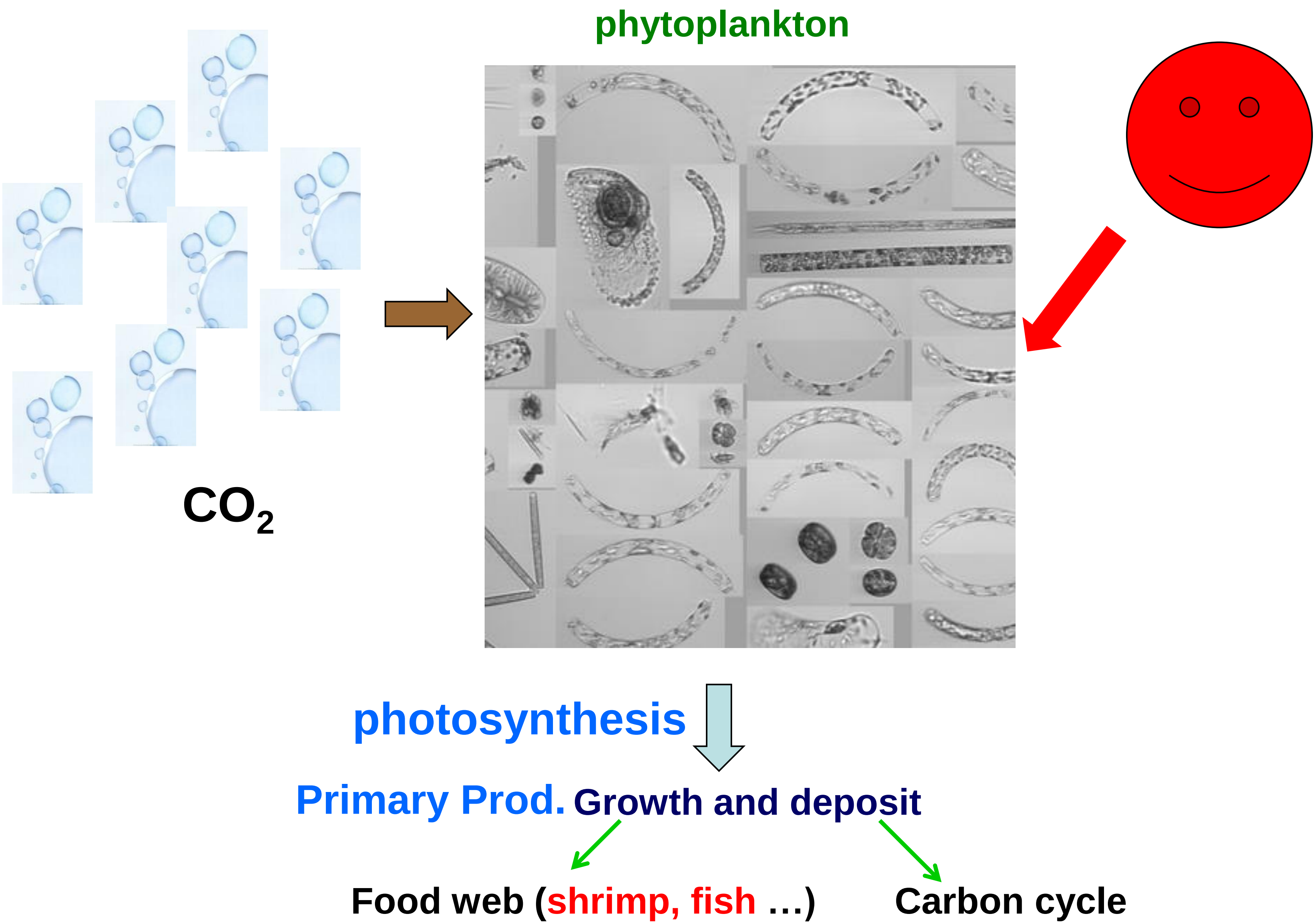
Sensing global primary production: Why Chl estimated empirically from ocean color is not a good input parameter

ZhongPing Lee


phytoplankton
CO_2
photosynthesis
Primary Prod.
Growth and deposit
Food web (shrimp, fish …)
Carbon cycle

Photosynthesis and Fish Production in the Sea

The production of organic matter and its conversion to higher forms of life vary throughout the world ocean.

John H. Ryther

Numerous attempts have been made to estimate the production in the sea of fish and other organisms of existing or potential food value to man (*1–4*). These exercises, for the most part, are based on estimates of primary (photosynthetic) organic production rates in

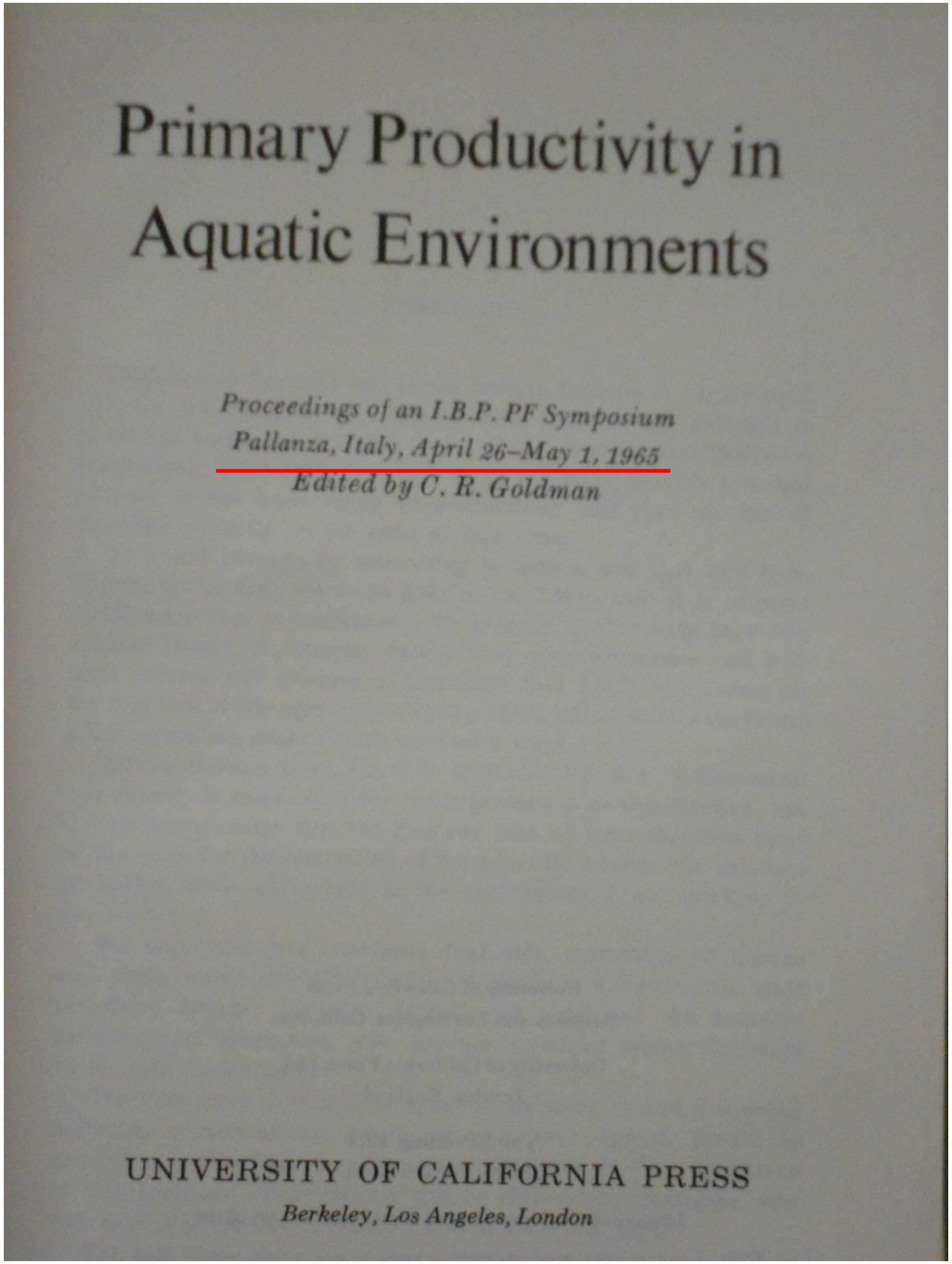
mine the trophic dynamics of marine food chains also vary widely and in direct relationship to the absolute level of primary organic production. As is shown below, the two sets of variables—primary production and the associated food chain dynamics—may act

gional studies of productivity in many parts of the world. Most of these have been brought together by a group of Soviet scientists to provide up-to-date world coverage consisting of over 7000 productivity observations (*7*). The result has been modification of the estimate of primary production in the world ocean from 1.2 to 1.5×10^{10} tons of carbon fixed per year (*5*) to a new figure, 1.5 to 1.8×10^{10} tons.

