Satellite tools and approaches for OA research

William M. Balch
Bigelow Laboratory for Ocean Sciences
E. Boothbay, ME 04544

With help from:
Acknowledgements

• Co-authors: Salisbury et al., 2015. *Oceanography Magazine*. In press. “How can present and future satellite missions support scientific studies that address ocean acidification?”

• Technical support: M. White, D. Drapeau, B. Bowler, L. Lubelczyk (BLOS) plus N.Bates and R. Garley (BIOS)- Gulf of Maine North Atlantic Time Series (GNATS)

• Financial Support:
Overview

• Space/time variability of
  – environmental variables measured,
  – relevant processes
  – Problem coastal waters
• Satellite constellation for OA work
• In search of two proxies of the carbonate system to measure
• Example: Focus on one product: [PIC] from space.
Introduction

- Surface $p\text{CO}_2$ is increasing by $\sim 2$ $\mu\text{atm yr}^{-1}$, (nearly same rate as for atmospheric $p\text{CO}_2$)(LeQuéré et al., *Earth System Science Data Discussions* 2014).
- Saturation state of aragonite ($\Omega_{\text{ar}}$), also decreasing by $\sim 0.01$ yr$^{-1}$
- **IS THERE ANY WAY USING SATELLITE TECHNOLOGY TO ESTIMATE OA-RELATED CHANGES?**
Is he kidding??
Measuring OA from 850km in space?!?
Major impacts of OA likely to occur in coastal regions

- Complexity in carbonate dynamics in coastal regions (Cai et al., 2010, JGR; Cross et al., 2013, Mar. Chem.).
  - Acidic inputs from rivers (Salisbury et al., 2008, *Eos Trans. AGU*),
  - Upwelling (Feely et al., 2008, Science),
  - Intense biological respiration fueled by productivity (Cai et al., 2010, JGR)
- Multiple stressors in coastal regions. Large changes in the carbonate system over short timescales combined with longer-term OA or other stressors (e.g., temperature).
Gulf of Maine GNATS

$$\Omega_{\text{aragonite}} = \frac{[\text{Ca}^{++}] [\text{CO}_3^{=}]}{\text{Ksp}_{\text{arag}}}$$
What satellite products can we use?

- Satellites do **not** directly measure chemistry;
- Satellites provide statistical proxies of carbonate, or as elements in quasi-mechanistic chemical reconstructions
- Need some support from in-water observations.
- Satellite-derived POC, Chlorophyll, or particulate inorganic carbon (PIC), yields information on production/remineralization balances, plus particle sinking or physical dispersion or convergence.
SATELLITES presently flying

- GOES
- Aquarius
- Grace
- OCO-2
- KOSI
- AQUA
- ASCAT
- SUOMI
- AVHRR
- DMSP
- SMAP
- DIGI
- SMOS
- MERIS
- SWOT
Scales of space and time for earth viewing satellites
Remote Sensing of environmental variables, standing stocks and processes relevant to OA:

- **SST** (Minnett and Barton, 2010, In *Radiometric Temperature Measurements: II. Applications*).
- **POC** (Stramski et al., 2008, Biogeosciences).
- **PIC** (Balch et al., 2005, JGR).
- **Photosynthetically Available Radiation (PAR)** (Frouin et al., 2012, Rem. Sensing Environ.).
- **Phytoplankton light absorption** (QAA algorithm, Lee et al. 2005, JGR).
- **Net primary productivity** (NPP; Behrenfeld and Falkowski, 1997, L&O).
- **Calcification** (Balch et al, 2007, DSR-II).
- **Net community production** (autotrophic fixation of CO$_2$ minus community respiration (Westberry et al., 2012, GBC; Jönssön et al., 2011, Biogeosciences).
- **Phytoplankton functional types** (diatoms, coccolithophores, diazotrophs (Westberry et al., 2005, JGR).
NASA Orbiting Carbon Observatory-2

- Atmospheric CO$_2$: a new data set for investigations of air-to-sea $p$CO$_2$ disequilibrium
Regional Gulf of Maine proxies with DIC

A

DIC (μequiv kg⁻¹)

Salinity

y = -1.4994x² + 151.83x - 1325
R² = 0.5317

B

Surface Density (Sigma theta)

y = -8.4507x + 2117
R² = 0.5494

C

Temperature (°C)

y = 44.083x + 935.75
R² = 0.8614

D

Vert. Temp gradient (°C/m over top 50m)

y = -572.49x + 2051.4
R² = 0.5812
Physical, biological, chemical proxies in the Gulf of Maine for $\Omega_{\text{aragonite}}$
Saturation State and $p\text{CO}_2$

$\Omega_{\text{aragonite}}$

$p\text{CO}_2$ (μatm)

$y = -0.0053x + 4.1251$

$R^2 = 0.2892$
Satellite approaches for estimating $p\text{CO}_2$ and air-sea $\text{CO}_2$ flux

