Statistical (empirical) ocean color algorithms

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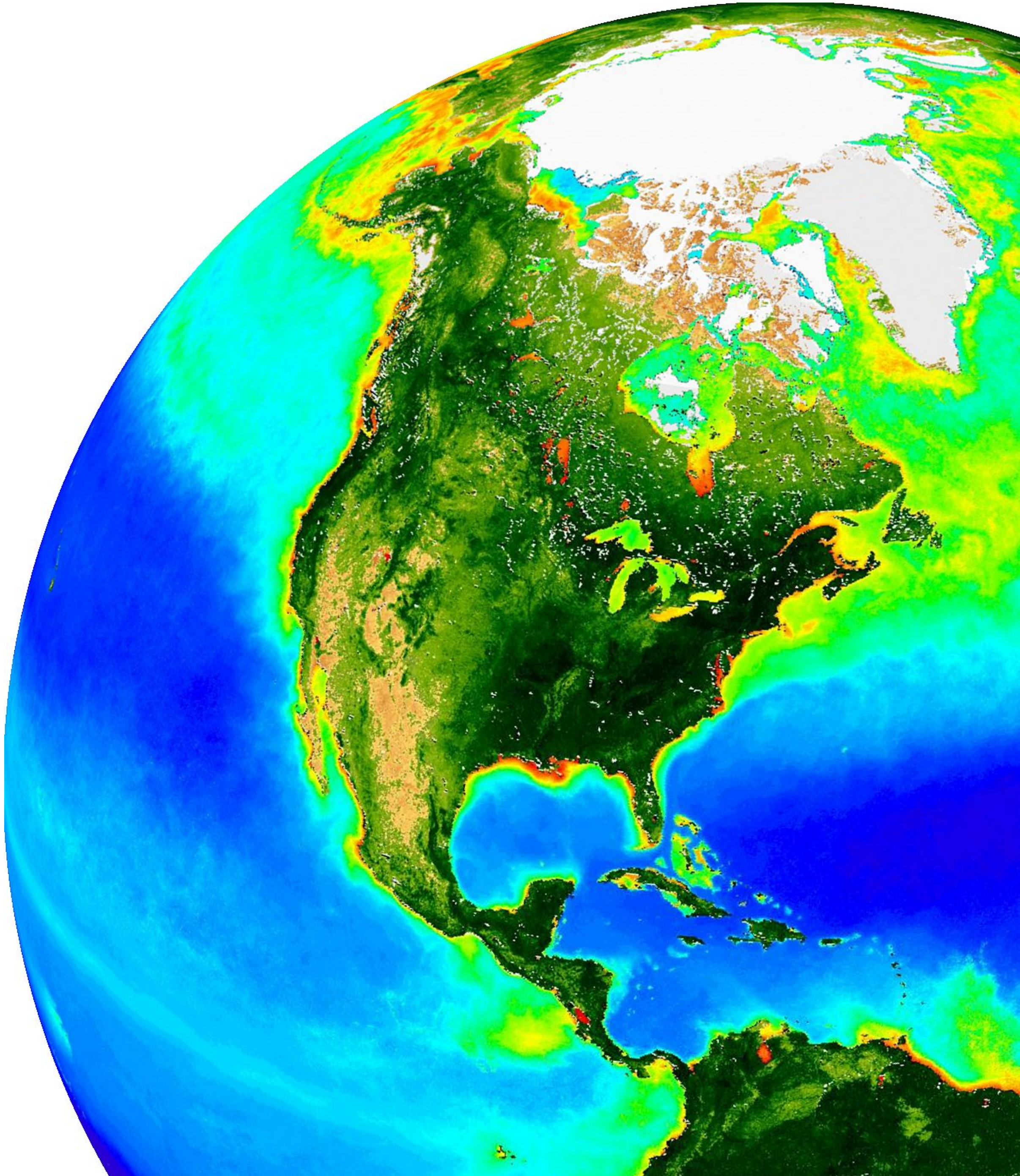
Acknowledgements: **Curtis Mobley**

2023 Ocean Optics Summer Course



Satellite instruments measure the spectral radiant flux leaving the top of Earth's atmosphere

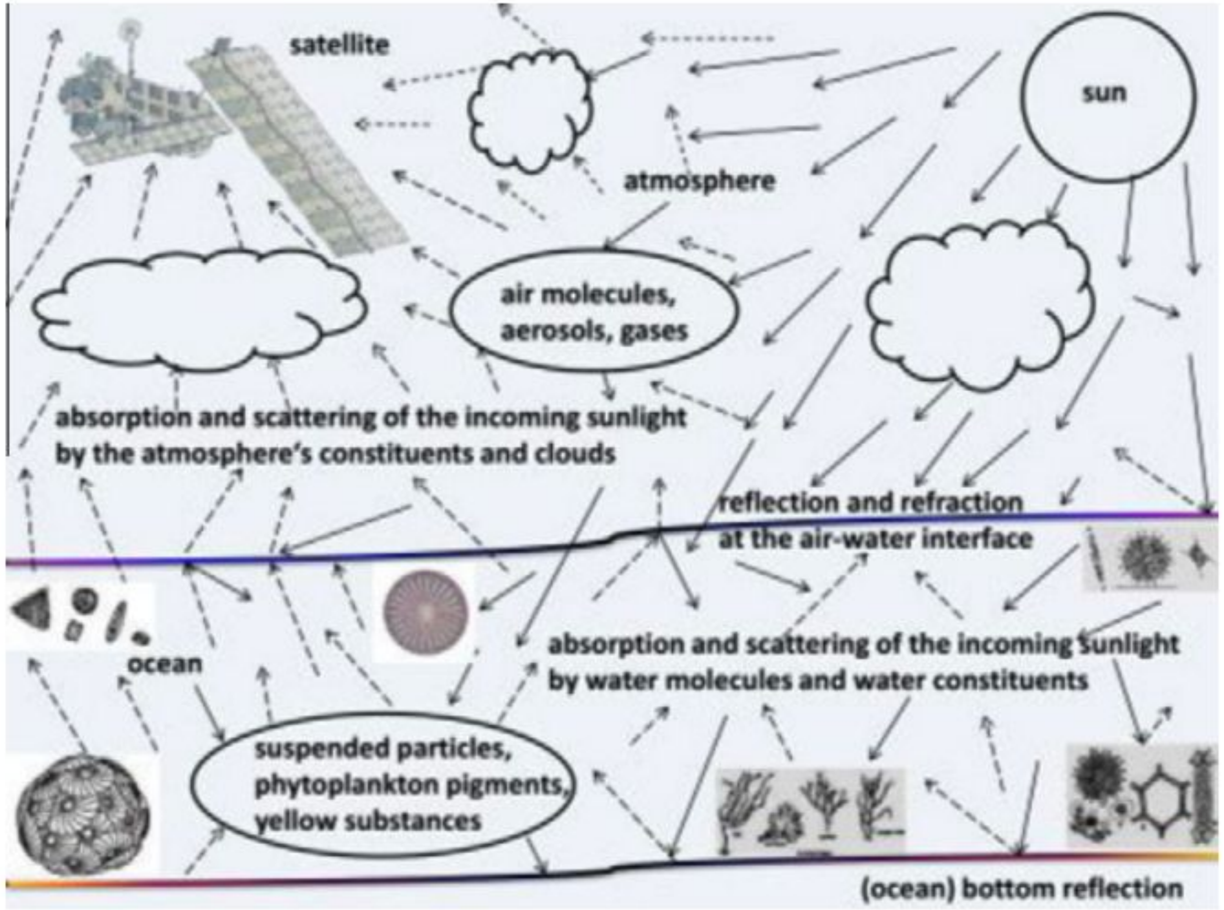
This includes contributions from everything directly in or directed into its instantaneous field of view

Ideally, forward models representing the combined ocean-atmosphere system (COAS) could be repeatedly run to find the combination that best reproduces the measured top-of-atmosphere radiance

Historically, this has been (and in many ways still is) too computationally expensive

1

2



Blum et al. 2012, Advances in Space Research

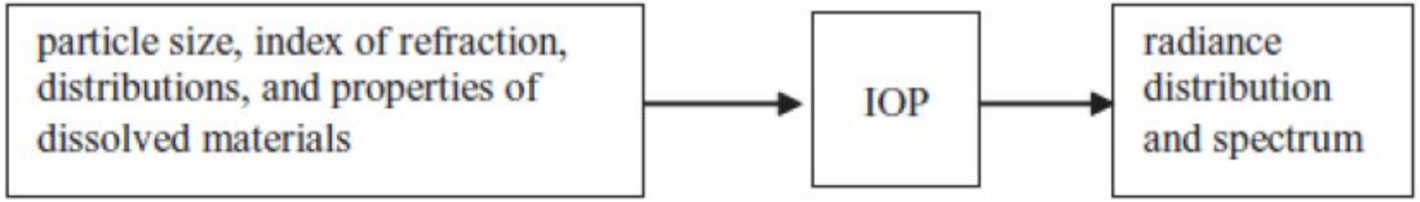
IOCCG Report Number 5, 2006

Remote Sensing of Inherent Optical Properties: Fundamentals, Tests of Algorithms, and Applications

Chapter 1

Why are Inherent Optical Properties Needed in Ocean-Colour Remote Sensing?

