Particulate Inorganic Carbon

William Balch

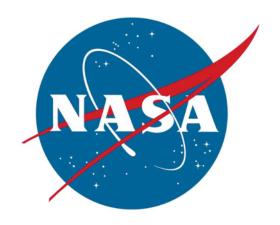Bigelow Laboratory for Ocean Sciences

E. Boothbay, ME 04544

bbalch@bigelow.org

Acknowledgments

- Bruce Bowler, Dave Drapeau and Laura Lubelczyk, (Bigelow Laboratory for Ocean Sciences)
- Captains and crew of: RRS Discovery, R/V Melville, R/V Revelle, R/V Ron Brown, RRS James Clark Ross, RRS James Cook, R/V Thompson; R/V Tangaroa; M/S Scotia Prince; M/S The CAT
- Norman Kuring- NASA Goddard
- Goddard Ocean Color Group
- Giovanni and Ocean Data View
- NASA support

PIC algorithm is typically focused on coccolithophores- ubiquitous, single-cell calcifying plants

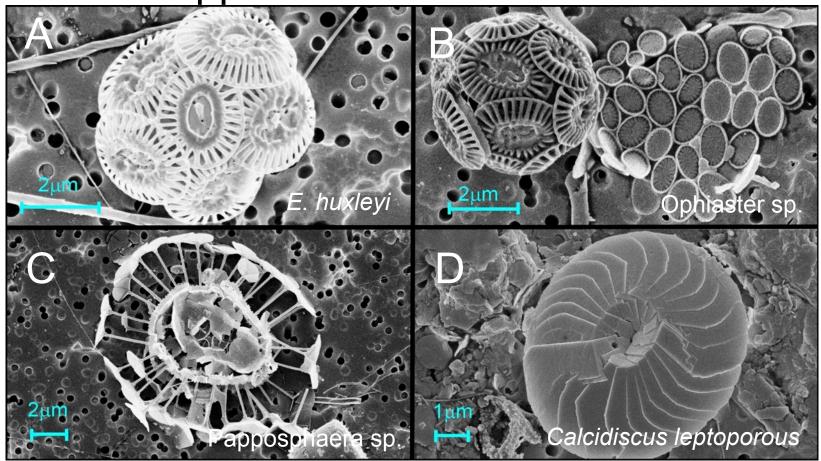Emiliania huxleyi, GOM 28/7/99, F2
151705 10KV X10.0K 3.0um

There are other PIC particles in the sea but coccoliths and coccolithophores have the highest scattering per unit PIC ("backscattering cross section")

Outline

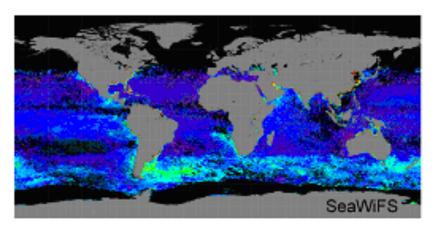- PIC algorithm cross platform comparisons
- PIC algorithm refinement
- Science applications

A — *E. huxleyi*
B — Ophiaster sp.
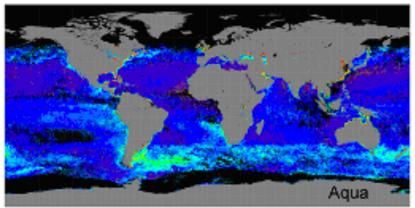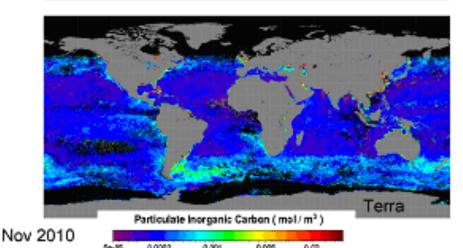C — Papposphaera sp.
D — *Calcidiscus leptoporous*

Cross platform algorithm variability

- SeaWiFS
- MODIS Terra
- MODIS Aqua

Merged Two-Band/Three band algorithm for PIC applied to SeaWiFS and MODIS-Aqua data (Collection 6)…Similar patterns

SeaWiFS

Aqua

Terra

Particulate Inorganic Carbon (mol / m³)
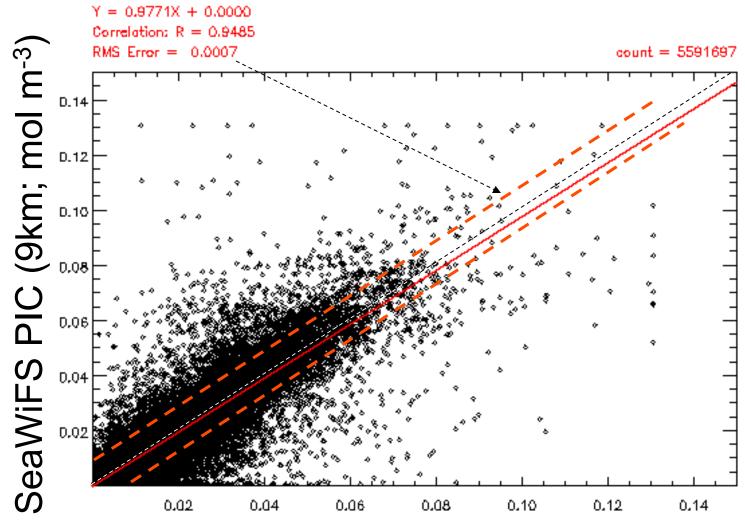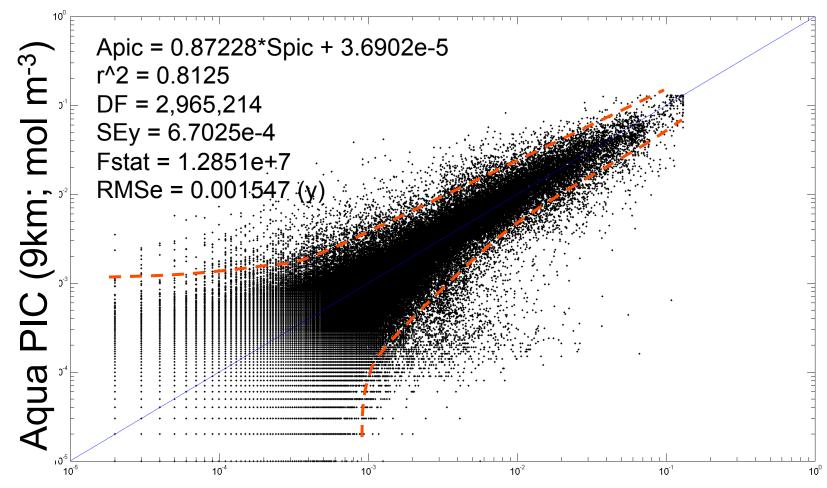
Nov 2010

5e-05   0.0002   0.001   0.005   0.02

PIC Algorithm Performance: Collection 6

Scatter Plot (Time Averaged)
Time: Jul2002–Dec2012   Area: (90S–90N, 180W–180E)

