What Can We Learn About Ocean Biogeochemistry from Satellite Data?

Dave Siegel

UC Santa Barbara

With help from:

Stéphane Maritorena, Norm Nelson, Mike Behrenfeld, Chuck McClain, Toby Westberry, Patrick Schultz, …

Original Talk Outline

- Phyto C & Chl/C

  Phytoplankton physiology & growth rates

- CDOM

  Precursor for marine photochemical reactions

  Potential tracer of ventilation & biogeochemistry

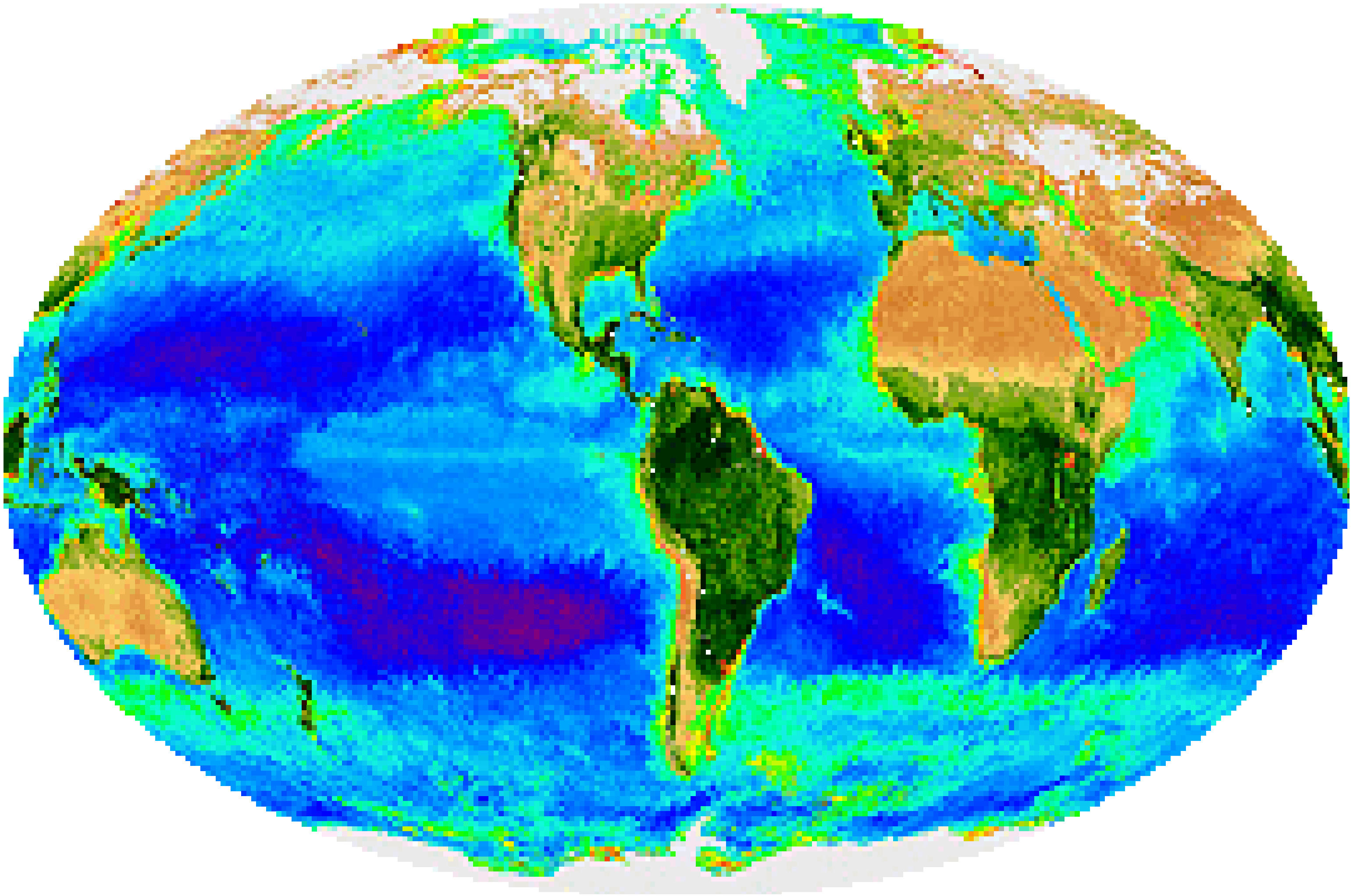
- Phytoplankton community structure

  Dominant group & specific algorithms

- Trends over time

  How we observe & assess change

Global Chlorophyll



http://oceancolor.gsfc.nasa.gov/SeaWiFS/HTML/SeaWiFS.BiosphereAnimation.html

Chlorophyll is great…

We can [finally] see the ocean biosphere!

- Assess local to global scale variability
- Trends of change on decade time scales
- Global data for building & validating models

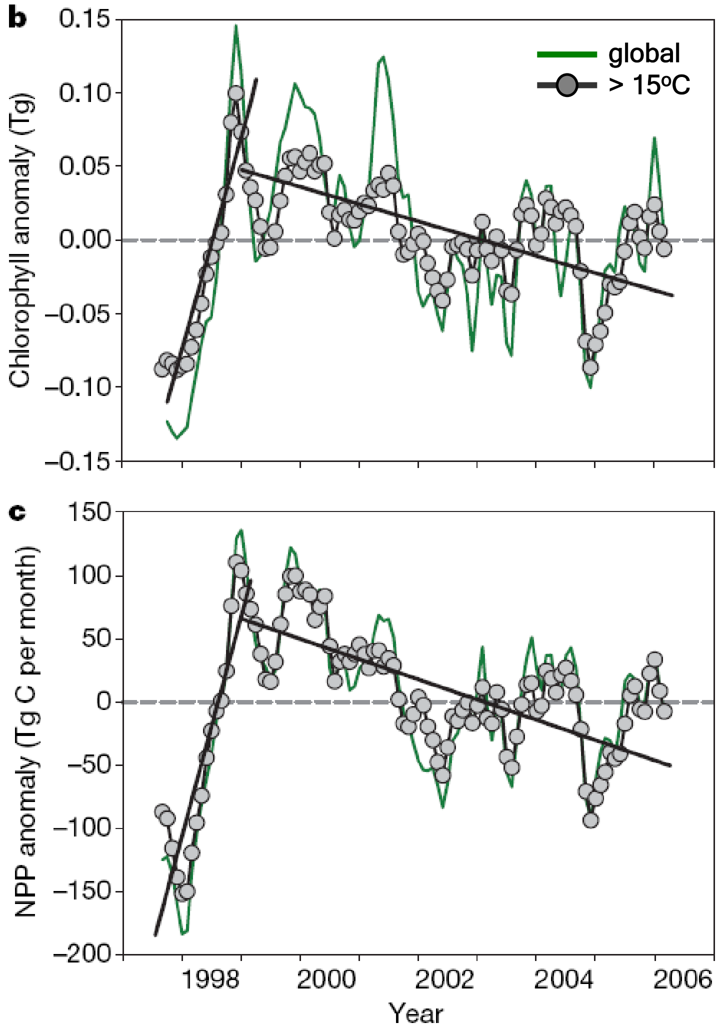
We can assess net primary production

- Model NPP as f(Chl & light)

Climate-driven trends in contemporary ocean productivity

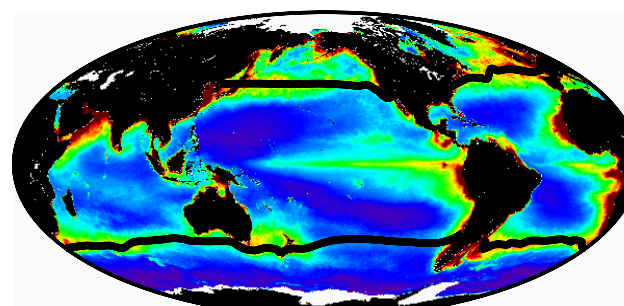
Michael J. Behrenfeld[1], Robert T. O'Malley[1], David A. Siegel[3], Charles R. McClain[4], Jorge L. Sarmiento[5], Gene C. Feldman[4], Allen J. Milligan[1], Paul G. Falkowski[6], Ricardo M. Letelier[2] & Emmanuel S. Boss[7]

7 December 2006 Vol. 444 Nature



Tidbits

- **Based on Vertically Generalized Production Model (VGPM)**
- **Initial increase = 1,930 TgC/yr**
- **Subsequent decrease = 190 TgC/yr**
- **Global trends dominated by changes in permanently stratified ocean regions (ann. ave. SST < 15ºC)**



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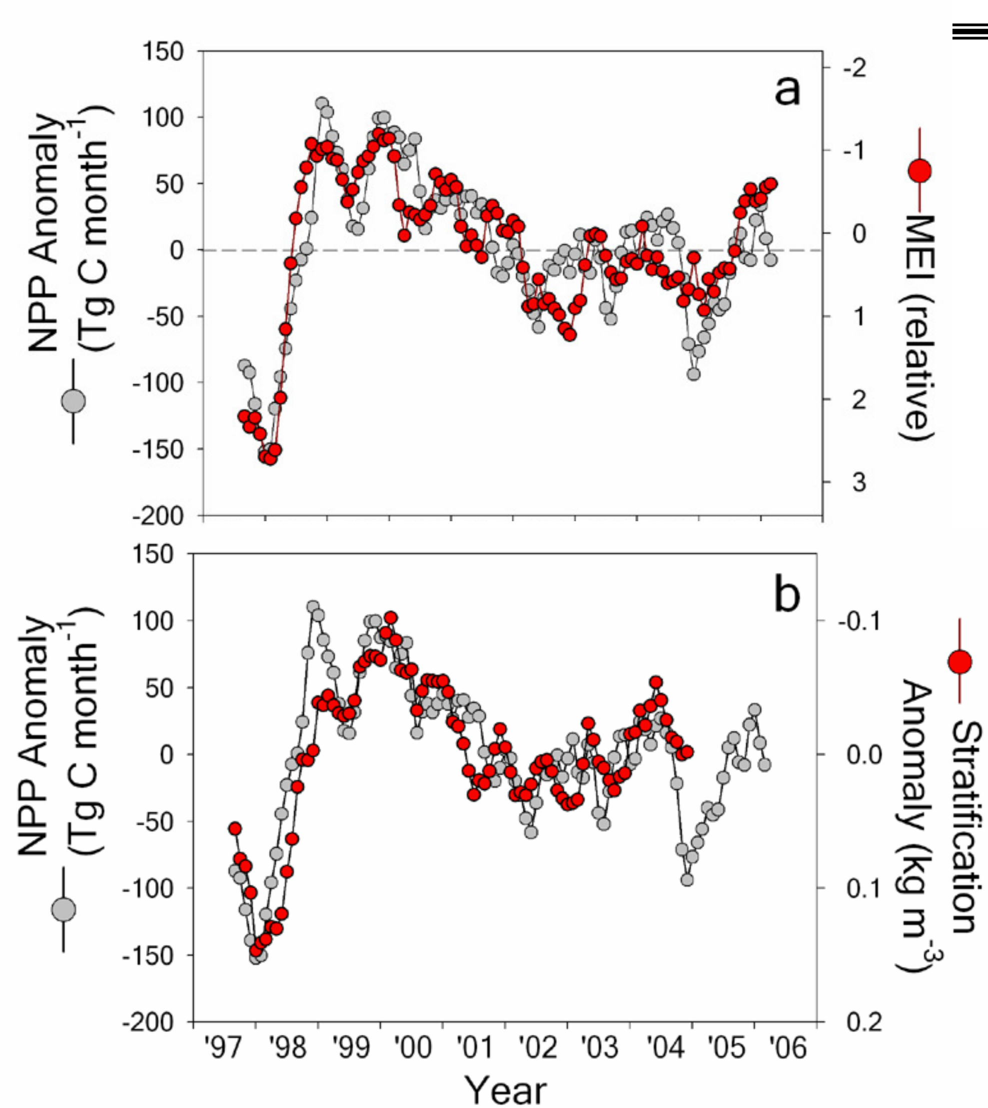
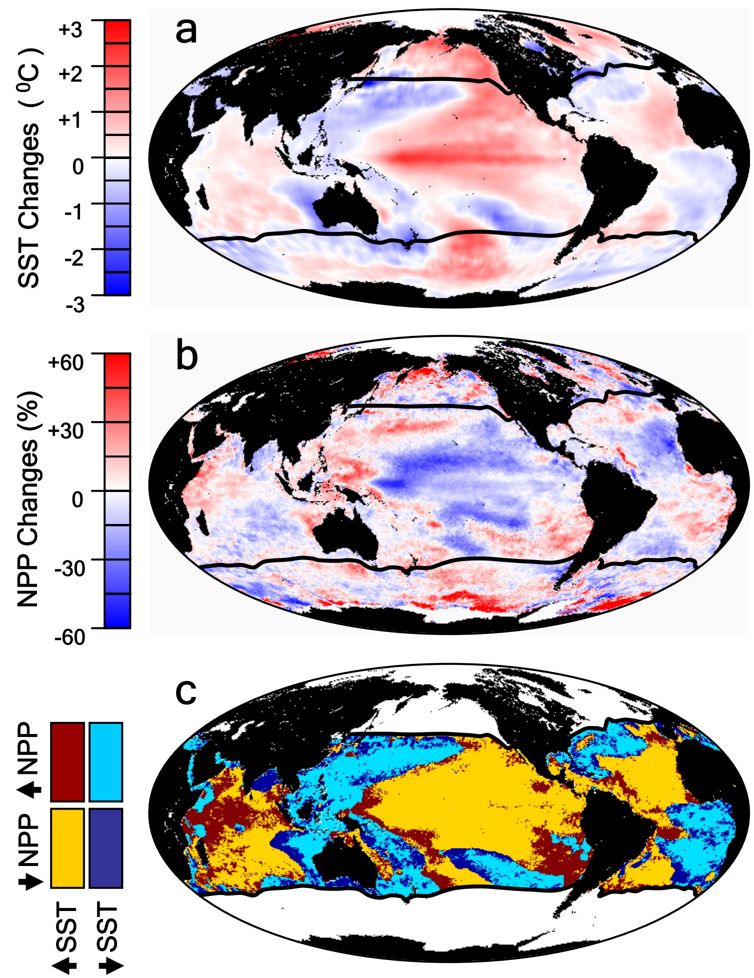




But, chlorophyll is …

Not What We Want

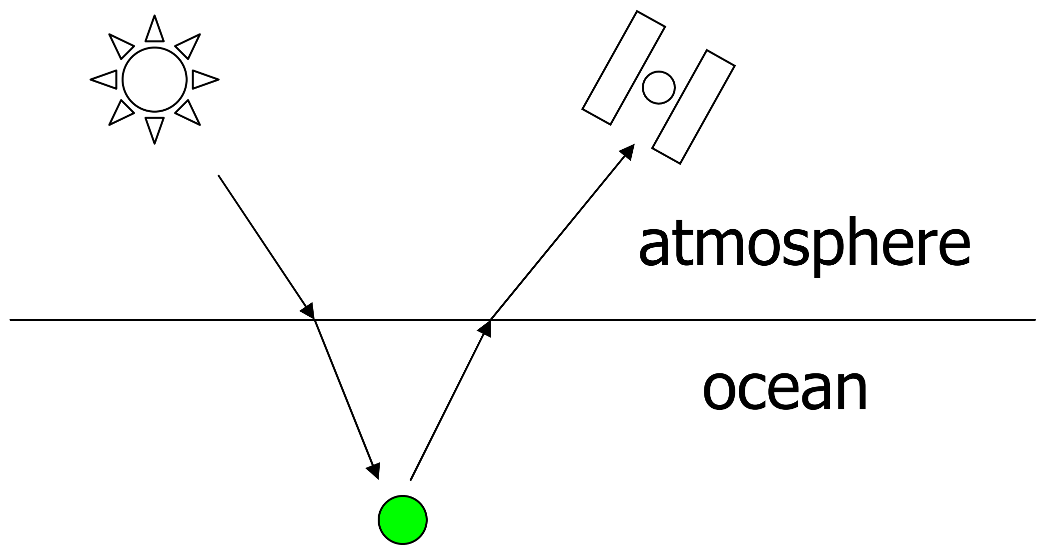
- We want BGC-relevant measures (biomass)
- Need Chl/C to compare w/ model output
- But Chl/C = f(light, nuts, species, etc.)

Nor is it The Whole Story

- There's more in the ocean that affects ocean color than just chlorophyll

What is Ocean Color?

