Viewing the ocean's carbonate cycle with MODIS

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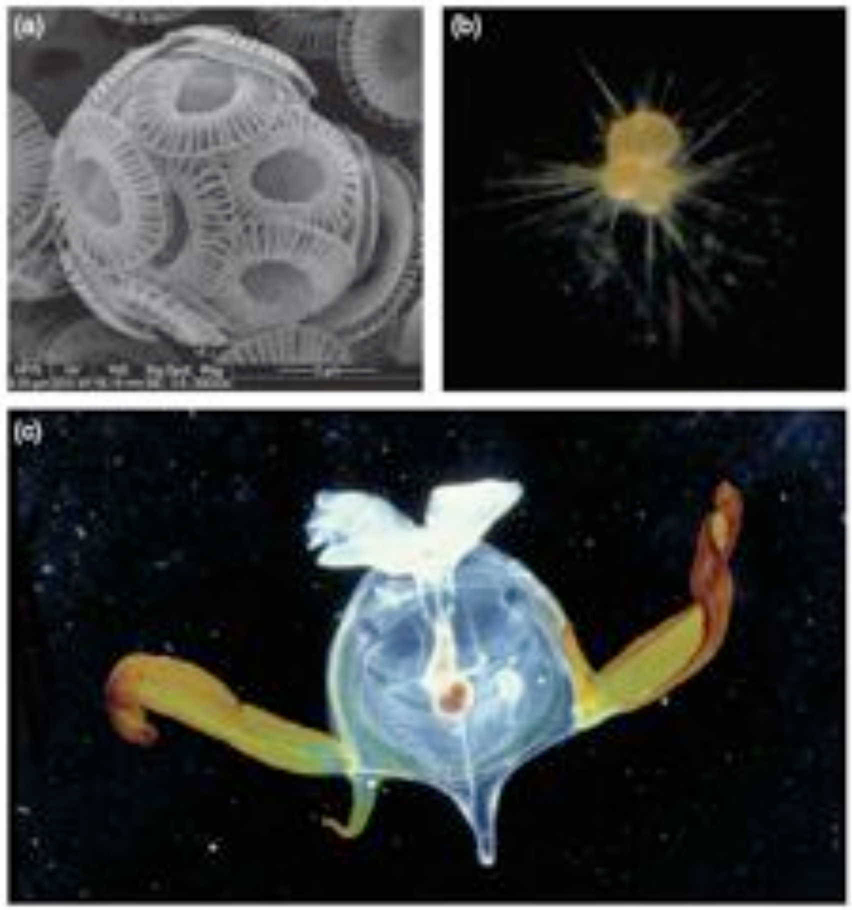
Outline of talk

- Brief review of the carbonate cycle in the sea
- MODIS PIC (particulate inorganic carbon) algorithm
- Looking at ocean PIC at different spatial scales
- The global MODIS PIC record
- Complex effects of ocean acidification and climate change
- Summary

Marine carbonate cycle

- Calcium carbonate (limestone, particulate inorganic carbon) is commonly produced by a wide variety of marine organisms
- Primarily as a defense against predation
- It is secreted by whole host of marine organisms across all most phyla: corals, molluscs, echinoderms, arthropods, annelids, foraminifera, algae, bacteria.

Main planktonic calcifiers…

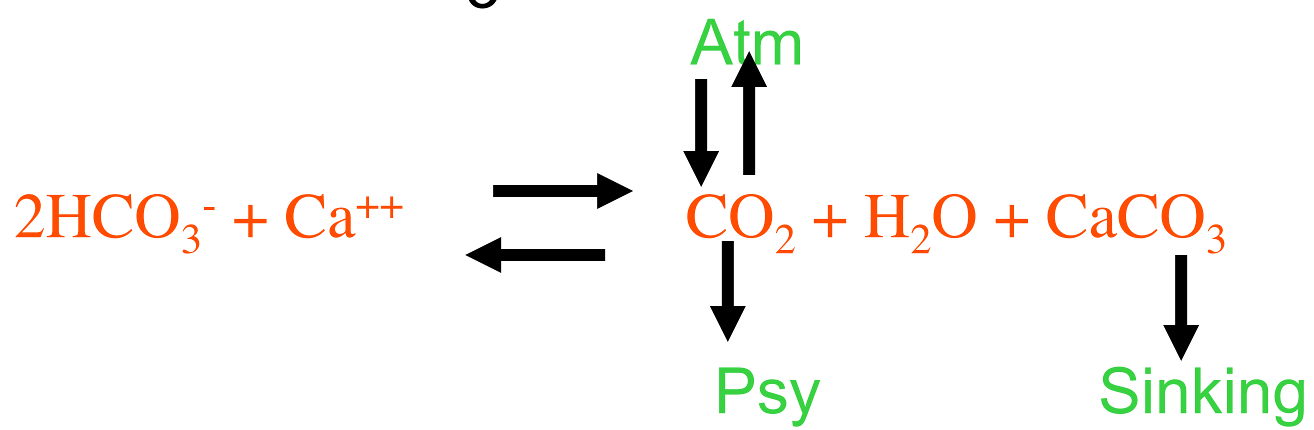


Calcium Carbonate and Global Carbon Pools

- Calcium carbonate (particulate inorganic carbon) is one of the major particulate carbon pools on earth, 1/4 of all marine sediments are $CaCO_3$.
- Biosphere has many calcifiers but the small ones play a disproportionately large role

Pool	***GT C***
PIC (sediments)	5.7×10^6
DOC (ocean)	1000
POC(sediments)	0.8×10^6
Atmos C	700

Stoichiometry and biogeochemistry of $CaCO_3$ biomineralization:



- In top kilometer of ocean, reaction strongly driven to right, but pressure, temperature and pH affect equilibrium
- Marine calcification thought to be about 1GT per year (~1/5 fossil fuel CO_2 generation or ~equivalent to CO_2 production associated with deforestation and agricultural tilling of soils) [Intergovernmental Panel on Carbon Climate]

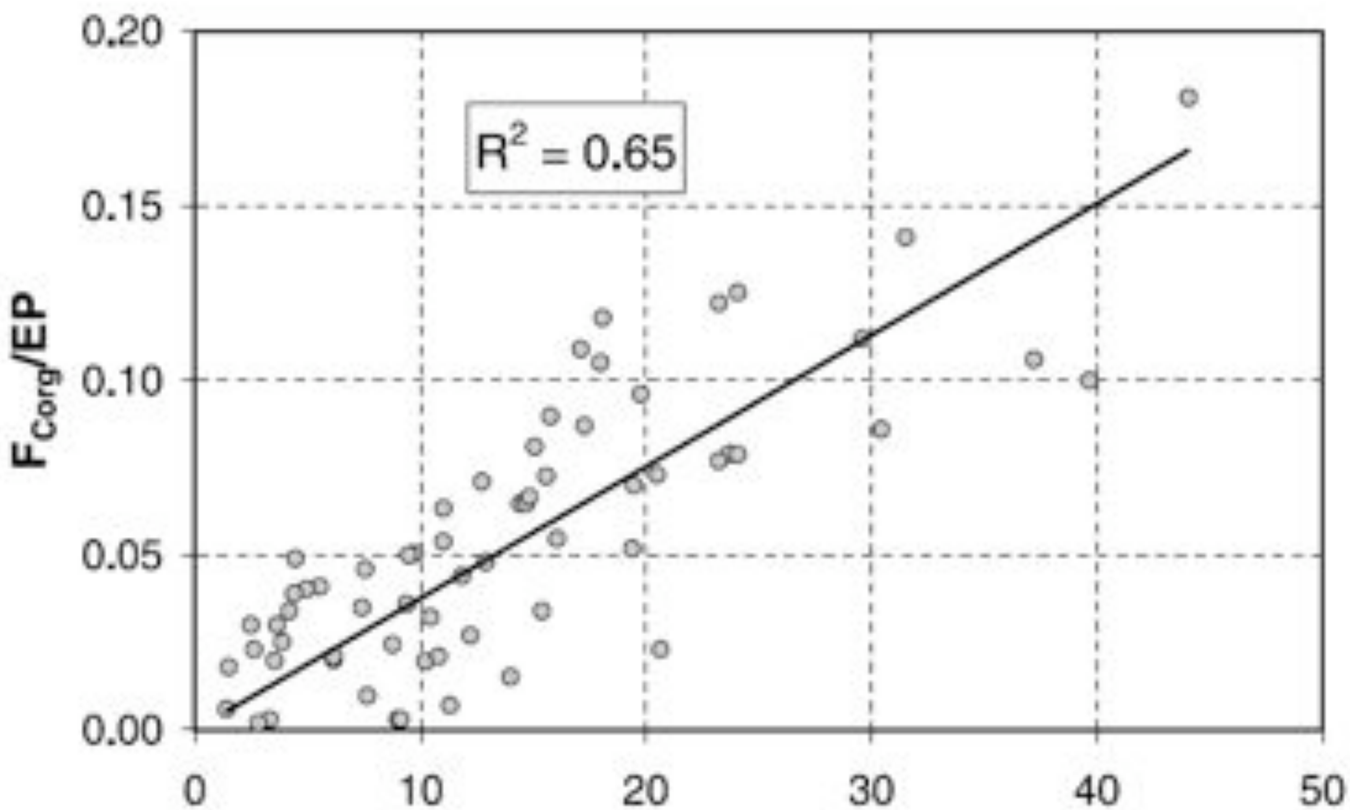
Wherever you go in the world

Planktonic $CaCO_3$

- PIC drives the ocean biological pump…it associates with detrital aggregates, acts as major ballast for POC, increasing sinking rates to sea floor
- Found in several chemical forms, it is stable in surface sea water, dissolving in deeper sea water
- Also absorbs dissolved organic matter and carries it to sea floor as POC/PIC matrix

Who cares about the marine carbonate cycle? Efficiency of transfer of carbon to the deep sea is related to the flux of PIC

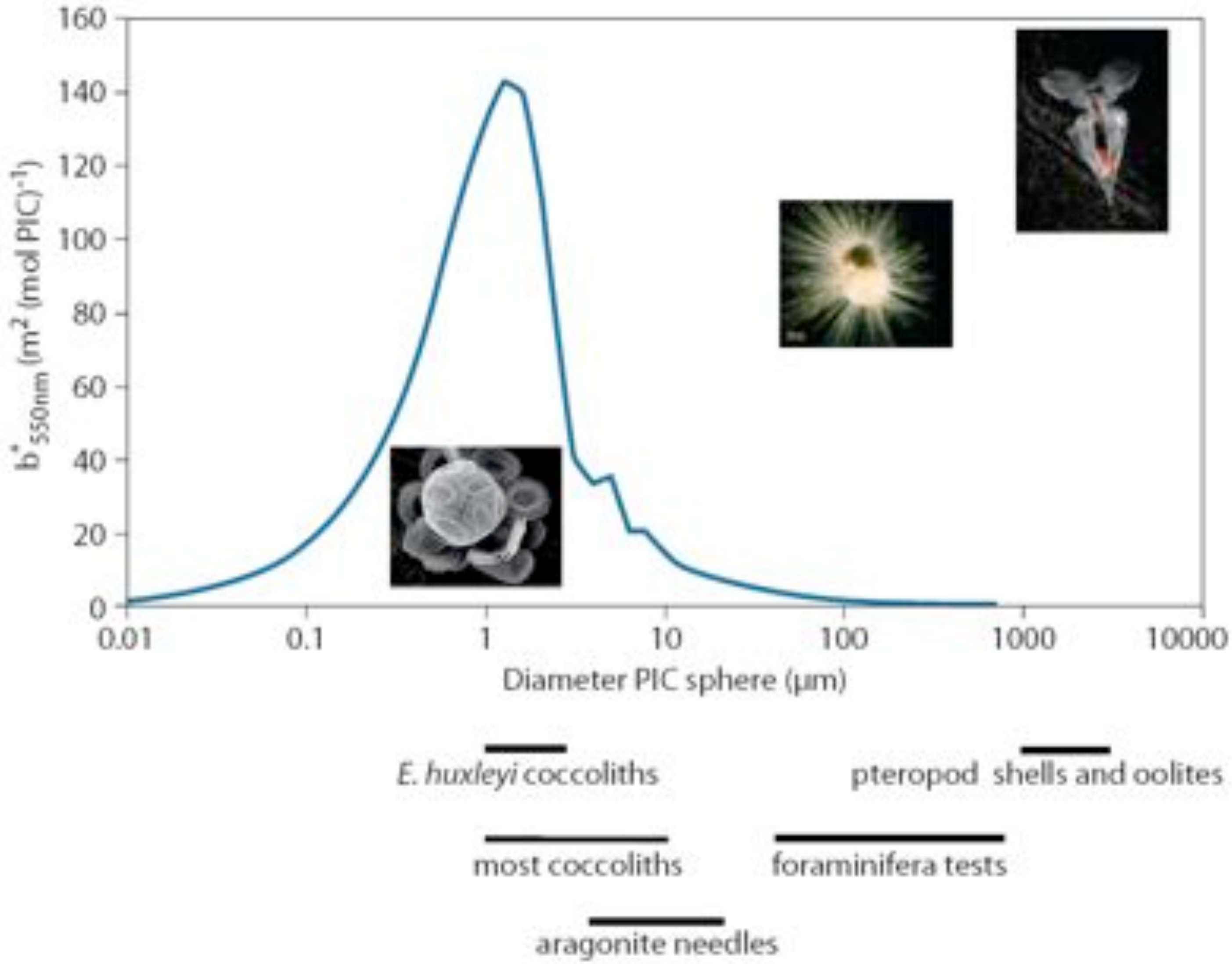
Efficiency of carbon transfer to the deep sea



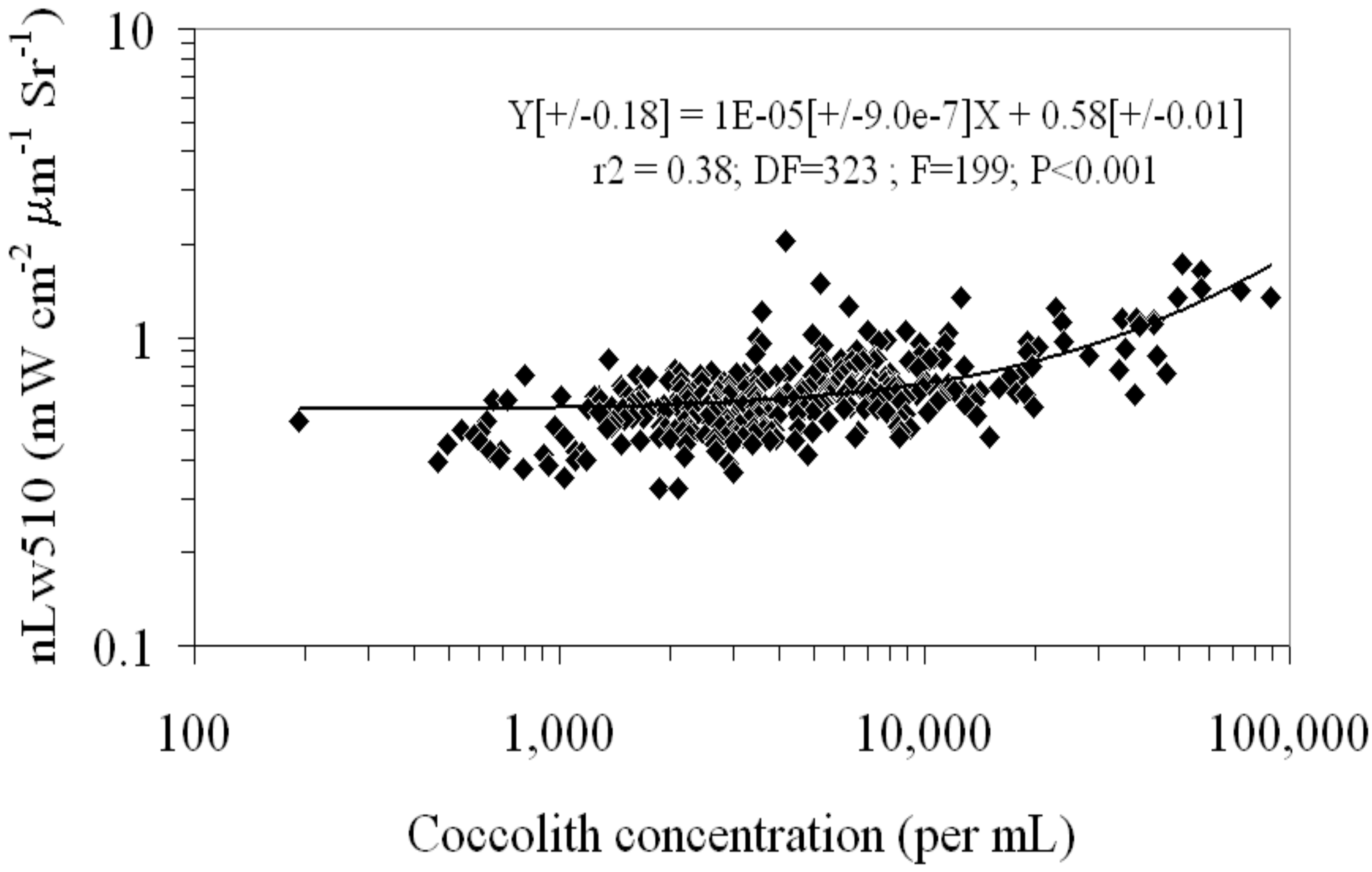
Francois et al. (2002)

Flux of PIC (gC m^{-2} y^{-1})

Light scattering properties of planktonic calcifiers



Coccoliths are a primary contributor to water-leaving radiance from the sea…



Two PIC algorithms are used by MODIS

- 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.)

