Use of remote sensing in assessing the impacts of ocean acidification

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Thanks to so many…

D. Drapeau, B. Bowler, E. Booth (Bigelow Lab)

G. Feldman, B. Franz, S. Bailey (NASA Goddard)

K. Kilpatrick, K. Voss and H. Gordon (U. Miami)

Support for this meeting from NSF, NASA, NOAA, USGS and our Scripps hosts!

Vicky Fabry and Chris Langdon for organizing this meeting!

Support from NASA and NSF for the work I'll present

NASA

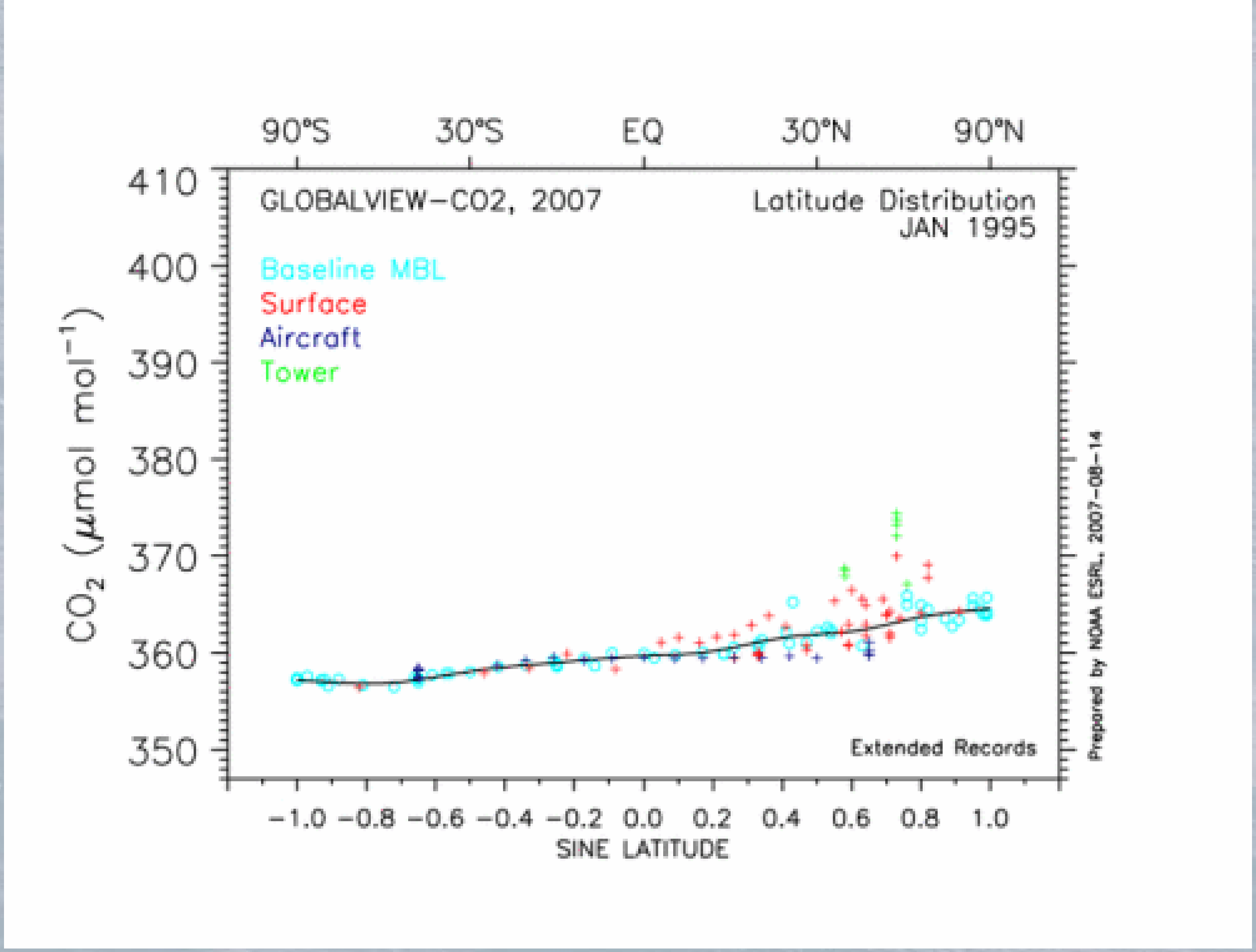
OCB

Ocean Carbon & Biogeochemistry

NSF

The partial pressure of CO_2 in the atmosphere over the globe…

CO2 (μmol mol^{-1})



S Latitude N

Earth System Research Laboratory, NOAA

Rationale

- Ocean acidification will occur at global spatial scales
- Significant decreases in pH might be expected over decades and greater but changes at high latitudes likely to be most pronounced due to ocean chemistry.
- Coccolithophores are more abundant at higher latitudes
- A remote sensing method to measure suspended PIC might provide evidence of ocean acidification at basin scales

First remote sensing images of coccolith-ophorids from space using CZCS…

Reprinted from Nature, Vol. 304, No. 5924, pp. 339-342, July, 28 1983

Satellite and ship studies of coccolithophore production along a continental shelf edge

P. M. Holligan*, M. Viollier†||, D. S. Harbour*, P. Camus‡ & M. Champagne-Philippe§

* Marine Biological Association, Citadel Hill, Plymouth PL1 2PB, UK
† Joint Research Centre, Ispra Establishment, 21020 Ispra, Italy
‡ Institution Scientifique et Technique des Pêches Maritimes, BP 1049, 44037 Nantes Cedex, France
§ Etablissement d'Etudes et de Recherches Météorologiques, CMS, 22302 Lannion, France

Holligan et al. ’83 motivated us into the coccolithophore business in the Gulf of Maine, in a 1988 bloom…

Limnol. Oceanogr., 36(4), 1991, 629–643

Biological and optical properties of mesoscale coccolithophore blooms in the Gulf of Maine

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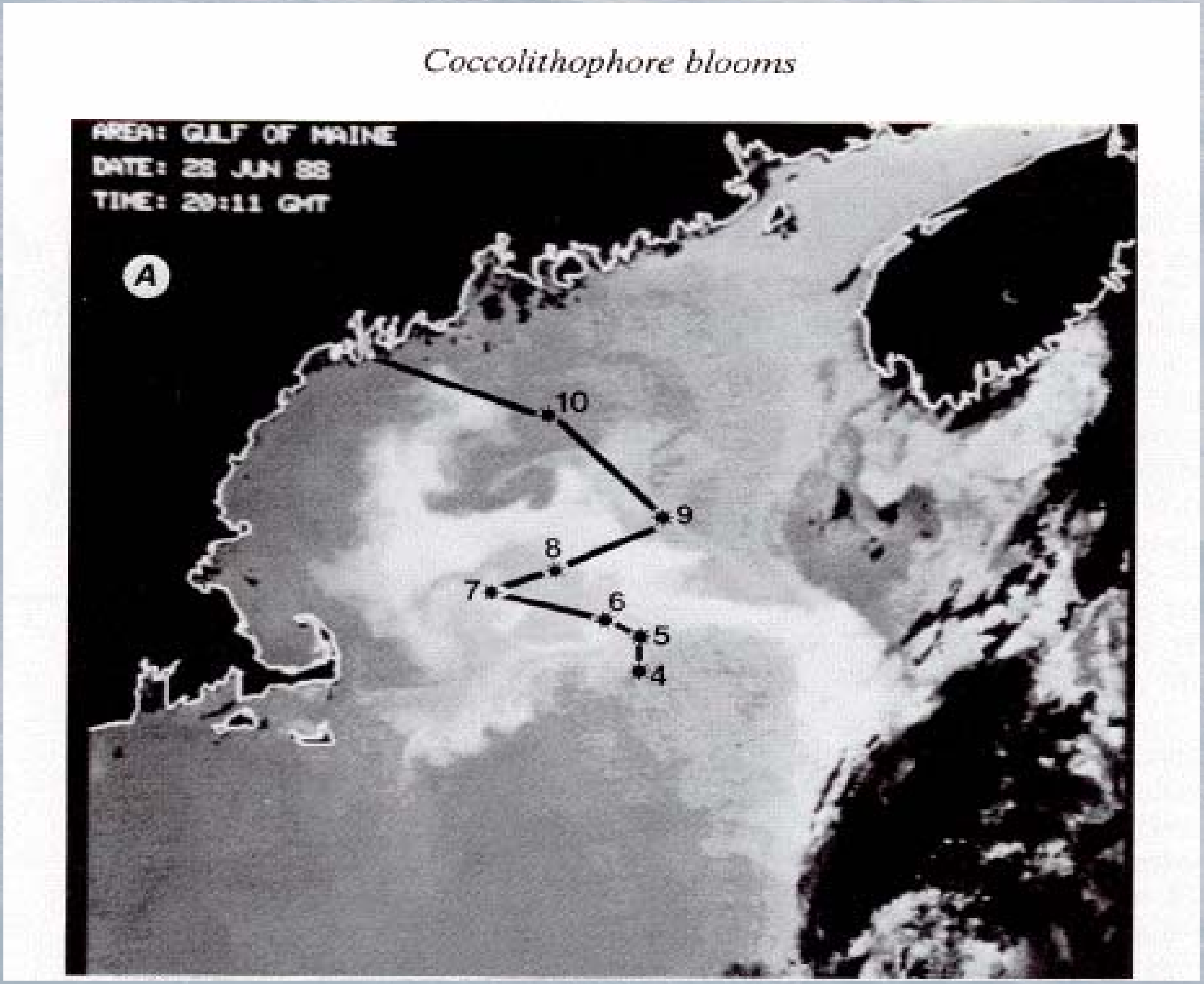
Department of Physics, University of Miami, Coral Gables, Florida 33124

We had no CZCS, so we used AVHRR broad-band, visible channel

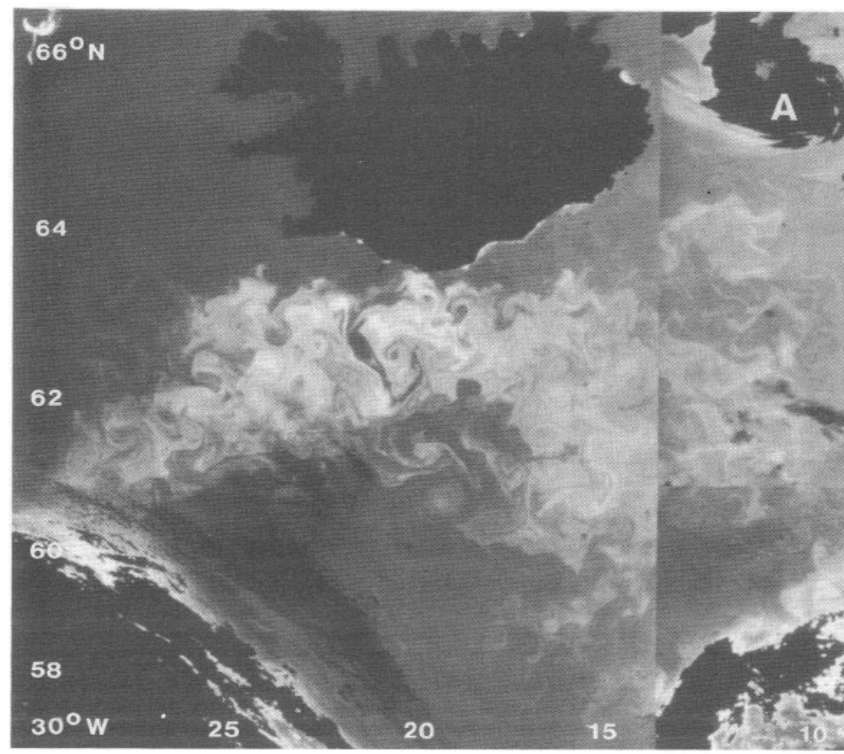


The largest coccolithophore bloom ever described (Holligan et al., 1993), also based on AVHRR

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 7, NO. 4, PAGES 879-900, DECEMBER 1993

A BIOGEOCHEMICAL STUDY OF THE COCCOLITHOPHORE, *Emiliania huxleyi*, IN THE NORTH ATLANTIC

Patrick M. Holligan,[1] Emilio Fernández,[1] James Aiken,[1] William M. Balch,[2] Philip Boyd,[3] Peter H. Burkill,[1] Miles Finch,[4] Stephen B. Groom,[5] Gillian Malin,[6] Kerstin Muller,[7] Duncan A. Purdie,[4] Carol Robinson,[7] Charles C. Trees,[8] Suzanne M. Turner,[6] and Paul van der Wal[9]



A global view of coccolithophorids from space, an algorithm for flagging cocco **blooms**…

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. C4, PAGES 7467–7482, APRIL 15, 1994

Coccolithophorid blooms in the global ocean

Christopher W. Brown[1] and James A. Yoder
Graduate School of Oceanography, University of Rhode Island, Narragansett