Attempts have also been made by Steemann Nielsen and Jensen (*5*), Ryther (*8*), and Koblentz-Mishke *et al.* (*7*) to assign specific levels or ranges of productivity to different parts of the ocean. Although the approach was somewhat different in each case, in general the agreement between the three was good and, with appropriate condensation and combination, permit the following conclusions.

1) Annual primary production in the open sea varies, for the most part, between 25 and 75 grams of carbon fixed

(Ryther, 1969, Science)



Primary Productivity in Aquatic Environments

Proceedings of an I.B.P. PF Symposium
Pallanza, Italy, April 26–May 1, 1965
Edited by C. R. Goldman

UNIVERSITY OF CALIFORNIA PRESS
Berkeley, Los Angeles, London

An effort started half century ago …

> 4000 articles since 1980

>> $120 million investment

Half century ago:

From over 7000 measurements (Former Soviet Union …)

⇨ **Global PP: ~15 Gt/year**


Sputnik (1957)

Assessing Marine Primary Production from Space

Satellite remote sensing has already improved understanding of phytoplankton standing stocks

Mary Jane Perry

Phytoplankton are responsible for over 95% of marine photosynthesis; as the dominant primary producers, they occupy key positions in marine food production and carbon dioxide regulation. With today's increasing interest in global-scale processes has come the realization that biogeochemical cycles and climatic changes are strongly linked. Thus, because the marine biosphere occupies 70% of the surface area of

Combined with other remotely sensed data, ocean color promises to produce new and better estimates of global marine productivity

complex and rapidly changing spatial patterns (Figure 1). Because a regional primary production estimate is made by extrapolating from a small number of shipboard measurements of biomass-specific photosynthetic rates and then interpolating those rates to regional biomass, the error in the biomass assessment is carried over into the calculation of regional primary production.[1]

Satellite remote sensing of ocean

(Perry, 1986, BioScience)

Remote sensing via satellite is the only feasible means …

Mission of ocean color remote sensing

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

Logically, the appropriate data product from an ocean color satellite to scale up local NPP measurement.

“Aspects of the photosynthetic process and of the environmental conditions (e.g., light or nutrients) are parameterized as a function of either biogeography and/or one or more variables which can be measured from spaceborne sensors.”

(Carr et al, 2006, PPARR_2)

Chl !!!

How ? Why?

Deep-Sea Research, 1963, Vol. 10, pp. 221 to 231. Pergamon Press Ltd. Printed in Great Britain.

A method for the determination of phytoplankton chlorophyll and phaeophytin by fluorescence*

CHARLES S. YENTSCH and DAVID W. MENZEL
Woods Hole Oceanographic Institution

(*Received* 25 *January* 1963)

Abstract—The concentration of chlorophyll, principally chlorophyll *a*, and after acidification phaeophytin, is measured in 85% acetone extracts using a sensitive fluorometer. The method is very sensitive in that 10 fluorescence units are equal to 0·001 O.D.$^{10\,cm}_{665\,m\mu}$. The maximum variation is 15%. The method is highly suitable for routine analysis at sea or in the laboratory.

Production is positively correlated (+ 0.964) with amount of chlorophyll *a*, as was expected, and negatively correlated with pigment ratio (—0.319) and, more feebly, with biotic diversity.

An appropriate estimate of production was

$$\log P = 1.047 + 0.728 \log C - 0.615 \log (D_{430}/_{665})$$

equal to

$$P = 11.1\, C^{0.728}/(D_{430}/D_{665})^{0.615}$$

(M. Margalef, 1965)

Chl-based approach to estimate PP

I. Wavelength-resolved models (WRMs)

nutrient energy

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

II. Wavelength-integrated models (WIMs)

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

II. Time-integrated models (TIMs)

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

IV. Depth-integrated models (DIMs)

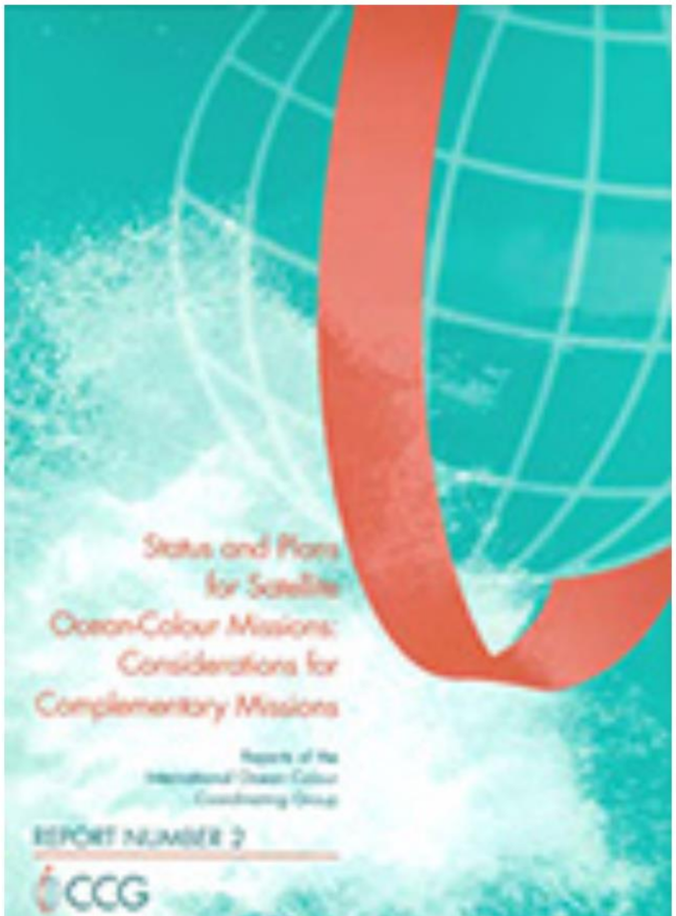
$$\sum PP = P^b{}_{opt} \times f[\text{PAR}(0)] \times DL \times \boxed{\text{Chl}} \times Z_{eu}$$

VGPM:

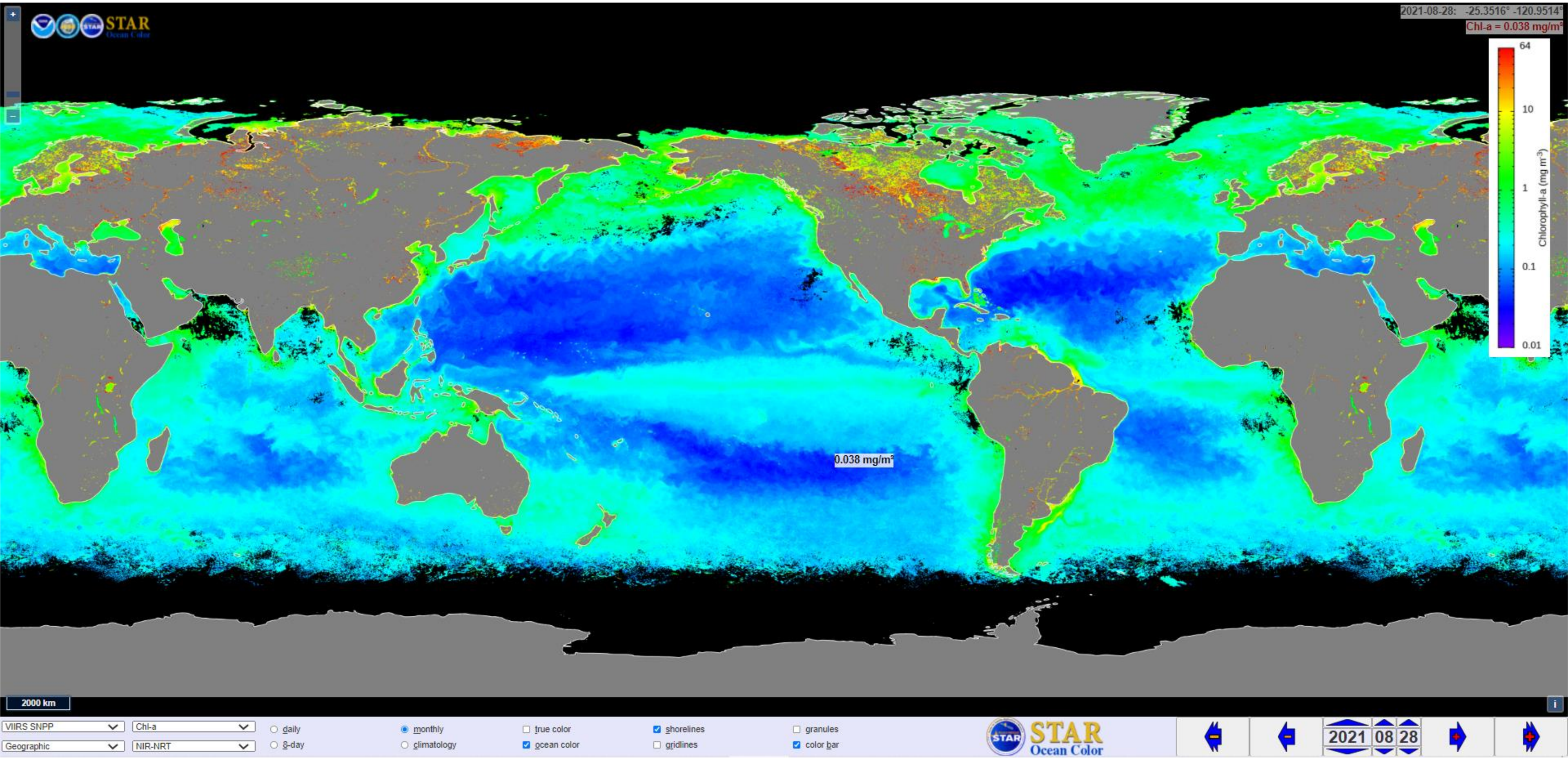
$$PP_{eu} = 0.66125 \times P^B{}_{opt} \times [E_0/(E_0 + 4.1)] \times Z_{eu} \times C_{opt} \times D_{irr}.$$