- Light backscattered from the ocean - but not absorbed



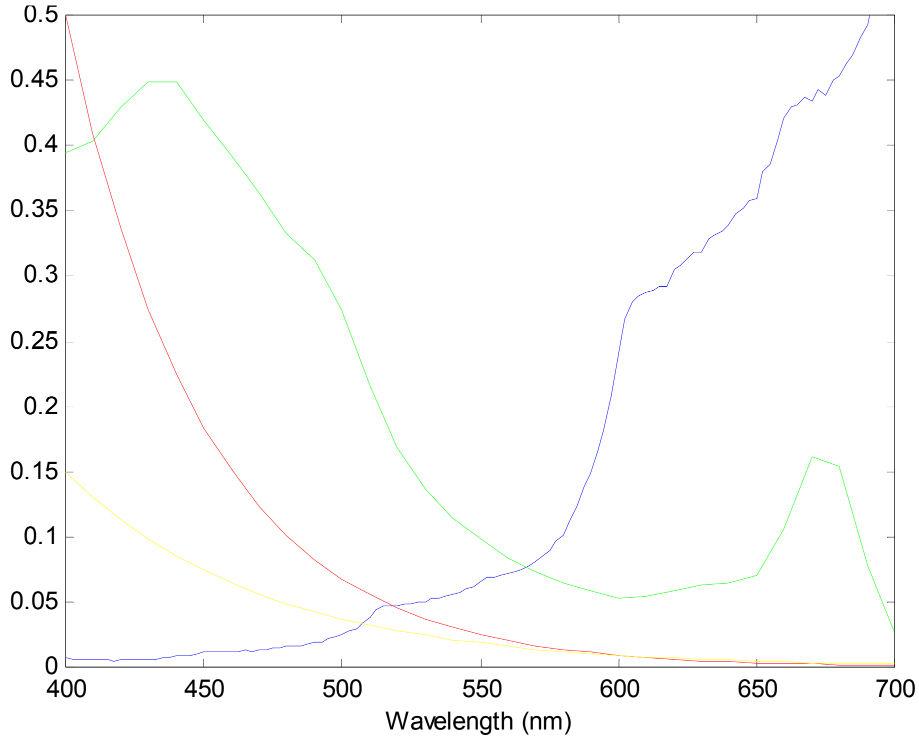
- Reflectance = f(backscattering/absorption)

$$R_{rs}(\lambda) = f(b_b(\lambda) / a(\lambda))$$

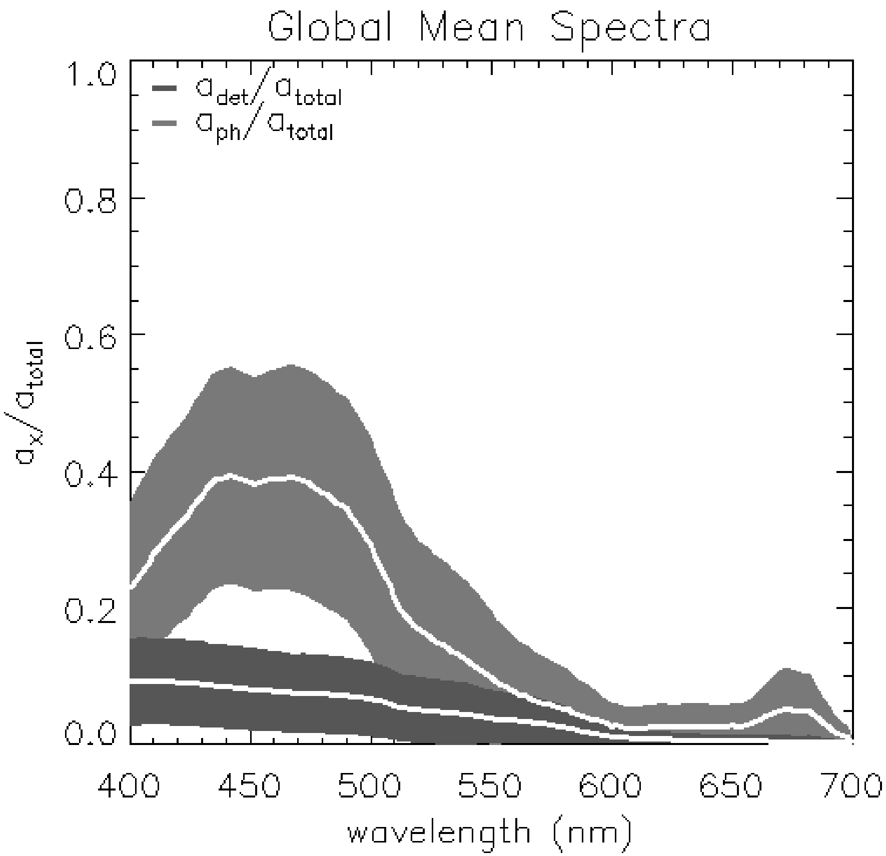
Absorption of light in seawater

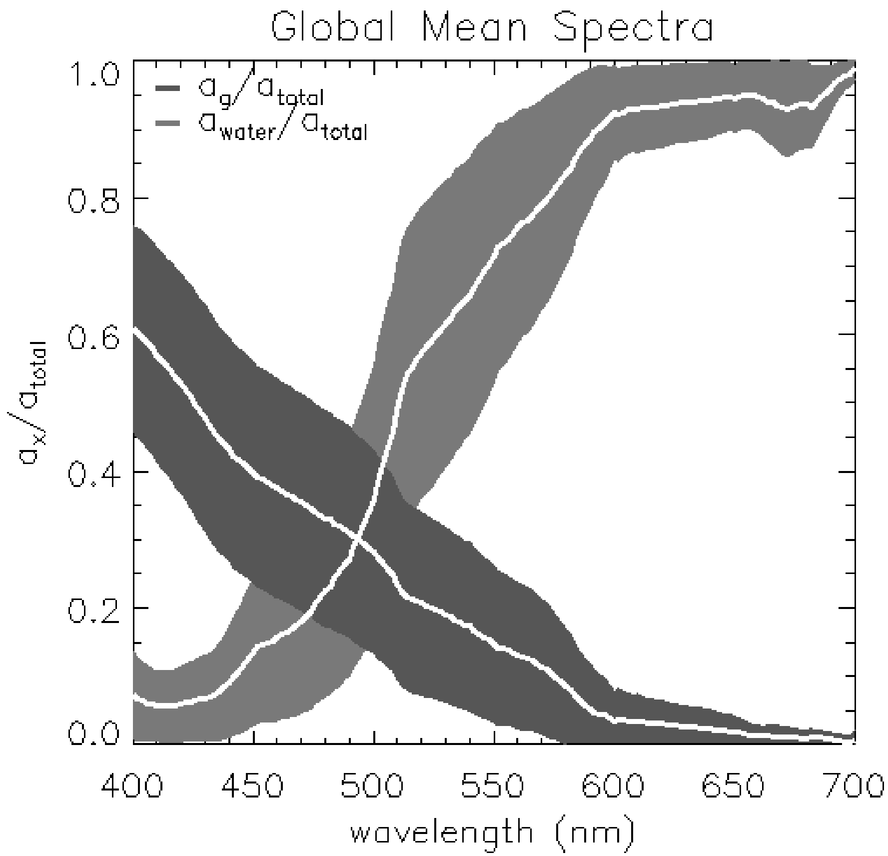
Total abs = water + phyto + CDOM + detritus

$$a(\lambda) = a_w(\lambda) + a_{ph}(\lambda) + a_g(\lambda) + a_{det}(\lambda)$$



Absorption of light in seawater





CDOM dominates for $\lambda < 450$ nm
Detritus is very small (< 10%)

Data tabulated in Siegel et al. [2002] JGR

Backscattering of seawater

Total b_b = water + particle = $b_{bw}(\lambda)$ + $b_{bp}(\lambda)$

Backscattering is very small

Open ocean …

water dominates λ < 450 nm

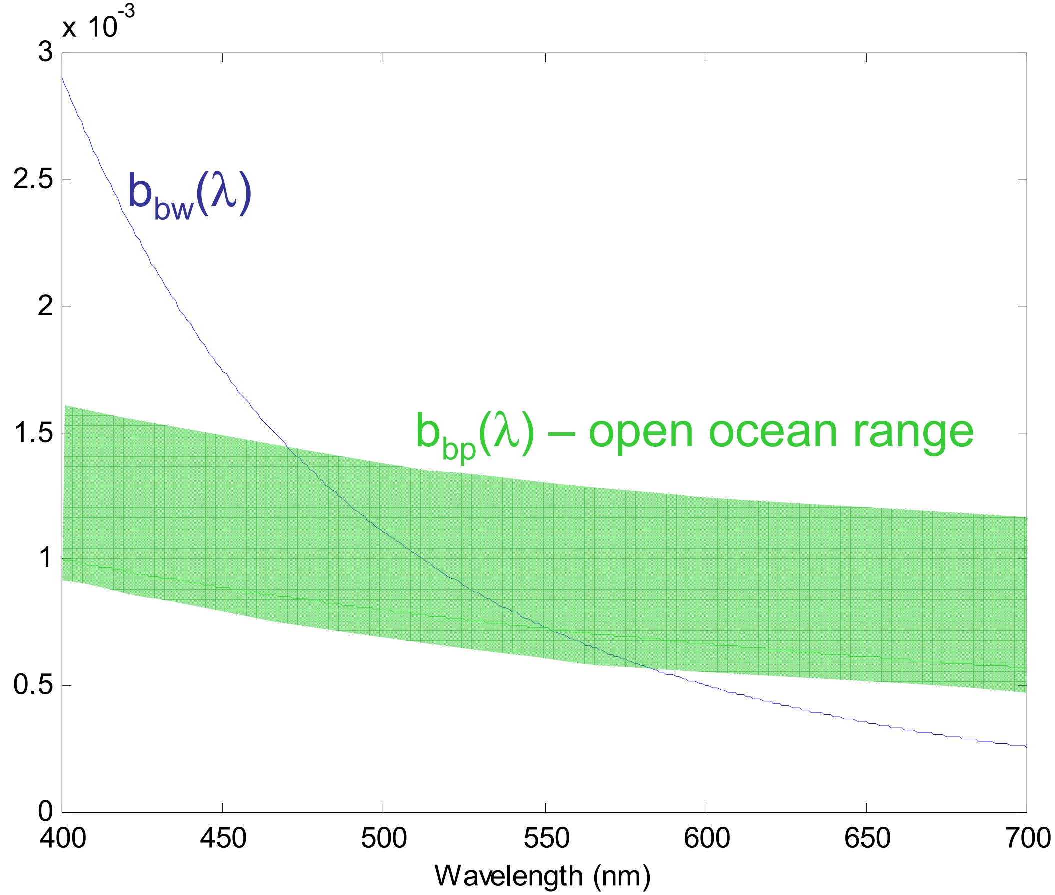
particles λ > 550 nm

theoretically - small particles

but b_{bp} variability is too large

Coastal waters …

all bets are off



The Whole Story According to DV

Ocean color is like your TV…

- You basically get 3 colors (RGB, HSL, etc.)

The Open Ocean Color Trio

- Chlorophyll, CDOM & particle backscattering
- Chl & CDOM (with water) set the color balance & BBP sets the brightness level
- There may a bit more $\Rightarrow$ community structure

What the trio tells us…

Property	**What's Sensed**	**Regulating Process**	**Forcing Mechanism**
BBP particulate backscatter	Particle biomass Suspended sediment	Primary production Terrestrial inputs	Nutrient input/upwelling Land/ocean interactions Dust deposition??
Chl chlorophyll concentration	Chlorophyll biomass	Primary production Physiological changes of phytoplankton C:Chl	Nutrient input/upwelling Growth irradiance & nutrient stress
CDM colored detrital materials	CDOM Detrital particulates	Heterotrophic production Photobleaching Terrestrial inputs	Upwelling/entrainment UV light dosage Land/ocean interactions

Retrieving Ocean Color Trio

- Semi-analytical algorithms for ocean color

  Theoretically based with some empirical results

  Optimized using a global optical data set

- Garver-Siegel-Maritorena (GSM-01)

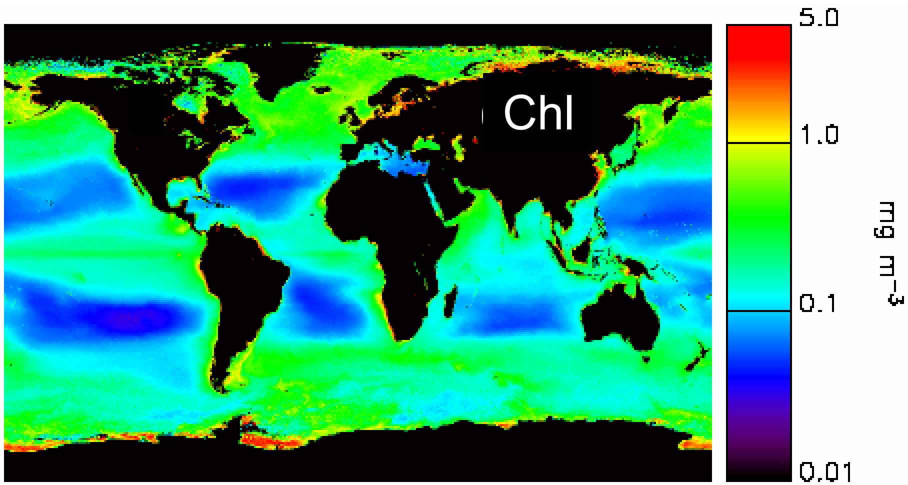
  Maritorena et al., 2002: *Applied Optics*

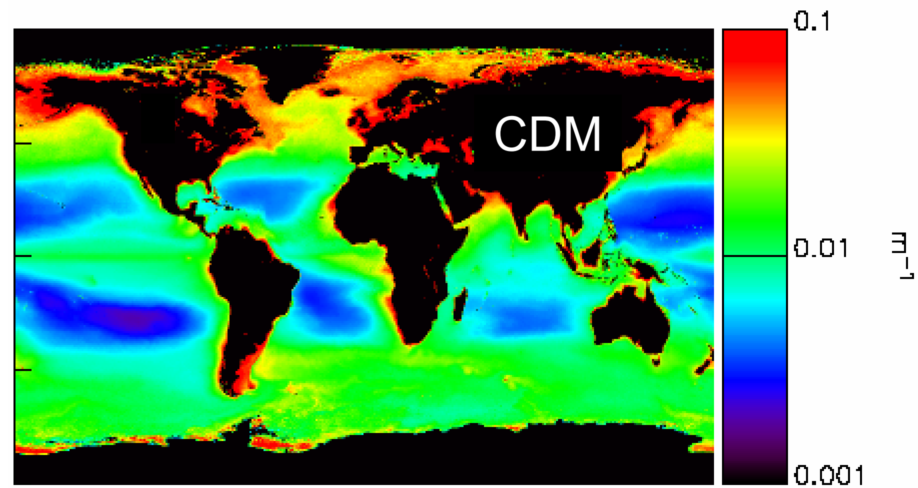
  Trio = Chl, CDM (= $a_g(443)+a_{det}(443)$) & BBP ($b_{bp}(443)$)

  Inputs are SeaWiFS and/or MODIS Aqua $L_{wN}(\lambda)$

Data: ftp://ftp.oceancolor.ucsb.edu/pub/org/oceancolor/REASoN

The Ocean Color Trio



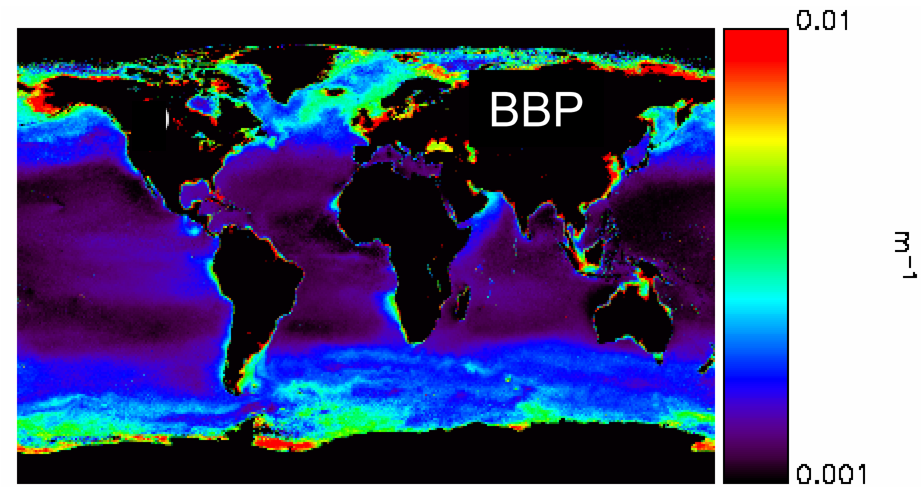


SeaWiFS 5 y climatology

Oceanic structures

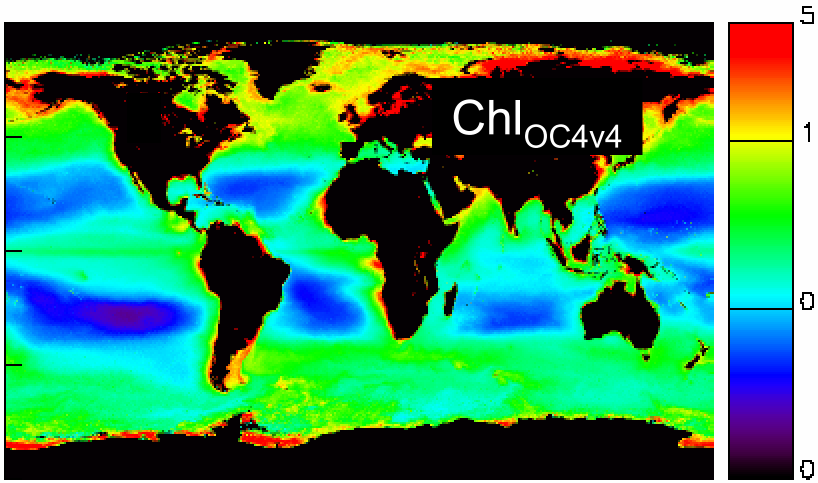
Gyres, upwelling, etc.

