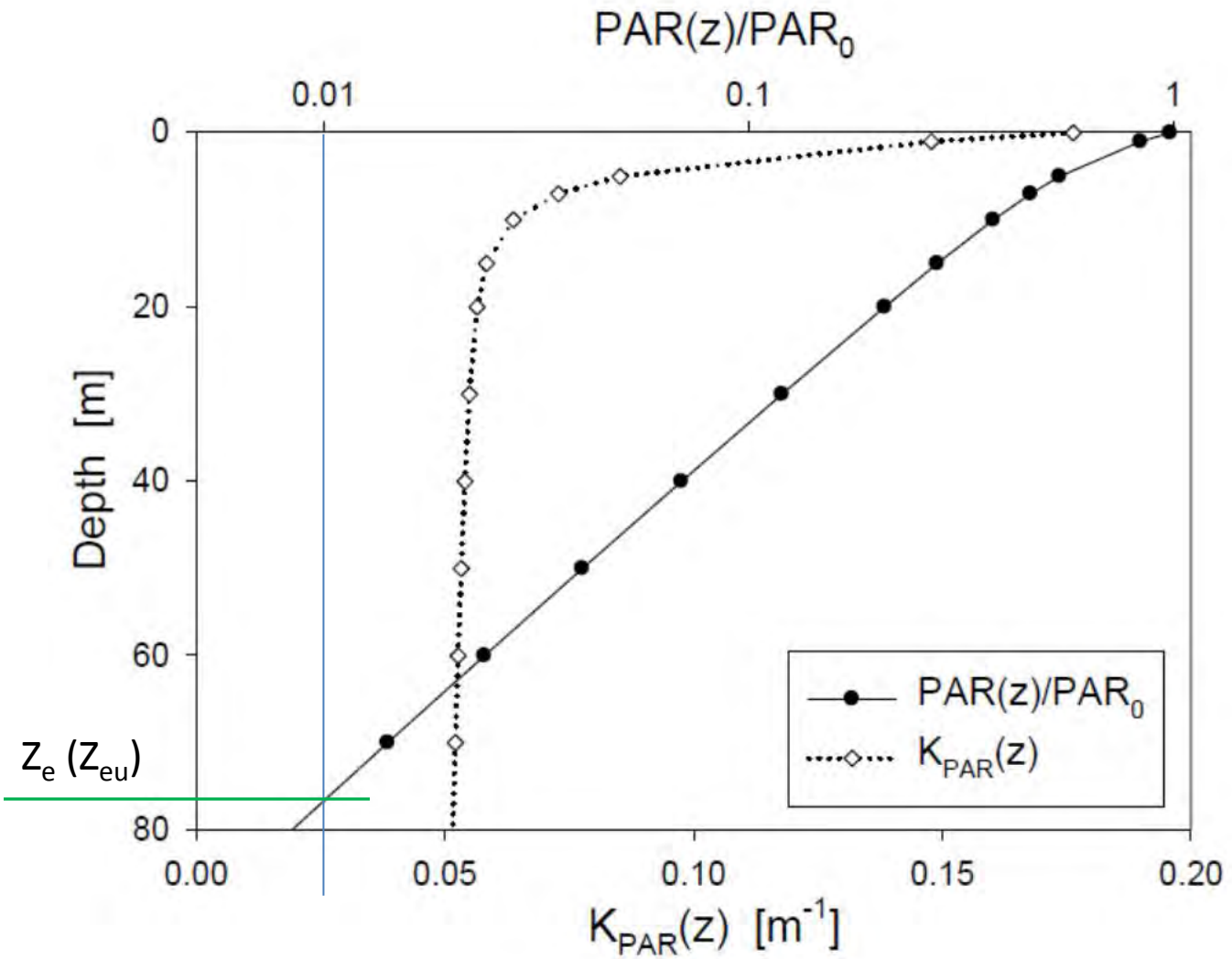
$$K_{PAR}(z) \approx K_1 + \frac{K_2}{(1+z)^{0.5}}$$

Key:

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

Euphotic depth (z_{eu}):

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



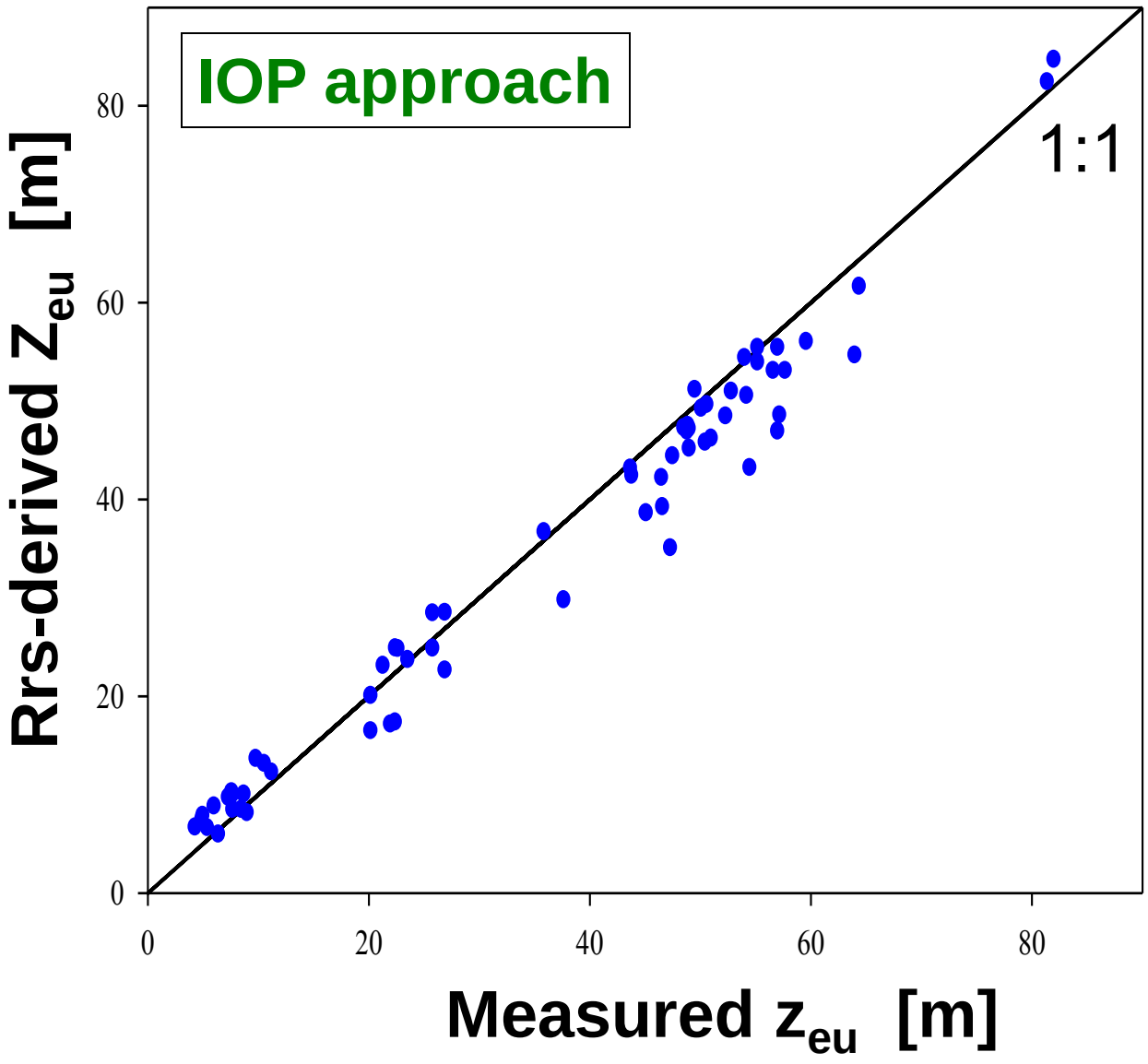
$$\frac{PAR(z_{eu})}{PAR(0)} = 1\%$$

IOP approach:

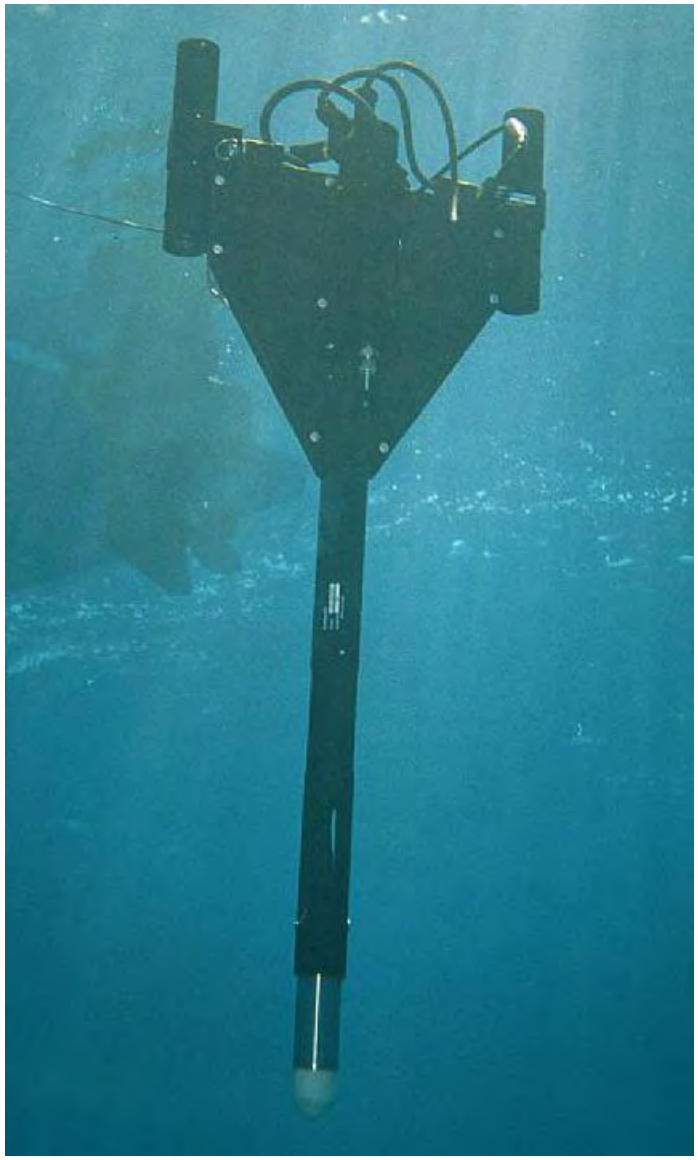
$$\mathrm{Rrs}(\lambda) \rightarrow a(\lambda)\&b_b(\lambda) \rightarrow K_{\mathrm{PAR}}(z) \rightarrow z_{eu}$$