Ronald Zaneveld, Andrew Barnard and ZhongPing Lee

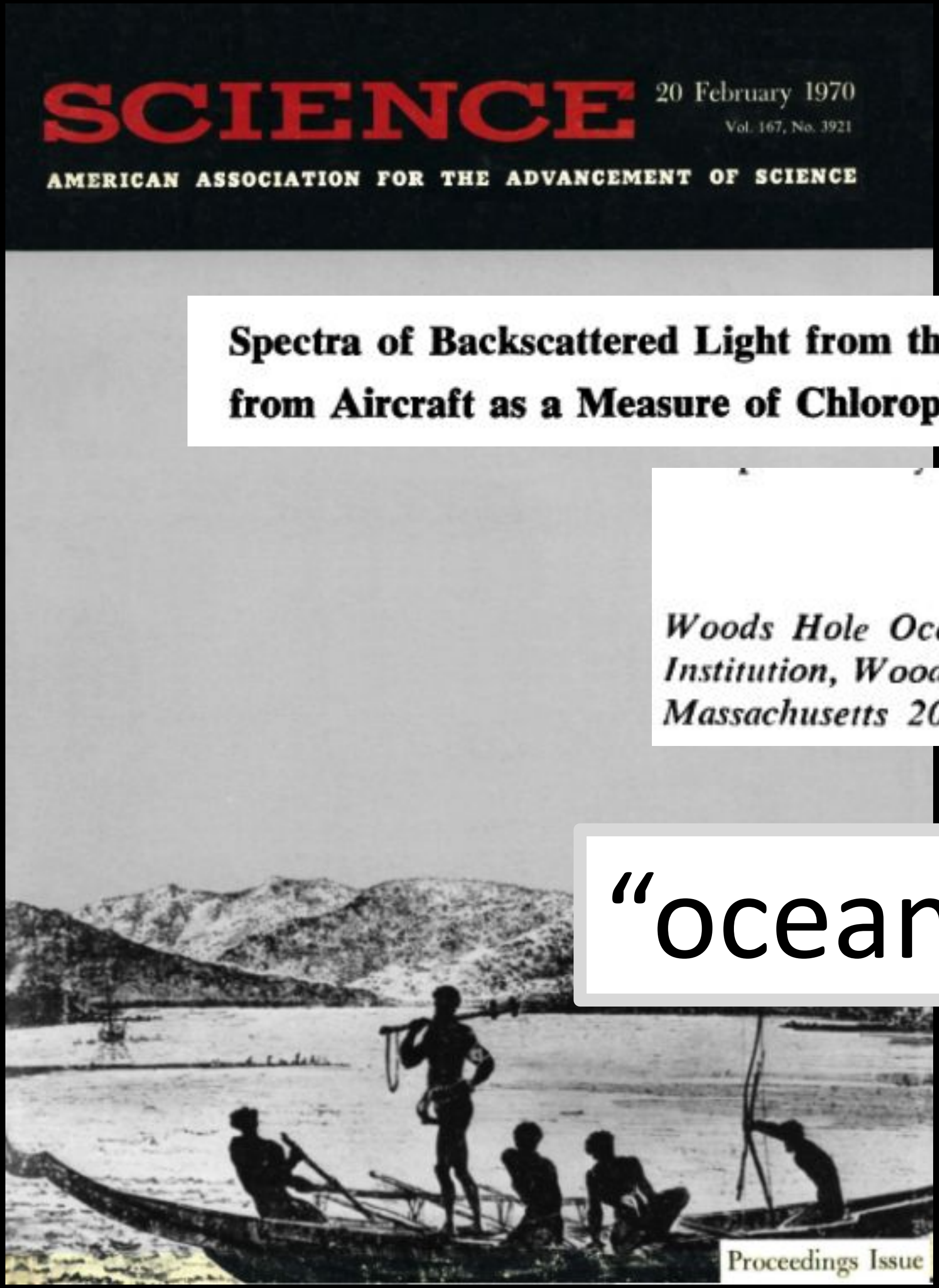


IOP(λ)[chl, whatever] → *forward model* → Rrs(λ)

Rrs(λ) → *inverse model* → IOP(λ), chl, whatever

empirical (adjective): based on, concerned with, or **verifiable by observation or experience rather than theory or pure logic**

These models are essentially just correlational models obtained from inspection of data sets containing both the inputs inputs (R_{rs}) and outputs (Chl, a_{CDOM}, water depth, etc). The models are not necessarily based on any physical insight as to why the correlation exists.



Spectra of Backscattered Light from the Sea Obtained from Aircraft as a Measure of Chlorophyll Concentration

GEORGE L. CLARKE
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"ocean color"

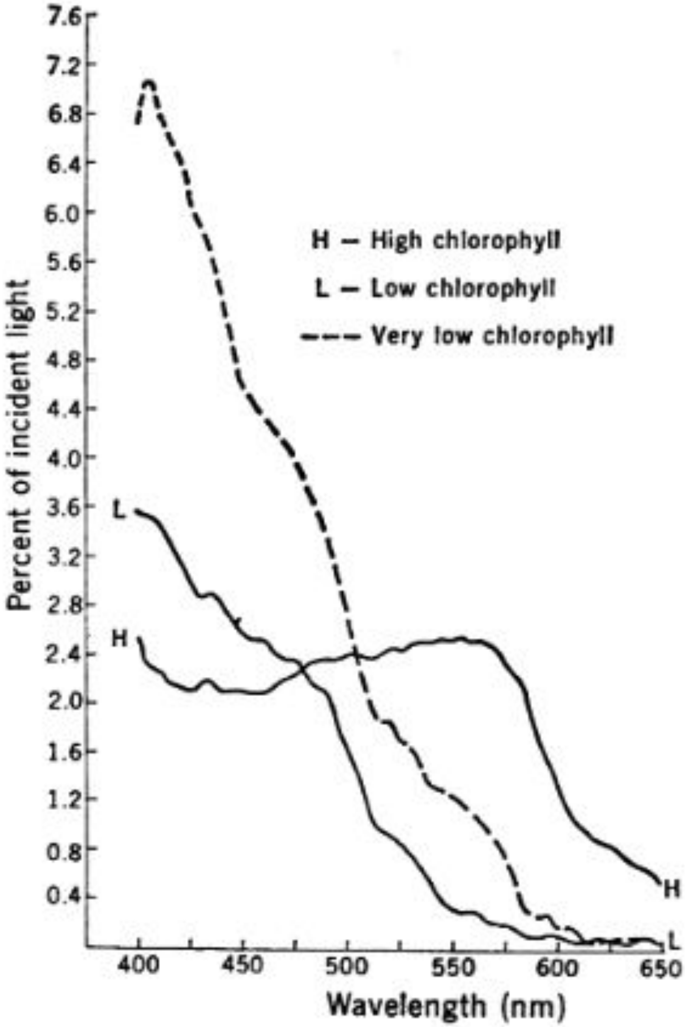
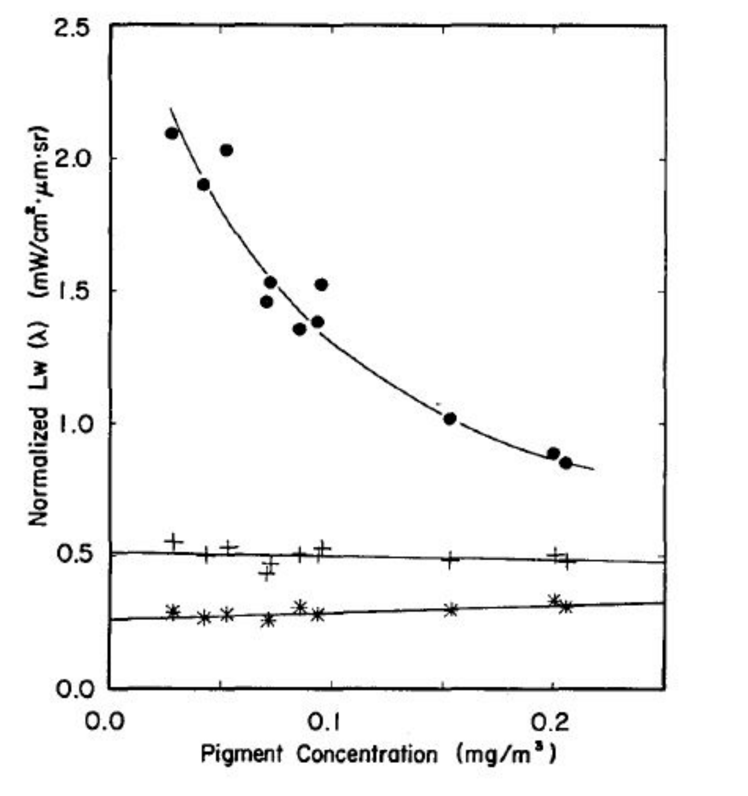


Fig. 3. Data from the high and low chlorophyll curves plotted as percentage of the incident light and compared with data taken on the same day from an area with very low chlorophyll concentration south of the Gulf Stream.

Clear water radiances for atmospheric correction of coastal zone color scanner imagery

Howard R. Gordon and Dennis K. Clark

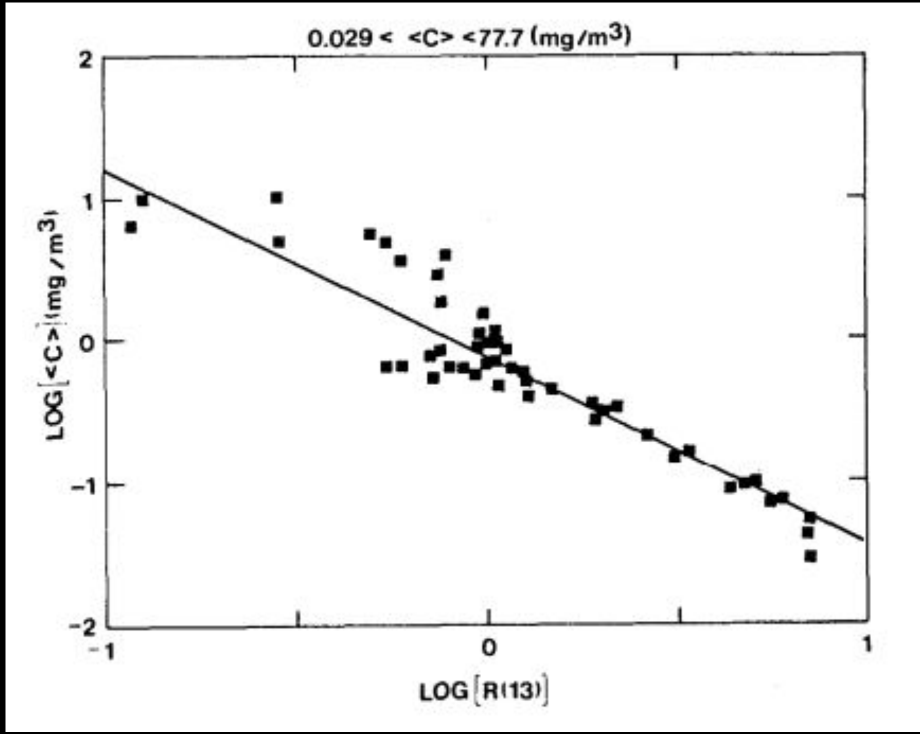
15 December 1981 / Vol. 20, No. 24 / APPLIED OPTICS 4175



