# Satellite tools and approaches for OA research

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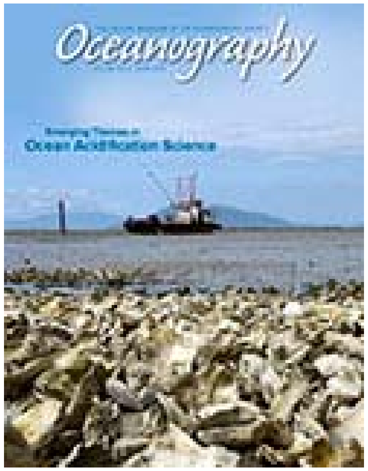
# Acknowledgements





- **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)**
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# Overview

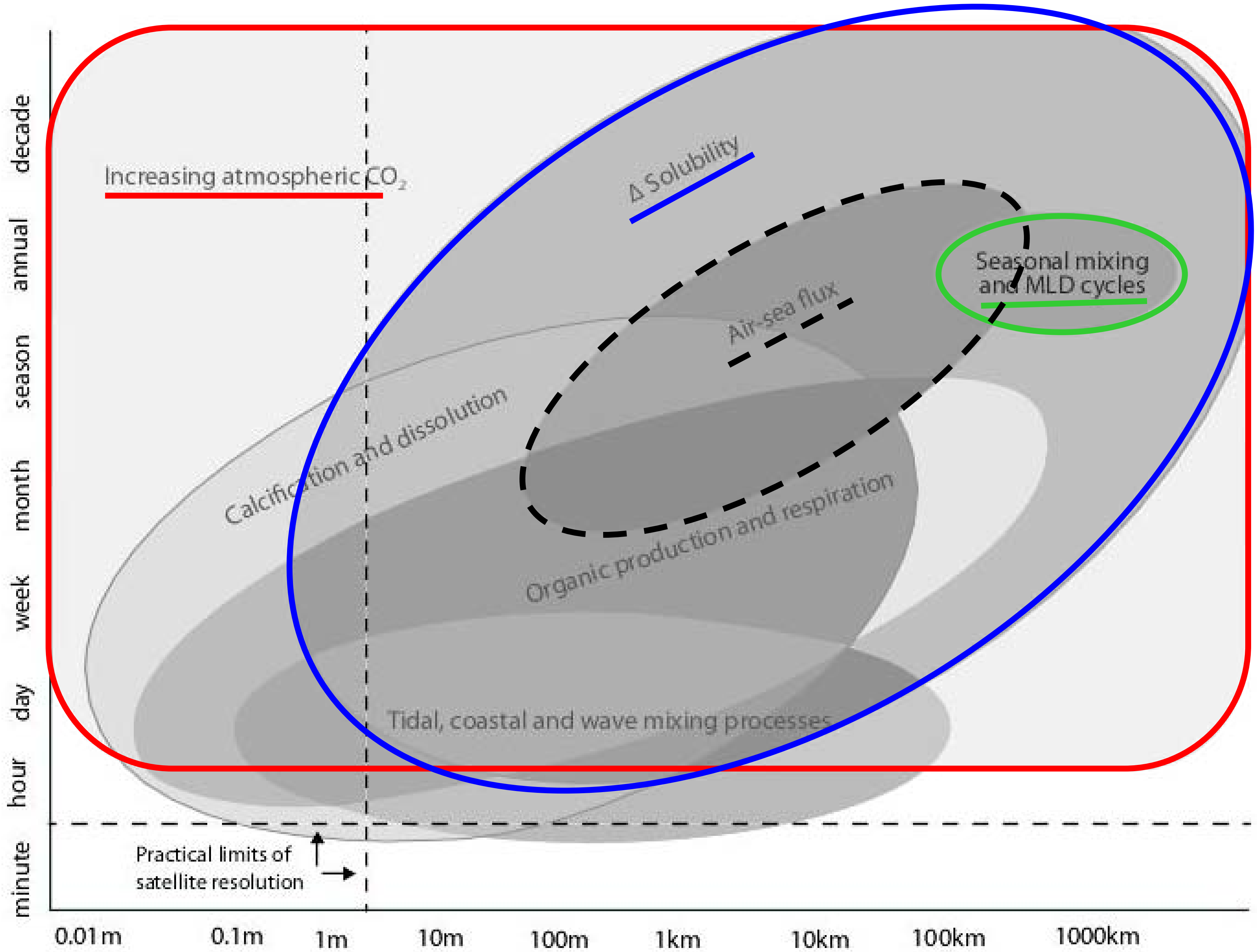
- Space/time variability of
  - environmental variables measured,
  - relevant processes
  - Problem coastal waters
- Satellite constellation for OA work
- In search of two proxies of the carbonate system to measure
- Example: Focus on one product: [PIC] from space.

# Introduction

- Surface $pCO_2$ is increasing by ~2 µatm $yr^{-1}$, (nearly same rate as for atmospheric $pCO_2$)(LeQuéré et al., *Earth System Science Data Discussions* 2014).
- Saturation state of aragonite ($\Omega_{ar}$), also decreasing by ~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?!?