Two-Band Algorithm

- PIC can add significantly to total backscattering.
- Algorithm separates the contribution of PIC from POC backscattering
- At sea, we separate the contribution of PIC b_b by dropping pH and dissolving it ($b_{bp\ acid}$)

  $b_{bp\ tot} - b_{bp\ acid} = b_b$’ (acid-labile back
- Derive statistical relation between $b_{bp\ acid}$ and Chl *a*.
- Derive statistical relation between b_b’ and PIC
- Based on absorption and scattering properties of chlorophyll and PIC, iteratively solve for Chl and PIC as function of absolute nLw440 and nLw550 (as look-up table).

For turbid blooms, switch to the 3-Band Algorithm

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

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

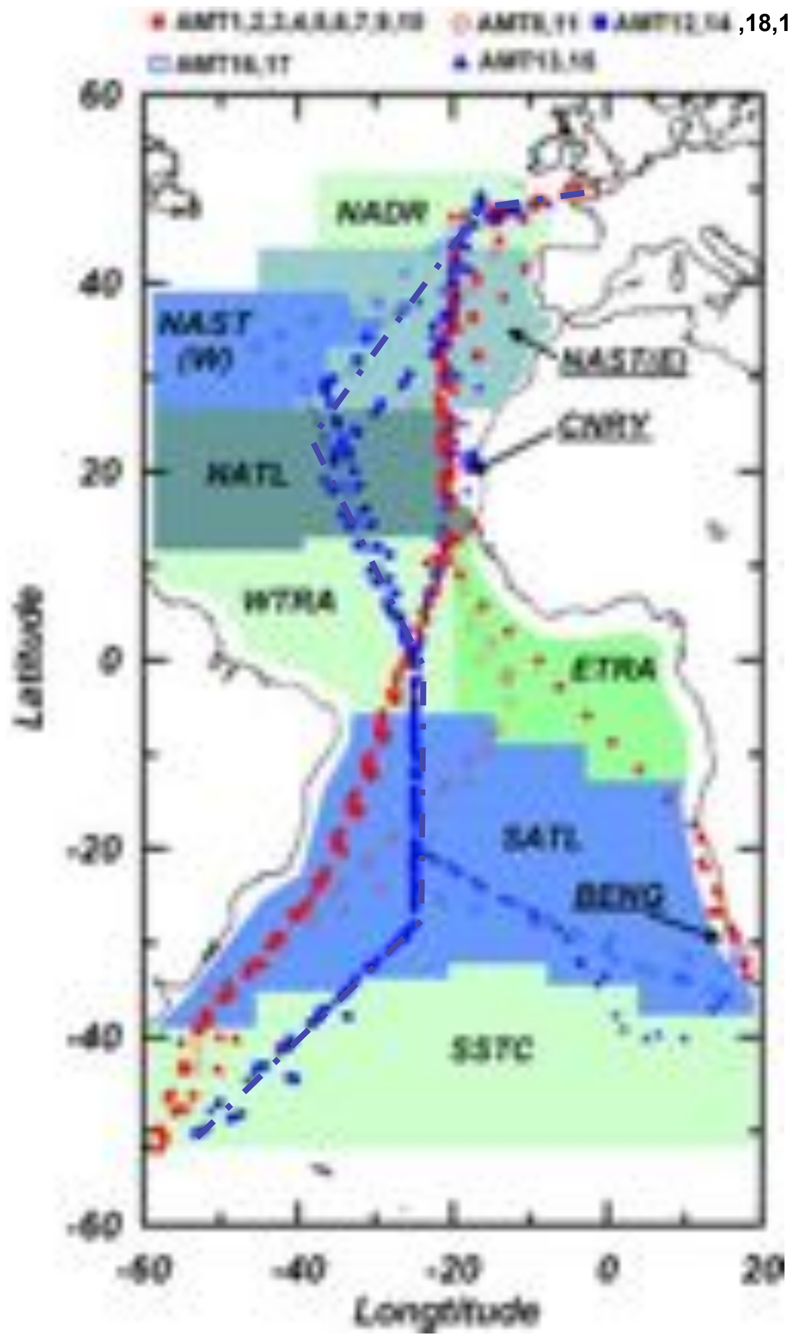
Measure $R(\lambda)$, use published $a_w(\lambda)$, estimate $b_b(\lambda)$.

- Also assume that: $b_b(\lambda) = b_b(550) * (550/\lambda)^n$

where n~1.35 based on empirical results with PIC particles

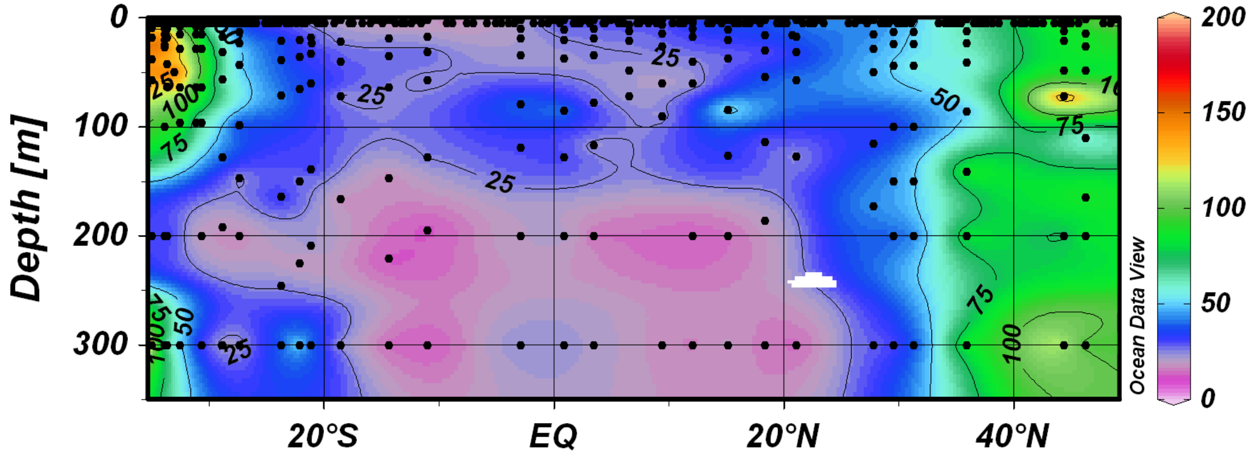
- These assumptions allow estimation of b_b at other wavelengths

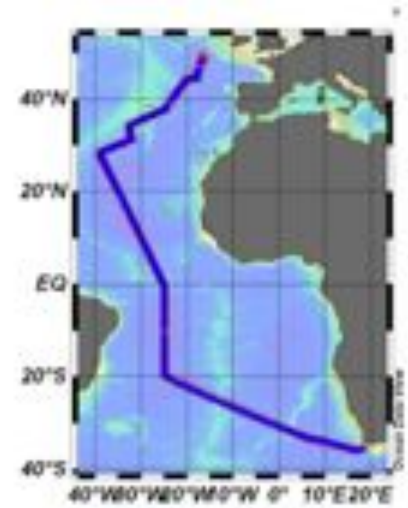
Our MODIS work has been to participate in 6 Atlantic Meridional Transect (AMT) cruises between the UK and either S. Africa or S. America to provide shipboard validation of the PIC algorithm…



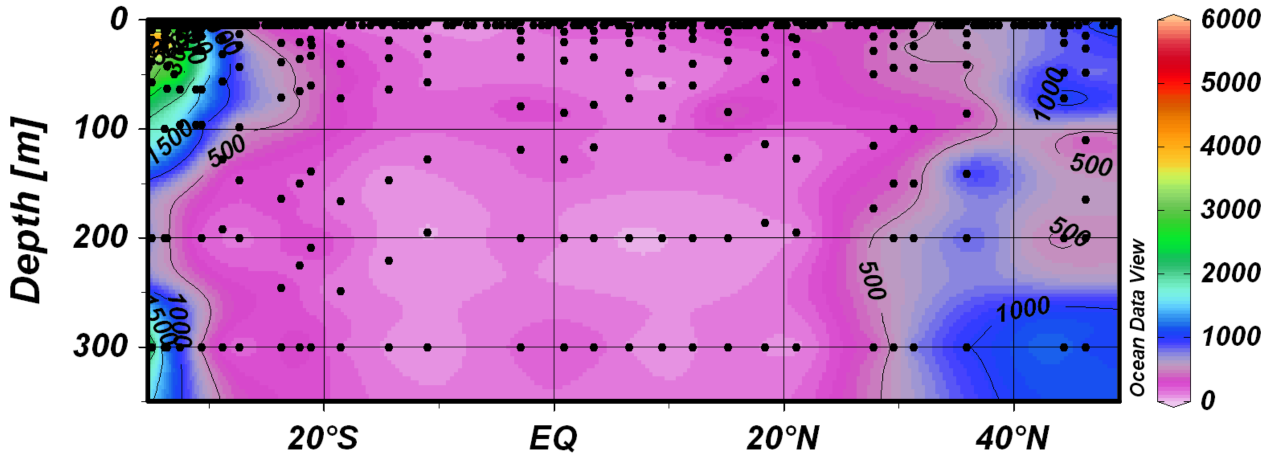
How abundant are coccolithophores and coccoliths across the Atlantic Ocean?

Coccolithophores + coccolith aggregates per mL



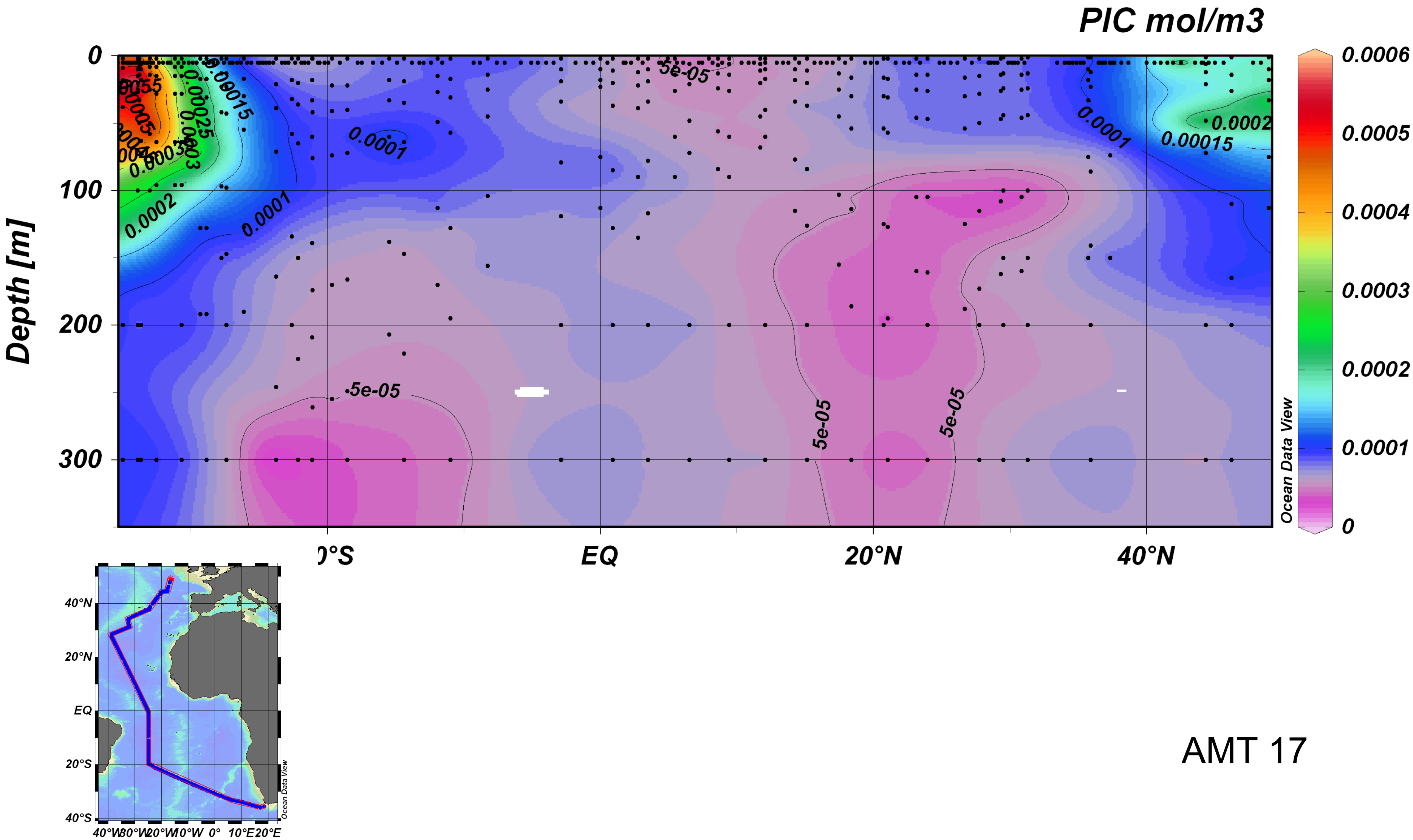


Coccoliths per mL



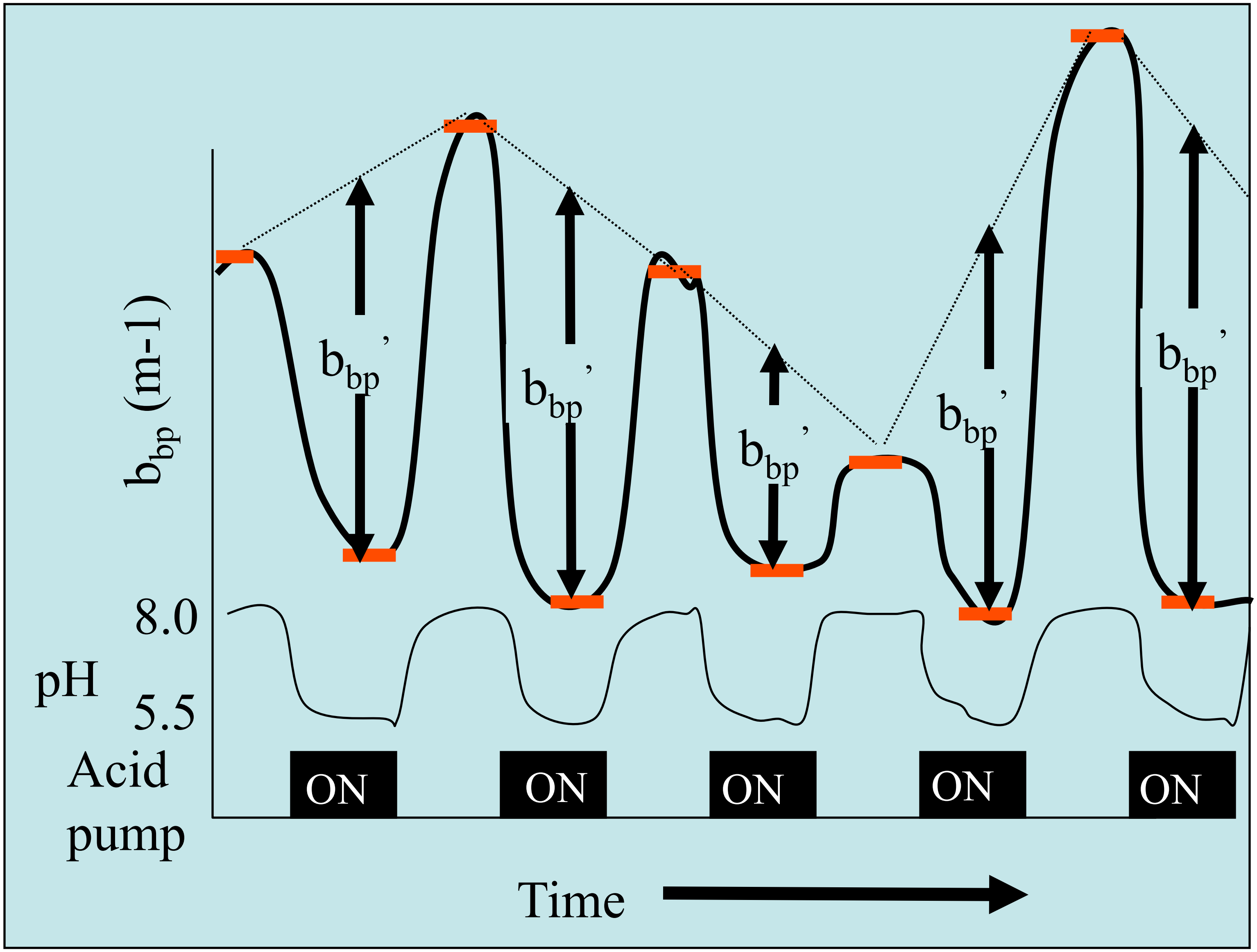
AMT 17

Patterns of PIC show a similar pattern across the entire Atlantic?