(Behrenfeld and Falkowski, 1997)

"A primary goal of ocean-colour remote sensing is to produce synoptic fields of chlorophyll pigment …"



--- IOCCG Report #2



STAR
Ocean Color
2021-08-28: -25.3516° -120.9514°
Chl-a = 0.038 mg/m³
64
10
1
0.1
0.01
Chlorophyll-a (mg m⁻³)
0.038 mg/m³
2000 km
VIIRS SNPP
Chl-a
Geographic
NIR-NRT
daily
8-day
monthly
climatology
true color
ocean color
shorelines
gridlines
granules
color bar
STAR
Ocean Color
2021 08 28

PPARR summary:

- **“The best performing algorithms agreed with the 14C-based estimates within a factor of 2.**
- **There were significant regional differences, as well as algorithm-region interactions”**

“… the tropical Pacific database captures a broad scale shift from low biomass-normalized productivity in the 1980s to higher biomass-normalized productivity in the 1990s, which was not successfully captured by any of the models.”

(Carr et al, 2006, PPARR_2)

Why the estimated PP from ocean color is not that exciting?

Chl !!

"成也萧何，败也萧何" –-- success and failure are determined by the same figure.

1. "Nature" of standard 'Chl' product:

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

Rrs: remote sensing reflectance
***a*: absorption coefficient**
b_b: backscattering coefficient

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

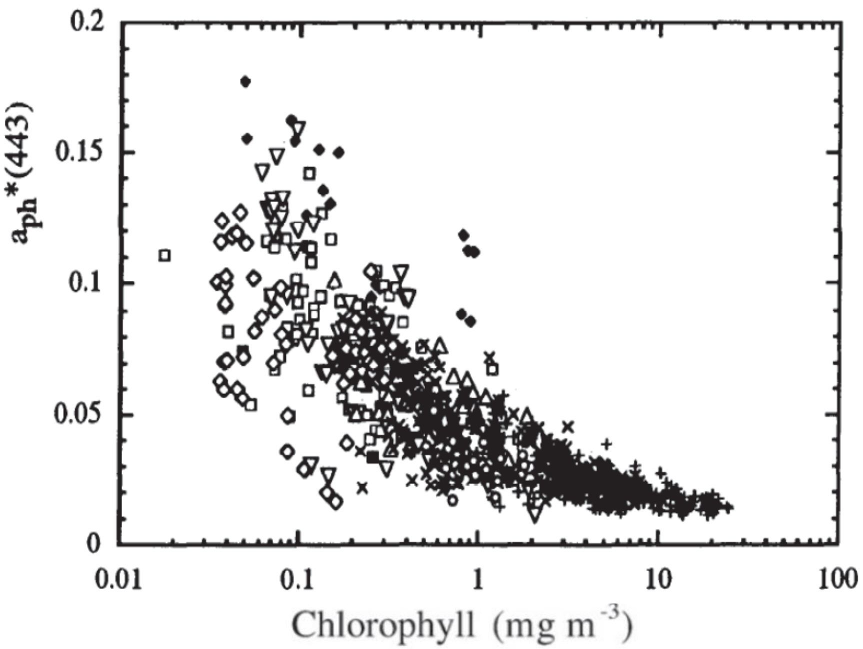
$$\frac{R_{rs}(440)}{R_{rs}(550)} \approx \frac{a(550)}{a(440)}\,\frac{b_{bw}(440)+b_{bp}(440)}{b_{bw}(550)+b_{bp}(550)}$$

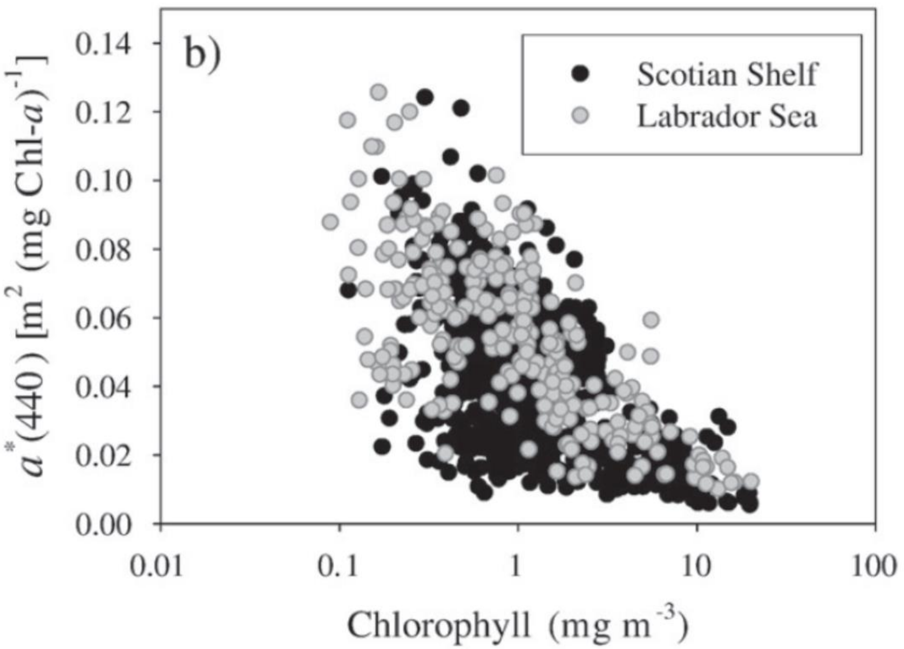
$$\frac{R_{rs}(440)}{R_{rs}(550)} \propto \frac{a(550)}{a(440)} = \frac{a_w(550)+a_{dg}(550)+a^*_{ph}(550)Chl}{a_w(440)+a_{dg}(440)+a^*_{ph}(440)Chl}$$

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

In addition:

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



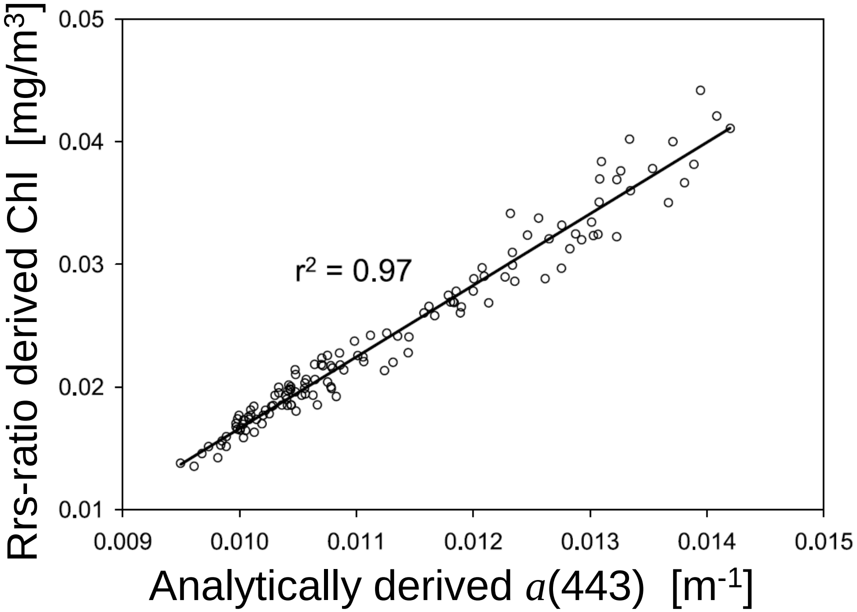


(Bricaud et al 1995, JGR)