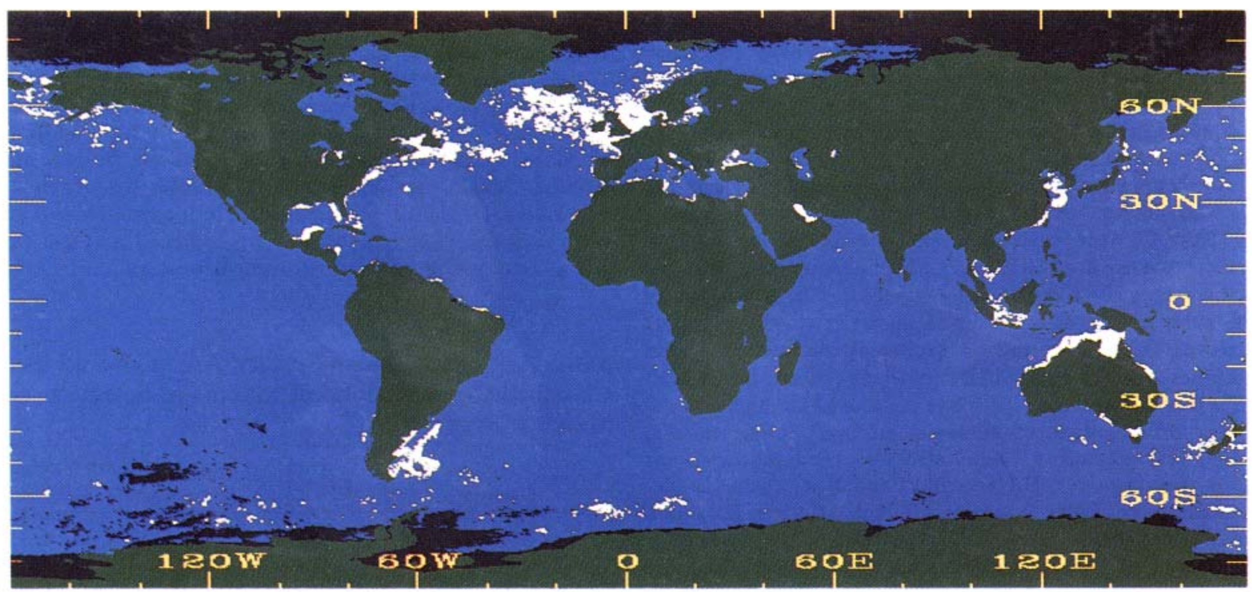
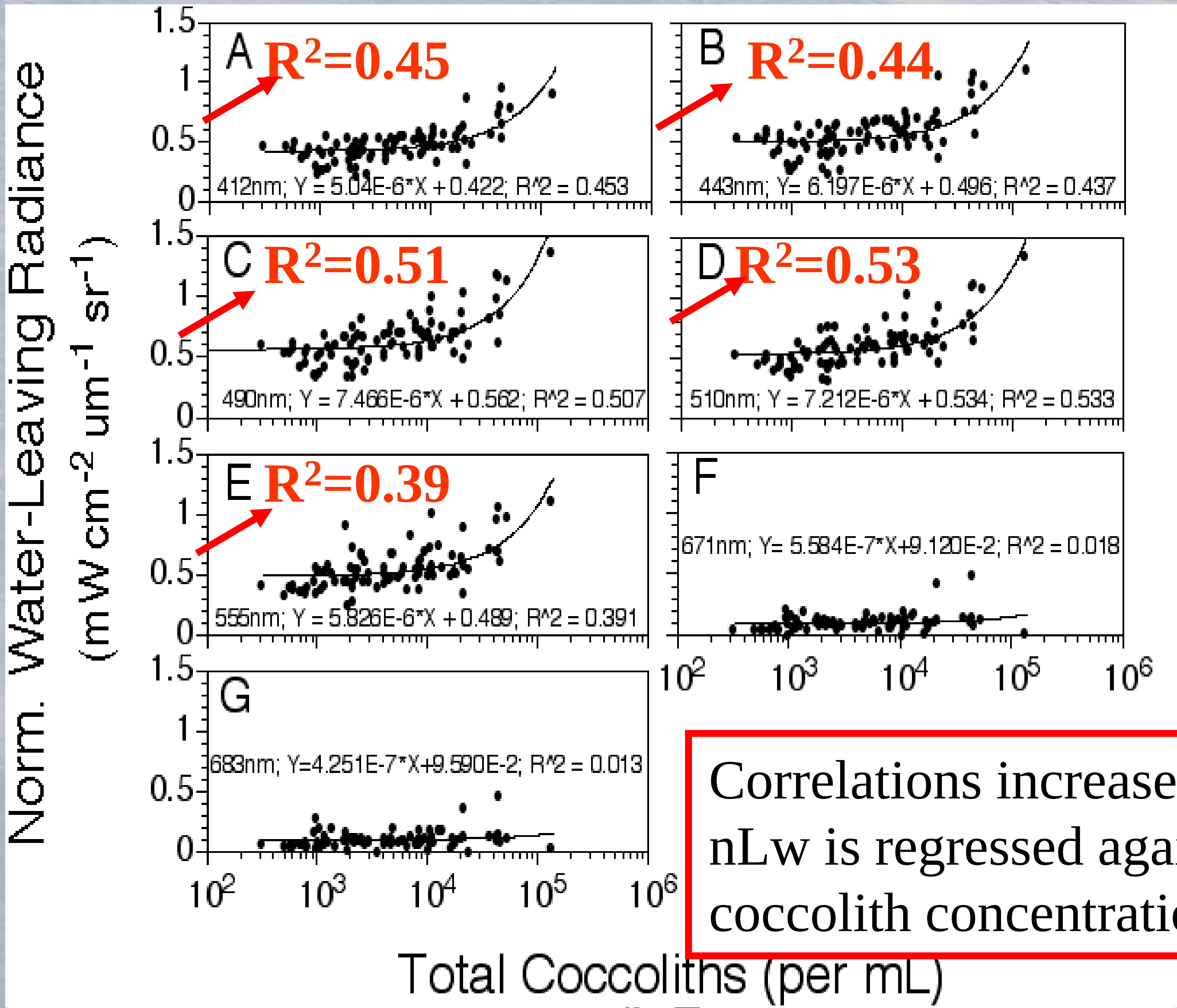


Plate 1. Climatology of classified coccolithophorid blooms (measuring >4800 km^2) for the world's oceans in CZCS imagery dating from November 1978 to June 1986. The maximum spatial extents of blooms detected during this period are displayed. The coccolithophorid bloom class is white, the noncoccolithophorid bloom class is blue, and the land is green. Black indicates areas lacking image coverage.

Optical properties of PIC

- PIC relative refractive index = 1.19 (POC relative refractive index = 1.05; biogenic silica=1.06), thus PIC is highly scattering.
- Dense ocean suspensions of coccoliths can have a high albedo (0.35)
- PIC is birefringent, rotates linearly polarized light by 90^{o}
- Negligible absorbance
- Mass and shape of coccoliths varies by species, hence variable scattering cross section; 1.1-1.6 m^{2} $mole^{-1}$
- Foram and pteropod scattering cross-sections are ~100-1000X lower than for coccolithophorids…you can’t see forams and pteropods see from space
- Coccoliths can be a primary determinant of water-leaving radiance…

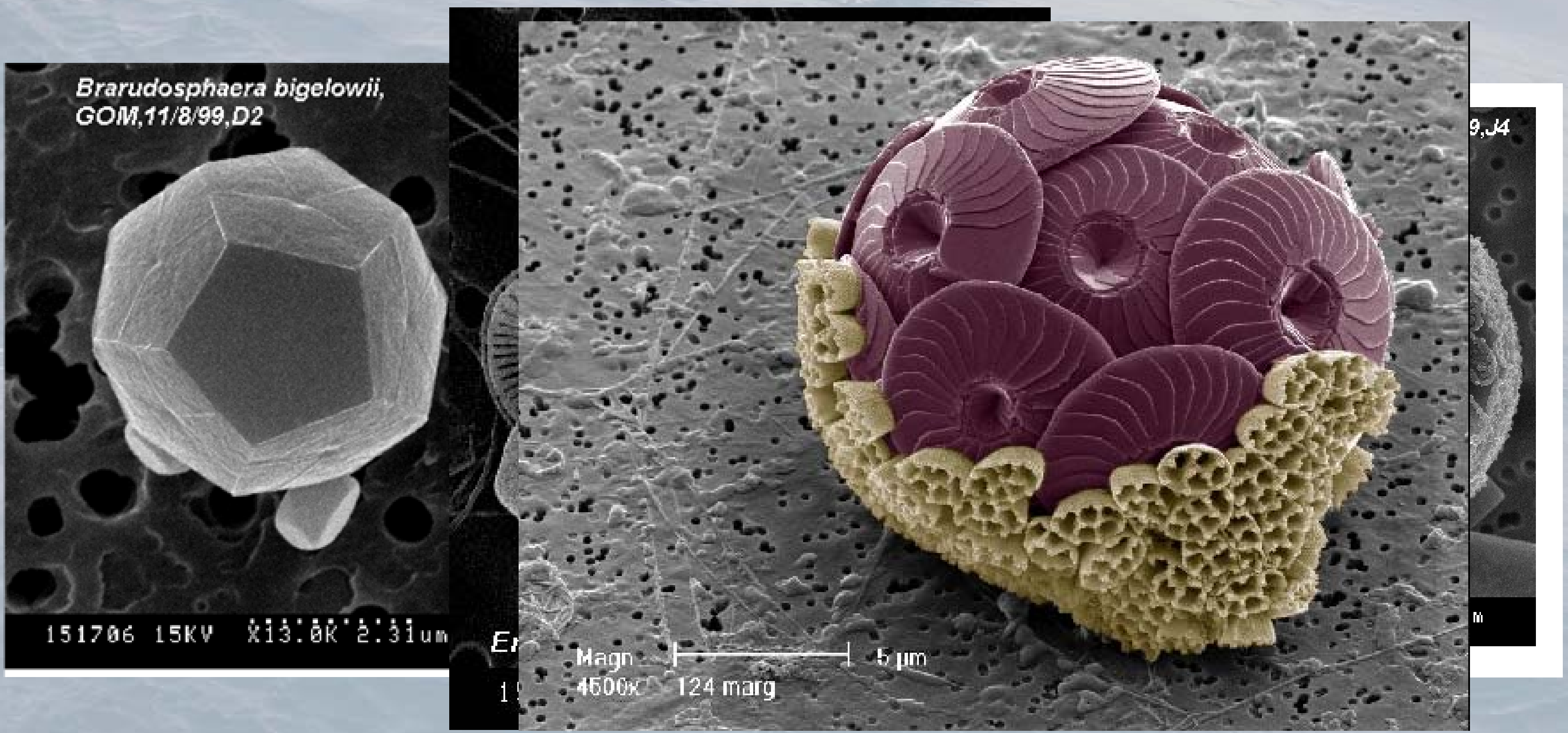
PIC can be a 1° determinant of nLw



Correlations increase when nLw is regressed against coccolith concentration!

Gulf of Maine

It isn't just *E. huxleyi* that increases the reflectance of seawater…



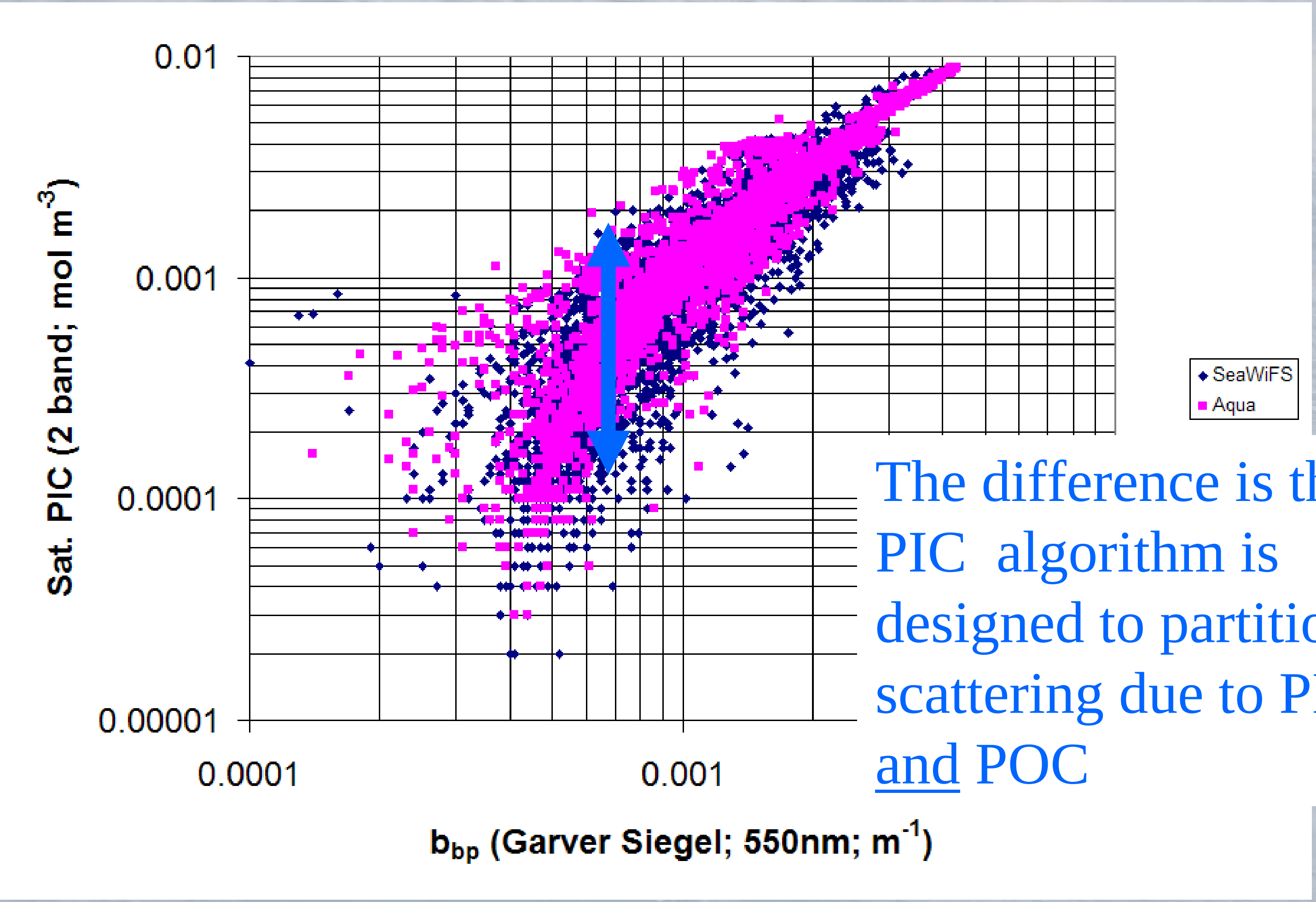
SEM's courtesy of Dr. Delors Blasco, Institute de Ciencias del Mar, Barcelona, Spain; Markus Geisen, Alfred Wegener Inst for Polar and Marine Res.

Two PIC algorithms exist

- Two band algorithm (based on nLw440 and nLw550); Balch et al. (2005 Calcium Carbonate Measurements in the Surface Global Ocean based on MODIS Data. *JGR-Oceans* ***110***, *C07001 doi:10.1029/2004JC002560*)

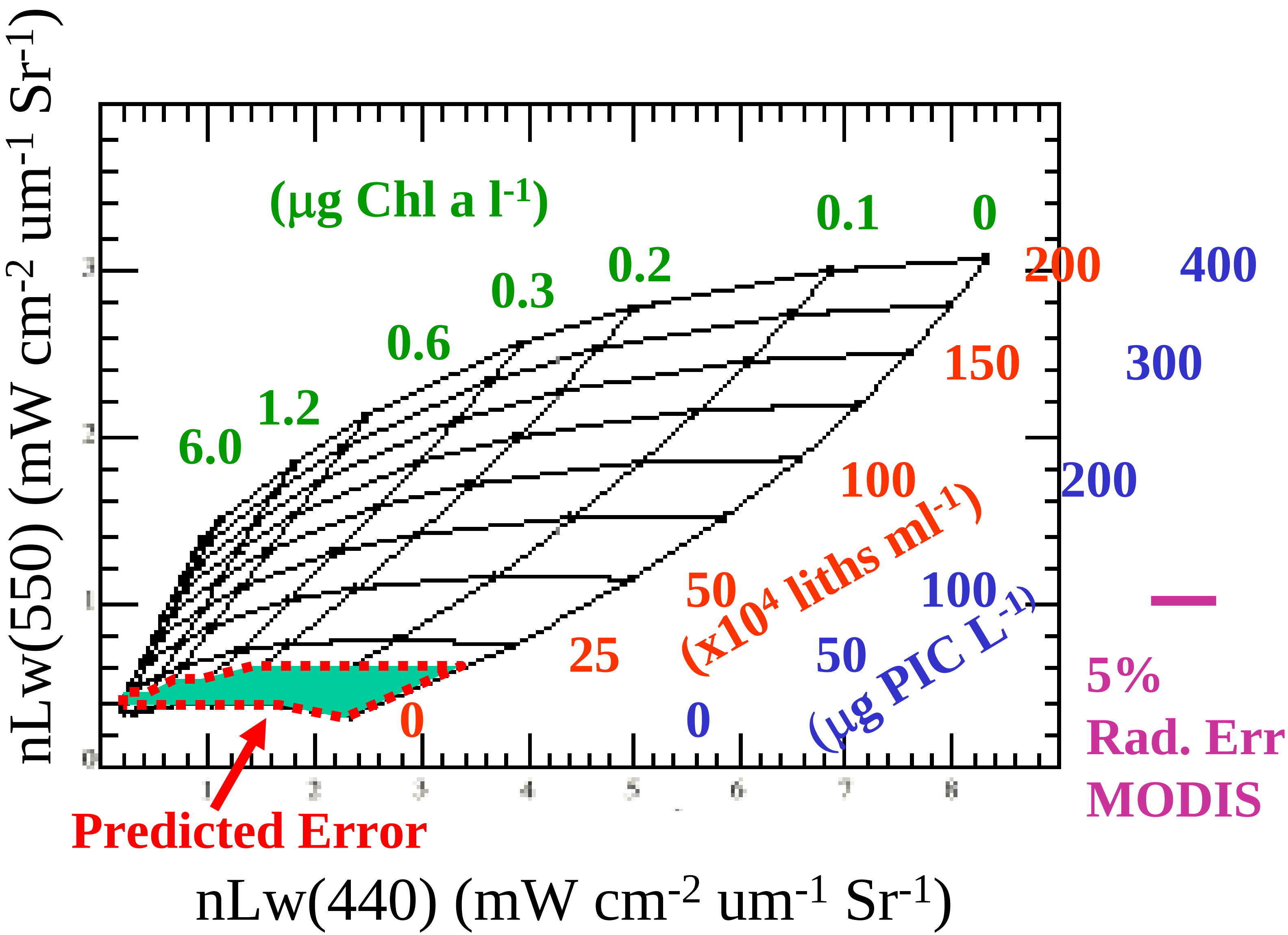
- Three-band algorithm (based on 670, 765, and 865nm bands; Gordon et al. (2001. Retrieval of coccolithophore calcite concentration from SeaWiFS imagery, *Geochemical Research Letters*, *28* (8), 1587-1590.)