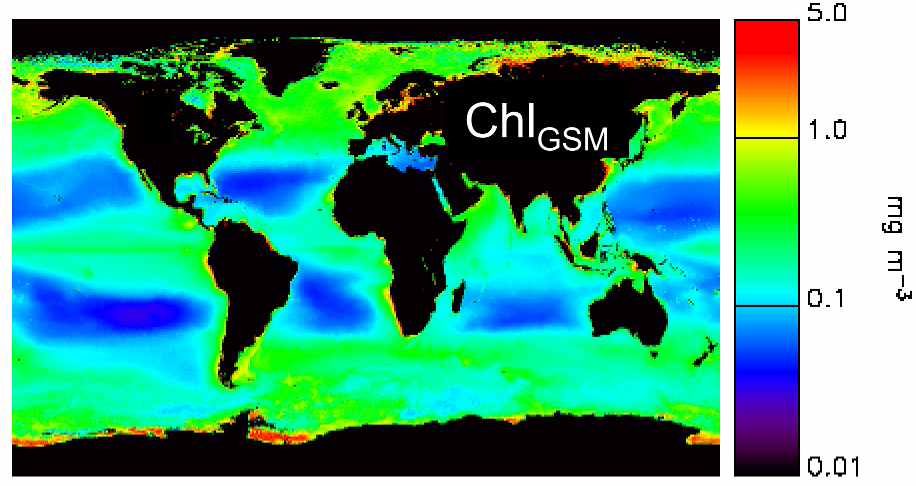
Large variability in Chl & CDOM but not BBP



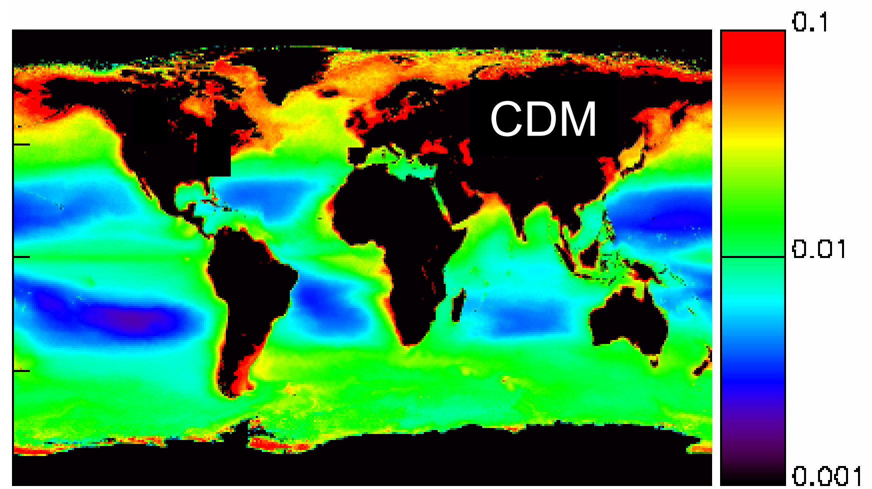
Siegel et al. (2005) JGR

An aside…



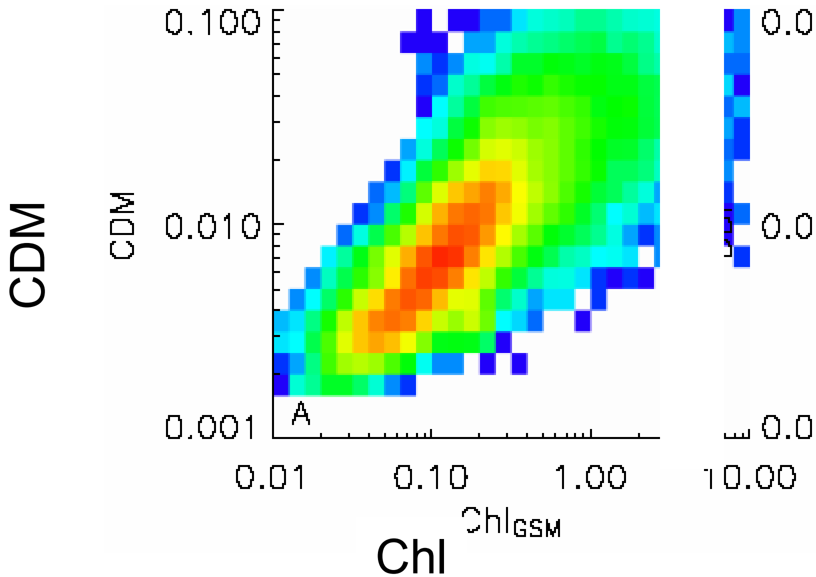


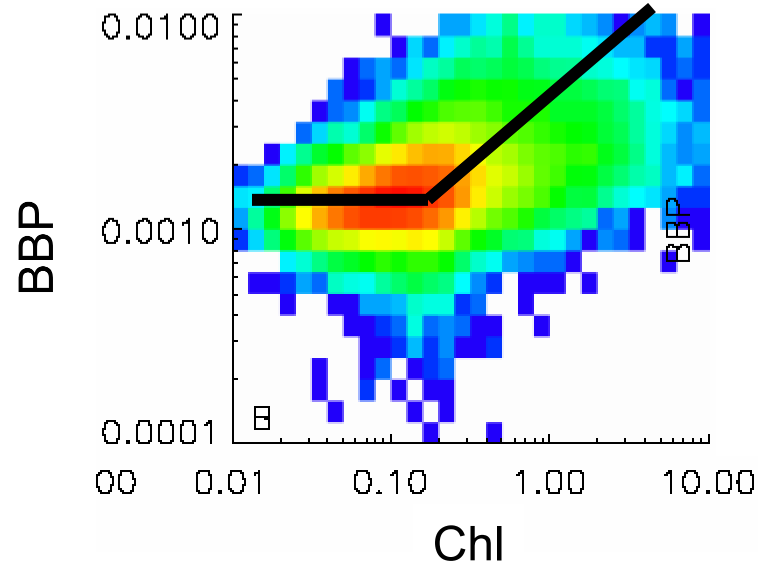
- OC4v4 Chl > GSM Chl in NH
- Reason is CDM in NH
- Models are only as good as the data used to derive them…

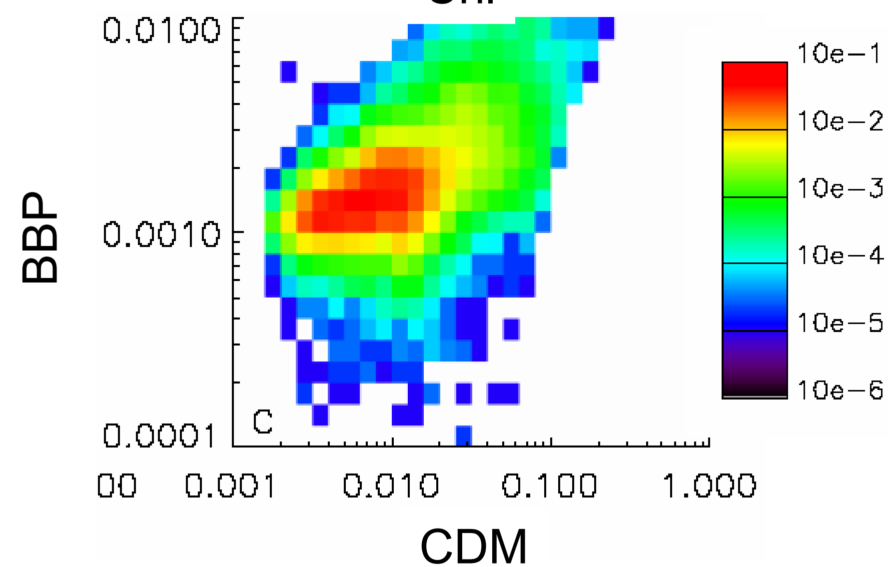


Siegel et al. (2005) GRL

How do the trio interrelate?







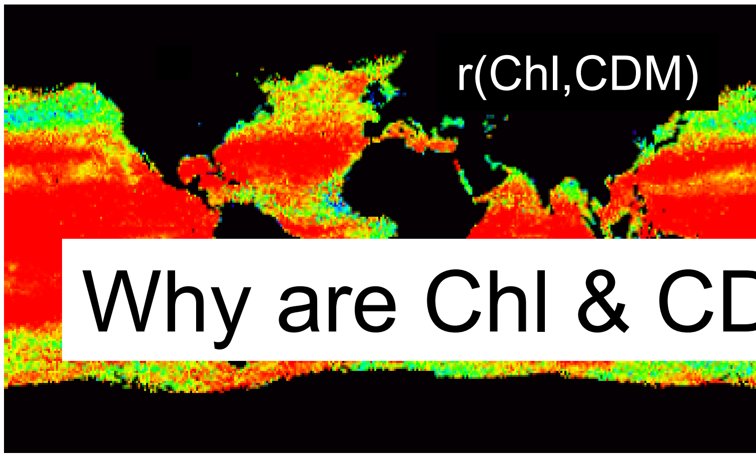
Mission mean relations

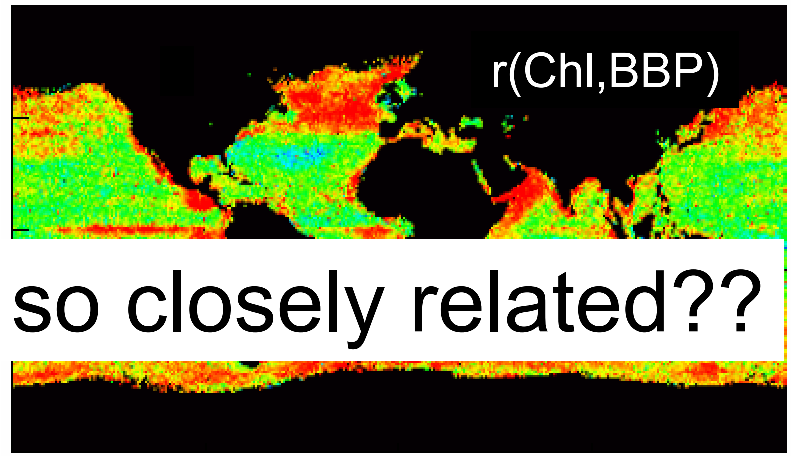
Chl & CDM are well related

BBP is mostly independent w/ a bit of a "hockey stick"

Siegel et al. (2005) JGR

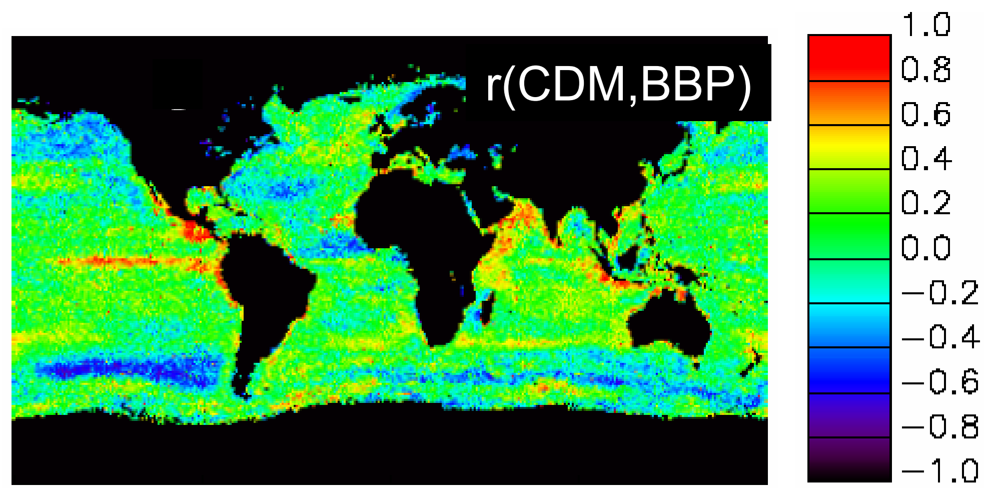
How do they relate spatially???





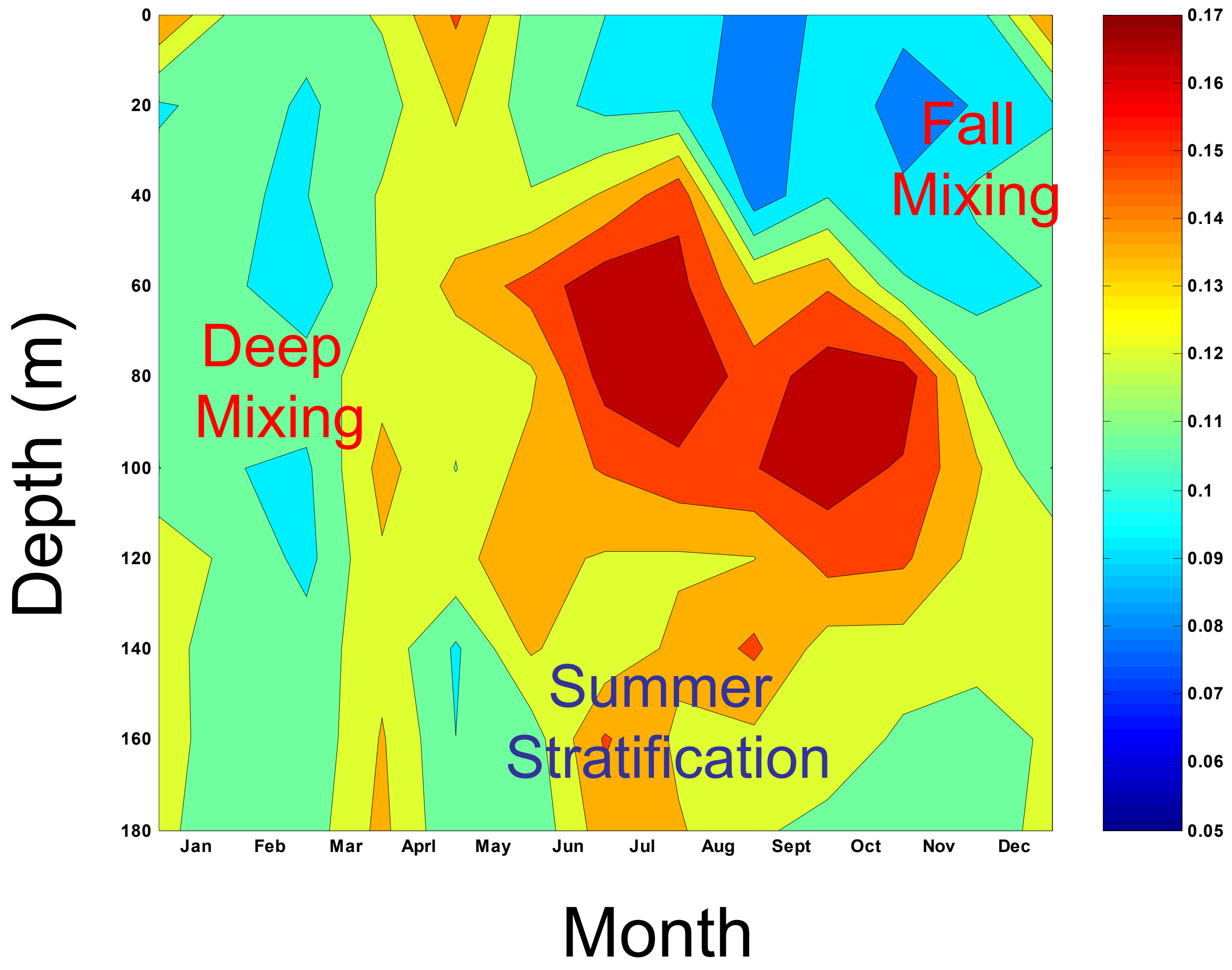
Why are Chl & CDM so closely related??