Y = 0.9771X + 0.0000
Correlation: R = 0.9485
RMS Error = 0.0007

count = 5591697
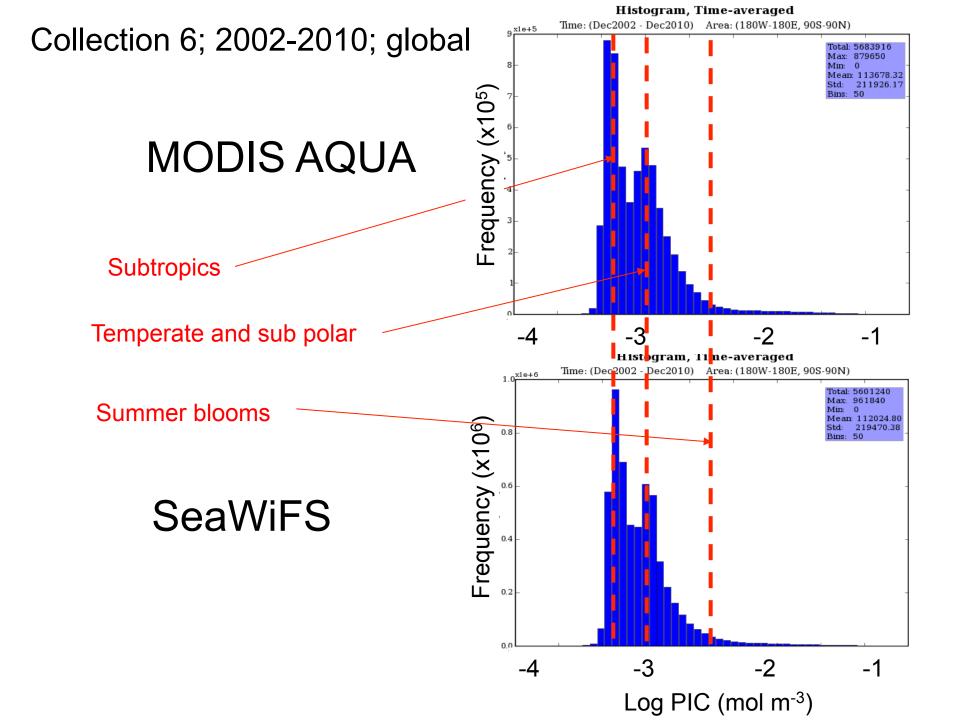
SeaWiFS PIC (9km; mol m^{-3})

MODIS Aqua PIC (9km; mol m^{-3})

Linear Scales
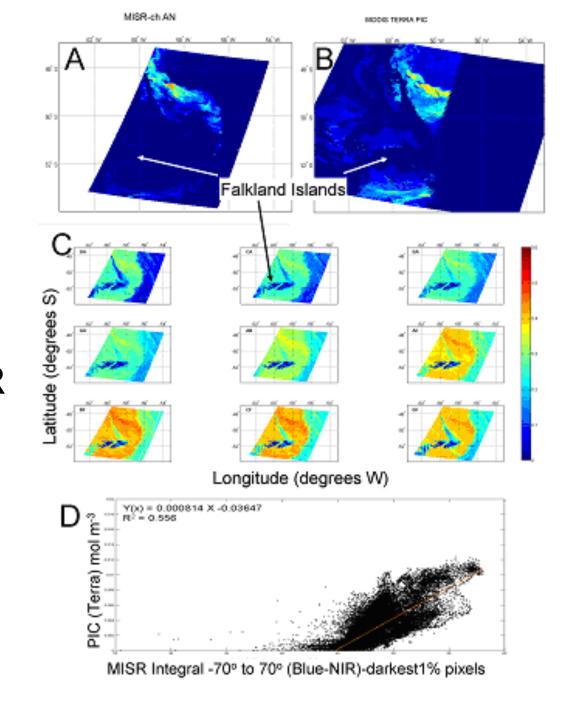
MODIS Aqua PIC, on average, < SeaWiFS

Apic = 0.87228*Spic + 3.6902e-5
r^2 = 0.8125
DF = 2,965,214
SEy = 6.7025e-4
Fstat = 1.2851e+7
RMSe = 0.001547 (y)

Aqua PIC (9km; mol m^{-3})

SeaWiFS Aqua PIC (9km; mol m^{-3})

Log Scales

Collection 6; 2002-2010; global

MODIS AQUA

Subtropics

Temperate and sub polar

Summer blooms

SeaWiFS

Histogram, Time-averaged
Time: (Dec2002 - Dec2010)   Area: (180W-180E, 90S-90N)

Total: 5683916
Max: 879650
Min: 0
Mean: 113678.32
Std: 211926.17
Bins: 50

Frequency (x10⁵)

Histogram, Time-averaged
Time: (Dec2002 - Dec2010)   Area: (180W-180E, 90S-90N)

Total: 5601240
Max: 961840
Min: 0
Mean: 112024.80
Std: 219470.38
Bins: 50

Frequency (x10⁶)

Log PIC (mol m⁻³)

We've used MISR to measure coccolith backscattering… using the Blue bands, integrated -70º to 70º, subtracting the NIR band (quasi atmosphere correction), then a dark pixel assumption to further correct.

MISR-ch AN

MODIS TERRA PIC

A

B

Falkland Islands

C

Latitude (degrees S)

Longitude (degrees W)

D

$Y(x) = 0.000814 \ X -0.03647$
$R^2 = 0.556$

PIC (Terra) mol m^{-3}

MISR Integral -70º to 70º (Blue-NIR)-darkest1% pixels

PIC algorithm refinement

- The backscattering that we associated with chlorophyll has been adjusted for PIC.

- The backscattering cross section of PIC (b_b^*; m^2 mol^{-1}) has been adjusted (based on cruise work). Variable b_b^* algorithm.

- New K_{490} formulation in PIC algorithm (formerly Baker and Smith 1982; now Morel and Martorena, 2001)