# OA-Related Processes

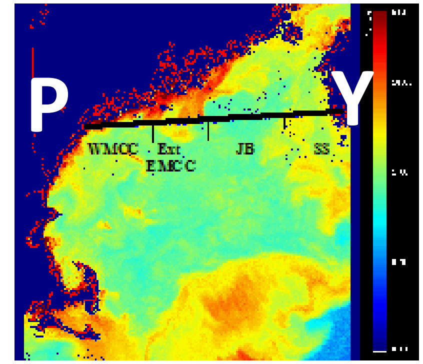


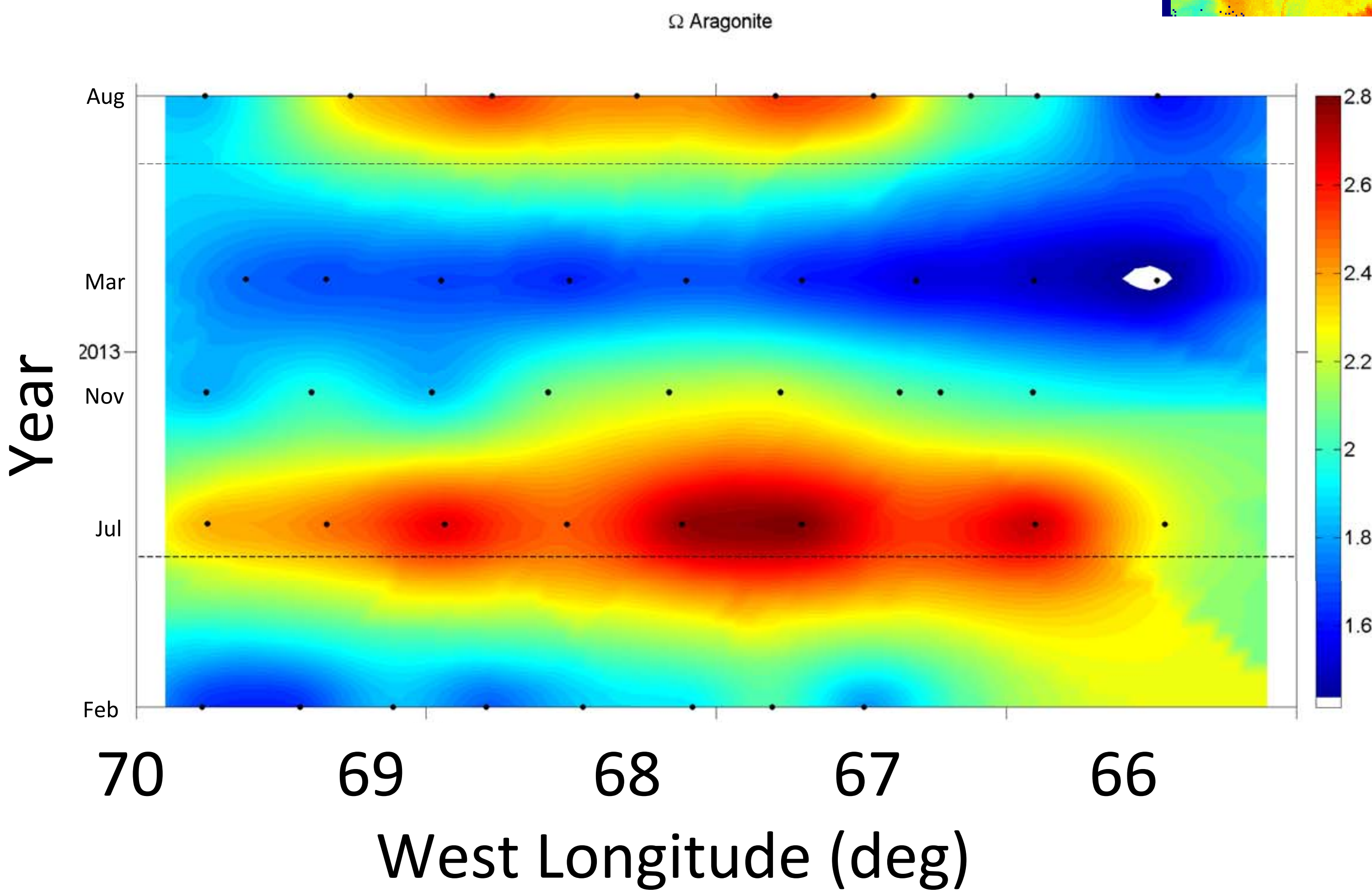
# Major impacts of OA likely to occur in coastal regions

- 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

$\Omega_{aragonite} = [Ca^{++}]\,[CO_3^{=}]/Ksp_{arag}$



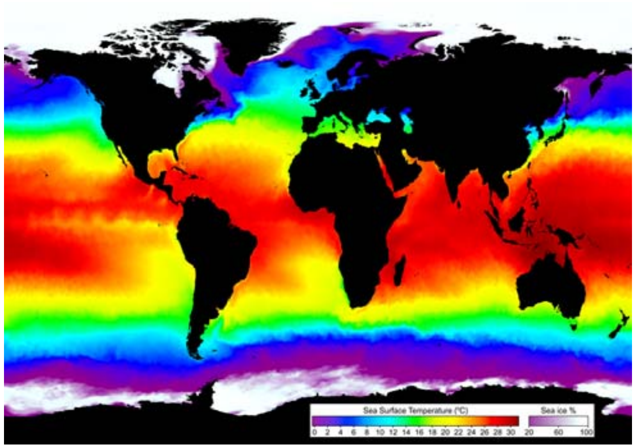



# What satellite products can we use?

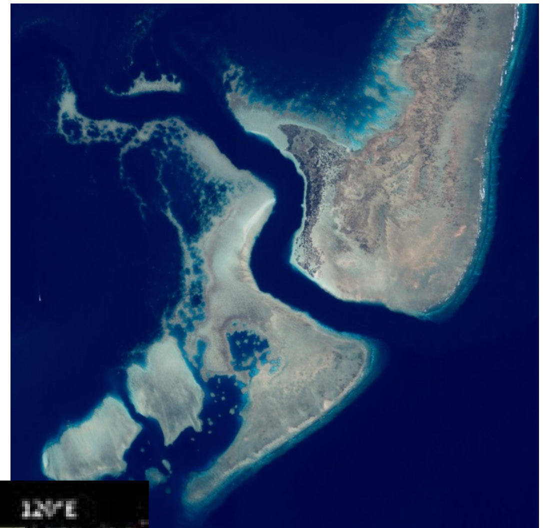
- Satellites do **<u>not</u>** directly measure chemistry;
- Satellites provide statistical proxies of carbonate, or as elements in quasi-mechanistic chemical reconstructions
- Need some support from in-water observations.
- Satellite-derived POC, Chlorophyll, or particulate inorganic carbon (PIC), yields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


SATELLITES
presently flying
GOES
OCO-2
Grace
Aquarius
KOSI
AQUA
ASCAT
SUOMI
DIGI
AVHRR
SMOS
DMSP
SMAP
MERIS
SWOT