- Chl & CDM are often related
- BBP is mostly independent
- Exceptions are important
  - Chl & CDM at high lat
  - Chl & BBP at high lat & upwelling zones



Siegel et al. (2005) JGR

Seasonal Cycle of CDOM at BATS



Jon Klamberg, MS thesis, 2005

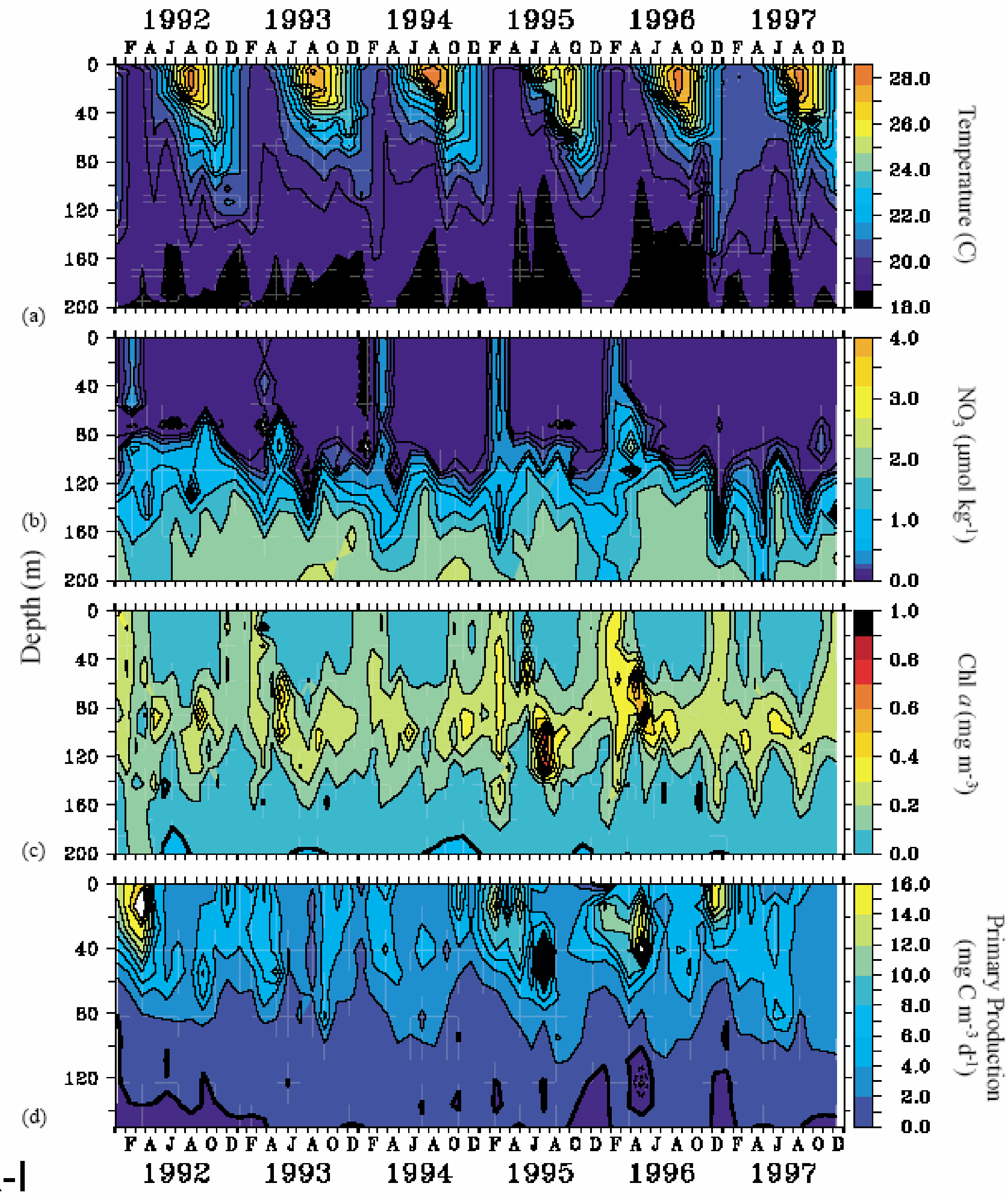
Seasonal CDOM Cycle at BATS

Links mixing, photolysis & production

- Low summer ML CDOM due to bleaching
- Shallow summer max of CDOM production
- Mixing homogenizes the system

BTW – CDOM is NOT f(DOC)

Seasonal Chl Cycle at BATS



Westberry & Siegel (2003) DSR-I

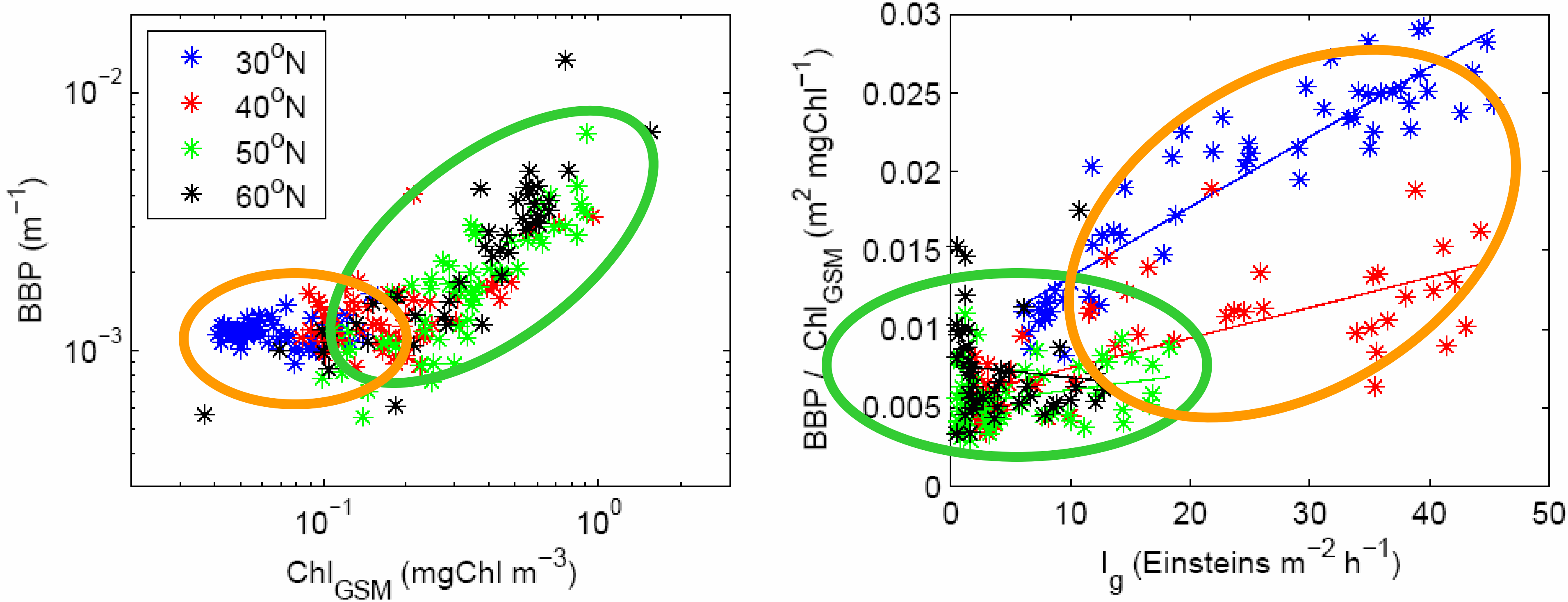
Seasonal Chl Cycle at BATS

Links mixing, NPP & photoacclimation

- Winter mixing brings nutrients to surface layer leading to a spring bloom
- Summer stratification isolates surface waters & increased light reduces surface cellular Chl levels
- Cycle repeats

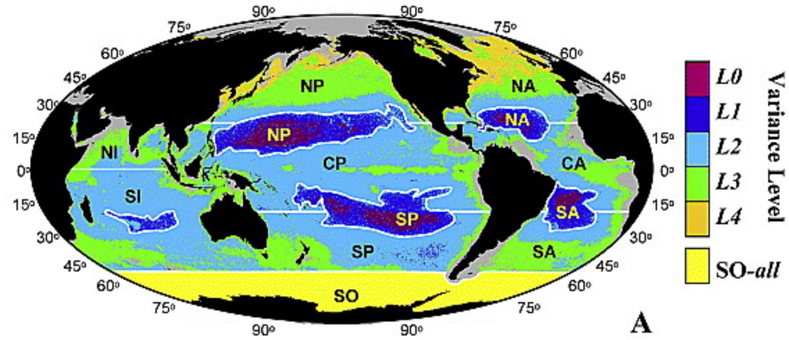
SS Chl & CDOM seasonal Δ's appear similar

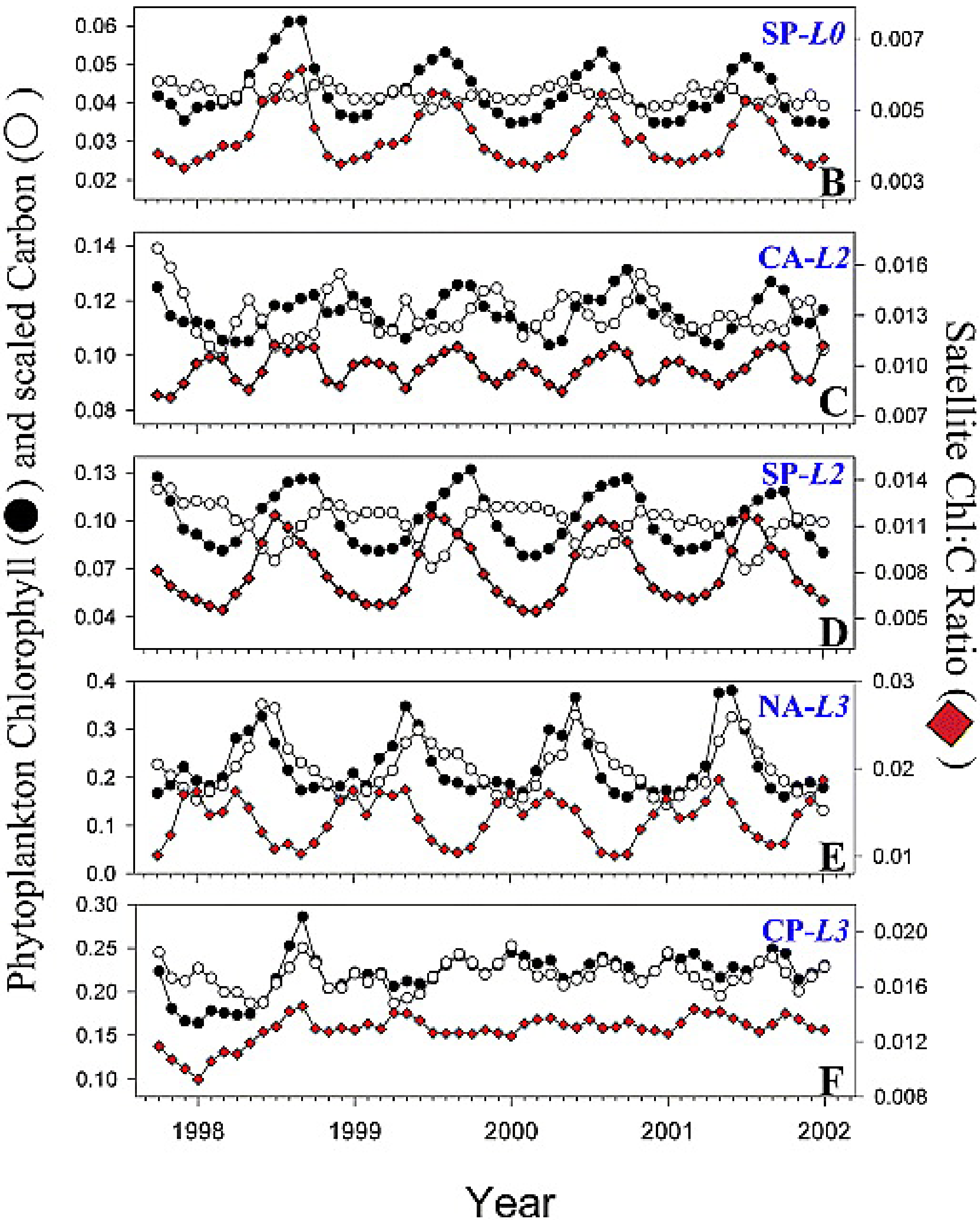
What about BBP & Chl



- Data are from a North Atlantic transect along 30°W
- Clusters for growth (f(Chl)) & photoacclimation (f(I_g)) regions

Siegel et al. (2005) JGR

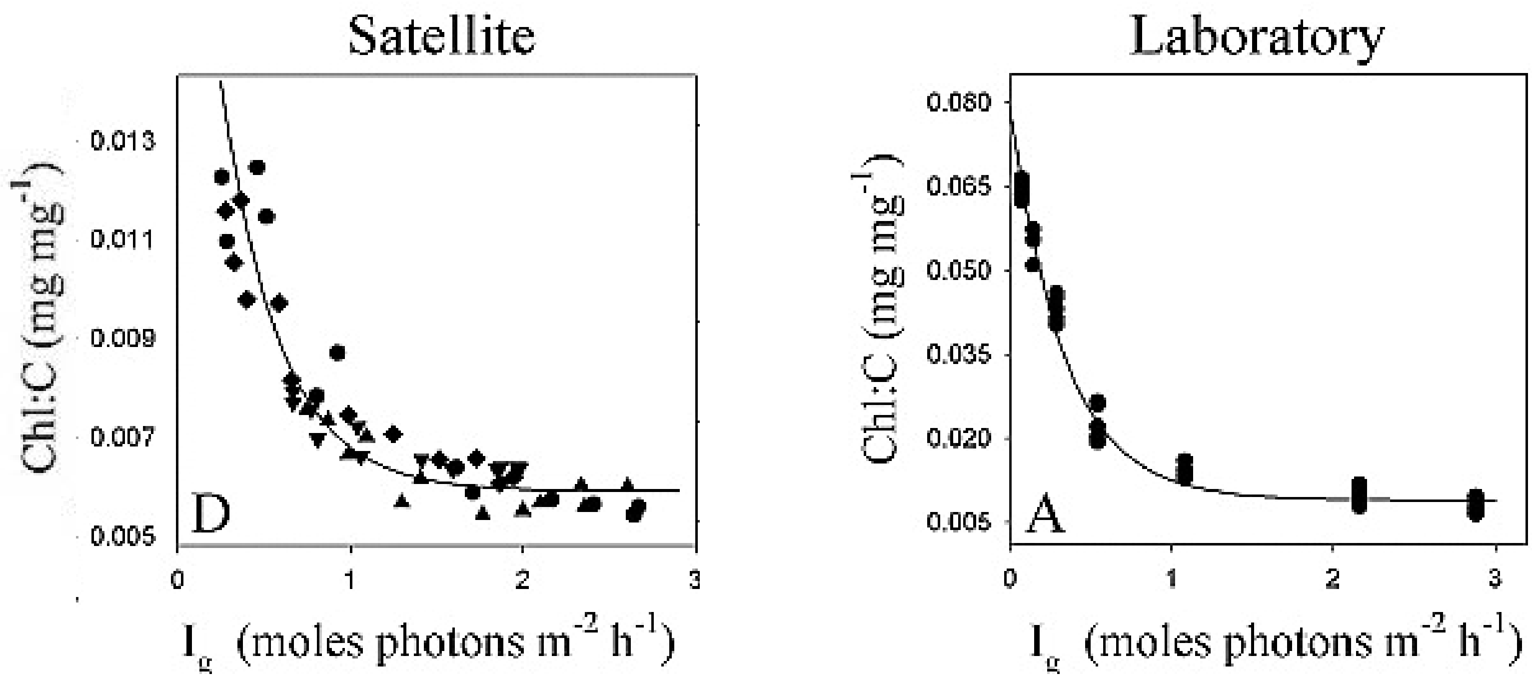




- Now Chl/C - ♦
- Linear mapping BBP to C - **O**
- Chlorophyll - ●
- Responses range from photoacclimation to growth

Behrenfeld et al. (2005) GBC

Chl:C from satellite??



Satellite Chl:C for several subtropical regions vs. light

Chl:C vs. growth irradiance for *D. tertiolecta*

Opens the door to modeling phytoplankton growth rates & carbon-based NPP

Behrenfeld et al. (2005) GBC

Regulation of the Trio

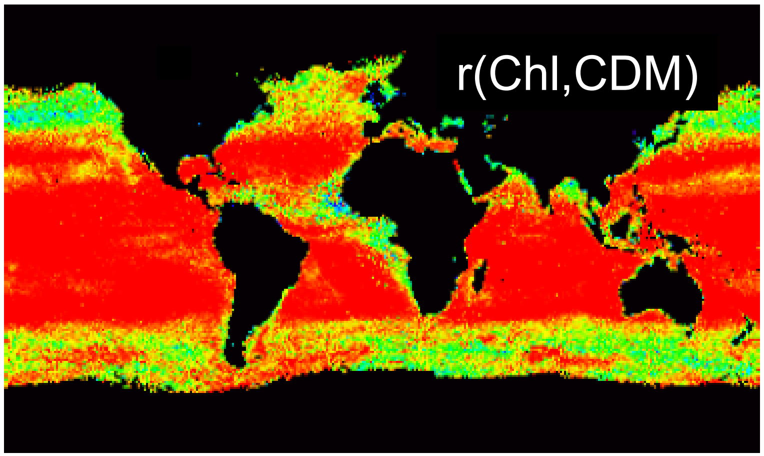
Chl & CDOM

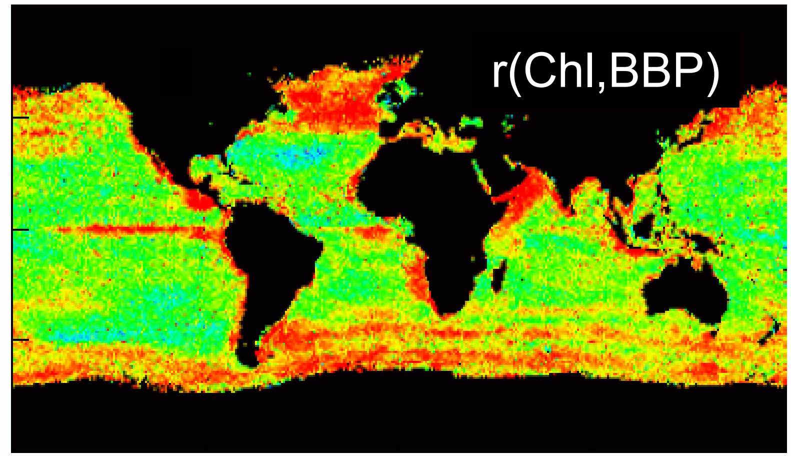
- Driven by same forcings (light, mixing, etc.)
- BUT, by fundamentally different processes
  - Chl – growth driven by NUT inputs, losses & photoacclimation
  - CDOM – heterotrophic production, photolysis & mixing

Chl & BBP

- Partition into growth & photoacclimation regimes
- Response is f(light, nuts, species, etc.)