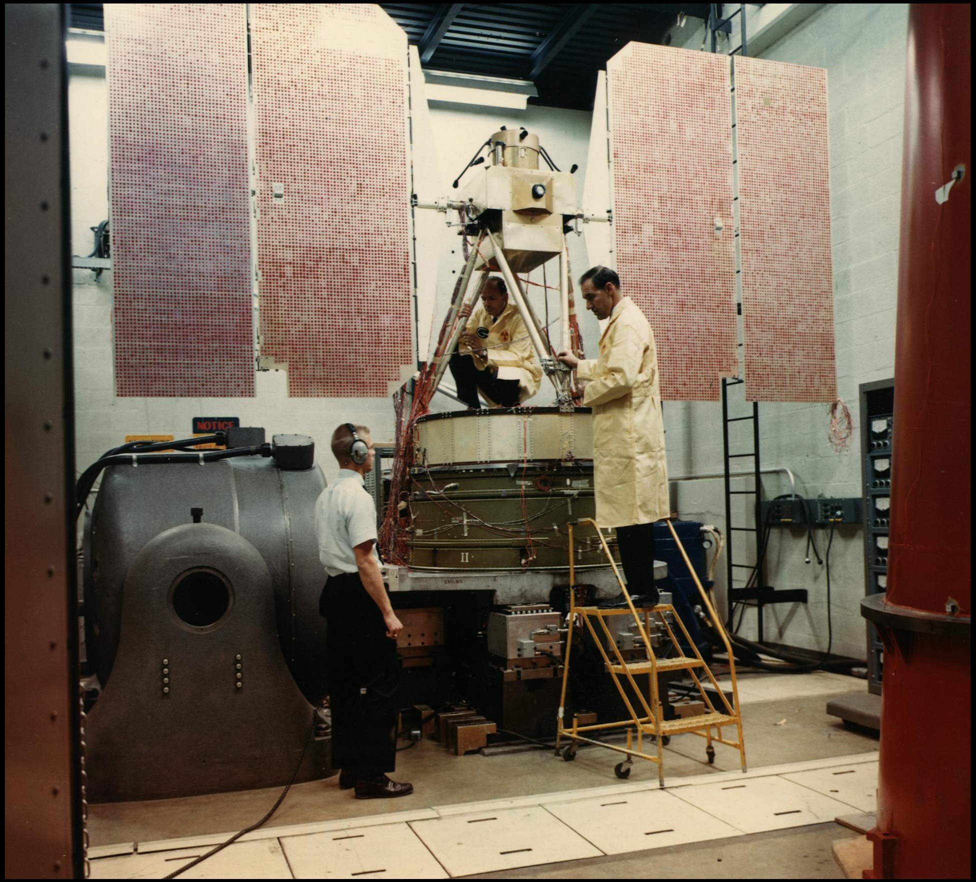
Phytoplankton pigment concentrations in the Middle Atlantic Bight: comparison of ship determinations and CZCS estimates

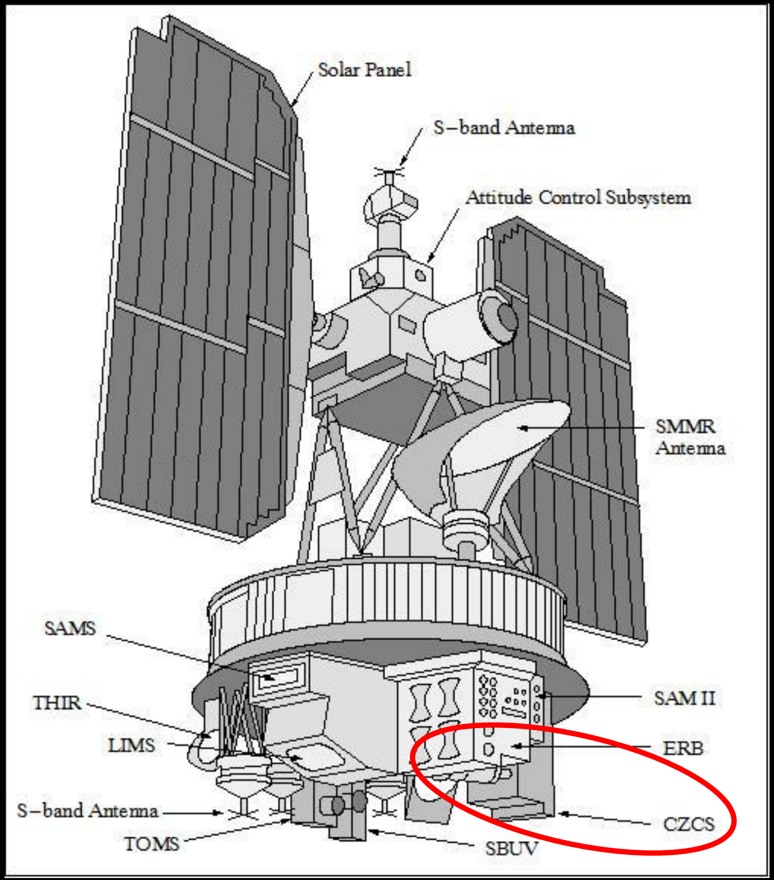
Howard R. Gordon, Dennis K. Clark, James W. Brown, Otis B. Brown, Robert H. Evans, and William W. Broenkow

20 APPLIED OPTICS / Vol. 22, No. 1 / 1 January 1983



Coastal Zone Color Scanner
1978-1986





metric	CZCS
primary ocean bands (nm)	443, 520, 550, 670
○ chl-a + phaeopigments ○ diffuse attenuation at 490 nm	
nadir res.	825 m
nadir swath	1636 km discontinuous operation
tilt	
det. per band	1
digitization	8 bits

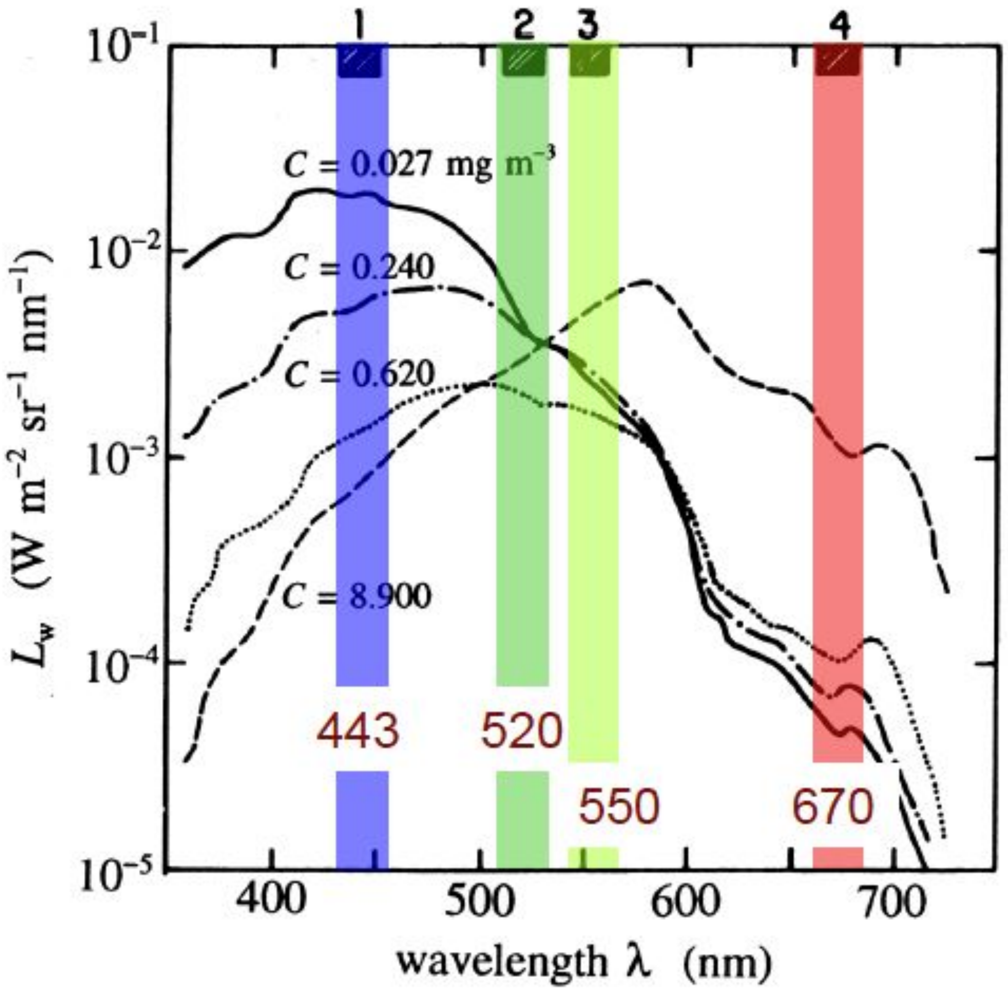
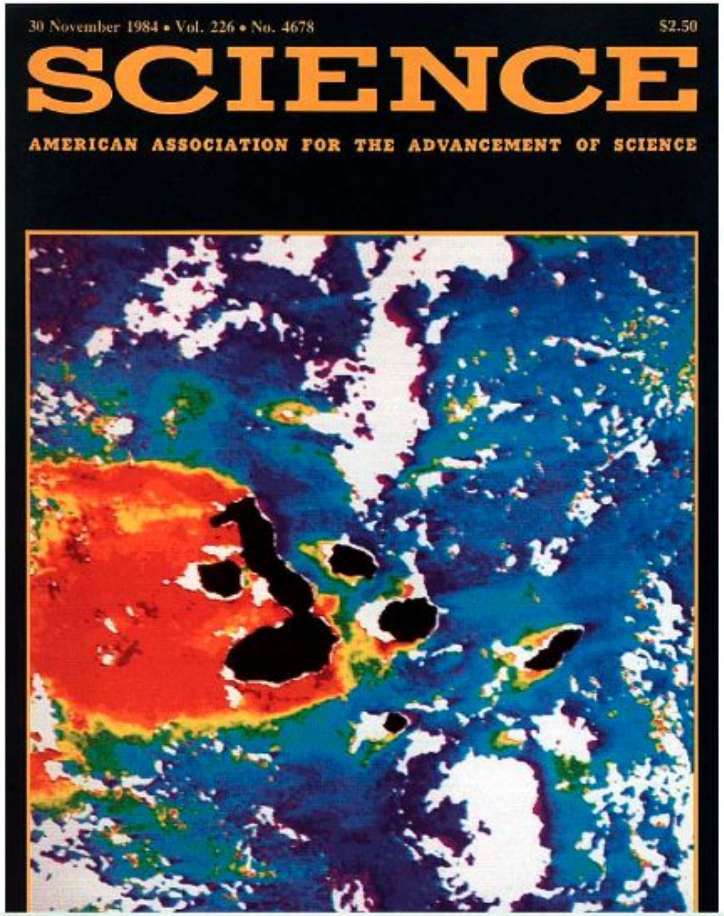