The PIC algorithms are fundamentally backscattering algorithms…



The difference is the the PIC algorithm is designed to partition the scattering due to PIC and POC

The 2-band PIC algorithm- best for low [PIC]



Pros and Cons of the 2-band algorithm

- **Pros**
  - Provides quantitative estimate of chlorophyll and PIC in waters where pigment retrievals have traditionally been problematic

- **Cons**
  - Two bands are in spectral regions influenced by chlorophyll and cDOM.
  - Atmospheric correction within these bands is significant, especially for absolute nLw.
  - More sensitive to radiance errors than band ratio algorithms (e.g. chlorophyll)

3-Band Algorithm-<u>for bright blooms</u>

- At 670nm, 765, and 865nm, we assume absorption is mainly due to water (a_w):

$$R = \sim b_b/[3(b_b + a_w)]$$

Measure $R(\lambda)$, use published $a_w(\lambda)$, estimate $b_b(\lambda)$.

- Assume: a) $b_b(\lambda) = b_b(550)*(550/\lambda)^{1.35}$

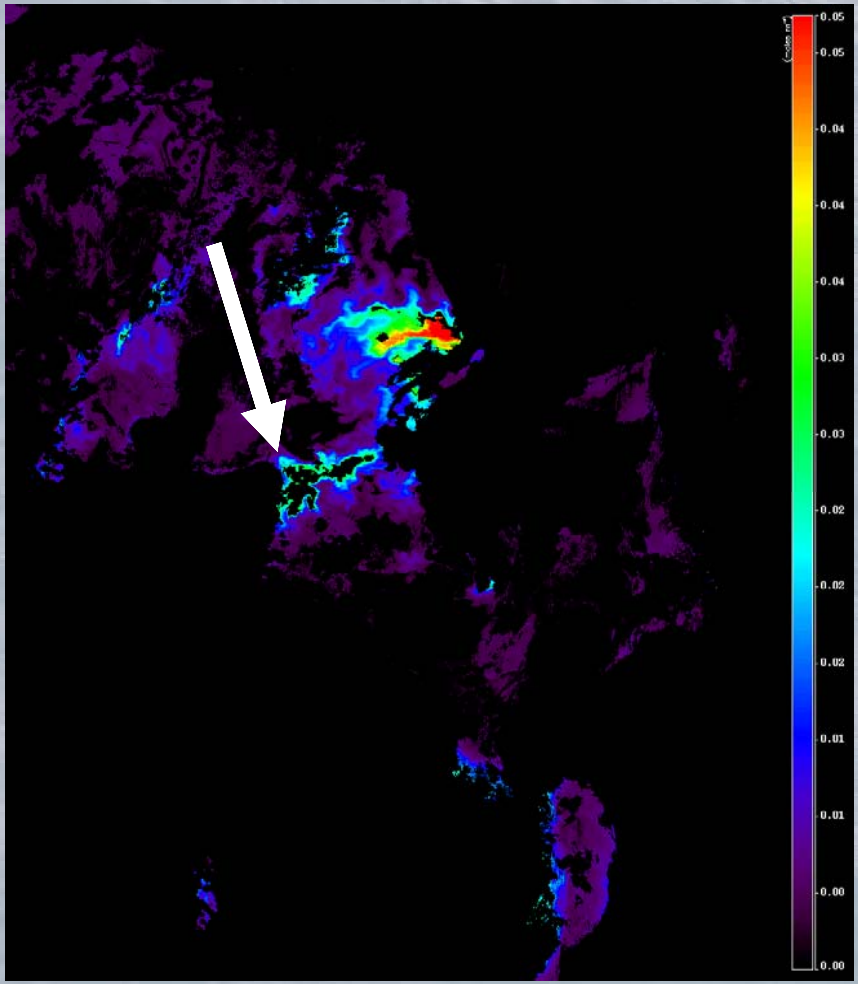
  b) background, non-PIC b_b

- These assumptions allow estimation of b_b at other wavelengths
- Works best in bright, turbid waters

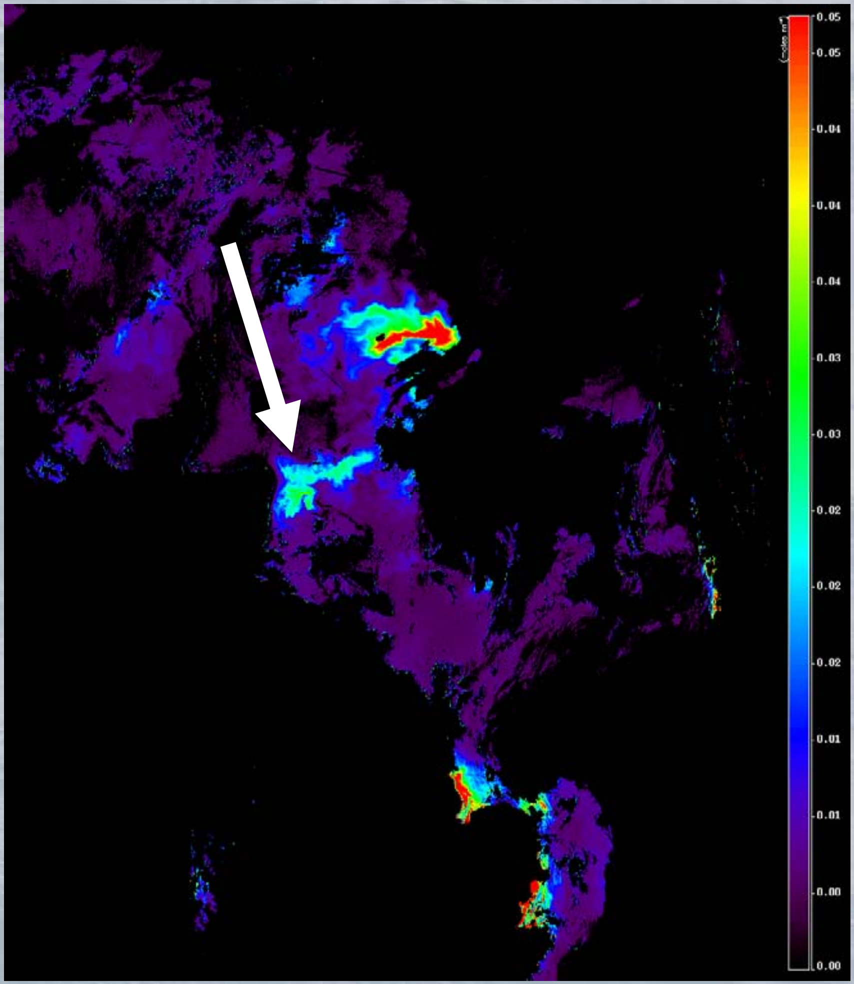
Pros and Cons of the 3-band algorithm

- **Pros**
  - Absorption coefficient of water is so high in red and near IR that added phytoplankton and cDOM absorption is negligible.
  - Bands less likely to saturate
  - Less extrapolation for atmospheric correction
- **Cons**
  - Assumption of background b_b for all non-PIC particles
  - Affected by other suspended sediments

2 Band

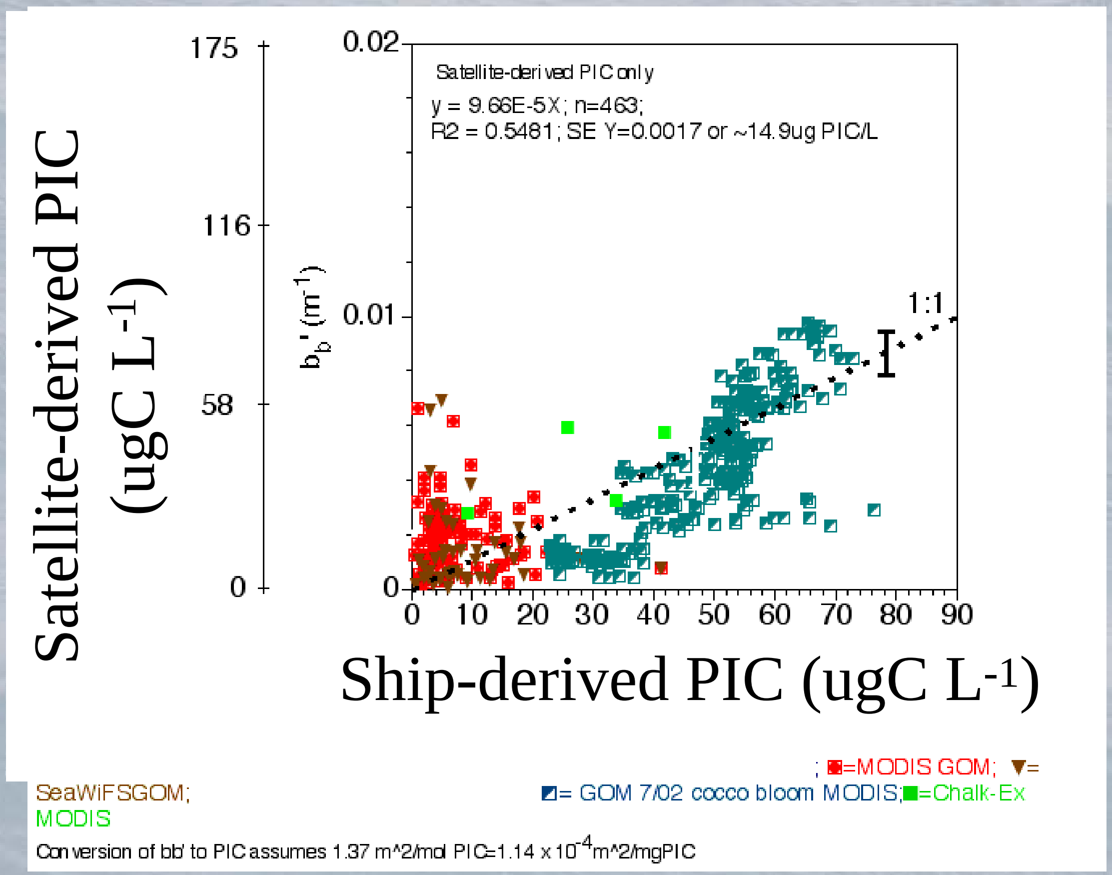


3 Band



SeaWiFS scene S2003147125430 of a coccolithophore bloom in the North Sea on May 27 2003. Comparison between 2-band PIC algorithm and 3-band PIC algorithm. Color scales range from 0-0.05 moles PIC m-3. Images by Sean Bailey and Brian Franz.

Real world tests in the Gulf of Maine…ship-satellite comparisons with 2-band algorithm



There is natural variability in PIC-specific scattering cross-section

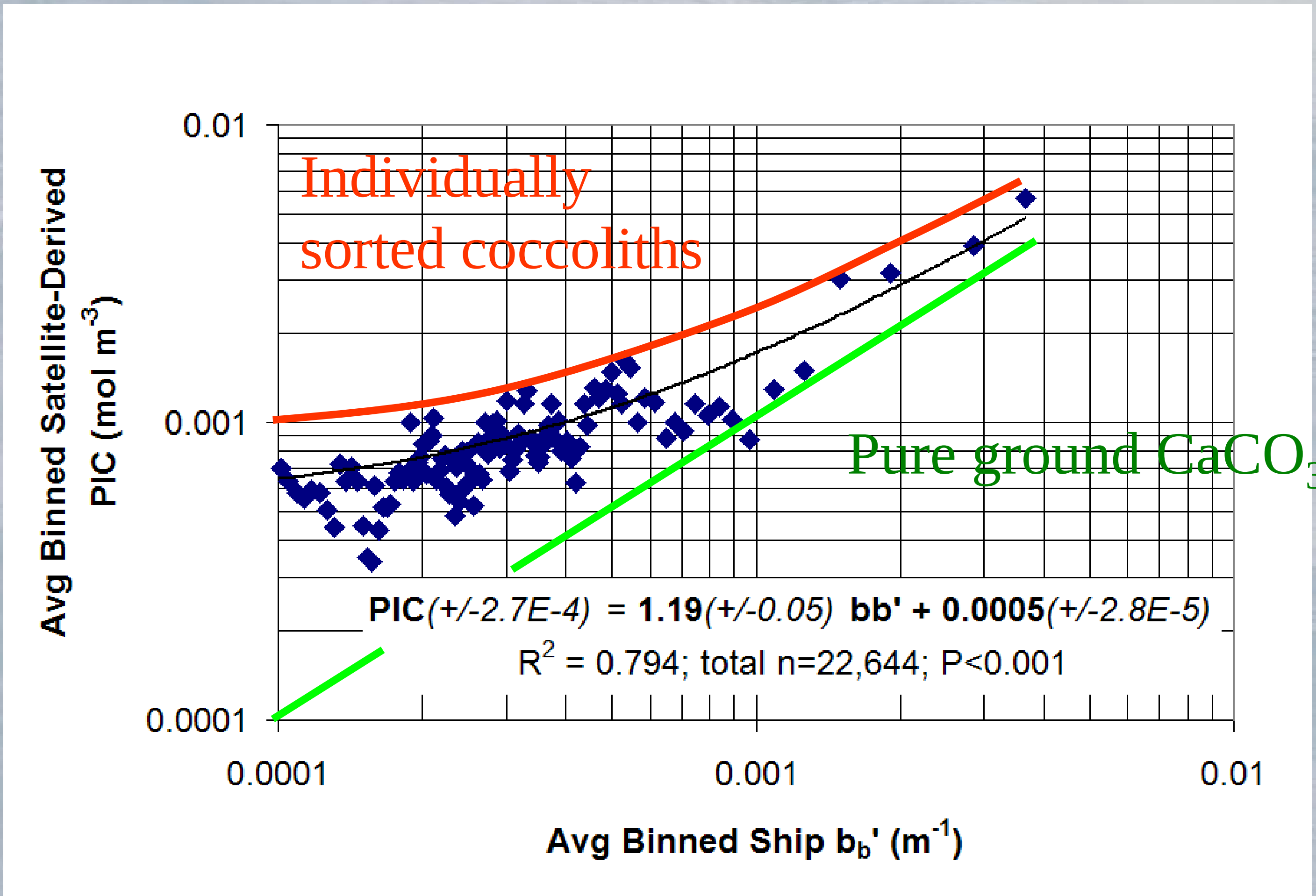
Global views: Important caveats

- The 2-band or 3-band PIC algorithm can be "fooled" by other scattering materials (e.g. error from scattering by suspended sediments).
- Standard deviation for mean satellite-derived b_b is ~14.9 ug PIC L^{-1}, based on 1km daily data. Assume random errors, SE decreases for binned data by $1/(n^{1/2})$.