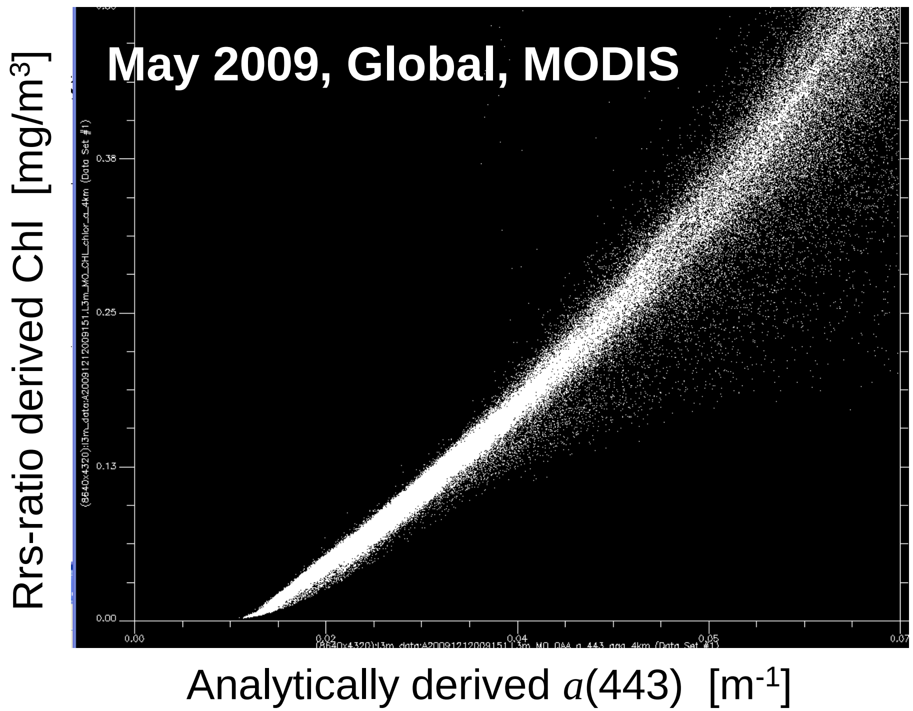
(Platt et al, RSE, 2008)

a^*_{ph} is not a constant for a given Chl, and it varies greatly!

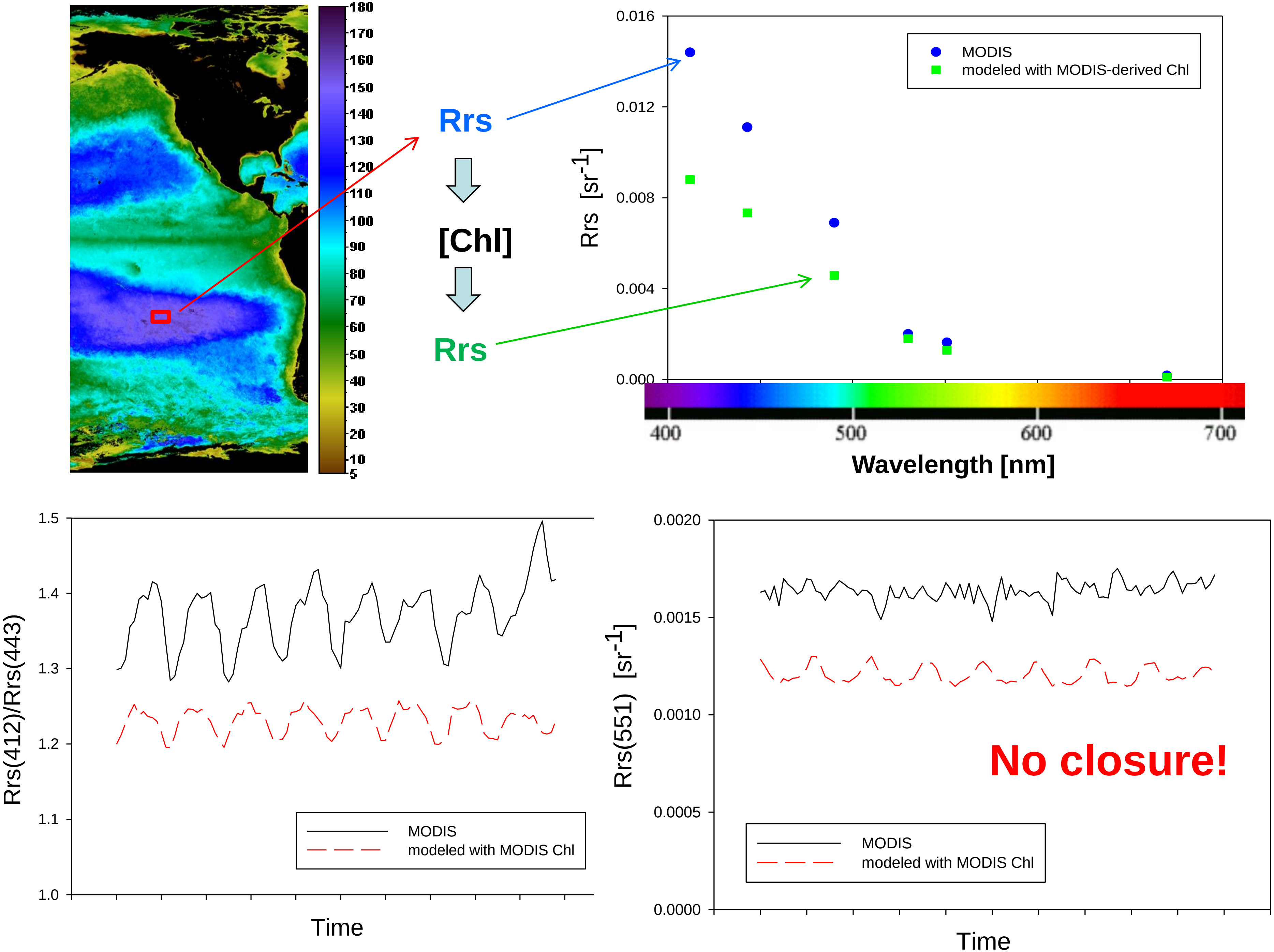
Nature of ratio-derived "Chl"



At the center of South Pacific Gyre

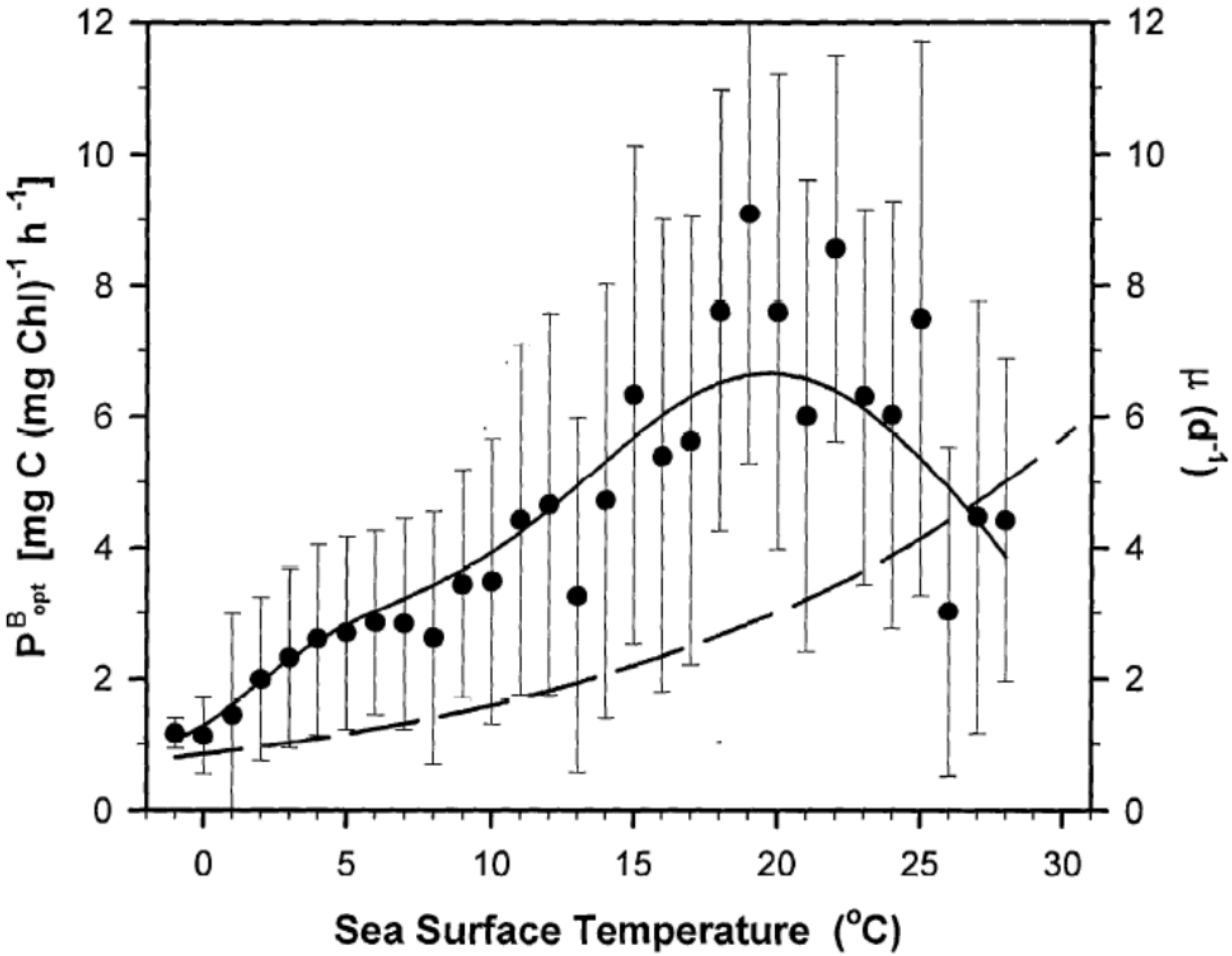


Ratio-derived "Chl" is re-scaled total absorption coefficient!