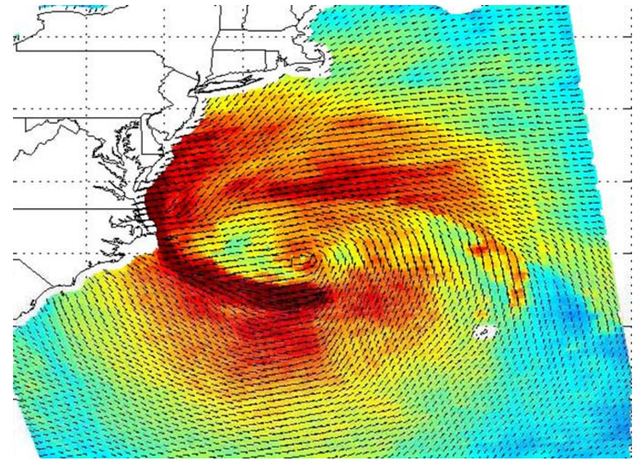
SST



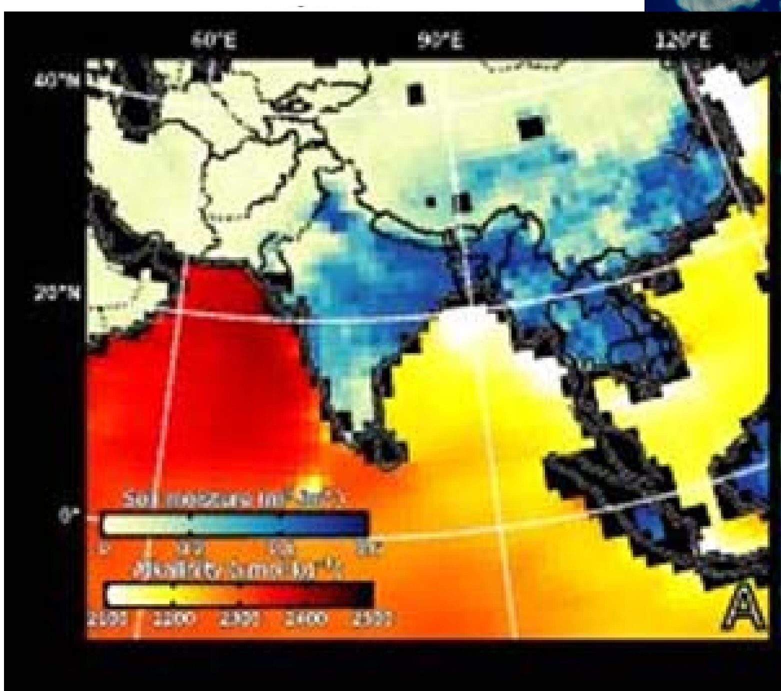
Visible Band
High res



Winds

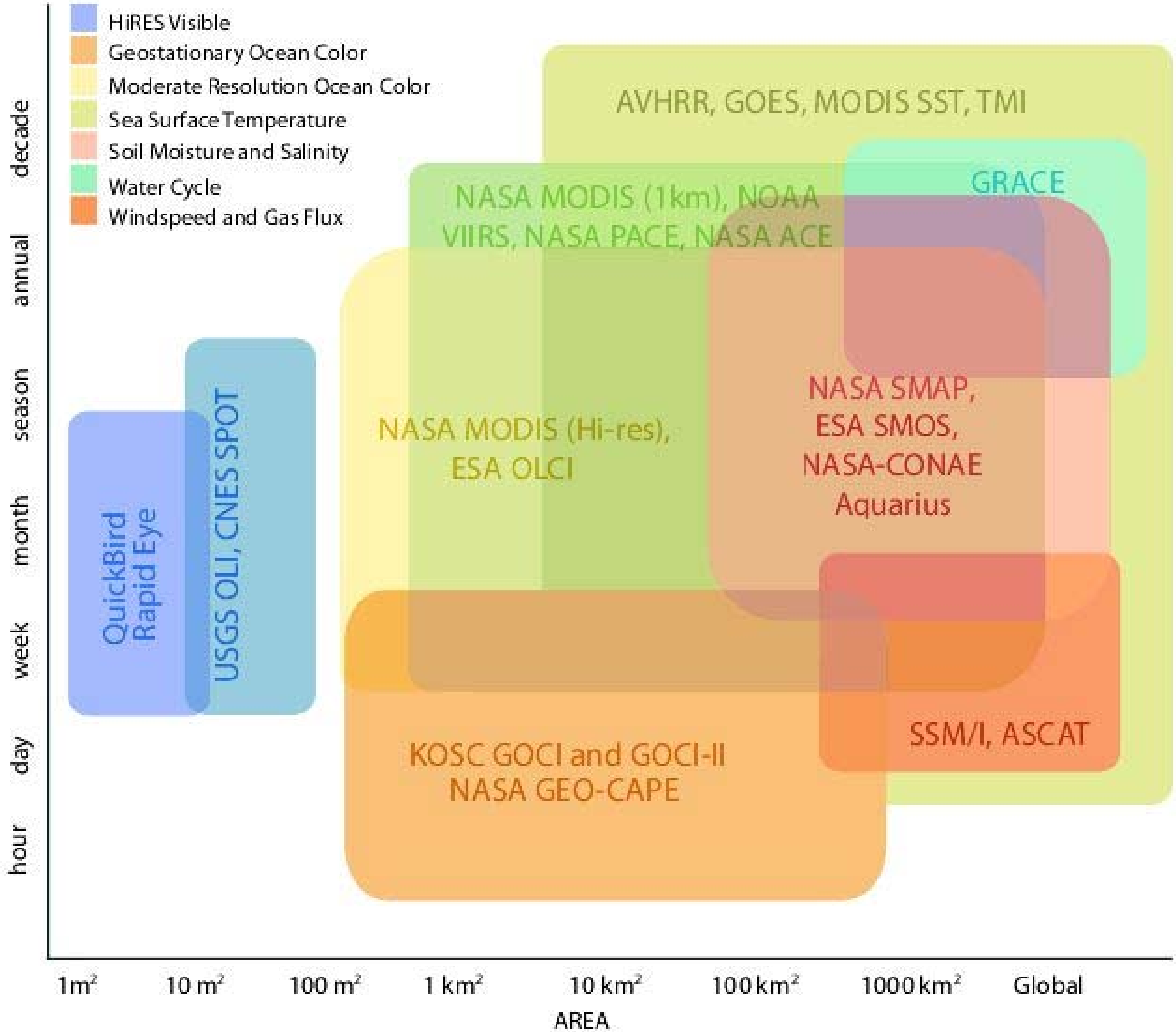


Salinity




PIC

# Scales of space and time for earth viewing satellites

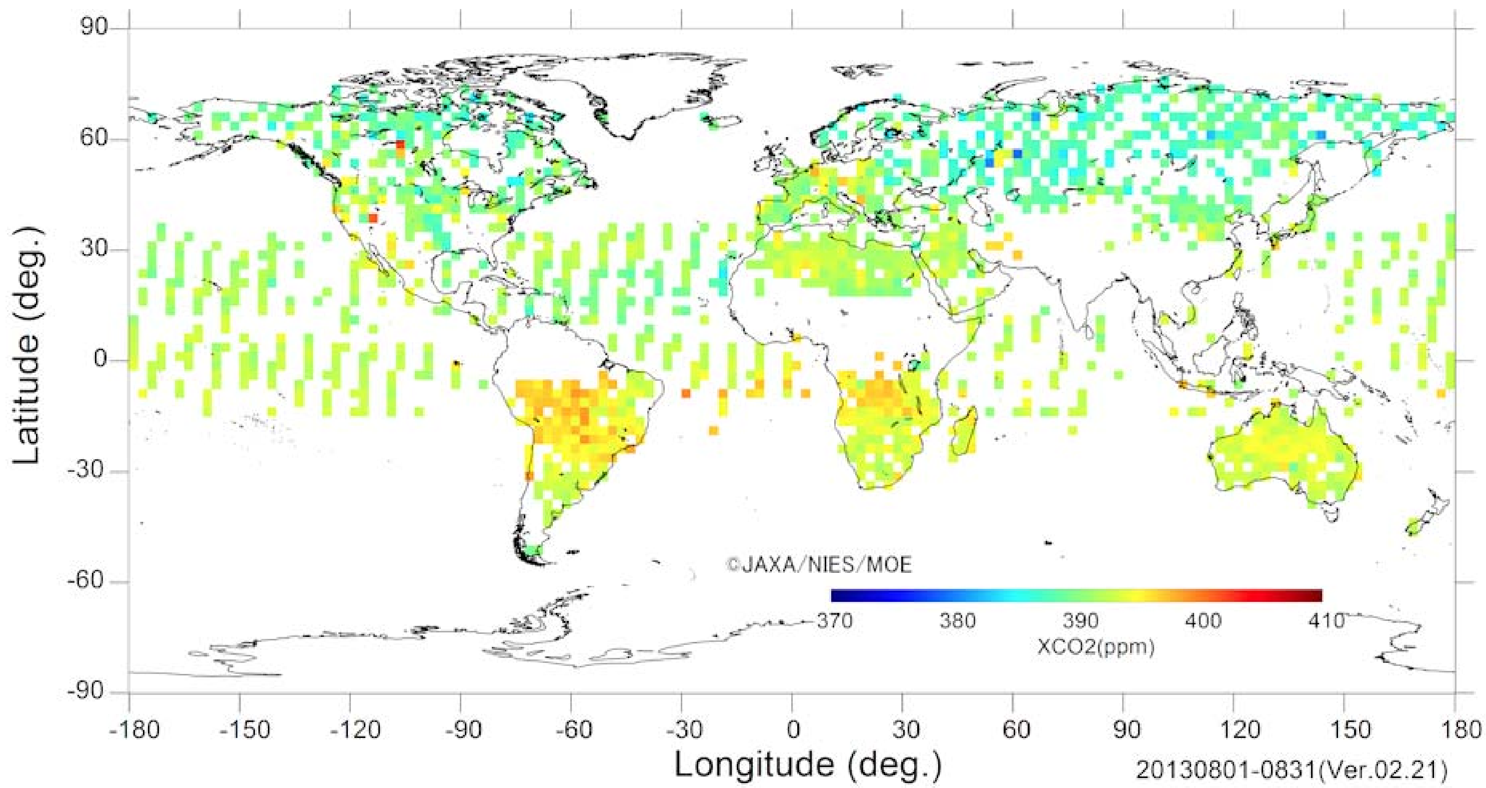


# Remote Sensing of environmental variables, standing stocks and processes relevant to OA:

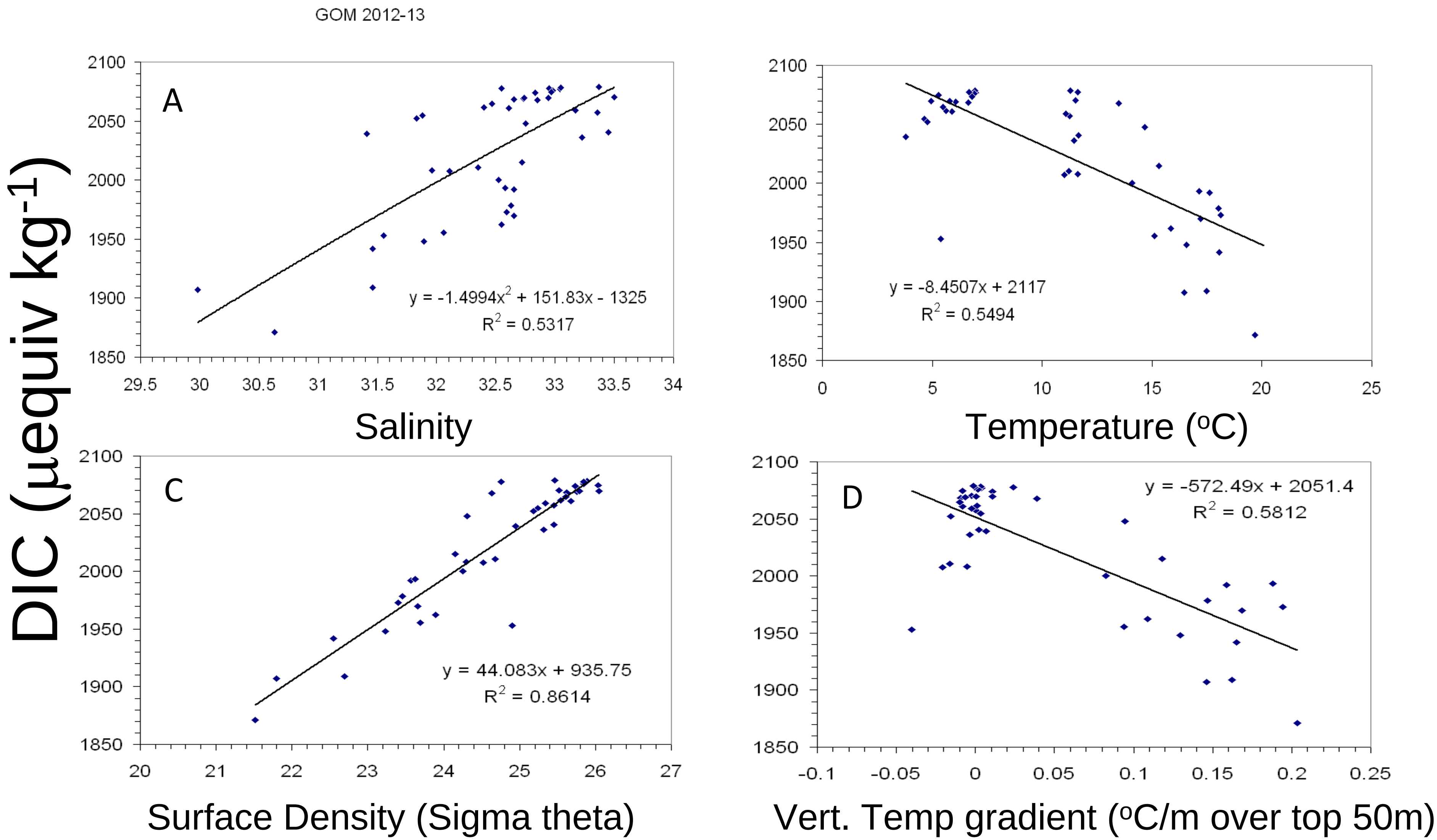