How do they relate spatially???





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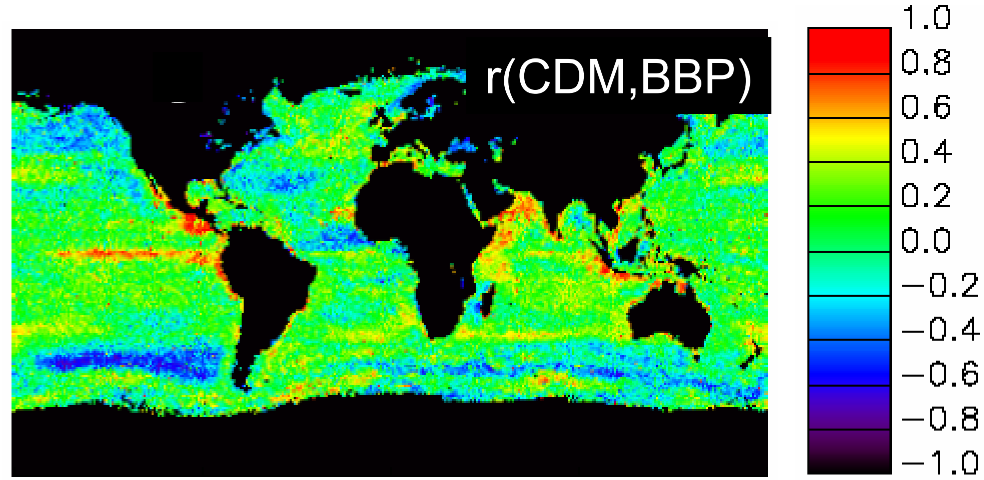


Siegel et al. (2005) JGR

Where & Why…

Biomes	**Forcings**	**Inter-dependent Ocean Color Properties**	**Independent Ocean Color Properties**
Subtropical Gyres	Large-scale downwelling High irradiance	Chl-CDM	BBP
Subarctic Gyres & Southern Ocean	Large-scale upwelling High vertical mixing Low irradiance	BBP-Chl	CDM
Equatorial Upwelling	Regionally intense upwelling Low vertical mixing High irradiance	BBP-Chl-CDM	-
Coastal Upwelling	Regionally intense upwelling Low vertical mixing Moderate irradiance	BBP-Chl-CDM	-
Land-Influence	Riverine inputs of high sediment and/or CDOM	BBP-CDM	Chl

Siegel et al. (2005) JGR

Chlorophyll Sucks…

It's just not very well constrained

- Chl/C varies widely regionally & temporally
- Chl/C has too many contributors to its variability
- It is not useful for building/validating BGC models
- Need to assess phytoplankton C [more] directly

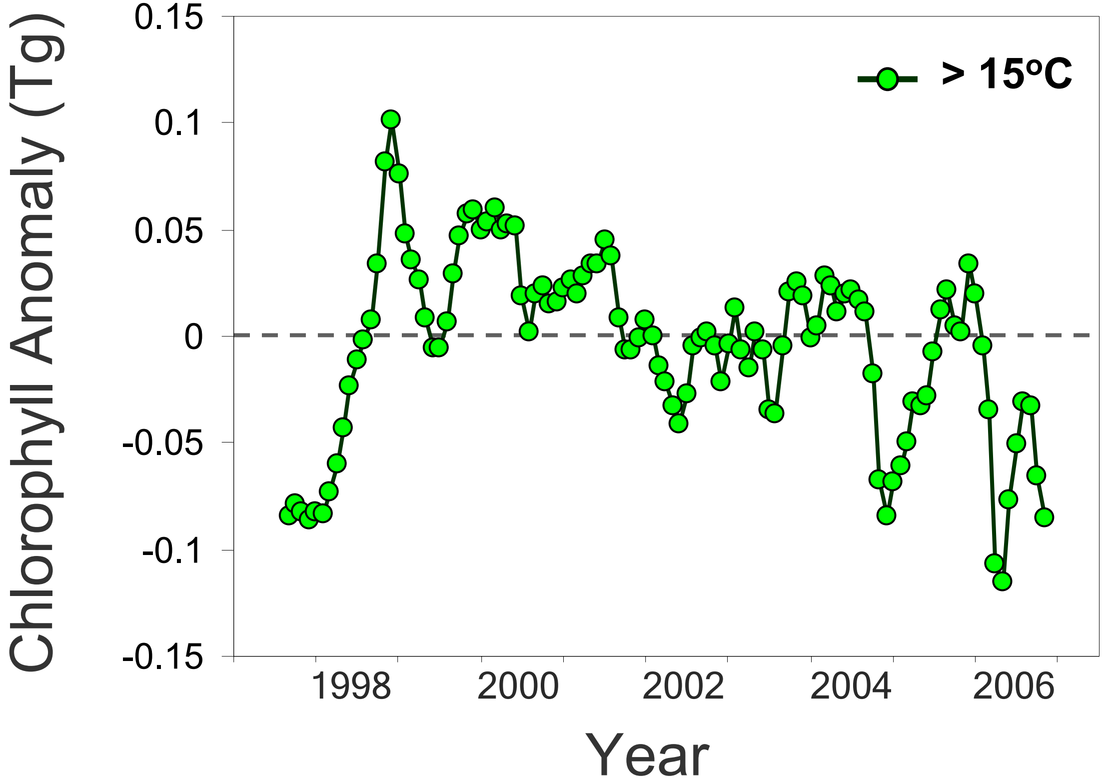
We may not even be measuring Chl right…

- Variations in Chl / CDOM may influence ocean color retrievals (issue for high NH lat's)

Improving Assessments of Phyto C

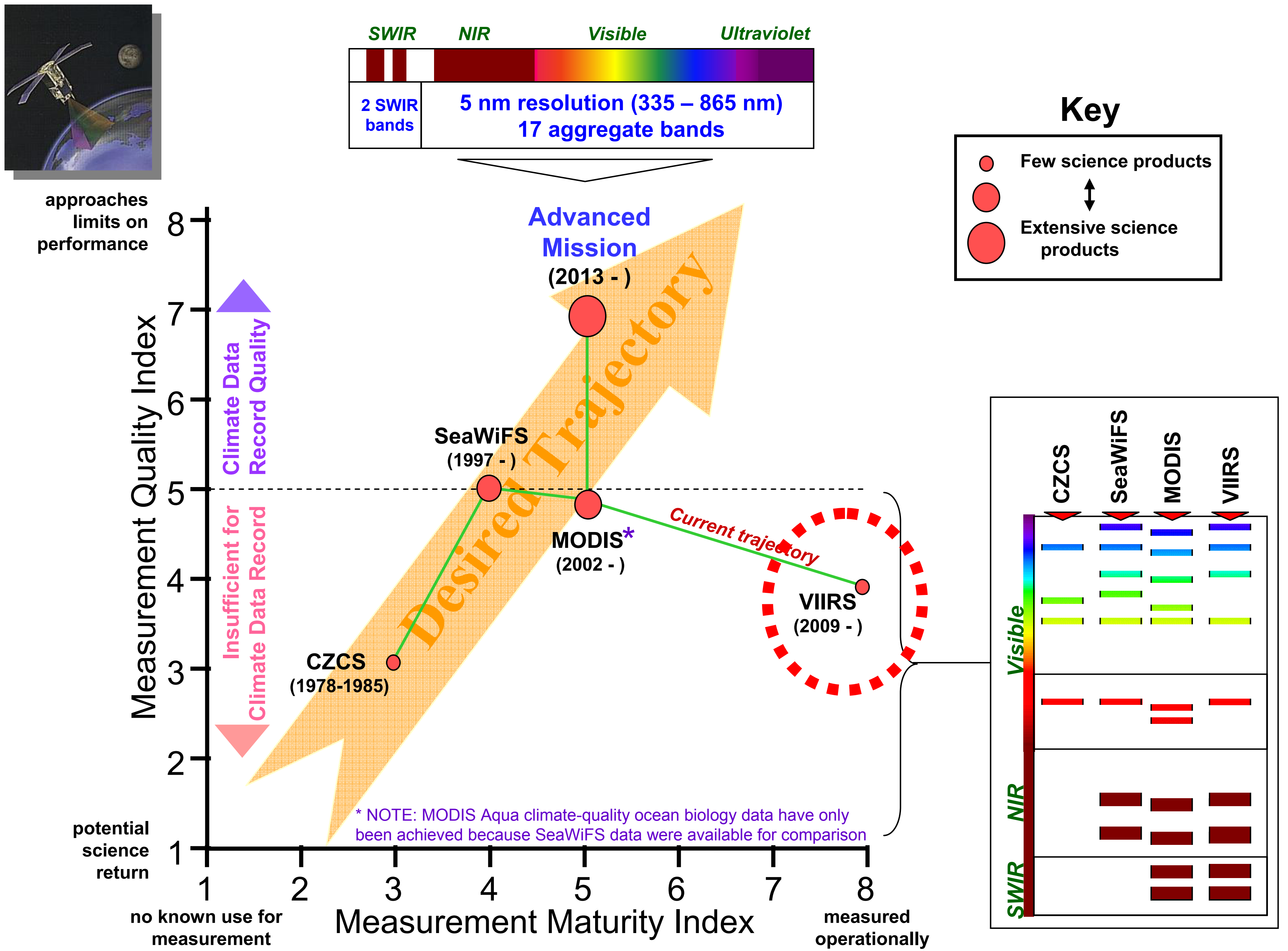
- Need useful field data!!
  - Routine protocols for phyto C do not exist
  - Differentiate autotrophic / heterotrophic / detrital C
  - Simultaneous optical & particle size observations
  - Wide range of biomes…
- Improve satellite methodologies
  - BBP is one way to get at Phyto C (but linear model?)
  - We can *nearly* assess $N_p(D)$ (Loisel et al. 2006)
  - Diagnosing mixed layer depth remains a big issue

Sensing Contemporary Changes in Ocean Color Parameters



Progress is driven by technology & infrastructure

SeaWiFS, NASA’s data processing group, etc.



SWIR
NIR
Visible
Ultraviolet
2 SWIR bands
5 nm resolution (335 – 865 nm)
17 aggregate bands
Key
Few science products
Extensive science products
approaches limits on performance
Advanced Mission
(2013 -)
Desired Trajectory
Climate Data Record Quality
Insufficient for Climate Data Record
SeaWiFS
(1997 -)
MODIS*
(2002 -)
Current trajectory
VIIRS
(2009 -)
CZCS
(1978-1985)
* NOTE: MODIS Aqua climate-quality ocean biology data have only been achieved because SeaWiFS data were available for comparison
Measurement Quality Index
Measurement Maturity Index
potential science return
no known use for measurement
measured operationally
CZCS
SeaWiFS
MODIS
VIIRS
Visible
NIR
SWIR

Original Talk Outline

- Phyto C & Chl/C

  Phytoplankton physiology & growth rates

- CDOM

  Precursor for marine photochemical reactions

  Potential tracer of ventilation & biogeochemistry

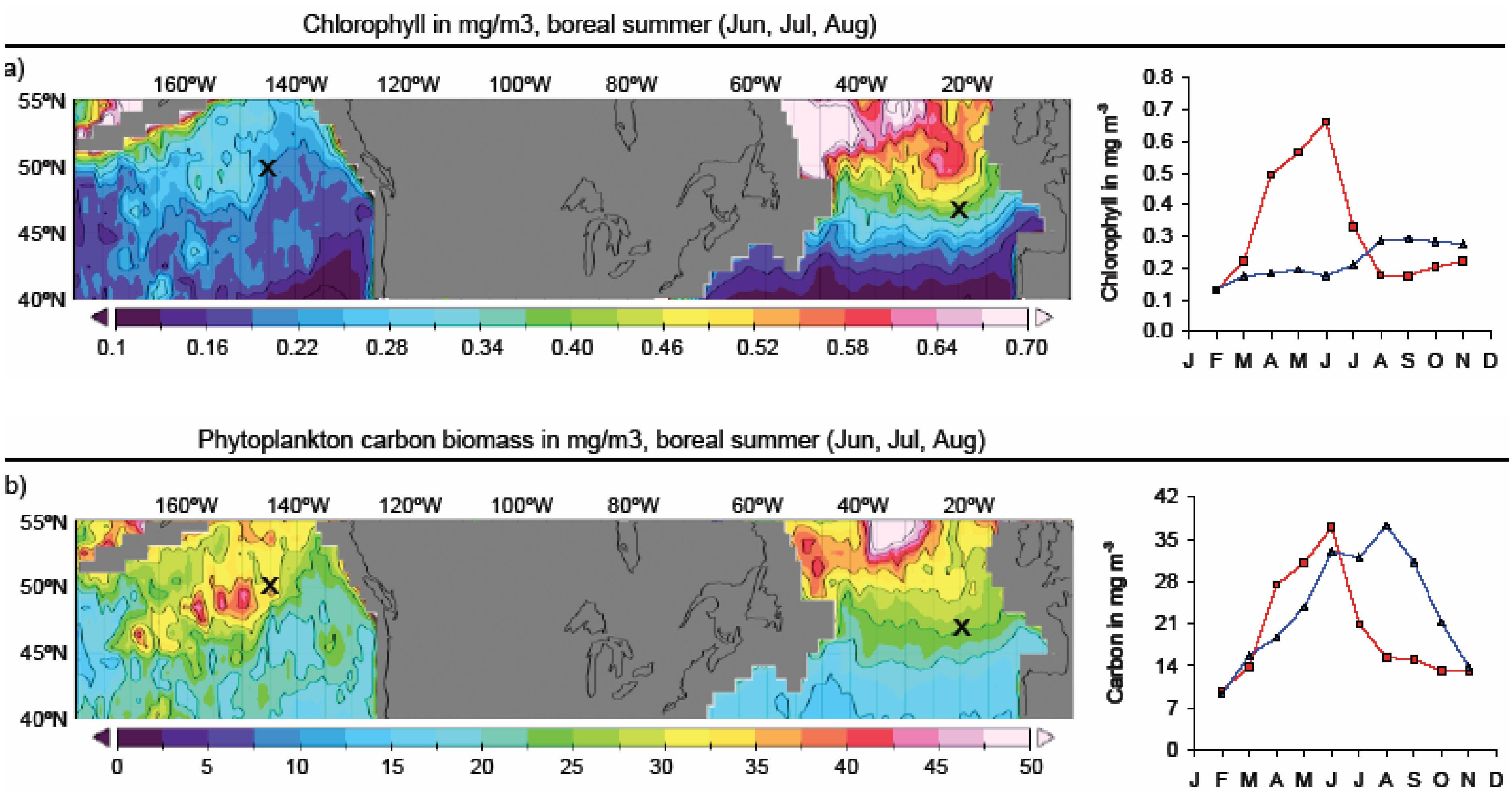
- Phytoplankton community structure

  Dominant group & specific algorithms

- Trends over time

  How we observe & assess change

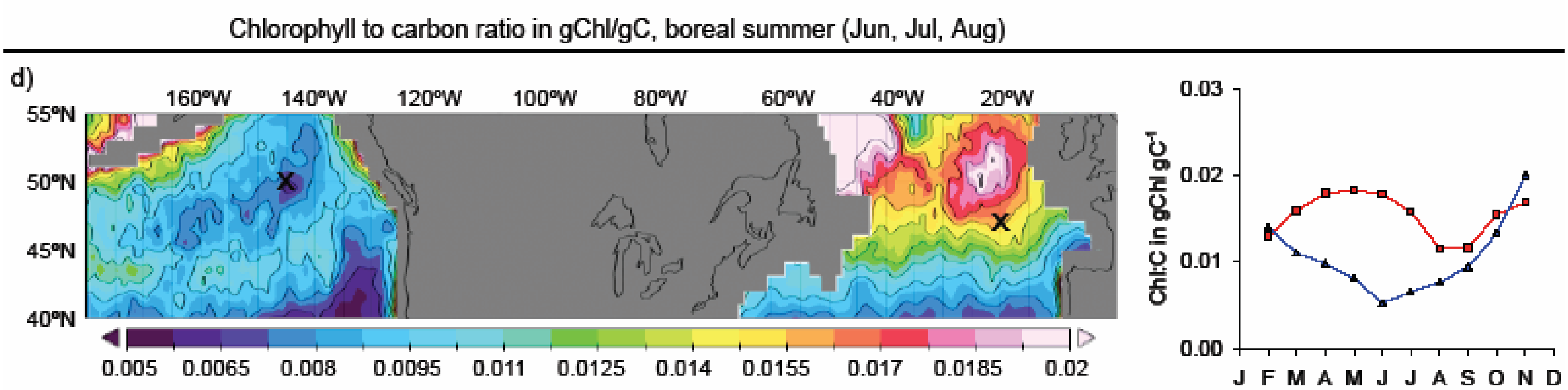
NH Spring Blooms



Why are the Phyto C values the same when the NP Chl's are lower?

Patrick Schultz's poster & paper in prep.