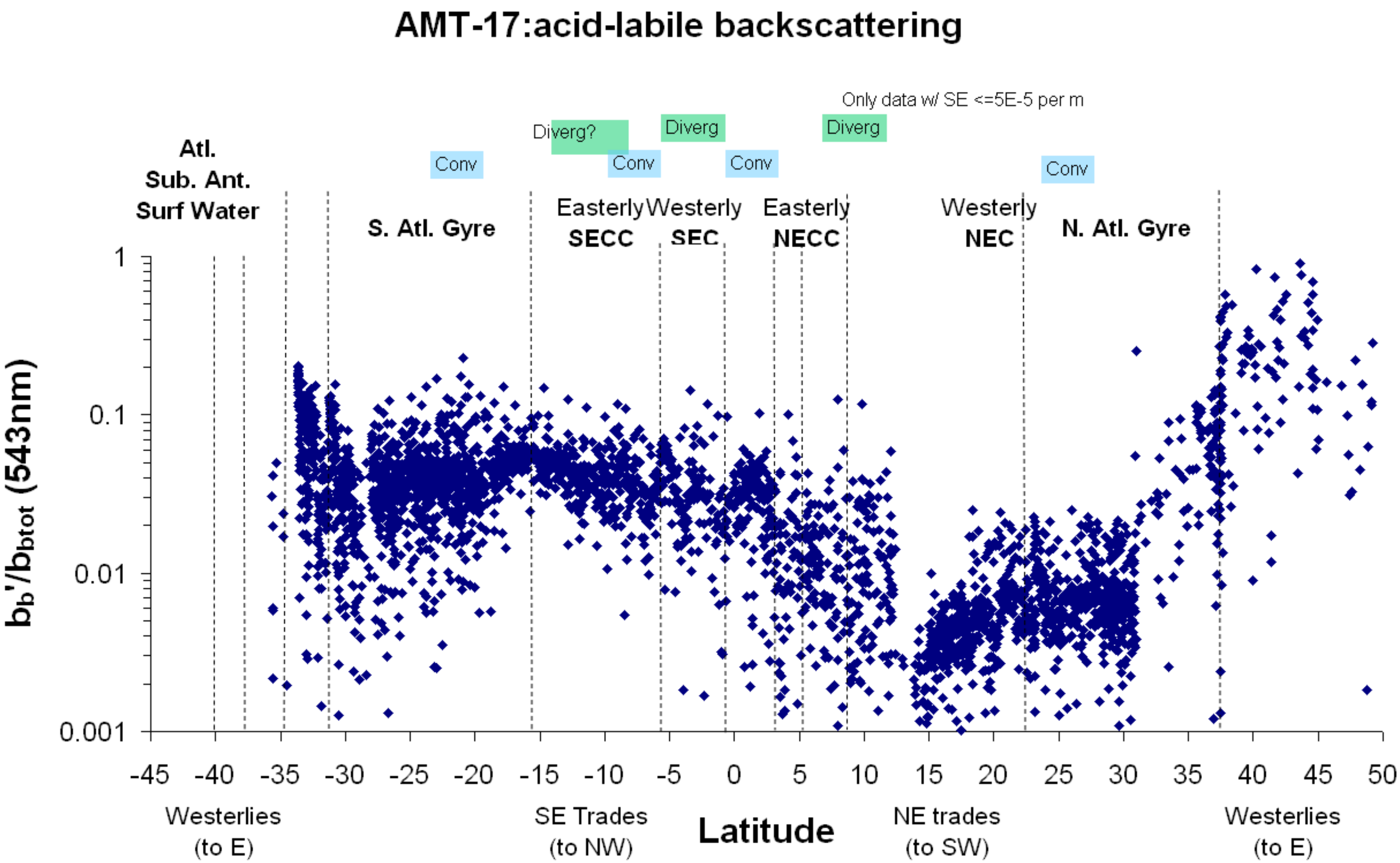


AMT 17

Acid-labile backscattering?

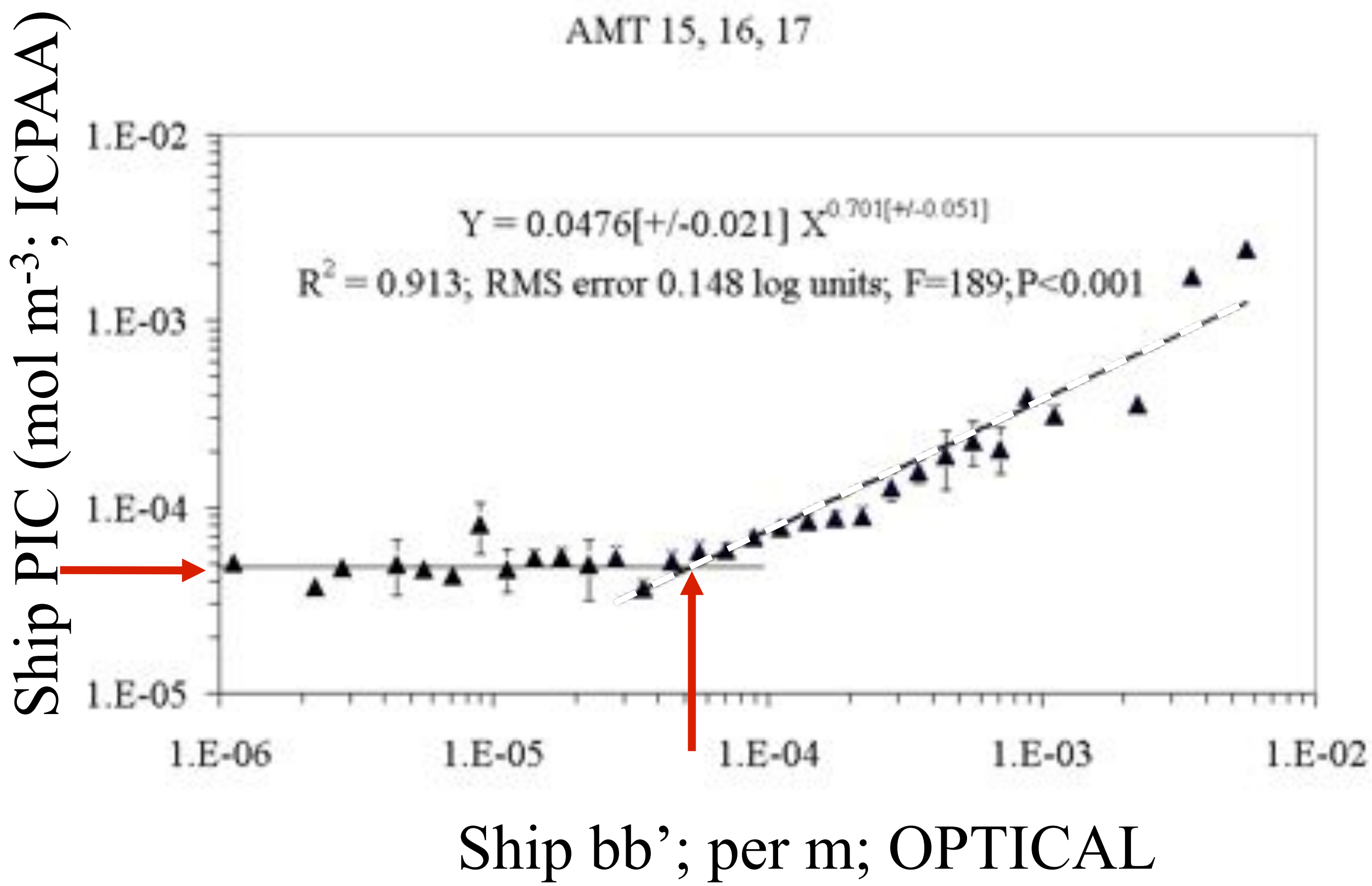


How important is this backscattering from PIC to total backscattering?



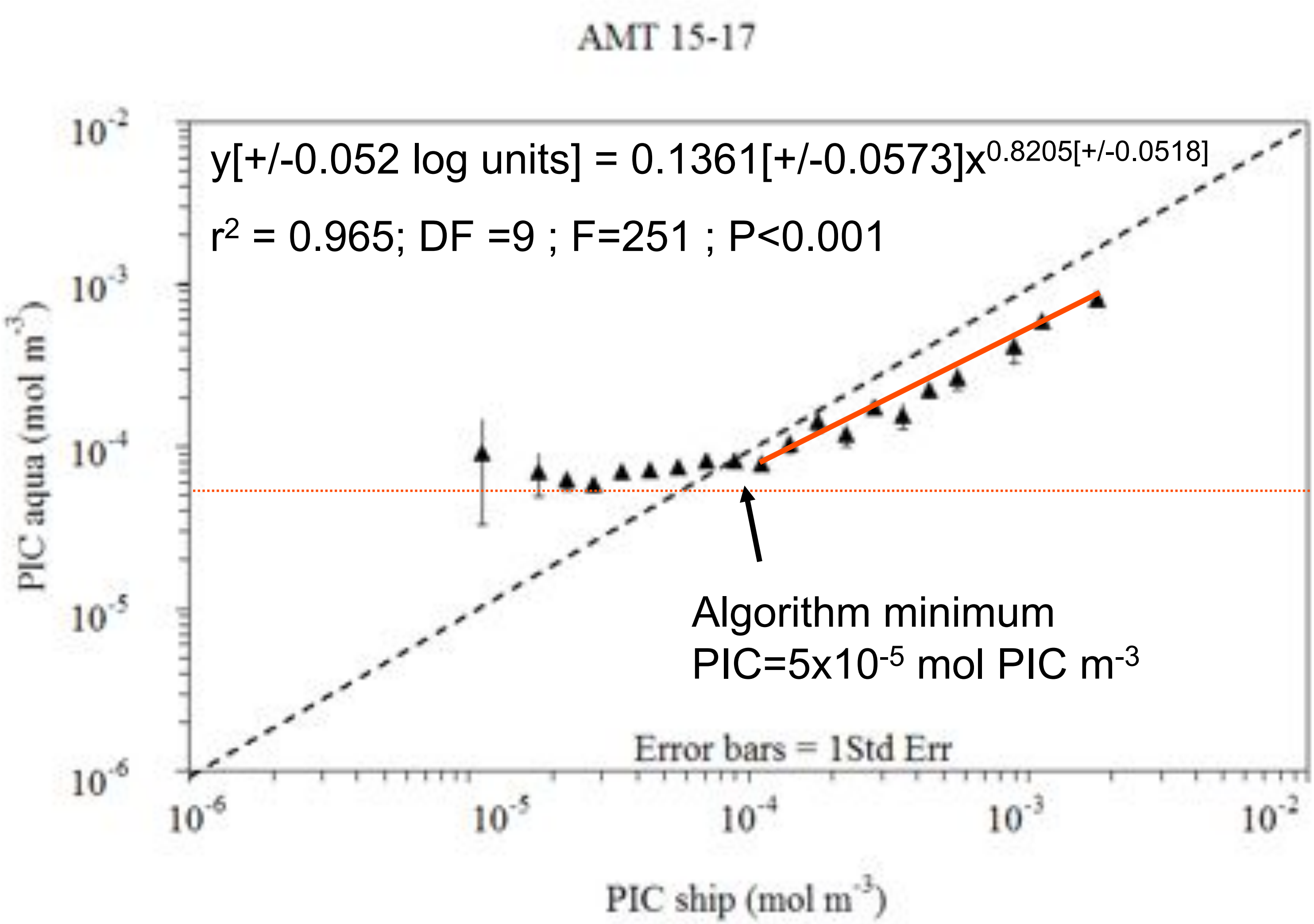
Mean relationship between PIC and b_b'…

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

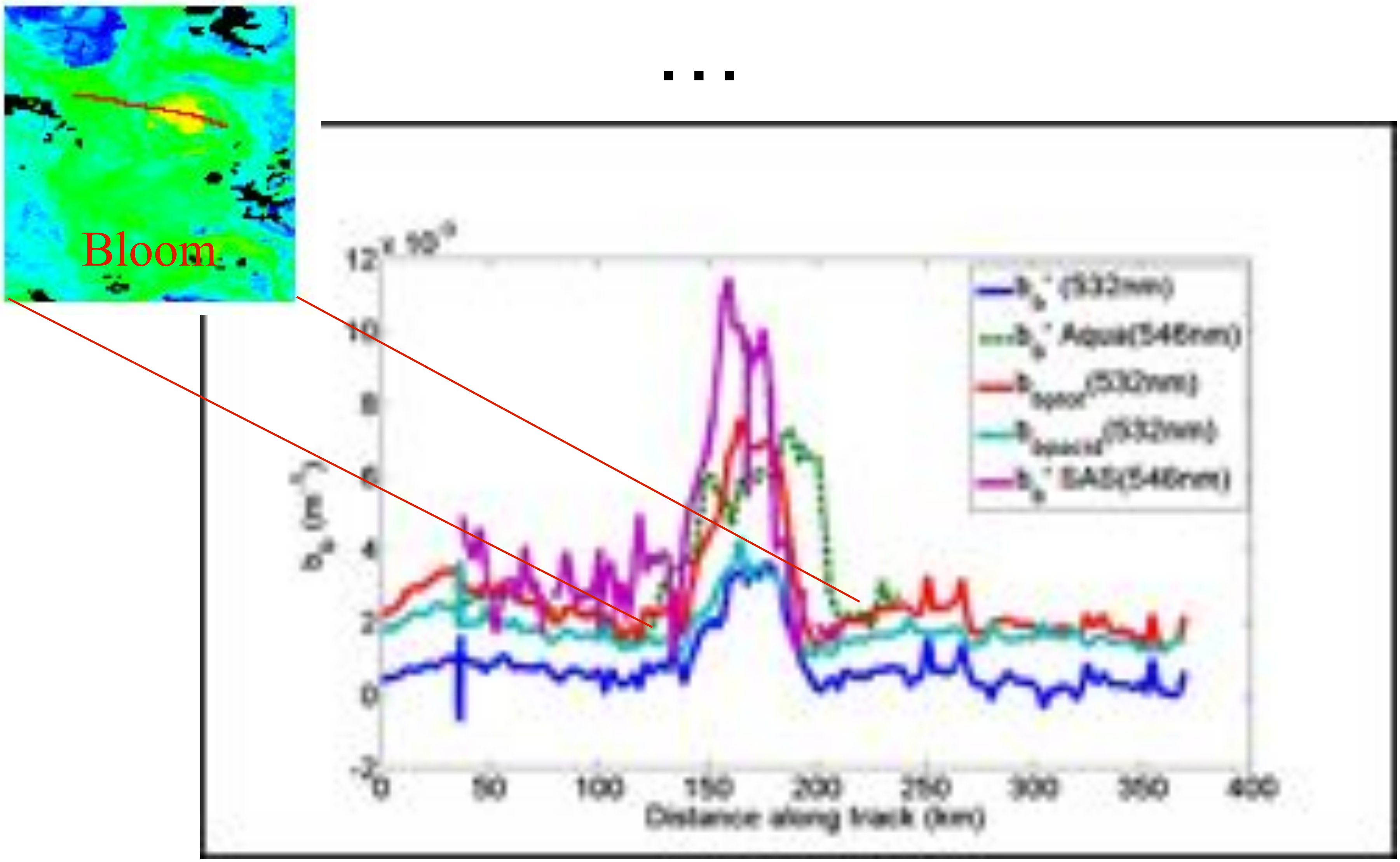


Optical technique linear down to b_b'= $5x10^{-5}$ m^{-1}

For binned results for AMT 15, 16 and 17 (n=528 surface measurements)