SE of time/space binned PIC averages (ug C L^{-1})

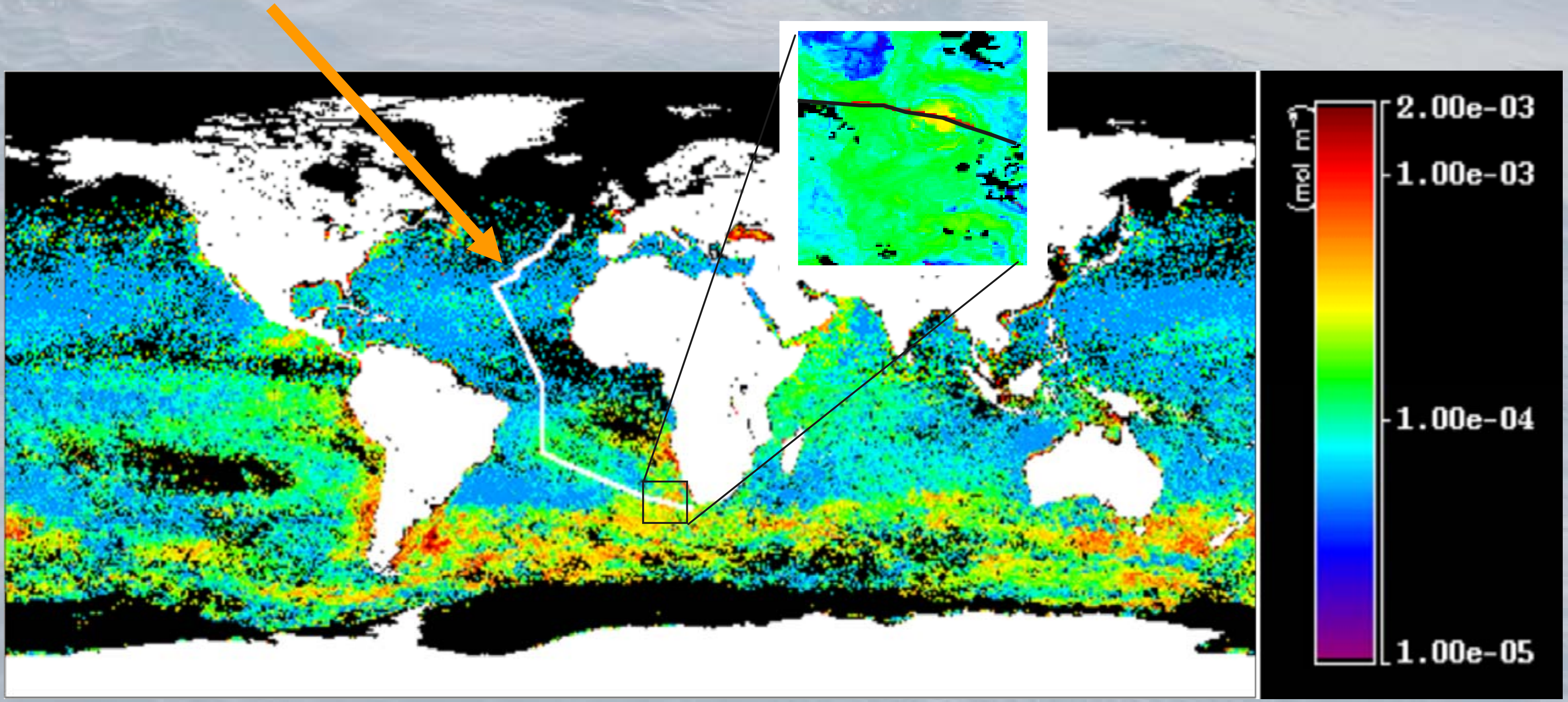
Spatial res (km)	1	4.63	36	111.2
Time bins (d)				
1	14.900	3.218	0.414	0.134
7	5.632	1.216	0.156	0.051
30	2.720	0.588	0.076	0.024
365	0.780	0.168	0.022	0.007

Using our data base of ship measurements in the GOM, binning can make a huge difference. SE of the PIC estimate is ~ +/- 2.7×10^{-4} mol PIC/m^3.

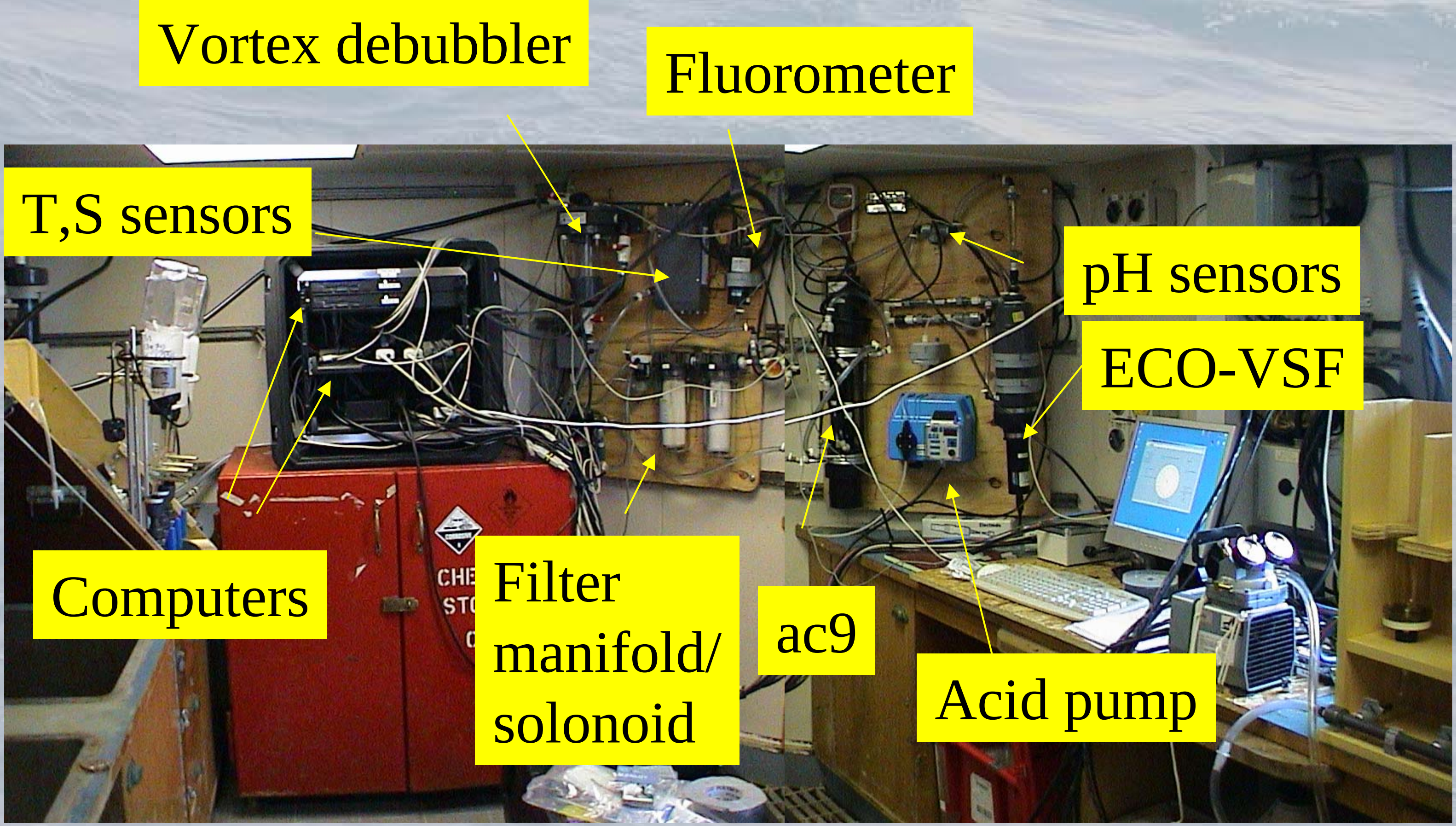


What does the calcite distribution look like in the central Atlantic?

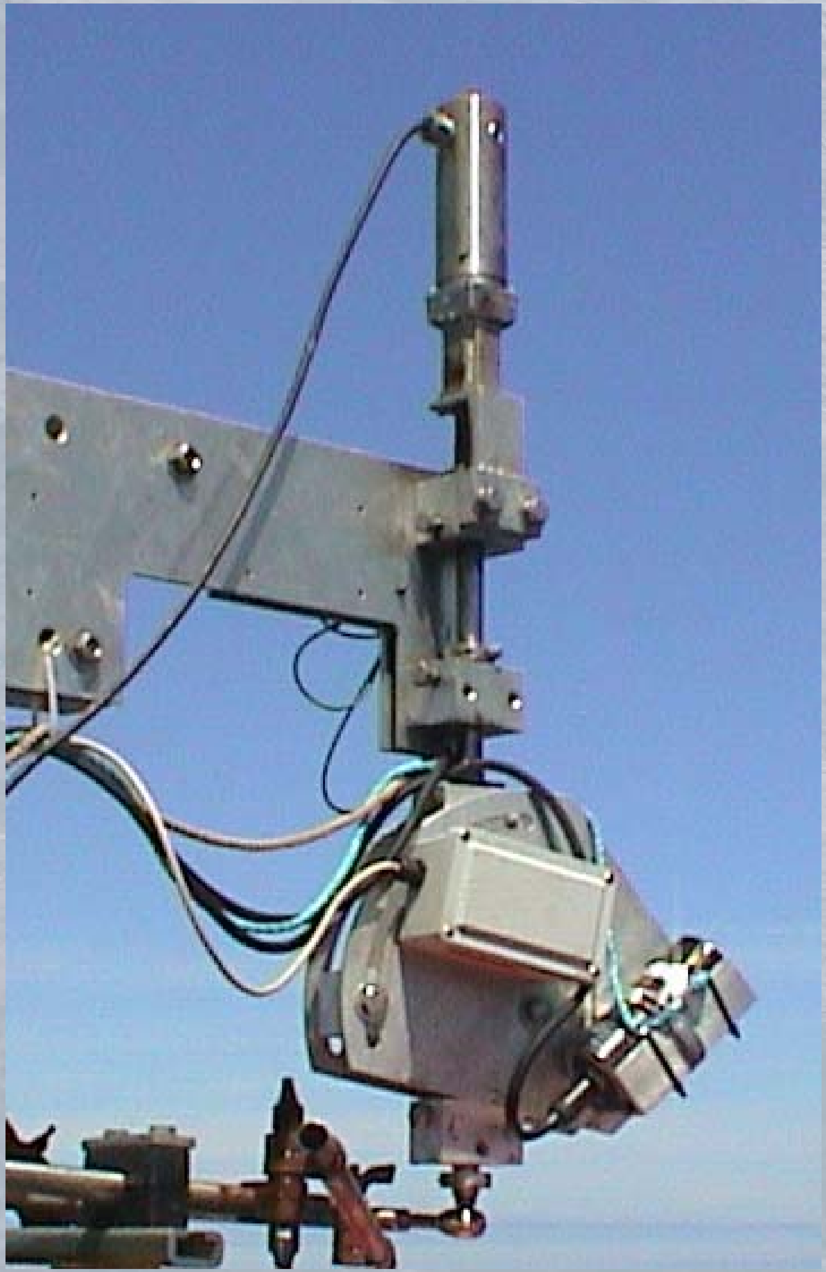
AMT 17 Cruise track



NOTE: MOST OF THESE ARE NOT BLOOMS BUT NORMAL BACKGROUND CONCENTRATIONS!

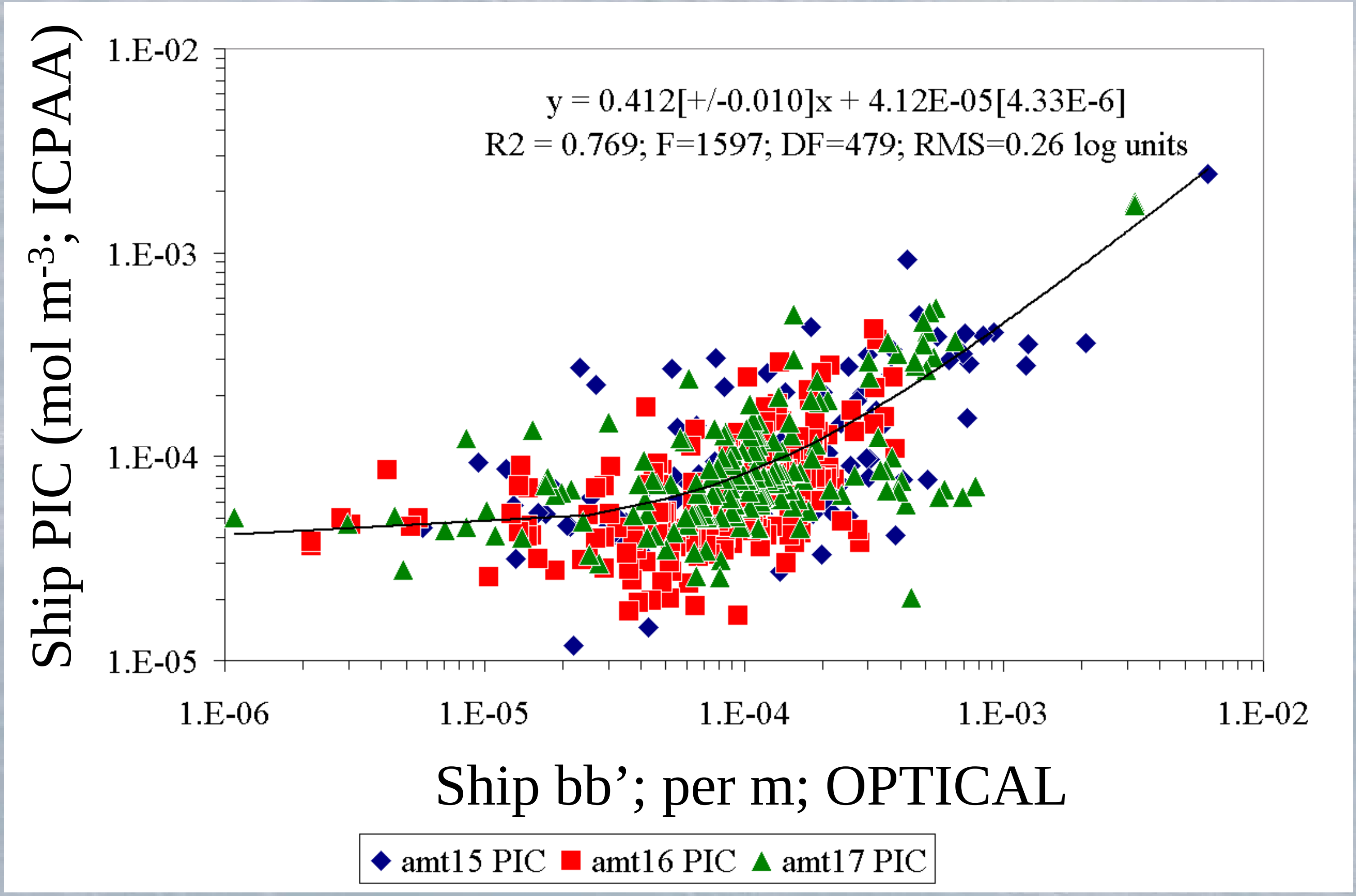


Underway system for continuous underway measurements of $a_{pg}(\lambda)$, $c_{pg}(\lambda)$, $a_g(\lambda)$, $c_g(\lambda)$, $b_b(543)$, bb'(543), fluorescence, temperature, salinity