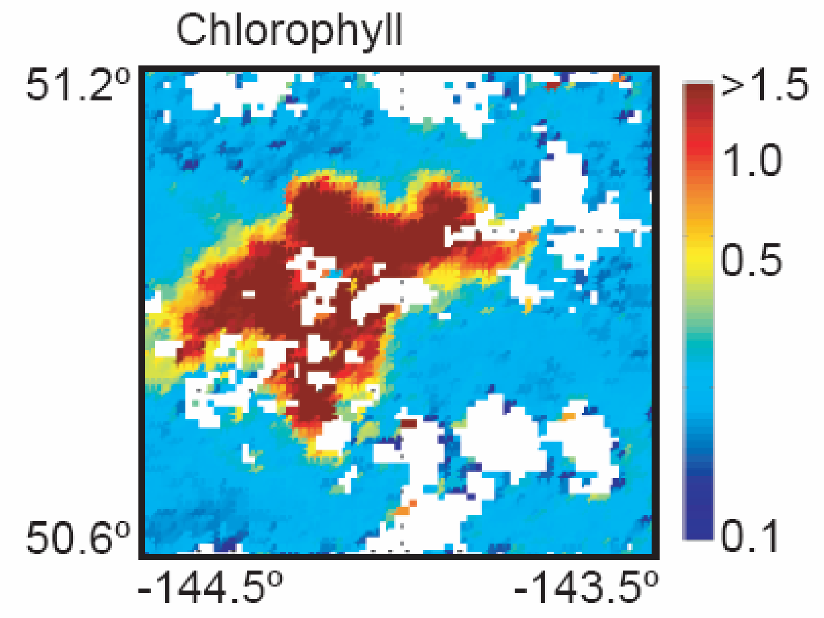
NH Spring Blooms

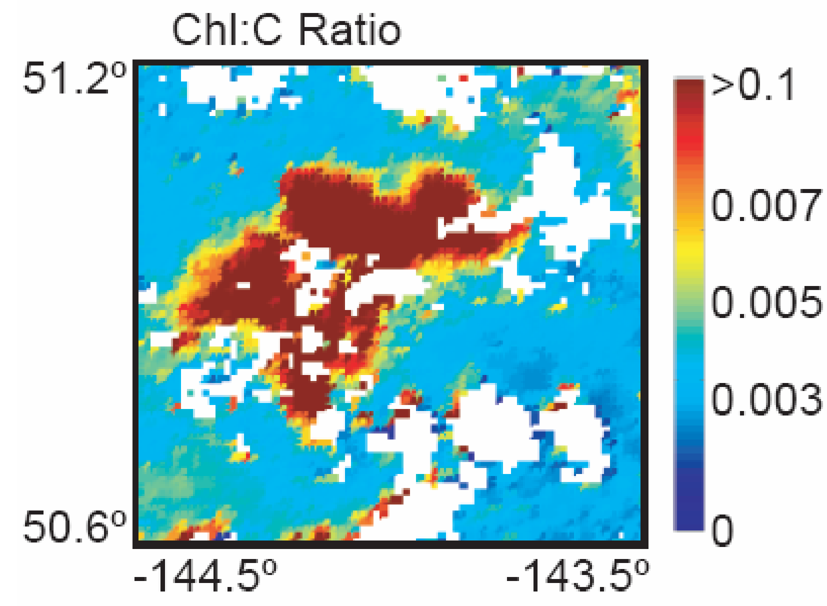


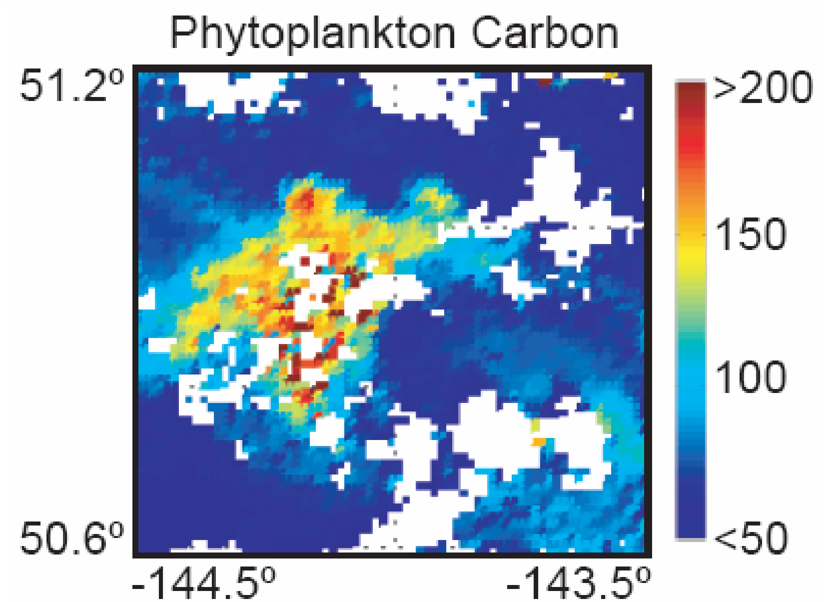
- Chl / C is greater in N Atlantic bloom than N Pacific
- N Atlantic bloom phytoplankton are "happier"
- Why? Maybe Fe limitation in N Pacific

Can we test this somehow??

SERIES (Station P) Fe Addition



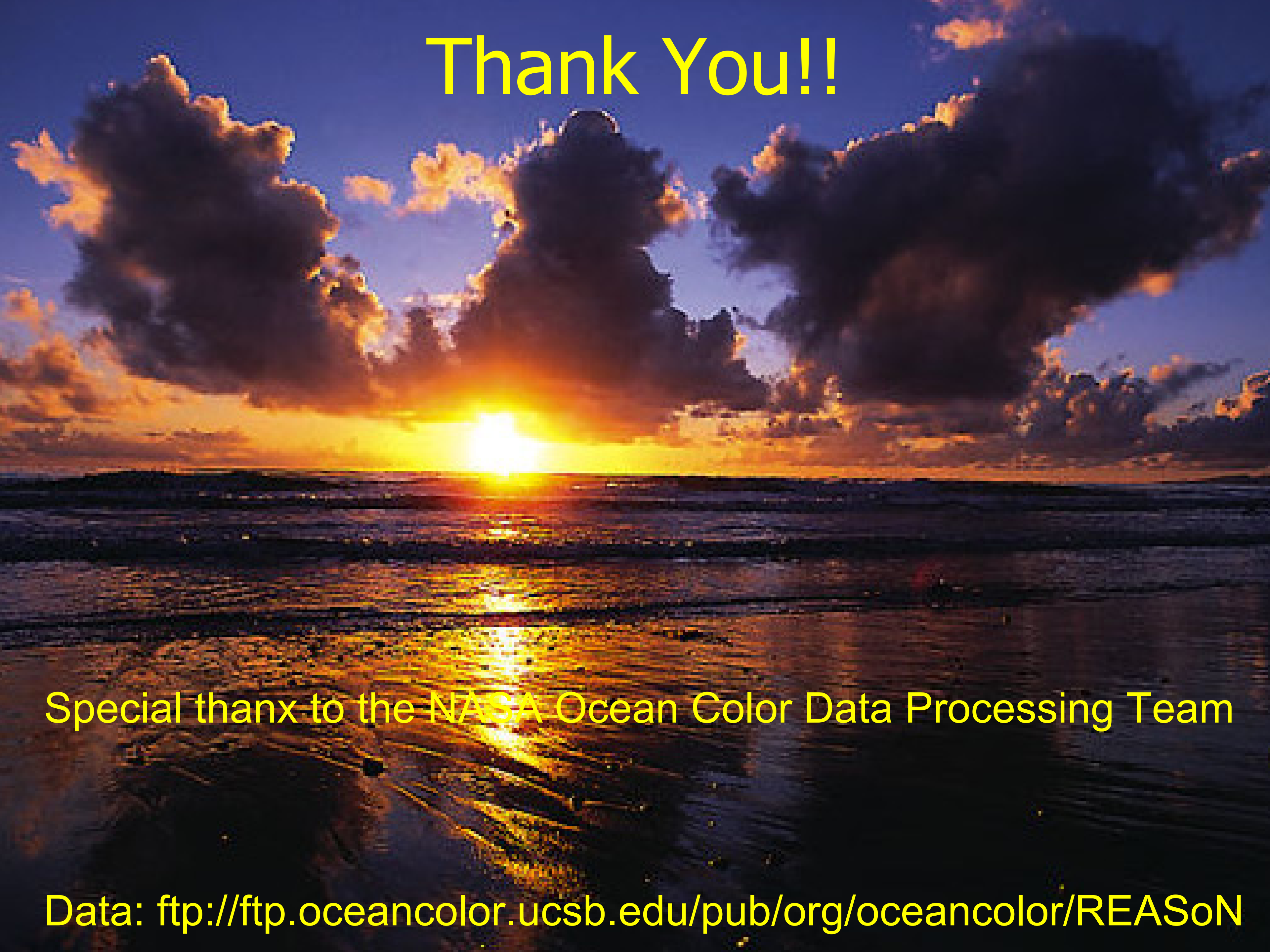




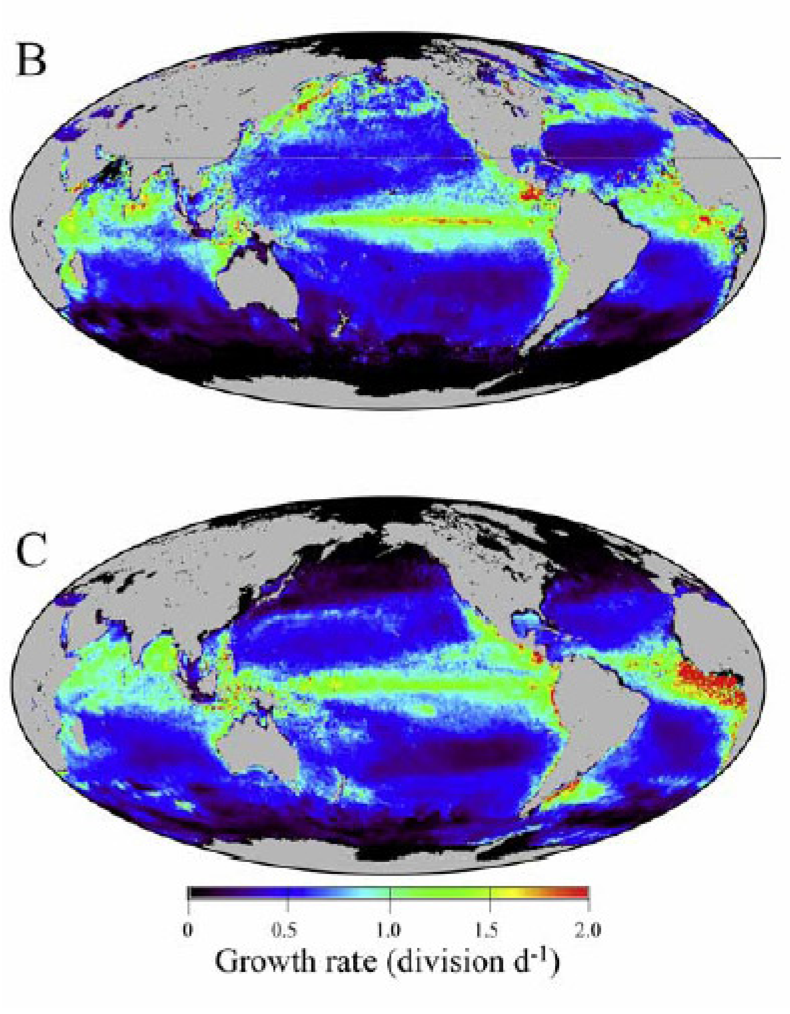
July 29, 2002 - 19 days after 1st Fe addition

SeaWiFS level 2 image

Chl:C supports Fe limitation hypothesis


Thank You!!
Special thanx to the NASA Ocean Color Data Processing Team
Data: ftp://ftp.oceancolor.ucsb.edu/pub/org/oceancolor/REASoN

Growth rate from satellite??



Ocean Productivity – Climate Linkages Imprinted in Satellite Observations

M. J. Behrenfeld and D. A. Siegel

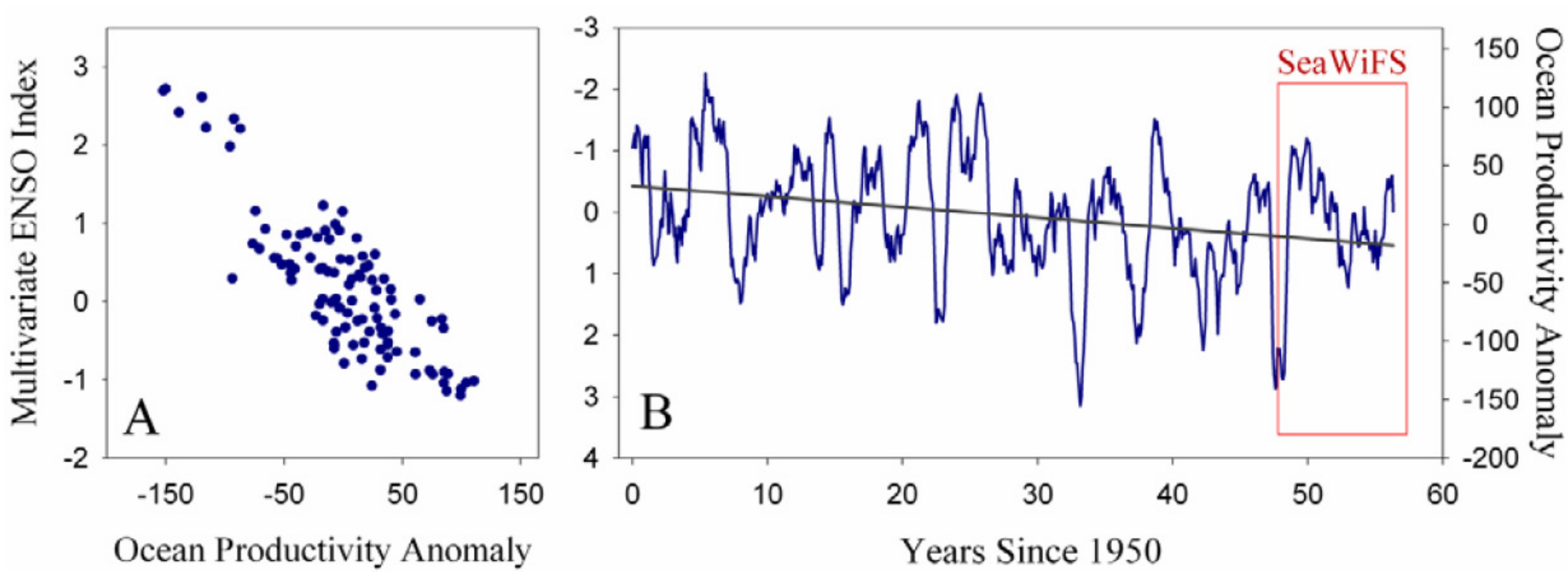
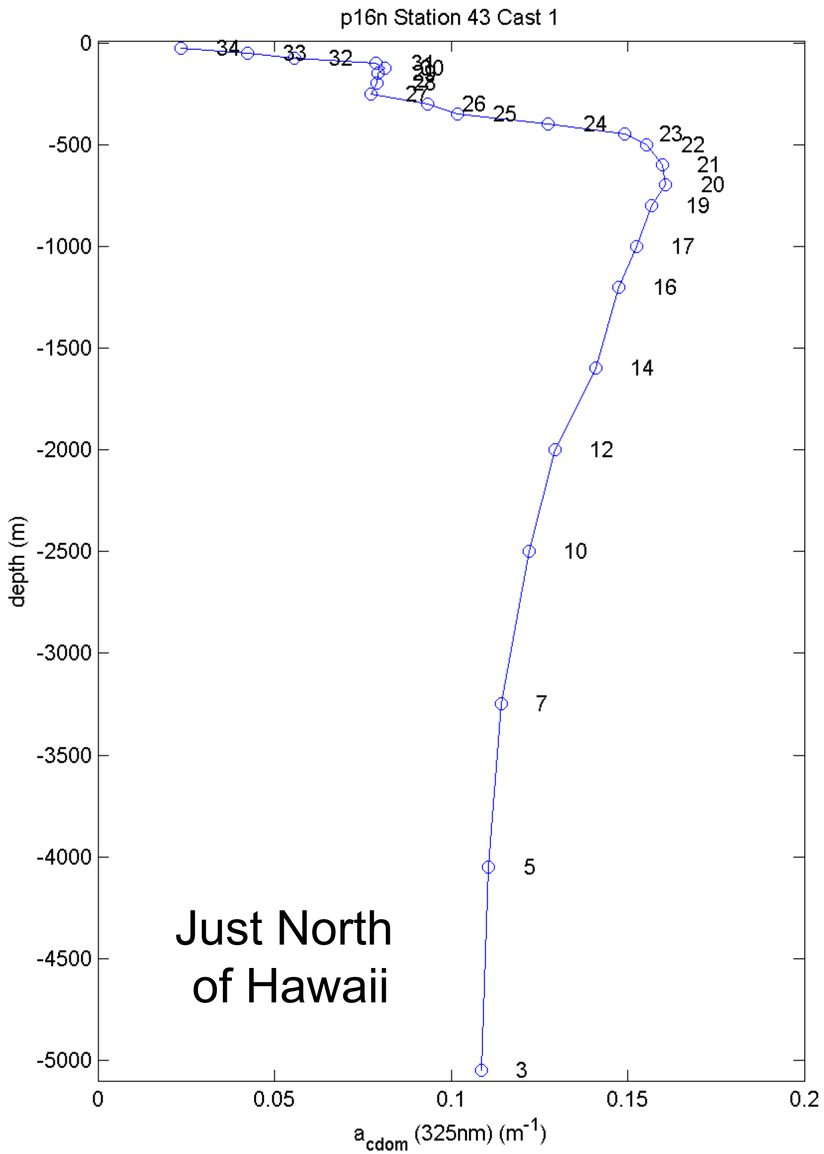


Figure 2. (A) Over the SeaWiFS record, ocean productivity in the global permanently stratified oceans varied with the strength of the ENSO cycle (assessed by the Multivariate ENSO Index (MEI)). Monthly productivity anomalies represent deviations from the 'average' monthly value calculated for the 9 year record. (B) MEI variability within the SeaWiFS era (red box) is within the range of variability observed since 1950 (left axis - note in this panel, MEI is low at the top and high at the bottom). Application of the relationship shown in (A) to the full MEI record may provide a sense of how ocean productivity varied over the same period (right axis; units = 10^{12} g C month^{-1}). Regression analysis of the full data set suggests a decreasing trend of 9 x 10^{12} g C per decade ($p < 0.001$).

