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)
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and our Scrippps hosts!
Vicky Fabry and Chris Langdon for organizing this meeting!
Support from NASA and NSF for the work I’ll present
The partial pressure of $\text{CO}_2$ in the atmosphere over the globe...
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 coccolithophorids from space using CZCS…

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

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§ 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...

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

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 Wal9
A global view of coccolithophorids from space, an algorithm for flagging coco blooms...

**Coccolithophorid blooms in the global ocean**

Christopher W. Brown and James A. Yoder

Graduate School of Oceanography, University of Rhode Island, Narragansett

**Plate 1.** Climatology of classified coccolithophorid blooms (measuring >4800 km²) 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 non-coccolithophorid 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°
• Negligible absorbance
• Mass and shape of coccoliths varies by species, hence variable scattering cross section; 1.1-1.6 m² 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 1º determinant of nLw

![Graphs showing correlations between Norm. Water-Leaving Radiance (mW cm⁻² um⁻¹ sr⁻¹) and Total Coccoliths (per mL) in the Gulf of Maine.](image)

Correlations increase when nLw is regressed against coccolith concentration!
It isn’t just *E. huxleyi* that increases the reflectance of seawater…

SEM’s courtesy of Dr. Delors Blasco, Institute de Ciencies del Mar, Barcelona, Spain; Markus Geisen, Alfred Wegener Inst for Polar and Marine Res
Two PIC algorithms exist


The PIC algorithms are fundamentally backscattering algorithms...

The difference is the PIC algorithm is designed to partition the scattering due to PIC and POC.
The 2-band PIC algorithm - best for low [PIC]

![Graph showing the relationship between nLw(440) and nLw(550) with predicted error and MODIS error.](image)
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-for bright blooms

- At 670nm, 765, and 865nm, we assume absorption is mainly due to water ($a_w$):
  \[ R \approx \frac{b_b}{3(b_b + a_w)} \]

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

- Assume: a) $b_b(\lambda) = b_b(550) \times (550/\lambda)^{1.35}$
  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
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 $\sim 14.9$ ug PIC L$^{-1}$, based on 1km daily data. Assume random errors, SE decreases for binned data by $1/(n^{1/2})$.

<table>
<thead>
<tr>
<th>Spatial res (km)</th>
<th>1</th>
<th>4.63</th>
<th>36</th>
<th>111.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time bins (d)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14.900</td>
<td>3.218</td>
<td>0.414</td>
<td>0.134</td>
</tr>
<tr>
<td>7</td>
<td>5.632</td>
<td>1.216</td>
<td>0.156</td>
<td>0.051</td>
</tr>
<tr>
<td>30</td>
<td>2.720</td>
<td>0.588</td>
<td>0.076</td>
<td>0.024</td>
</tr>
<tr>
<td>365</td>
<td>0.780</td>
<td>0.168</td>
<td>0.022</td>
<td>0.007</td>
</tr>
</tbody>
</table>
Using our data base of ship measurements in the GOM, binning can make a huge difference. SE of the PIC estimate is ~ +/− 2.7x10^{-4} mol PIC/m^{3}.
What does the calcite distribution look like in the central Atlantic?

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

AMT 17 Cruise track
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 $L_t$, $L_{sky}$, and $E_d$ for estimation of $nL_w$ as input to the two PIC algorithms.
On the ship we measure PIC optically and chemically.

\[
y = 0.412[\pm 0.010]x + 4.12E-05[4.33E-6]
\]

\[
R^2 = 0.769; F=1597; DF=479; RMS=0.26 \text{ log units}
\]
Binning can improve the fit considerably...

Optical technique linear down to $bb' = 5 \times 10^{-5}$ m$^{-1}$
How does the merged algorithm work in the mid-Atlantic section?

![Graph showing the distribution of [PIC] in the mid-Atlantic section with Bloom highlighted.]

- sat AQUA
- ship ICPAA

[Graph axes: S (South) and Latitude (deg) with N (North) at the bottom.]

[Legend for graph elements: squares for satellite data, triangles for ship data, and Bloom highlighted in green.]
Ship and satellite measurements of the same feature (all using $b_b$)…
How do the data distributions compare between ship and satellite?