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

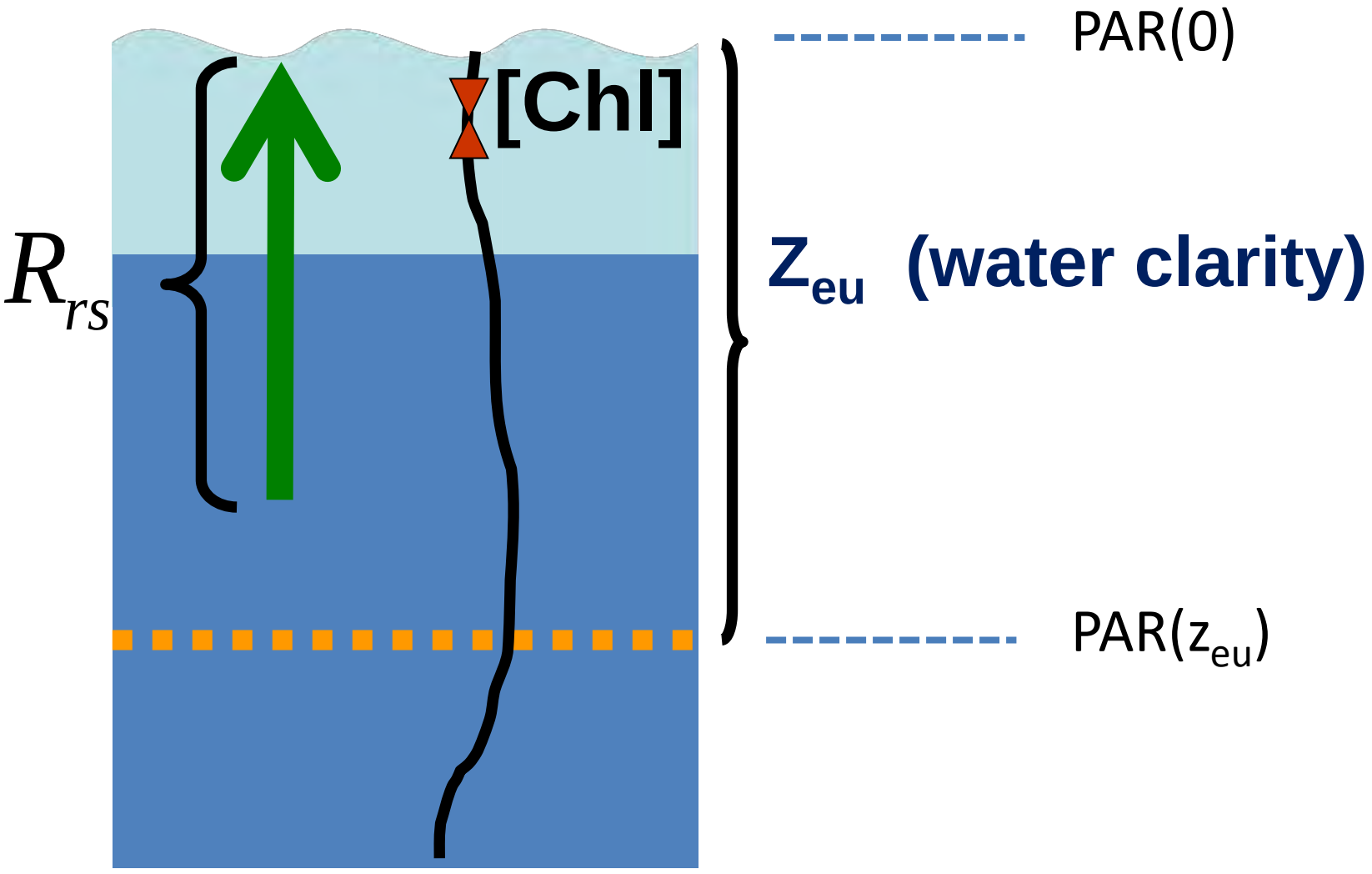
Water clarity (z_{eu})



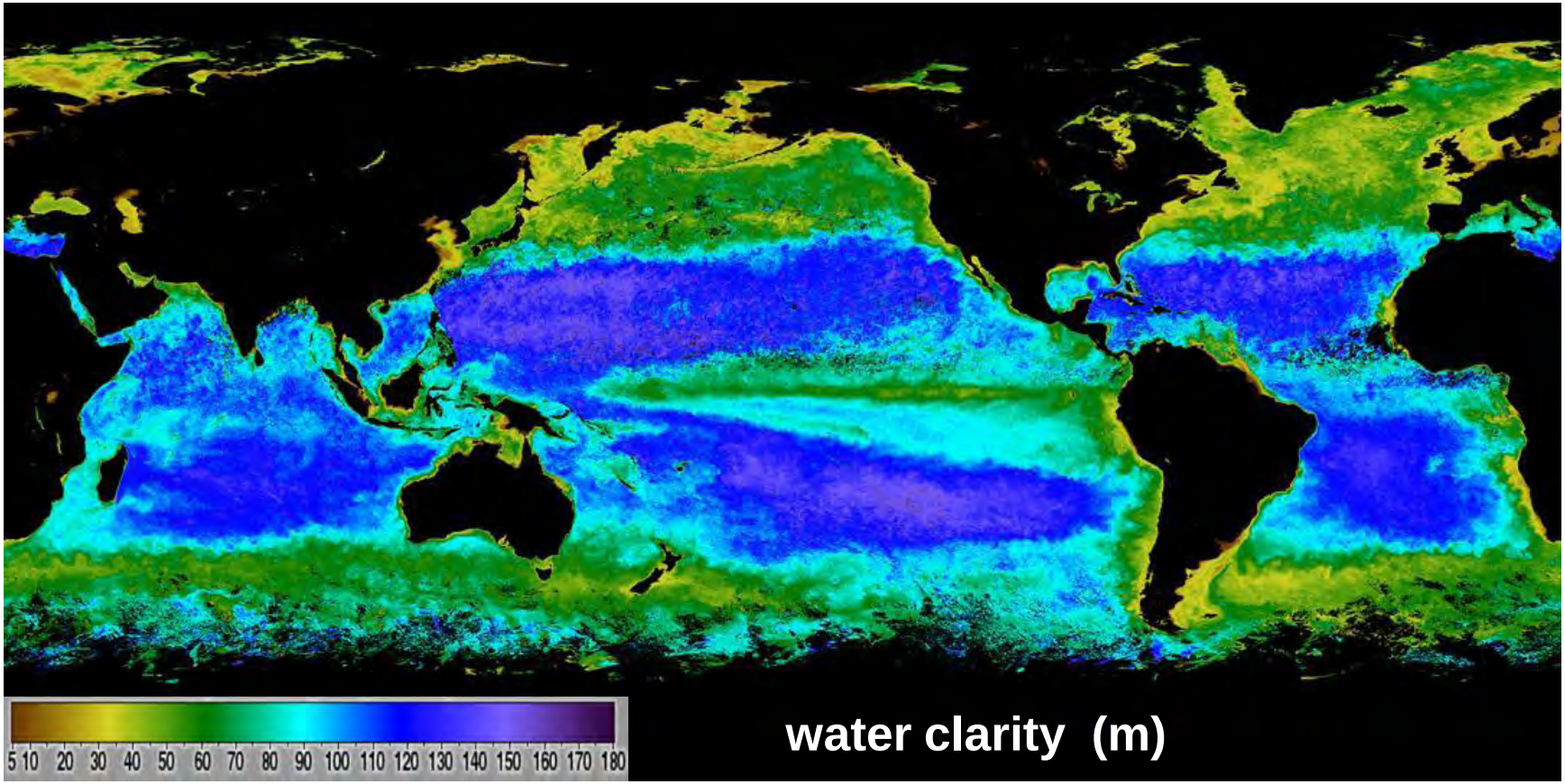
Z_{eu} can be ‘measured’ with advance optical-electronic system



Euphotic depth (Z_{eu})

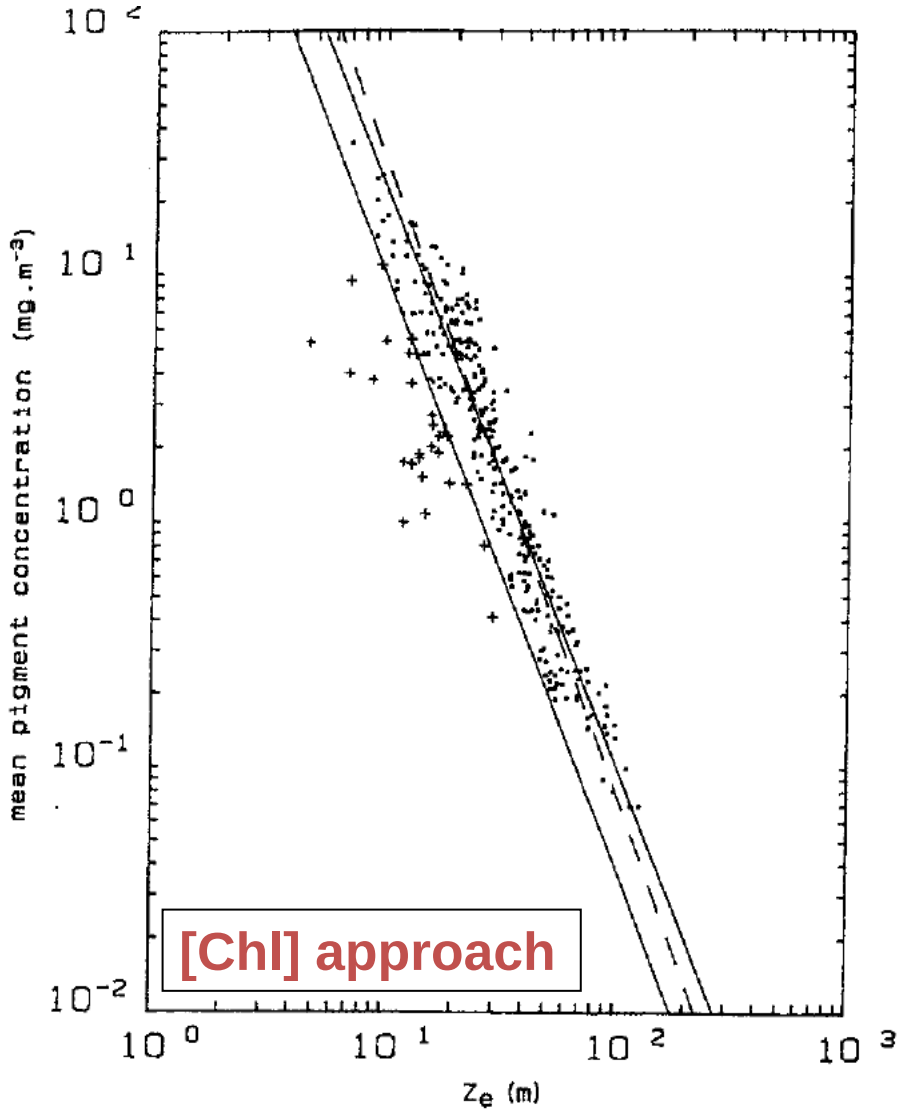


Global distribution of Z_{eu}



[Chl] (empirical) approach:

Rrs(λ) → [Chl] → z_{eu}



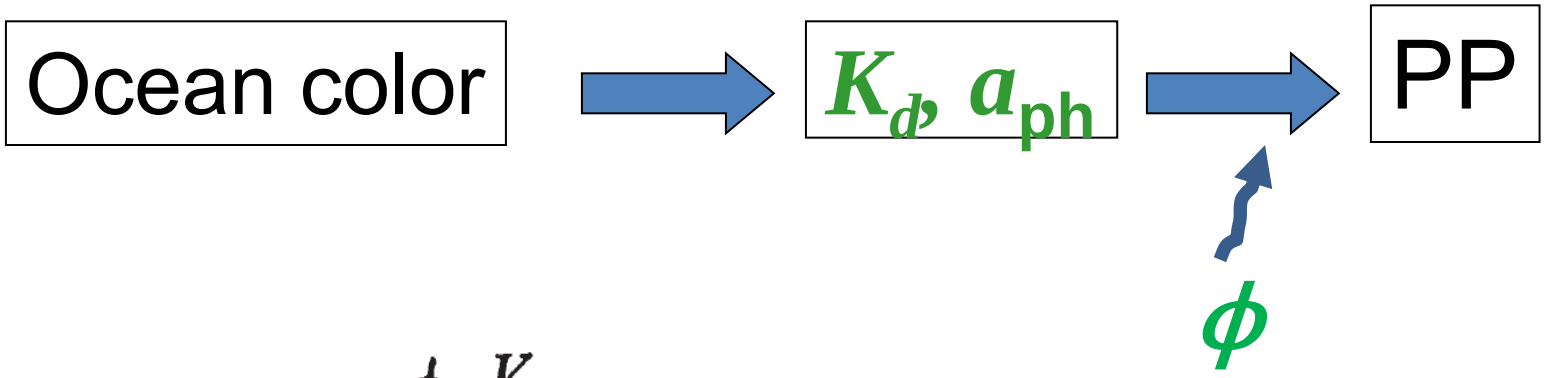
$$Z_e = 38.0C^{-0.428}$$

(Morel 1988)

1.3 IOP based PP estimation:

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

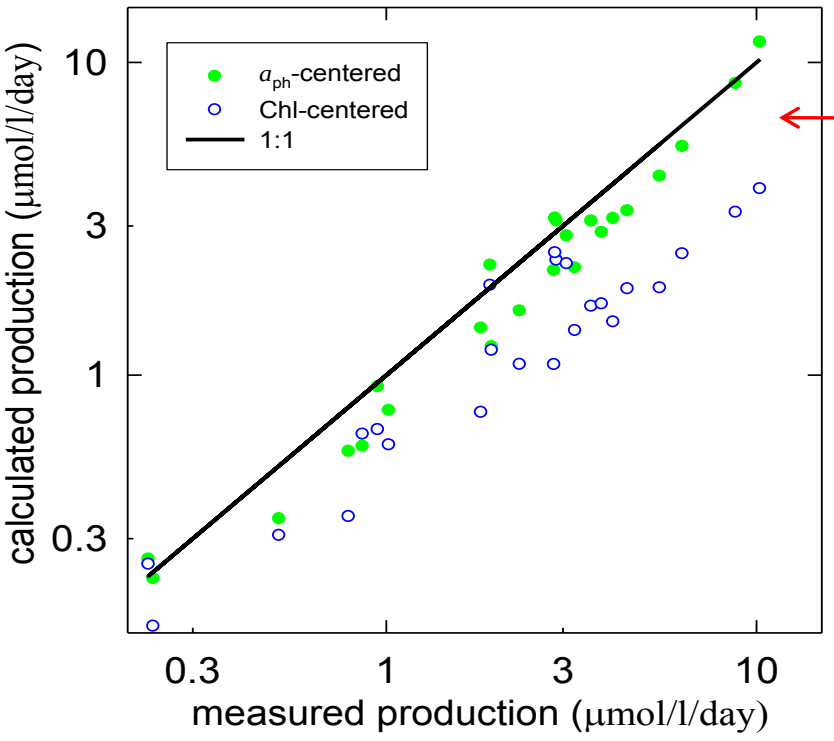
represents 'photosynthesis'



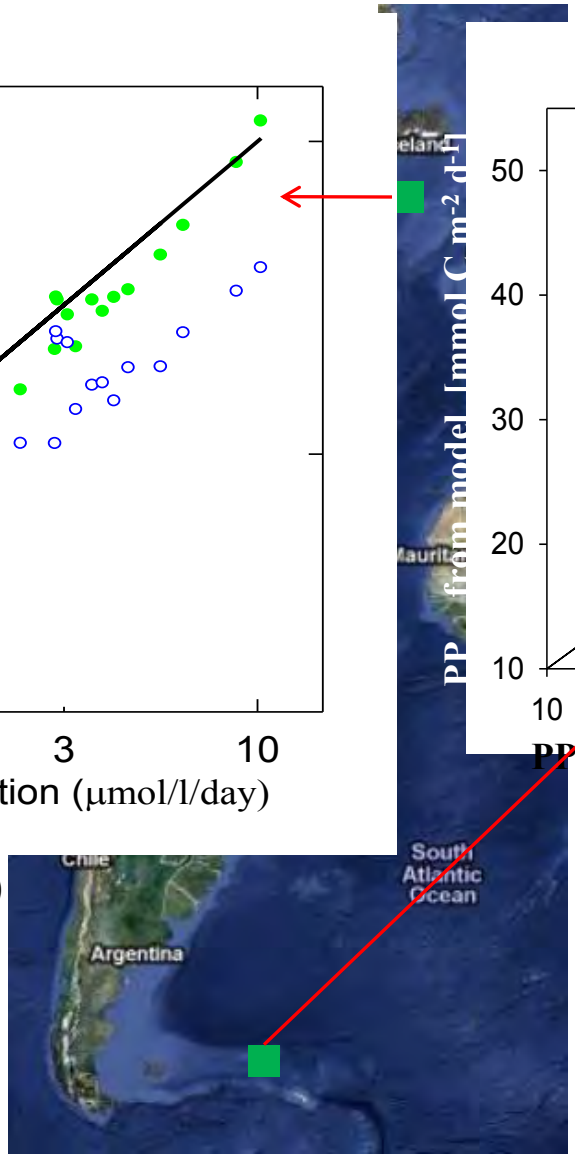
$$\phi(E_o) = \frac{\phi_m K_\phi}{K_\phi + E_o} \qquad (2)$$

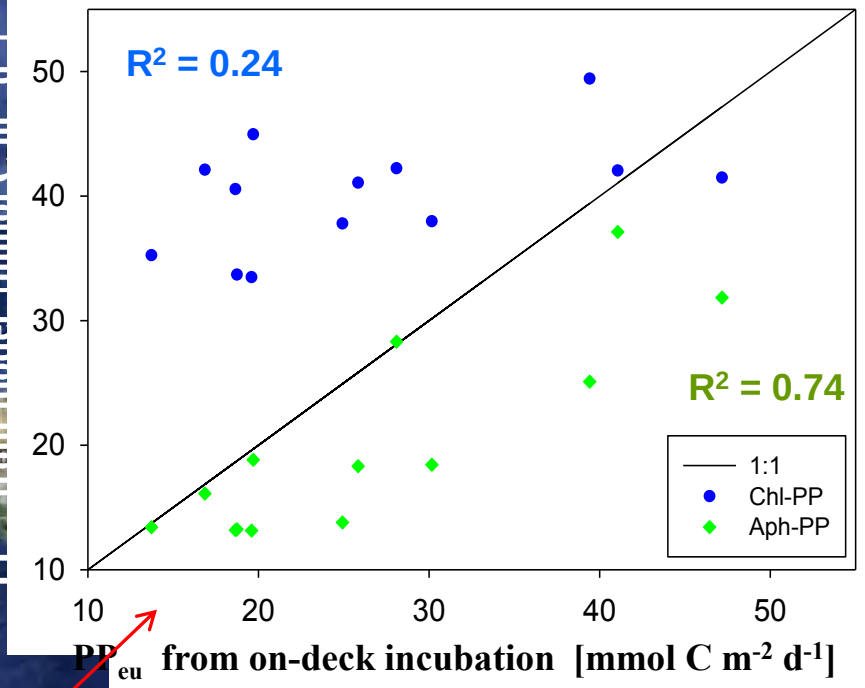
(Kiefer and Mitchell, 1983, L&O)

Remotely-estimated PP compared with measured PP



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





(*Lee et al., JGR, 2010*)

Why a_{ph} based approach is likely better?

Essence of present satellite Chl product:

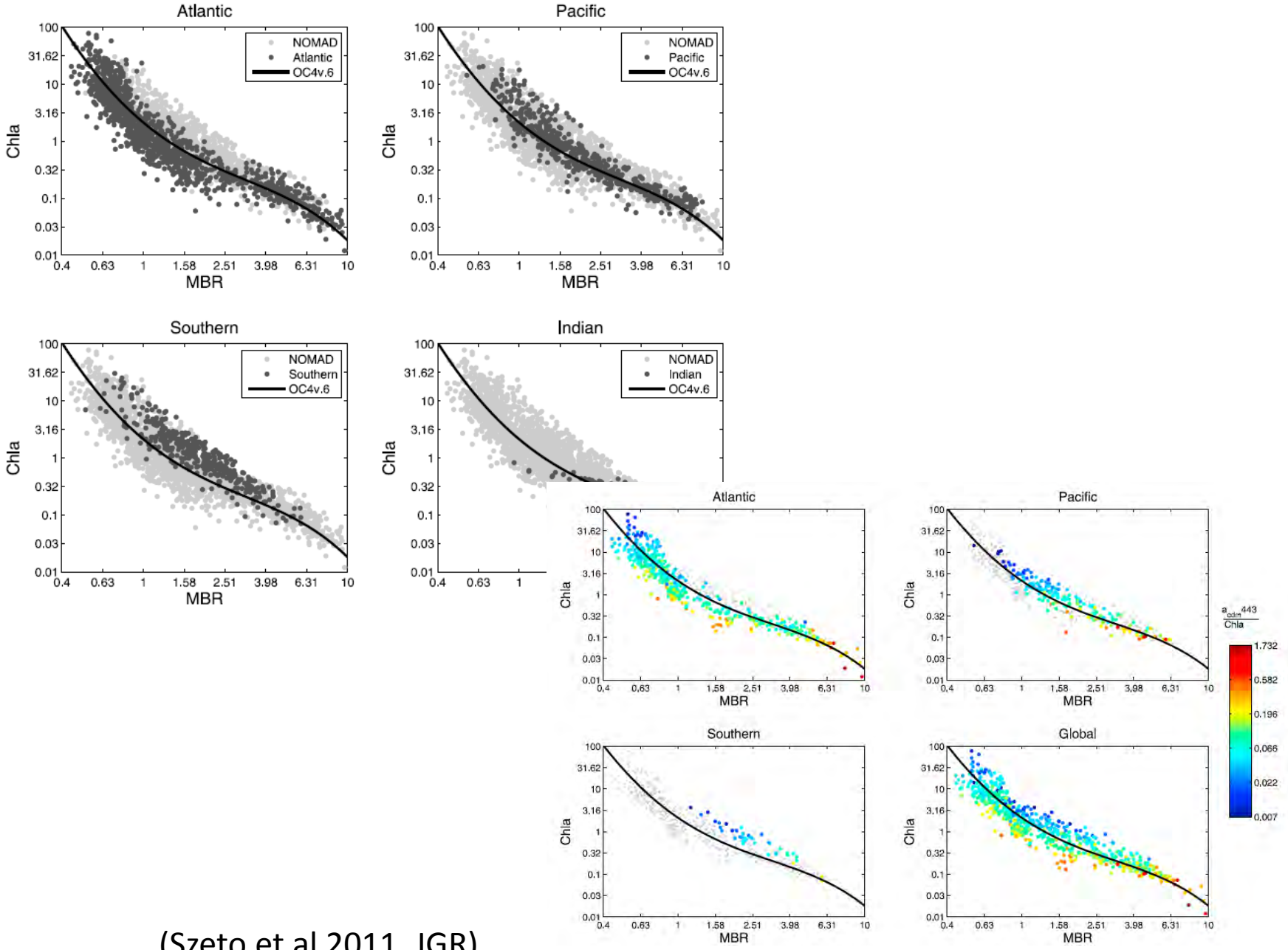
$$Chl = fun\left(\frac{R_{rs}(\lambda_1)}{R_{rs}(\lambda_2)}\right)$$