Rrs
[Chl]
Rrs
MODIS
modeled with MODIS-derived Chl
Rrs [sr-1]
Wavelength [nm]
Rrs(412)/Rrs(443)
Time
MODIS
modeled with MODIS Chl
Rrs(551) [sr-1]
No closure!

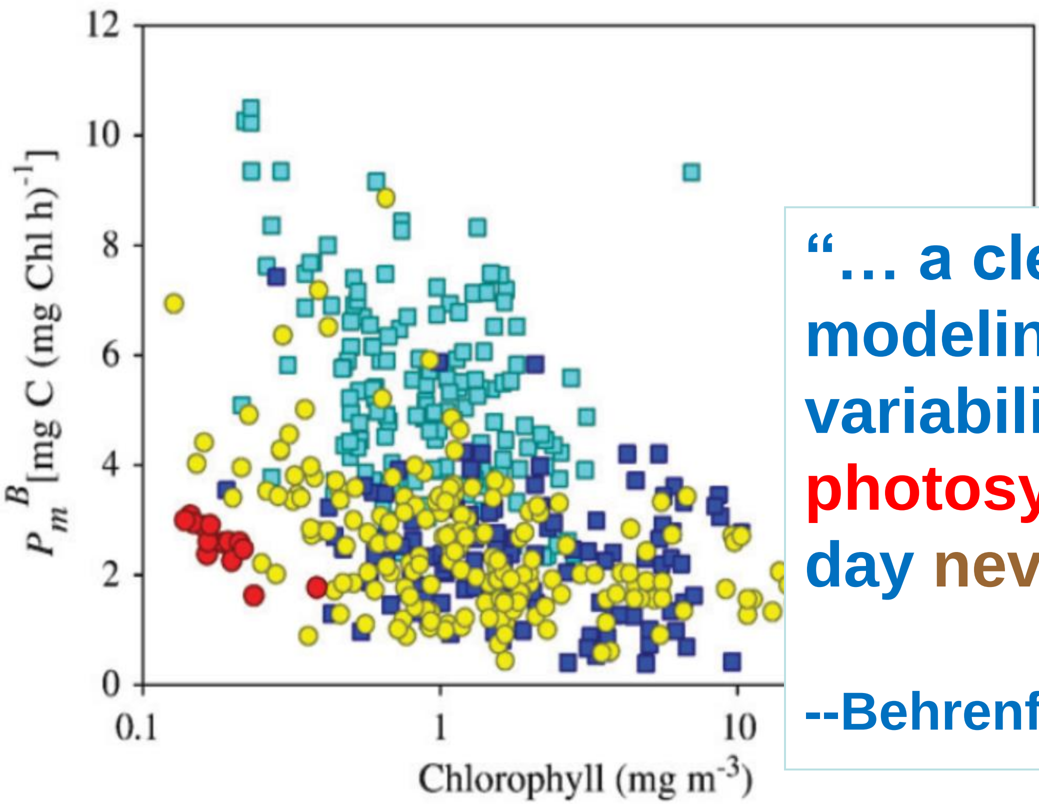
2. chlorophyll-normalized photosynthetic rate



$$
\begin{aligned}
P^B{}_{opt} = &-3.27\times10^{-8}T^7 + 3.4132\times10^{-6}T^6 \\
&- 1.348\times10^{-4}T^5 + 2.462\times10^{-3}T^4 - 0.0205T^3 \\
&+ 0.0617T^2 + 0.2749T + 1.2956. \qquad (11)
\end{aligned}
$$

(Behrenfeld and Falkowski 1997)

Variation of chlorophyll-normalized maximum photosynthetic rate (P^B_m)



(Platt et al 2008, RSE)

“… a clear path for globally modeling or remotely observing variability in chlorophyll-specific photosynthesis has even to this day never been identified. ”

--Behrenfeld et al (2005)

“… the single most important parameter needed to improve algorithms is information on the maximum light-saturated rate of photosynthesis, P^B_{max} (or P^B_{opt}).”

(Behrenfeld and Falskowski, 1997, L&O)

Alternative approach 1:

Carbon-based PP Model (CBPM) or b_{bp}-based approach

$$PP(z) = C_{ph} \times \mu \qquad C_{ph} = x * b_{bp}; \quad \mu \propto \frac{Chl}{C_{ph}} \times h(\mathrm{PAR})$$

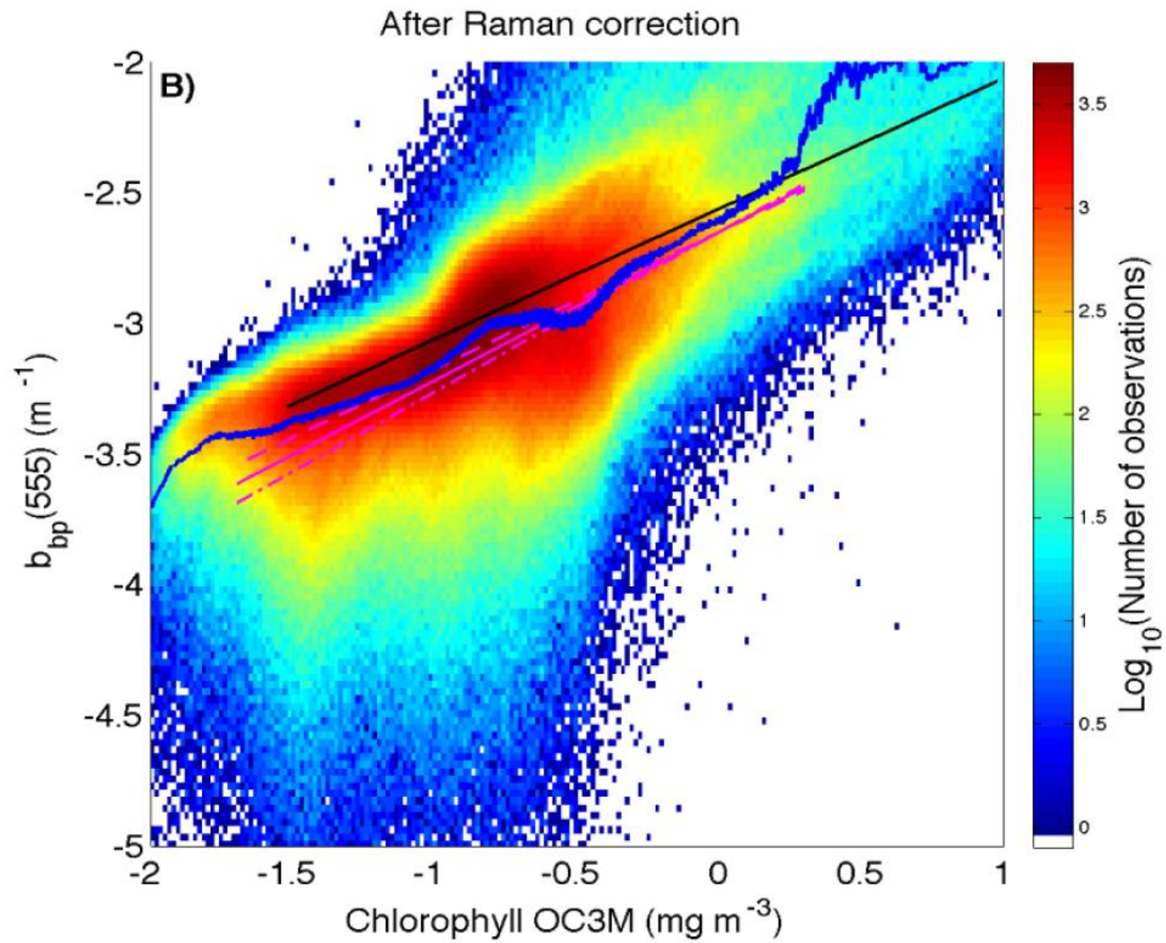
Advantages:

1. b_{bp} can be directly inverted from Rrs
2. good understanding of μ

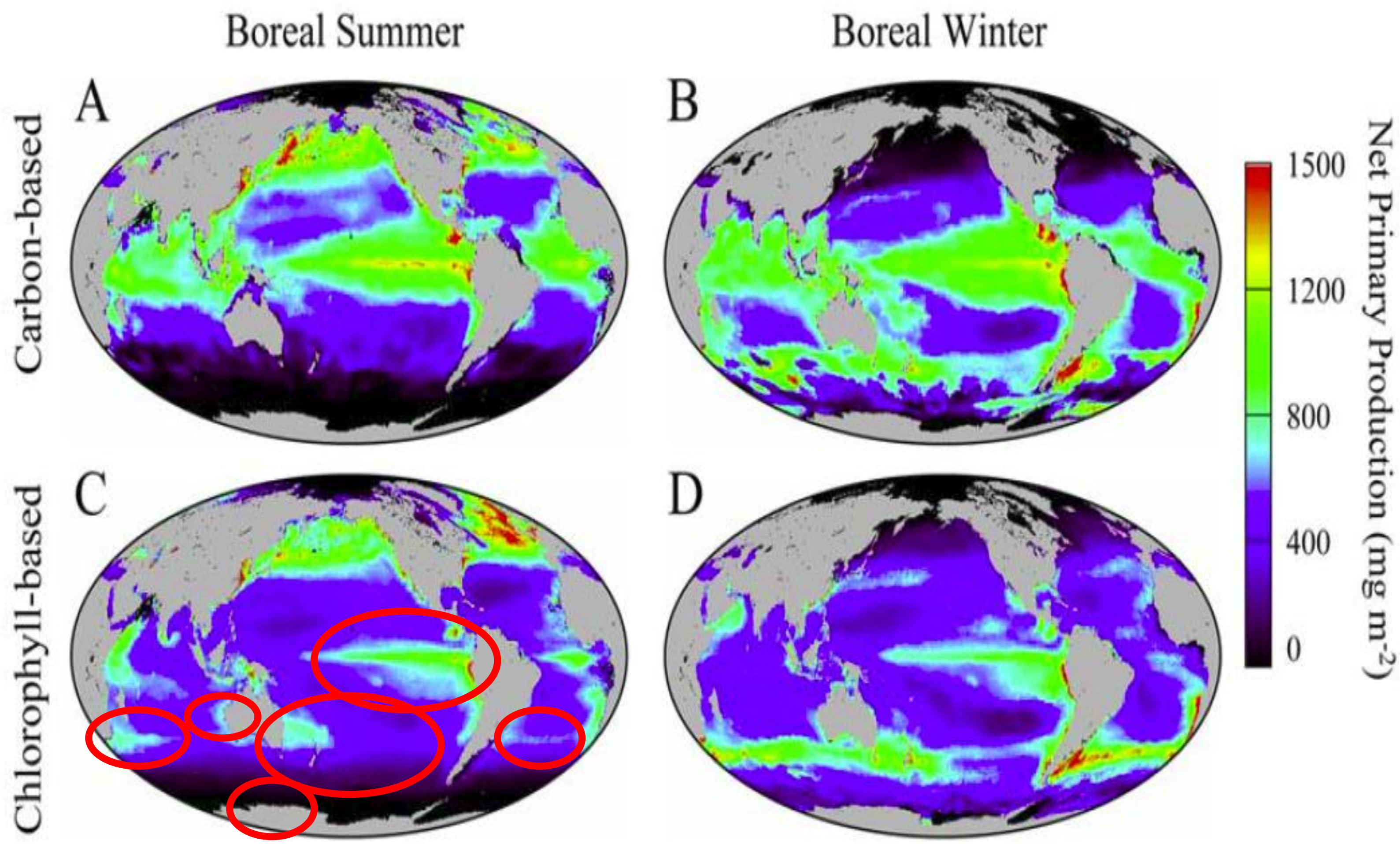
Issues/Challenges:

1. b_{bp} is a lump sum of <u>many</u> contributions
2. Large uncertainties in retrieved b_{bp}
3. Difficult to determine χ

$$R_{rs}^{mea}(\lambda) = G(\lambda)\frac{b_{bw}(\lambda)+b_{bph}(\lambda)+b_{det}(\lambda)+b_{bub}(\lambda)}{a(\lambda)+b_b(\lambda)} + R_{resi}(\lambda)$$



(Lee and Huot 2014)



(Behrenfeld et al 2005)

Alternative approach 2:

Absorption based PP estimation: Aph-based approach

I. Wavelength-resolved models (WRMs)

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

II. Wavelength-integrated models (WIMs)

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

(Behrenfeld and Falkowski, 1997)

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

$a_{ph}(\lambda)$:**phytoplankton absorption coefficient**

I. Wavelength-resolved models (WRMs)

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

II. Wavelength-integrated models (WIMs)

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

(Behrenfeld and Falkowski, 1997)

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

Basic relationship of photosynthesis (first principle):

$$P(z) = \phi(z) \times 12{,}000 \times Q_{\mathrm{phar}}(z) \quad (1)$$

Quantum yield

(Kirk 1983; Smith et al 1989)

Absorbed photons by phytoplankton

$$Q_{phar}(z) = \iint Q(\lambda, t, z) \times a_{ph}(\lambda, z)\, d\lambda\, dt$$

Ocean color → a_{ph} → PP

Absorption-based approach

Absorption based PP estimation

$$PP(z) \propto \phi \times Aph \times PAR$$

Advantages:

1. Follows the first principle of photosynthesis
2. Aph can be directly inverted from Rrs
3. Aph has PFT information

Issues/Challenges:

1. Limited Aph-PP data
2. Variation of ϕ is still fuzzy

Quasi-Analytical Algorithm (QAA) for a_{ph}:

$$\boldsymbol{r_{rs}(\lambda)}$$

$$\boxed{\eta}$$

$$\boxed{a(\lambda_0) = a_w(\lambda_0) + \Delta a(\lambda_0)}$$

$$b_{bp}(\lambda_0) = F_2\left(r_{rs}(\lambda_0), \boxed{a(\lambda_0)}, b_{bw}(\lambda_0)\right)$$

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

$$a(\lambda) = F_3\left(r_{rs}(\lambda), b_{bp}(\lambda), b_{bw}(\lambda)\right)$$

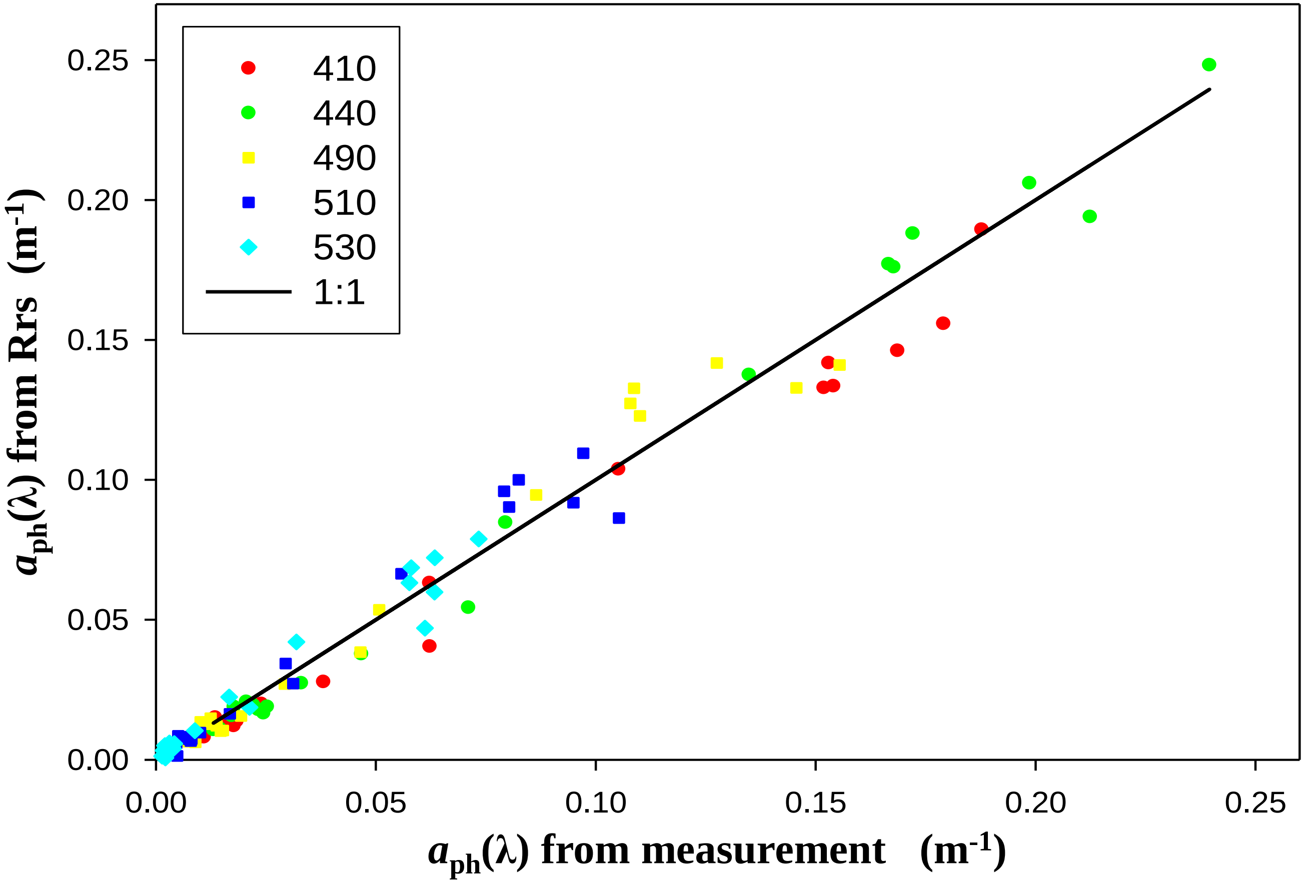
$$\begin{cases} a(411) = a_w(411) \boxed{+\zeta} a_{ph}(443) \boxed{+\xi} a_{dg}(443) \\ a(443) = a_w(443) + a_{ph}(443) + a_{dg}(443) \end{cases}$$