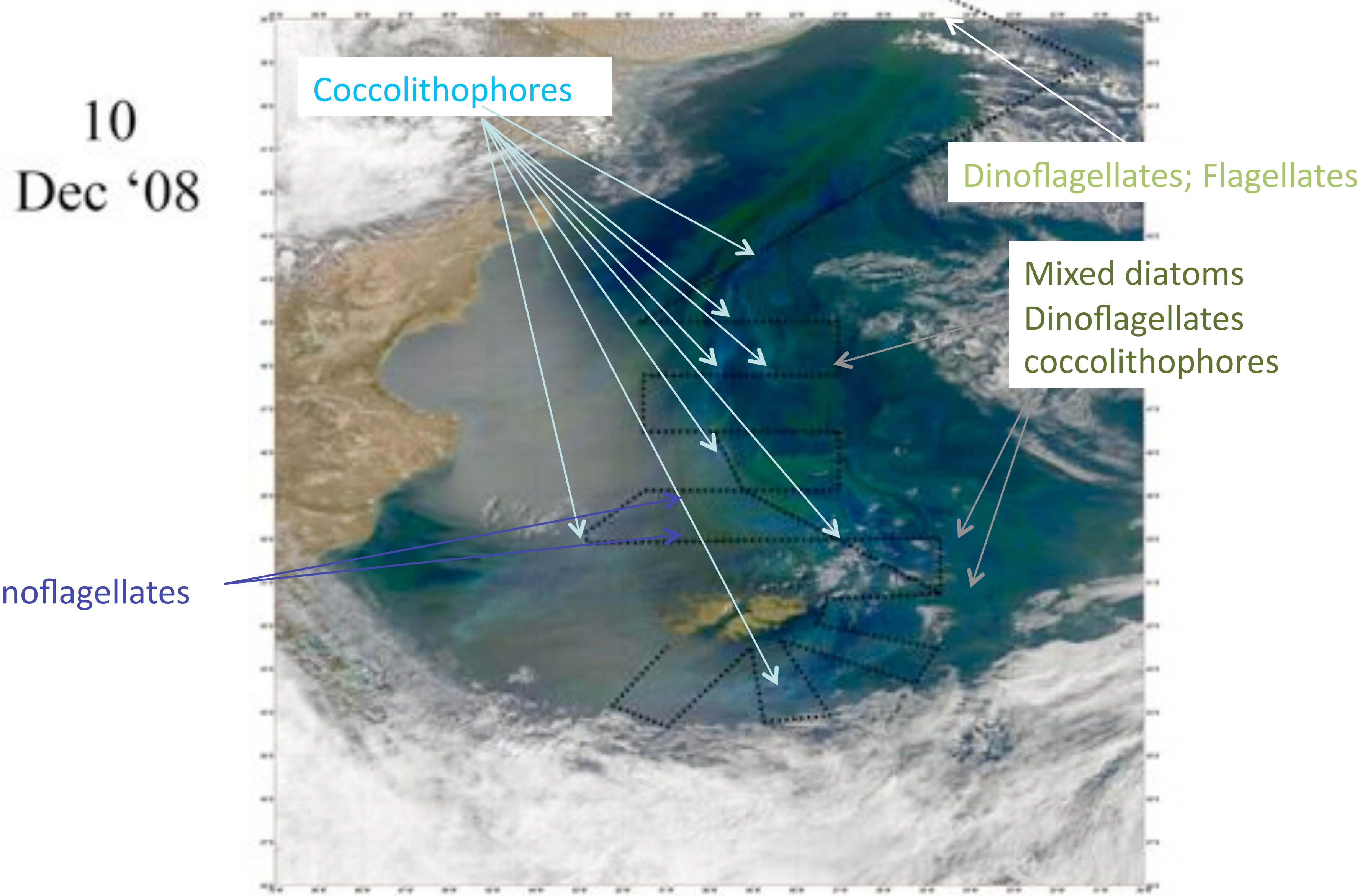
Ship and satellite measurements of the same feature (all using b_b) …



COPAS '08-Patagonian Shelf Cruise

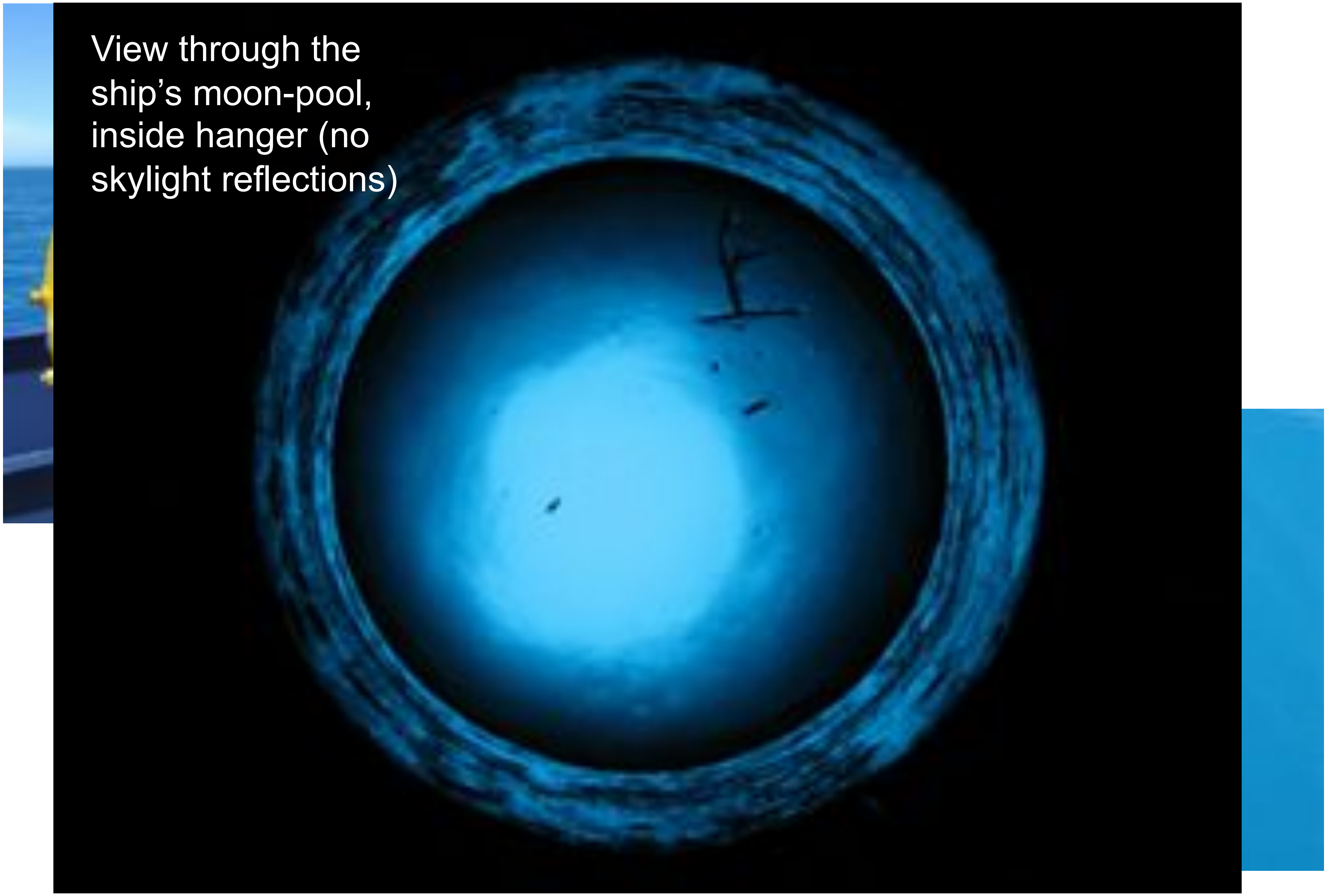
- December'08 to January '09 ; *R/V Roger Revelle* survey of the the Patagonian Shelf coccolithophore bloom
- PIC algorithm validation
- Experiments on ocean acidification and coccolithophorids

Observations from the Balch et al. R/V Revelle cruise; 4 December, 2008 to 2 January, 2009

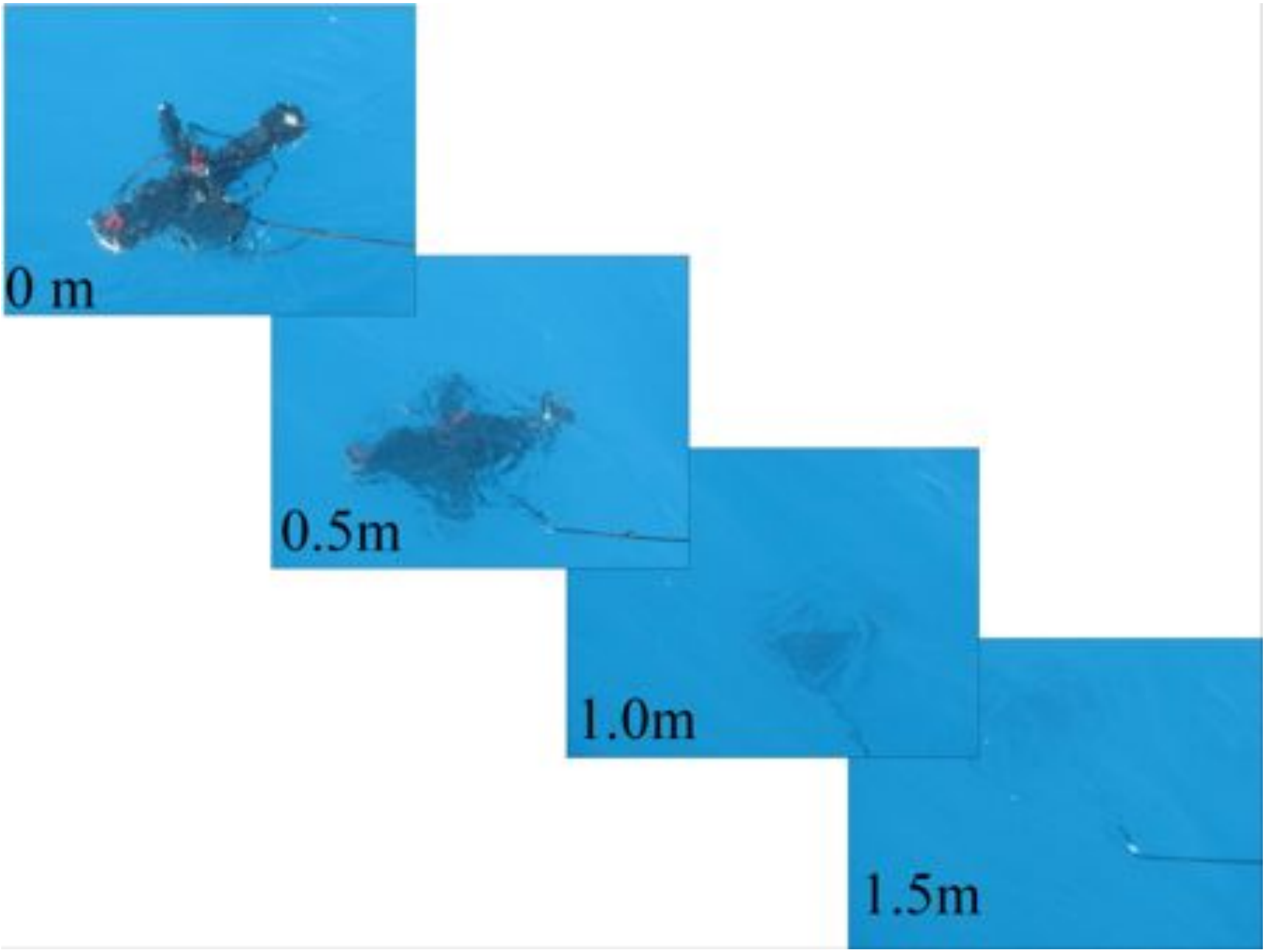


Cruise track of R/V Revelle shown with black dotted line

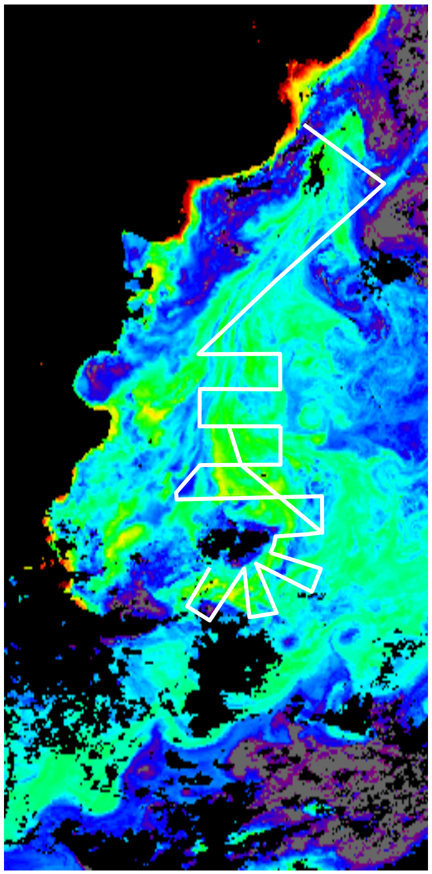
COPAS '08-Patagonian Shelf Cruise



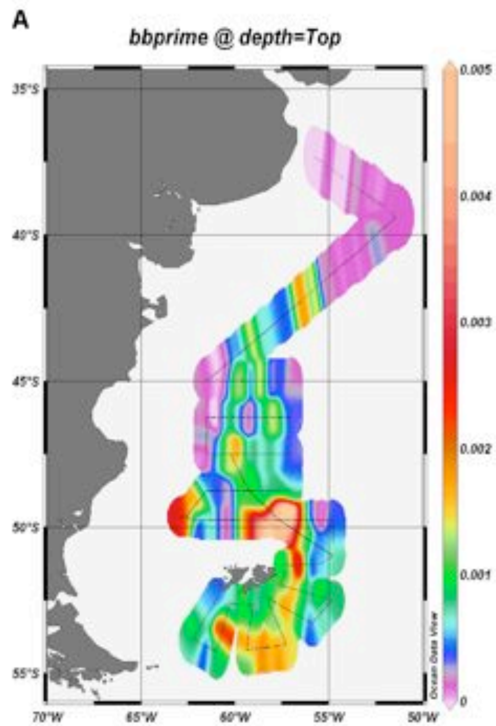
PIC shoals the euphotic zone



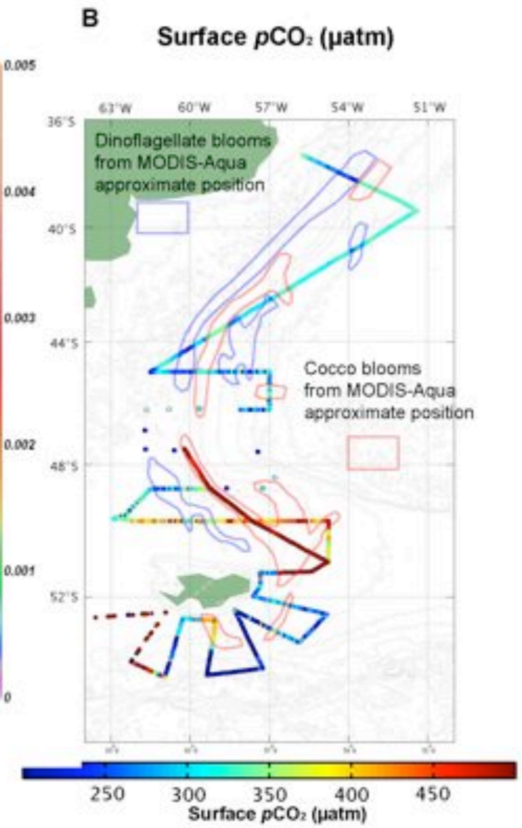
So do coccolithophores really affect the *p*CO_2 of seawater?