Fig. 10.1. Water-leaving radiances L_w as a function of wavelength for four chlorophyll concentrations *C*, in case 1 waters. The shaded regions labeled 1-4 indicate the detector bandwidths of the CZCS sensor. [redrawn from Gordon, *et al.*, (1985), by permission]

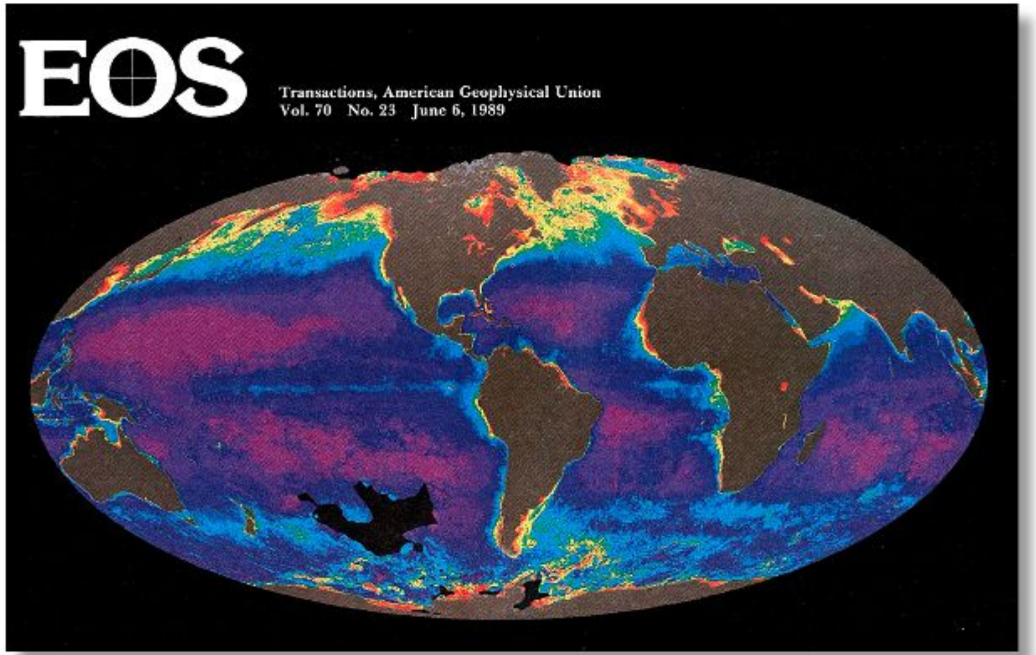
The seminal idea of ocean color remote sensing: *Chl* concentration and water-leaving radiance are correlated.

revolutionized perceptions of the ocean



Satellite Color Observations of the Phytoplankton Distribution in the Eastern Equatorial Pacific During the 1982–1983 El Niño

first ever look at global distribution of marine phytoplankton, ocean productivity



Feldman et al. 1984 and 1989

since the CZCS-era, 3 general flavors* of empirical Chl algorithms have emerged:

1. Rrs band ratios
2. Rrs line heights
3. neural networks
4. blended band ratios & line heights

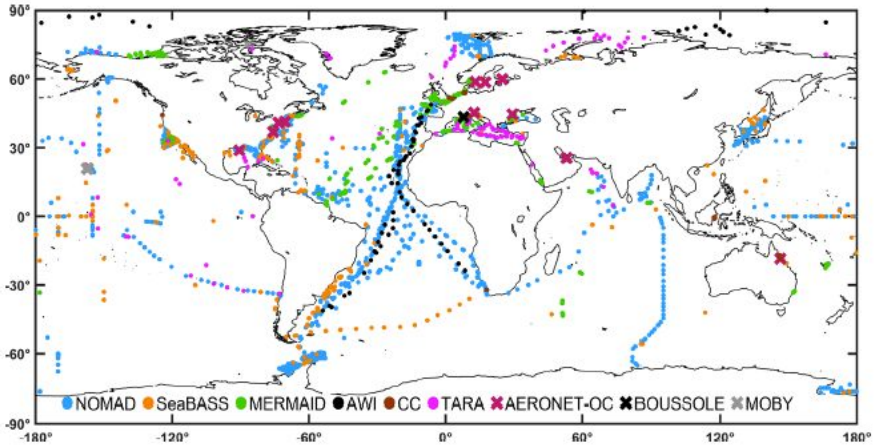
* this, of course, is a grand oversimplification of progress and algorithm development, as many other approaches exists and many have been trained to retrieve IOPs, Kd, water depth, and other aquatic parameters

Rrs maximum band ratio

$X = \log_{10}[$ Rrs(443 > 490 > 510) / Rrs(555) $]$

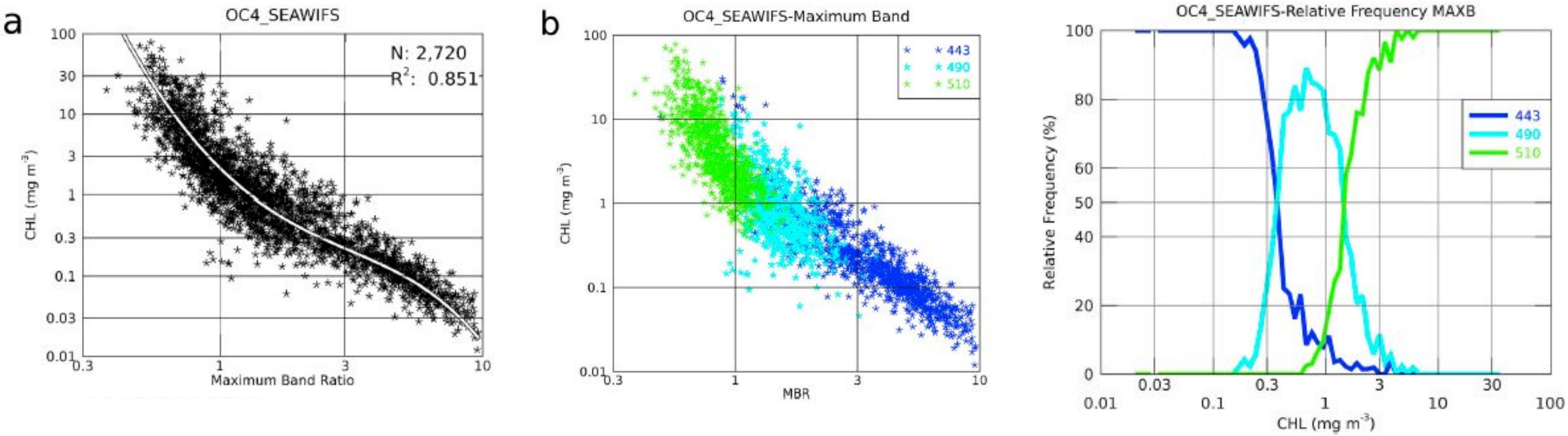
$\log_{10}(\text{chl}) = a_0 + a_1X + a_2X^2 + a_3X^3 + a_4X^4$

O'Reilly & Werdell 2019, Rem. Sens. Environ. [after O'Reilly et al. 1998, J. Geophys. Res.; O'Reilly et al. 2002, NASA TM, Werdell 2005, NASA OceanColor Web, others]



Valente et al. 2022, Earth Syst. Sci. Data

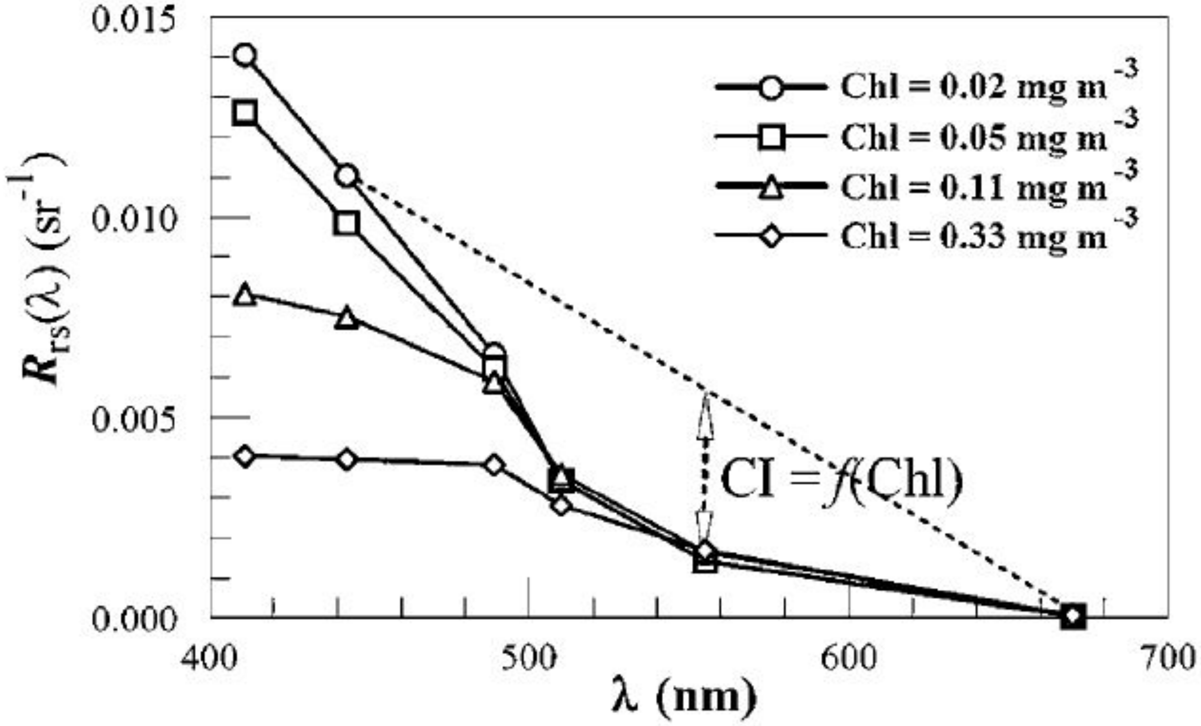
developed using a "global" dataset of in situ Rrs(λ) and chl