- **SST** (Minnett and Barton, 2010, In *RadiometricTemperature Measurements: II. Applications*)
- **POC** (Stramski et al., 2008, Biogeosciences)
- **PIC** (Balch et. al, 2005, JGR)
- **Photosynthetically Available Radiation (PAR)** (Frouin et al., 2012, Rem. Sensing Environ.)
- **Phytoplankton light 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

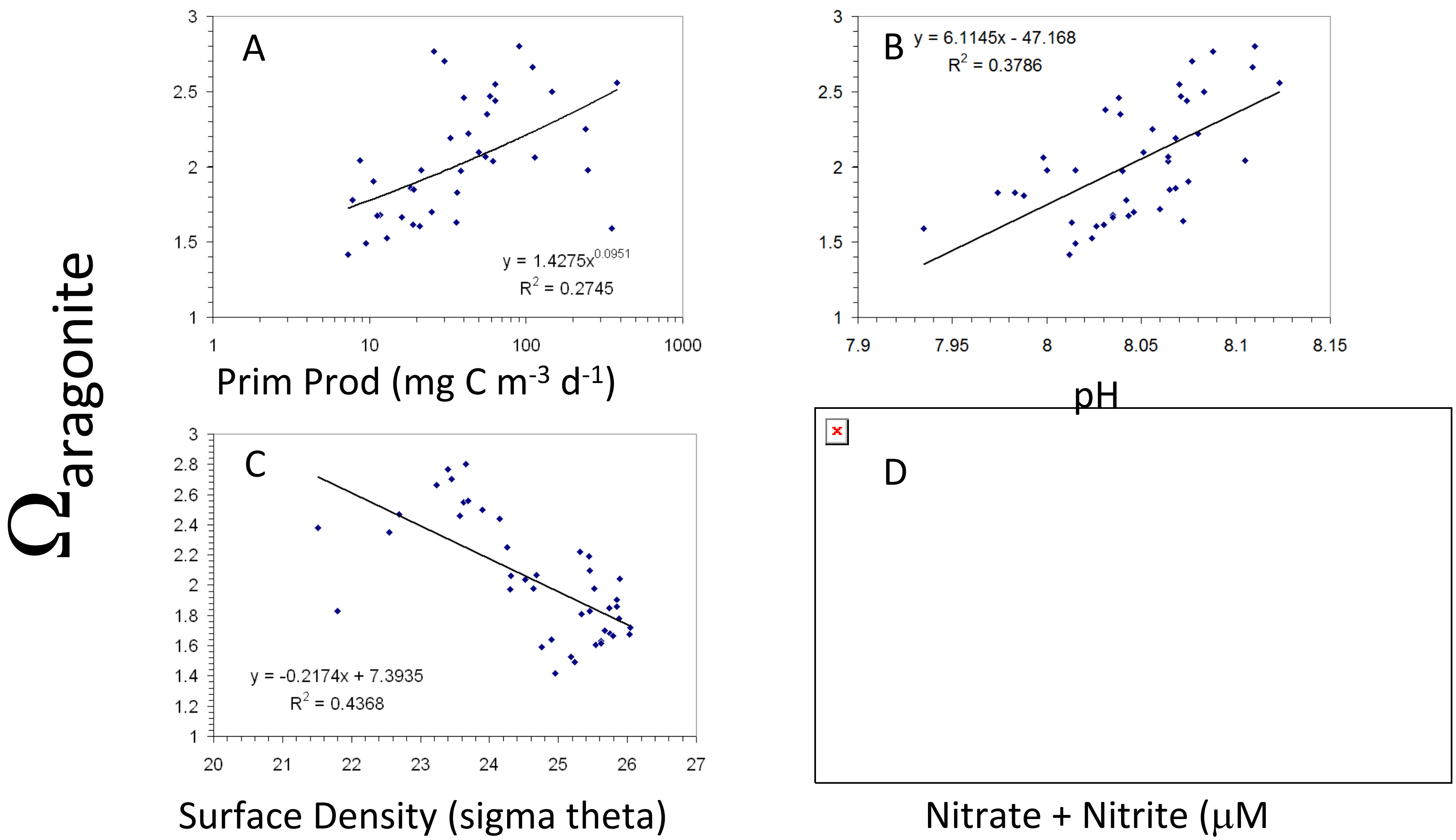
- Atmospheric $CO_2$: a new data set for investigations of air-to-sea $pCO_2$ disequilibrium