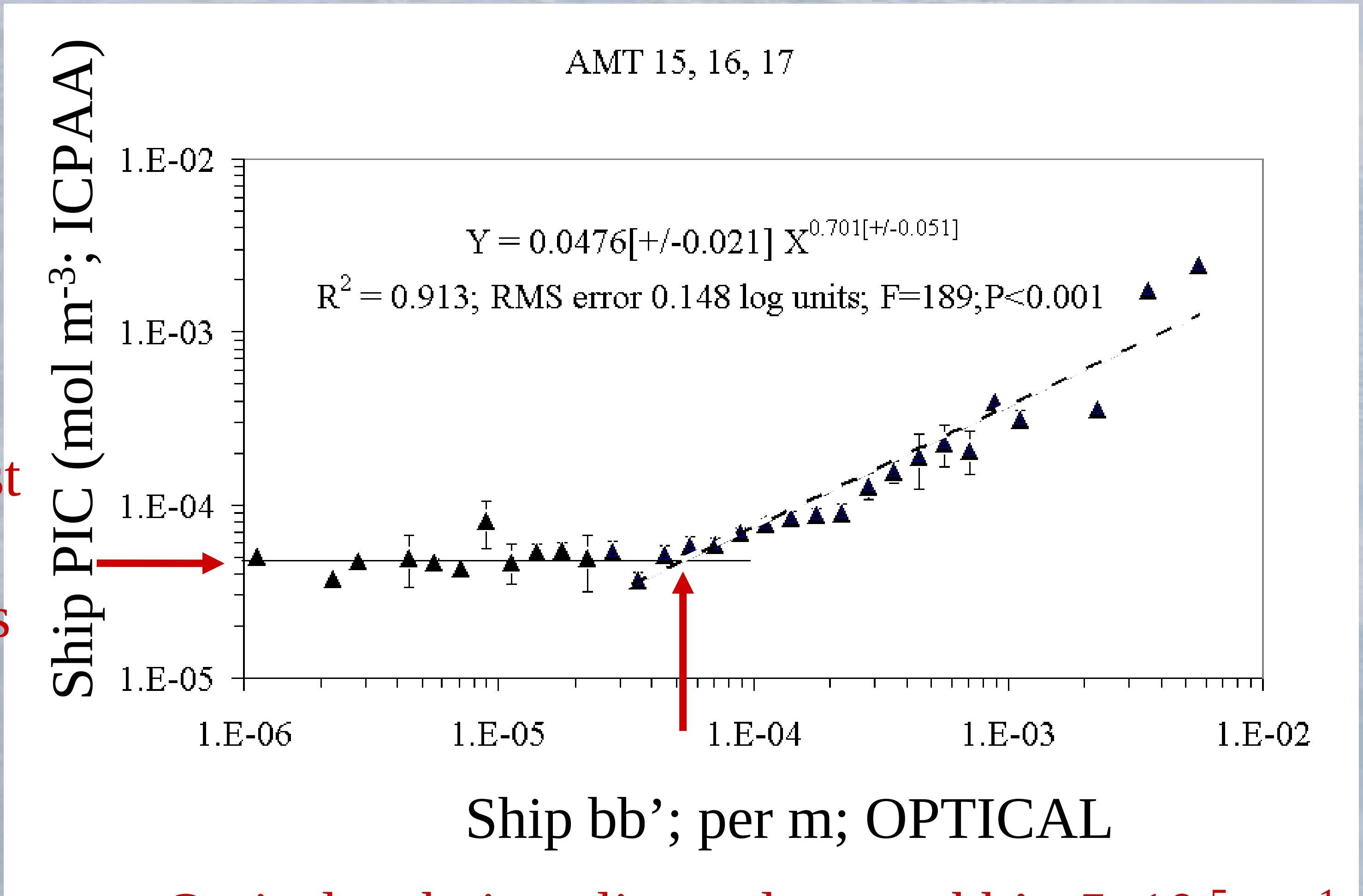


Satlantic Micro-SAS radiometers collected along-track data for Lt, Lsky, and Ed for estimation of nLw as input to the two PIC algorithms.

On the ship we measure PIC optically and chemically



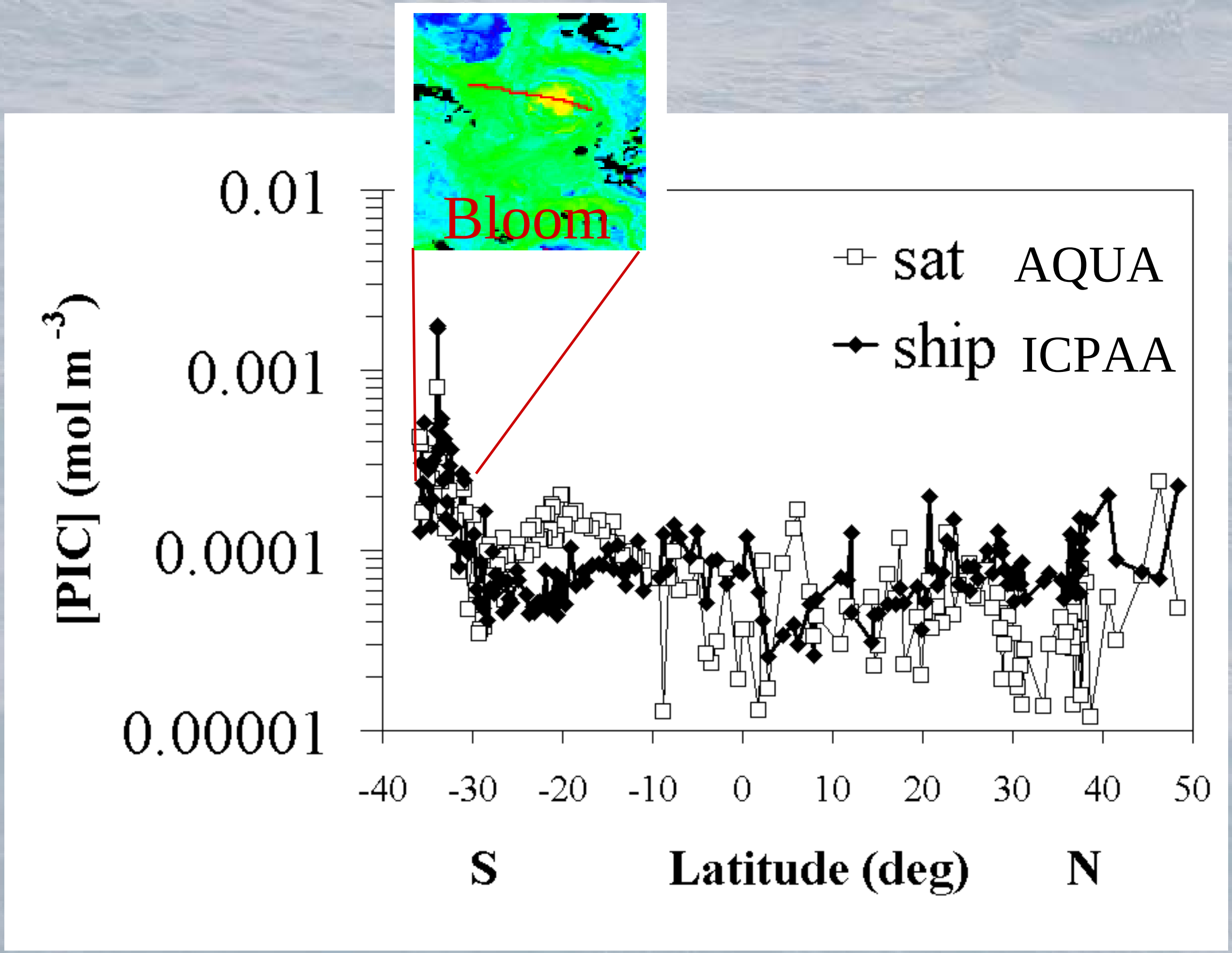
Binning can improve the fit considerably…



Lowest obs Values $5x10^{-5}$ mol m^{-3} PIC

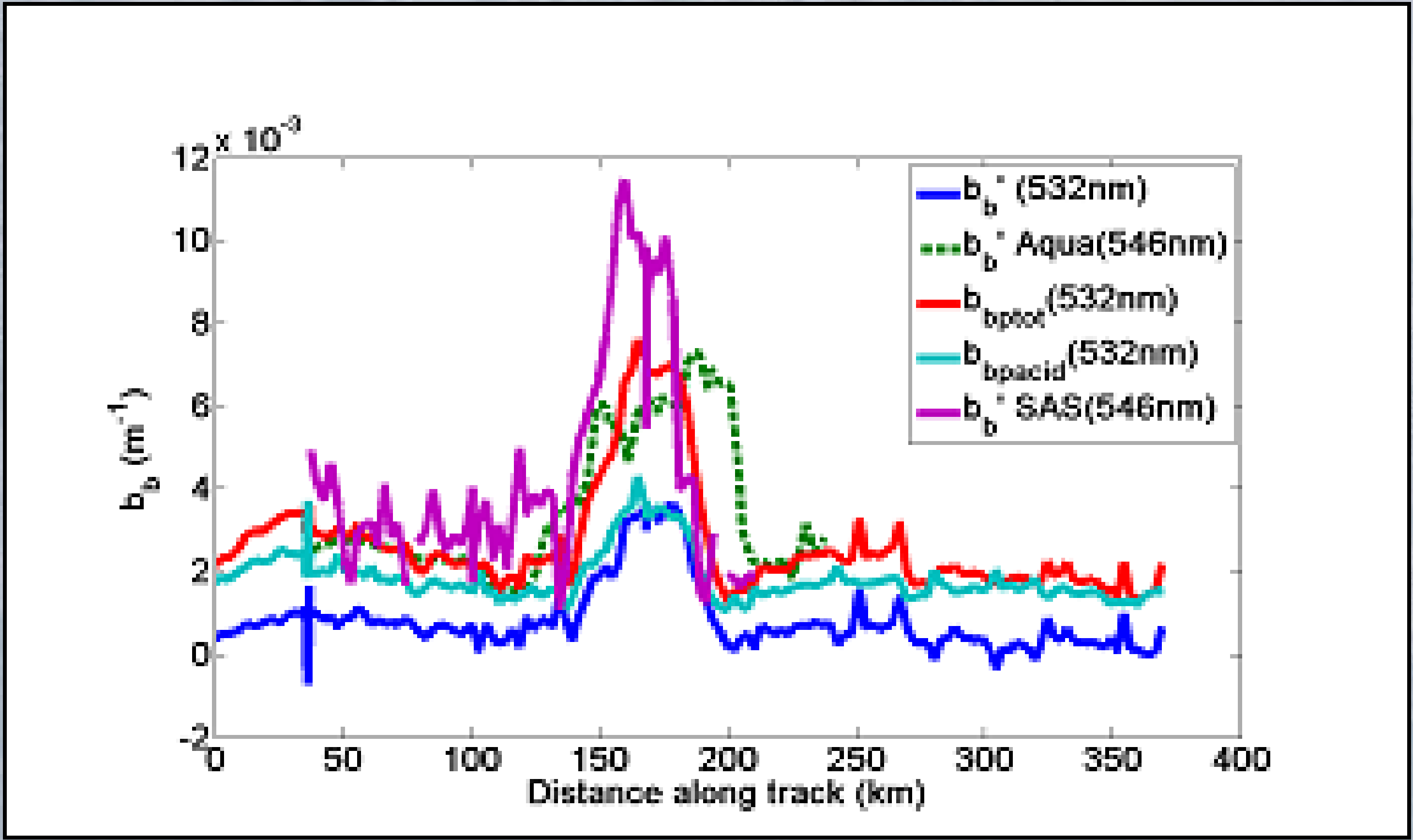
Optical technique linear down to bb'= $5x10^{-5}$ m^{-1}

How does the merged algorithm work in the mid-Atlantic section?



AMT17

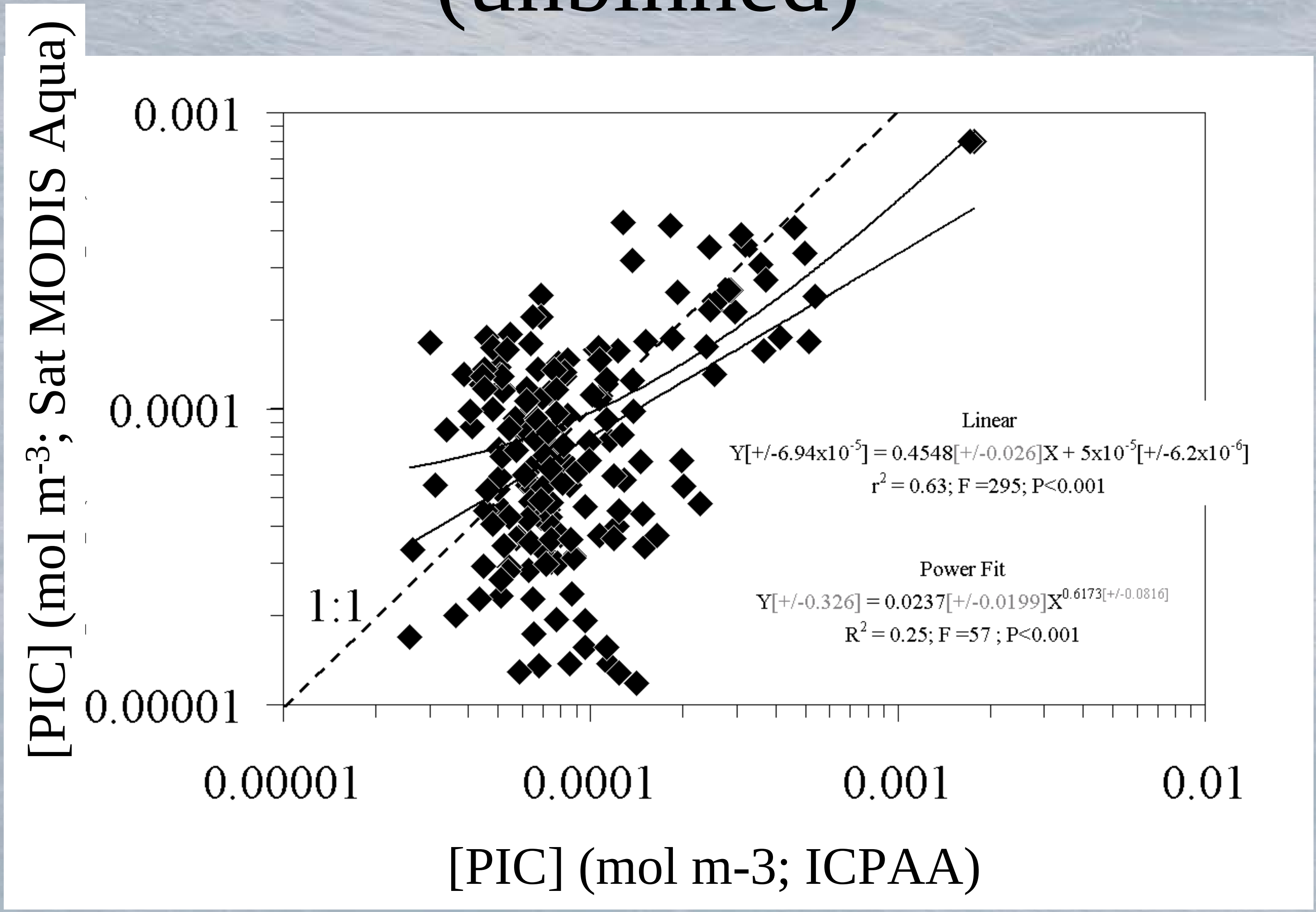
Ship and satellite measurements of the same feature (all using b_b)…