<table>
<thead>
<tr>
<th></th>
<th>log10 [PICsat]</th>
<th>log10[PIC ship]</th>
<th>Diff (sat-meas)</th>
<th>abs diff (% ; sat-meas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg</td>
<td>-4.121</td>
<td>-4.044</td>
<td>-0.077</td>
<td>-16.28</td>
</tr>
<tr>
<td>Std dev</td>
<td>0.375</td>
<td>0.302</td>
<td></td>
<td></td>
</tr>
<tr>
<td>median</td>
<td>-4.117</td>
<td>-4.121</td>
<td>0.004</td>
<td>0.91</td>
</tr>
<tr>
<td>max</td>
<td>-3.098</td>
<td>-2.751</td>
<td>-0.347</td>
<td></td>
</tr>
<tr>
<td>min</td>
<td>-4.928</td>
<td>-4.588</td>
<td>-0.340</td>
<td></td>
</tr>
</tbody>
</table>
Comparing ship and satellite (unbinned)

Linear
\[ Y[+/-6.94x10^{-5}] = 0.4548[+/-0.026]X + 5x10^{-5}[+/-6.2x10^{-6}] \]
\[ r^2 = 0.63; F = 295; P < 0.001 \]

Power Fit
\[ Y[+/-0.326] = 0.0237[+/-0.0199]X^{0.6173[+/-0.0116]} \]
\[ R^2 = 0.25; F = 57; P < 0.001 \]
Now bin the data...

![Graph showing correlation between [PIC] (mol m⁻³; Sat MODIS Aqua) and [PIC] (mol m⁻³; ICPAA). Error bars indicate ±1 SE. The regression line is given by Y = 0.0402[⁺/₋0.132]X⁻⁰.₆₆₃[⁺/₋0.₀₇₀]. The coefficient of determination (r²) is 0.872, and the root mean square (RMS) is 0.13 log units. The sample size (n) is 15, and the p-value is <0.001.](image)
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?

Log PIC (mgC m$^{-3}$)

Year

'98 '99 '00 '01 '02 '03 '04 '05

Summer solstice

Portland, ME Yarmouth, NS

Longitude (deg. W)

Dist. from Yarmouth, N.S. (km)

70 68 66

300 200 100 0
Sanity check… how about changes in plated coccolithophores in the Gulf of Maine?
Now the global perspective...
Example MODIS Aqua; 8 November 2004
Seasonally binned global data calcite-July-Sept

Balch; Bigelow Lab
Southern hemisphere summer- Jan-Mar
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!

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 $1-2 \times 10^{-4}$ mol m$^{-3}$.
[BSi] and [Chlorophyll] are correlated

\[ y[\pm 0.394] = 0.00019[\pm 1.90e-5]x^{1.0527[\pm 0.044]} \]

\( n=633; R^2 = 0.522; P<0.001 \)
[BSi] and POC are correlated

\[
Y_{\pm 0.364} = 1.0039_{\pm 0.585}X^{2.0041_{\pm 0.101}}
\]

n = 369; R^2 = 0.517; P < 0.001

AMT 15-17
A quantitative summary of global PIC imagery

<table>
<thead>
<tr>
<th>Biome</th>
<th>Jan-Mar</th>
<th>July-Sept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tot PIC</td>
<td>% Total</td>
</tr>
<tr>
<td></td>
<td>Mt</td>
<td></td>
</tr>
<tr>
<td>Polar</td>
<td>2.41</td>
<td>12.3</td>
</tr>
<tr>
<td>Westerlies</td>
<td>7.70</td>
<td>39.4</td>
</tr>
<tr>
<td>Trades</td>
<td>6.41</td>
<td>32.8</td>
</tr>
<tr>
<td>Coastal</td>
<td>2.99</td>
<td>15.3</td>
</tr>
<tr>
<td>Total</td>
<td>19.55</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>Mt</td>
<td></td>
</tr>
<tr>
<td>Polar</td>
<td>2.14</td>
<td>11.4</td>
</tr>
<tr>
<td>Westerlies</td>
<td>6.58</td>
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<tr>
<td>Trades</td>
<td>6.57</td>
<td>35.1</td>
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<tr>
<td>Coastal</td>
<td>3.38</td>
<td>18.1</td>
</tr>
<tr>
<td>Total</td>
<td>18.70</td>
<td>100.0</td>
</tr>
</tbody>
</table>

…or “x10¹²g PIC”