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

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

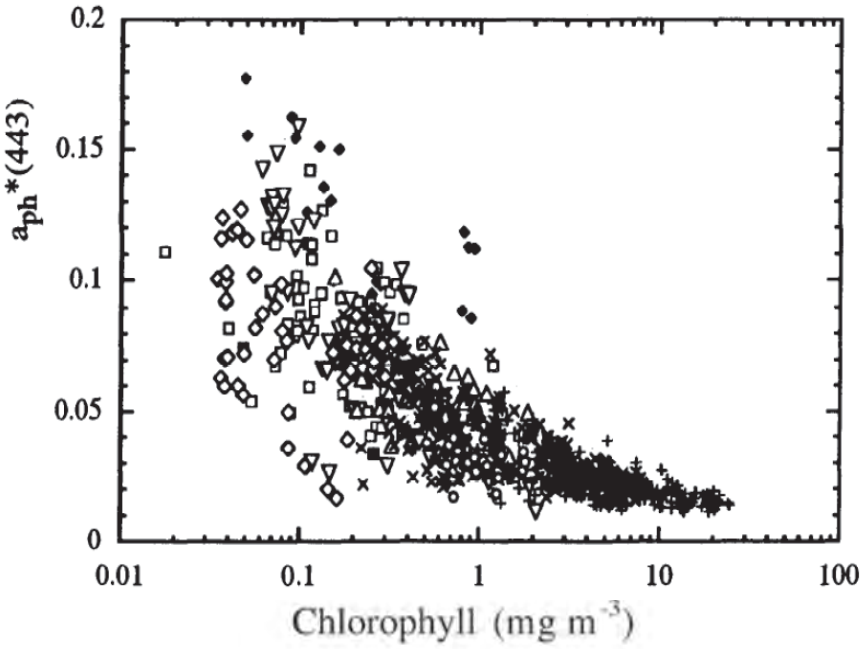
$$\frac{R_{rs}(440)}{R_{rs}(550)} \propto \frac{a(550)}{a(440)} = \frac{a_w(550)+a_{dg}(550)+a^*_{ph}(550)Chl}{a_w(440)+a_{dg}(440)+a^*_{ph}(440)Chl}$$

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

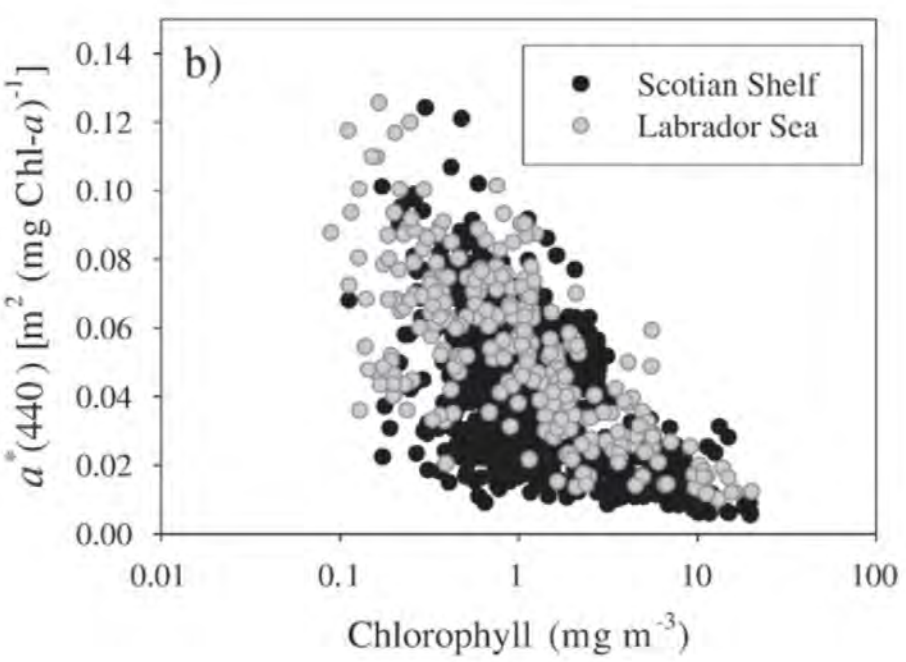


(Szeto et al 2011, JGR)

In addition:



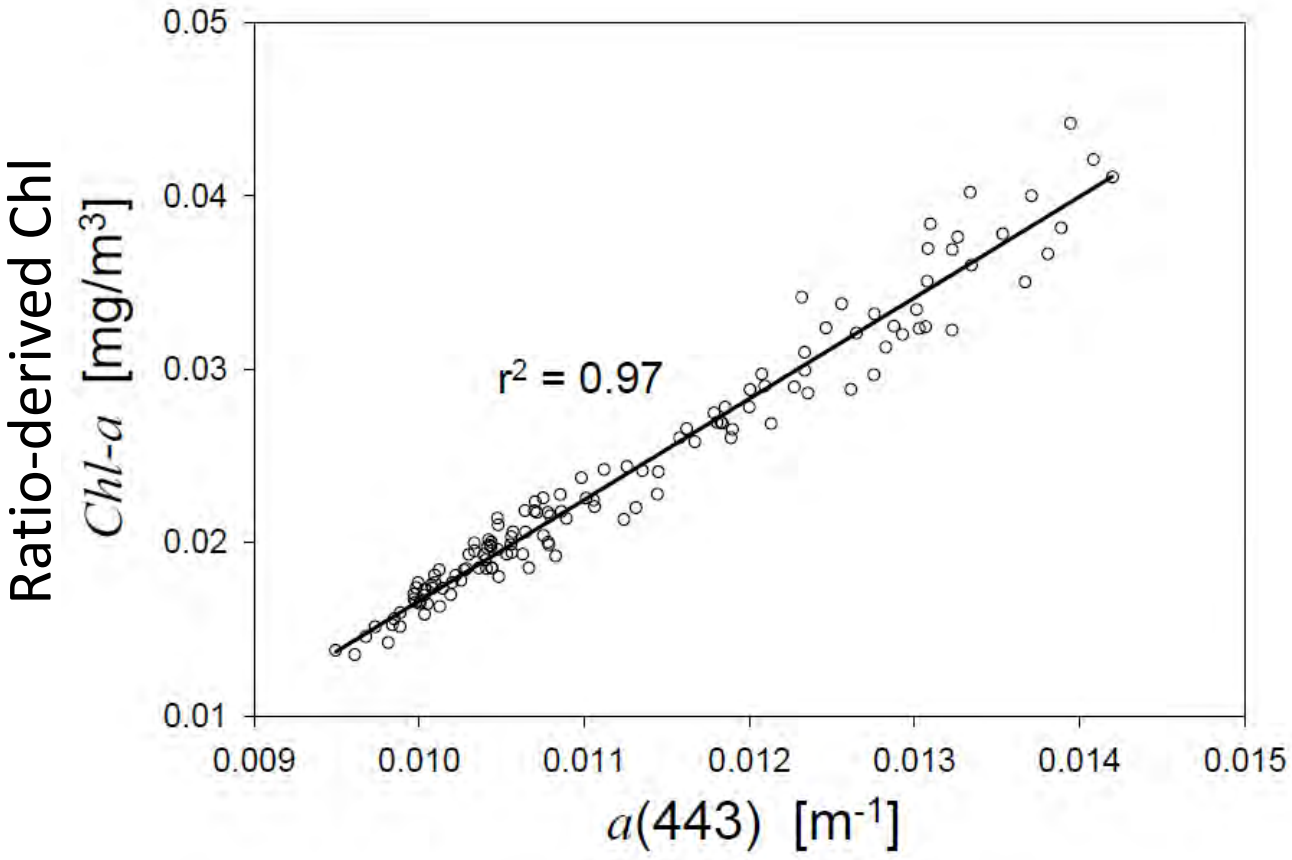
(Bricaud et al 1995, JGR)



(Platt et al, RSE, 2008)

Phytoplankton- (or chlorophyll-) specific absorption coefficient is not a constant for either a given Chl or varying Chl.

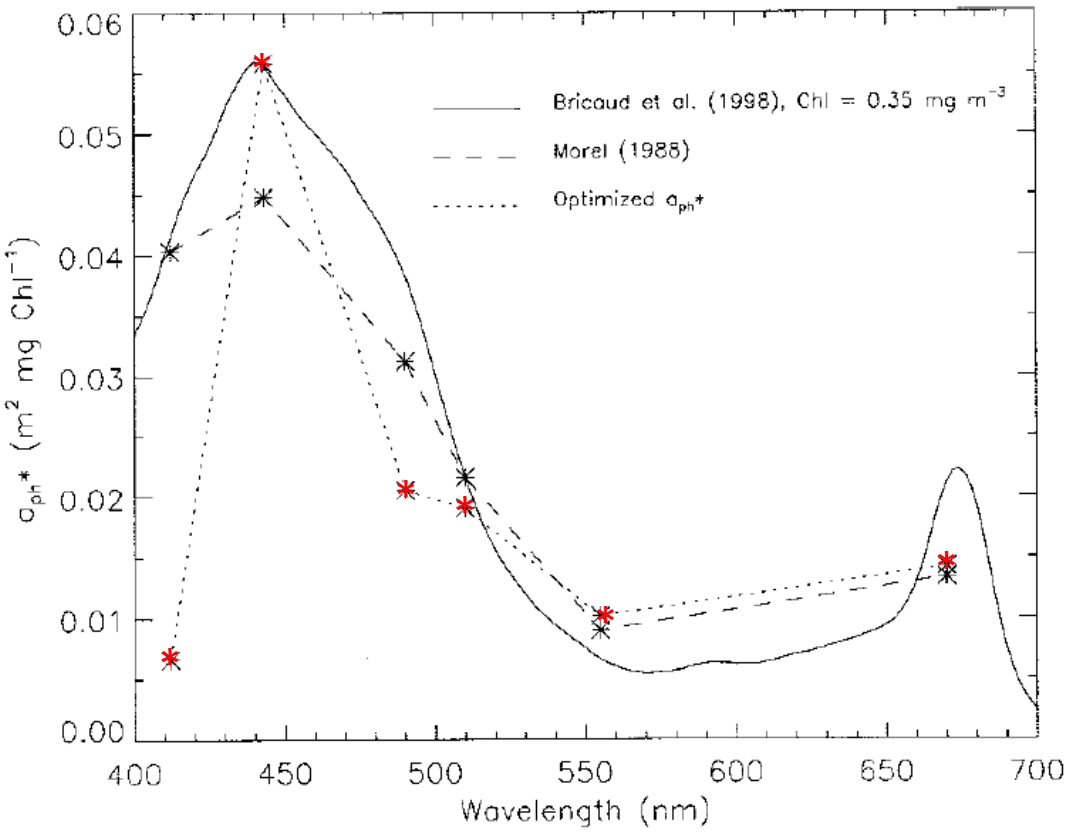
The change of Rrs ratio really reflects change of total absorption!