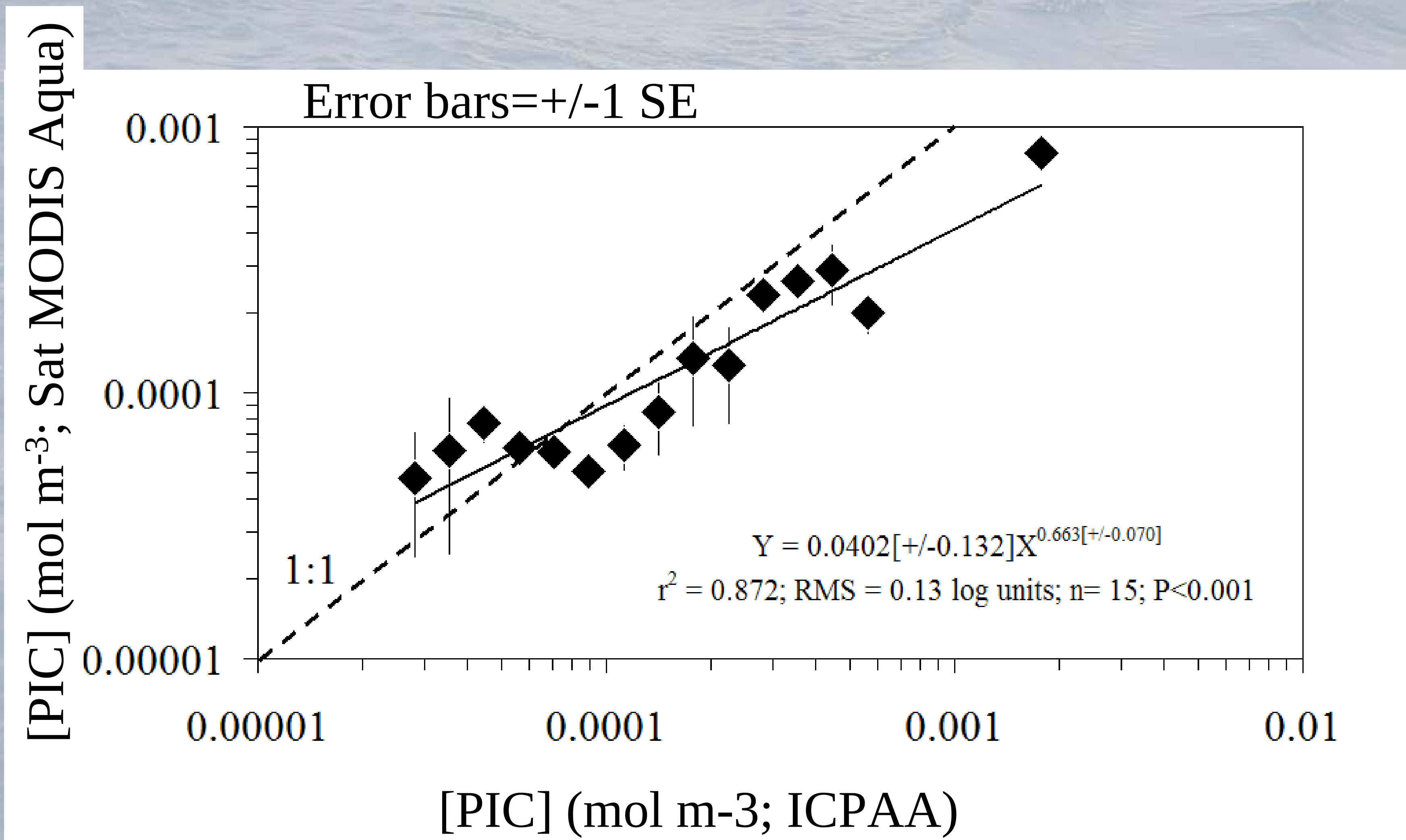
How do the data distributions compare between ship and satellite?

	log10 [PICsat]	log10[PIC ship]	Diff (sat-meas)	abs diff (% ; sat-meas)
avg	-4.121	-4.044	-0.077	**-16.28**
Std dev	0.375	0.302		
median	-4.117	-4.121	0.004	**0.91**
max	-3.098	-2.751	-0.347	
min	-4.928	-4.588	-0.340	

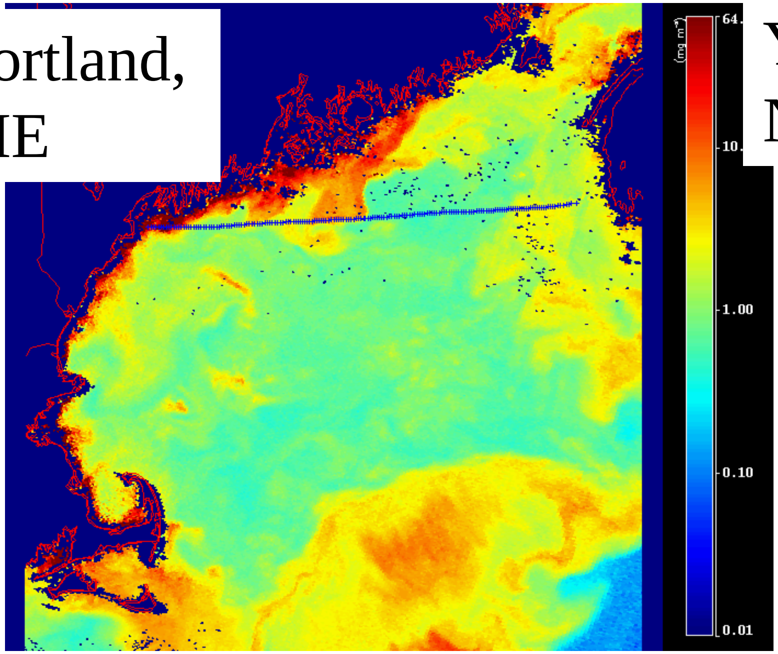
Comparing ship and satellite (unbinned)



Now bin the data…



GNATS: Gulf of Maine North Atlantic Time Series



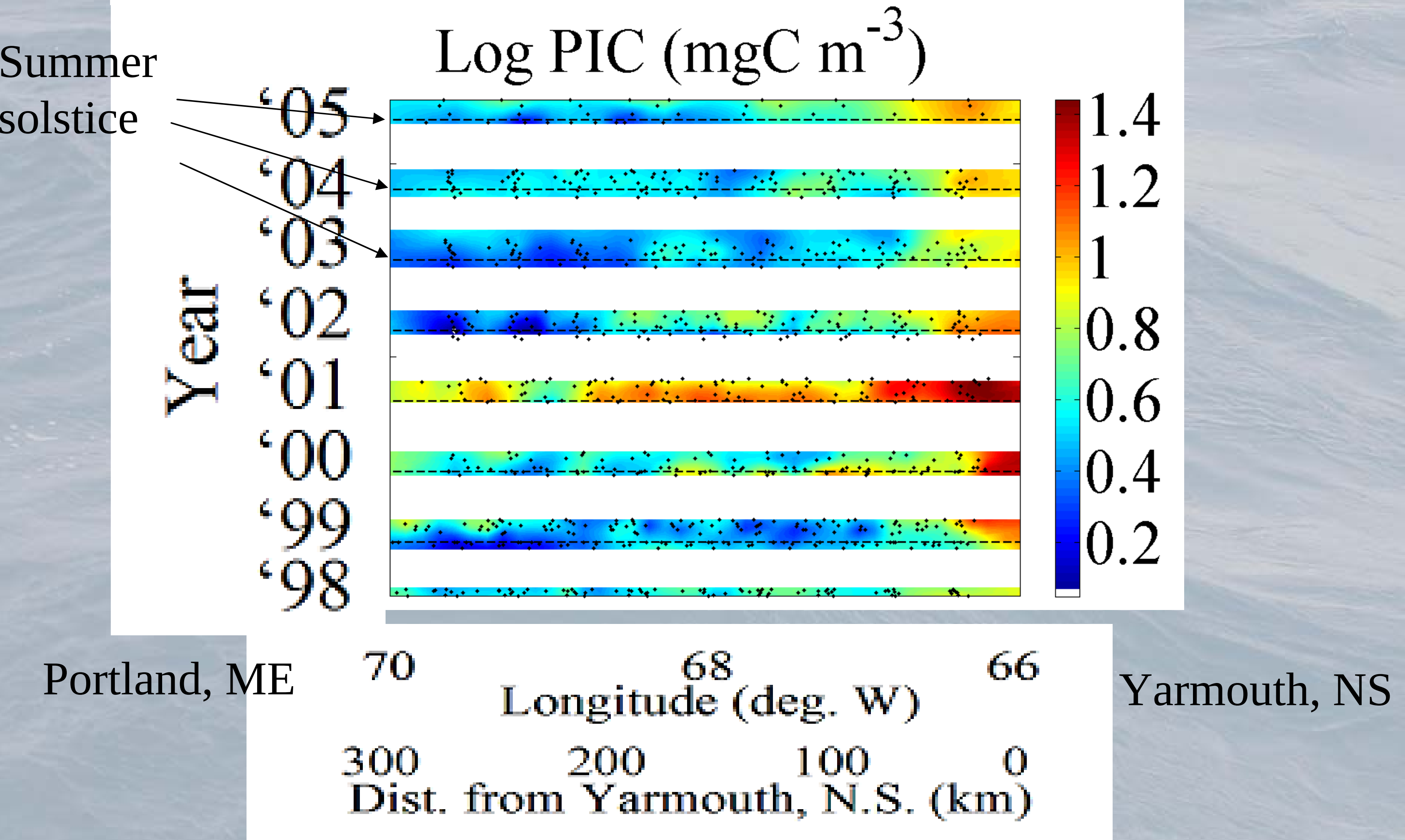
Run transect on clear-sky days

Acquire parallel remotely-sensed observations

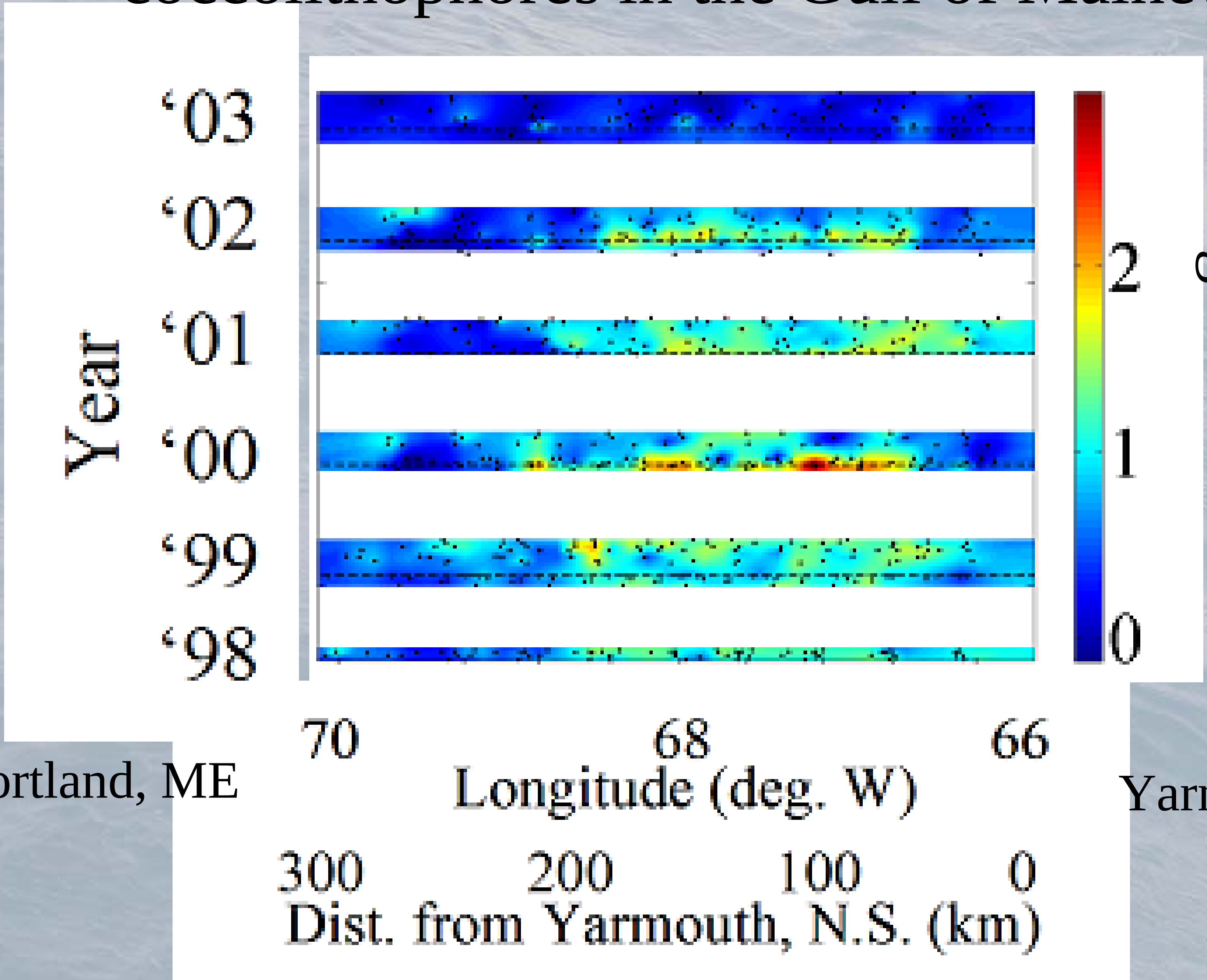
Measure a suite of bio-optical and hydrographic variables including PIC, calcification, coccolithophore abundance and acid-labile b_b.

Supported by NASA since 1998.

Sanity check… what might we expect for annual variability in PIC in the Gulf of Maine?