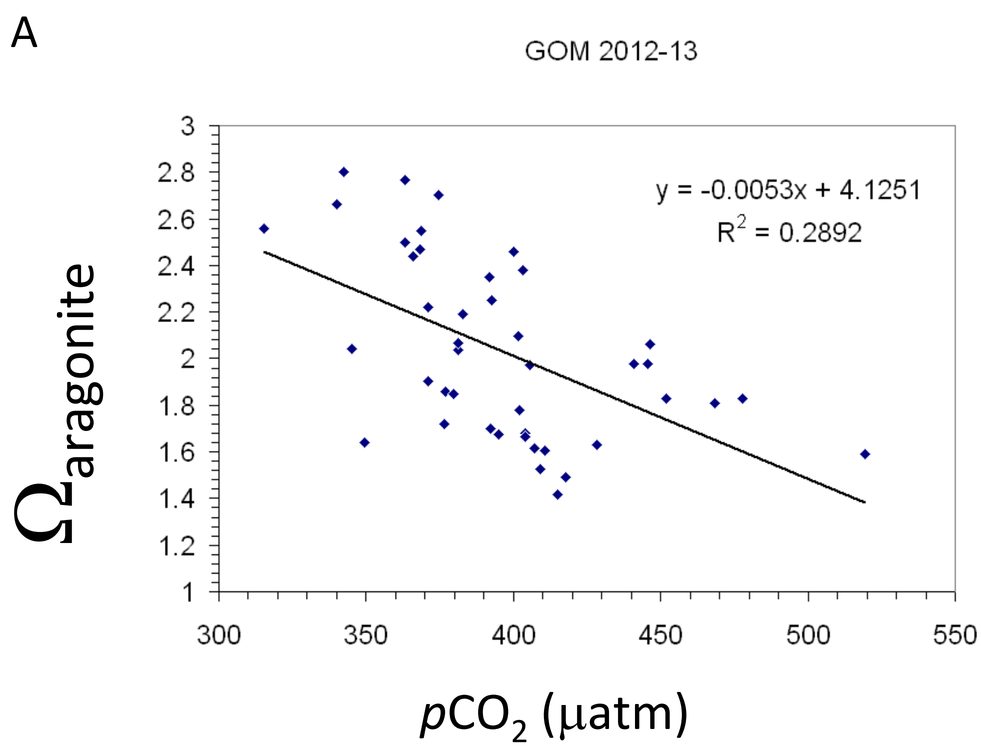
# Regional Gulf of Maine proxies with DIC



# Physical, biological, chemical proxies in the Gulf of Maine for $\Omega_{aragonite}$



# Saturation State and $pCO_2$



# Satellite approaches for estimating $pCO_2$ and air-sea $CO_2$ flux

- *In situ* surveys and global $p$$CO_2$ monitoring: Surface Ocean $CO_2$ Atlas (SOCAT) database
- Air-sea flux estimates: created by combining $p$$CO_2$ disequilibrium with satellite sea state data (often based on wind-speed) to estimate $CO_2$ gas-exchange coefficients (Wanninkhof, 2014, L&O Methods).
- Knowledge of $p$$CO_2$ and Talk allows estimation of Ω calcite and Ω aragonite saturation states, and global Ω 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 Ω within the greater Caribbean region (Gledhill et al., 2009, Oceanography)

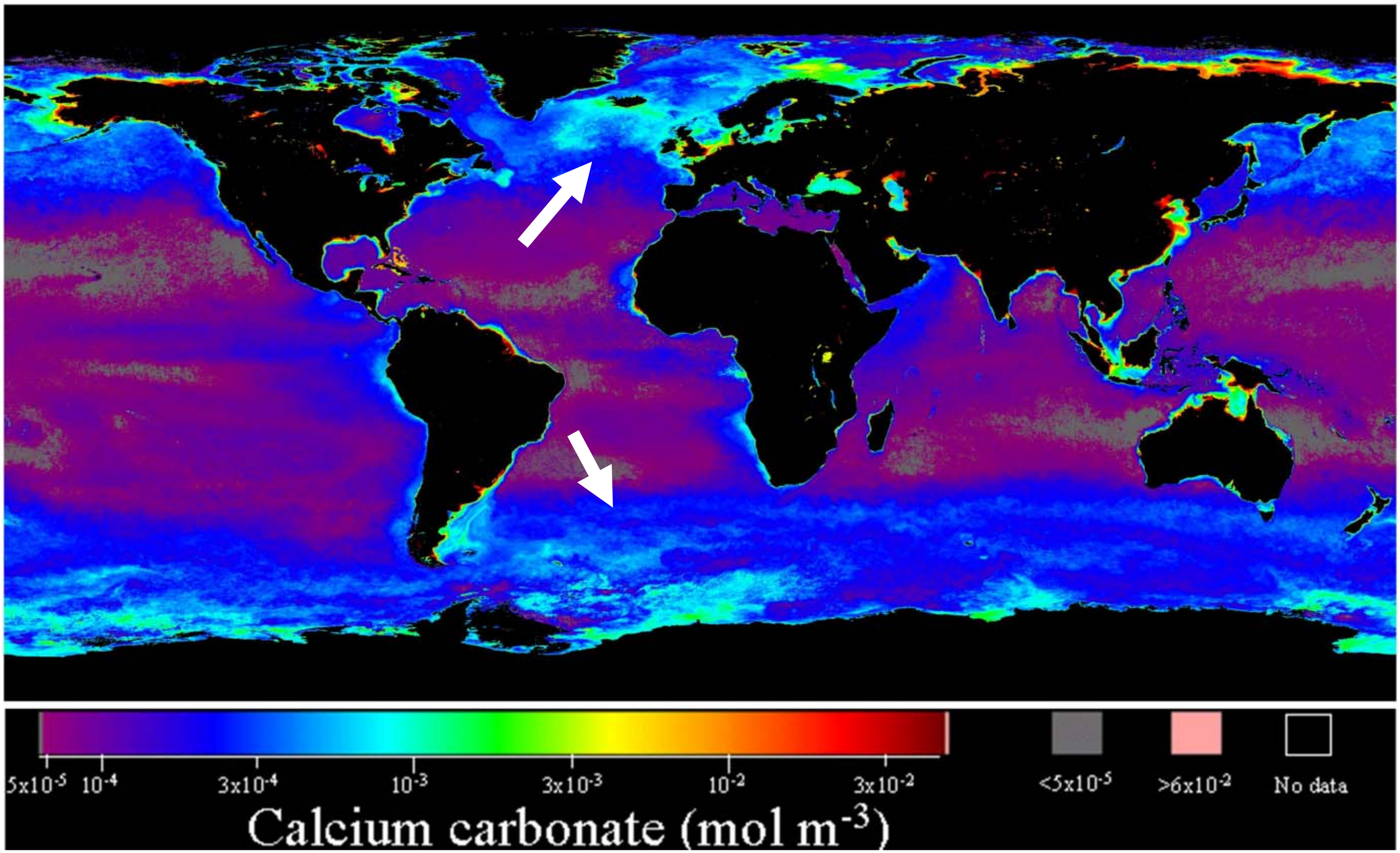
# State of the Art in Remote Sensing of Carbonate System Variability