(Lee et al, 2010, JGR)

GSM

$$\hat{L}_{wN}(\lambda) = \frac{tF_0(\lambda)}{n_w^2} \sum_{i=1}^{2} g_i \left\{ \frac{b_{bw}(\lambda) + b_{bp}(\lambda_0)(\lambda/\lambda_0)^{-\eta}}{b_{bw}(\lambda) + b_{bp}(\lambda_0)(\lambda/\lambda_0)^{-\eta} + a_w(\lambda) + \mathrm{Chl}\, a_{\mathrm{ph}}{}^*(\lambda) + a_{\mathrm{cdm}}(\lambda_0)\exp[-S(\lambda - \lambda_0)]} \right\}^i. \quad (4)$$



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)

p^b:

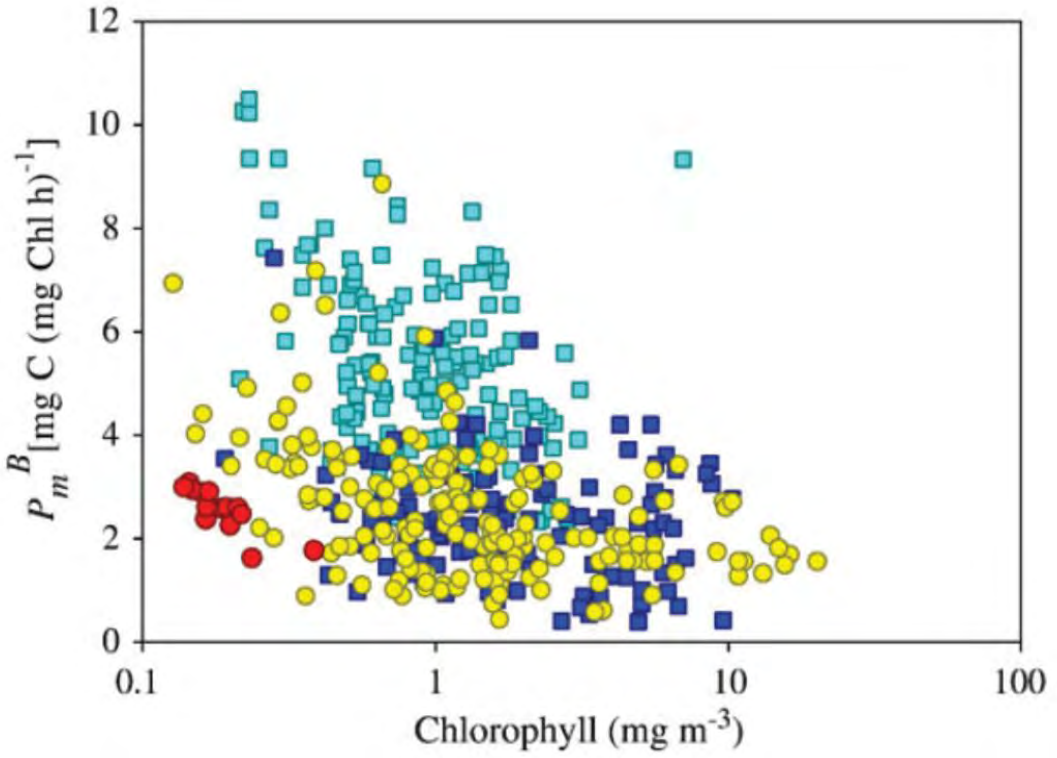
(Behrenfeld and Falkowski, 1997)

II. Time-integrated models (TIMs)

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

IV. Depth-integrated models (DIMs)

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



$$p^b \propto \phi_m \, a^*_{ph}$$

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)

$$\mu = 2 \times \mathrm{Chl}:\mathrm{C}_{\mathrm{sat}} / \left[0.022 + (0.045 - 0.022)\exp^{-3\mathrm{Ig}}\right] \times \left(1 - \exp^{-3\mathrm{Ig}}\right).$$

(Behrenfeld et al 2005; Westberry et al 2008)

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

actually a_{ph} from GSM

b_{bp}

'IOP-based growth rate'

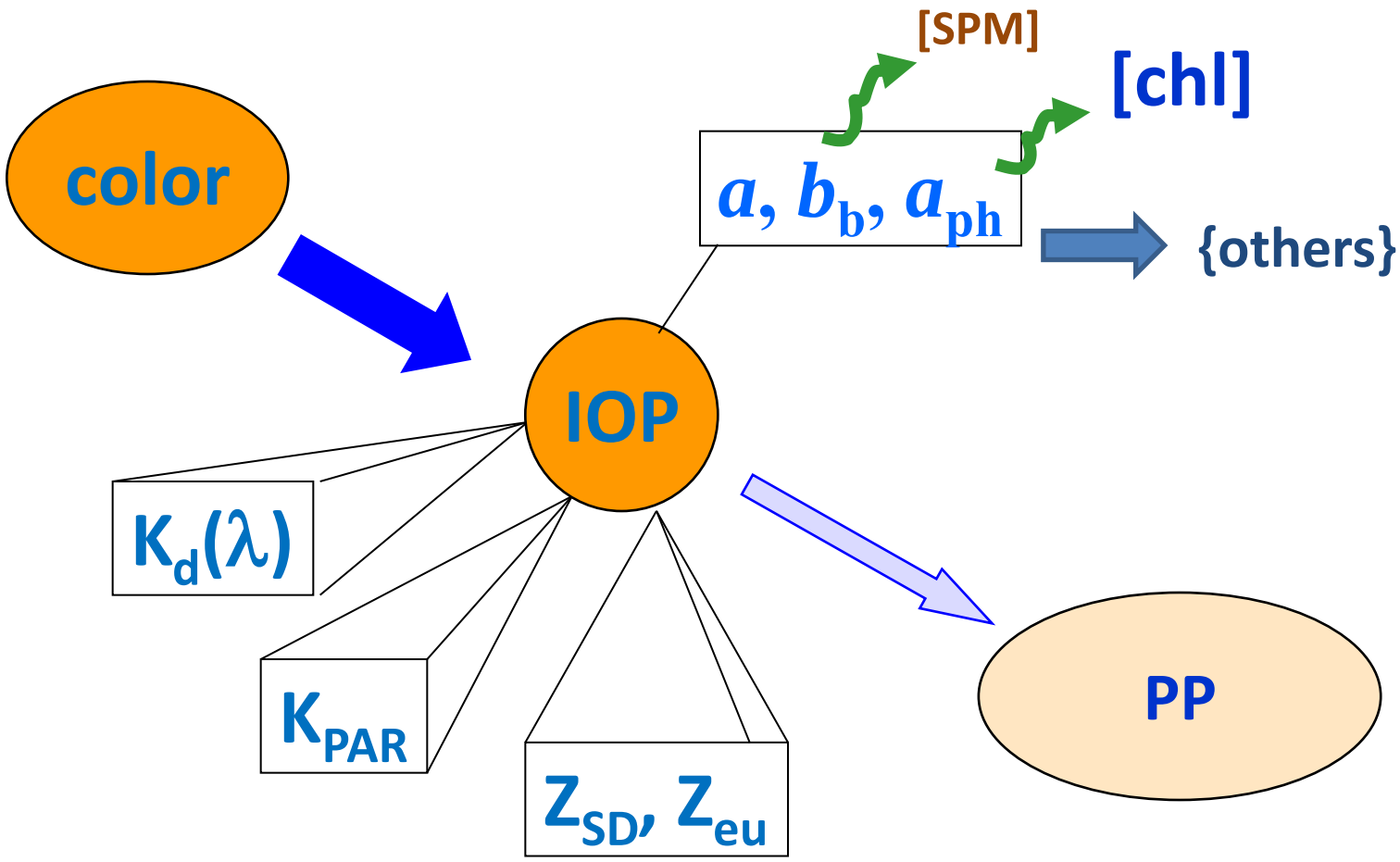
$$\mathrm{NPP} = \mathrm{C} \times \mu \times \mathrm{Z}_{\mathrm{eu}} \times h(\mathrm{I}_0),$$

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

a_{ph} from GSM

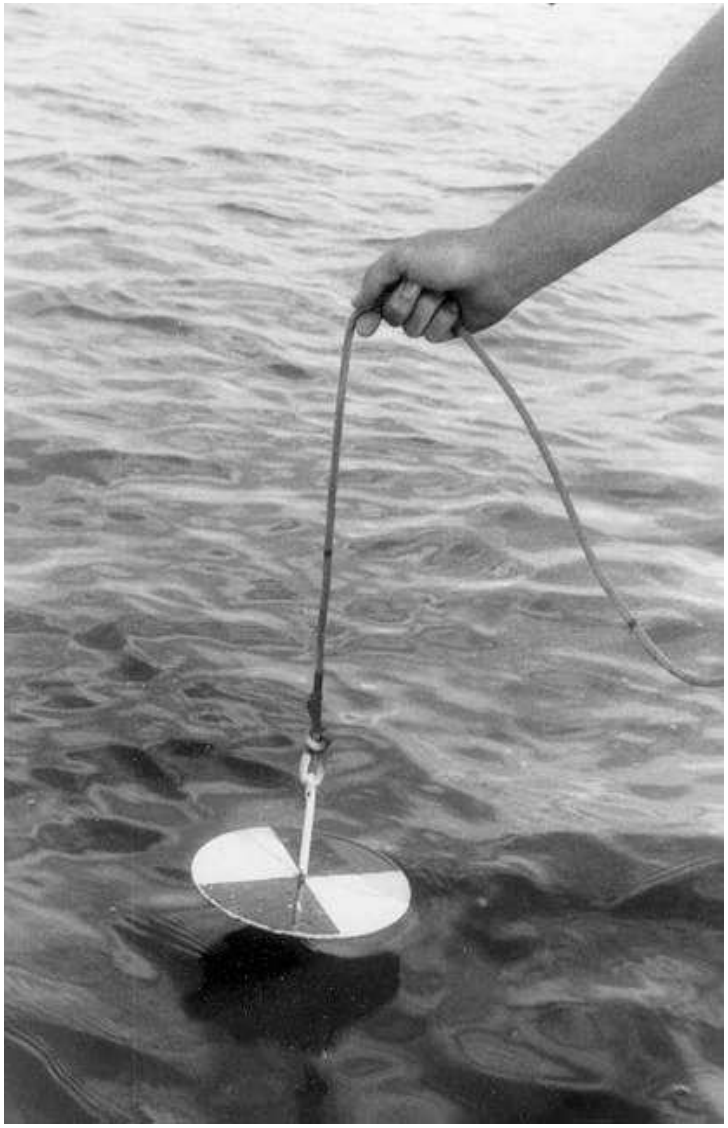
'IOP-based NPP'

2. Example of other applications of IOP products



Works for most waters.