- F_o has been updated to what is used in SeaDAS

Optical Modeling of the Upper Ocean in Relation to Its Biogenous Matter Content (Case I Waters)
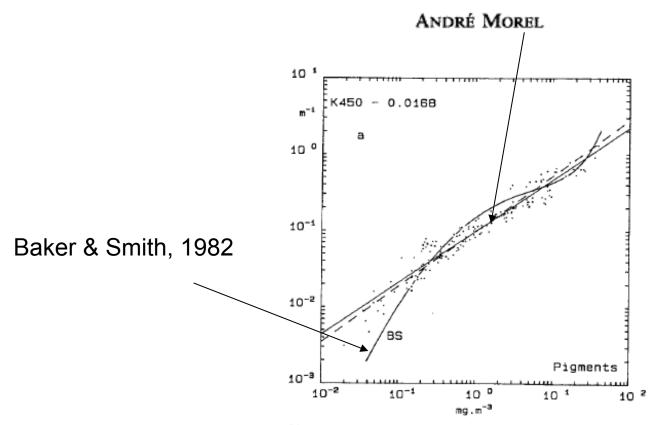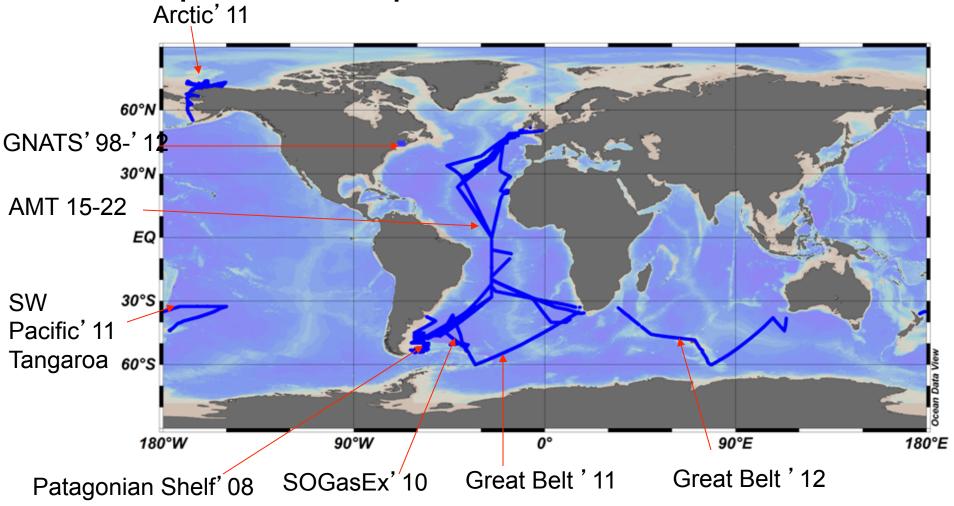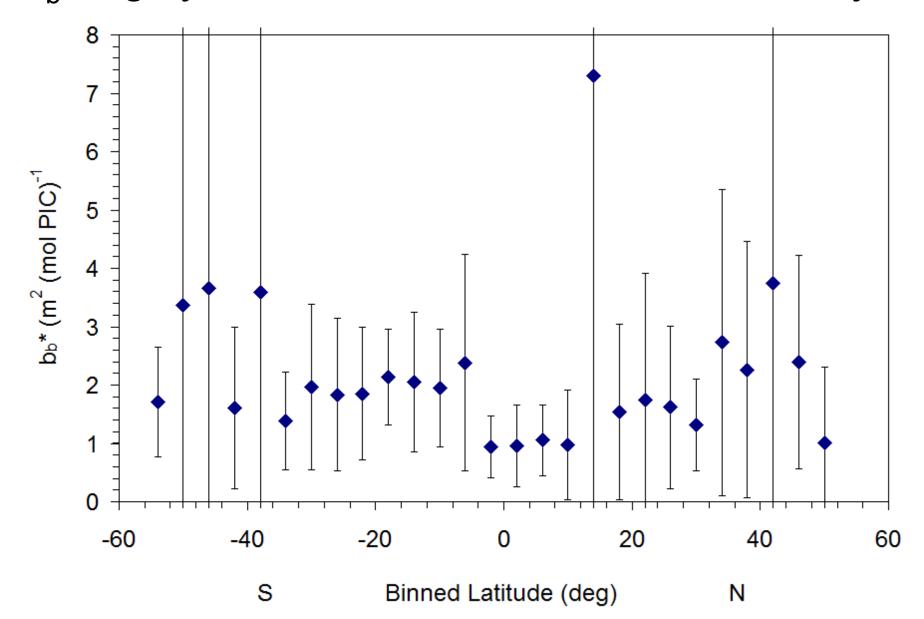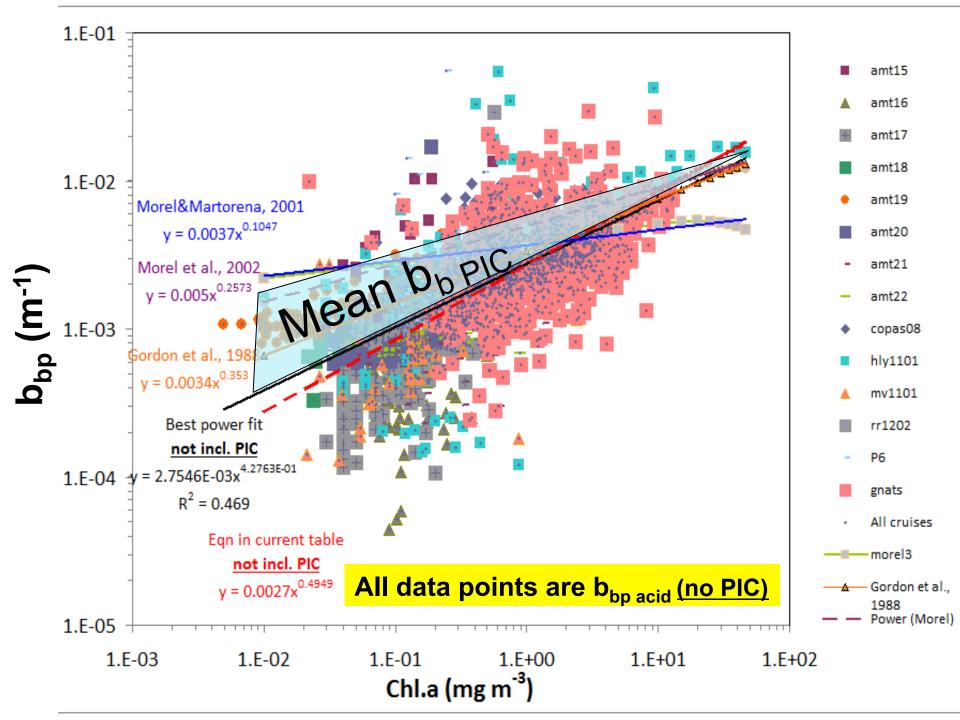
André Morel

Baker & Smith, 1982

Fig. 7a. A log-log plot of the difference $K(450) - K_w(450)$ as a function of the pigment concentration for case I waters only. The straight lines correspond to linear fits obtained by regression, whereas the curve comes from *Baker and Smith* [1982]. The case II waters, excluded from regression, are not shown.

Many major cruises to study coccolithophores- both northern and southern hemisphere; sampled over >212,000 km…
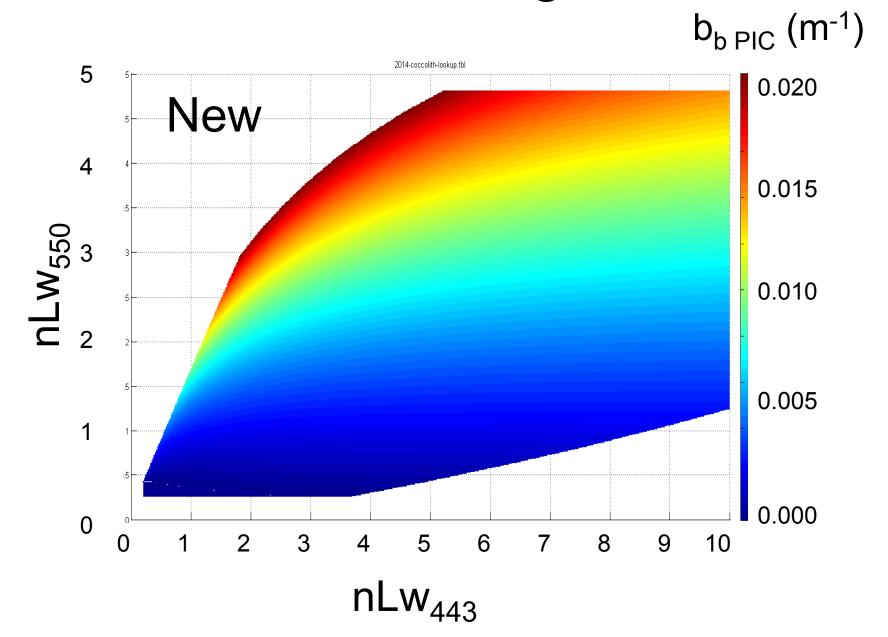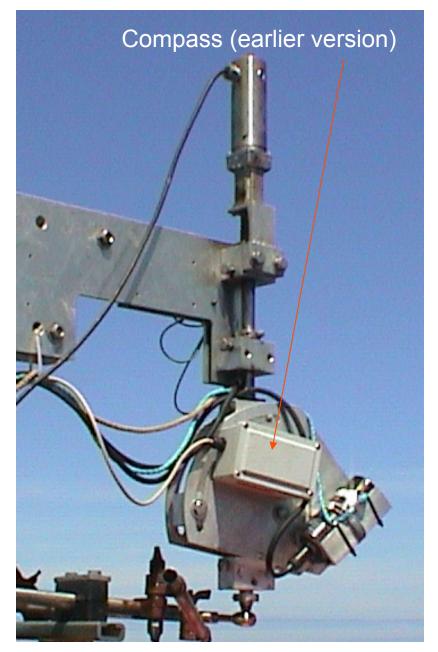