Global Change Newsletter [Feb. 07]

The Global CDOM Project



CLIVAR - Repeat Hydrography Survey

Full hydrographic suite
T, S, O_2, Nuts, CFC's, CO_2,...

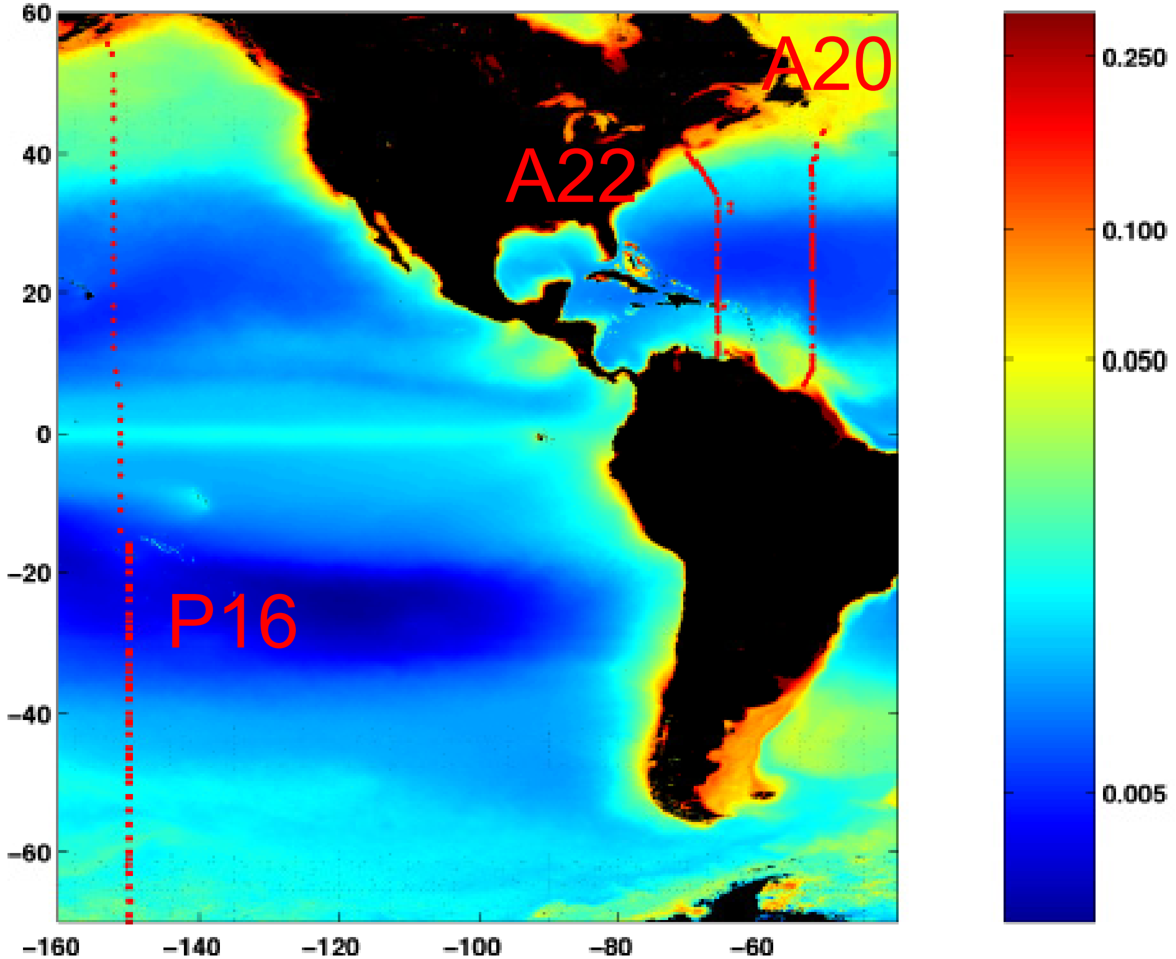
CDOM measured using WPI Ultrapath

CDOM reported as $a_g(325)$

Nelson et al., DSR-I [in press]

www.icess.ucsb.edu/GlobalCDOM

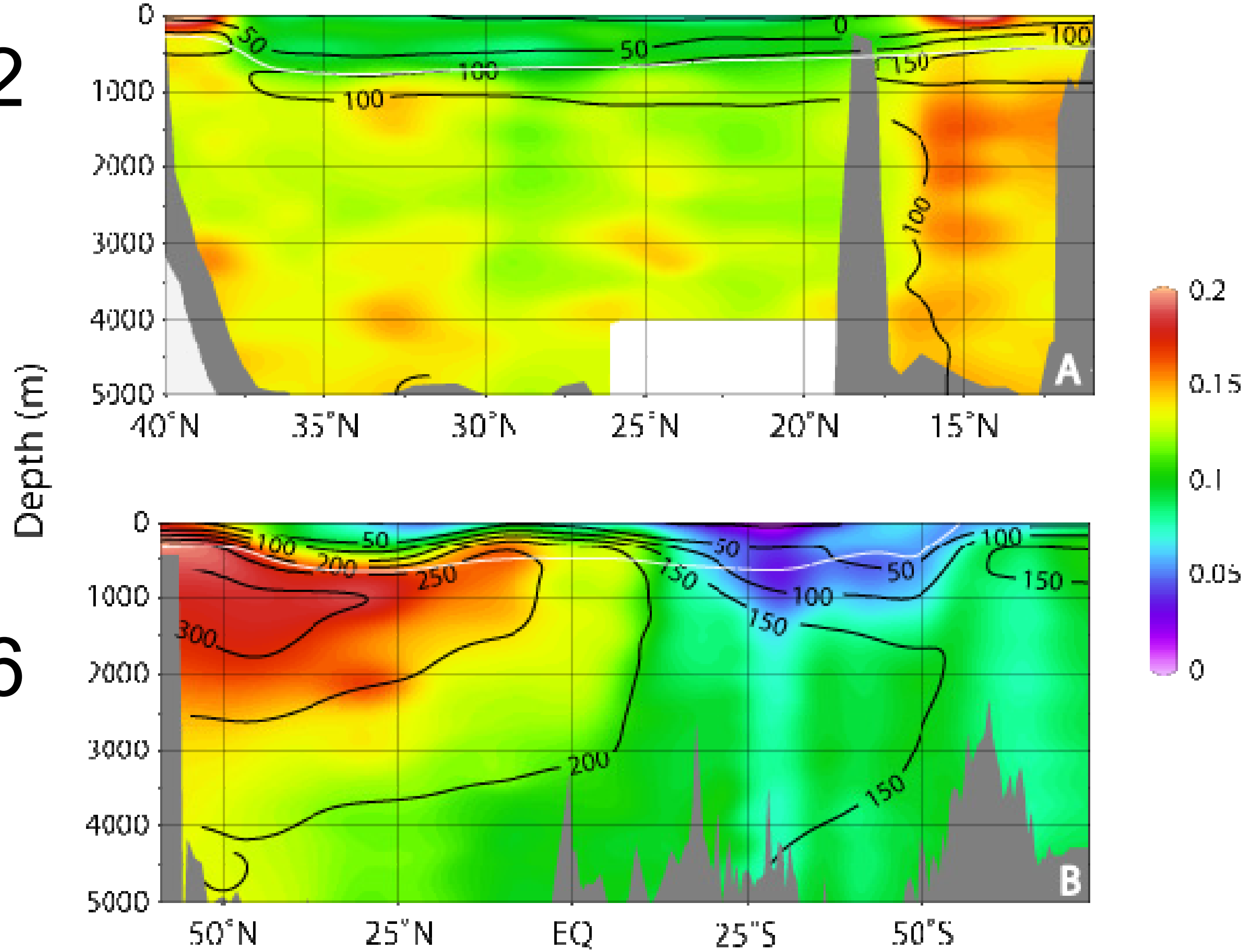
Repeat Hydrography Sections



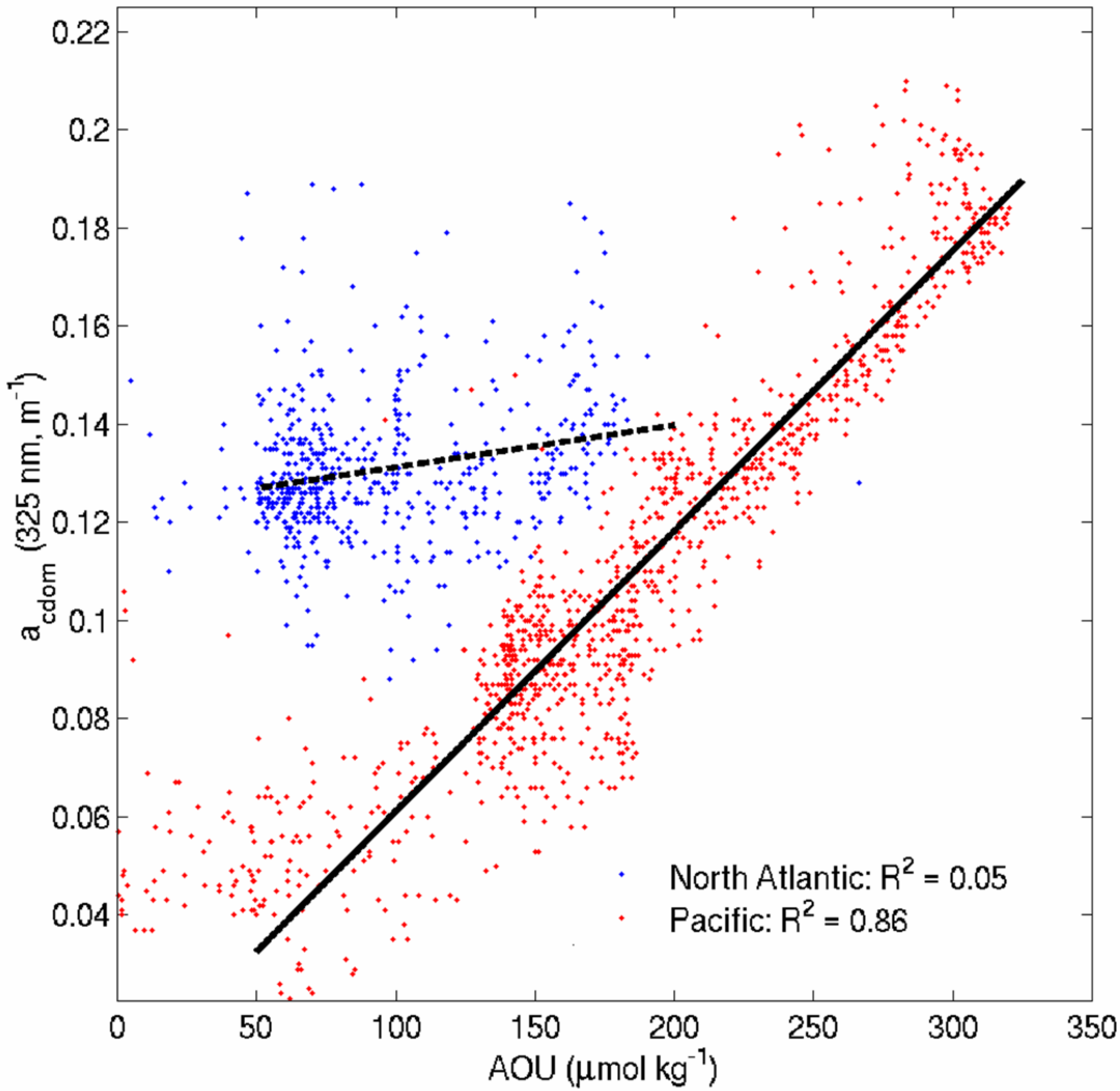
CDOM & AOU

A22

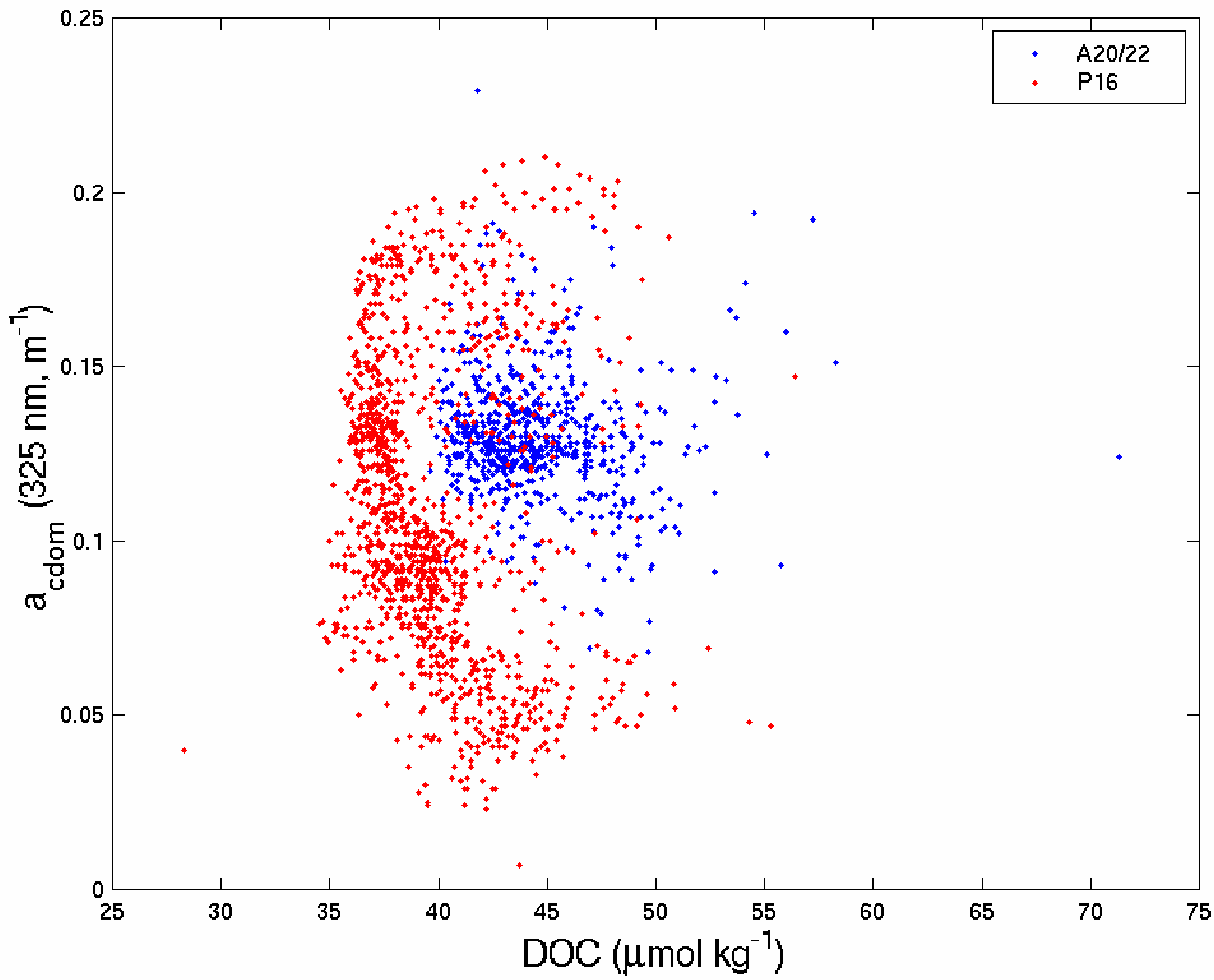
P16



CDOM = $a_g(325)$



0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
a_{cdom} (325 nm, m^{-1})
0
50
100
150
200
250
300
350
AOU (μmol kg^{-1})
North Atlantic: R^2 = 0.05
Pacific: R^2 = 0.86



A20/22
P16
a_{cdom} (325 nm, m^{-1})
DOC (µmol kg^{-1})
0.25
0.2
0.15
0.1
0.05
0
25
30
35
40
45
50
55
60
65
70
75