PIC concentration; MODIS Aqua
Dec 10-17, 2008

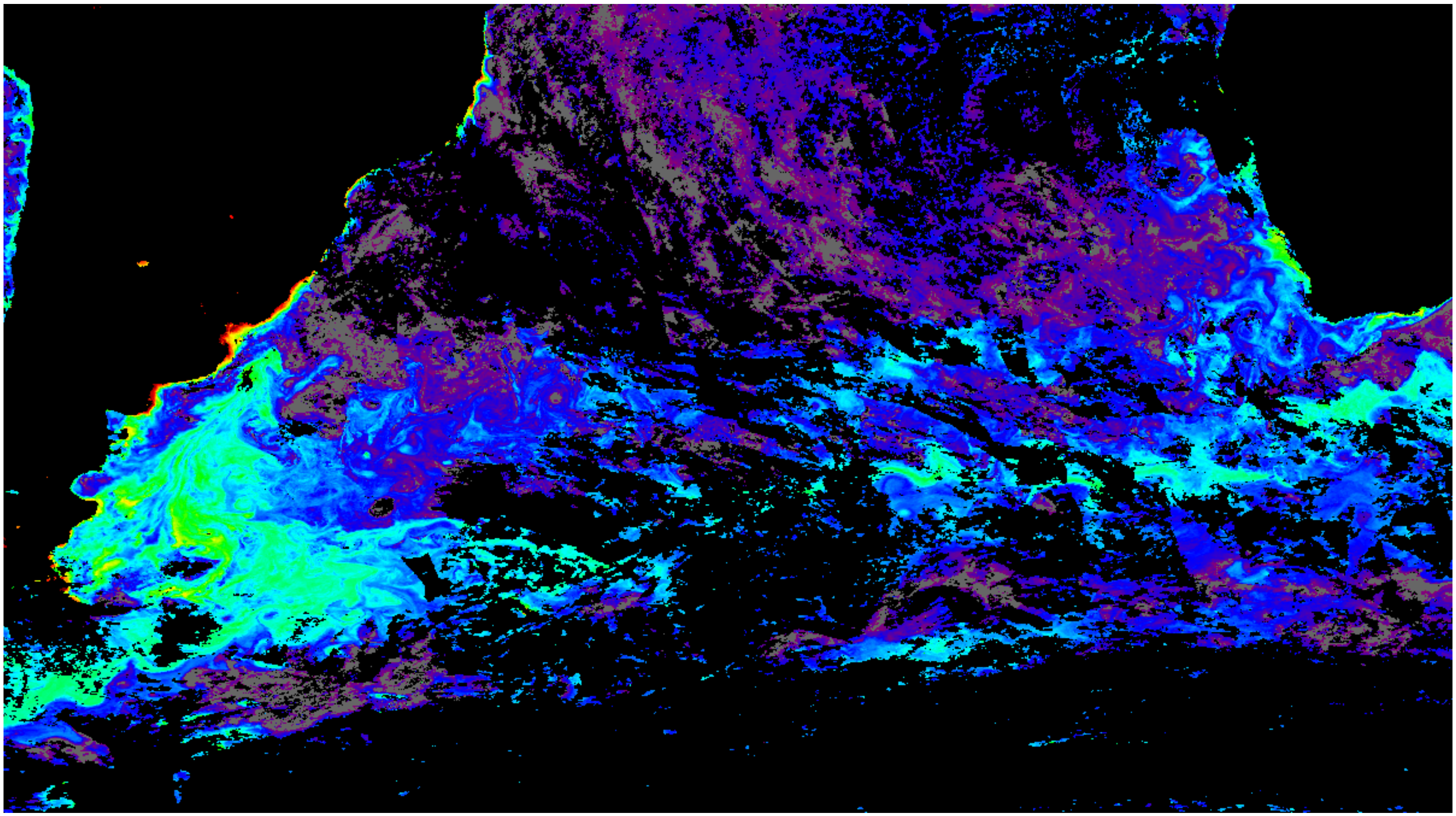


Acid-labile backscattering

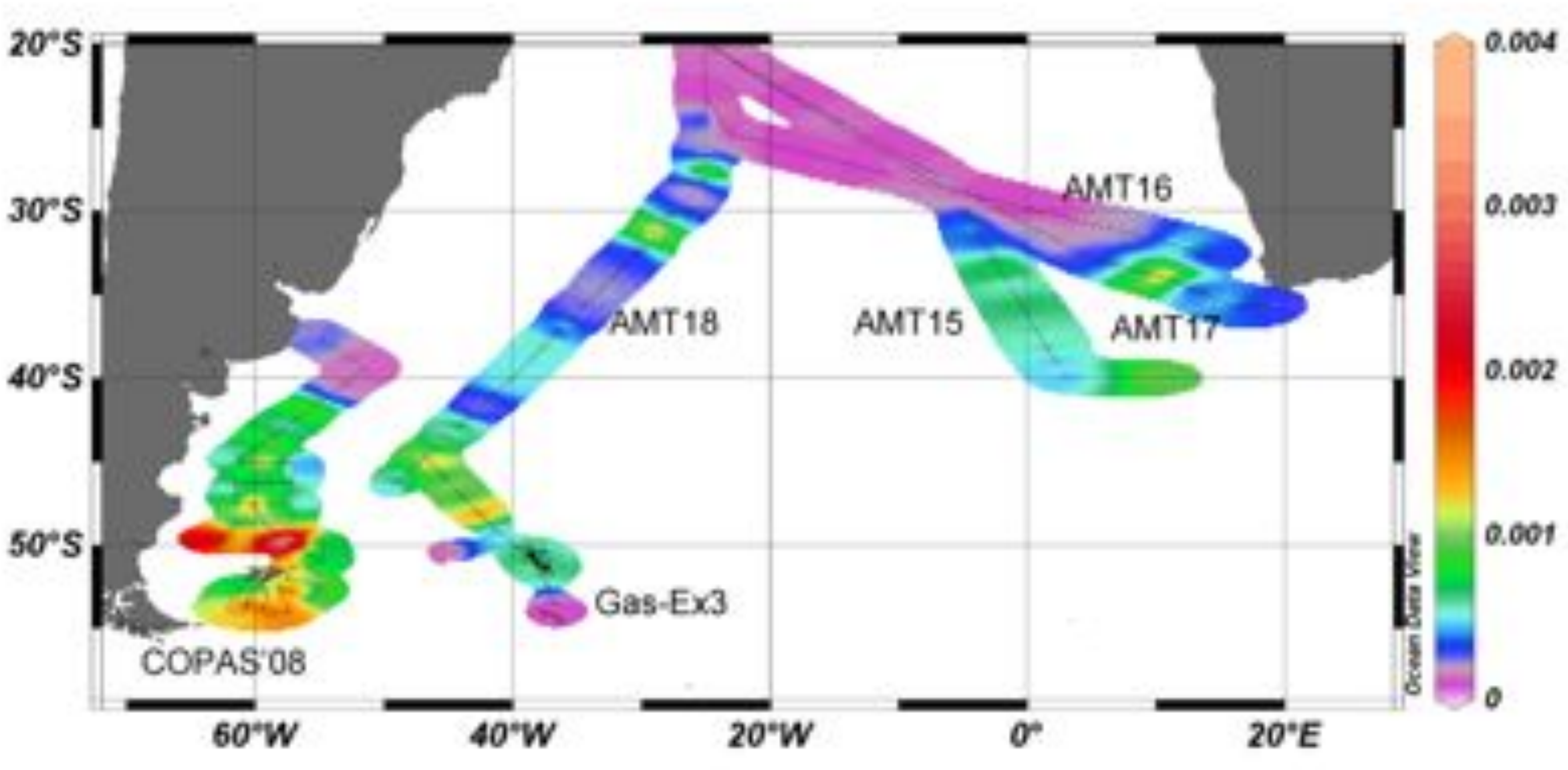


pCO_2 data courtesy of Nick Bates, Bermuda Institution of Ocean Science

Viewing at a larger perspective with MODIS: the Atlantic Sector of the Southern Ocean

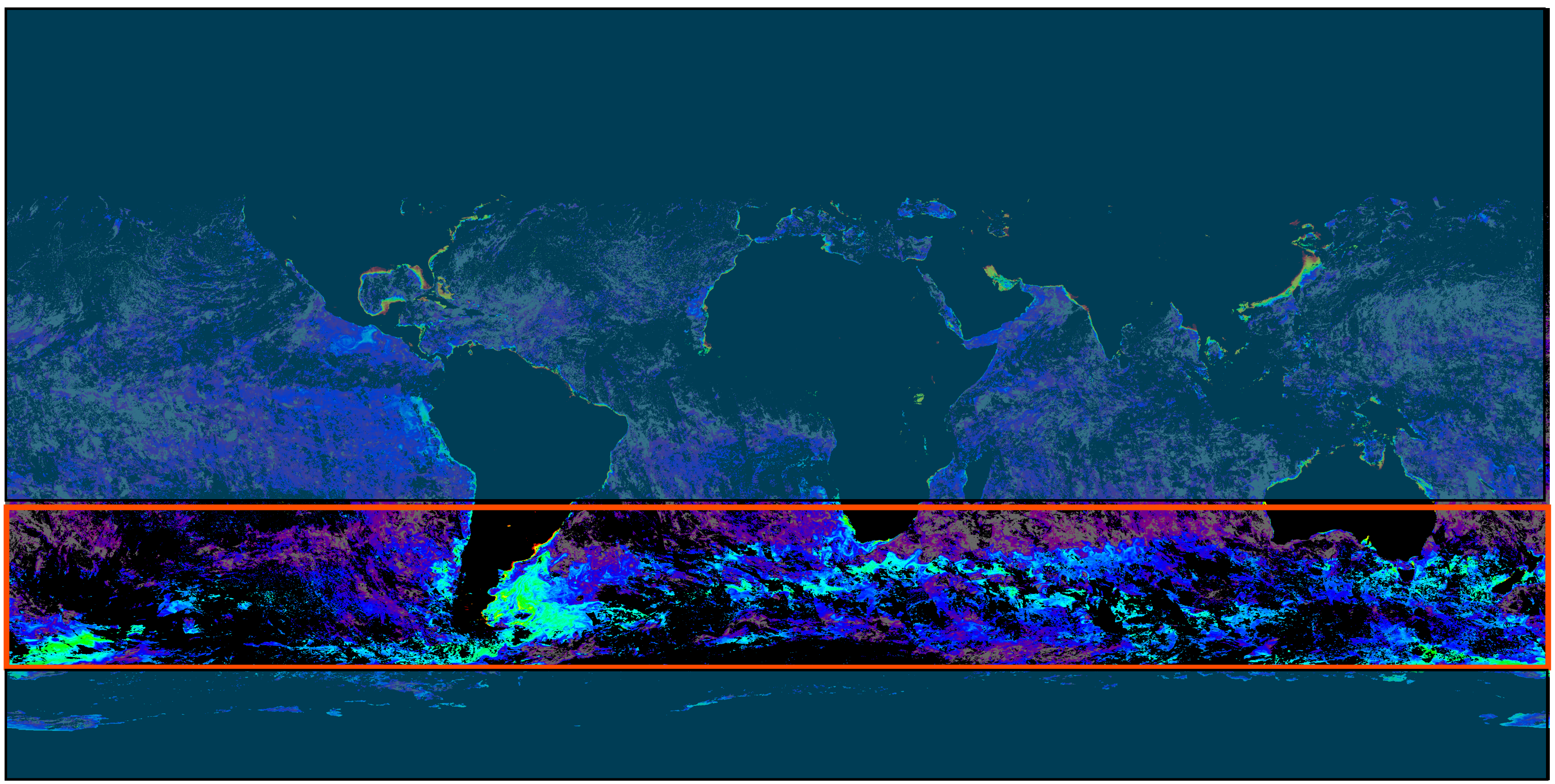


Viewing at a larger perspective: Results for acid-labile backscattering from 6 cruises to the Atlantic Sector of the Southern Ocean

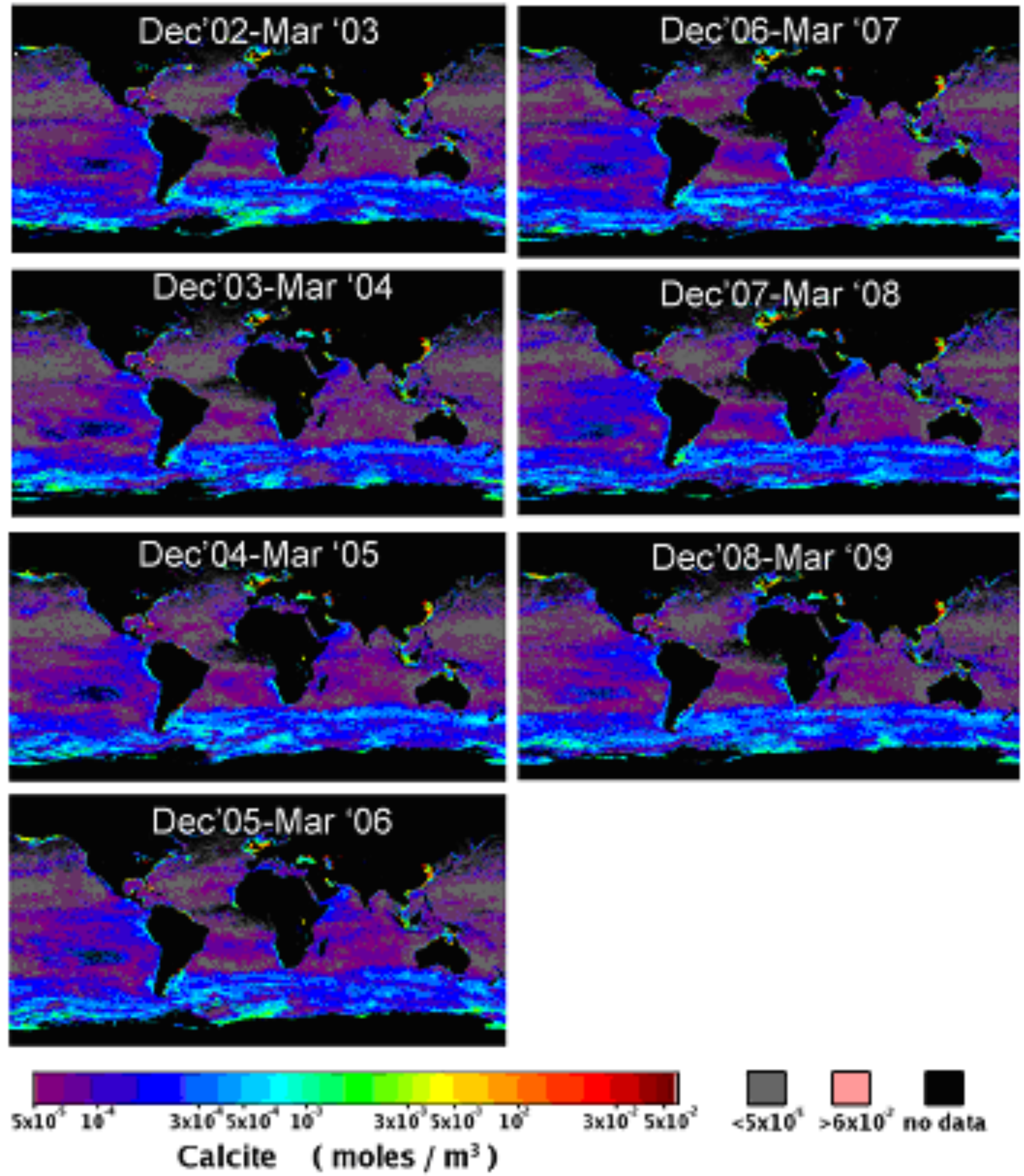


Viewing at the global scale: The great calcite belt

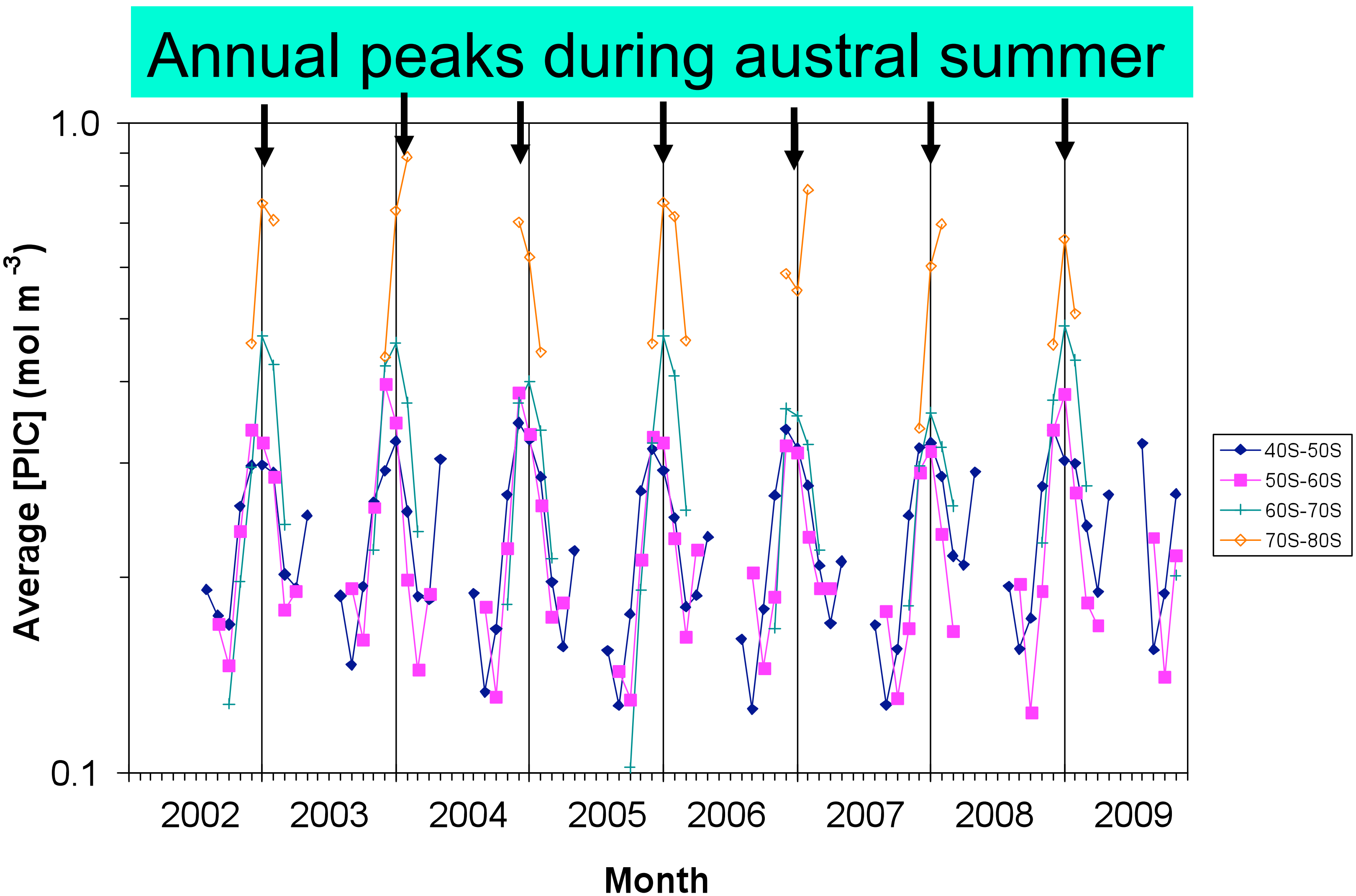
- 88 million square kilometers
- ~1/4 of the global ocean
- contains over 1/3 of the PIC in the ocean