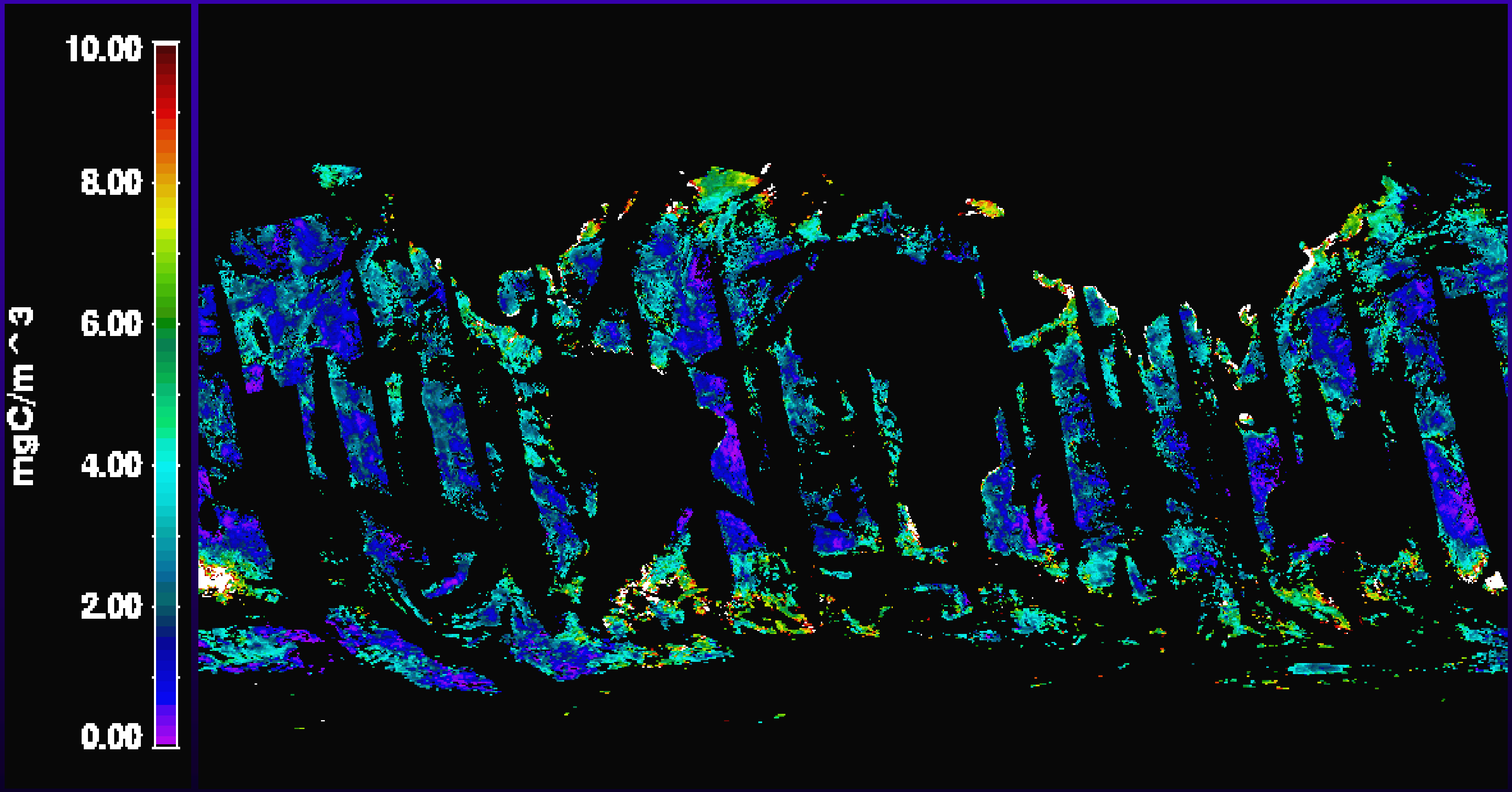
Sanity check… how about changes in plated coccolithophores in the Gulf of Maine?



Portland, ME

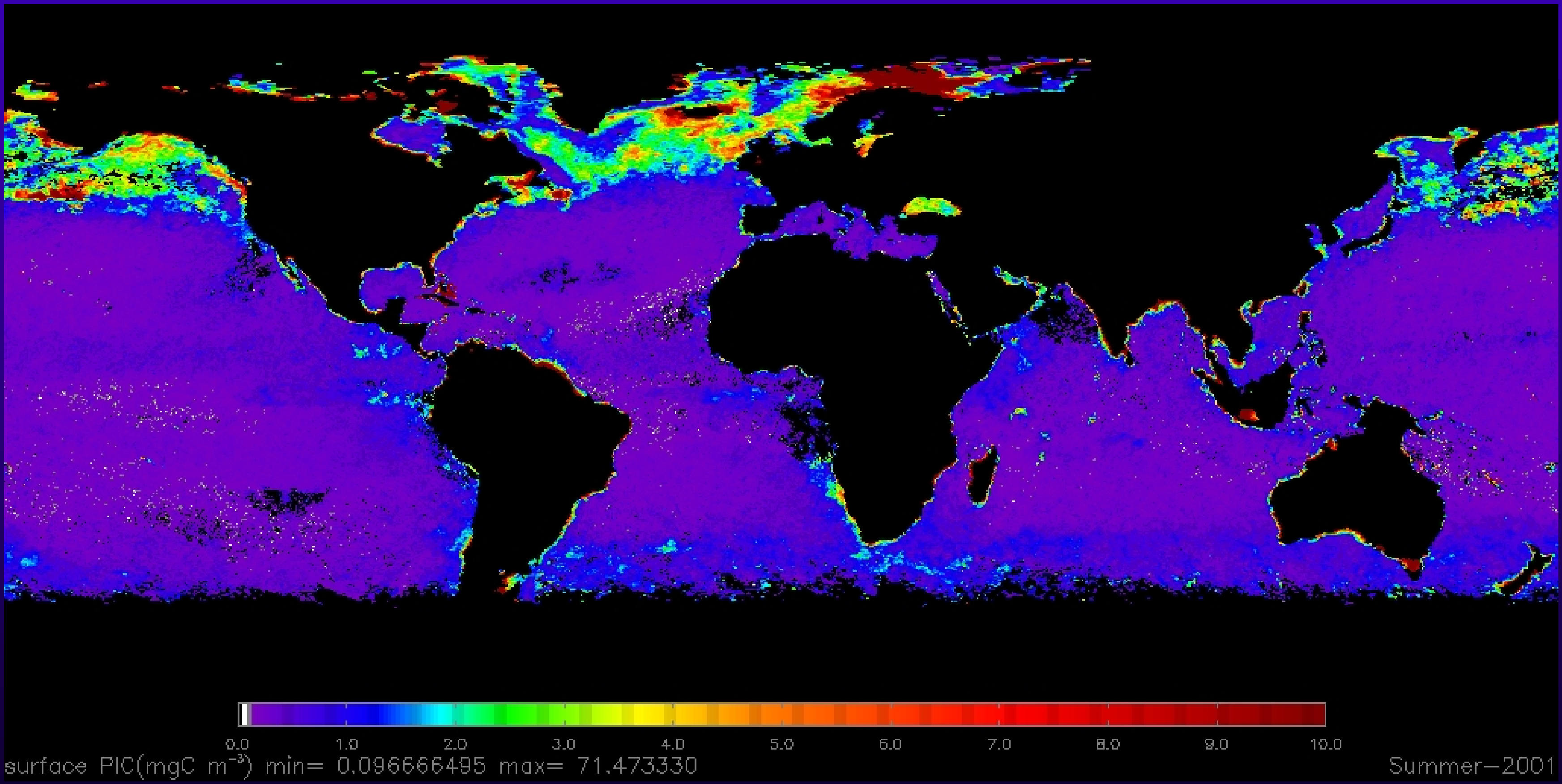
Yarmouth, NS

Now the global perspective…
Example MODIS Aqua; 8 November 2004



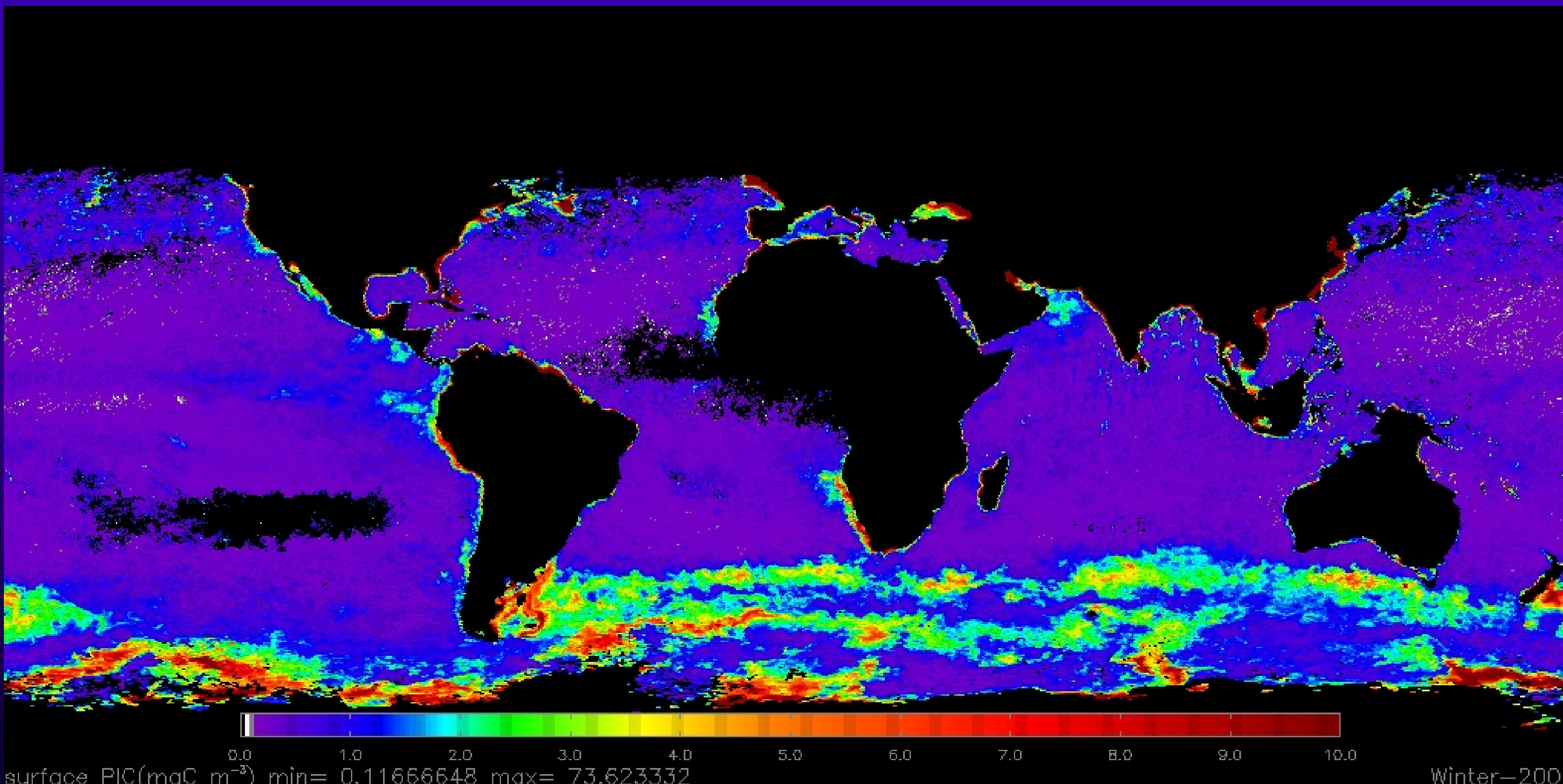
Balch; Bigelow Lab

Seasonally binned global data calcite- July-Sept



Balch, Bigelow Lab

Southern hemisphere summer- Jan-Mar



Balch, Bigelow Lab

Summary

- PIC algorithm is accurate to +/- 0.15 log units *binning of data is critical (~4km, 8d averages)*
- PIC algorithm only focuses on coccolithophorids and micron-sized PIC particles
- Basin-scale budgets will likely be the best way to address ocean acidification impact, but beware of changes in coccolithophores due multiple stressors (e.g. stratification, warming, etc.)
- New directions: Using other satellite platforms to understand the angular dependence of backscattered light as well as new active ways of estimating backscattering. We still have lots of room for algorithm improvement…rather not have to bin data since that lowers spatial-temporal resolution!

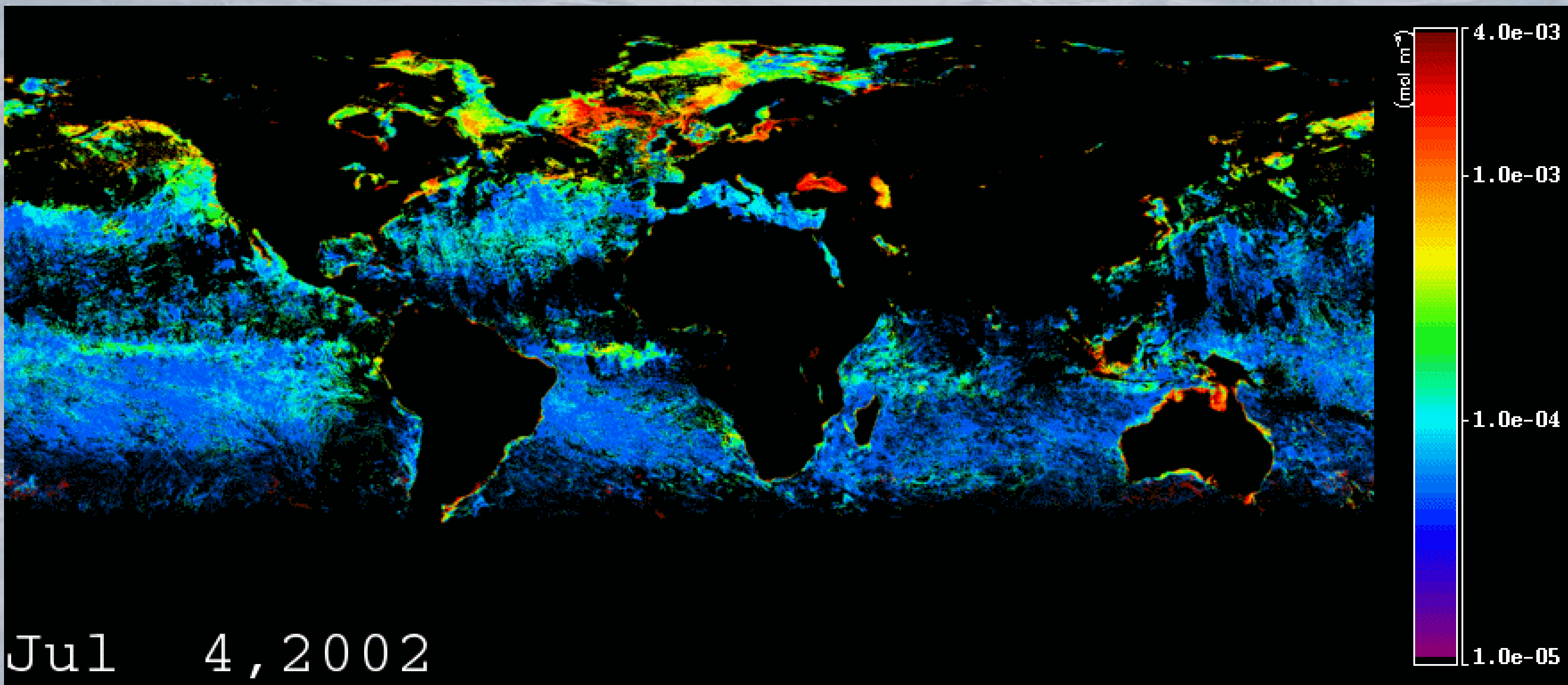
THANK YOU VERY MUCH!