- *In situ* surveys and global $p\text{CO}_2$ monitoring: Surface Ocean $\text{CO}_2$ Atlas (SOCAT) database
- Air-sea flux estimates: created by combining $p\text{CO}_2$ disequilibrium with satellite sea state data (often based on wind-speed) to estimate $\text{CO}_2$ gas-exchange coefficients (Wanninkhof, 2014, *L&O Methods*).
- Knowledge of $p\text{CO}_2$ and Talk allows estimation of $\Omega$ calcite and $\Omega$ aragonite saturation states, and global $\Omega$ maps
- Satellite estimates ultimately rely on SST, ocean color, wind, wave, roughness, and circulation data
- Modeled salinity and remotely sensed SST and wind data to estimate the variability of $\Omega$ within the greater Caribbean region (Gledhill et al., 2009, *Oceanography*)
State of the Art in Remote Sensing of Carbonate System Variability

- Remote Sensing of Total Alkalinity: arguably most viable in support of carbonate system and OA studies
  - $T_{\text{alk}}$ weakly impacted by biological processes
  - strongly covariant with seawater salinity
  - now continuous access to surface salinity observations from space
- Nonlinear combination of salinity and SST further resolves remaining non-conservative variation in $T_{\text{alk}}$
- Satellite $T_{\text{alk}}$ product resolution 50-150 km spatial resolution in salinity data; (e.g. $\pm 0.2$ in satellite-derived salinity translates to $\pm 10-15$ uMol/kg in $T_{\text{alk}}$)
- Sparse literature on using satellite data for $T_{\text{CO}_2}$ and pH retrievals
  - weaker covariance with salinity (than $T_{\text{Alk}}$)
  - visible and thermal data not robustly correlated with pH or $T_{\text{CO}_2}$ over larger spatial scales.
Bottom line on deriving $p\text{CO}_2$...

• Diversity and complexity of ocean biogeochemical provinces, plus steadily increasing surface water CO$_2$ levels, suggest, no single $p\text{CO}_2$ algorithm will be applicable at the global scale.

• State-of-the-art for these satellite-based algorithms =± 15ppmv accuracy in regional $p\text{CO}_2$. However, in complex coastal regions with large magnitude variation, accuracy will likely be lower (Hales et al., 2012, Prog. Oceanogr.).
PIC Product: 2B/3B algorithm (Vis, IR, NIR)
PIC view from ships...

Log10SurfPIC [mmol m^-3] @ Depth [m]=first
PIC shoals the euphotic zone
All CaCO$_3$ particles are not equal!
PIC Global Time Series (MODIS-Aqua)
Mission record - Highest PIC during austral summer
What we’ve learned about PIC turnover in the sea from satellite PIC measurements?

- Average global PIC = \(\sim 5^{+/-1} \times 10^{11}\) moles PIC (Balch et al., unpublished)
  
  Standing Stock = \(6 \times 10^{12}\) g PIC

- Global calcification = \(1.6^{+/-0.3}\) Pg PIC y\(^{-1}\)
  
  (Balch et al., 2007, DSRII); about magnitude of global C production from biomass burning

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

- What is happening to it? It sinks or dissolves

- No indication of a trend in global PIC (e.g. negative trend associated with OA)
How long to detect a change in OA-related variables using satellites

- $pCO_2$ - the current rate of $pCO_2$ change over the globe is ~2 - 2.5 ppm per year. Given overall +/-15 uatm error in estimating $pCO_2$ from space, it will take ~6-8 years to detect a significant change in $pCO_2$

- **Change in $\Omega$** - Monte Carlo analysis. (Note, SST and salinity impart error in both the solubility and the TA algorithm). 1000 Monte Carlo trials yields $\Omega$ error of 0.11 using above assumptions. With annual change in $\Omega$ of 0.01-0.016 units (for rate of $CO_2$ increase of 2-2.5ppm), need about a decade
Take Home Messages

Satellite-derived OA proxies will be important!

- **Satellite measurements:** Sea surface temperature, color, salinity, wind, waves, currents. **DISADVANTAGE:** Satellites mainly see the surface; **ADVANTAGES:** Synopticity, high n (for statistics)
- These enable understanding of physical, chemical, and biological phenomena that drive regional OA dynamics
- Elucidate potential impacts of carbon cycle change on a broad range of ecosystems.
Take Home Messages (cont.)

• Visible and thermal satellite data not robustly correlated with pH or $T_{CO2}$ over larger spatial scales.

• Total Alkalinity arguably most viable in support of carbonate system and OA studies. T_{alk} accuracy of ±10-15 uMol/kg

• Probably no single $pCO_2$ algorithm will be applicable at the global scale. State-of-the-art ~± 15ppmv accuracy in regional $pCO_2$. Tougher near coasts. Will need help from in-water data.
So hang onto your hats... satellite remote sensing of OA is coming!
Global PIC Time Series- MODIS Aqua

Thank you!