Arctic' 11

GNATS' 98-' 12

AMT 15-22

SW Pacific' 11 Tangaroa

Patagonian Shelf' 08

SOGasEx' 10

Great Belt ' 11

Great Belt ' 12

b_b^* highly variable; some latitudinal variability

Figure axes: b_{bp} (m^{-1}) vs Chl.a (mg m^{-3})

Morel&Martorena, 2001
$y = 0.0037x^{0.1047}$

Morel et al., 2002
$y = 0.005x^{0.2573}$

Gordon et al., 1988
$y = 0.0034x^{0.353}$

Mean b_b PIC

Best power fit
not incl. PIC
$y = 2.7546E-03x^{4.2763E-01}$
$R^2 = 0.469$

Eqn in current table
not incl. PIC
$y = 0.0027x^{0.4949}$

All data points are $b_{bp\ acid}$ (no PIC)

Legend:
- amt15
- amt16
- amt17
- amt18
- amt19
- amt20
- amt21
- amt22
- copas08
- hly1101
- mv1101
- rr1202
- P6
- gnats
- All cruises
- morel3
- Gordon et al., 1988
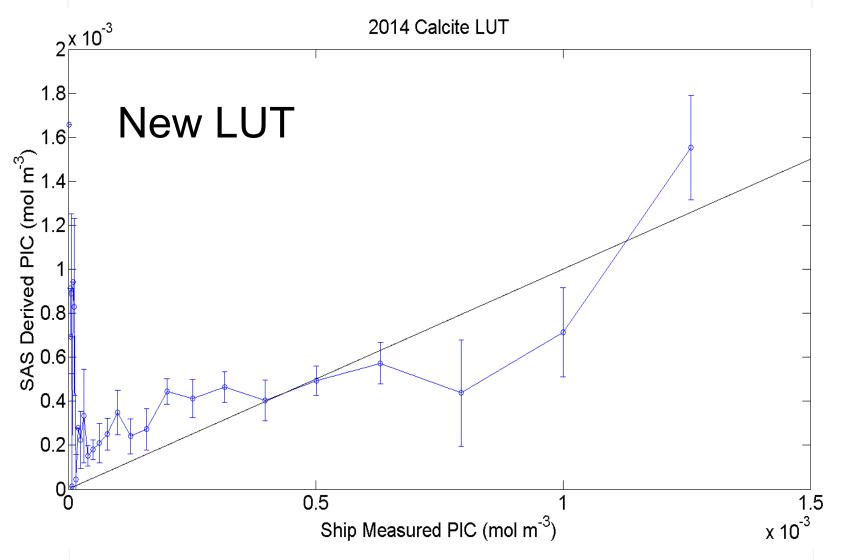- Power (Morel)

LUT changes

Compass (earlier version)

Satlantic Micro-SAS radiometers collect along-track data for Lt, Lsky, and Ed. We designed a mount which compensated real-time for changes in sun's azimuth relative to ship heading.
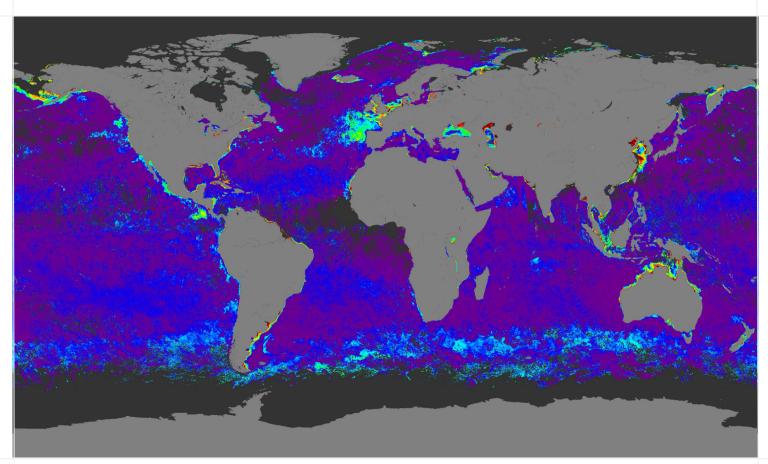
Radiometers mounted on the RRS Discovery
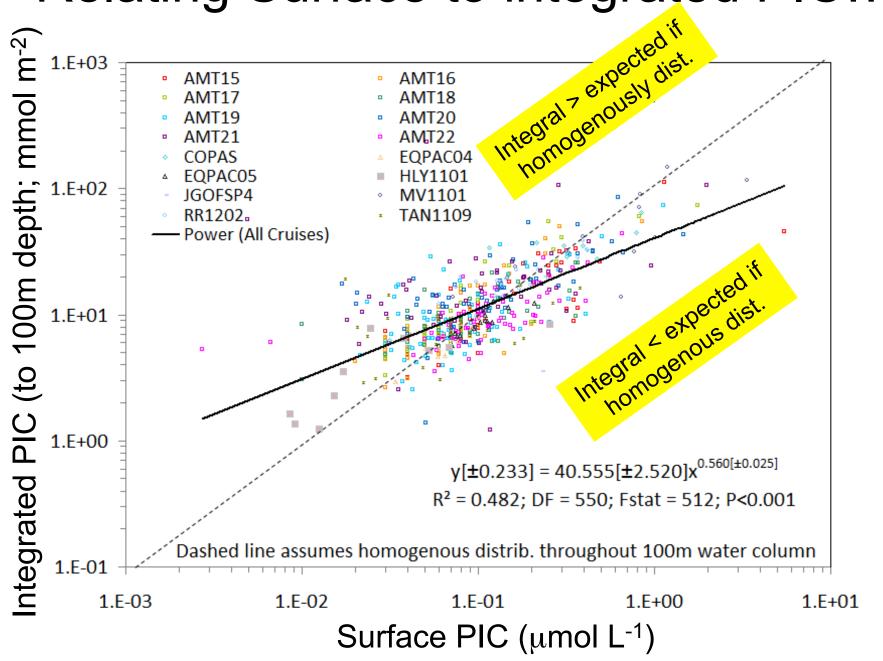
Balch; Bigelow Lab

Algorithm improvement (n=~800)

2014 Calcite LUT

New LUT

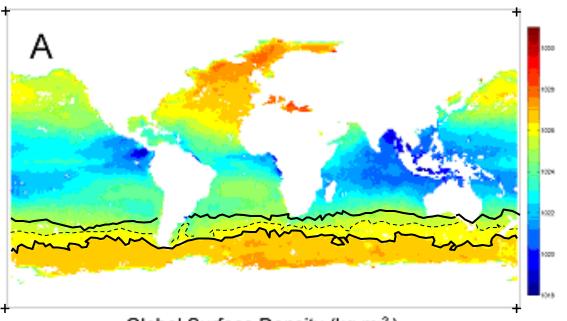# New algorithm changes (LUT & bb*)

Particulate Inorganic Carbon Mean [mol m^-3]

0.0 0.003 0.005 0.008 0.01 0.013 0.015 0.018 0.02 0.023 0.025 0.028 0.03 0.033 0.035 0.038 0.04 0.043 0.045 0.048 0.05

Relating Surface to integrated PIC…

Y-axis: Integrated PIC (to 100m depth; mmol m^{-2})

X-axis: Surface PIC (μmol L^{-1})

Legend:
- AMT15
- AMT16
- AMT17
- AMT18
- AMT19
- AMT20
- AMT21
- AMT22
- COPAS
- EQPAC04
- EQPAC05
- HLY1101
- JGOFSP4
- MV1101
- RR1202
- TAN1109
- Power (All Cruises)

Integral > expected if homogenously dist.