2.1 Secchi depth (Z_{SD})



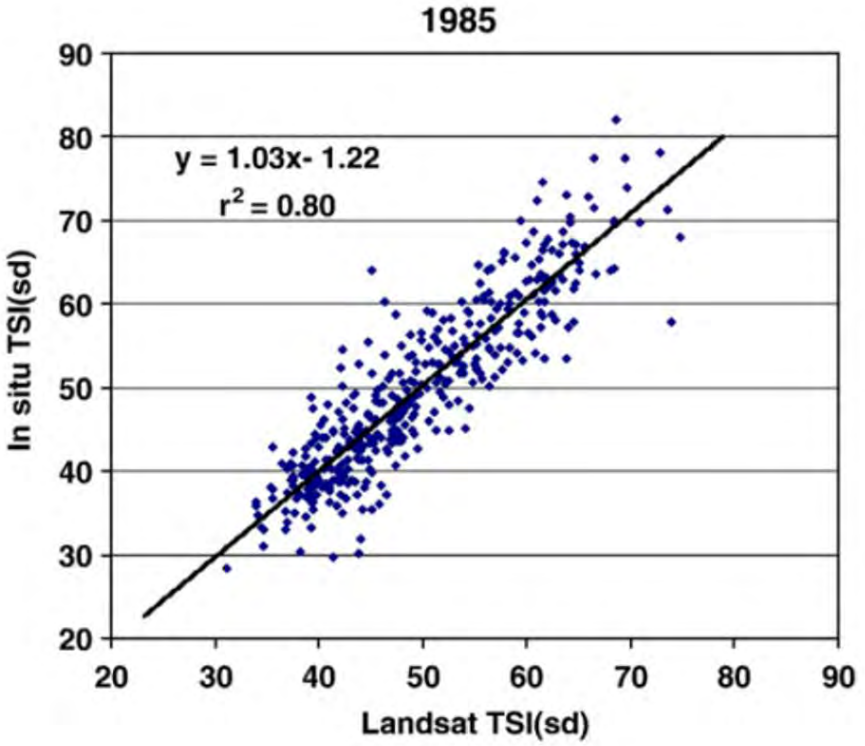
Water clarity

empirical approach:

least-squares multiple regression using the general form:

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

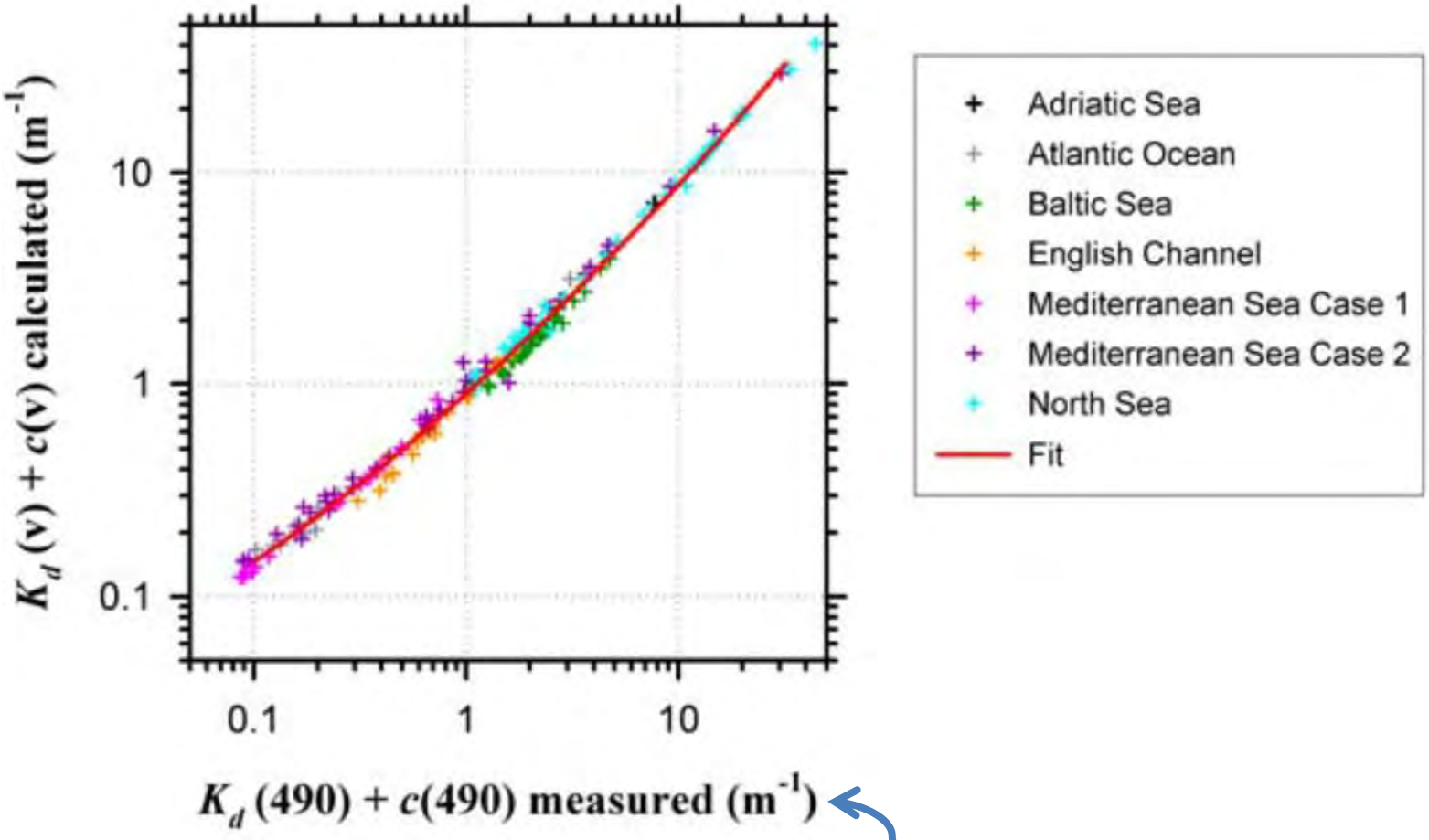
where a, b and c are coefficients fit to the calibration data by the regression analysis, ln(SD) is the natural logarithm of Secchi depth for a given lake, and TM1 and TM3 are the Landsat brightness values for the selected lake pixels in the blue and red bands, respectively. Kloiber



(Olmanson et al 2008)

IOP approach:

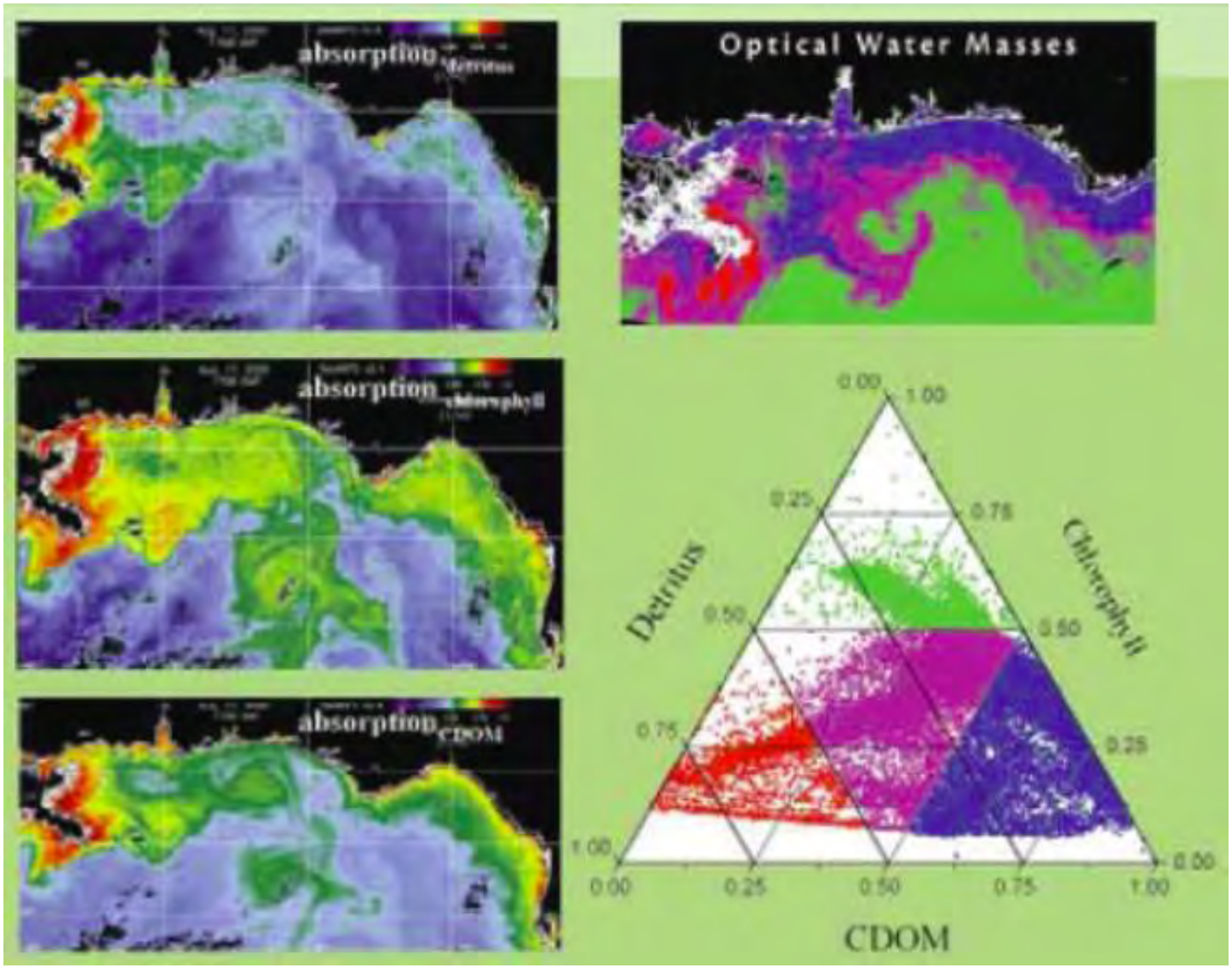
$$Z_{SD} = \frac{\ln\left(\frac{C_0}{C_{min}}\right)}{K_d(v) + c(v)},$$