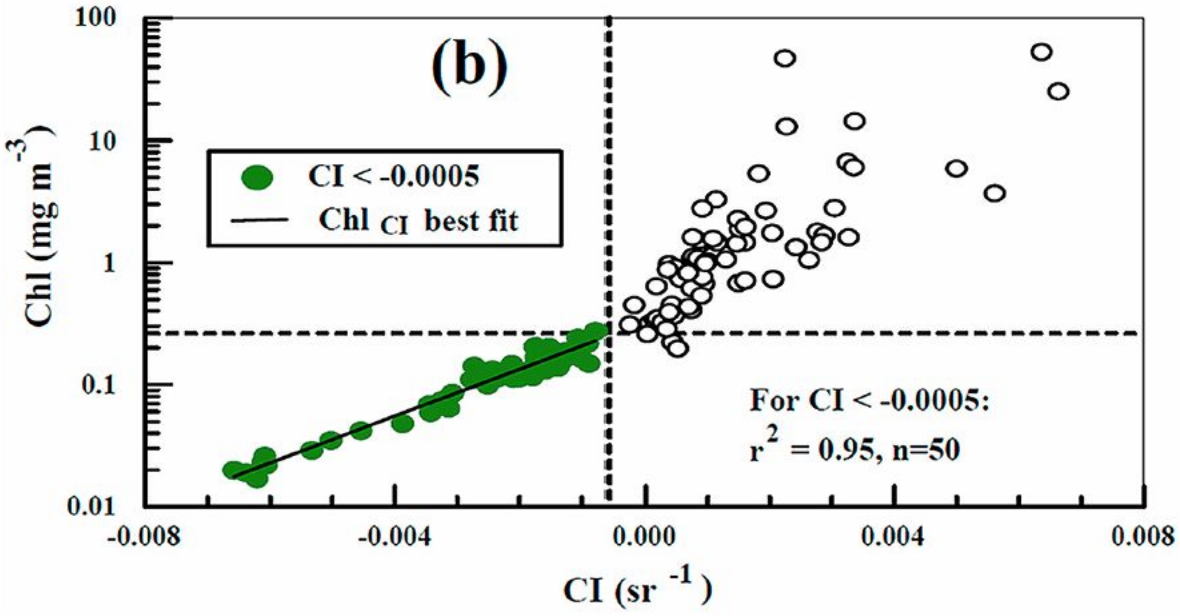


Rrs line height (baseline subtraction)

Chlorophyll Index (CI) from Hu et al. 2012, J. Geophys. Res. and Hu et al. 2019, J. Geophys. Res.

$$CI = R_{rs,555} - \left[R_{rs,443} + (555-443)/(670-443)\, x \left(R_{rs,670} - R_{rs,443}\right)\right]$$





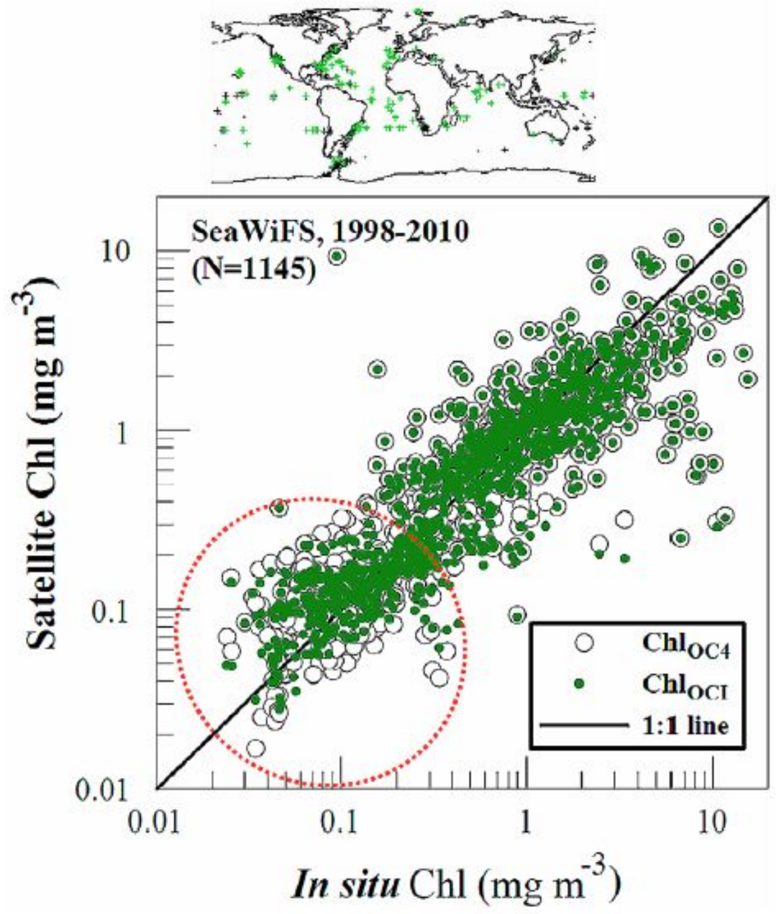
$$Log_{10}(Chl) = a\,CI + b$$

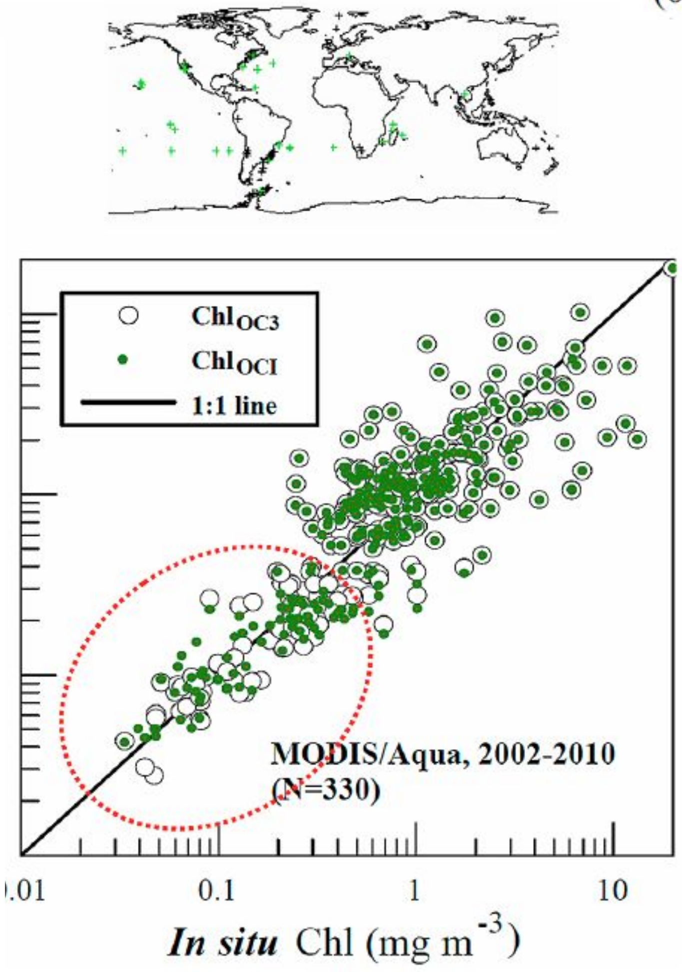
blended band ratio & line height

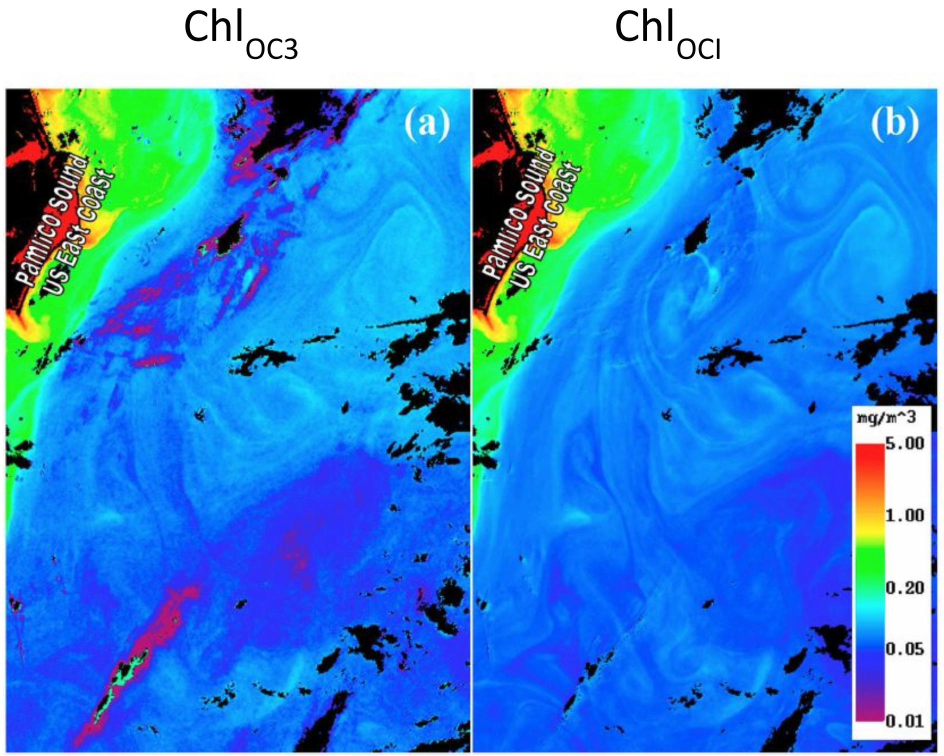
OCI from Hu et al. 2012, J. Geophys. Res.

$$\mathrm{Chl_{OCI}} = \begin{cases} \mathrm{Chl_{CI}}\left[\text{for } \mathrm{Chl_{CI}} \leq 0.25 \text{ mg m}^{-3}\right] \\ \mathrm{Chl_{OC4}}\left[\text{for } \mathrm{Chl_{CI}} > 0.3 \text{ mg m}^{-3}\right] \\ \alpha \times \mathrm{Chl_{OC4}} + \beta \times \mathrm{Chl_{CI}}\left[\text{for } 0.25 < \mathrm{Chl_{CI}} \leq 0.3 \text{ mg m}^{-3}\right], \end{cases} \quad (5)$$

where $\alpha = (\mathrm{Chl_{CI}} - 0.25)/(0.3 - 0.25)$ and $\beta = (0.3 - \mathrm{Chl_{CI}})/(0.3 - 0.25)$.