Integral < expected if homogenous dist.

$$y[\pm0.233] = 40.555[\pm2.520]x^{0.560[\pm0.025]}$$

$$R^2 = 0.482; DF = 550; Fstat = 512; P<0.001$$

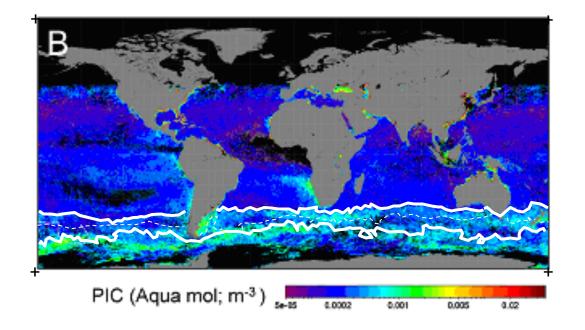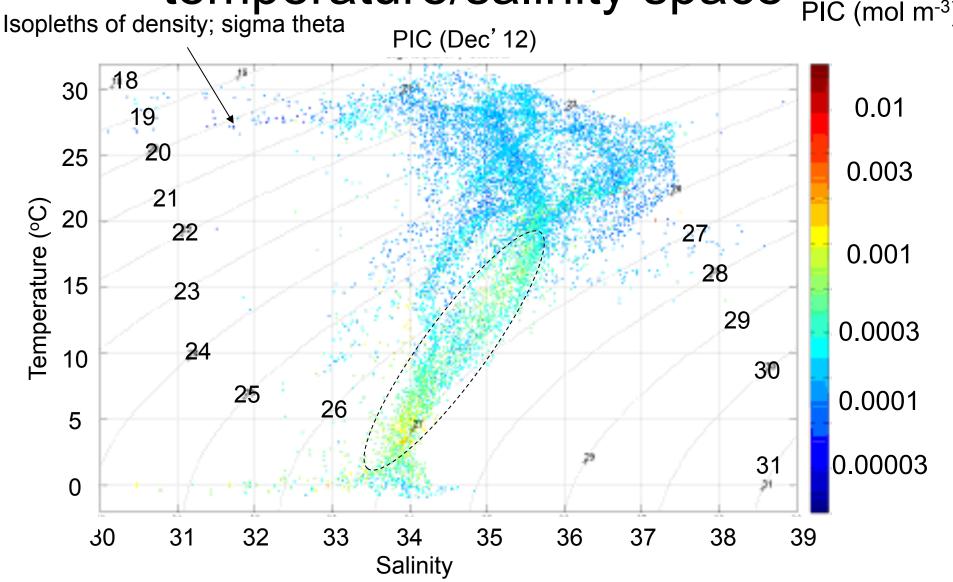Dashed line assumes homogenous distrib. throughout 100m water column

Science applications

Using MODIS SST, Aquarius SSS to define global surface density field. High PIC sits at the strong gradients of Sub Antarctic Frontal boundary
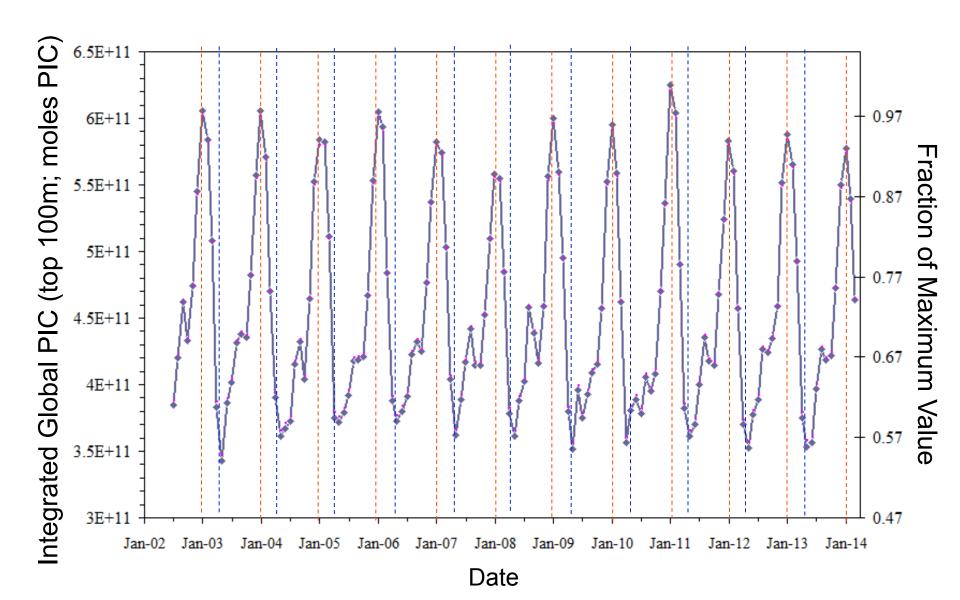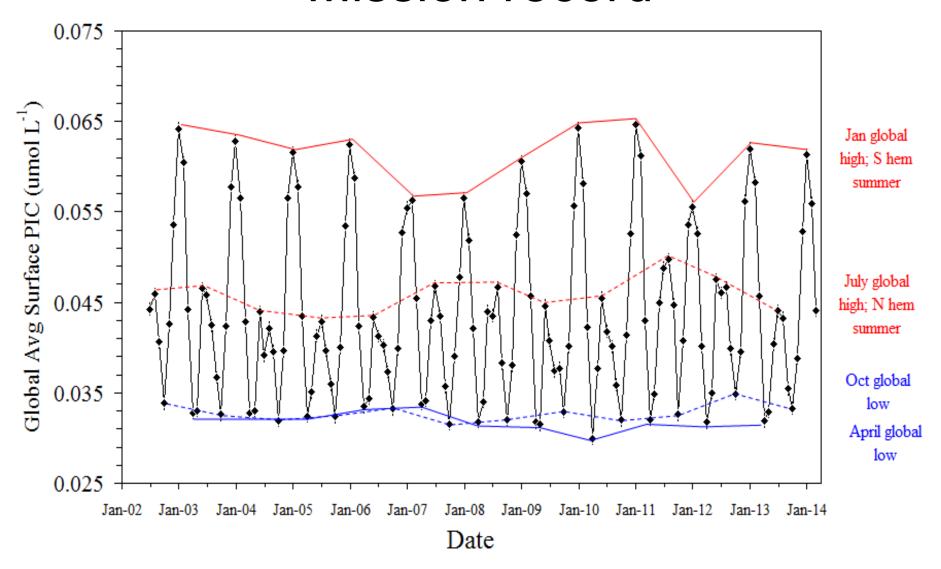