$a(490)$ & $b_b(490)$

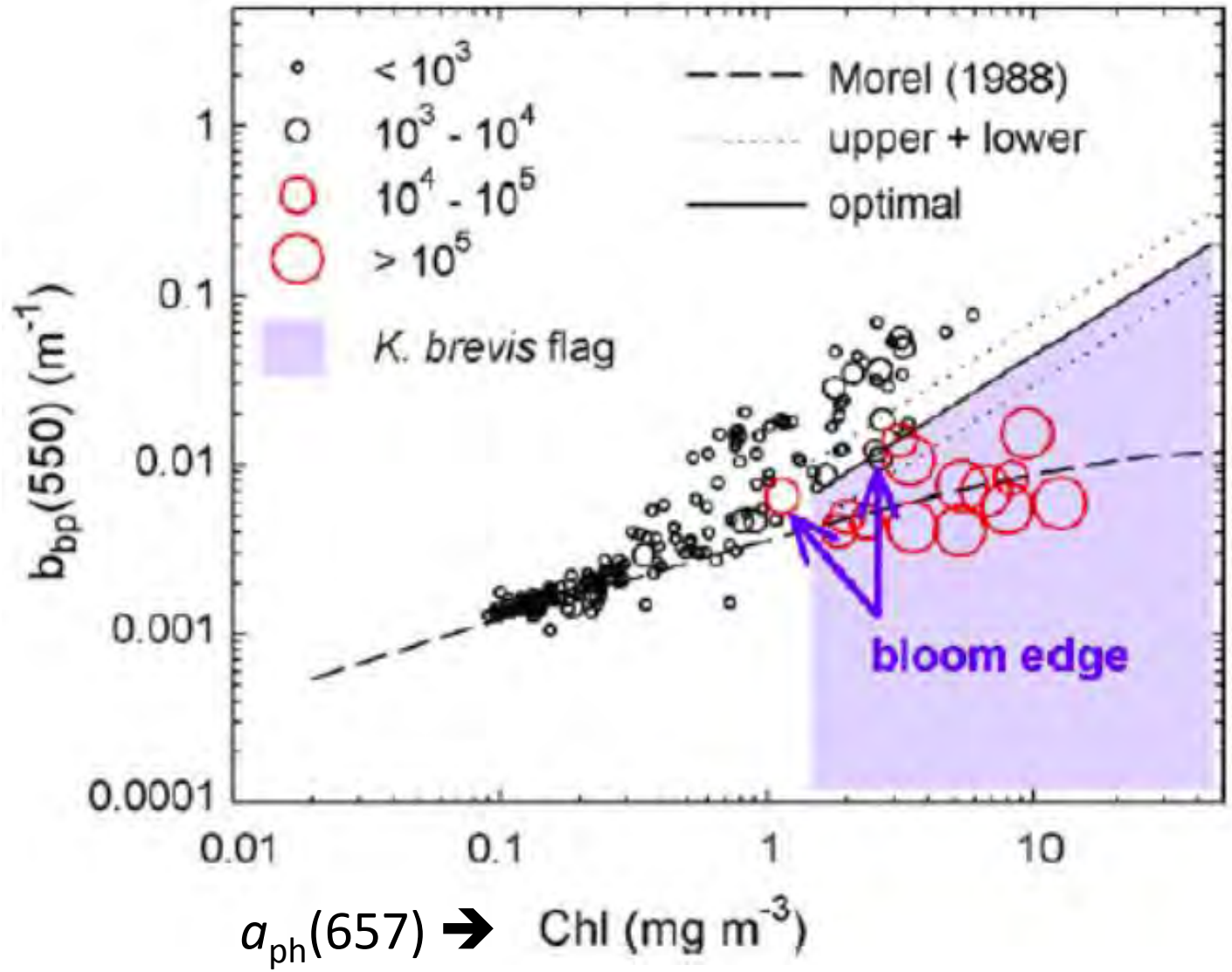
(Doron et al 2007)

2.2 Water mass classification



(Arnone et al 2004)

2.3 HAB identification



(Carnizzaro et al 2006)

2.3 Salinity estimation

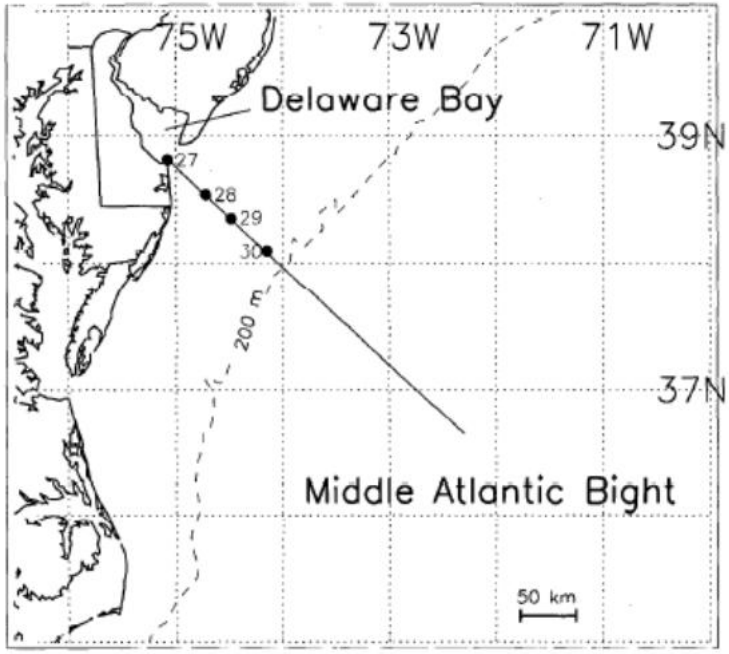
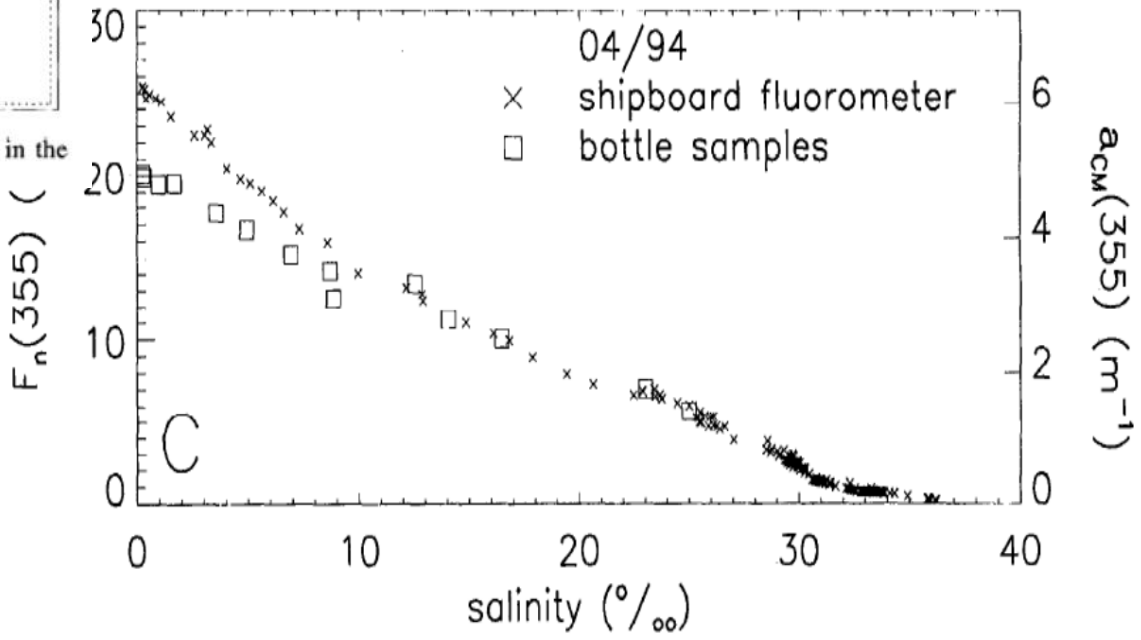
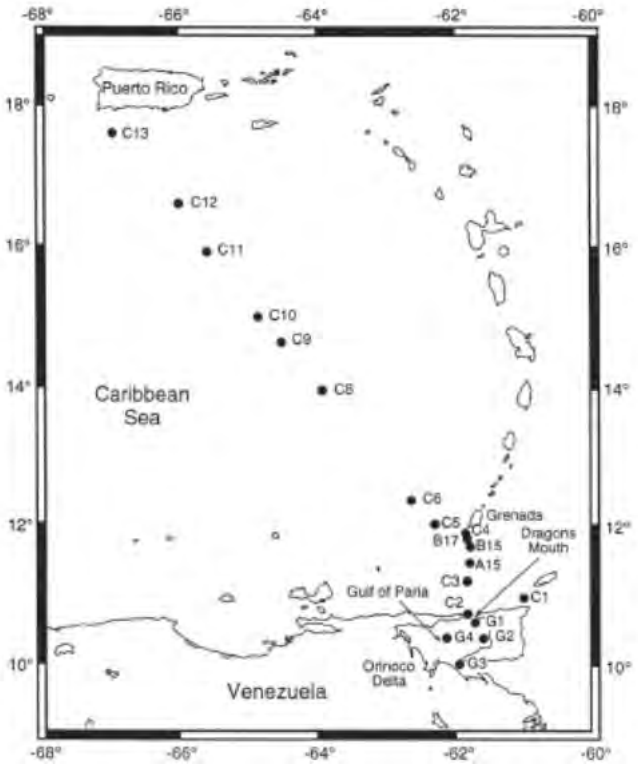
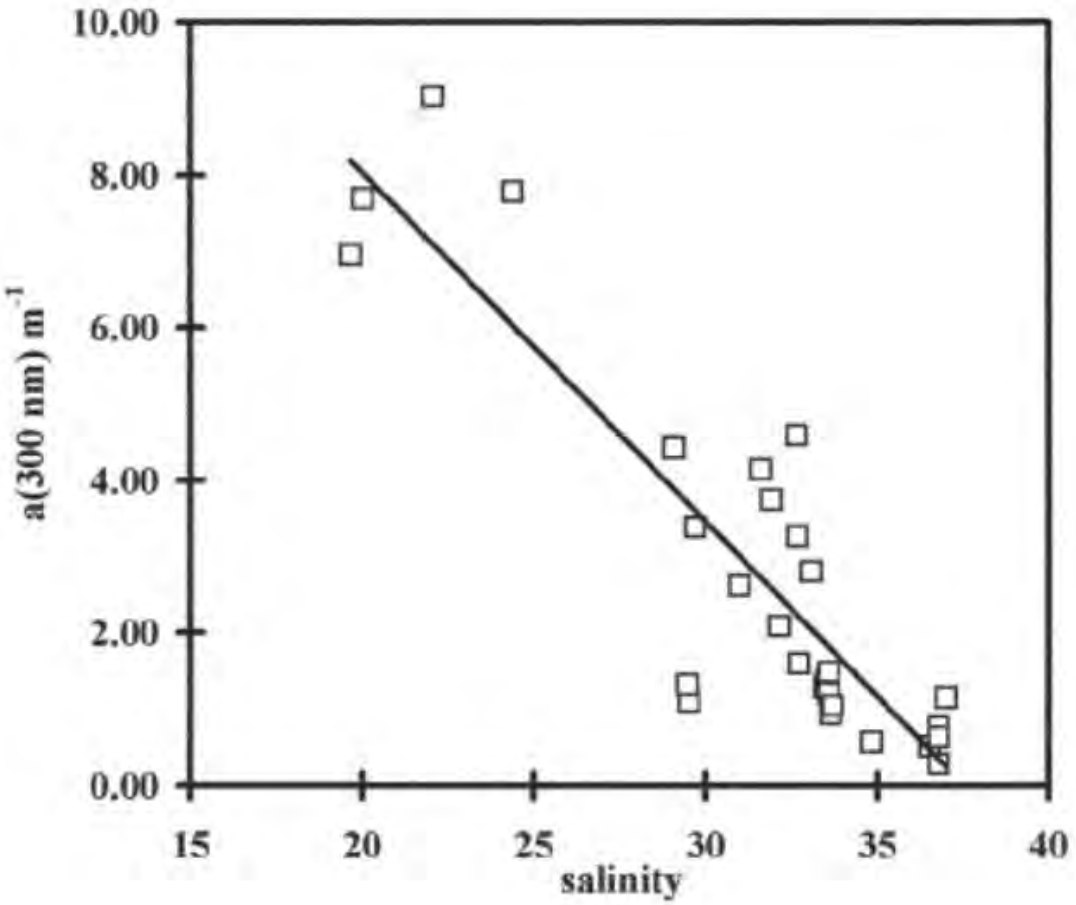


Fig. 1. Locations of the transect and hydrocast stations in the Middle Atlantic Bight.