- Remote Sensing of Total Alkalinity: arguably most viable in support of carbonate system and OA studies
  - $T_{alk}$ 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 $T_{alk}$
- Satellite $T_{alk}$ product resolution 50-150 km spatial resolution in salinity data; (e.g. ± 0.2 in satellite-derived salinity translates to ±10-15 uMol/kg in $T_{alk}$)
- Sparse literature on using satellite data for $T_{CO2}$ and pH retrievals
  - weaker covariance with salinity (than $T_{Alk}$)
  - visible and thermal data not robustly correlated with pH or $T_{CO2}$ over larger spatial scales.

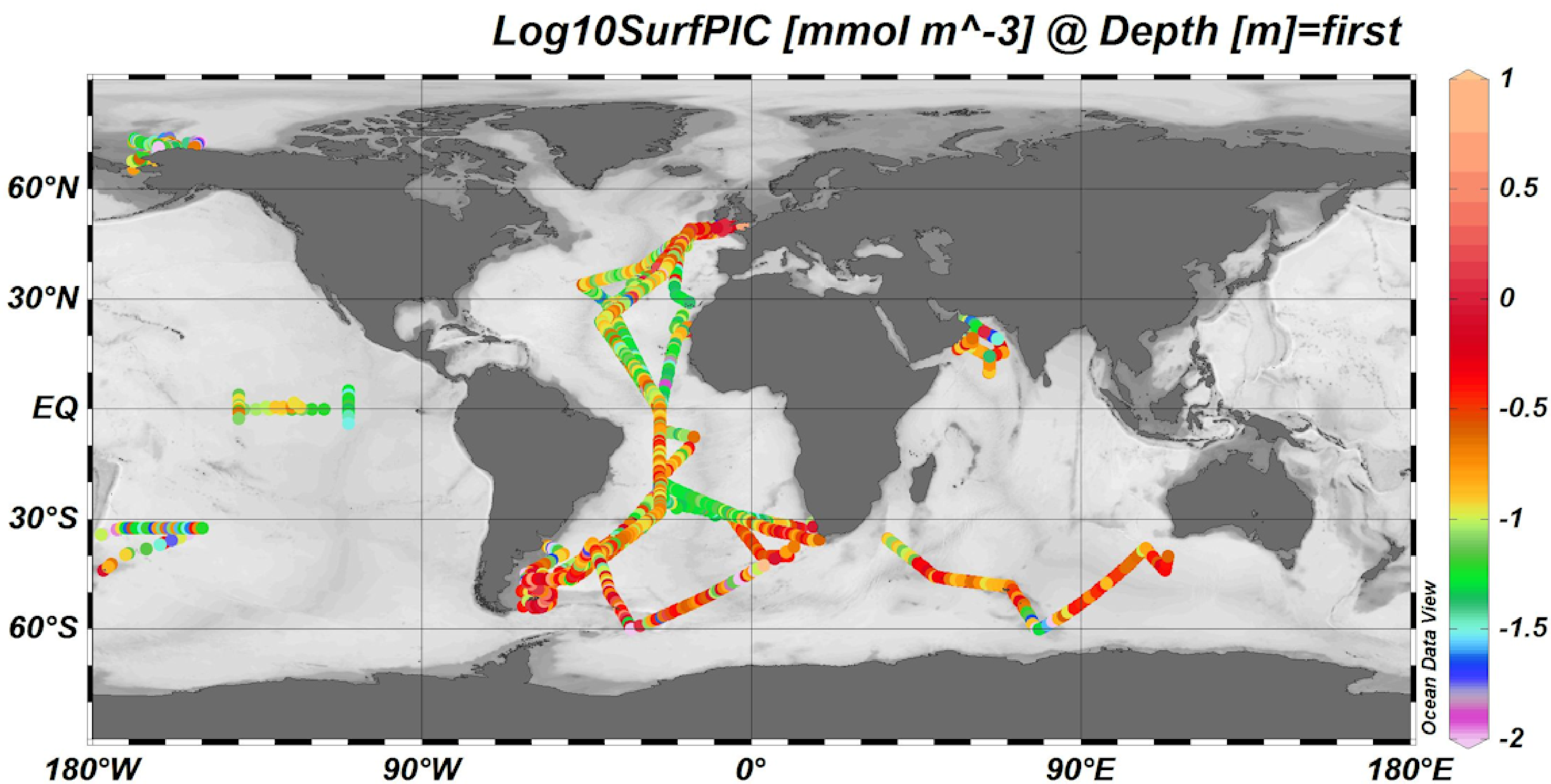
# Bottom line on deriving $p CO_2$…

- Diversity and complexity of ocean biogeochemical provinces, plus steadily increasing surface water $CO_2$ levels, suggest, no single $p CO_2$ algorithm will be applicable at the global scale.
- State-of-the-art for these satellite-based algorithms =± 15ppmv accuracy in regional $p CO_2$. However, in complex coastal regions with large magnitude variation, accuracy will likely be lower (Hales et al., 2012, Prog. Oceanogr.).