Global Surface Density (kg m^{-3})

PIC (Aqua mol; m^{-3})   5e-05   0.0002   0.001   0.005   0.02

Plot surface PIC concentration in temperature/salinity space

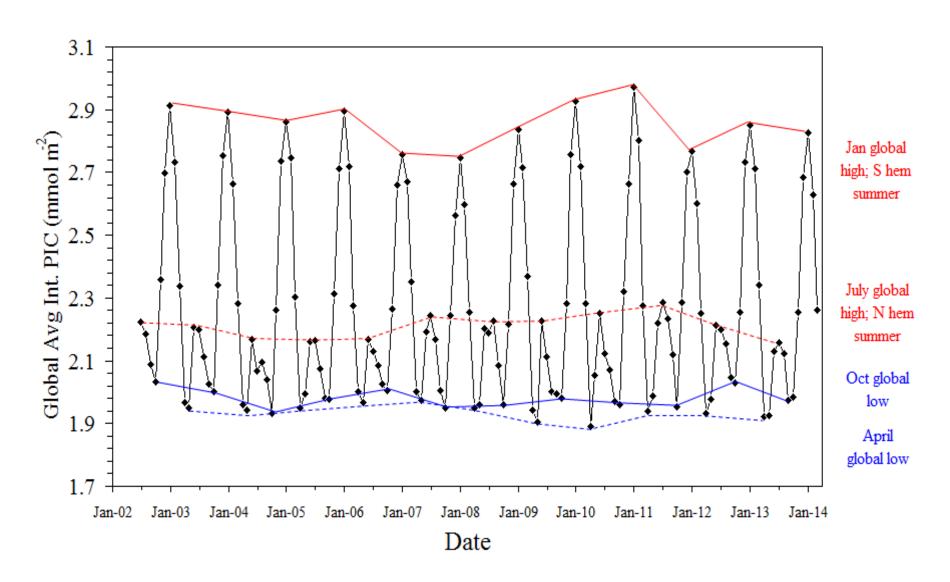Isopleths of density; sigma theta

PIC (Dec' 12)

PIC (mol m^{-3})

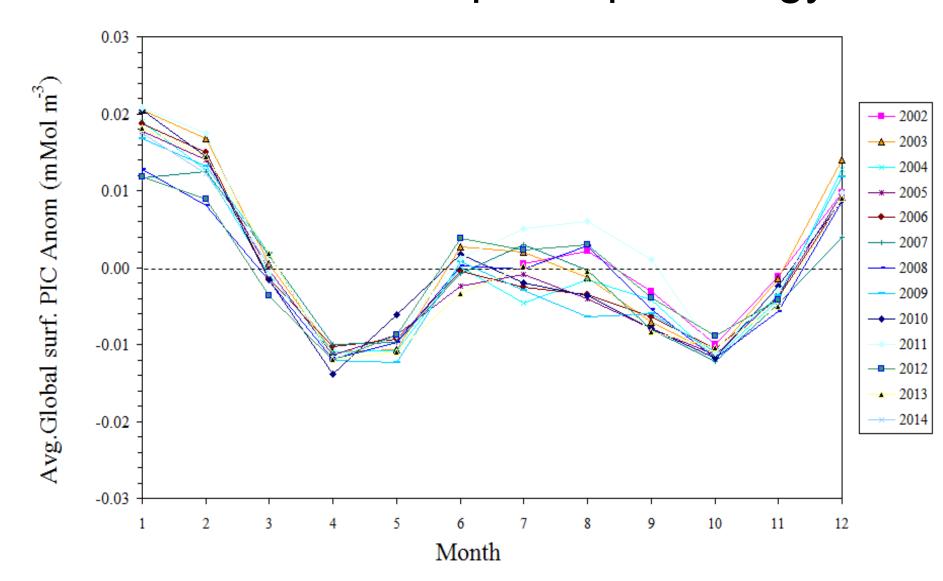# PIC Global Time Series (MODIS-Aqua) Mission record
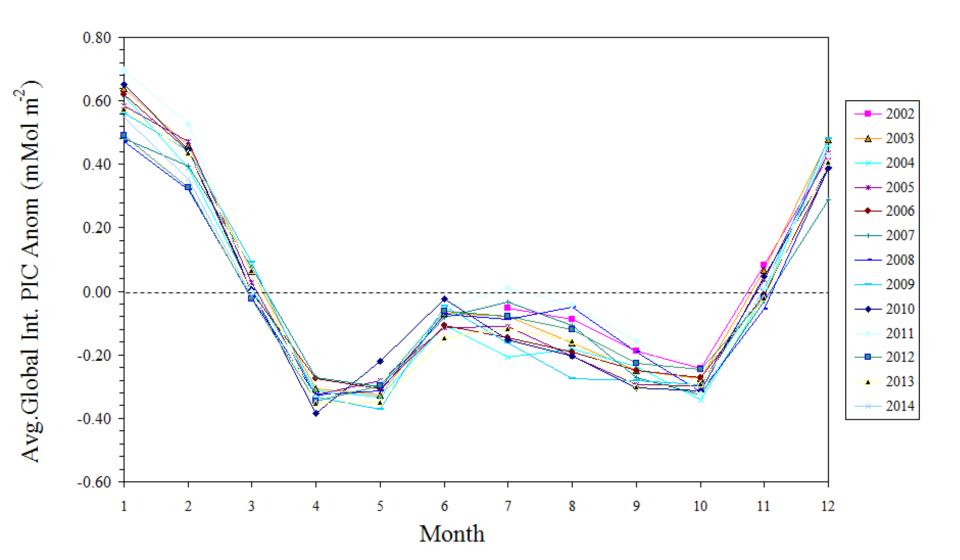
Global Surface PIC (MODIS-Aqua) Mission record

Global Int. PIC (MODIS-Aqua) Mission record

PIC Global Time Series (MODIS-Aqua)
Annual coccolithophore phenology

PIC Global Time Series (MODIS-Aqua)
Annual coccolithophore phenology

Implications of these results to PIC turnover…

- Average global PIC $=\sim 5[+/-1] \times 10^{11}$ moles PIC

    $$=6 \times 10^{12} \text{ g PIC}$$

- Global calcification = $1.6[+/-0.3]$ Pg PIC y^{-1}

    Balch et al., 2007

- $(6 \times 10^{12} \text{ g PIC})/(1.6 \times 10^{15} \text{ g PIC } y^{-1}) = 0.003$ y
  $=\sim 1.1$d turnover

- What is happening to it? It sinks or dissolves

- No indication of a trend in global PIC (e.g. negative trend associated with OA)

Summary- PIC algorithm

- <u>Cross platform comparisons of PIC</u> are within 3-13% depending on the platform
- <u>MISR can be used to detect coccolithophores</u>
- New improved PIC algorithm has <u>accuracy of +/-0.2-0.3mmol PIC m^{-3}= 2-3μg PIC L^{-1}</u>
- <u>PIC is not homogenously distributed</u> but shows subsurface maxima in oligotrophic waters, and surface maxima in blooms; use this to improve vertical integrations based on surface PIC estimates

Summary- Science Issues

- <u>Highest [PIC] seen globally at frontal boundaries</u> between surface seawater densities (σ_θ) 26-27 (SSS 34-36 and SST 2-15°C)