OCB

Ocean Carbon
& Biogeochemistry

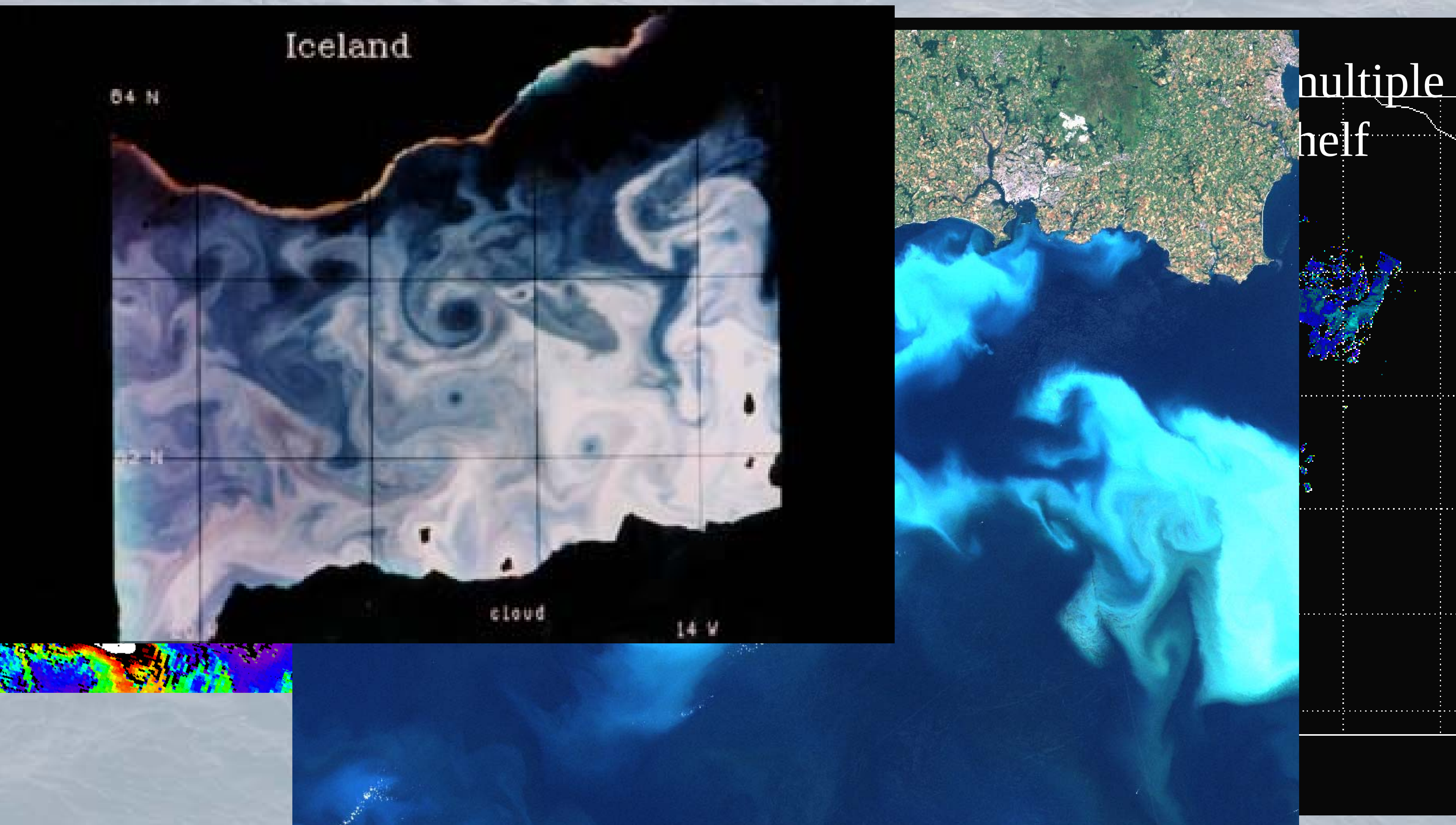
Global PIC movie…

World premiere of the global calcite movie
…as estimated with revised, merged, 2-band 3-band algorithm. Aqua mission 2002-2007

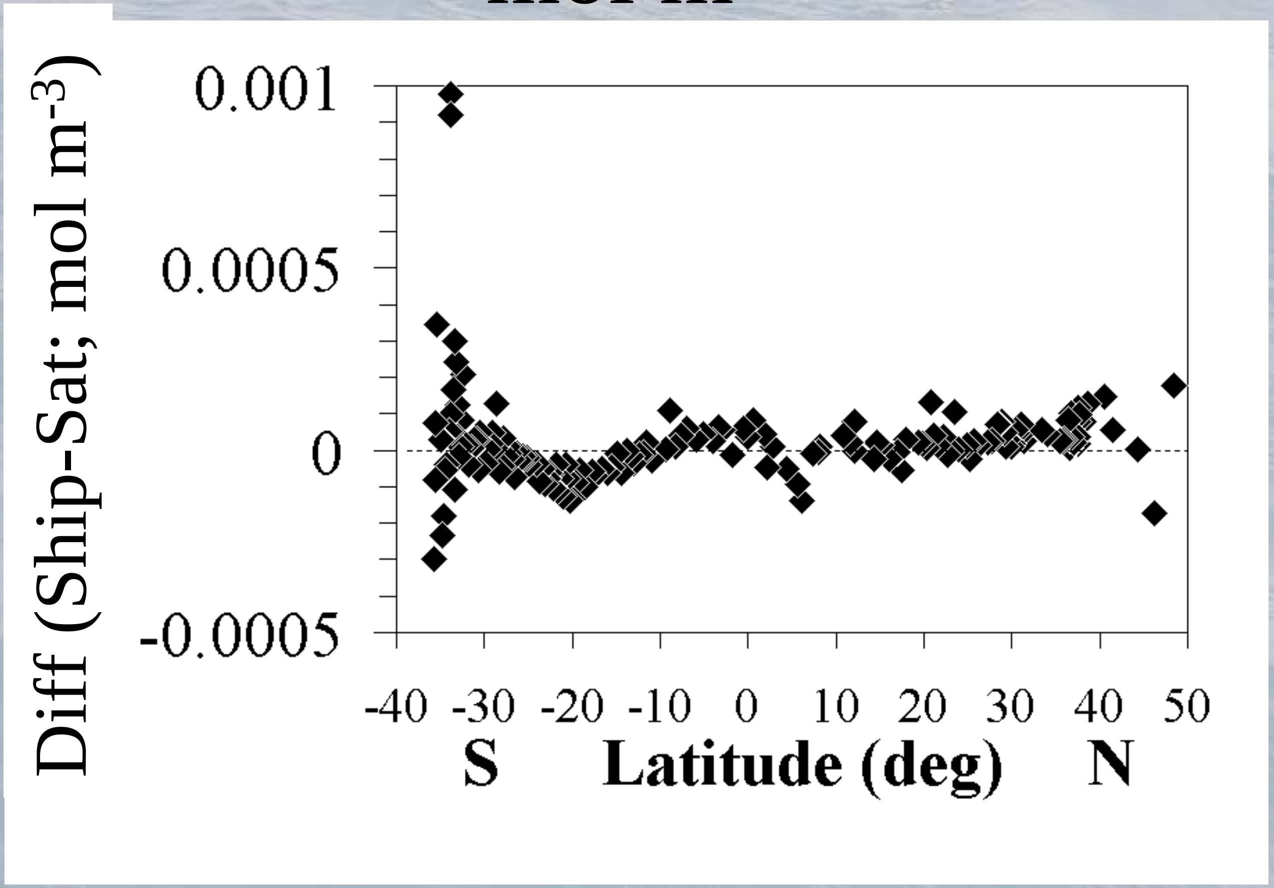


Acknowledgements: Processing: Gene Feldman, Bryan Franz (NASA Goddard); Bruce Bowler (Bigelow Laboratory)

Other examples of ocean blooms…

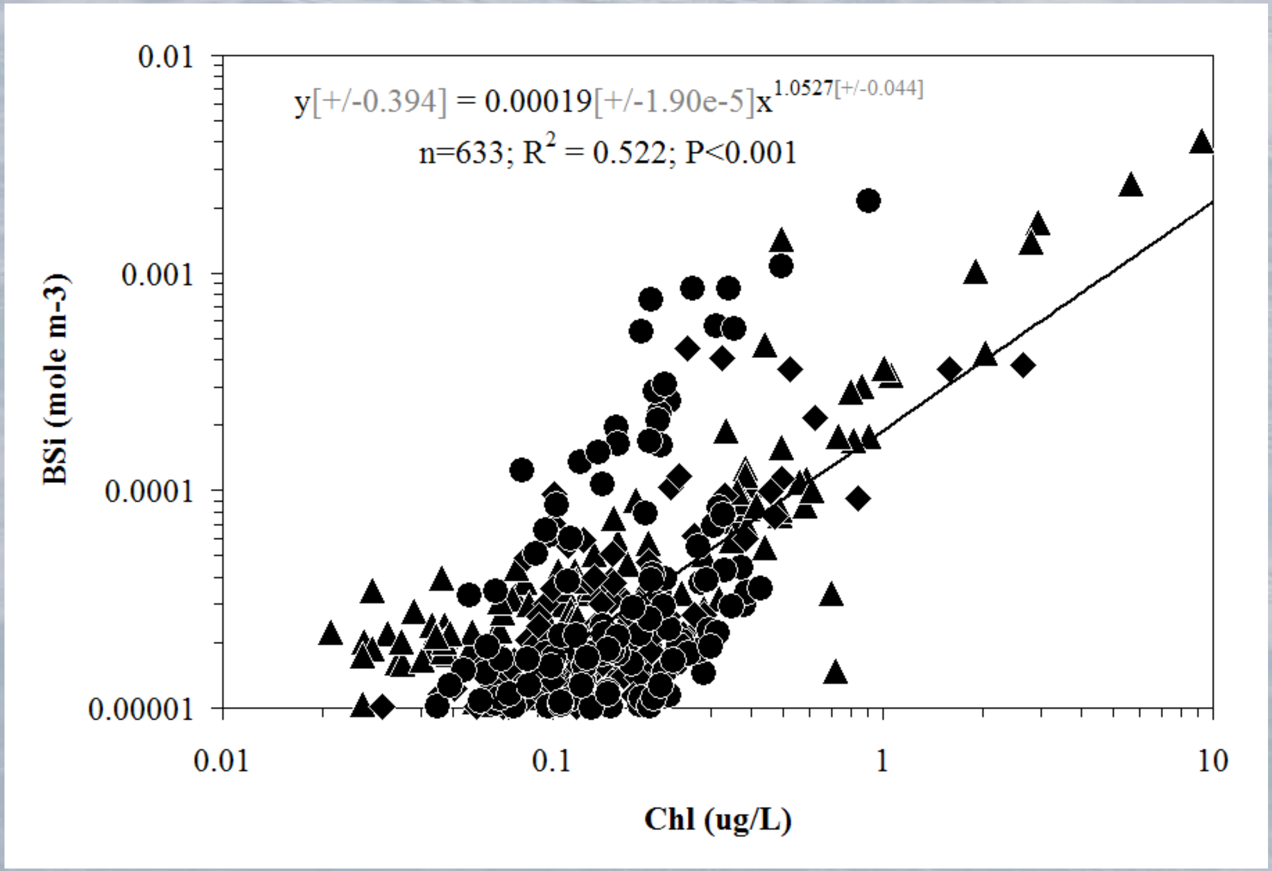


Unbinned differences between ship and satellite generally are within 1-2x10^{-4} mol m^{-3}



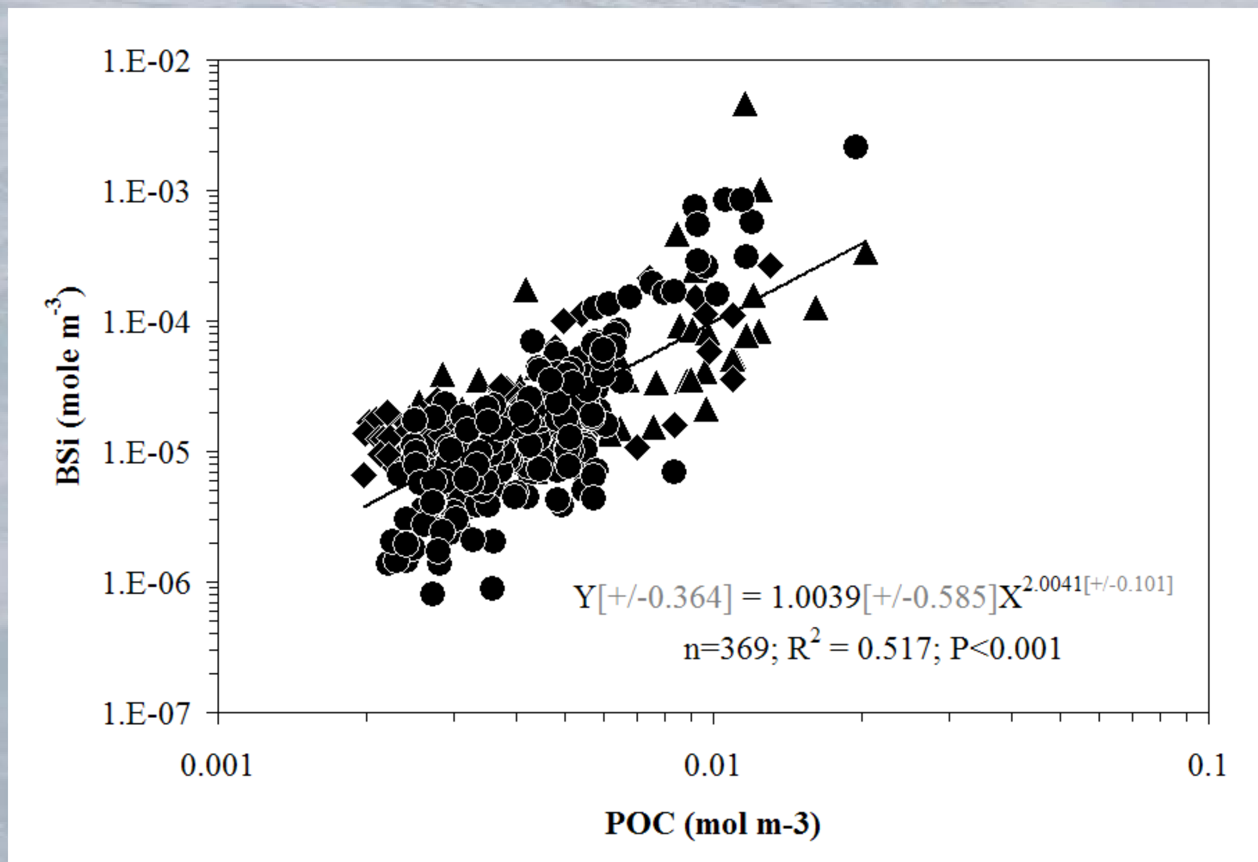
AMT17

[BSi] and [Chlorophyll] are correlated



AMT 15-17

[BSi] and POC are correlated



AMT 15-17

A quantitative summary of global PIC imagery

Integrated PIC over Euph. Zone

Biome	***Jan-Mar***	**Tot PIC Mt**	**% Total**	**Avg Int.PIC (mg/m2)**	**PIC:POC**
	…or "x10^{12}g PIC" →				
Polar		2.41	12.3	91.3	0.040
Westerlies		7.70	39.4	67.0	0.033
Trades		6.41	32.8	51.0	0.026
Coastal		2.99	15.3	134.3	0.062
Total		19.55	100.0	88.4	0.048
	July-Sept				
Polar		2.14	11.4	172.5	0.067
Westerlies		6.58	35.2	106.0	0.057
Trades		6.57	35.1	51.8	0.025
Coastal		3.38	18.1	116.9	0.052
Total		18.70	100.0	99.5	0.051

Balch et al. (2005) . JGR Oceans 110: C07001 doi:07010.01029/02004JC002560