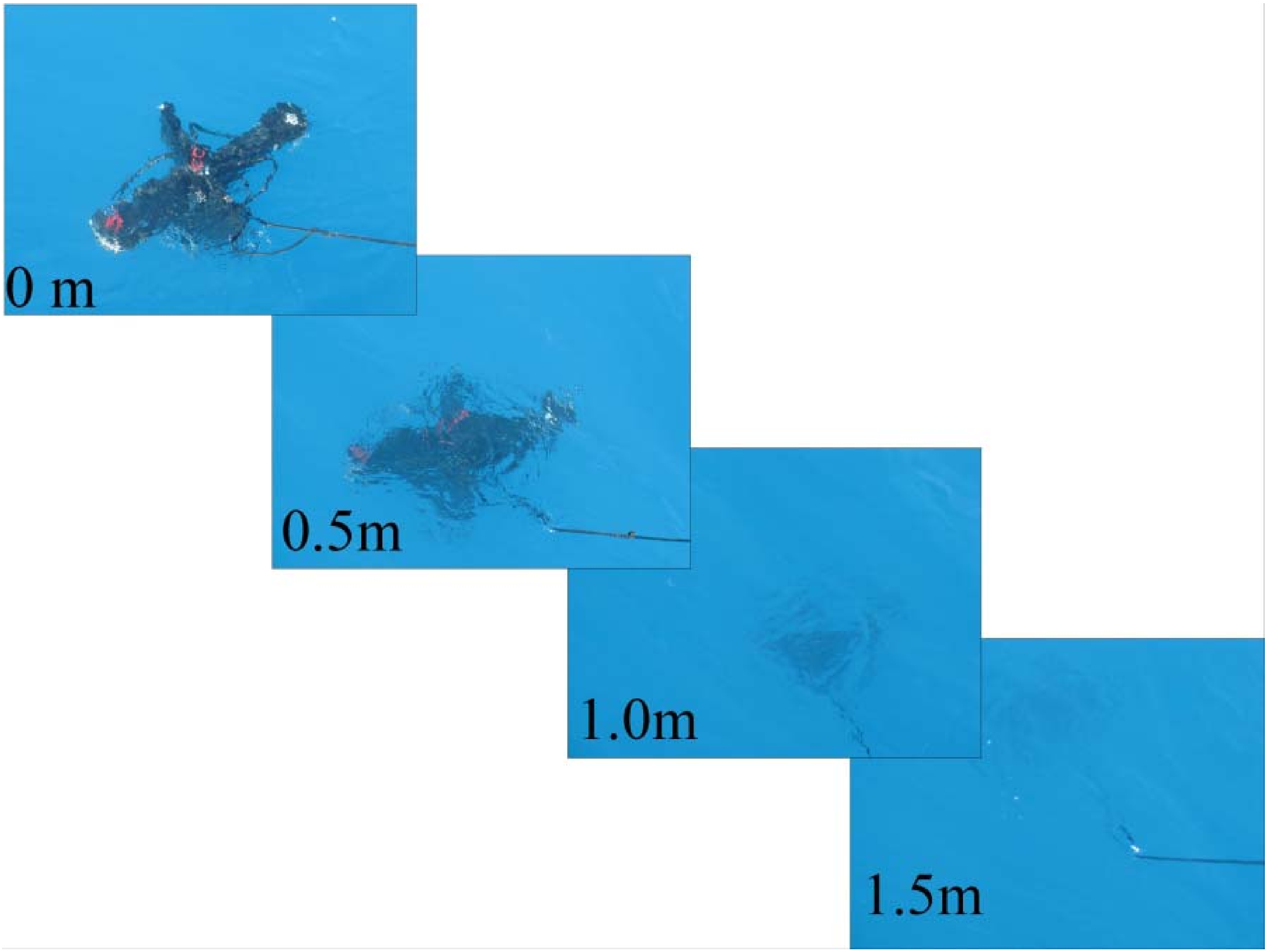
# PIC Product: 2B/3B algorithm (Vis, IR, NIR)