- <u>Greatest global PIC standing stock in January and lowest in March</u>

- <u>Global phenology of coccolithophore blooms shows greatest average [PIC] associated with austral summer</u>, boreal summer lower, lowest at the equinoxes

Future tasks at hand;
Improve PIC algorithm performance

- <u>Examine using reflectance-differencing algorithm</u> (Hu et al., 2012) for determining $b_{b\ chl}$

- <u>Improve predictions of global variability of b_b*</u>

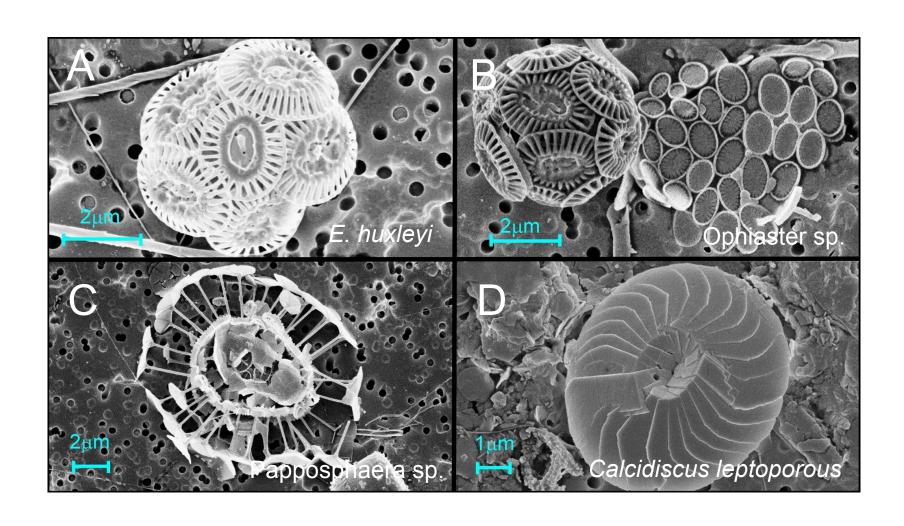- <u>Partition backscattering</u> into $b_{b\ POC}$, $b_{b\ PIC}$ and $b_{b\ BSi}$

Future: MODIS Science

- Examine <u>coccolithophore bloom at sub-kilometer pixel resolution</u> using MISR and high-resolution land bands. What can we learn about processes driving bloom at these scales?

- Examine <u>global coccolithophore phenology</u> <u>in different portions of world ocean</u> (different biogeochemical provinces)

- Frontal impacts on <u>coccolithophore growth</u> (using Aquarius salinity; MODIS SST)
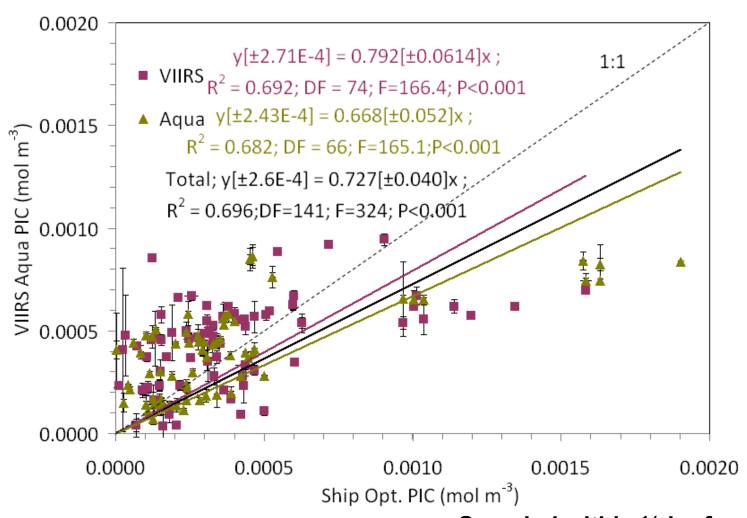
Future: MODIS Science

- <u>Impact of wind speed on coccolithophore standing stocks</u> (AMSR-E or Aquarius winds)

- Examine <u>PIC Turnover</u> in different regions of world <u>as foci for ballasted sinking POC</u>

- Are there <u>long-term negative trends of PIC associated with Ocean Acidification</u>, especially in polar provinces where OA will have biggest effects?
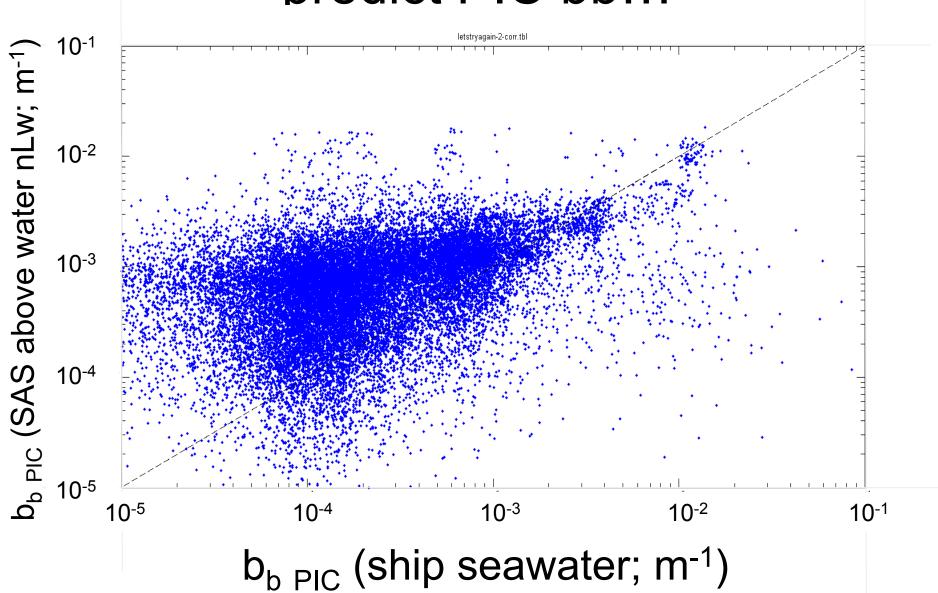
Thank you!

A — *E. huxleyi* — 2μm

B — Ophiaster sp. — 2μm

C — Papposphaera sp. — 2μm

D — *Calcidiscus leptoporous* — 1μm

While satellites generally agree with collection 6, shipboard validation data show underestimates...the issue is b_b*

GB II and AMT22 PIC vs bb' (within 0.5 hr)

Plot legend content:

$y[\pm2.71E-4] = 0.792[\pm0.0614]x$;
VIIRS $R^2 = 0.692$; DF = 74; F=166.4; P<0.001

Aqua $y[\pm2.43E-4] = 0.668[\pm0.052]x$;
$R^2 = 0.682$; DF = 66; F=165.1; P<0.001