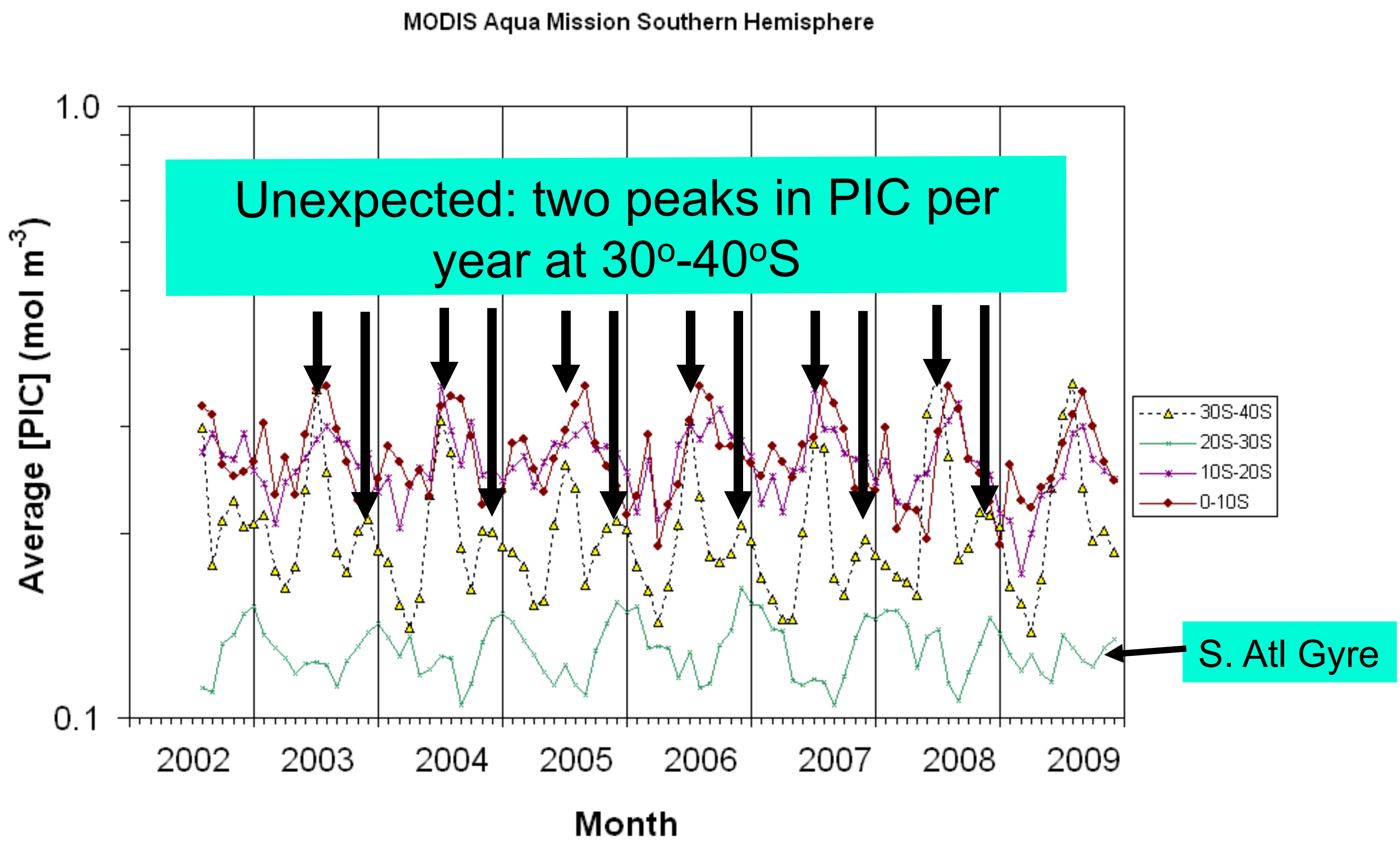
The great calcite belt as seen by MODIS is a recurring pattern in the Southern Ocean



So over the entire Aqua mission, how does the global PIC vary with latitude? 40^o-80^{o}S

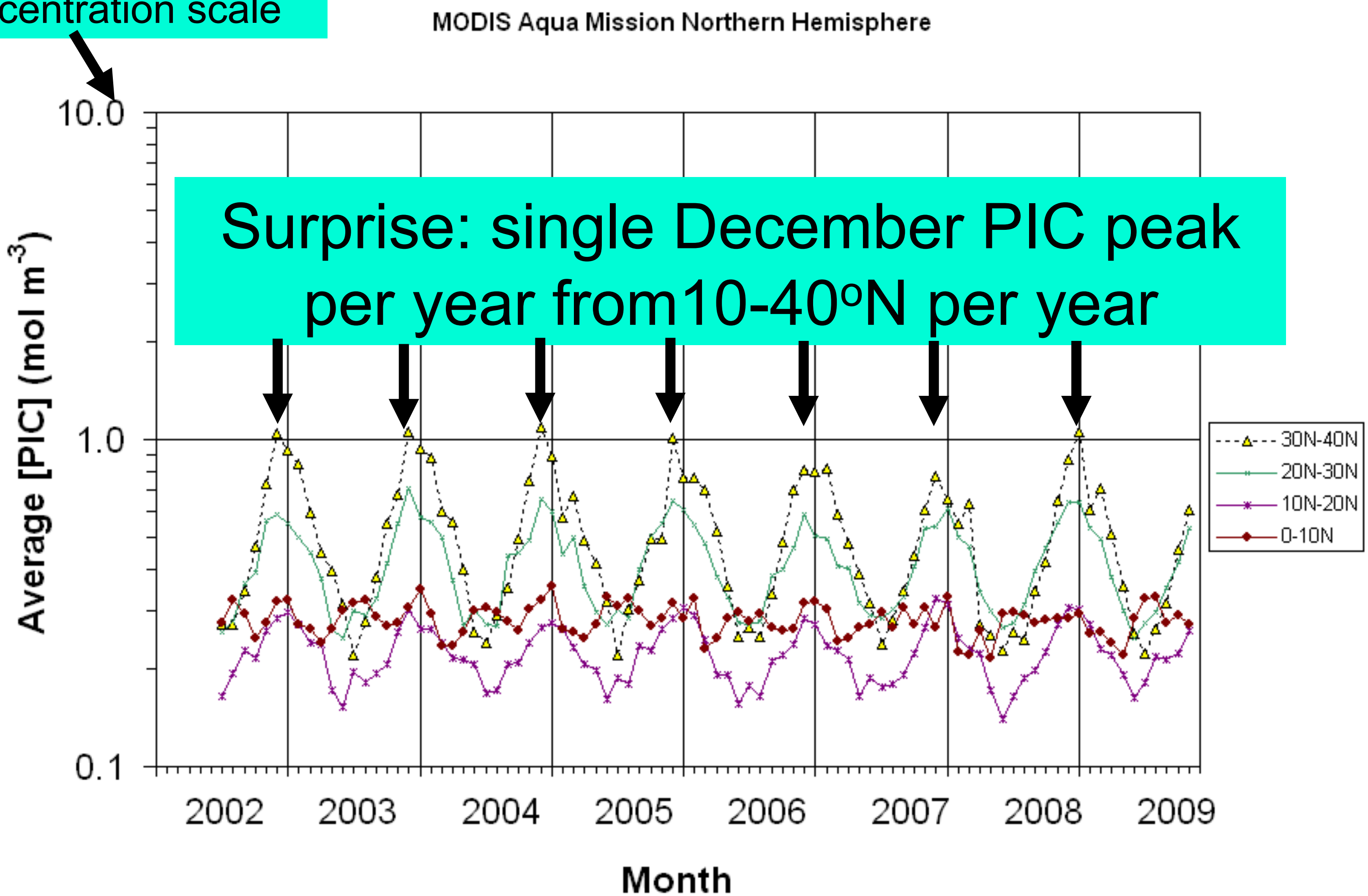


PIC variability… 0°-40°S



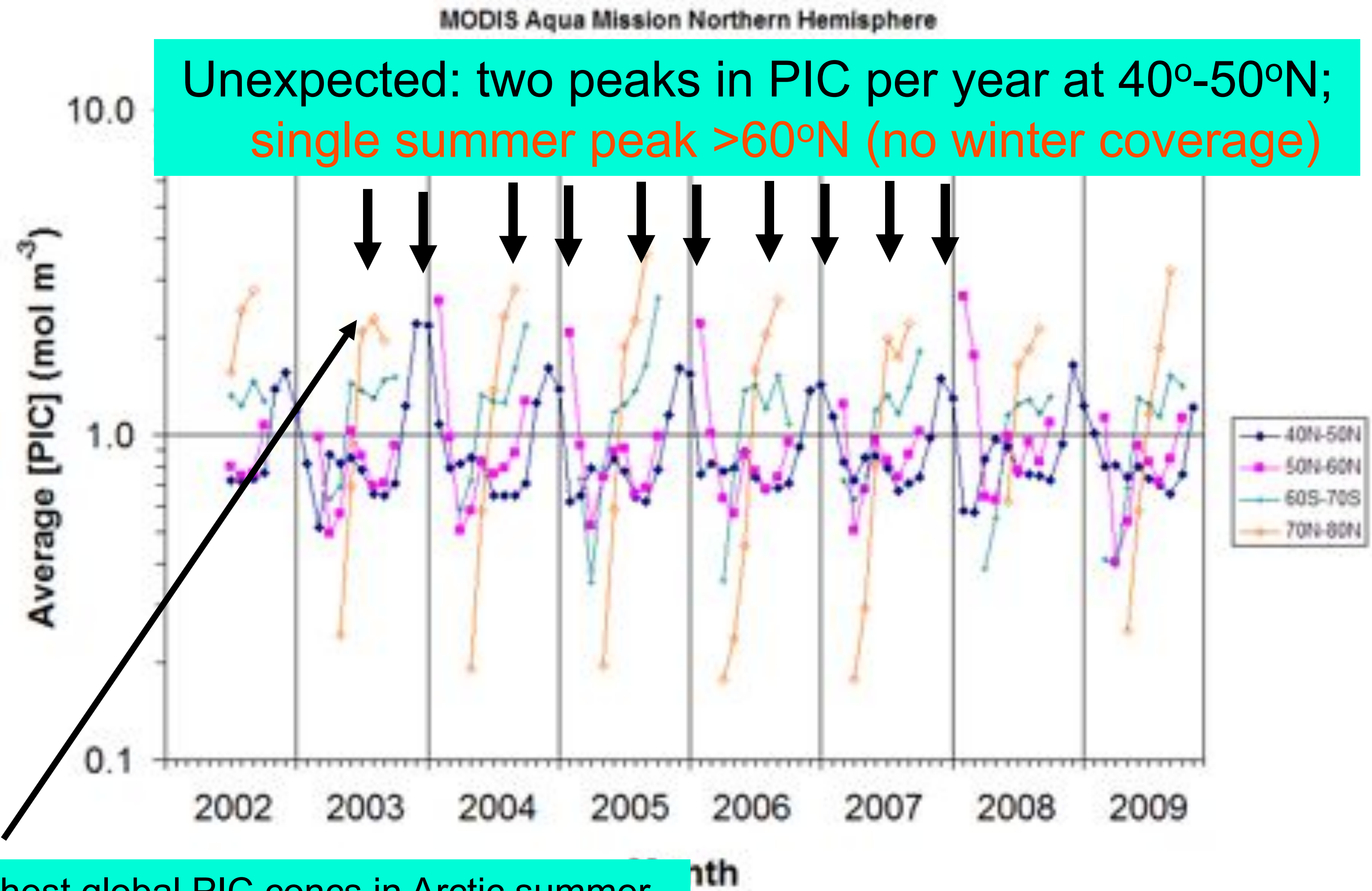
PIC variability… 0°-40°N

Note elevated concentration scale



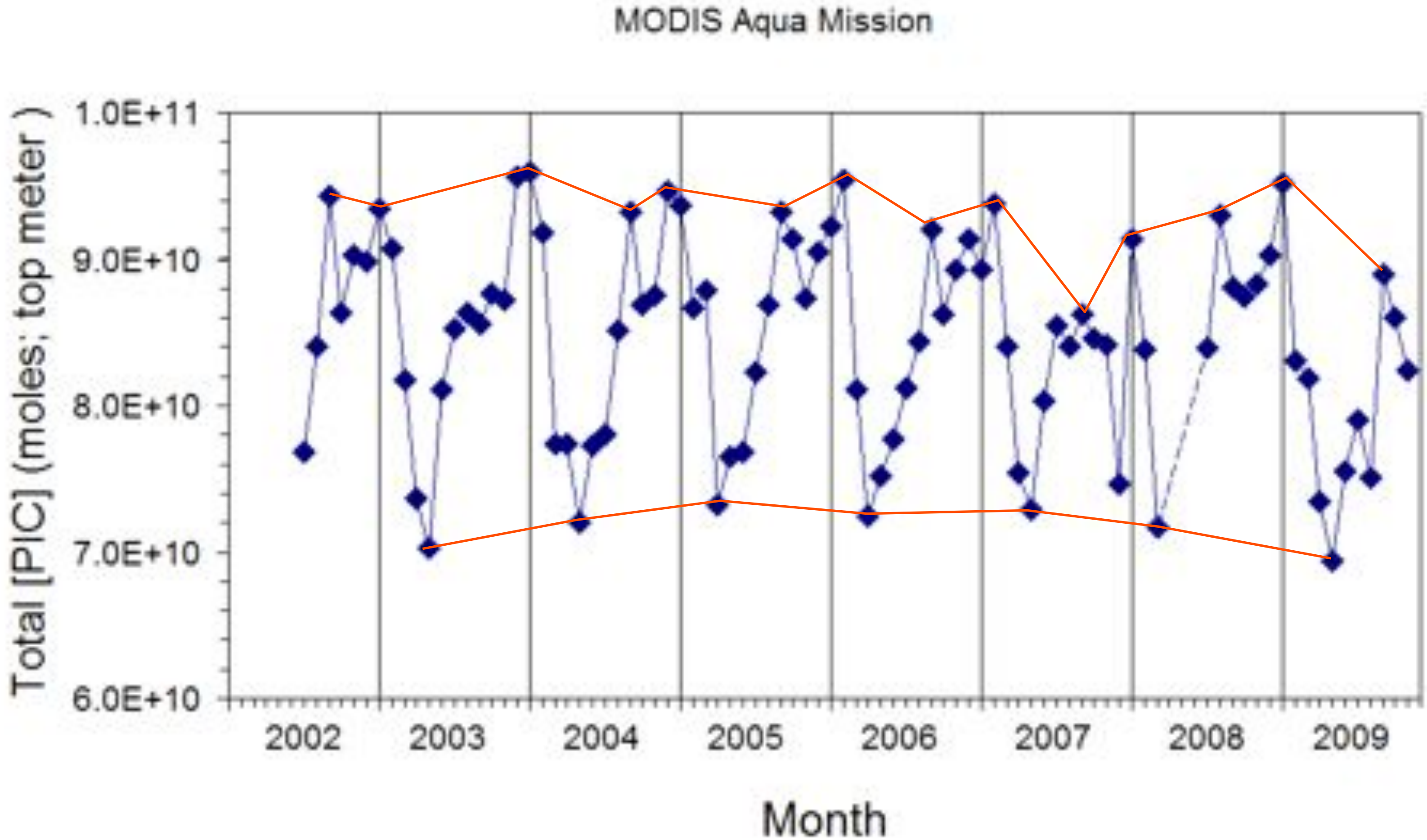
PIC variability… 40^{o}-80^{o}N

Unexpected: two peaks in PIC per year at 40^{o}-50^{o}N;
single summer peak >60^{o}N (no winter coverage)



Highest global PIC concs in Arctic summer

Global PIC variability…



Annual variations ~26%

Global Ocean Acidification

- Increasing fossil fuel CO_2 is lowering pH in the surface ocean
- Pre-industrial CO_2 = 280ppm, pH_{surf} = 8.15
- "2X" scenario (560 ppm) → pH_{surf} of 7.91
- "3X" scenario (840ppm) → pH_{surf} of 7.76
- CO_2 + sea water produces carbonic acid, which decreases $[CO_3^{=}]$, building block for $CaCO_3$
- This decrease in pH and $[CO_3^{=}]$, will happen first at the poles