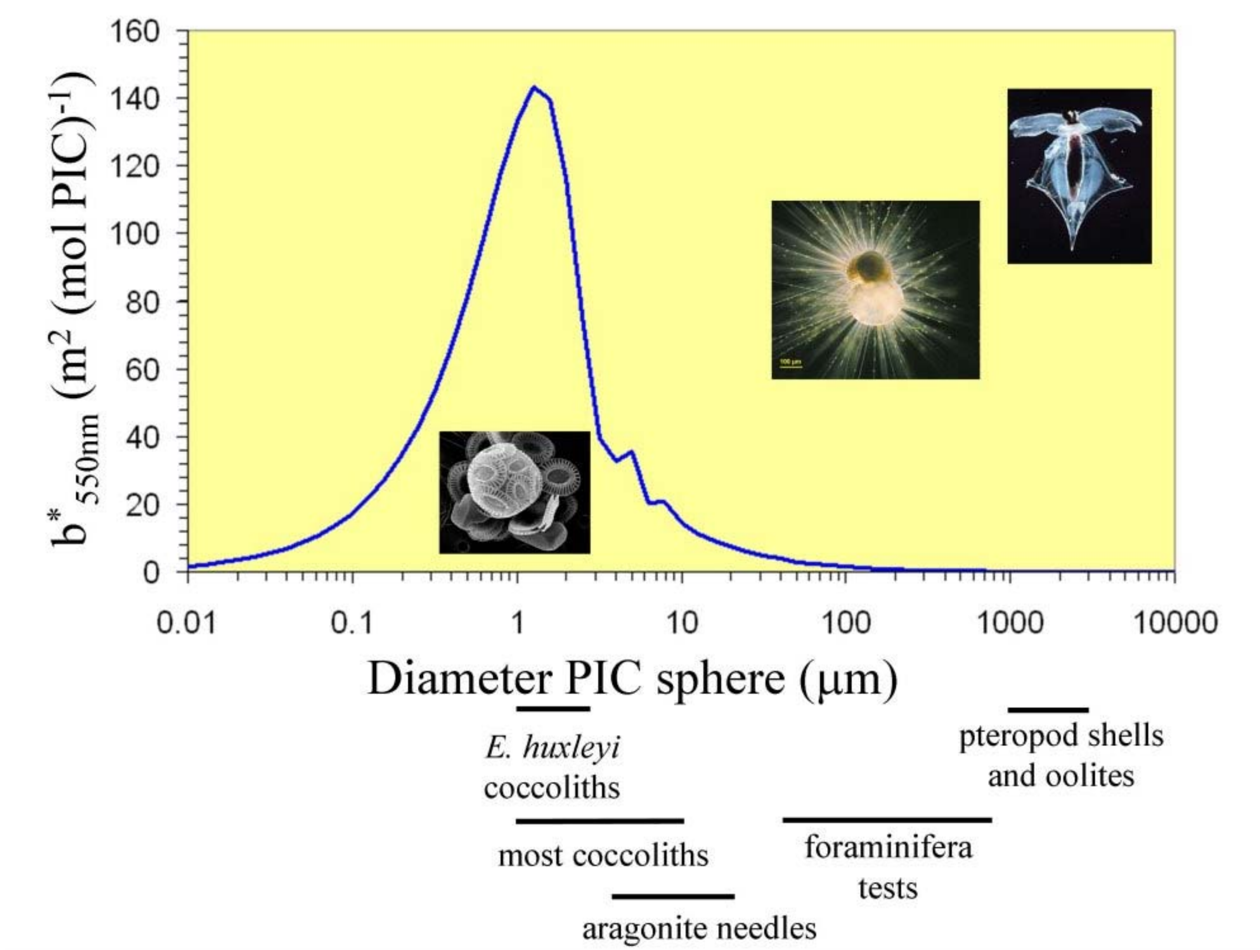
# PIC view from ships…



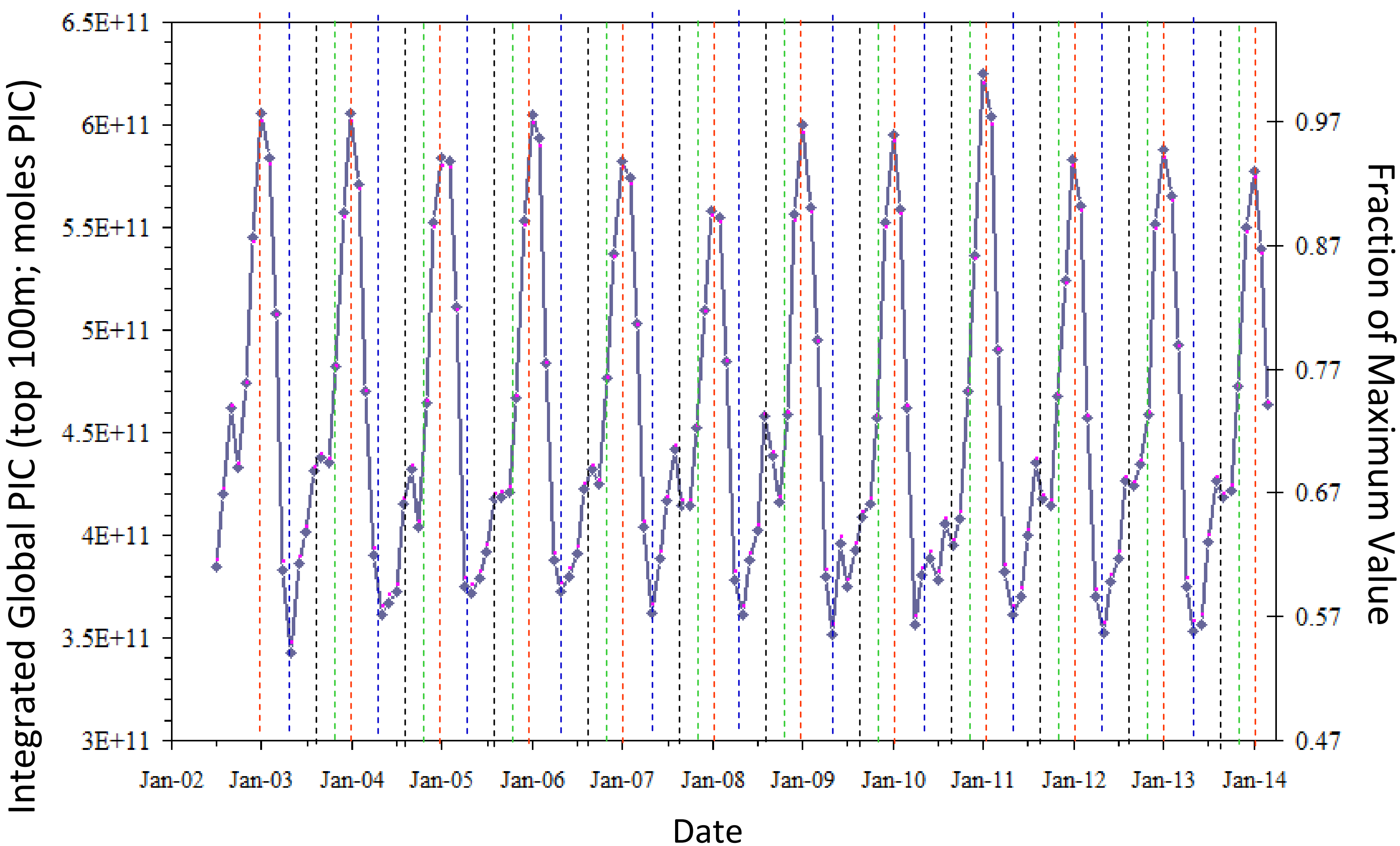
# PIC shoals the euphotic zone



# 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 =~5[+/-1] x $10^{11}$ moles PIC (Balch et al., unpublished)

  Standing Stock =6 x $10^{12}$ 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 x $10^{12}$ g PIC)/(1.6 x $10^{15}$ g PIC $y^{-1}$)= 0.003 y =~1.1d 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 Ω* -** Monte Carlo analysis. (Note, SST and salinity impart error in both the solubility and the TA algorithm). 1000 Monte Carlo trials yields *Ω* error of 0.11 using above assumptions. With annual change in *Ω* of 0.01- 0.016 units (for rate of $CO_2$ increase of 2-2.5ppm), need about a decade

# Take Home Messages

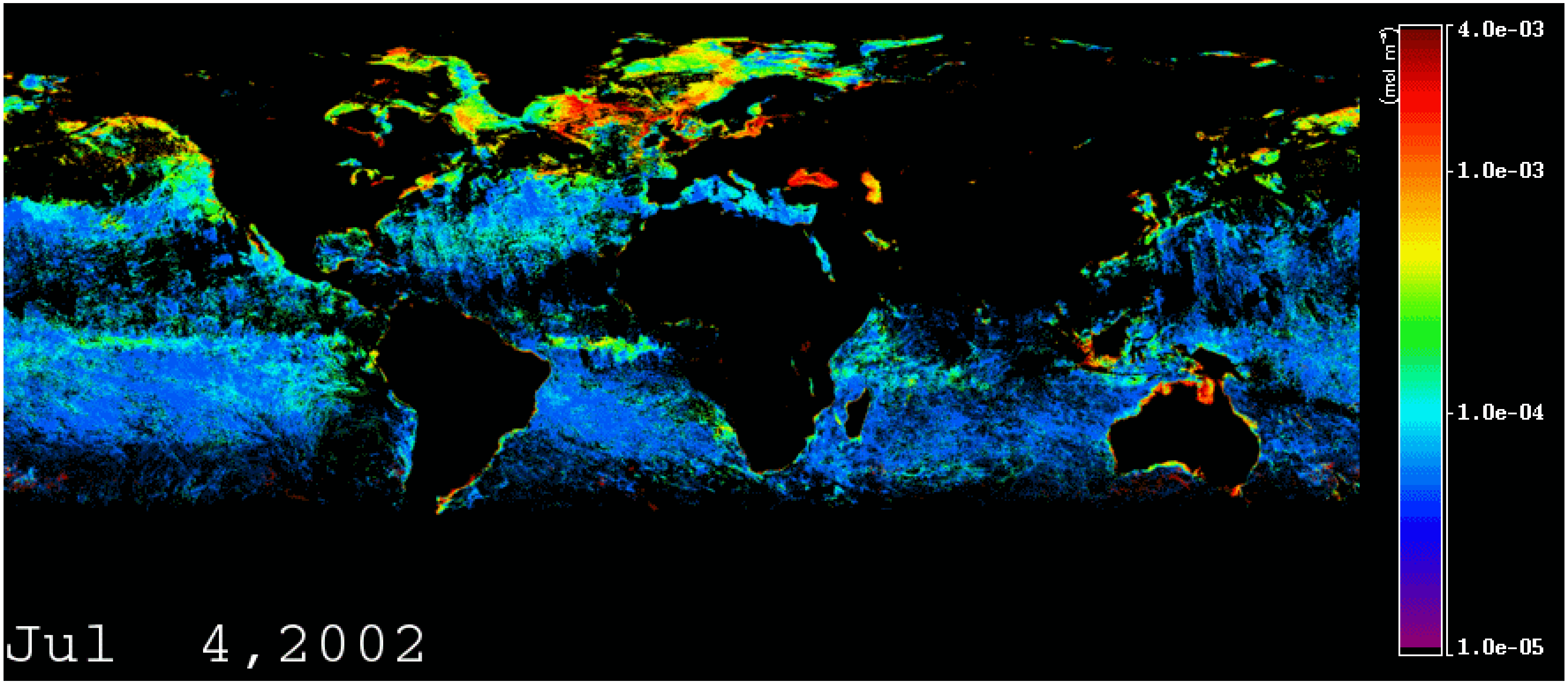
**Satellite-derived OA proxies will be important!**


- **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 $p$CO$_2$ algorithm will be applicable at the global scale. State-of-the-art ~± 15ppmv accuracy in regional $p$CO$_2$. 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!*

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