Total; $y[\pm2.6E-4] = 0.727[\pm0.040]x$;
$R^2 = 0.696$; DF=141; F=324; P<0.001

1:1

Axis labels: VIIRS Aqua PIC (mol m^{-3}); Ship Opt. PIC (mol m^{-3})
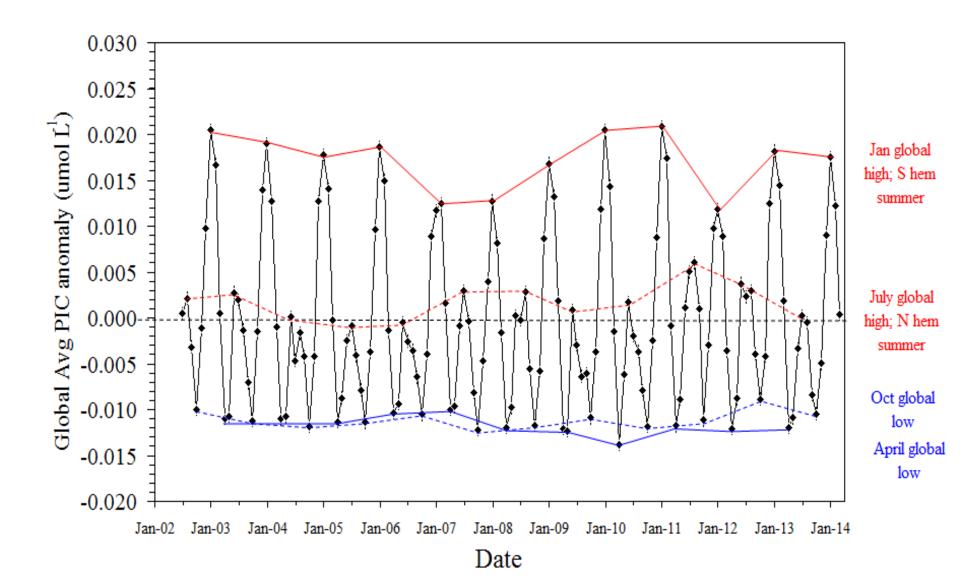
Sampled within ½ h of overpass
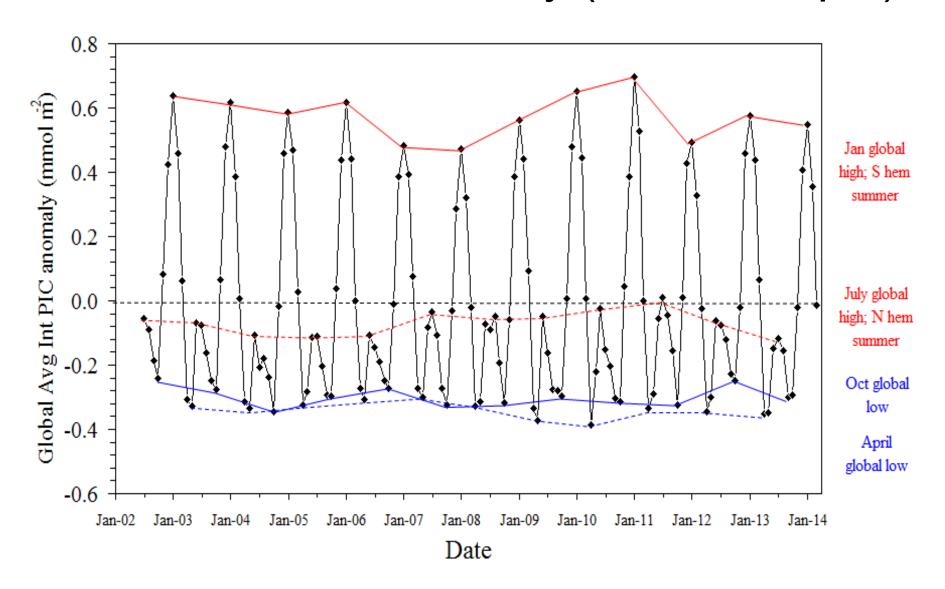
Use shipboard radiance data to predict PIC bb…

Figure: Scatter plot titled "letstryagain-2-corr.tbl" with x-axis labeled $b_{b\ PIC}$ (ship seawater; m^{-1}) ranging from 10^{-5} to 10^{-1} and y-axis labeled $b_{b\ PIC}$ (SAS above water nLw; m^{-1}) ranging from 10^{-5} to 10^{-1}.
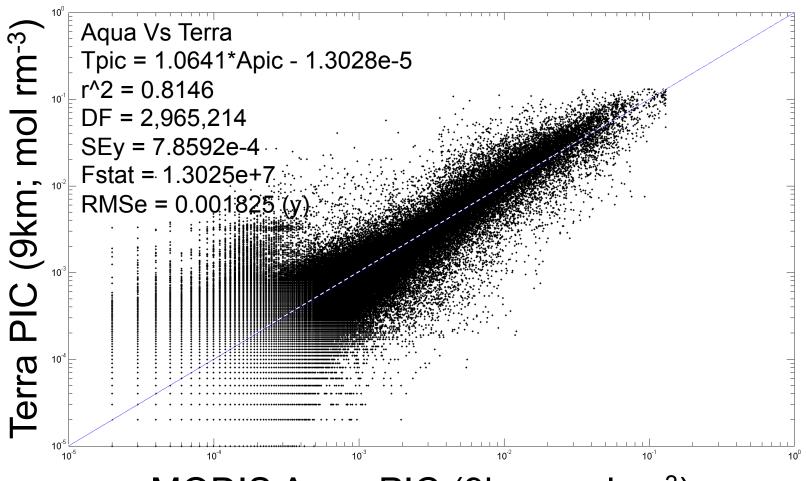
Global Surf. PIC Anomaly (MODIS-Aqua)

Global Int. PIC Anomaly (MODIS-Aqua)
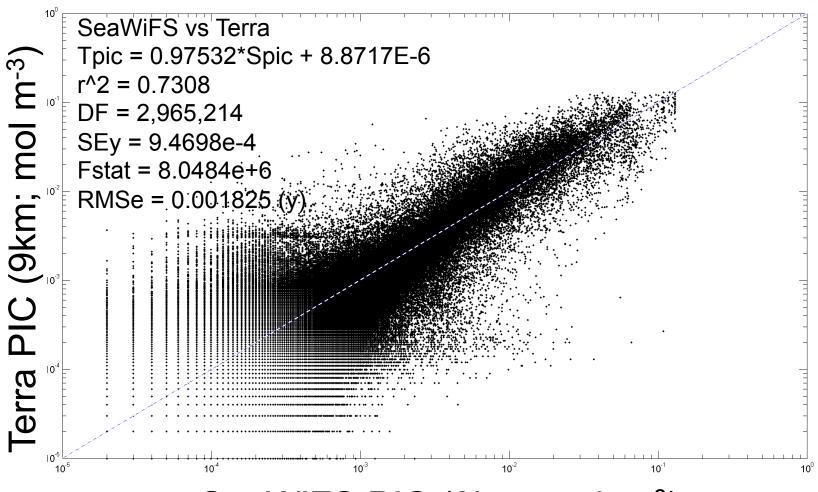
MODIS Terra PIC, on average, ~6% > MODIS Aqua

Aqua Vs Terra
Tpic = 1.0641*Apic - 1.3028e-5
r^2 = 0.8146
DF = 2,965,214
SEy = 7.8592e-4
Fstat = 1.3025e+7
RMSe = 0.001825 (y)

Terra PIC (9km; mol rm^{-3})

MODIS Aqua PIC (9km; mol m^{-3})

MODIS Terra, on average, within ~3% of SeaWiFS

SeaWiFS vs Terra
Tpic = 0.97532*Spic + 8.8717E-6
r^2 = 0.7308
DF = 2,965,214
SEy = 9.4698e-4
Fstat = 8.0484e+6
RMSe = 0.001825 (y)

Terra PIC (9km; mol m^{-3})

SeaWiFS PIC (9km; mol m^{-3})

Ocean area viewed varies annualy