$$\zeta = \frac{a_{ph}(411)}{a_{ph}(443)}$$

$$\xi = \frac{a_{dg}(411)}{a_{dg}(443)}$$

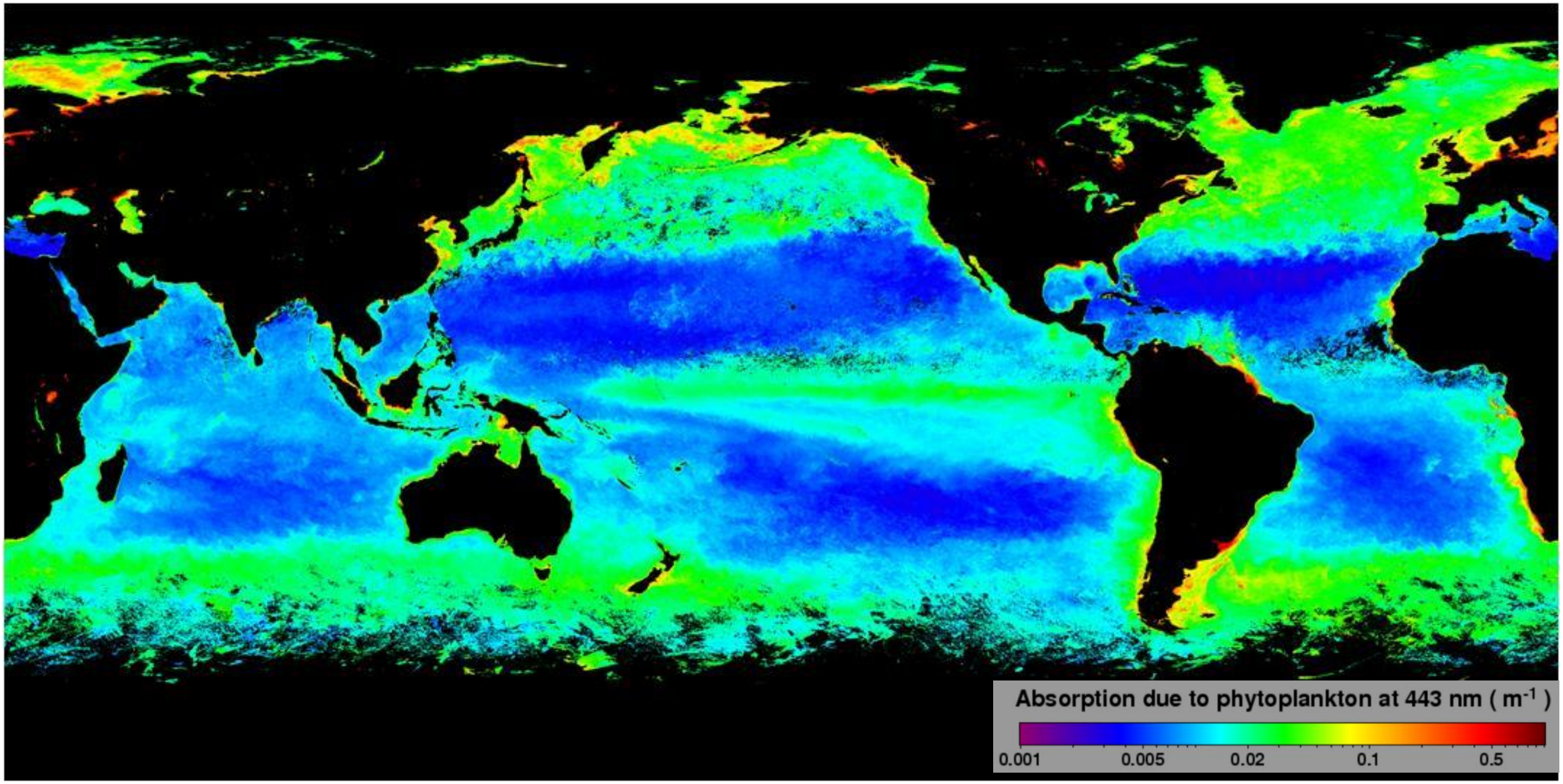
(Lee et al 2002)

Comparison of phytoplankton absorption coefficients

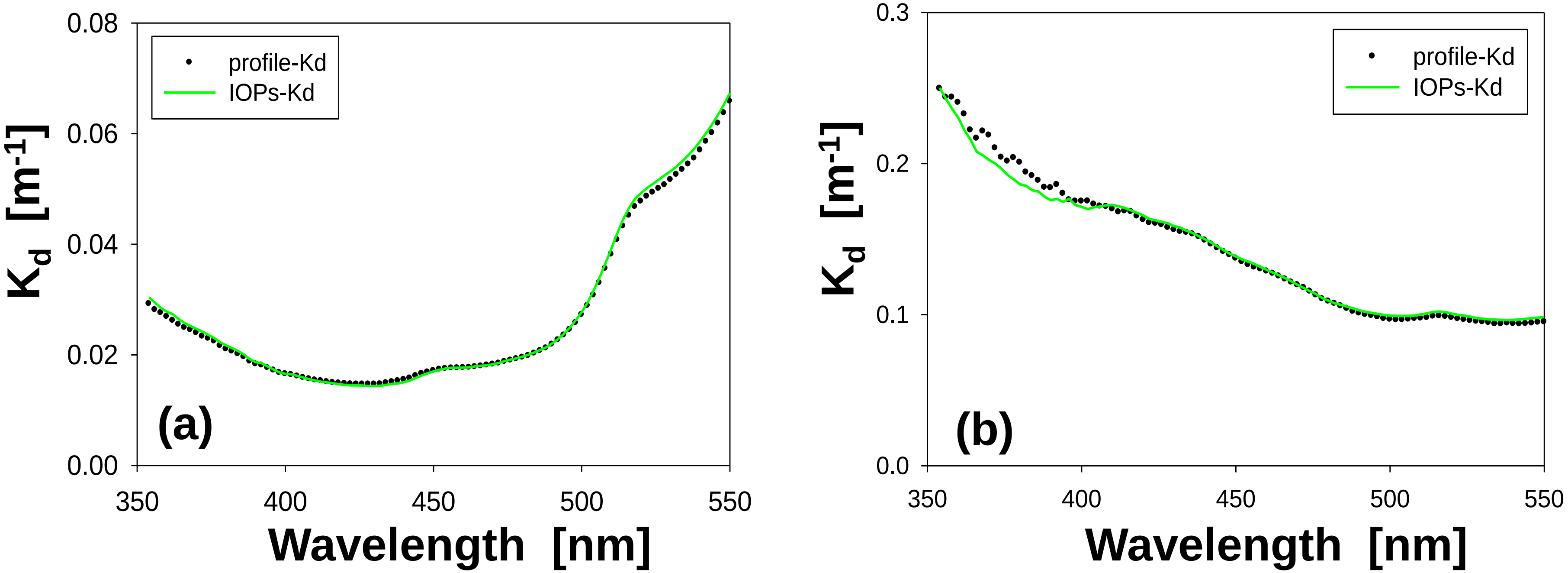


(*Lee et al 2002*)

Global $a_{ph}(443)$ from MODIS , Spring, 2010



Comparison of K_d spectrum



Spectral K_d can be well derived based on physics!