(Vodacek et al 1997)

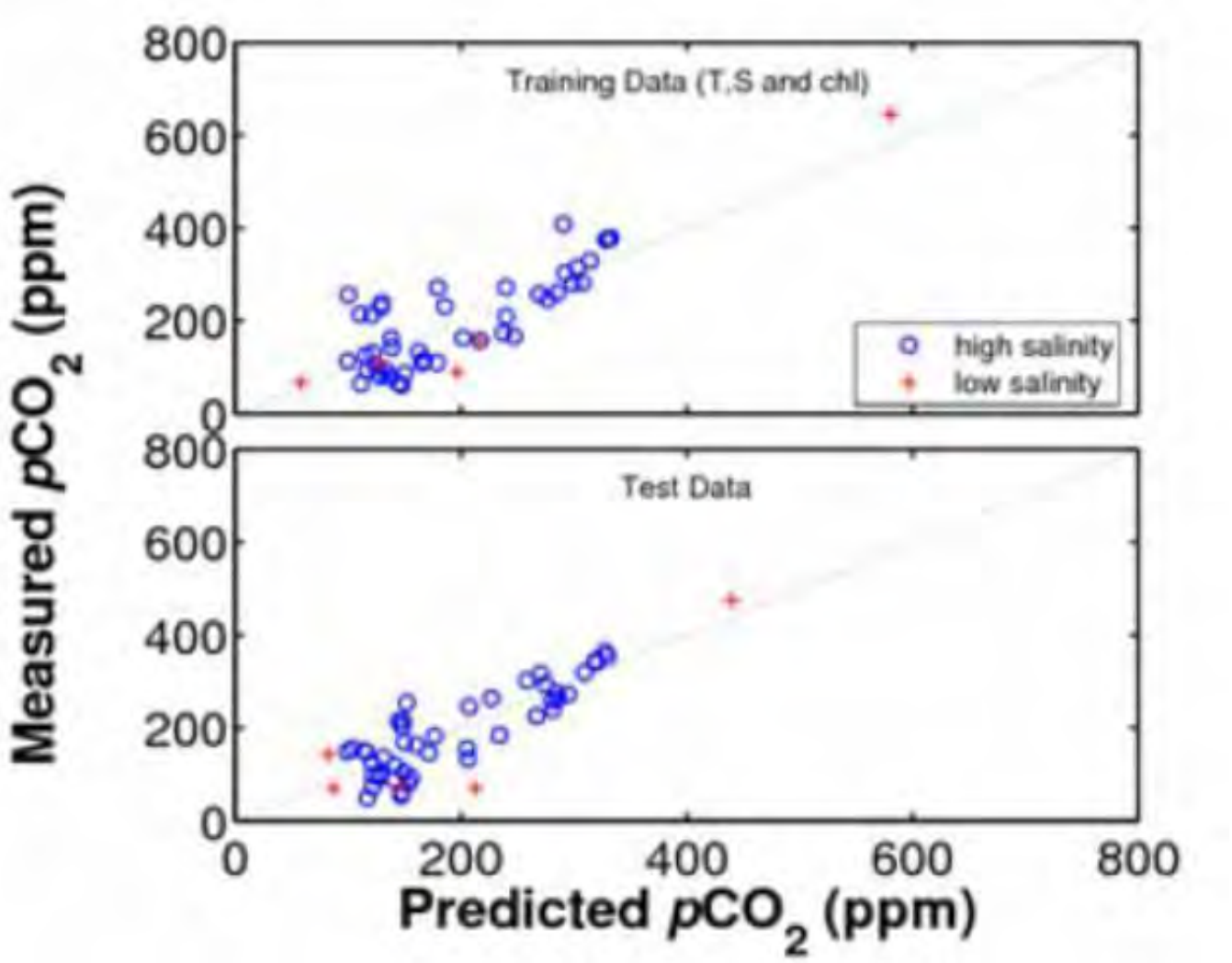




$$SSS = x\ a_{CDOM} + y$$

(Castellio et al 1999)

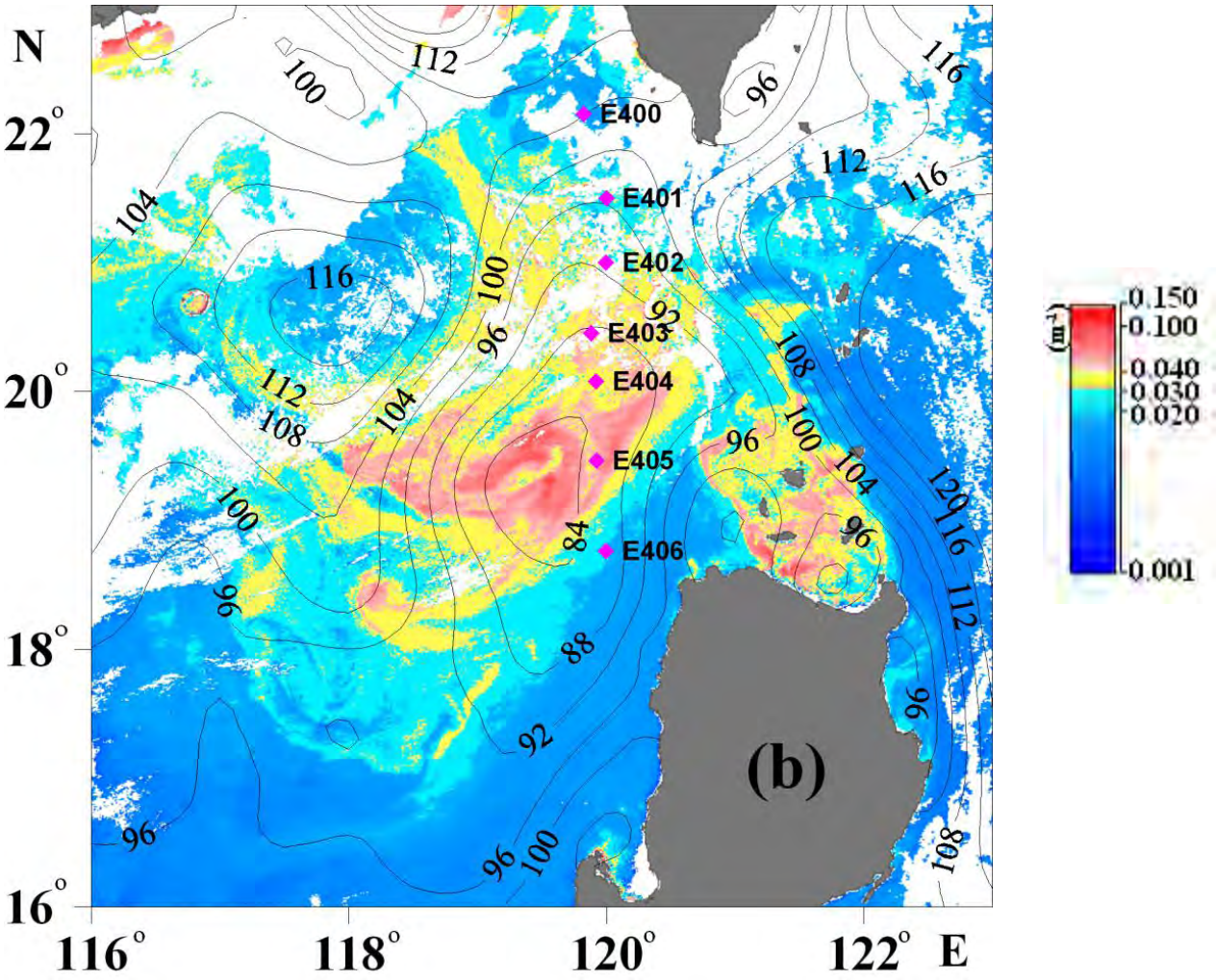
2.4 pCO2 estimation



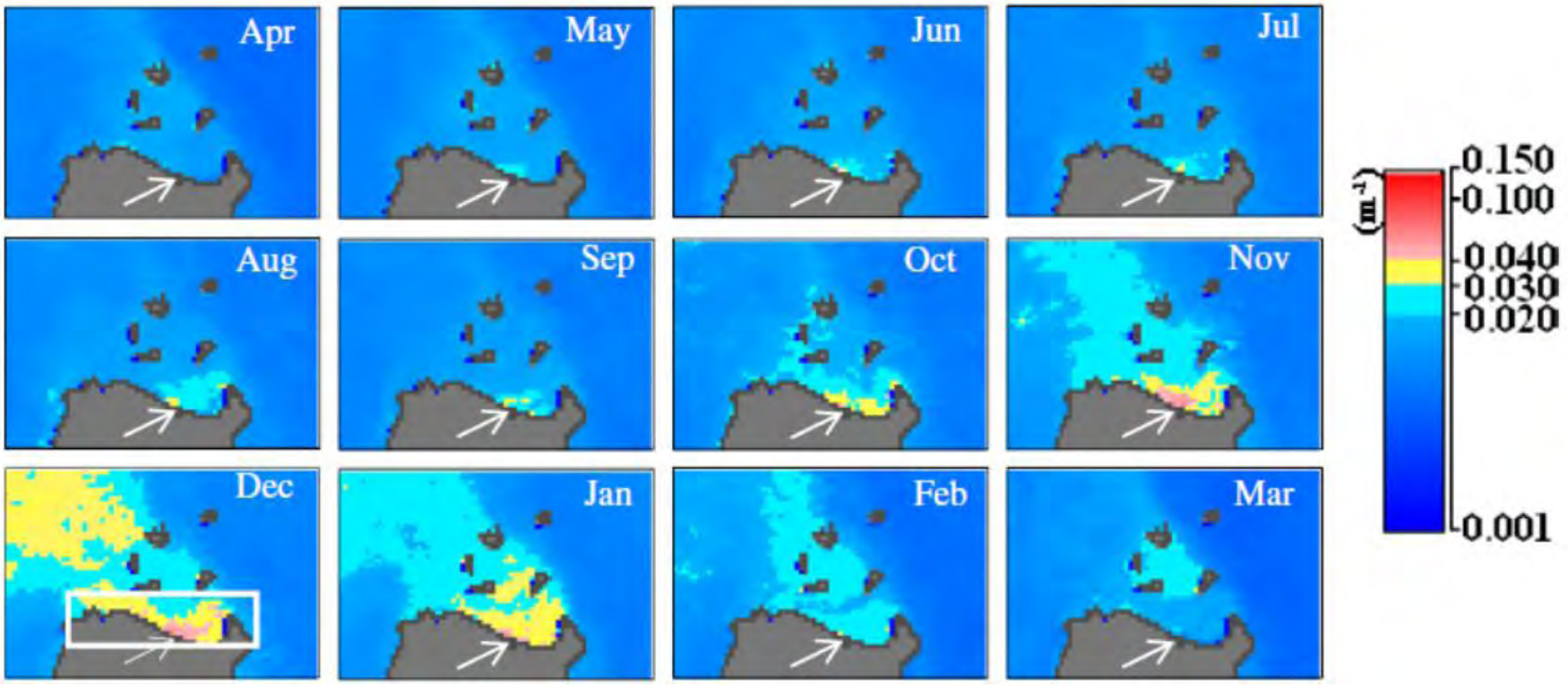
Lohrenz and Cai, 2006

pCO2 = f(T, S, Chl)

2.5 Bloom dynamics



(Shang et al, 2012)



(Shang et al, 2012)

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. Kd, Zeu, PP, could be estimated more accurately.

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