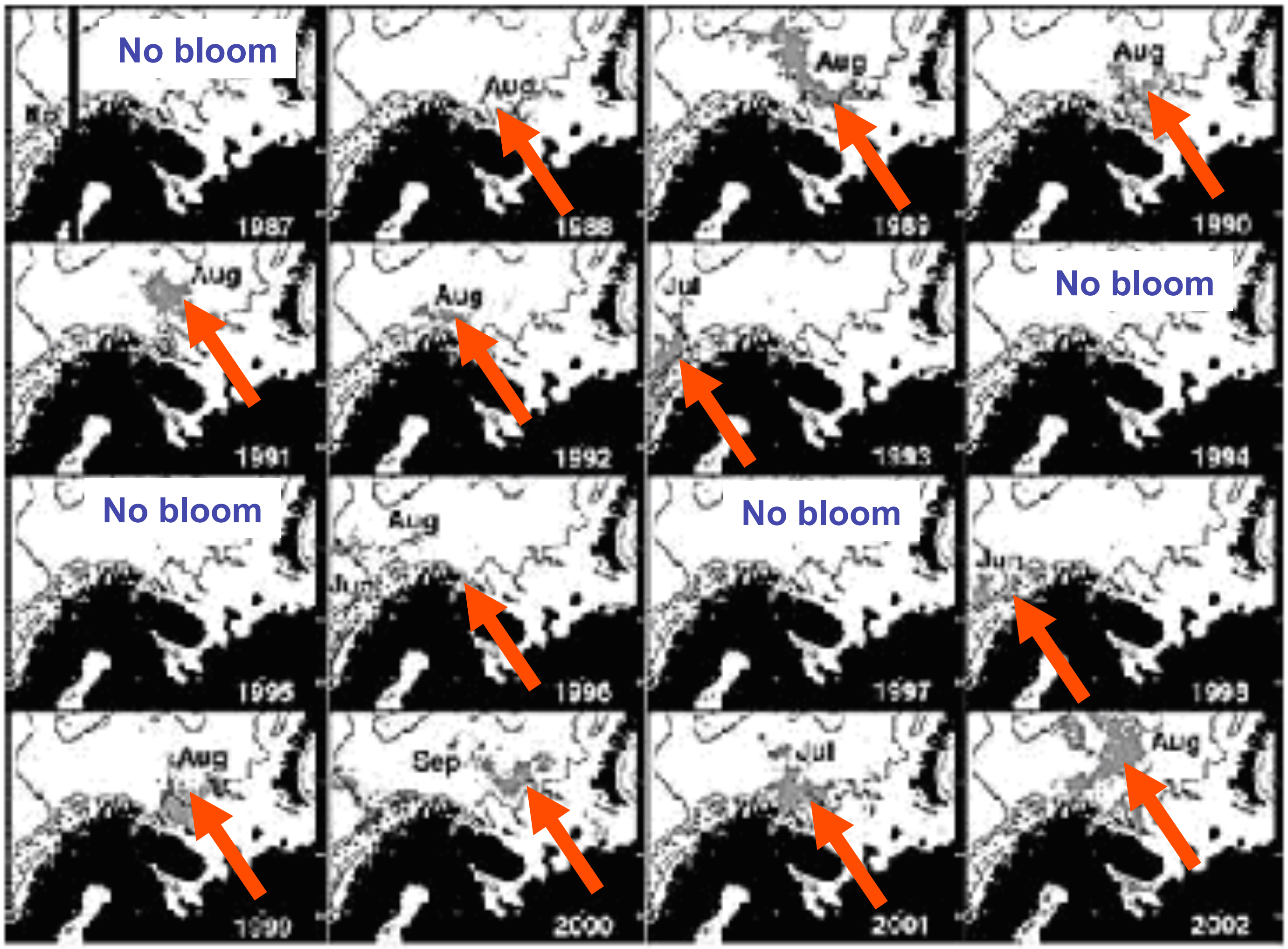
Climate change and coccolithophores…the global "squeeze play"…what will happen?

- There is evidence th… biogeoch… …g …… …e moving to higher …udes

Bottom line: WE DON'T KNOW WHAT WILL HAPPEN!

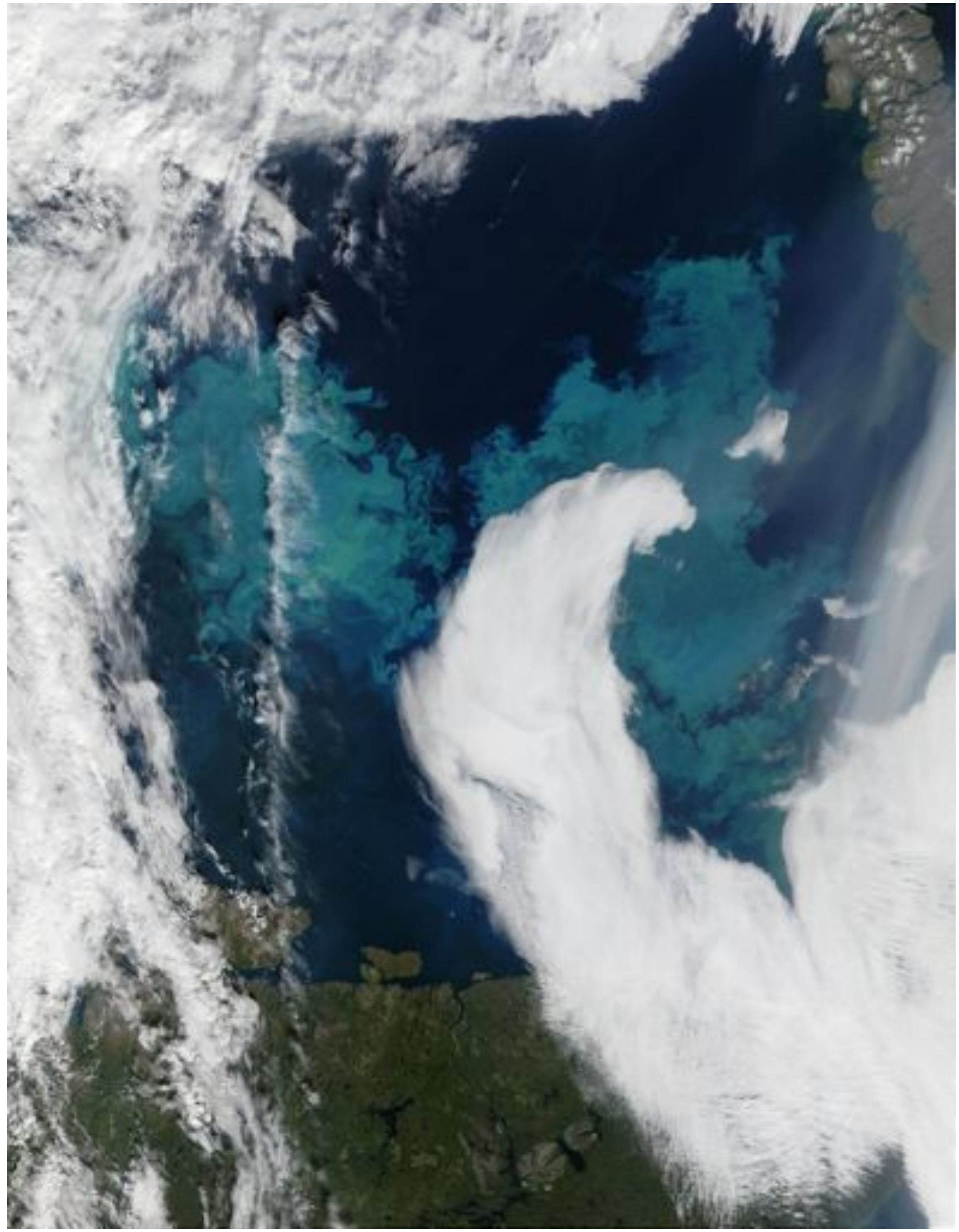
- Ocean acidification (due to anthropogenic CO_2) is causing the largest decreases in pH and saturation state of calcium carbonate in high latitudes…this may limit negatively impact their distribution.

A 16 year time series from the Barents Sea using AVHRR imagery…1987-2002

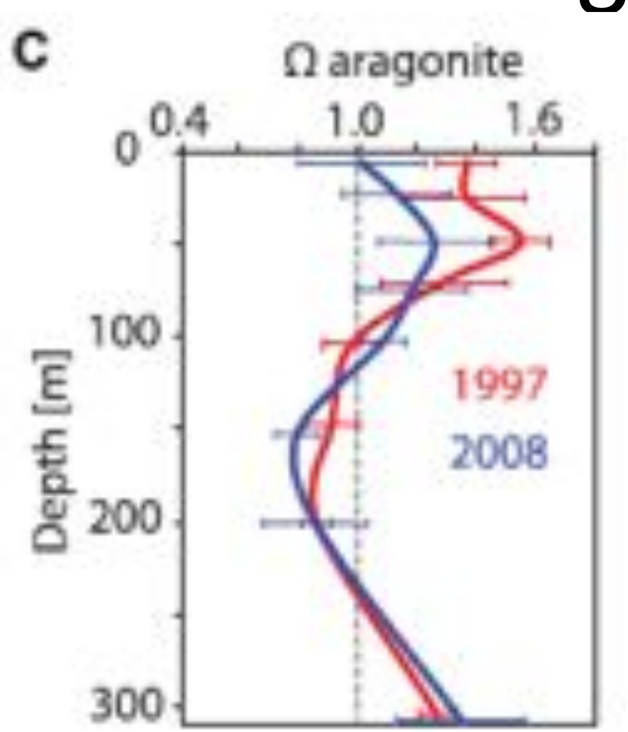


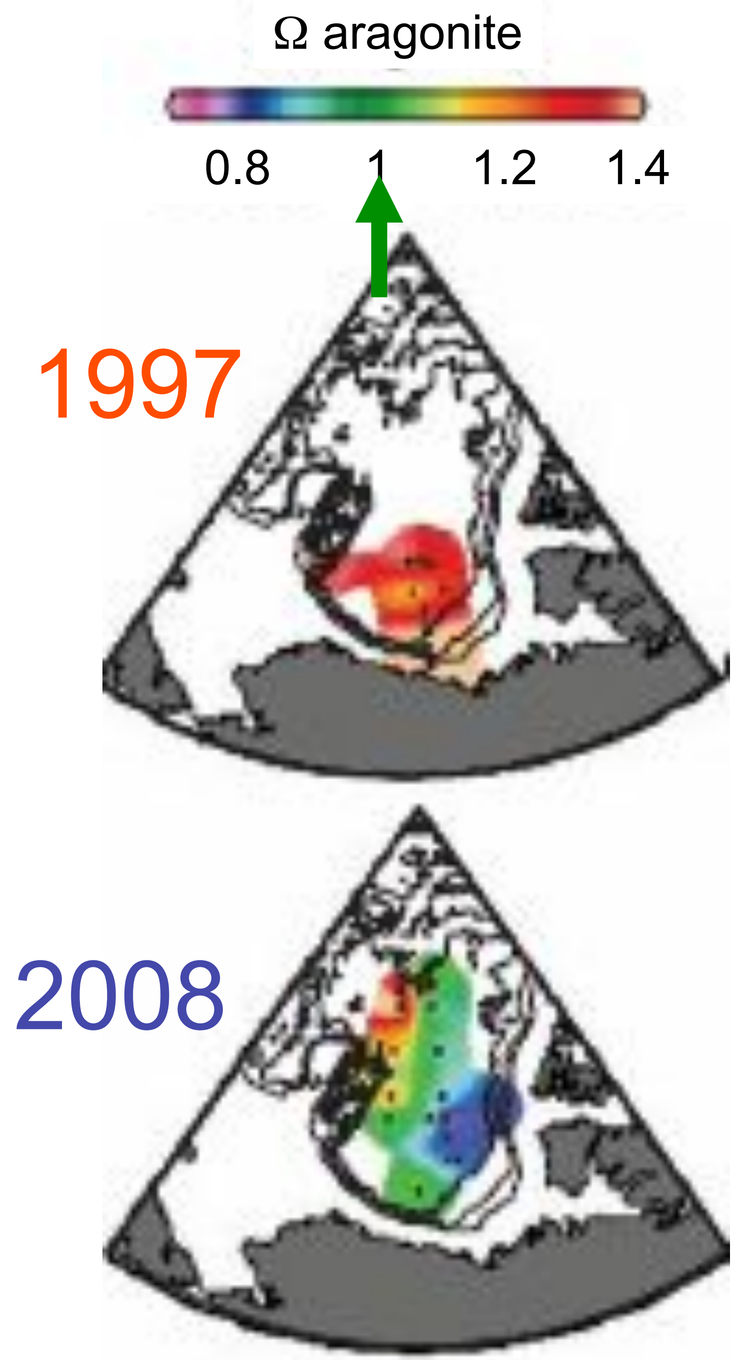
Smyth et al 2004

Aug 2002
MODIS



The saturation state for aragonite in the high Arctic is decreasing…





Yamamoto-Kawai et al 2009 Science

Summary

- MODIS provides us the means to assess global ocean PIC concentration at two-day resolution
- PIC is a major driver of the biological carbon pump in the sea; strong biogeochemical relevance
- Globally, strong annual cycles in [PIC], function of both latitude and season
- "Great Calcite Belt" in Sub-Antarctic waters appears to be the largest cocco-rich feature on earth- 88 million km^2 ; ¼ of global ocean
- Climate change impacts on coccolithophores could be complex (effects of warming and acidification→ "Global Squeeze play")

Acknowledgments

- My incredibly dedicated lab group:
  - Dave Drapeau
  - Bruce Bowler
  - Emily Lyczskowski
  - Danielle Alley

- NASA
- NSF for COPAS'08 expedition


Thank you!

[redacted]

Pros and Cons of the 2-band algorithm

- **<u>Pros</u>**
  - Provides quantitative estimate of chlorophyll and PIC in waters where pigment retrievals have traditionally been problematic
- **<u>Cons</u>**
  - Two bands are in spectral regions influenced by chlorophyll and cDOM.
  - Atmospheric correction within these bands is significant, especially for absolute nLw.
  - Potential confusion from other suspended minerals?

Pros and Cons of the 3-band algorithm

- **<u>Pros</u>**
  - 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
- **<u>Cons</u>**
  - Assumption of background b_b
  - Presumably affected by other suspended minerals like biogenic silica

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 or diatom frustules).
- Expected standard error for mean satellite-derived b_b is ~14.9 ug PIC $L^{-1}/(n^{1/2})$ based on 1km daily data.