(Lee et al 2013)

Absorption-based approach:

a_{ph} centered approach: (a_{ph} is pigment absorption coefficient)

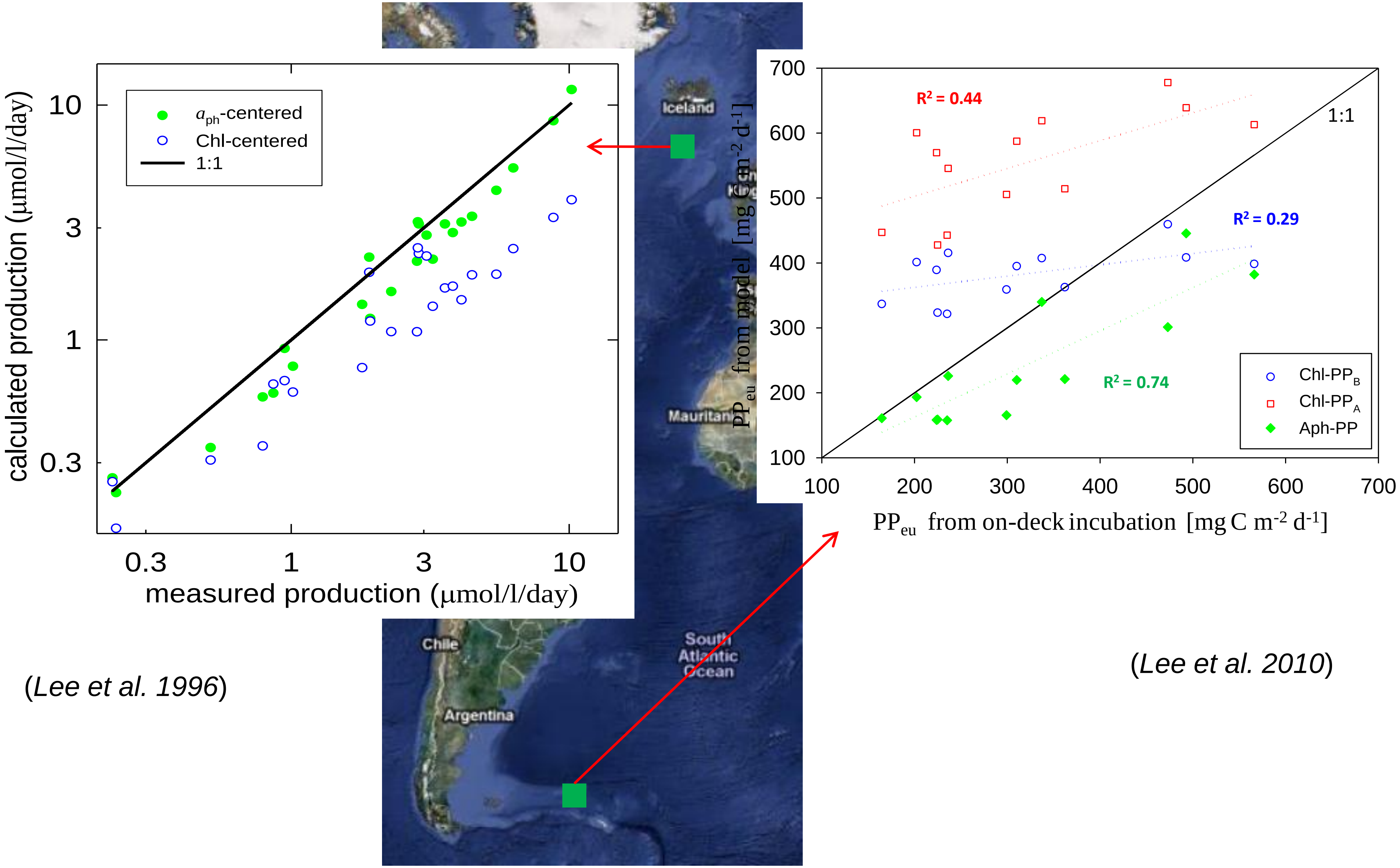
$$PP(z) = \iint \phi(\lambda, t, z) \times E_0(\lambda, t, z) \times a_{ph}(\lambda, z)\, d\lambda\, dt$$

A model for quantum yield:

$$\phi = \phi_{\max} \times \frac{K_\phi}{K_\phi + Q_{\mathrm{par}}}$$

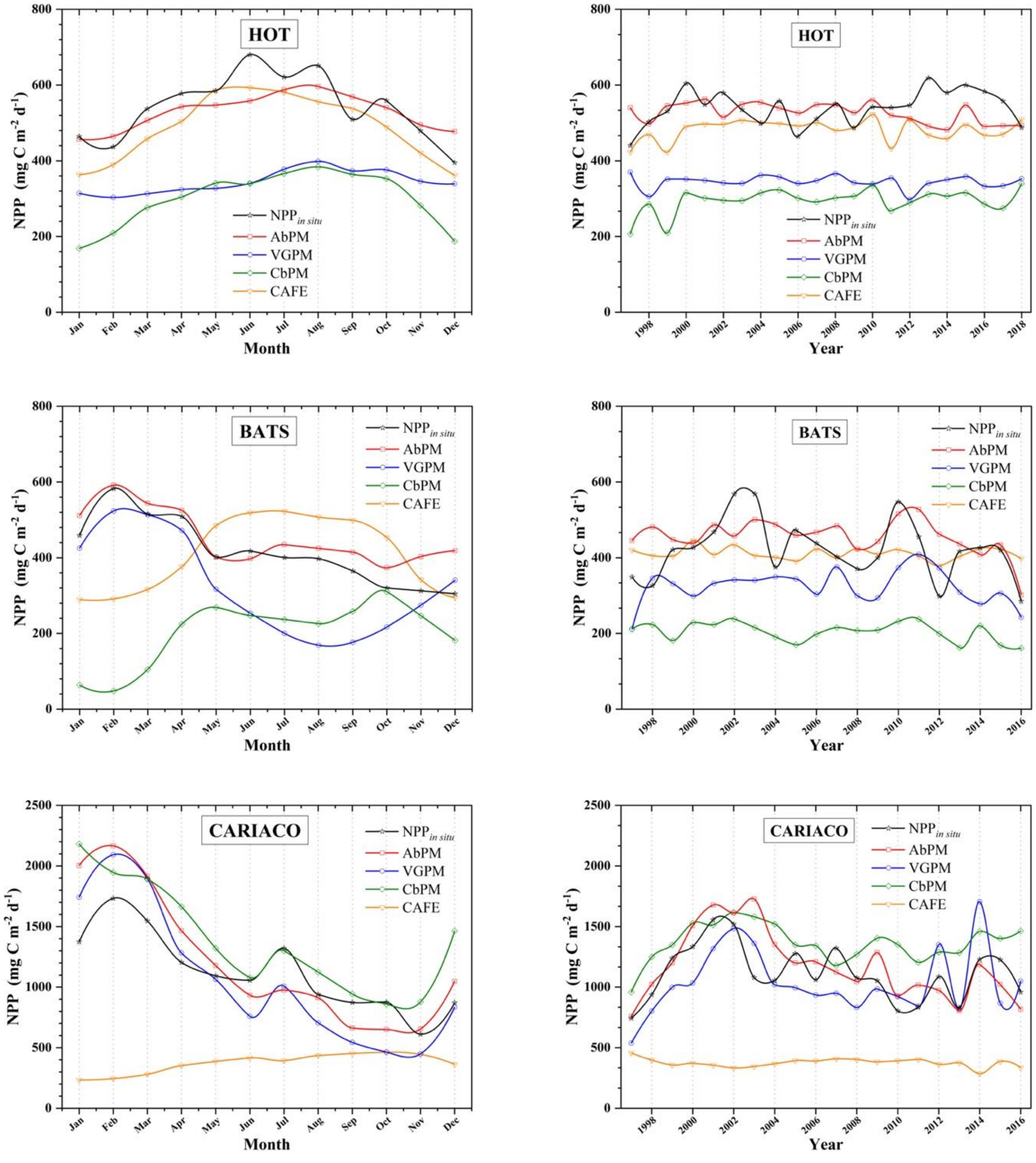
(Kiefer and Mitchell, 1983)

Remotely-estimated PP compared with measured PP



(*Lee et al. 1996*)

(*Lee et al. 2010*)



(Wu et al., under review)

phytoplankton absorption (a_{ph}) per unit carbon rather than Chl:C. This approach has the benefit of accounting for all accessory pigments which can play an important role in light absorption and photosynthesis. Absorption-based NPP modeling has shown superior predictive ability in some field datasets (Lee et al. 1996). In addition, this approach should also reduce uncertainties arising from empirical retrievals of Chl, as phytoplankton absorption is more closely tied to the fundamental satellite measurements of radiance.

(Westberry and Behrenfeld, 2013)

Chl has been a convenient index for phytoplankton biomass and intermediate parameter for PP for decades, due to its easiness in field measurements, not really based on the first principle of photosynthesis.

It is time to move to Aph for the estimation of PP in the global ocean.

Thanks!