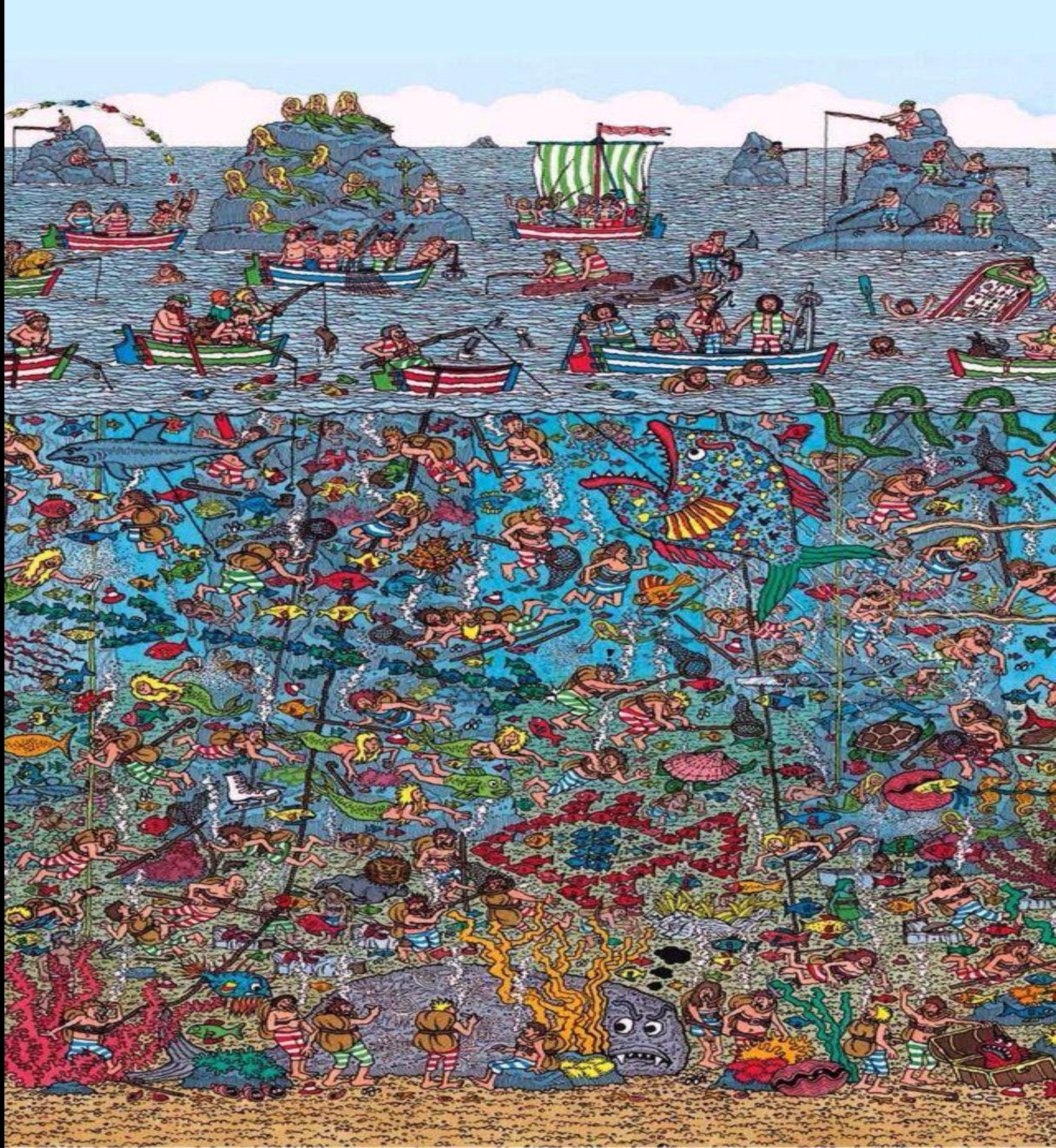






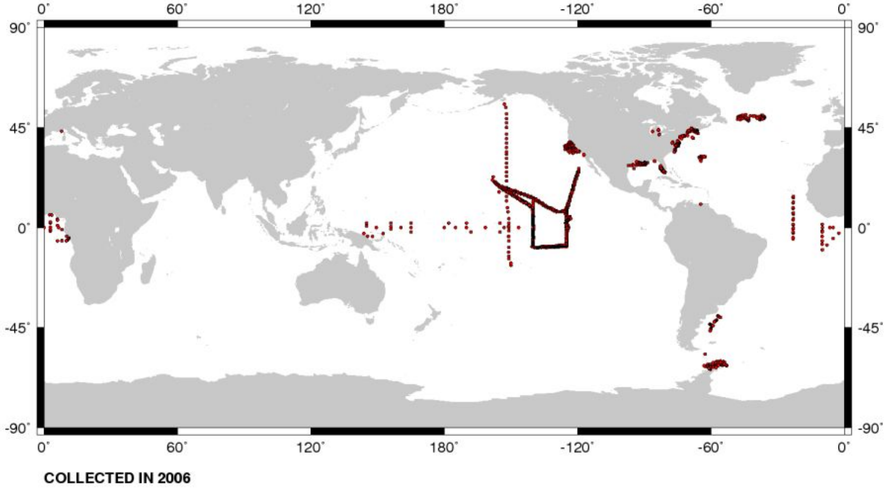
cannot emphasize enough how many empirical (statistical) approaches exist and for how many varied aquatic retreivals (IOPs, Kd, water depth, others …)

some are even nested (e.g.,
Kd, bb = f[Chl = f(Rrs)]

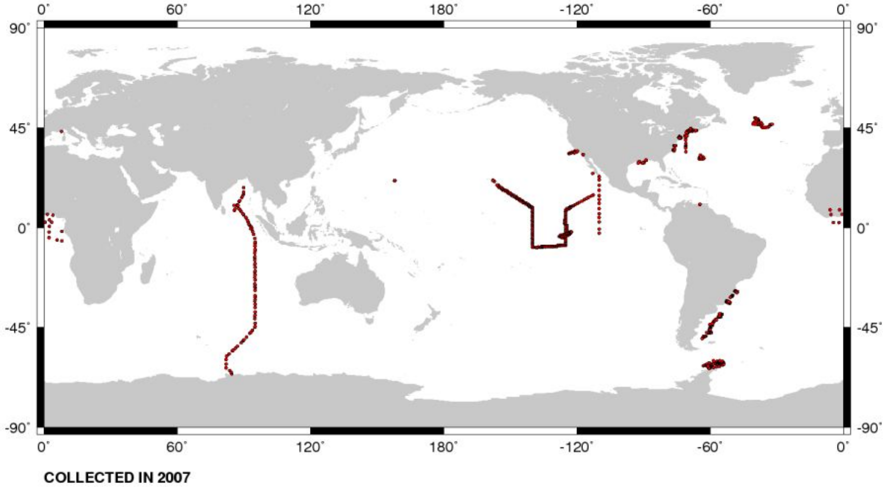


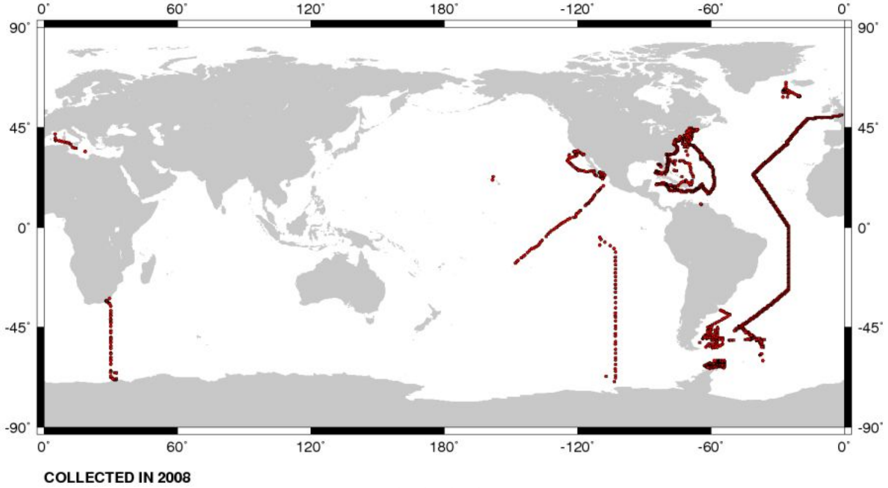
SeaBASS holdings by year: 2006-2009

2006

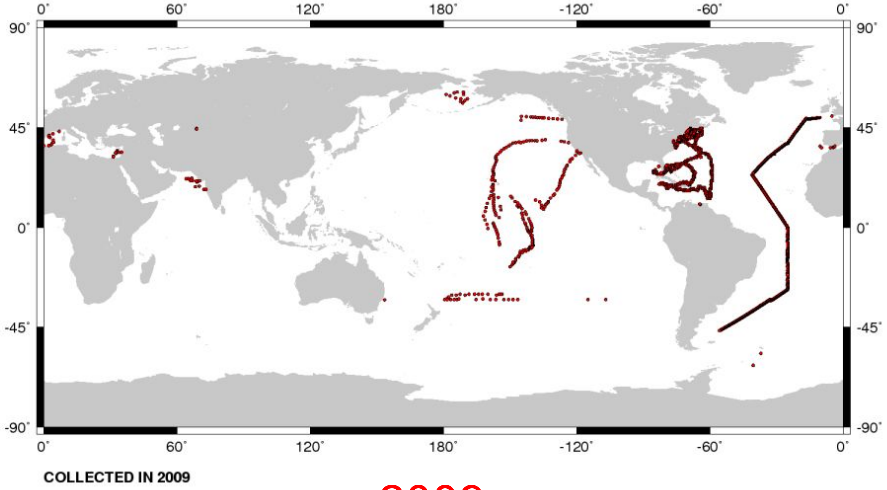


2007





2008



2009

Advantages:

- fast (computationally inexpensive)
- easily portable & reconfigurable
- often immune to some atmospheric correction issues
- sometimes insensitive to Rrs uncertainties
- easily expanded to consider other info (PCs, SST; e.g., Lange et al. 2020, Optics Express)
- often simply good enough

Disadvantages:

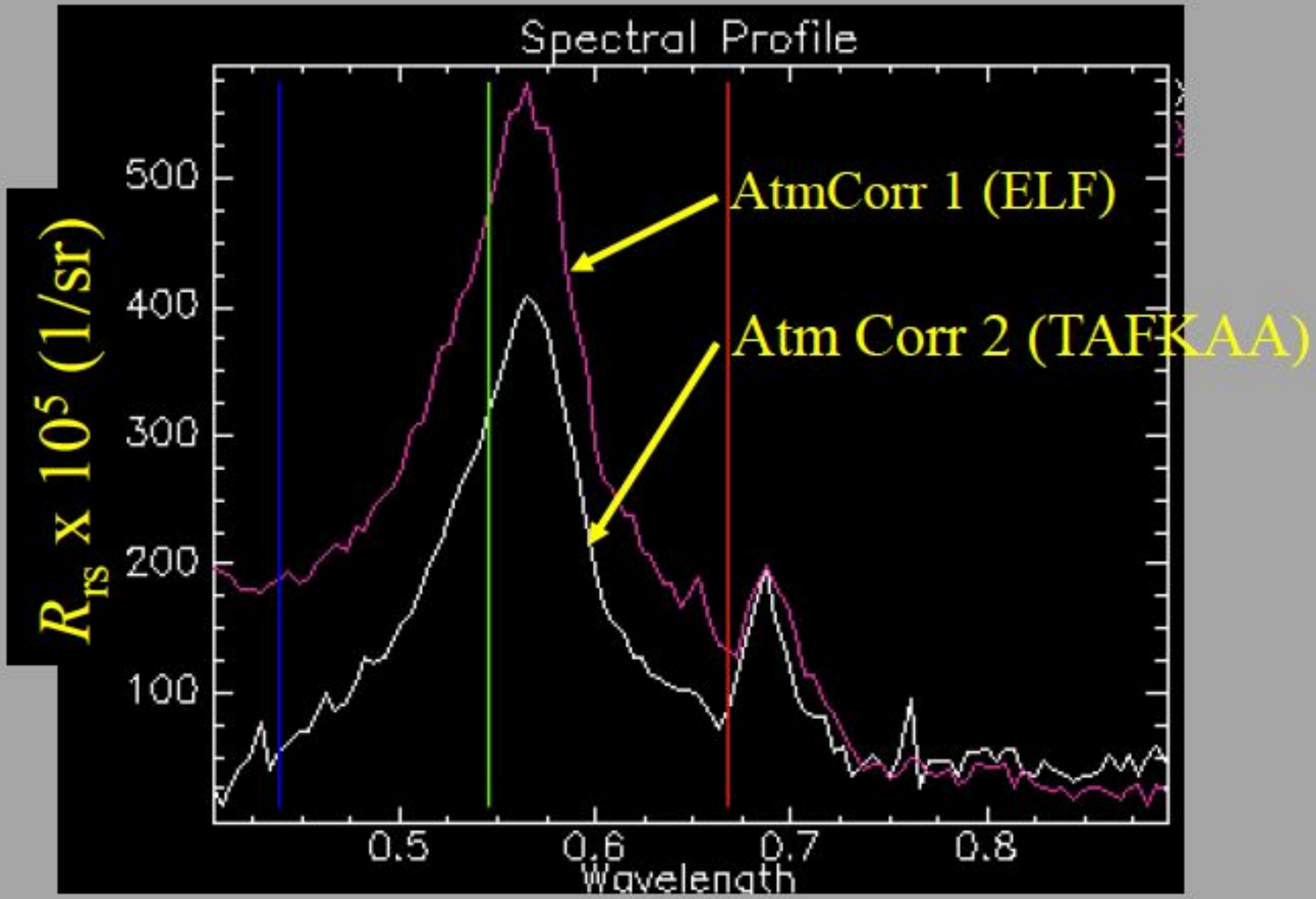
- non-unique (pervasive in inverse modeling)
- geographically biased (when using global products)
- Chl approaches considered "too Case-1"
- sometimes highly sensitive to Rrs uncertainties
- can easily prohibit insightful, conscientious interpretation of results
- not predictive

Your opinions and thoughts?

Dirty secret:

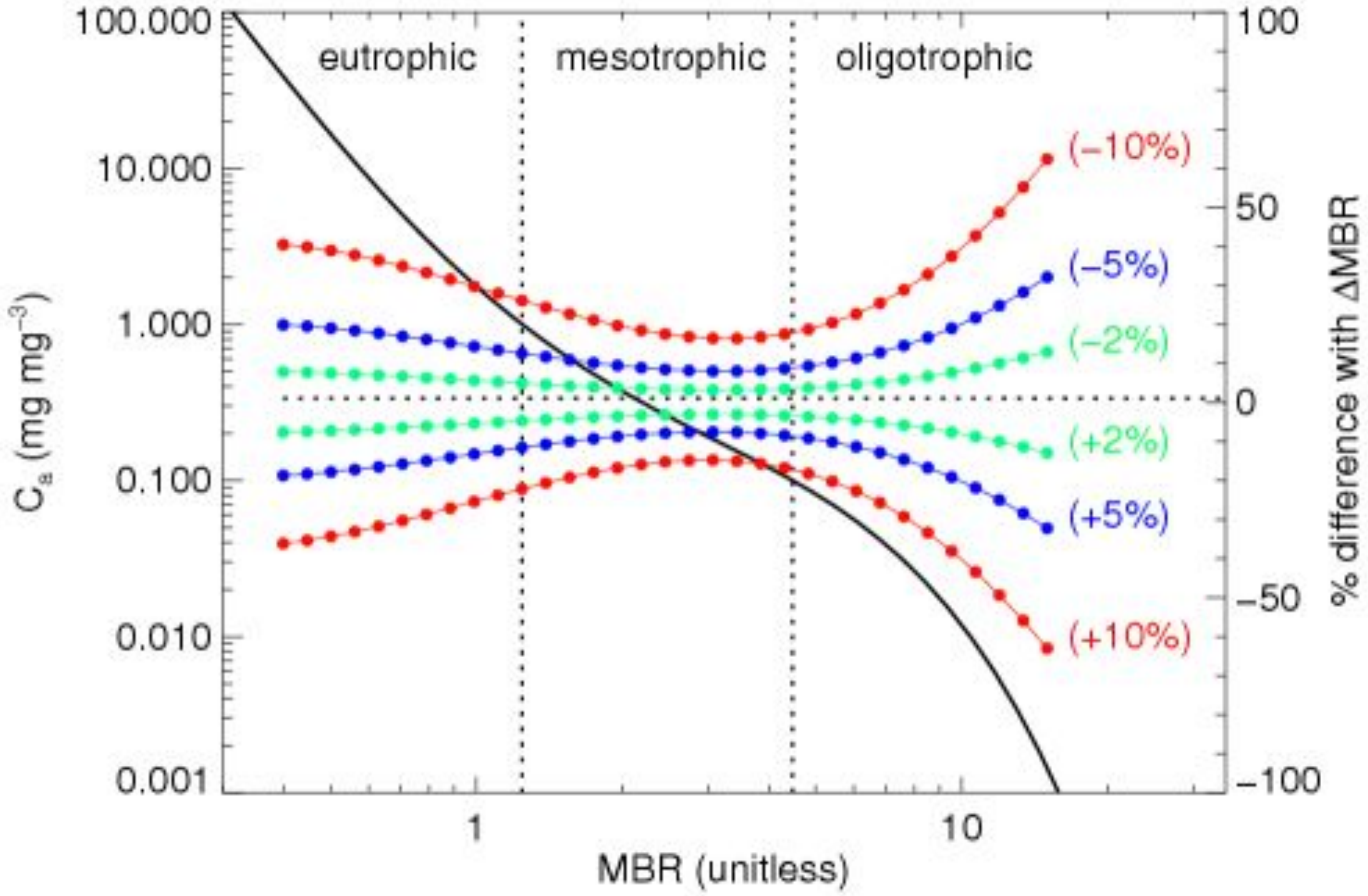
- embedded into nearly 100% of all ocean color

Band-ratio algorithms can be less sensitive to bad atmospheric correction than some other techniques such as spectrum matching

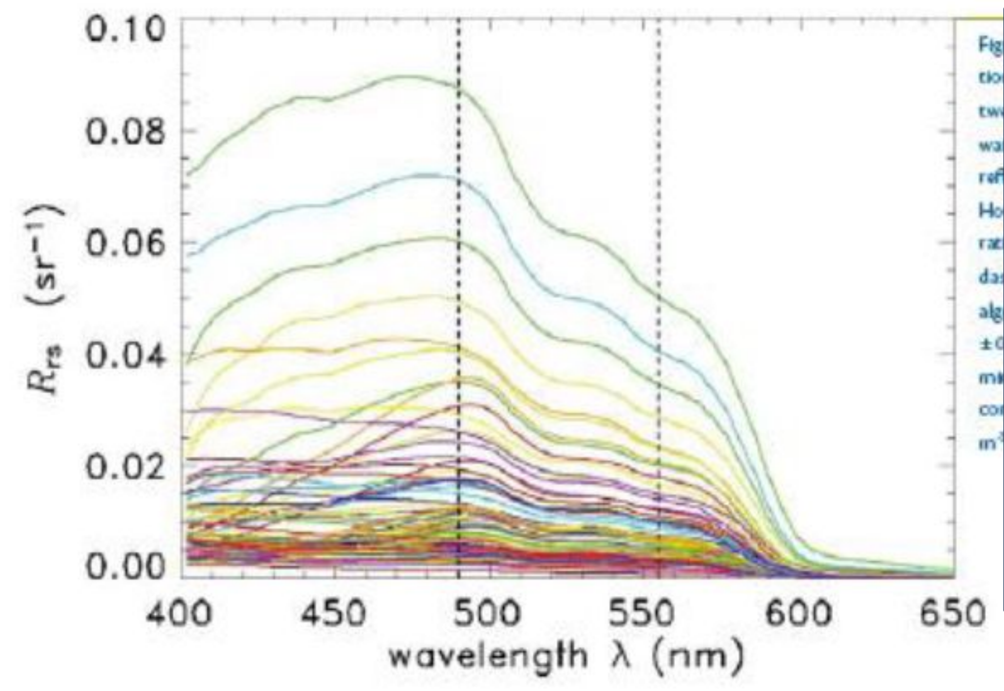


While errors in the same direction for both Rrs(blue) and Rrs(green) can cancel out …

… opposite direction errors in Rrs(blue) and Rrs(green) amplify errors in many retrievals