Potential Biases in Operational Chl

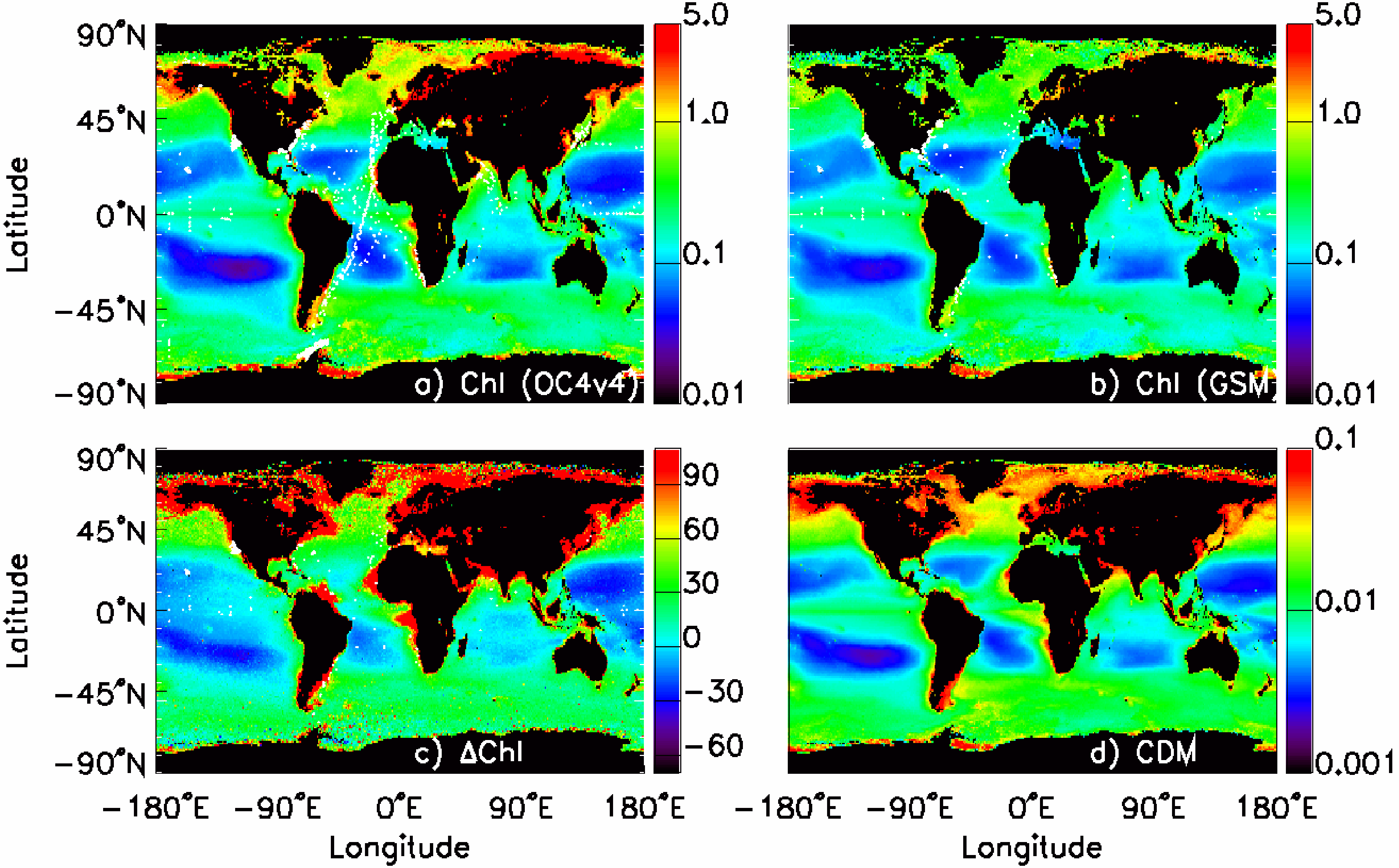
- Compare GSM & OC4v4 Chl's from SeaWiFS
  - Open ocean validation statistics are identical
- Define ΔChl as normalized difference between GSM & OC4v4 Chl's
- Retreivals of ΔChl track CDOM
  - Indicating CDOM role in biasing operational Chl retrievals
  - Operational algorithms overestimate Chl to compensate for not retrieving CDOM
- Siegel and others [submitted] - GRL

Validation using SeaWiFS Matchups

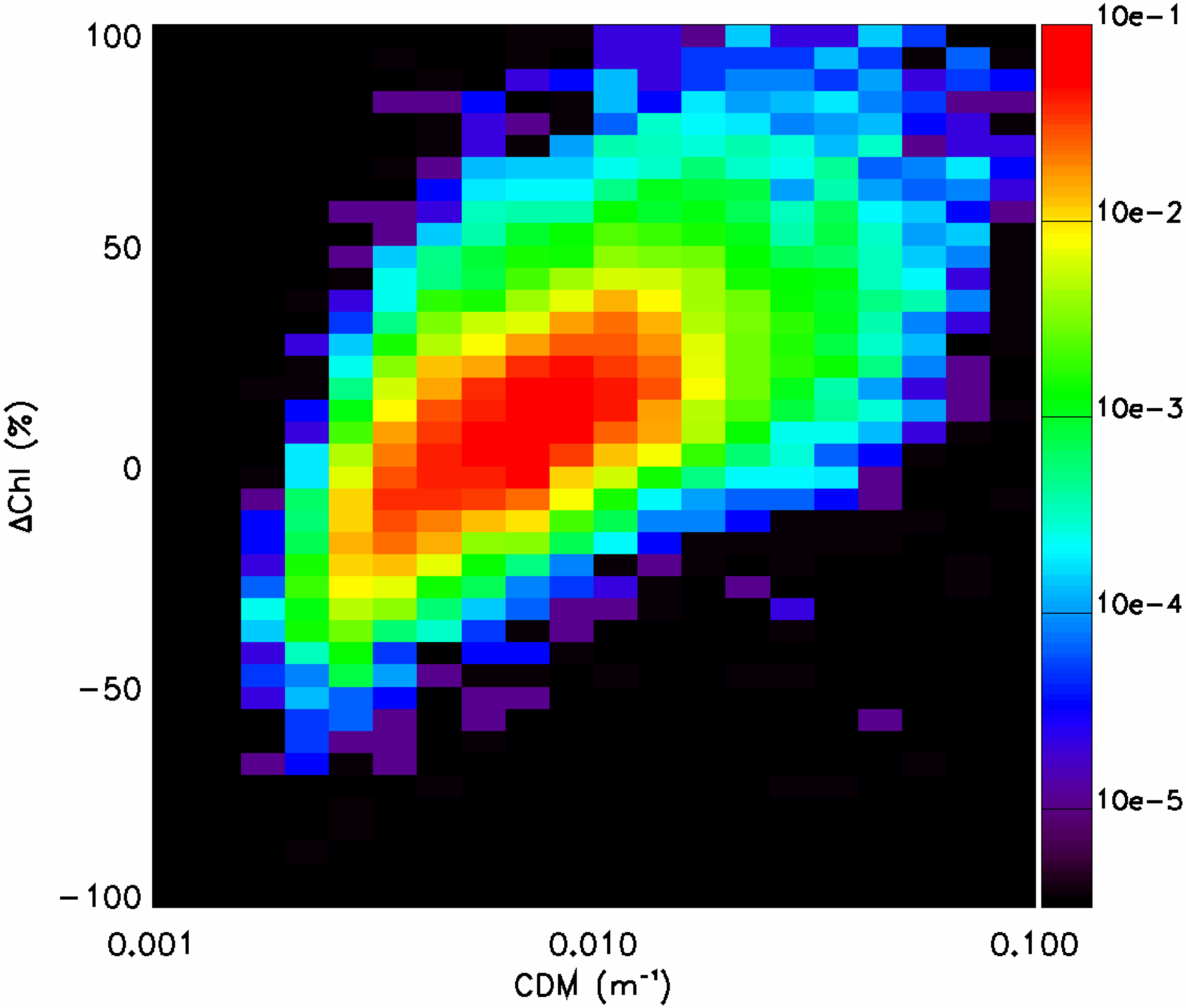
	OC4v4 vs. In Situ	GSM vs. In Situ	OC4v4 vs. InSitu (Z >1000m)	GSM vs. InSitu (Z >1000m)
N	1378	979	344	324
R^2	0.757	0.689	0.706	0.823
Slope	0.947	0.876	0.951	0.815
Intercept	-0.015	-0.244	-0.161	-0.156
RMS	0.290	0.381	0.175	0.259
BIAS	-0.011	-0.216	-0.047	-0.148

Significant differences when coastal sites are left in

No consistent differences when only open ocean sites are considered

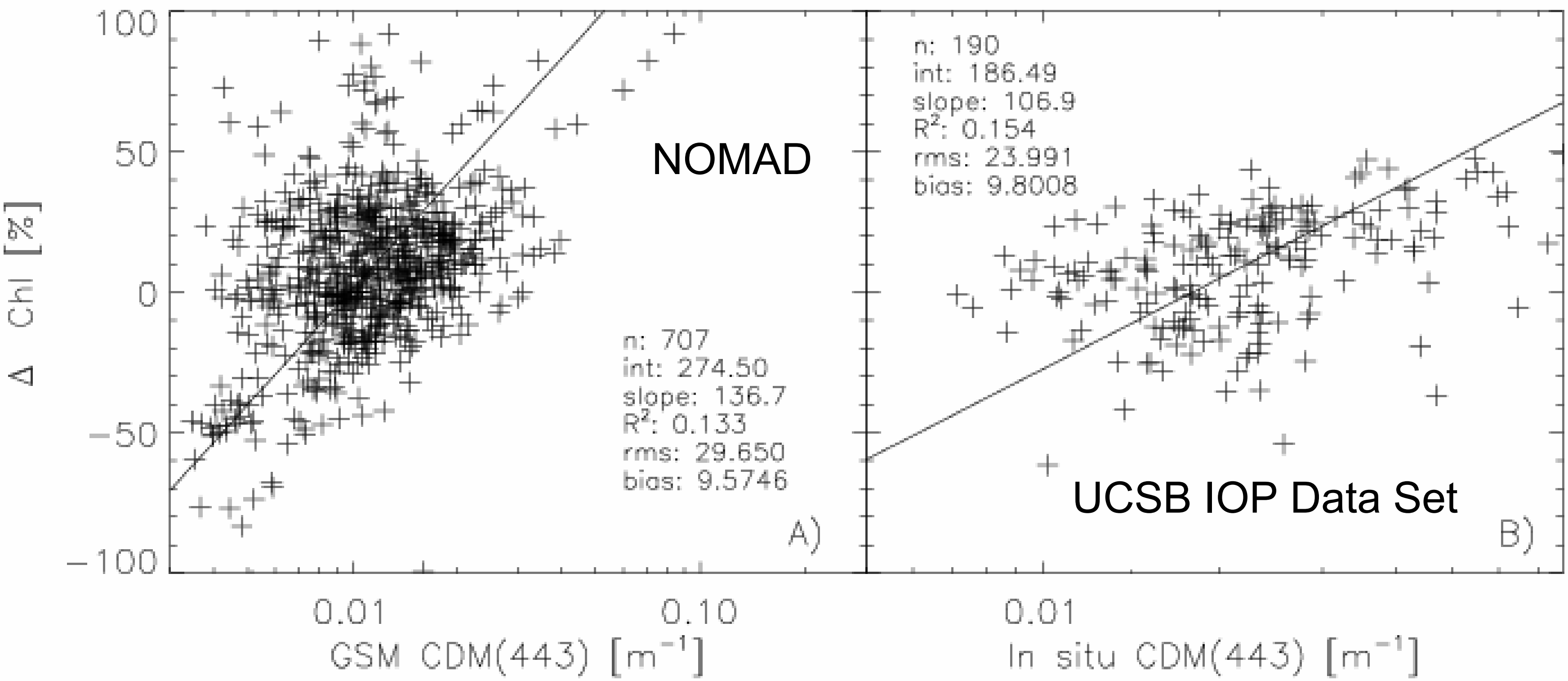


a) Chl (OC4v4)
b) Chl (GSM)
c) ΔChl
d) CDM
5.0
1.0
0.1
0.01
90
60
30
0
−30
−60
0.1
0.01
0.001
90°N
45°N
0°N
−45°N
−90°N
Latitude
−180°E
−90°E
0°E
90°E
180°E
Longitude



100
50
0
−50
−100
ΔChl (%)
0.001
0.010
0.100
CDM (m⁻¹)
10e−1
10e−2
10e−3
10e−4
10e−5

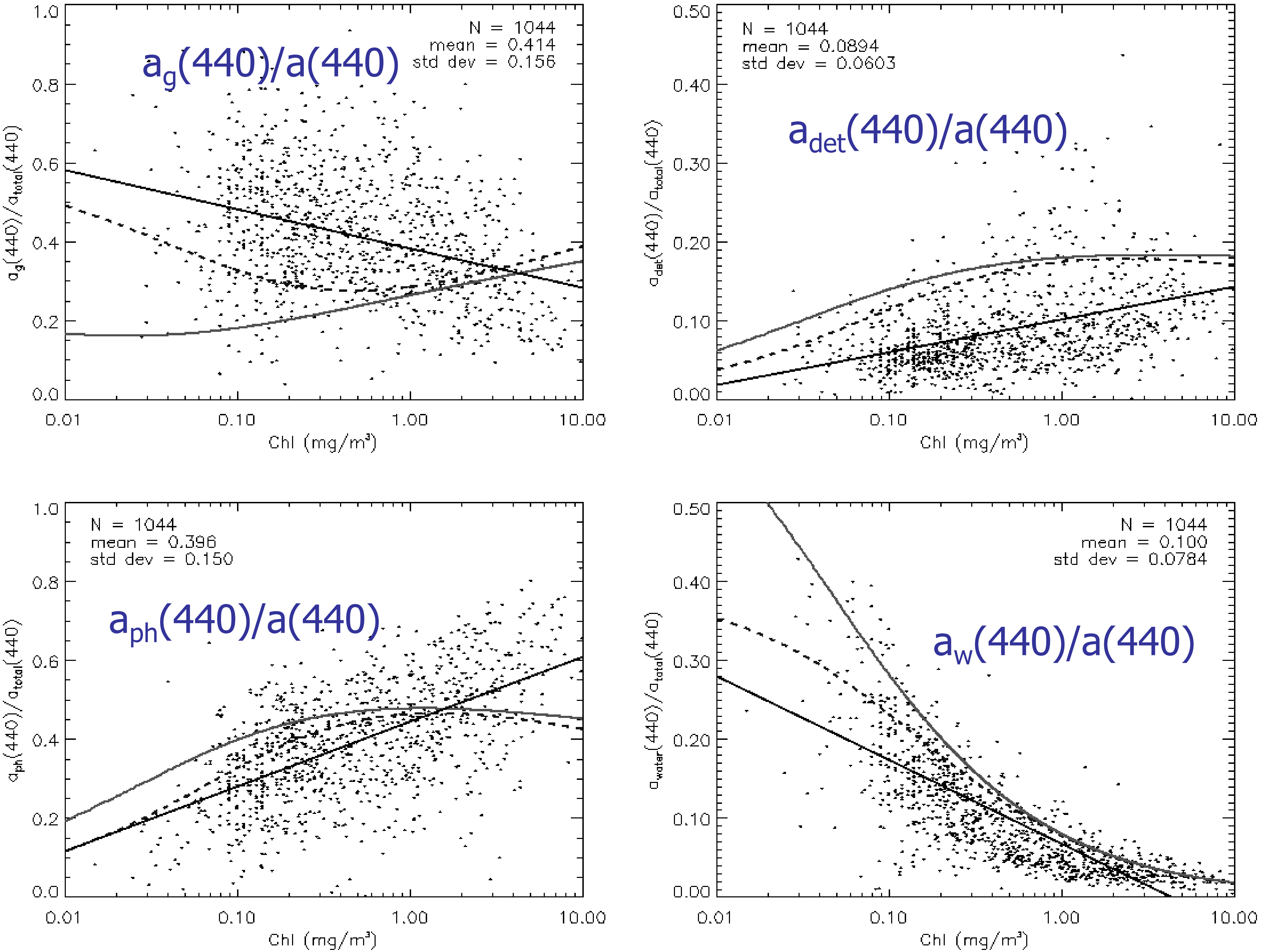
Differences are also found in the *in situ* data sets



Chl < 0.25 mg m^{-3}

Potential Biases in Operational Chl

- Implications are huge
  - Global NPP estimates (BF97) are reduced 30%
  - Long-term trends in Chl may actually be due to CDOM
- At issue is the CDOM / Chl relationship
  - Empirical models assume this is fixed
  - Semi-analytical models do not
- Differences are due to model formulation & how limited, in situ data are used to tune them



N = 1044
mean = 0.414
std dev = 0.156
ag(440)/a(440)
ag(440)/atotal(440)
Chl (mg/m³)
0.01
0.10
1.00
10.00
N = 1044
mean = 0.0894
std dev = 0.0603
adet(440)/a(440)
adet(440)/atotal(440)
Chl (mg/m³)
N = 1044
mean = 0.396
std dev = 0.150
aph(440)/a(440)
aph(440)/atotal(440)
Chl (mg/m³)
N = 1044
mean = 0.100
std dev = 0.0784
aw(440)/a(440)
awater(440)/atotal(440)
Chl (mg/m³)