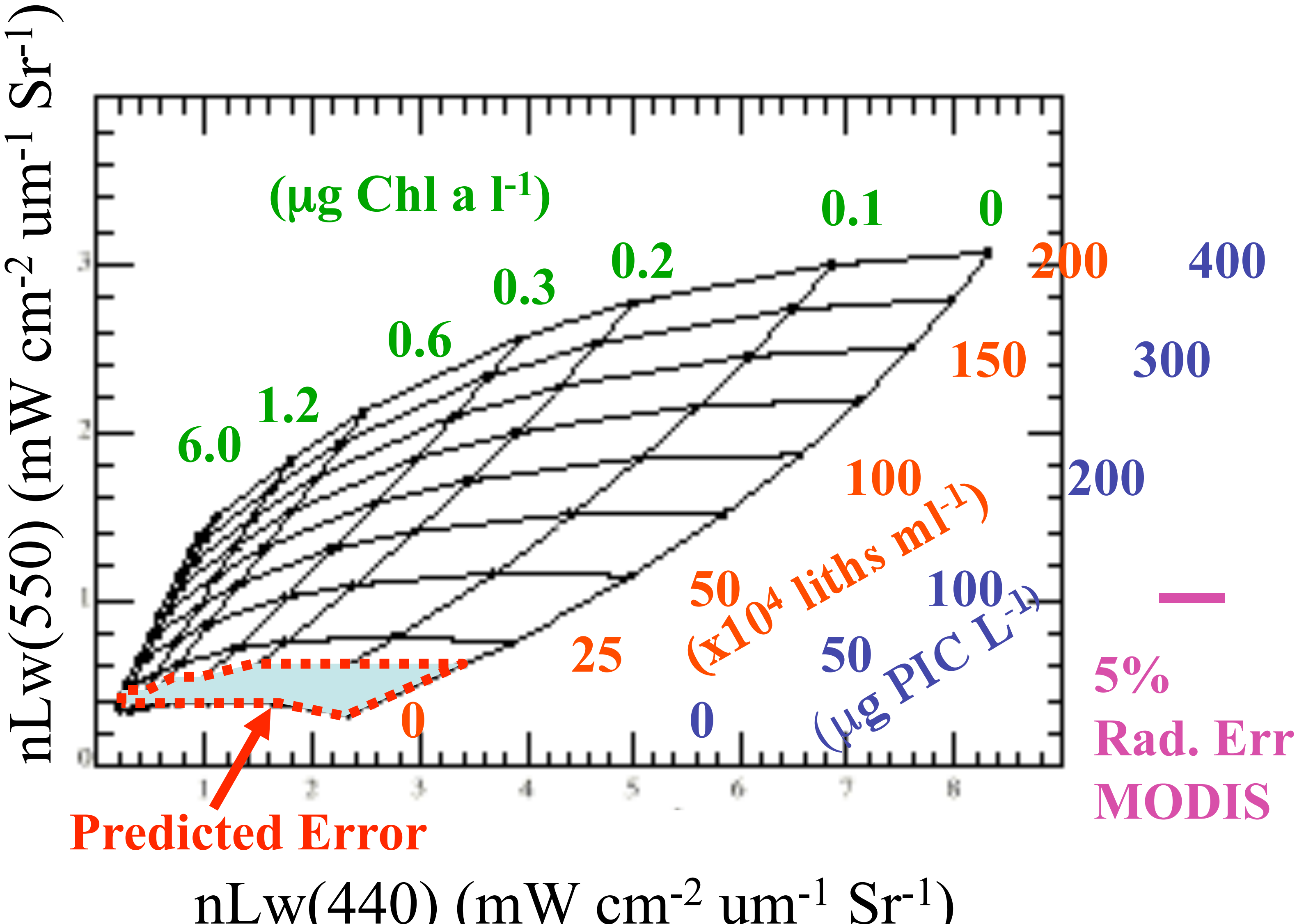
SE of time/space binned PIC averages (ug C L^{-1})

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

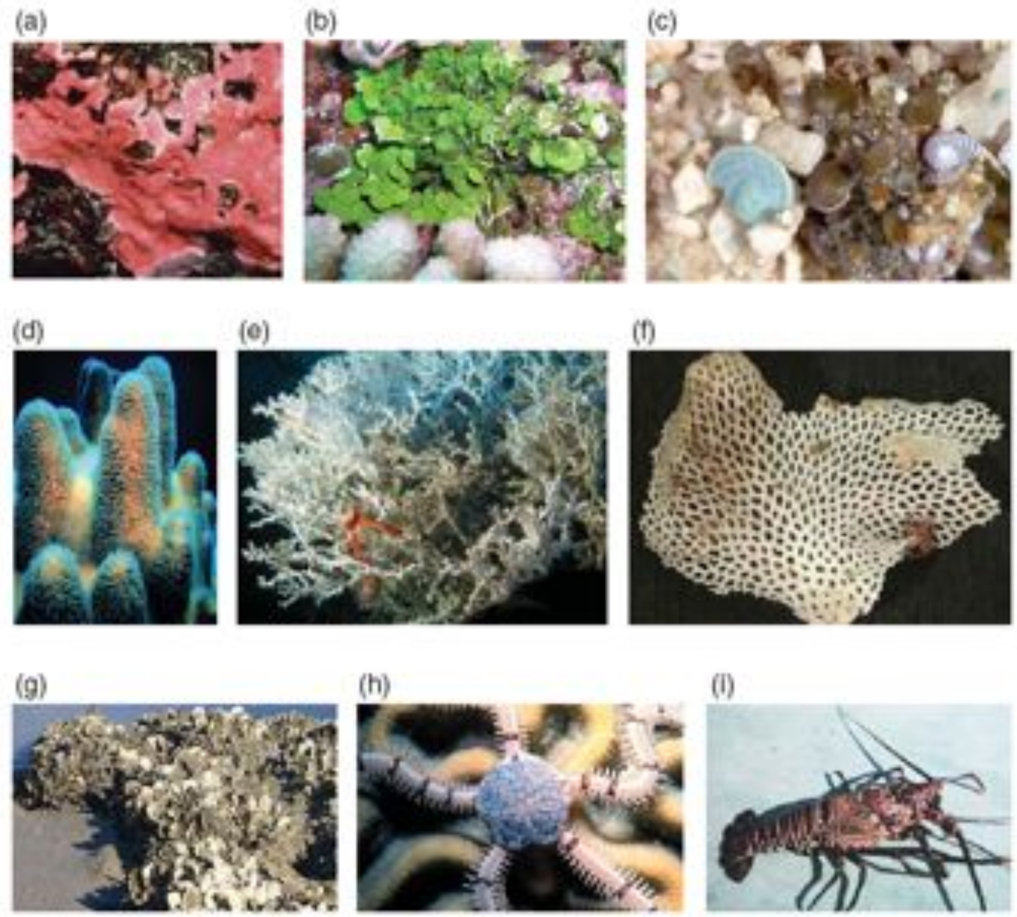
How do the data distributions compare between ship and satellite?

	log10 [PICsat[	log10[PIC ship]	Diff (sat-meas)	abs diff (%; sat-mean)
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	

The 2-band PIC algorithm look-up table

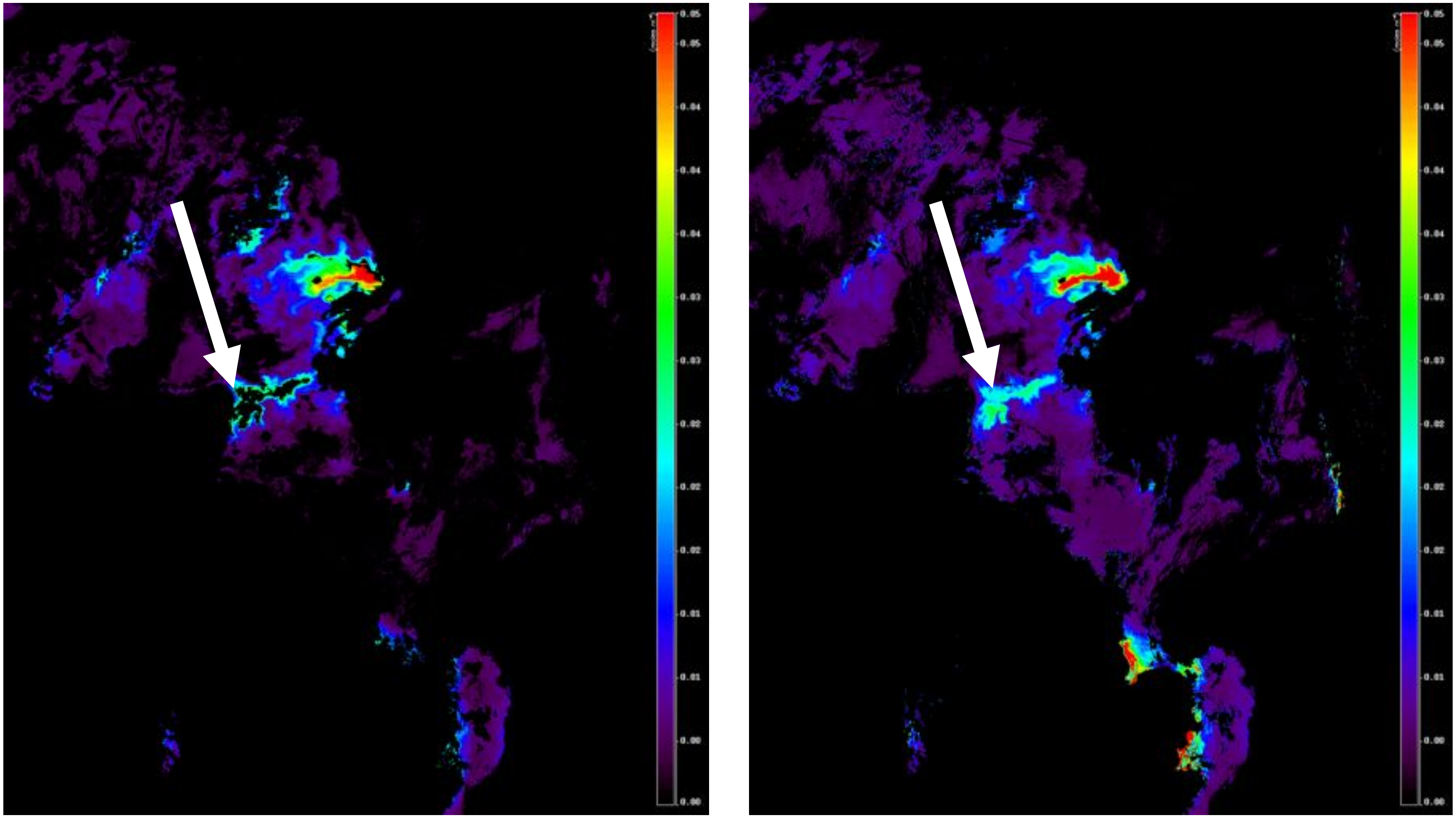


Common biocalcifiers ….



Kleypas et al., 2005

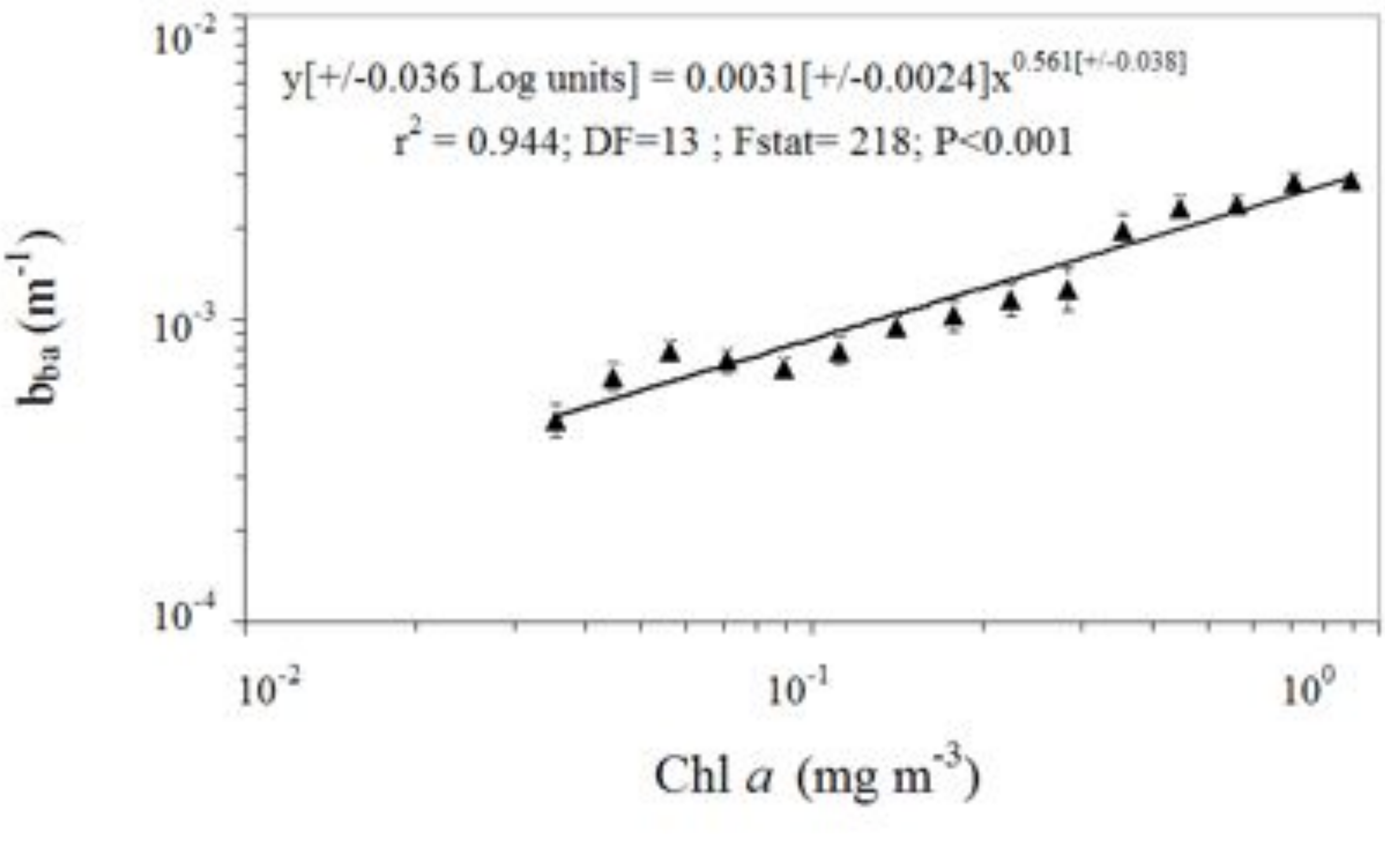
2 Band 3 Band



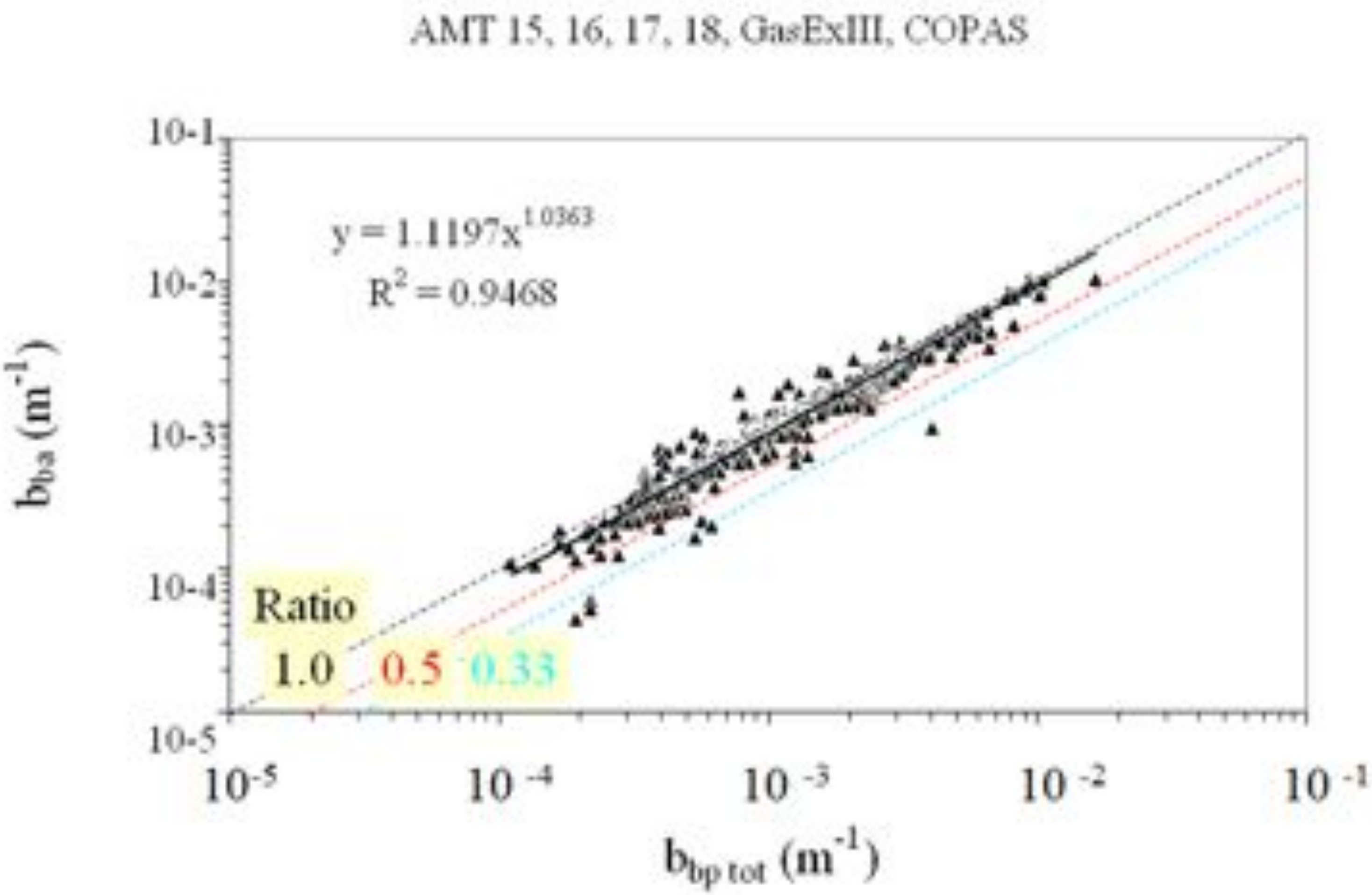
SeaWiFS scene S2003147125430 of a coccolithophore bloom in the North Sea on May 27 2003. Comparison between 2-band PIC algorithm and 3-band PIC algorithm. Color scales range from 0-0.05 moles PIC m-3. Images by Sean Bailey and Brian Franz.

The mean relationship between chlorophyll and $b_{bp\ acid}$ is critical to our ability to separate POC b_{bp} from PIC b_{bp}

AMT 15, 16, 17, 18, GasExIII, COPAS



Note, b_{bptot} is well correlated to $b_{bp\ acid}$ but the ratio of the two is more variable than it looks!



Just POC

Includes both PIC and POC

Global variability in PIC concentration…