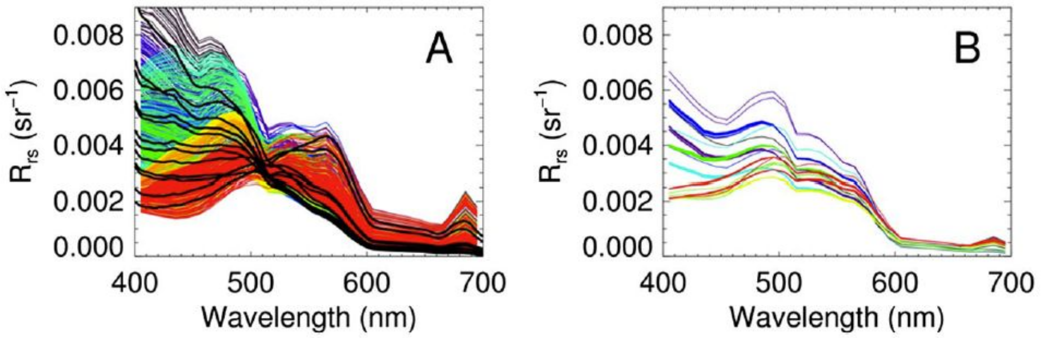


Band-ratio algorithms are vulnerable to non-uniqueness problems because the R_{rs} ratioing throws out magnitude information that makes spectra unique. Every unique spectrum below has $R_{rs}(490)/R_{rs}(555)$ = 1.71±0.01, which gives *Chl* = 0.59 mg/m^3 by the SeaWiFS OC2 algorithm; all of these spectra had Chl < 0.2 mg/m^3 (these spectra are influenced by bottom reflectance).

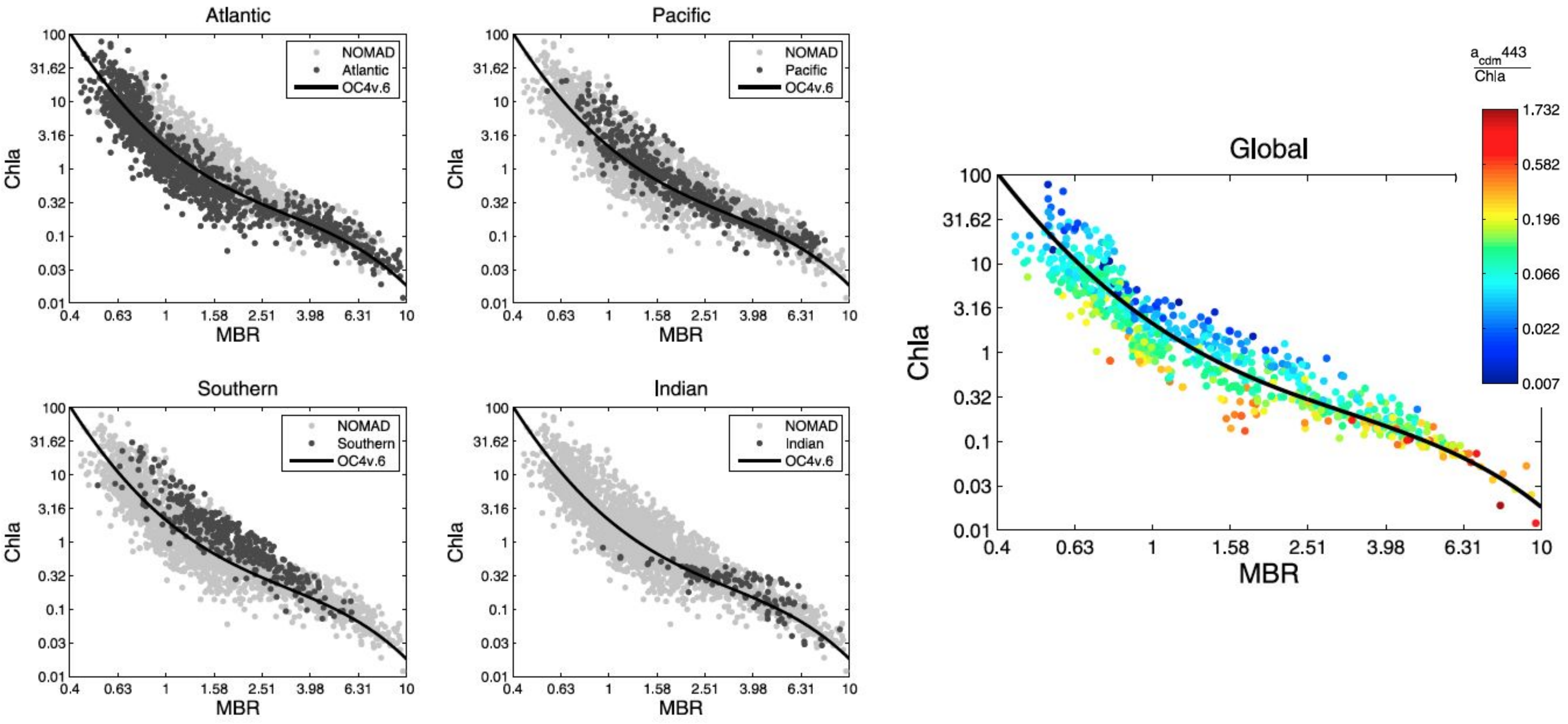


Oceanography | June 2004 27

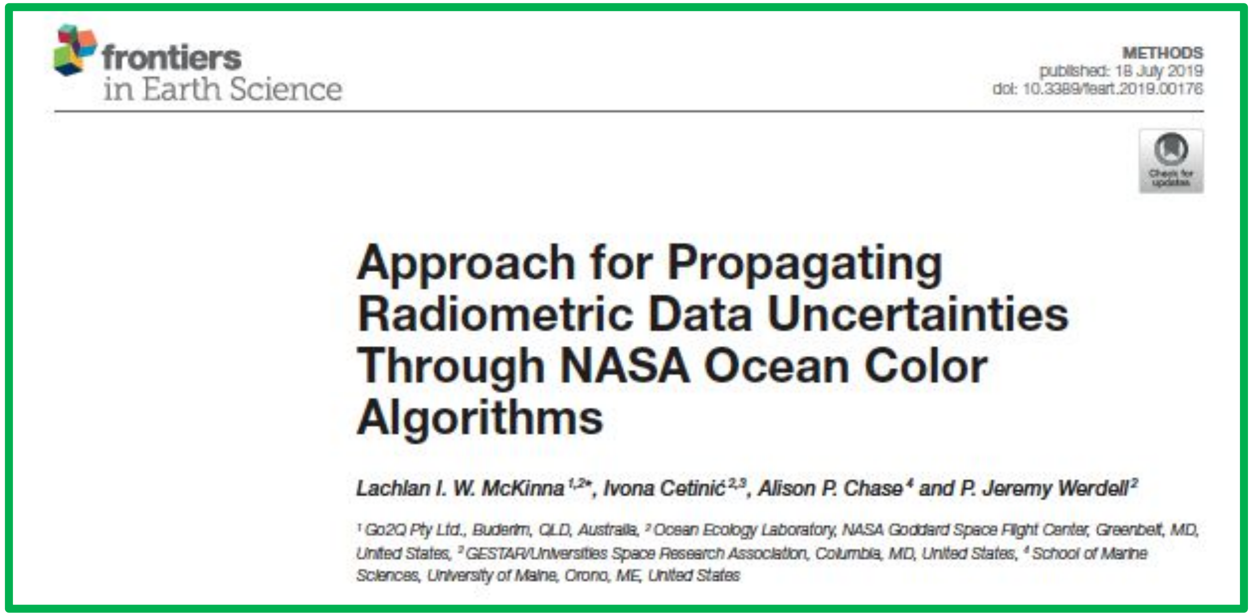
The spectra in panel B were all generated from Chl profiles with optically weighted values between 0.95 and 1.05 mg m^{-3}



Werdell et al. 2014, Applied Optics



Szeto et al. 2011, J. Geophys. Res.



frontiers in Earth Science

METHODS
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Approach for Propagating Radiometric Data Uncertainties Through NASA Ocean Color Algorithms

Lachlan I. W. McKinna[1,2*], Ivona Cetinić[2,3], Alison P. Chase[4] and P. Jeremy Werdell[2]

[1] Go2Q Pty Ltd., Buderim, QLD, Australia, [2] Ocean Ecology Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, United States, [3] GESTAR/Universities Space Research Association, Columbia, MD, United States, [4] School of Marine Sciences, University of Maine, Orono, ME, United States

analytical methods to calculate uncertainties exist …

… but they don’t encompass all sources (yet), such as those assigned to the in situ measurements and fit parameters

Model Selection

In some situations, you can figure out (from intuition, theoretical guidance, or data analysis) the general mathematical form of the model that links the input and output (e.g., the polynomial functions that relate the band ratios to Chl). You can then use the available data (e.g., simultaneous measurements of $R_{rs}(\lambda)$ and Chl) to get best-fit coefficients in the model via least-squares fitting.

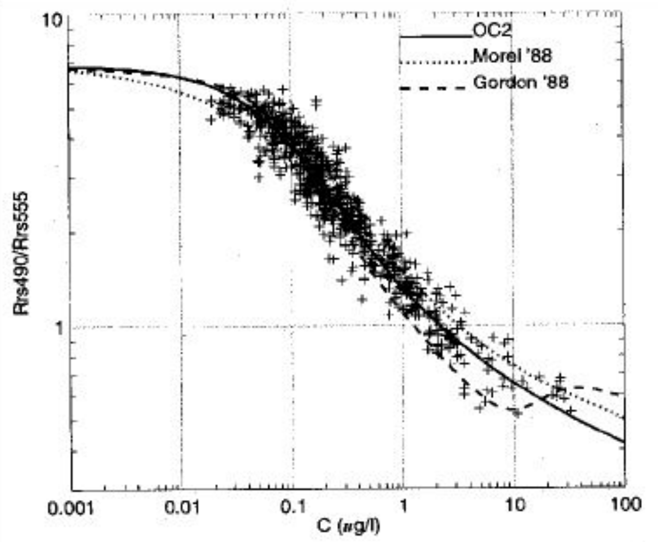

Figure 6. Relationship between chlorophyll and Rrs490/Rrs555 for the ocean chlorophyll 2 empirical algorithm (solid

O'Reilly et al., JGR, 1998

But what if you don't have any idea what the mathematical form of the model is?